Cold atoms and Condensed Matter

T. Giamarchi

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

UNIVERSITÉ DE GENÈVE

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

MaNEP
SWITZERLAND

Theory:

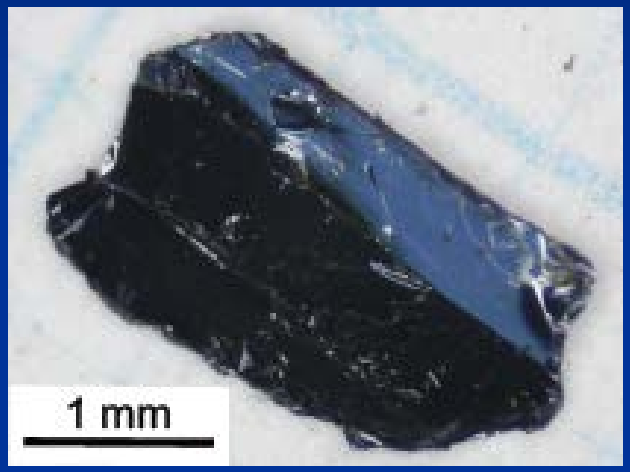
C. Berthod (Geneva)
A. Kantian (Geneva U.)
C. Kollath (Bonn U.)
U. Schollwoeck (Munich U.)
G. Orso (Paris-Diderot)
A. Iucci (la Plata)
M. Cazalilla (Taiwan)
Z. Ristivojevic (ENS, Paris)
A. Petkovic (ENS, Paris)

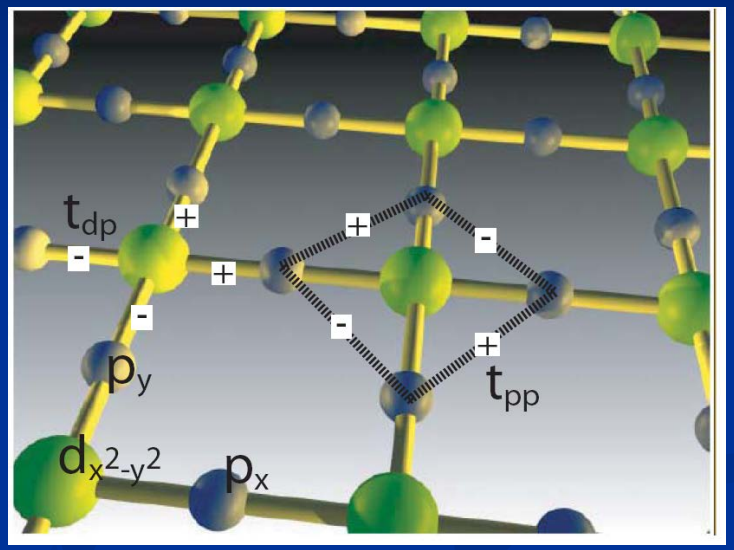
P. Le Doussal (ENS)
M. Zvonarev (LPTMS)
V. Cheianov (Lancaster)
G. Roux (LPTMS)
I. McCulloch
(Queensland U.)
……

Experiments :

Florence: G. Modugno, F. Minardi, M. Inguscio groups
Munich : S. Kuhr, I. Bloch groups
Bonn: M. Koehl's group
Kyoto: Y. Takahashi's group

CM: From reality to a simplified model

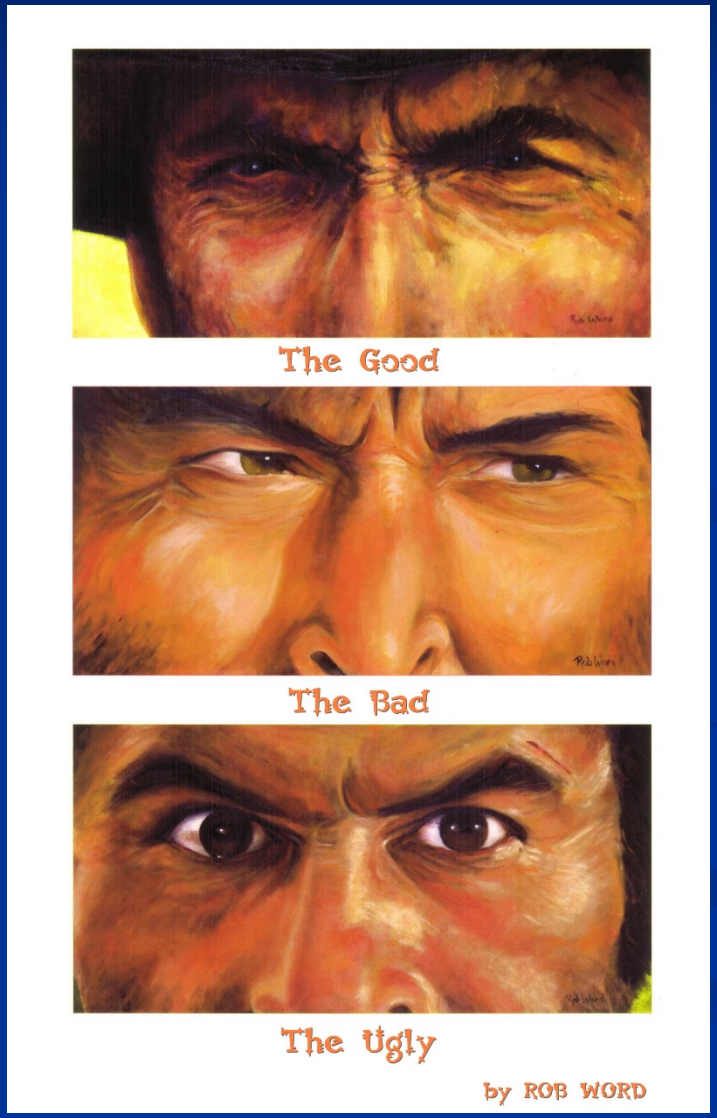




Usually still too complicated to solve !

Results: approximations on the model or reality

The result :

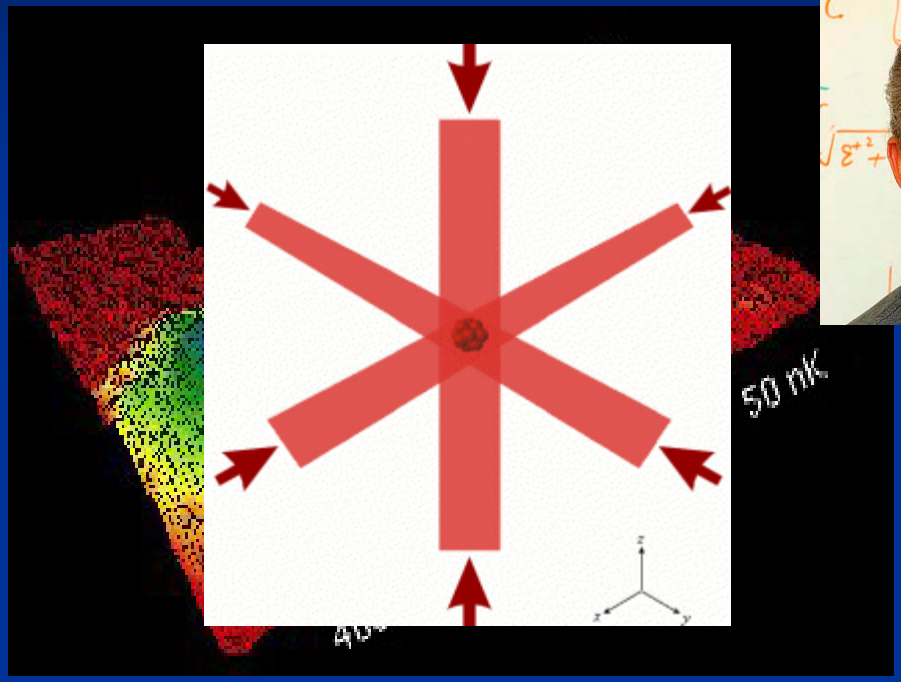


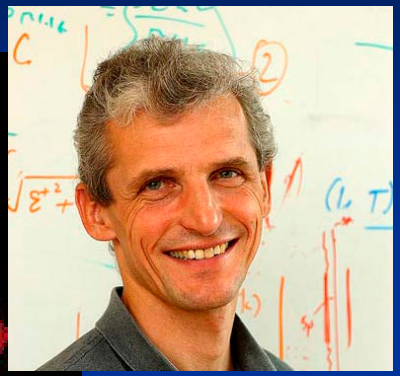
Quantum simulators

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)

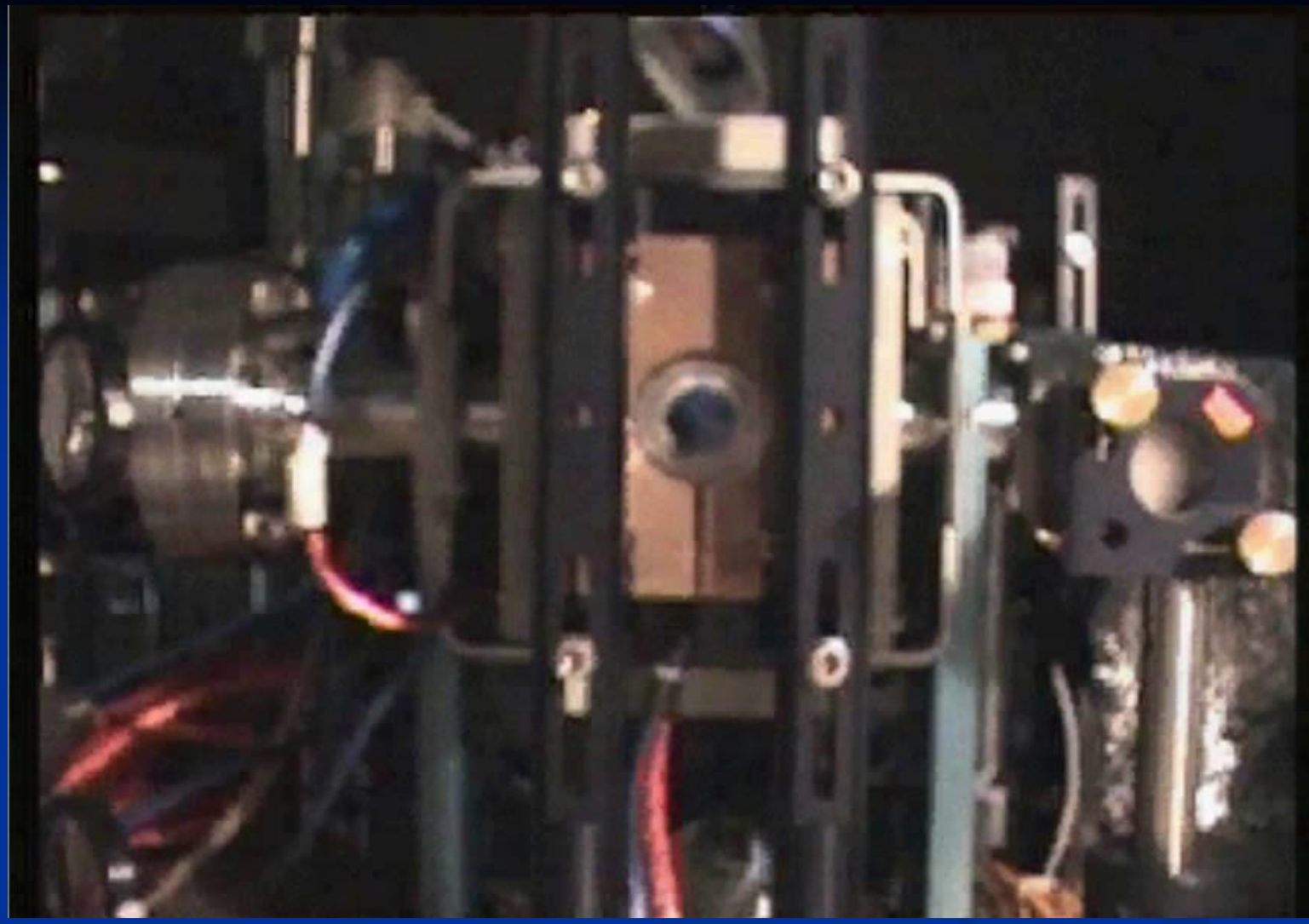
BEC in cold atomic gases





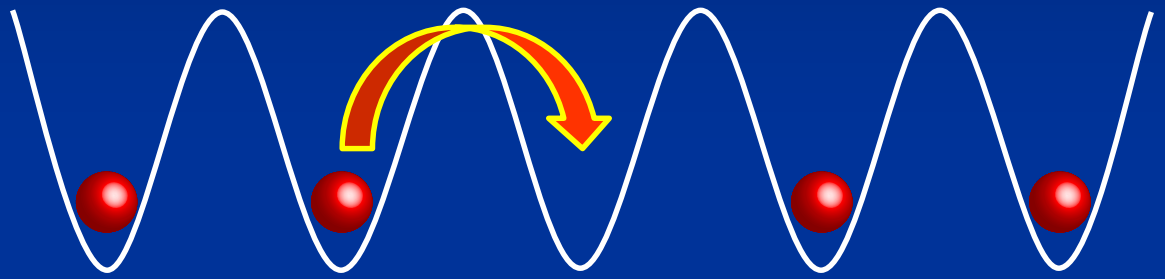
2001: Cornell, Ketterle, Wieman

Groupe: T. Esslinger (ETH, Zurich)

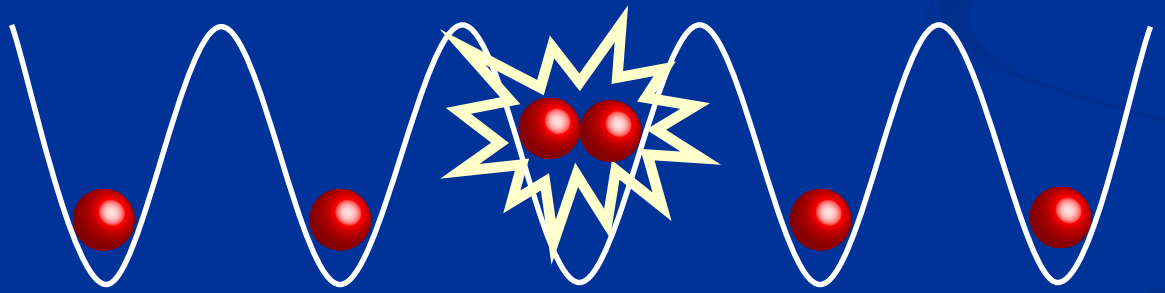


Groupe: I. Bloch (Munich U.)

Virtual solids



Tunnelling

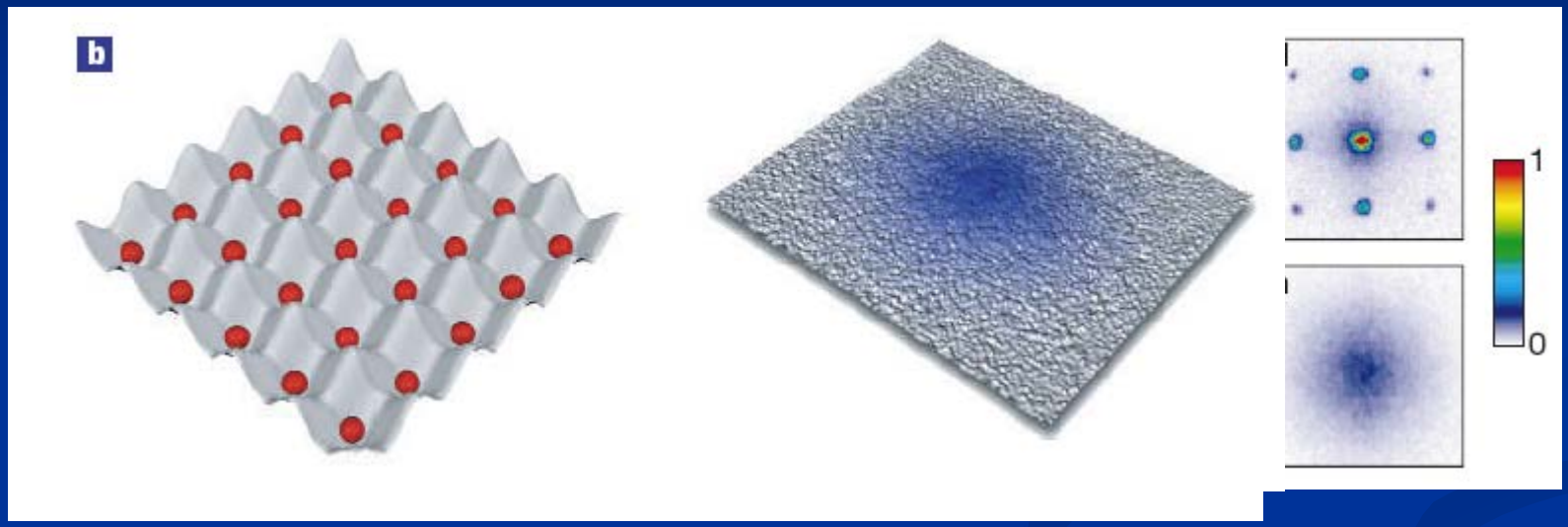


Short range interaction

P. Zoller

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

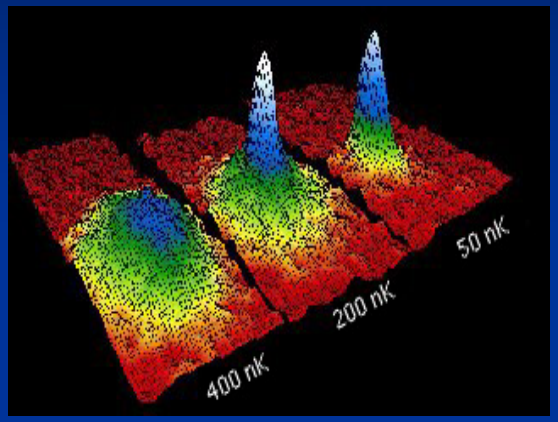
Simulators for condensed matter



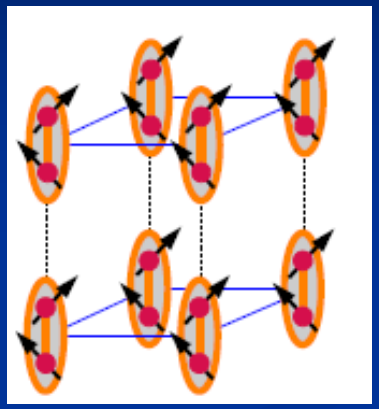
M. Greiner, O. Mandel, T. Esslinger, T. W. Hansch, I. Bloch, Nature 415 39 (2002)

Other quantum simulators

Cold atoms



Dimers/Spins



Bose gas	Antiferromagnet
Particles	Spin excitations ($\Delta S^z = \pm 1$)
Boson number N	Spin component S^z
Charge conservation U(1)	Rotational invariance O(2)
Condensate wavefunction $\langle \psi(\mathbf{r}) \rangle$	Transverse magnetic order $\langle s_i^x + i s_i^y \rangle$
Chemical potential μ	Magnetic field B
Superfluid density ρ_s	Transverse spin stiffness
Mott insulating state	Integer magnetization plateau

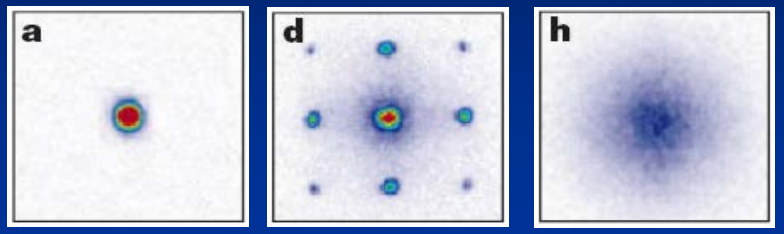
TG, Ch. Rüegg, O. Tchernyshyov, Nat. Phys. 4 198 (08)

Cold atoms

Dream

Perfect control on the model

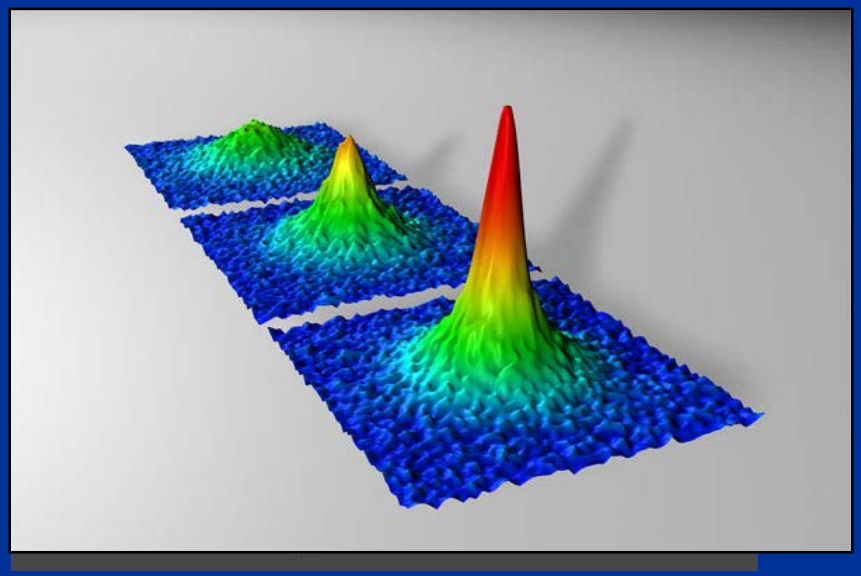
Interactions
(Lattice, Feschbach resonnance)

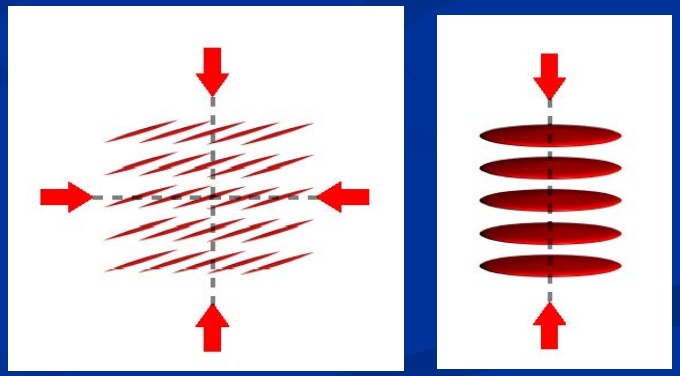


Statistics

Fermions
Bosons

Dimensionality





Hubbard model

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

LETTERS

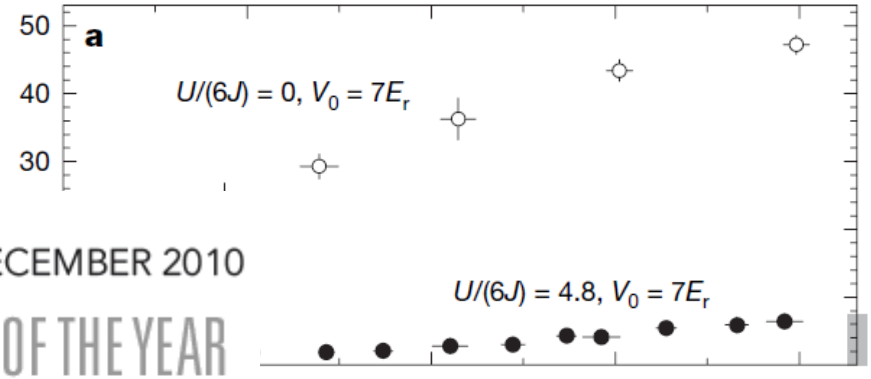
A Mott insulator of fermionic atoms in an optical lattice

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

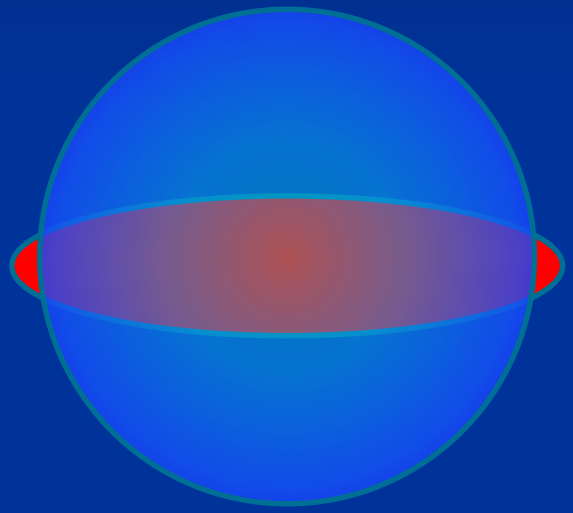
Many possibilities

- Exotic lattices
- Novel probes (double occupation etc.)
- Artificial gauge fields (A)
- Out of equilibrium phyiscs (pump probes)
- Long range interactions (dipolar; Rydberg)

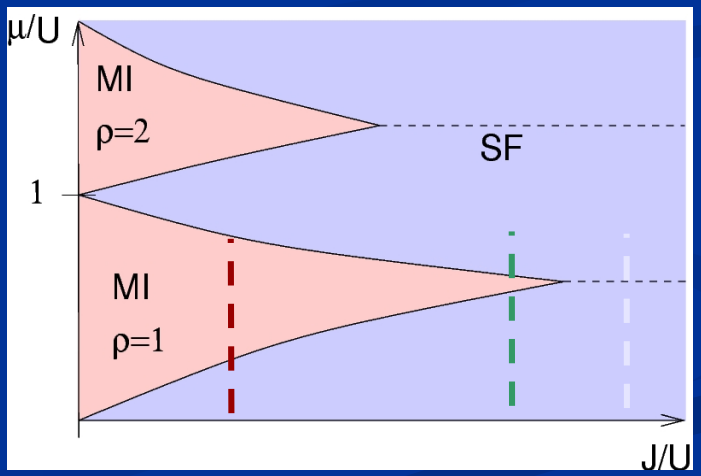
But …..

I am your worst nightmare

Confining potential



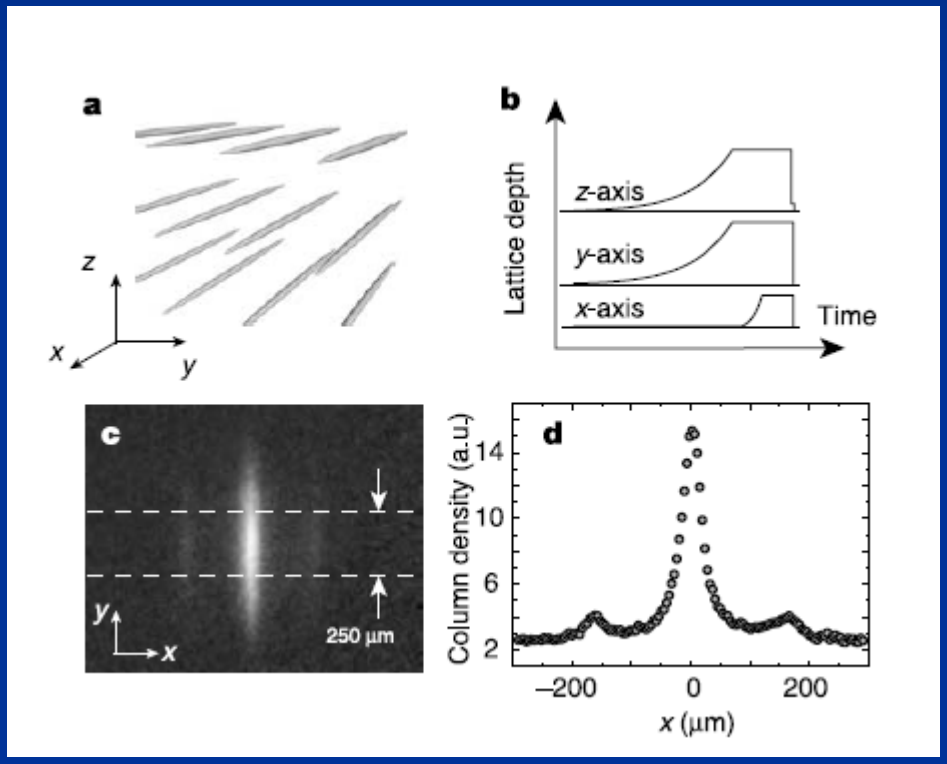
$$H = \int d^3 r \frac{1}{2} \omega_0^2 r^2 \rho(r)$$

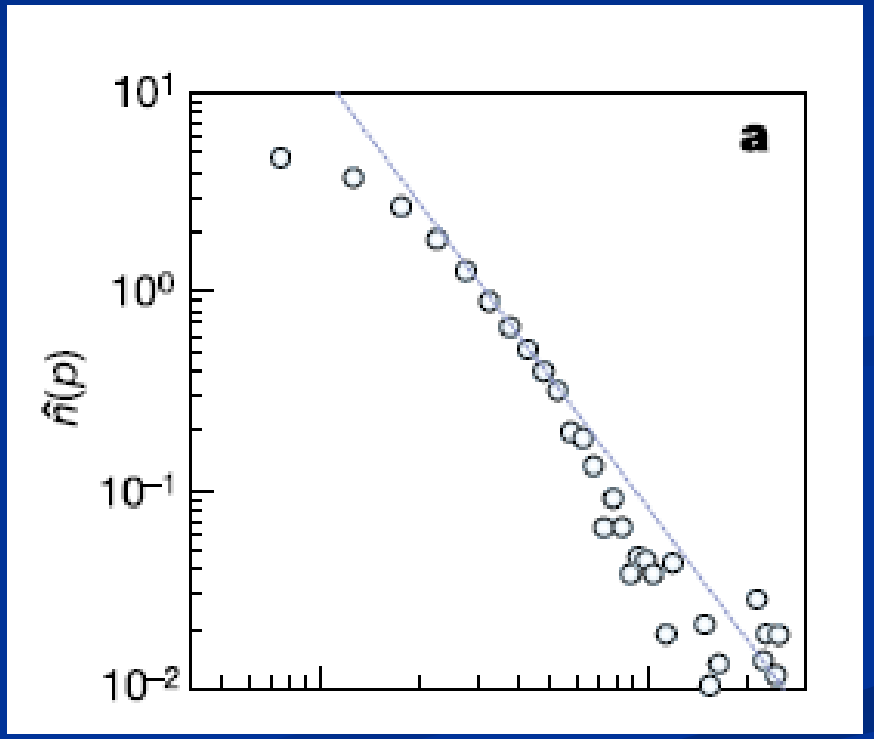


- No homogeneous phase !

Very repulsive bosons : TLL ?

B. Paredes et al., Nature 429 277 (2004)





$$n(k) = \int dx e^{ikx} \langle \psi^\dagger(x)\psi(0)\rangle \sim 1/\sqrt{k}$$

Important ``problems”

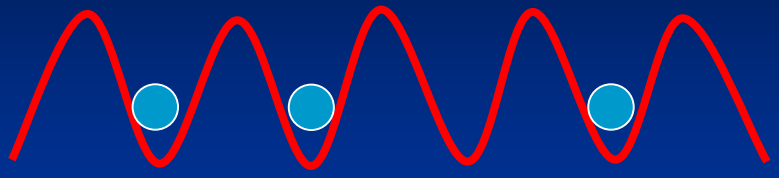
- Inherent inhomogeneity
- Fermions: temperature T_F/6 = 2000 K !
- Probes

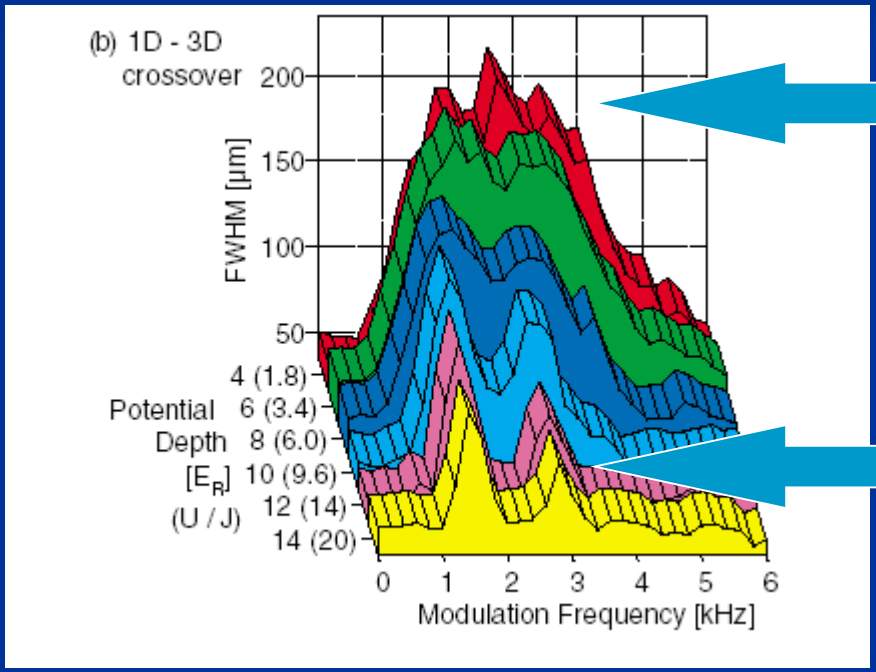
Some examples of CA-CM

Shaking and optical conductivity

Shaking of the lattice

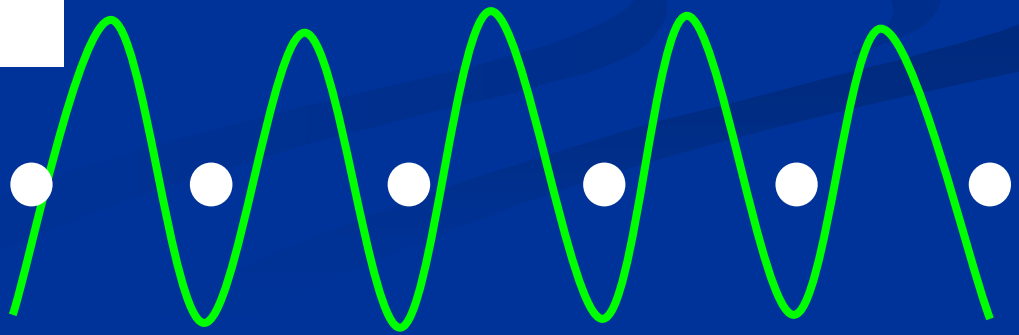
T. Stoferle *et al.* PRL **92** 130403 (2004)





3D superfluid

Mott ins.

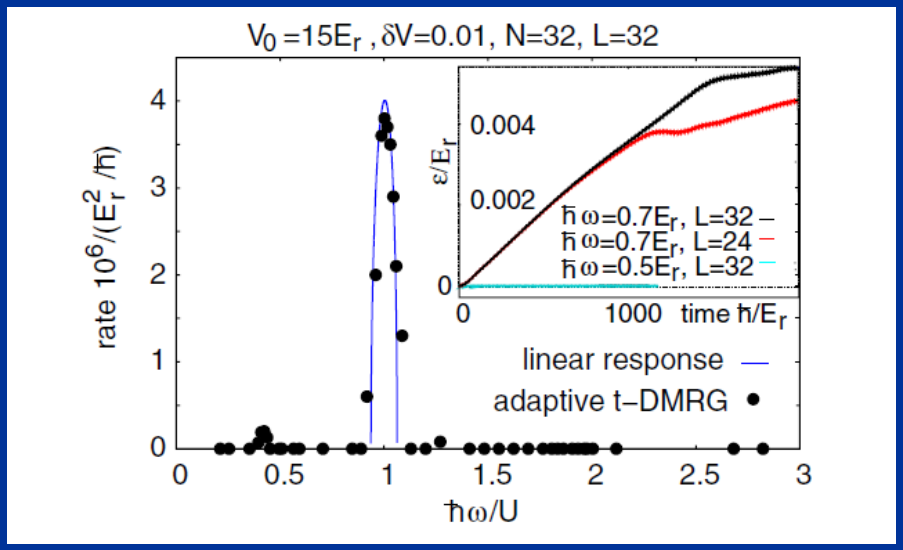


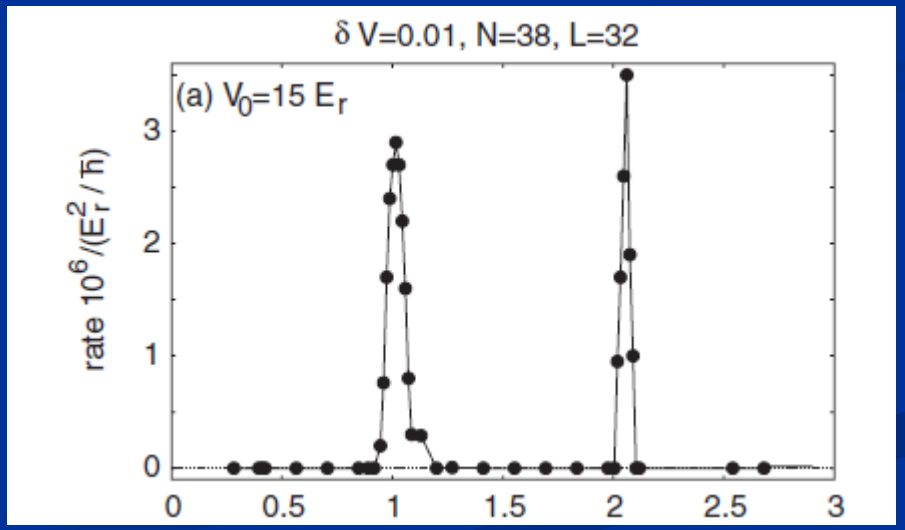
Theory

A. Iucci, M.A. Cazalilla, AF Ho, TG, PRA **73**, 041608R (2006)

$$\frac{dE}{dt} \propto \ldots \langle [H_K(t), H_K(0)] \rangle_\omega$$

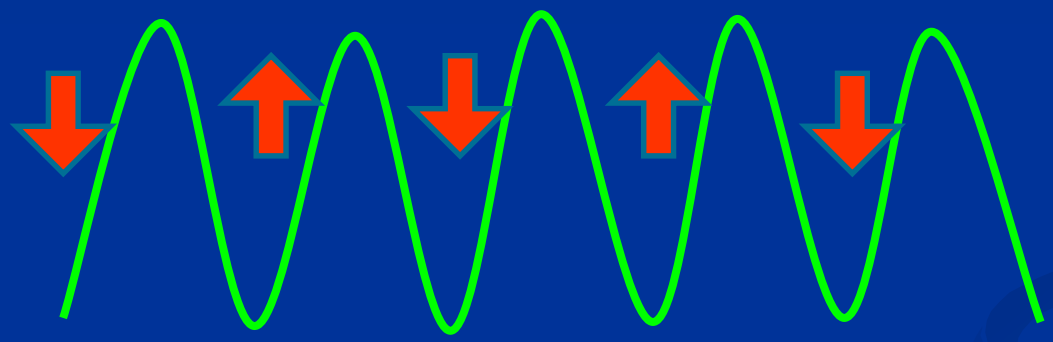
- Modulation too strong 20%





Fermion: another probe needed

- Proposal: measure variation of N_d
  [C. Kollath et al. PRA 74 041604(R) (2006)]

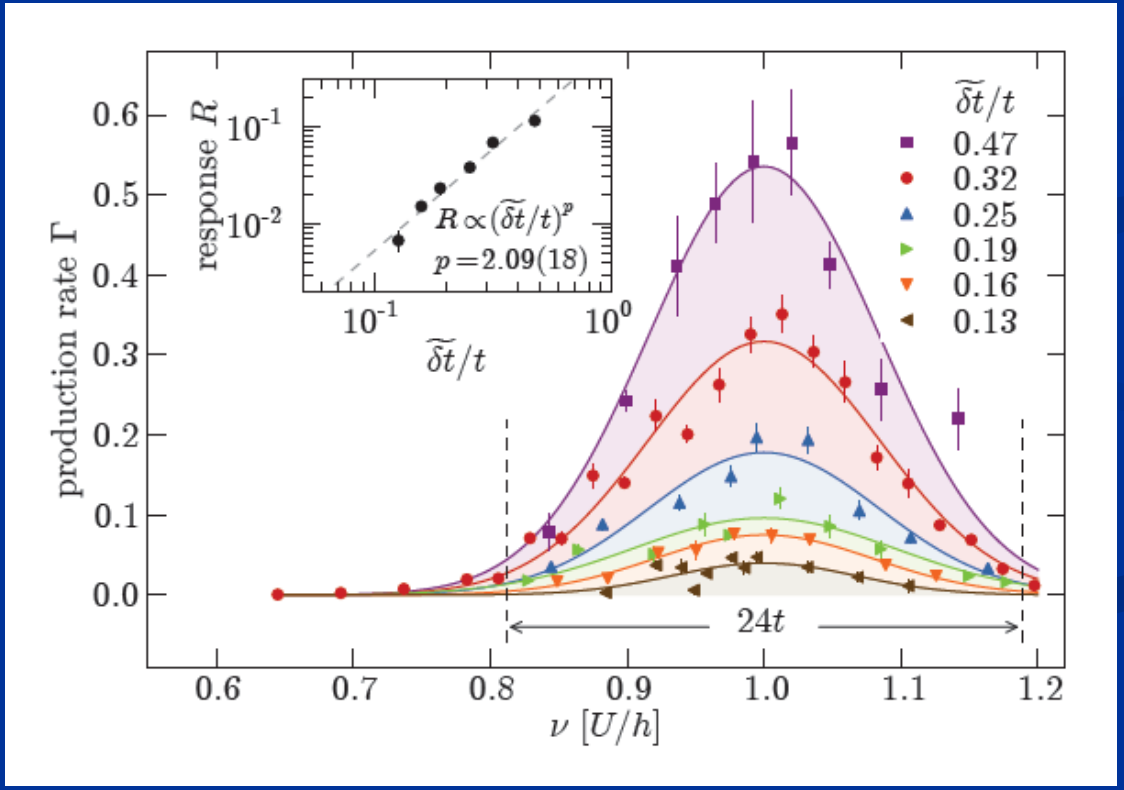


- Weight of peak: measure of (short range) AF order

Measured experimentally

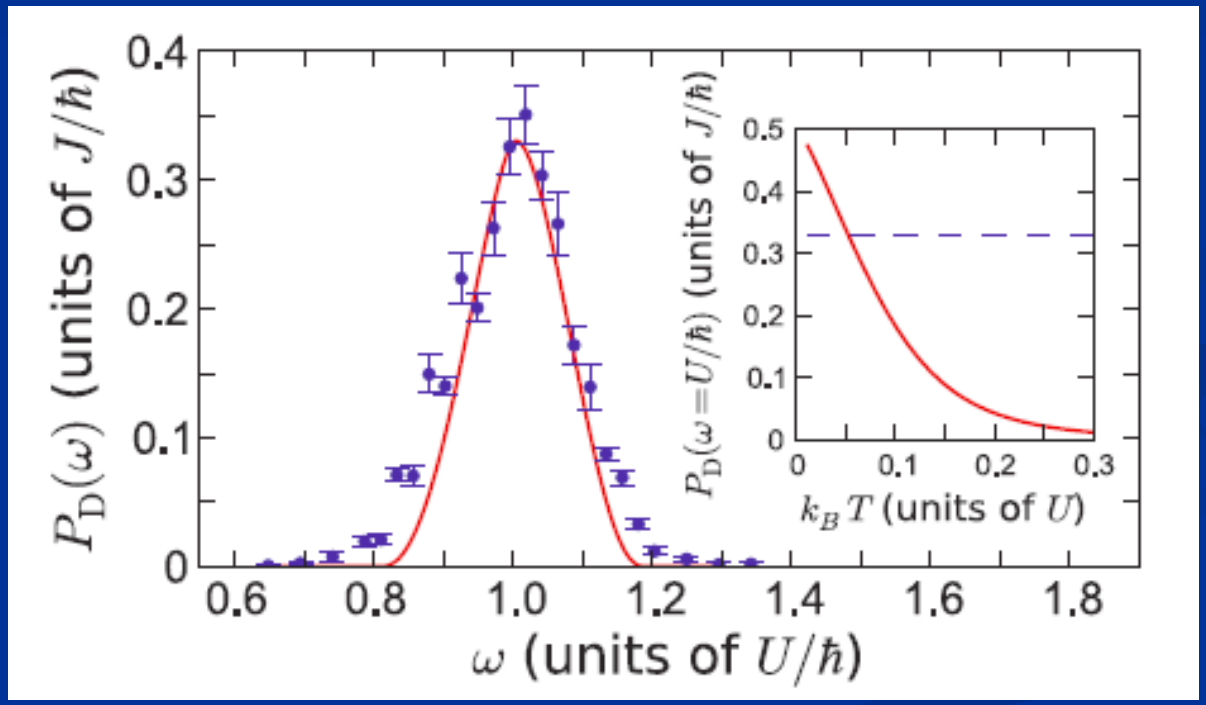
- Sensitive enough: linear response

D. Greif, L. Tarruell, T.Uehlinger, R. Jordens, T. Esslinger PRL 106 145302 (2011)



Theory of shaking (slave bosons)

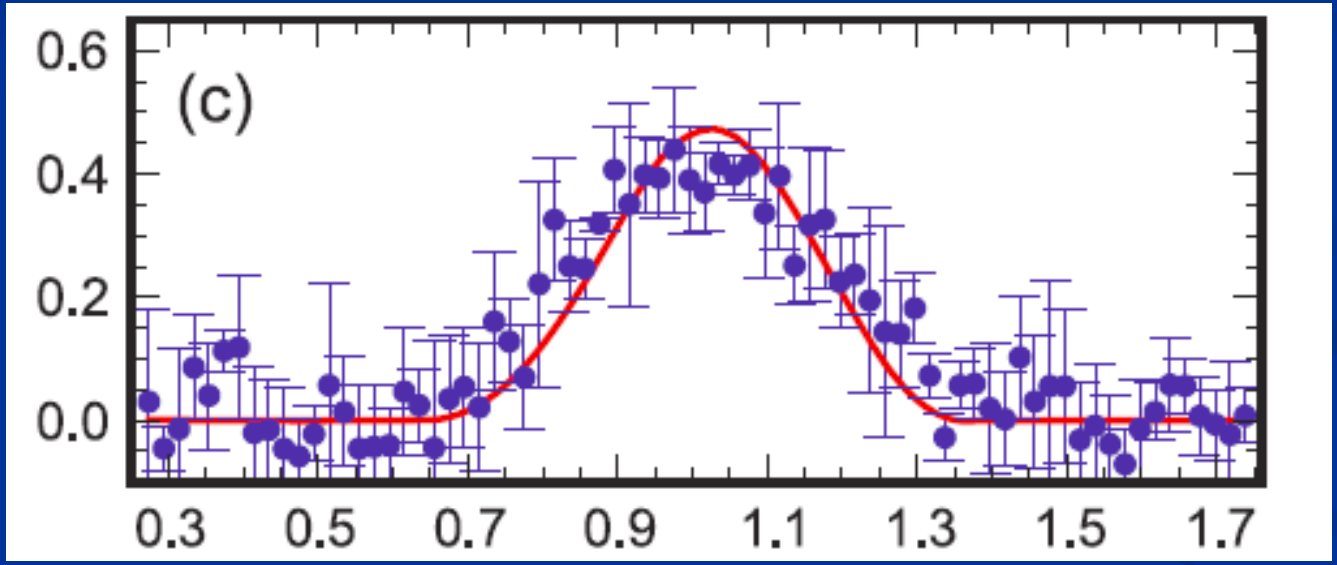
A. Tokuno, E. Demler, TG PRA 85, 053601 (2012);
A. Tokuno, TG PRA 85, 061603 (2012);



Total weight of the peak : gives short range AF

The ``theoretical" SU(N)

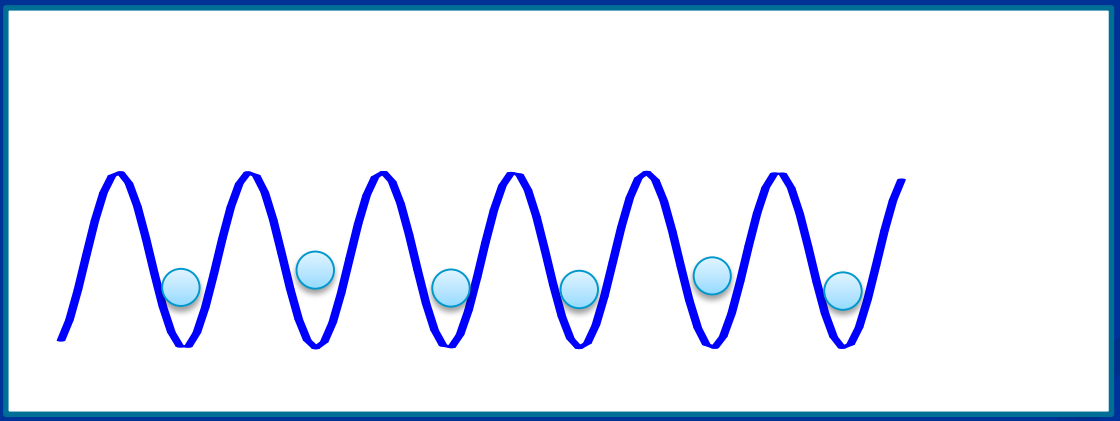
Can be realized with Ytterbium: 9/2

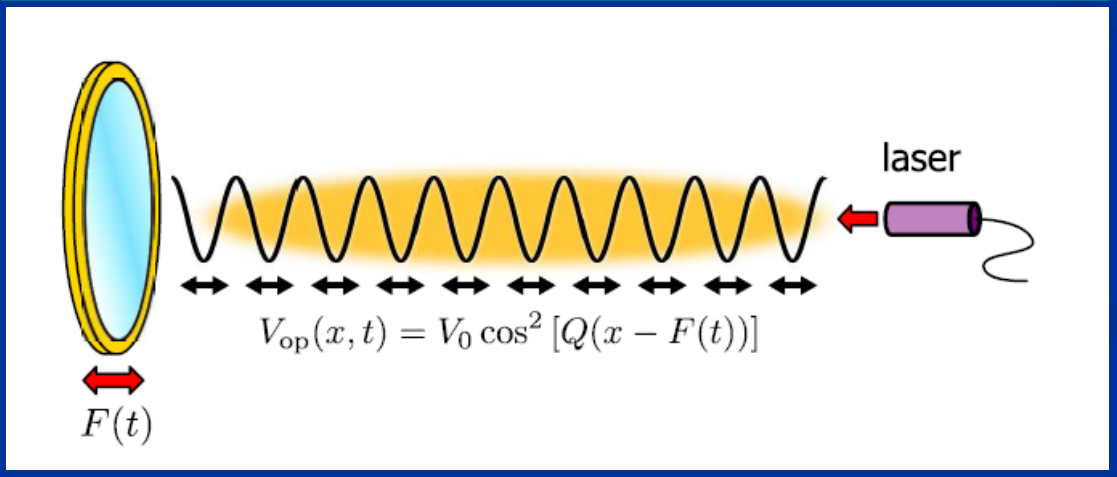


Exp: S. Taie, et al. Nat. Phys. 8, 825 (12);
Theo: A. Tokuno, TG PRA 86 053614 (12)

Optical conductivity

A. Tokuno, TG, PRL 106 205301 (2011)



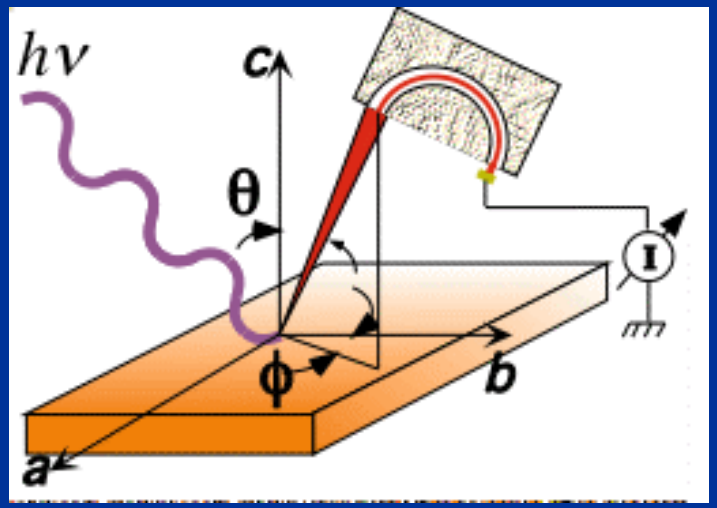


ARPES

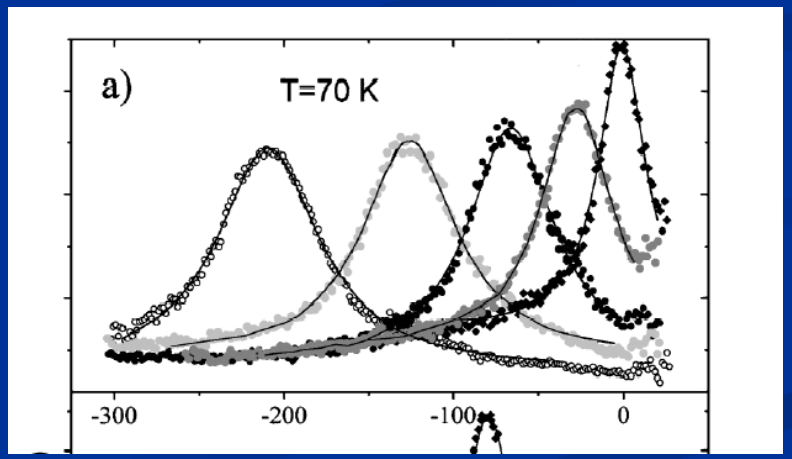
Arpes and Landau FL

- Interacting electrons: Landau quasiparticles

$$m \rightarrow m^*$$



A. Damascelli et al. RMP 75 473 (2003)



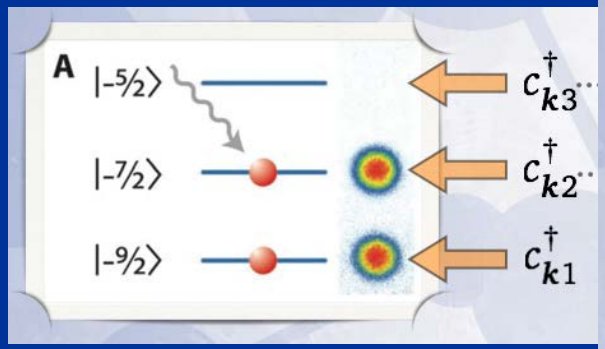
T. Valla et al. PRL 83 2085 (1999)

Effective mass for 2D fermions

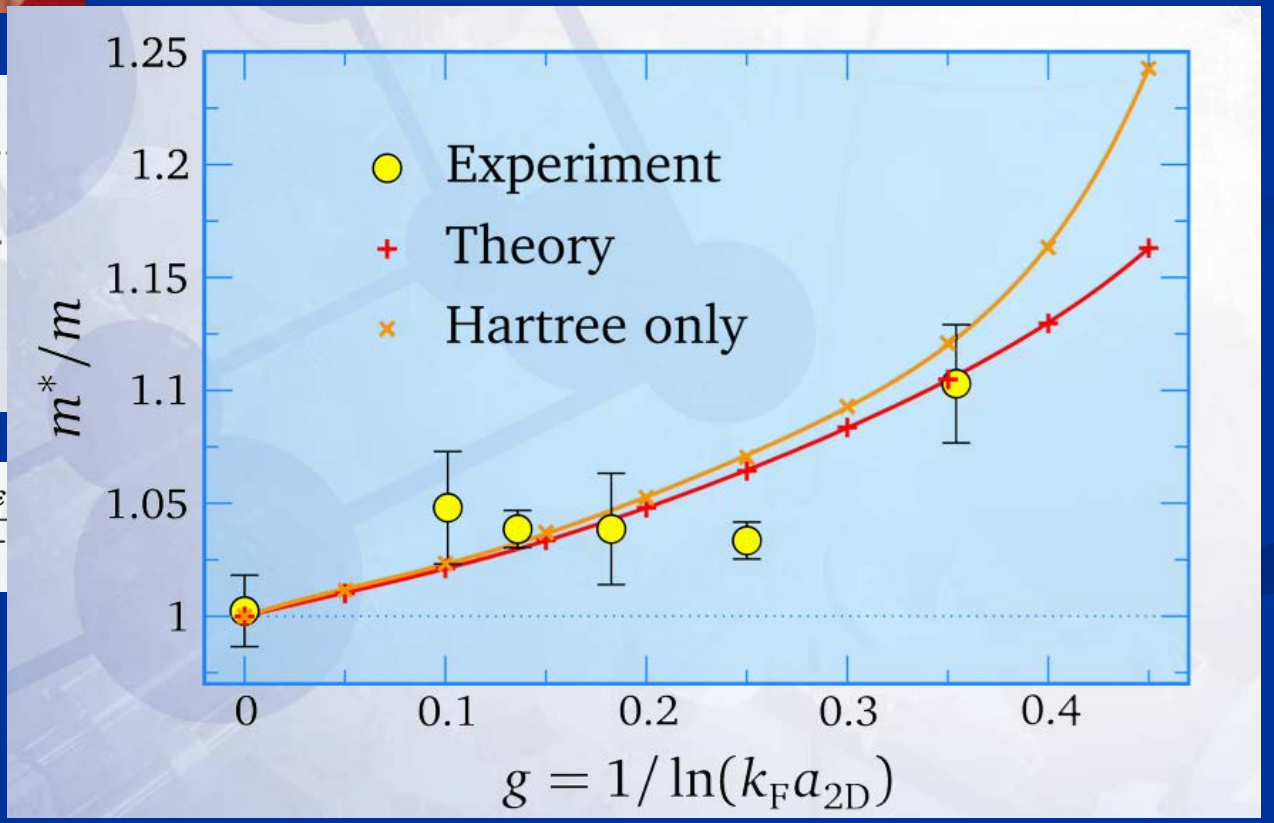
PRL 109, 130403 (2012) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2012

Two-Dimensional Fermi Liquid with Attractive Interactions

B. Fröhlich,[1] M. Feld,[1] E. Vogt,[1] M. Koschorreck,[1] M. Köhl,[1] C. Berthod,[2] and T. Giamarchi[2]



$$\langle\langle n_k \rangle\rangle \propto \int dr \int d\omega R(\omega - hv) \mathrm{Im} \left[\frac{f(\varepsilon}{\omega - hv_0 +} \right.$$

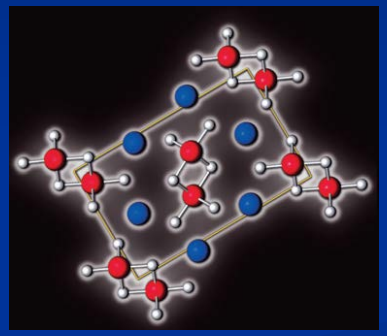


Magnon excitations

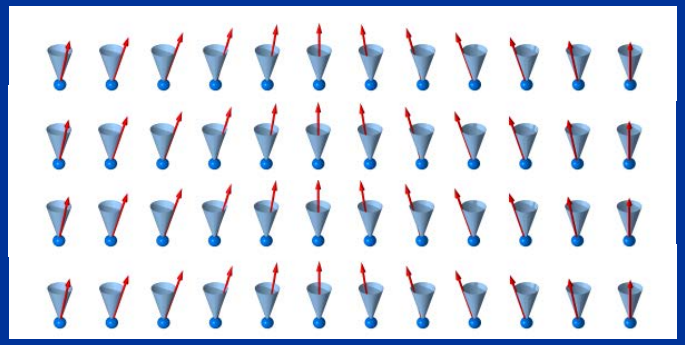
Condensed matter

- Ferromagnetism / Antiferromagnetism

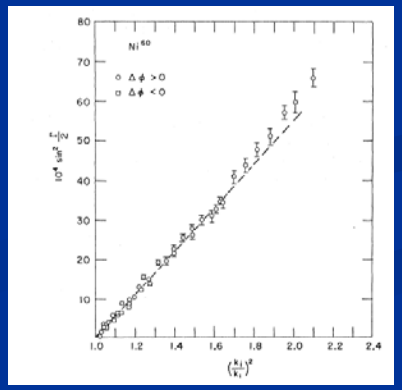
$$H = J\vec{S}_1 \cdot \vec{S}_2$$



- Large exchanges J: quantum regime
- Probes: neutrons, NMR, ESR, etc.

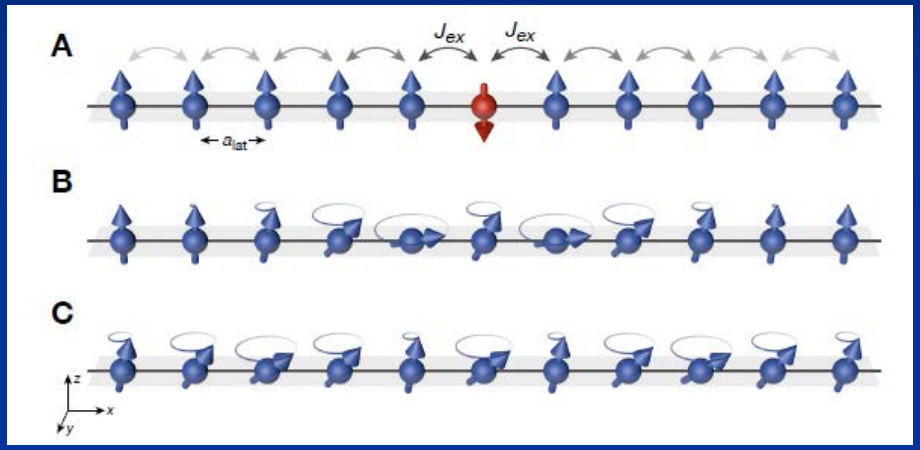


From A. Zheludev's web page

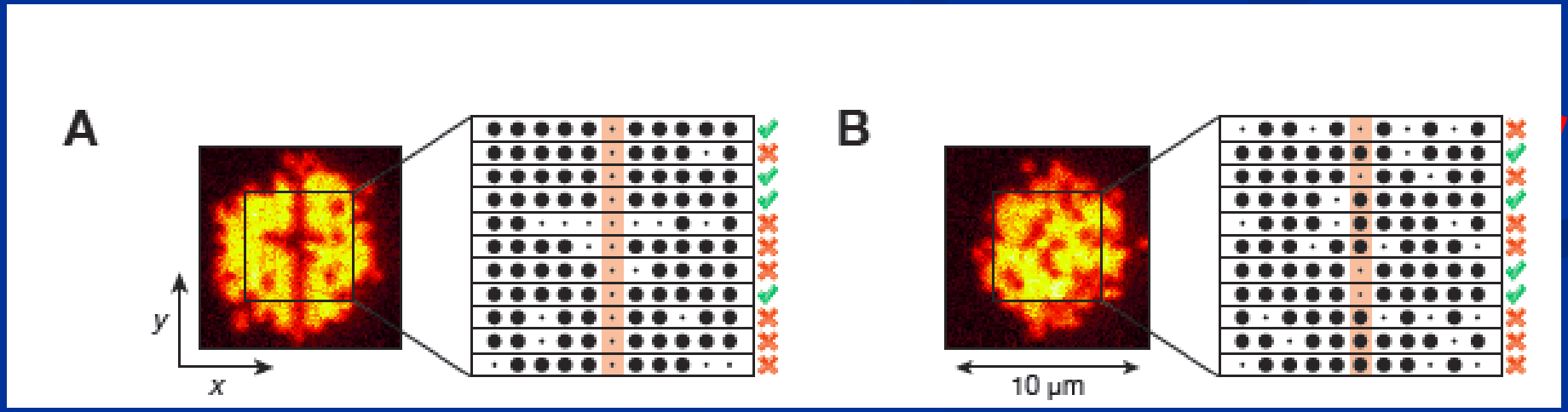


S. Pickart and H. Alperin, PR, 1967

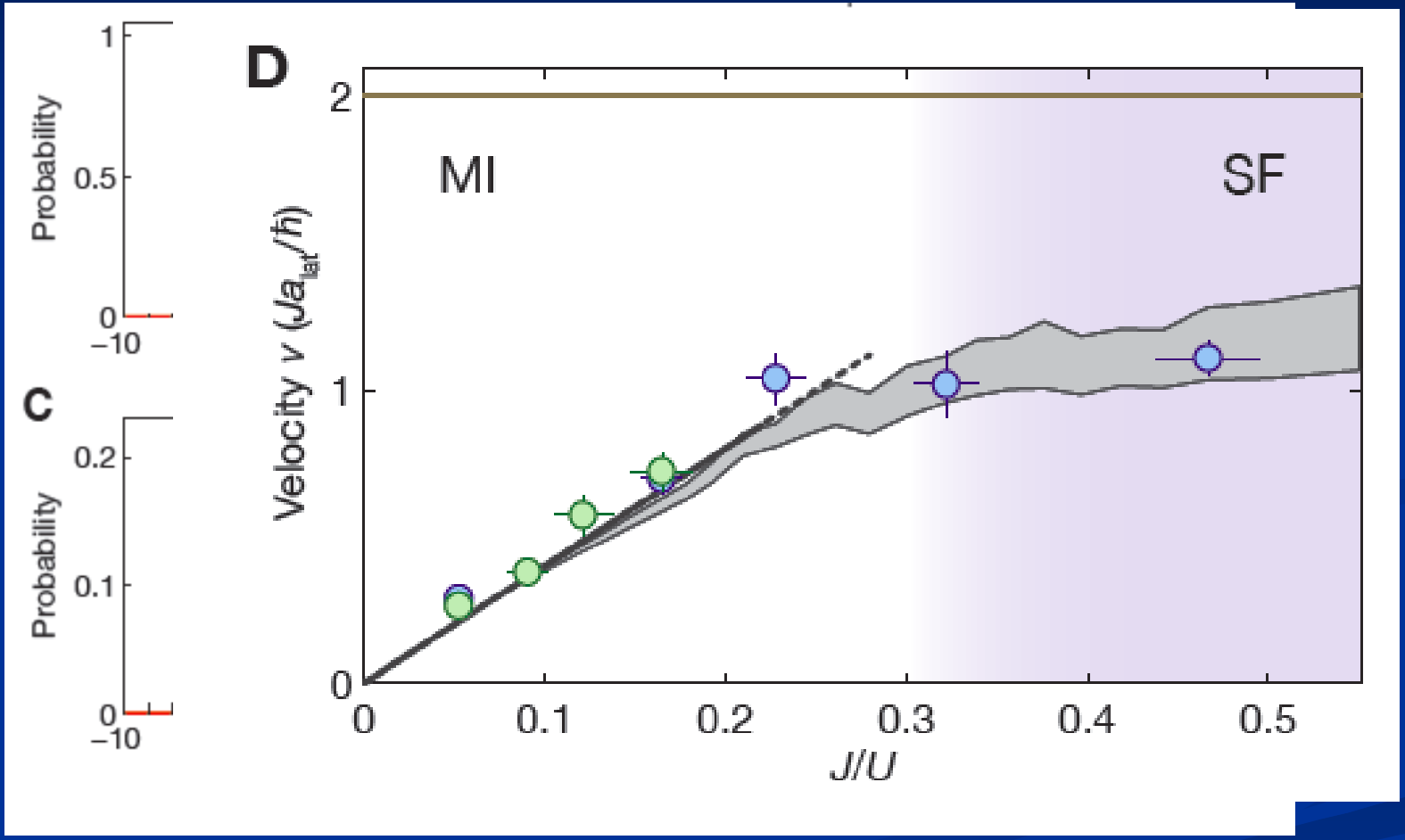
Real space/time propagation



T. Fukuhara, A. Kantian, et al., Nat. Phys. (2013)

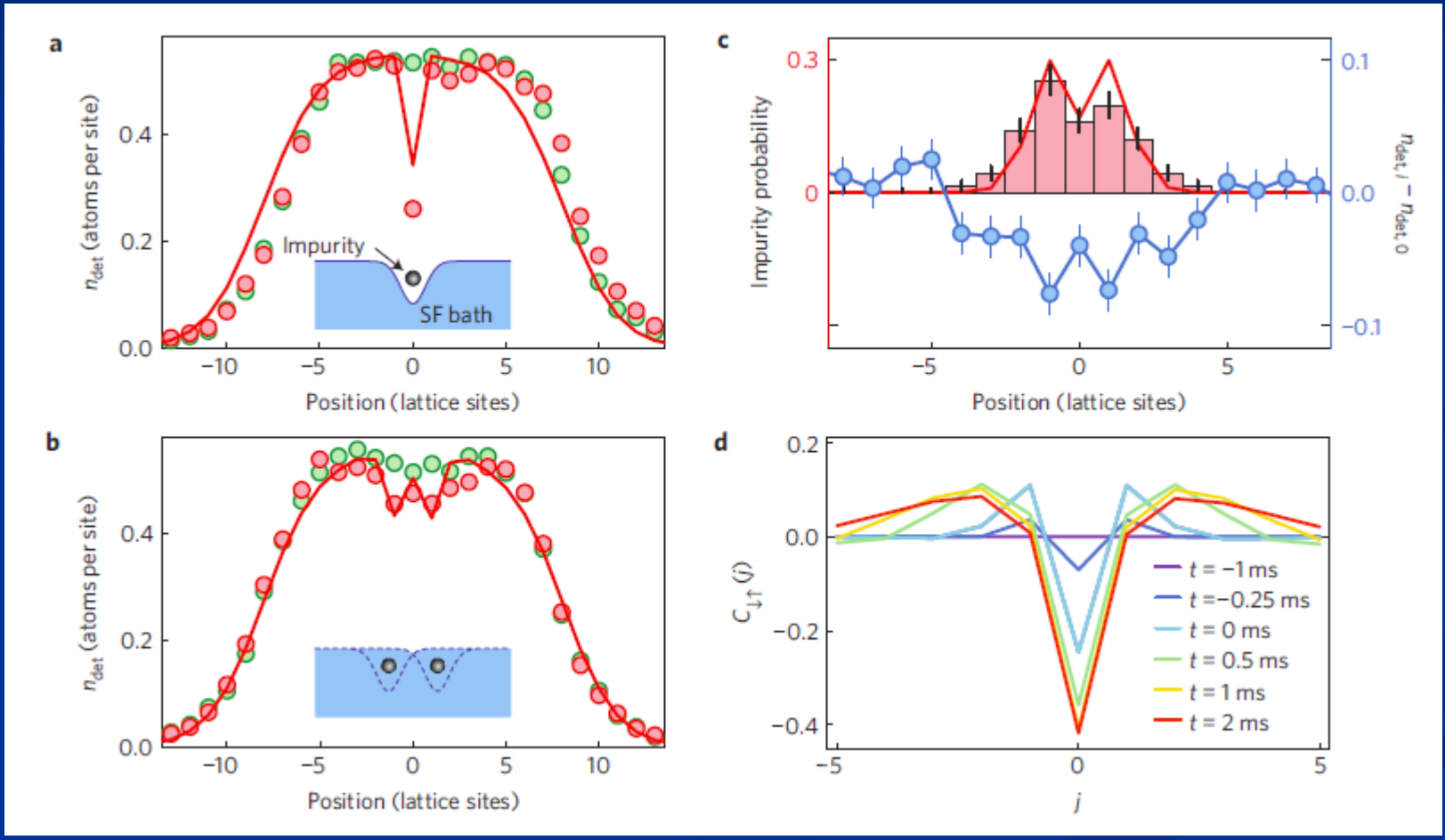


Coherent propagation of a magnon

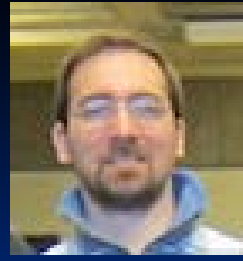


Heisenberg model : $H = J_{ex} \sum_i \vec{S}_i \cdot \vec{S}_{i+1}$ $\qquad J_{ex} = \frac{4J^2}{U}$

Polaronic effect

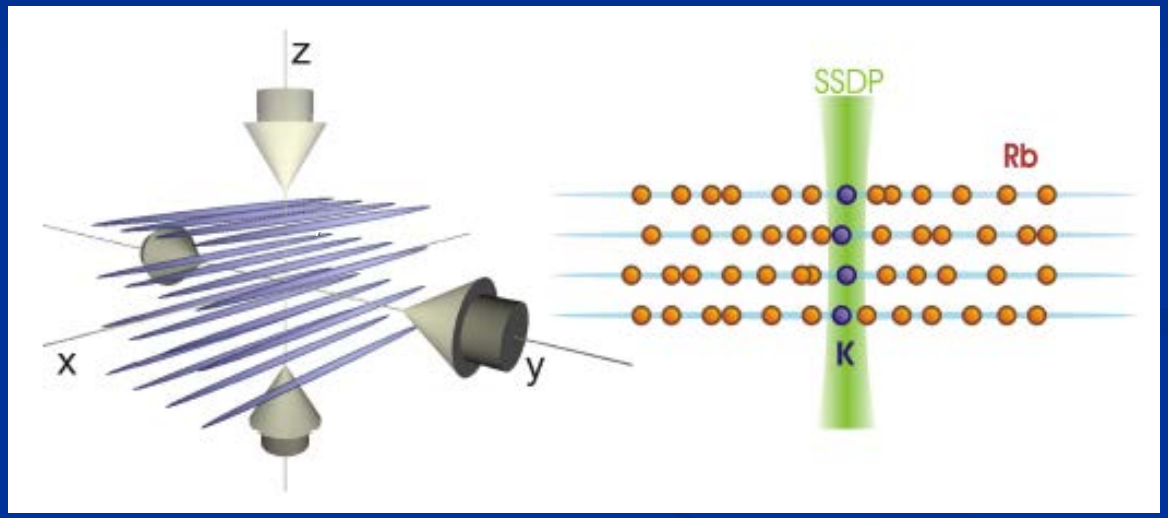


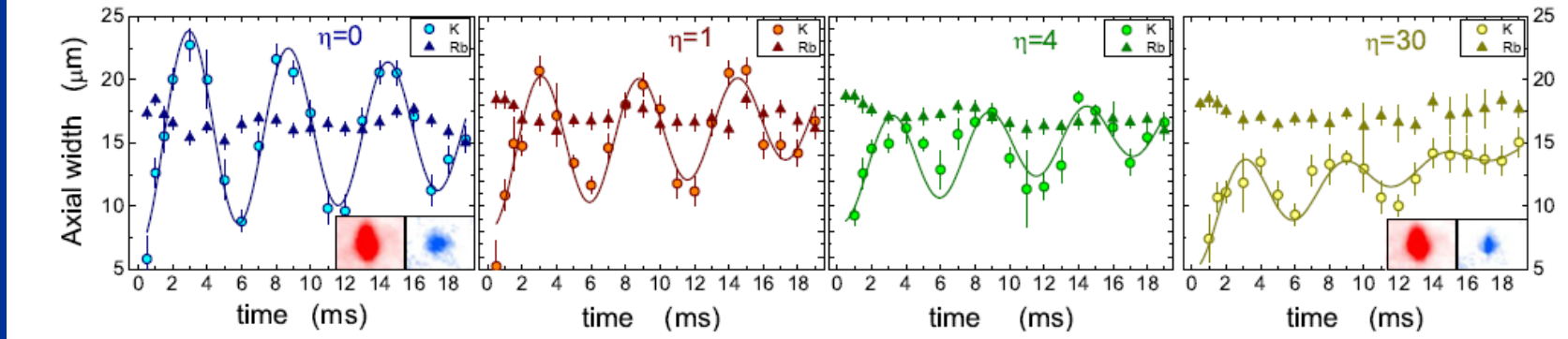
Diffusive impurity



J. Catani, G. Lamporesi, D. Naik, M. Gring, M. Inguscio, F. Minardi, A. Kantian, TG

PRA 85 023623 (2012)





Pinning by disorder

Disorder and interacting bosons

$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \text{h.c.}) + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i V_i n_i$$

One dimension: Bosonization $\quad \rho(x) \sim \rho_0 - \frac{1}{\pi}\nabla\phi(x)$

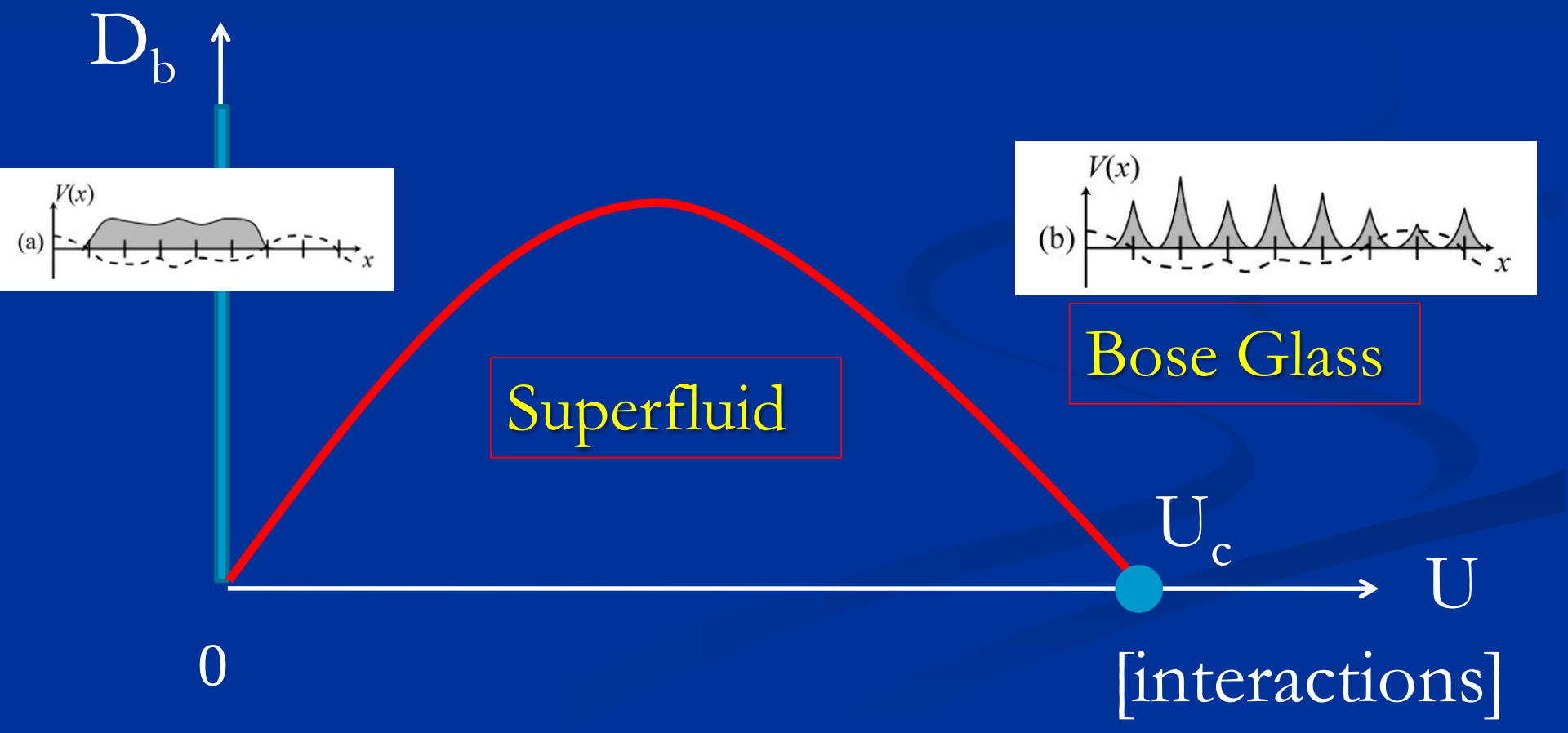
$$H = \frac{1}{2\pi}\int dx u K(\pi\Pi)^2 + \frac{u}{K}(\nabla\phi)^2 + \int dx (V(x)e^{i(2\pi\rho_0 x - 2\phi(x))} + \text{h.c.})$$

Similar to pinning of (quantum) CDW

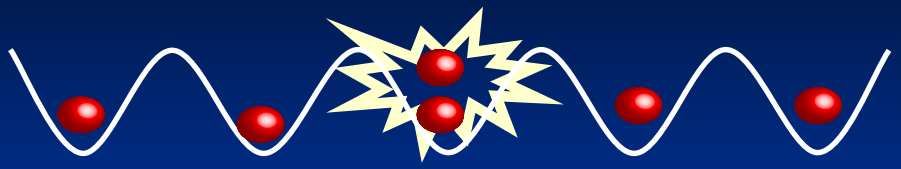
Dirty bosons

TG + H. J. Schulz EPL 3 1287 (87); PRB 37 325 (1988);

M.P.A. Fisher et al. PRB 40 546 (1989)

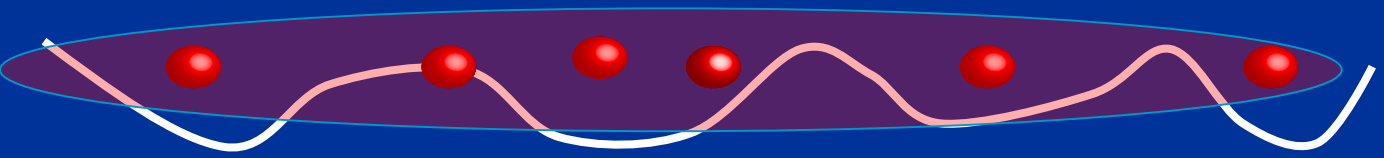


Various phases



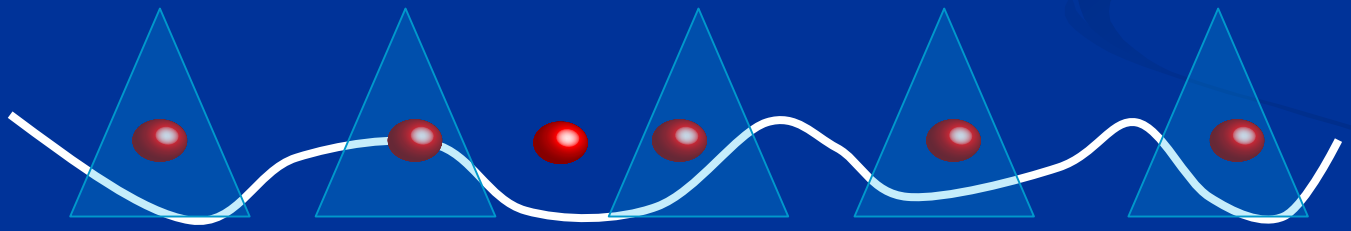
$$\frac{dN}{d\mu} = 0$$

- Mott insulator: incompressible; $\langle\psi\rangle = 0$



$$\frac{dN}{d\mu} \neq 0$$

- Superfluid: compressible; $\langle\psi\rangle \neq 0$

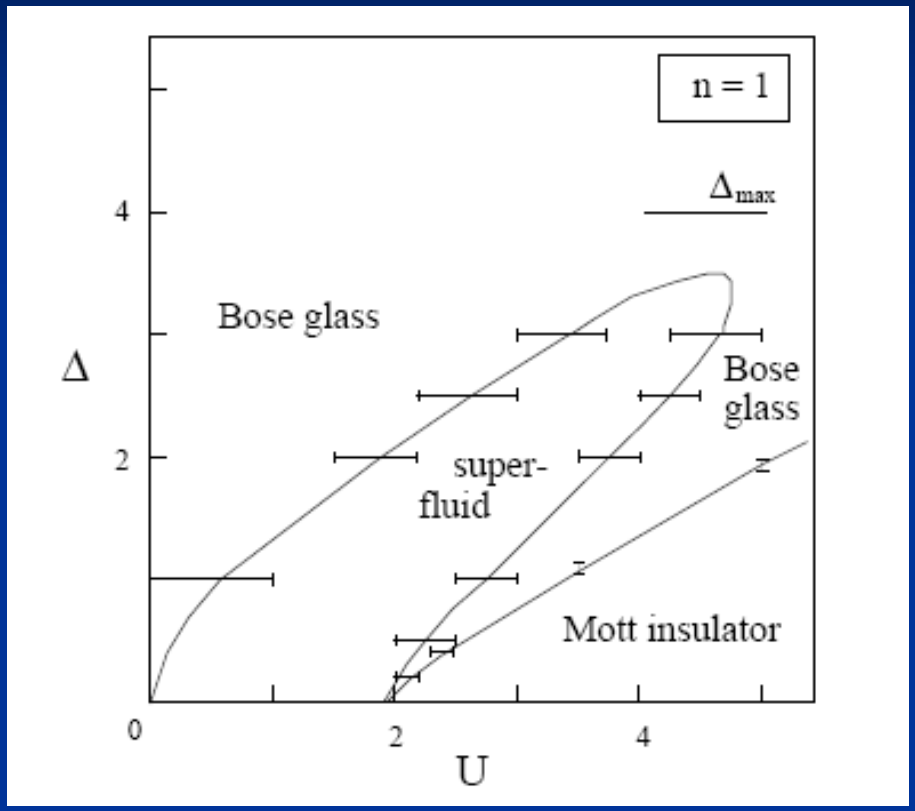


$$\frac{dN}{d\mu} \neq 0$$

- Bose Glass : compressible; $\langle\psi\rangle = 0$

TG, P. le Doussal PRB 53 15206 (96); T. Nattermann et al. PRL 91 056603 (03); E. Altman et al PRB 81 174528 (10),…….

Numerics (disorder)



S. Rapsch, U. Schollwoeck, W. Zwerger EPL 46 559 (1999);

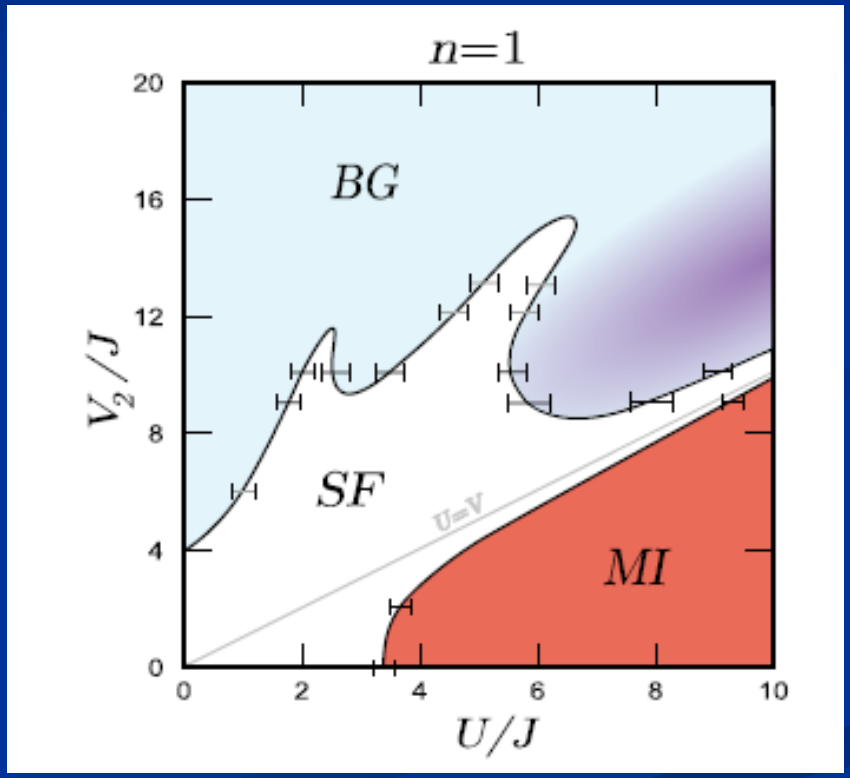
G. Batrouni et al. PRL 65 1765 (90);
N. V. Prokof'ev and B. V. Svistunov, PRL 80 4355 (96);
N. Prokofev et al. PRL 92 015703 (04);
O. Nohadani et al. PRL 95, 227201 (05)
K. G. Balabanyan et al. PRL 95, 055701 (05);
L. Pollet et al. PRL 103, 140402 (2009)
…..

Other potentials: Biperiodics

$$V(x) = V_0 \cos(Q_0 x) + V_1 \cos(Q_1 x)$$

- U= 0
  Aubry-André model
- Localization transition

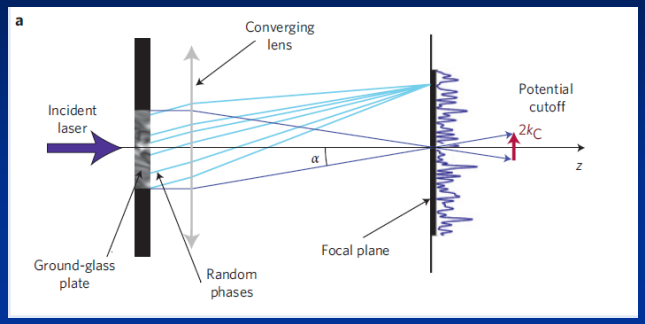
Effect of interactions?
Same as ``true'' disorder ?



J. Vidal, D. Mouhanna, TG PRL 83 3908 (1999); PRB 65 014201 (2001)

G. Roux et al. PRA 78 023628 (2008); T. Roscilde, Phys. Rev. A 77, 063605 2008; X. Deng et al PRA 78, 013625 (2008);

Cold atomic gases



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PROGRESS ARTICLE
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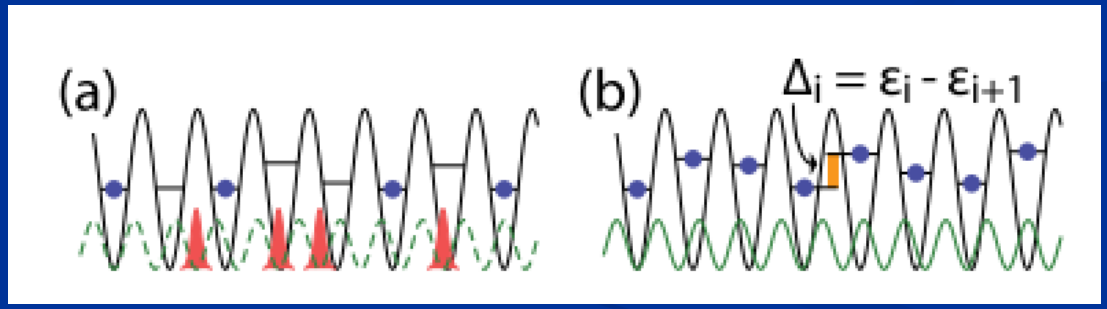
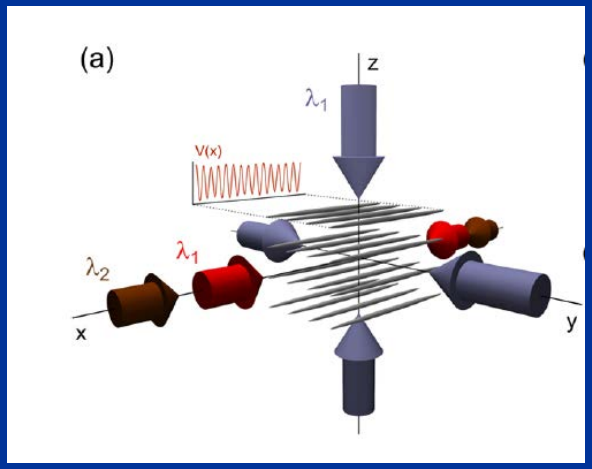
Disordered quantum gases under control

Laurent Sanchez-Palencia[1]* and Maciej Lewenstein[2]*

Speckle (Palaiseau, Florence, Urbana)





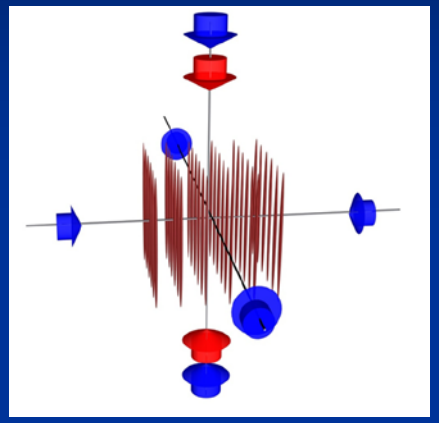
Biperiodic lattices (Florence)

Mixtures (Stony Brook)

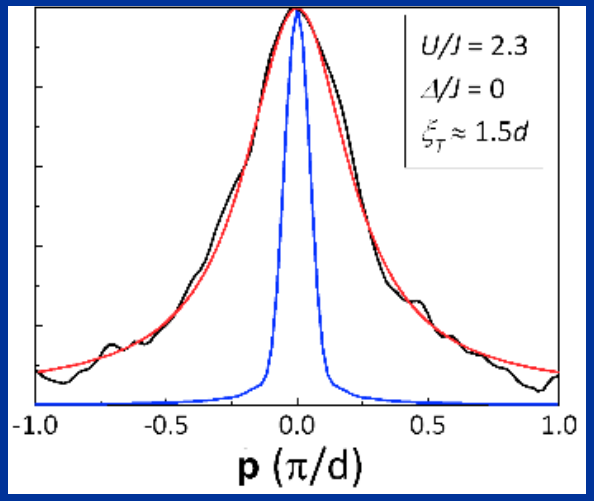
Control of Interactions and Disorder

Chiara D Errico, Eleonora Lucioni, Luca Tanzi, Lorenzo Gori, Guillaume Roux, Ian P. McCulloch, TG, Massimo Inguscio, Giovanni Modugno, PRL (2014)

Bosons in bichromatic lattice

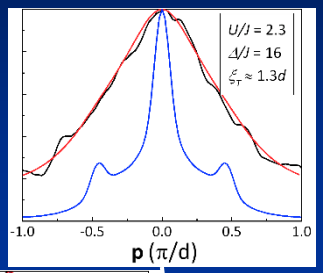


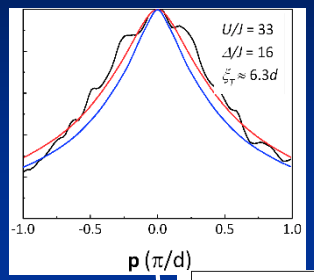
39K atoms
Bichromatic r = 1.243
J = 110 Hz

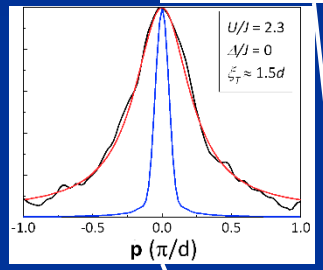


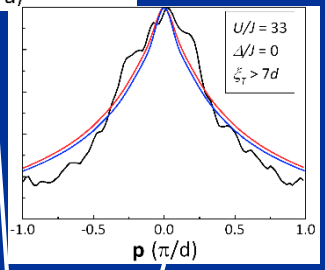
Measure of n(k) (TOF)
Comparison with LL and DMRG calculations

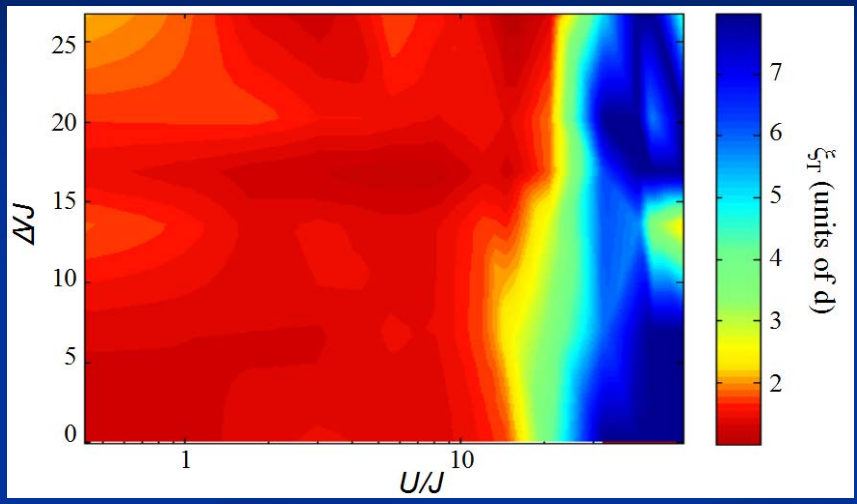
Fitted thermal length

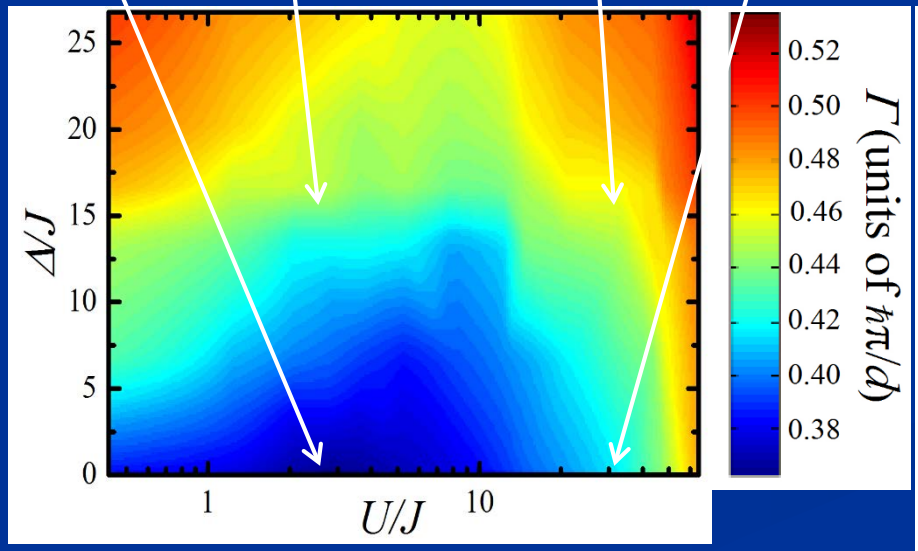


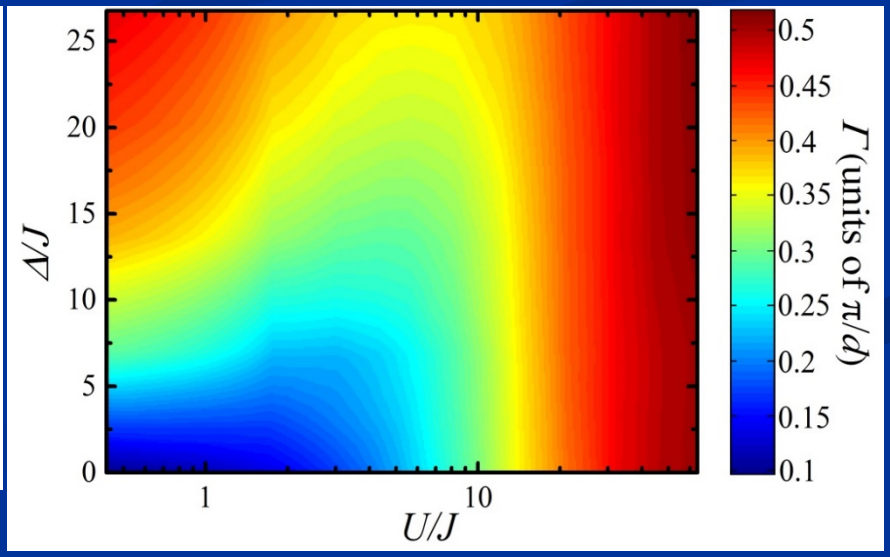




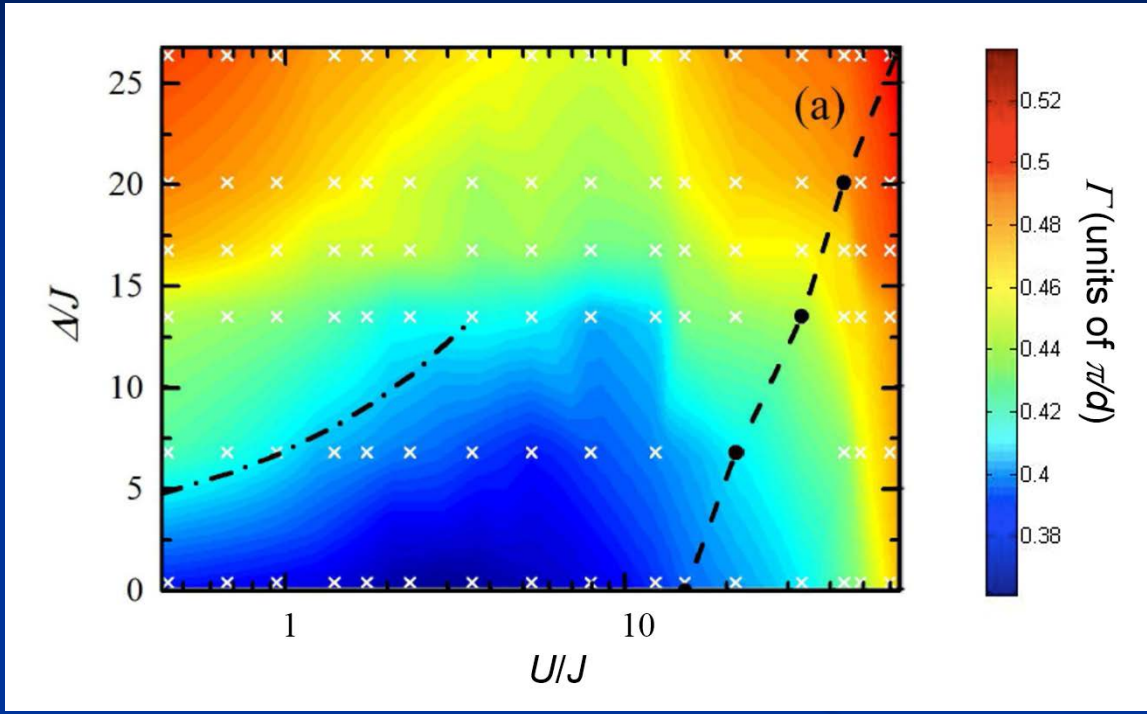


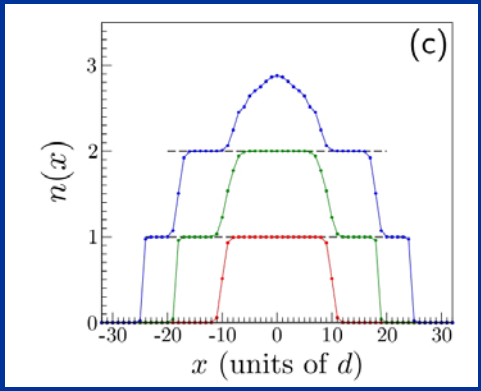






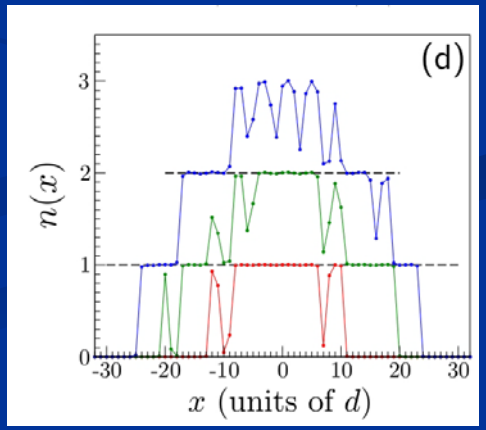
Loss of coherence



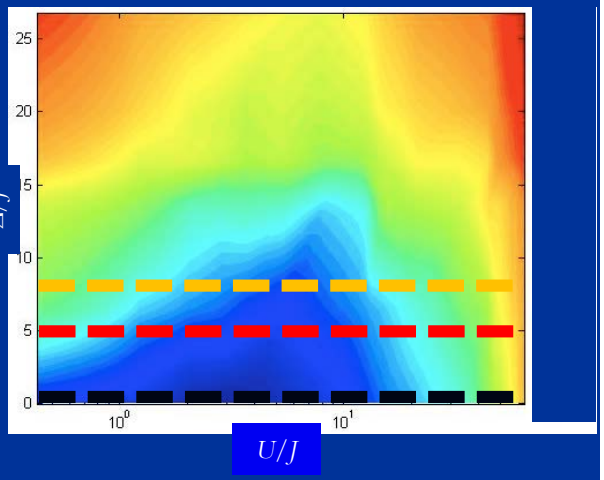


$\Delta = 6.3\ J$

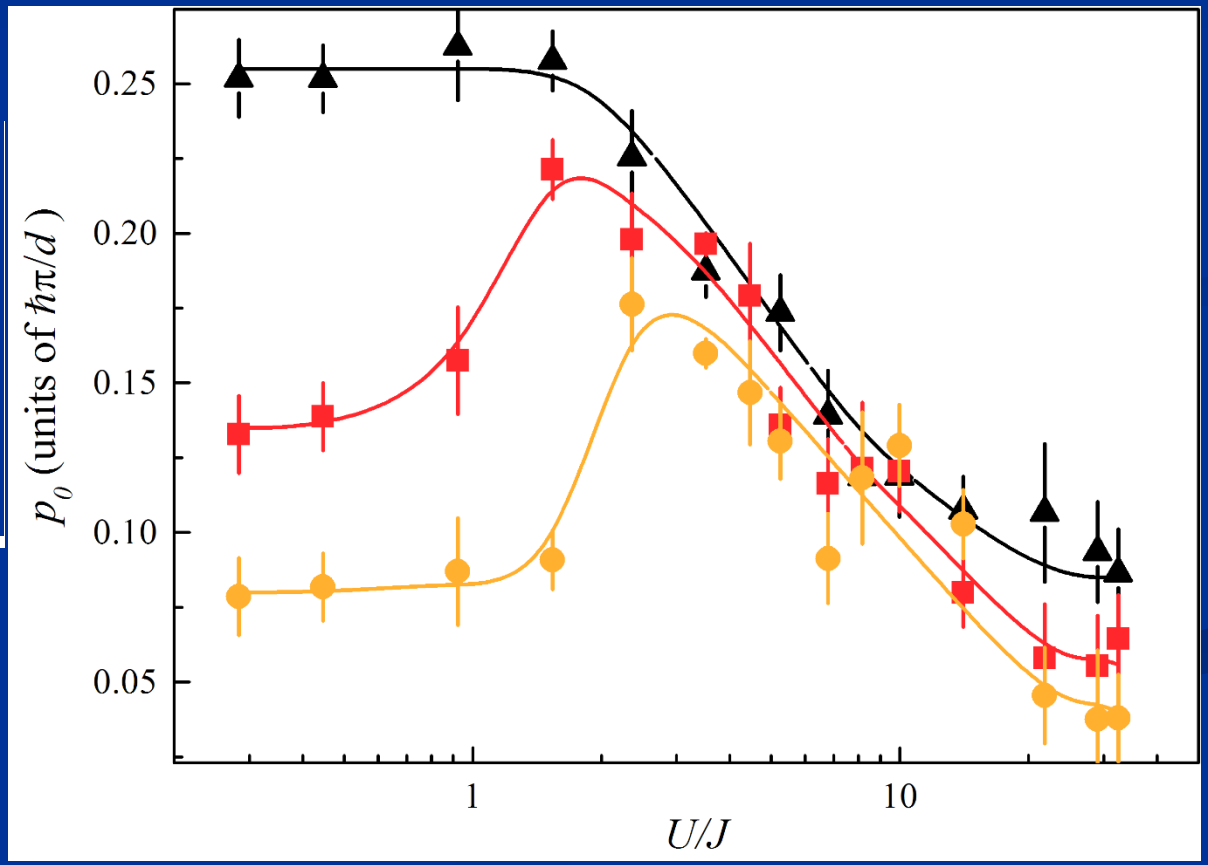
$\Delta = 9.5\ J$



Insulating phase(s)



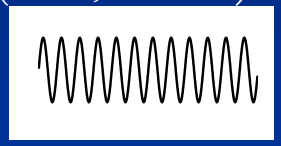
Incoherent regimes are also insulating



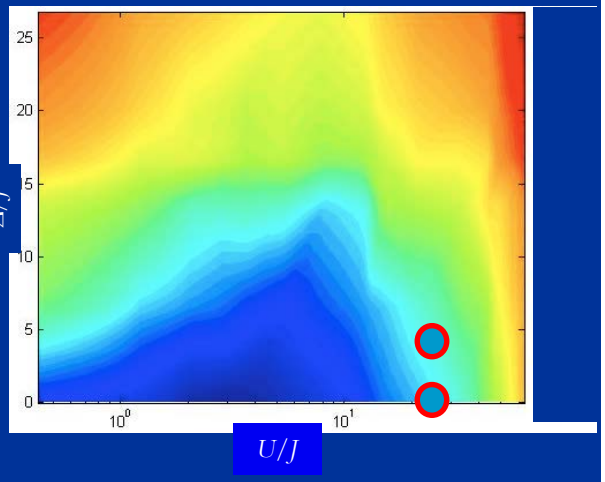
Experiment

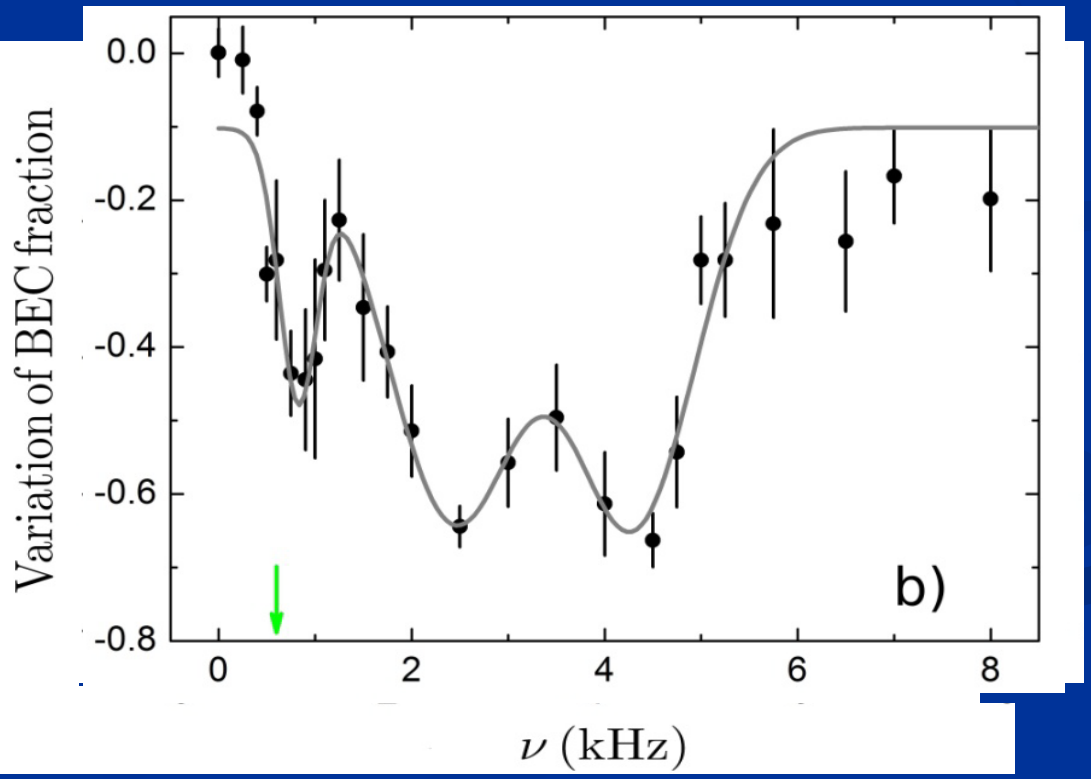
prepare in equilibrium

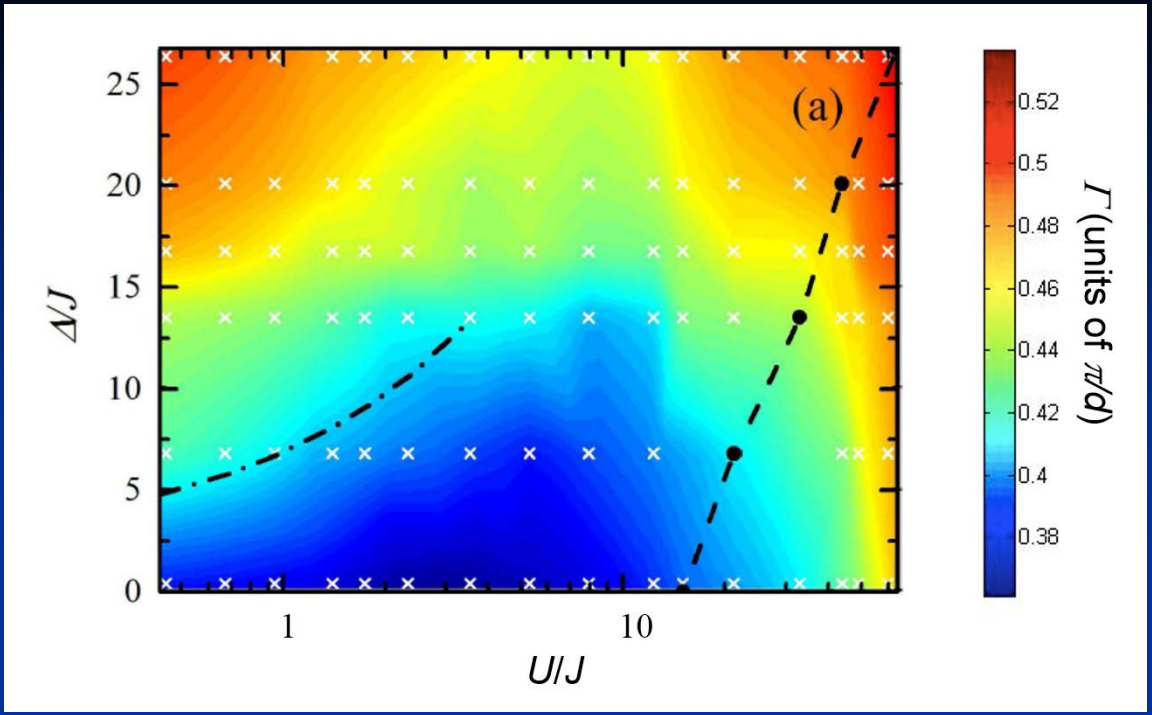
main lattice modulation
(15%, 200ms)



"energy" measurement





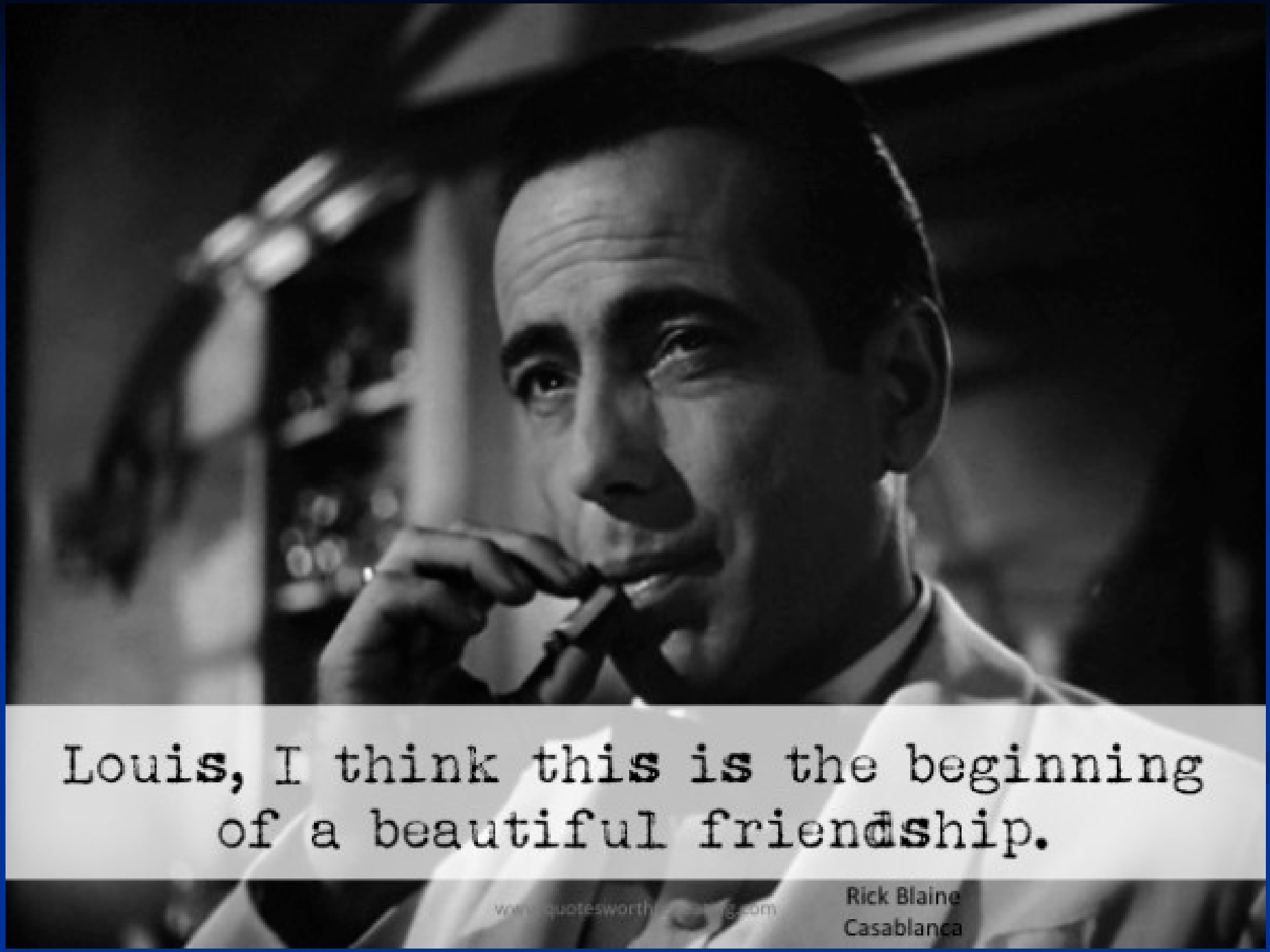


- Reentrant phase diagram (consistent with theory)
- Disordered insulator (``Bose glass")

- But one can improve on : temperature, Mott insulator, trap

Conclusions / Perspectives

- Remarkable CM-CA interplay
- Quantum simulators
- Remarkable new way to think/measure
- Many important development coming soon


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