Cold atoms as quantum simulators. (emulators?)

David Hutchinson

University of Otago

Dalibard 2D experiment

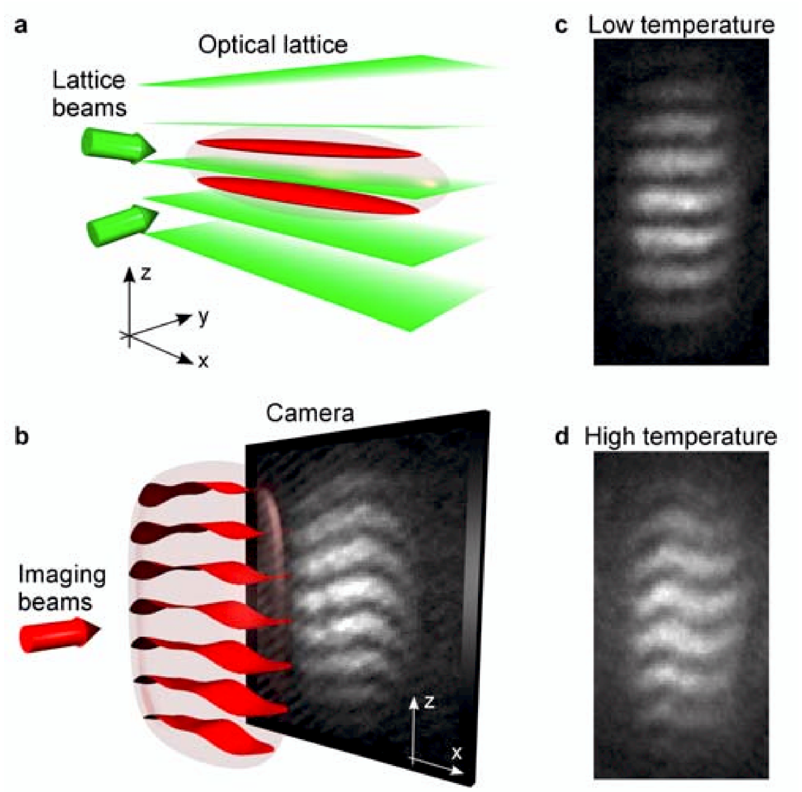


Figure 1 | Probing the coherence of 2D atomic gases using matter wave heterodyning. a, An optical lattice potential of period d =3 μm along the vertical direction z is formed by two laser beams with a wavelength of 532 nm intersecting at a small angle. It is used to split a quantum degenerate 3D gas into two independent planar systems. The transparent ellipsoid indicates the shape of the gas before the lattice is ramped up. b, After abrupt switching off of the confining potential, the two atomic clouds expand, overlap and interfere. The interference pattern is recorded onto a CCD camera using the absorption of a resonant probe laser. The waviness of the interference fringes contains information about the phase patterns in the two planar systems. c and d, Examples of interference patterns obtained at a low and a high temperature, respectively.

Theory Vs Experiment

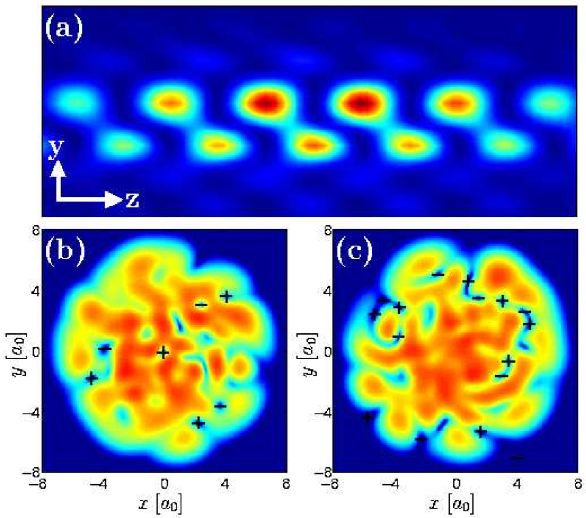
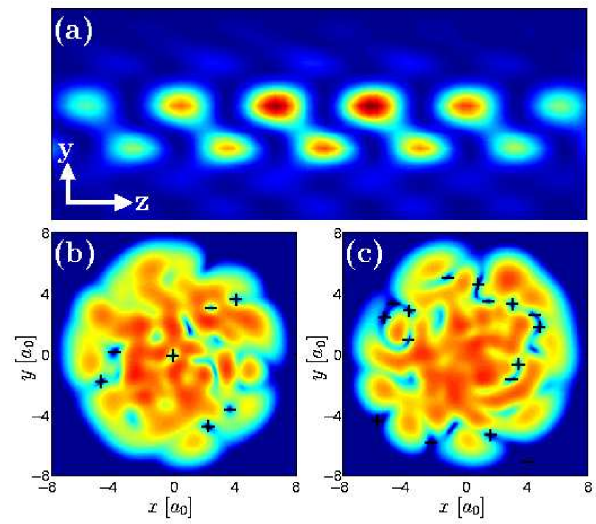


FIG. 3: Interference pattern (a) produced by two independent classical fields (b) and (c) at temperature $T = 0.86\ T_0$. The relevant particle numbers are $N_{\rm cl} = 3.0 \times 10^3$ and $N = 4.0 \times 10^4$. The zipper structure in (a) is the telltale signature of the phase singularity associated with the central vortex in (b). The locations of vortices and antivortices are marked by $+$ and $-$ signs, respectively.

Theory Vs Experiment



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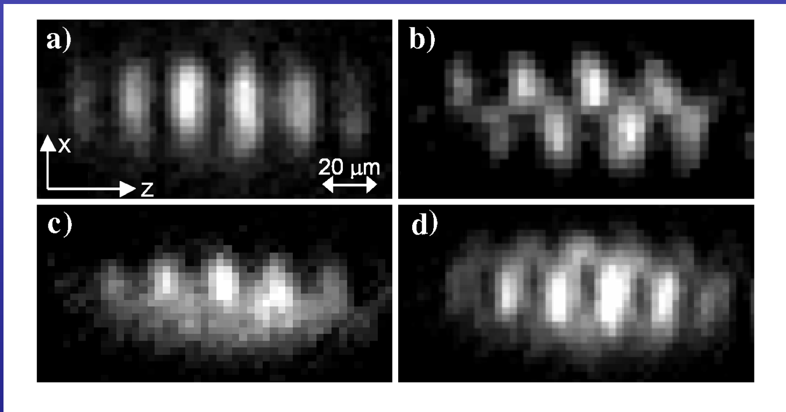


Disorder in Ultracold Gases

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]

[1]Laboratoire Charles Fabry de l'Institut d'Optique, CNRS and Univ. Paris-Sud, Campus Polytechnique, RD 128, F-91127 Palaiseau cedex, France

Nature, **453**, 891 (12 June 2008)

Anderson localization of a non-interacting Bose-Einstein condensate

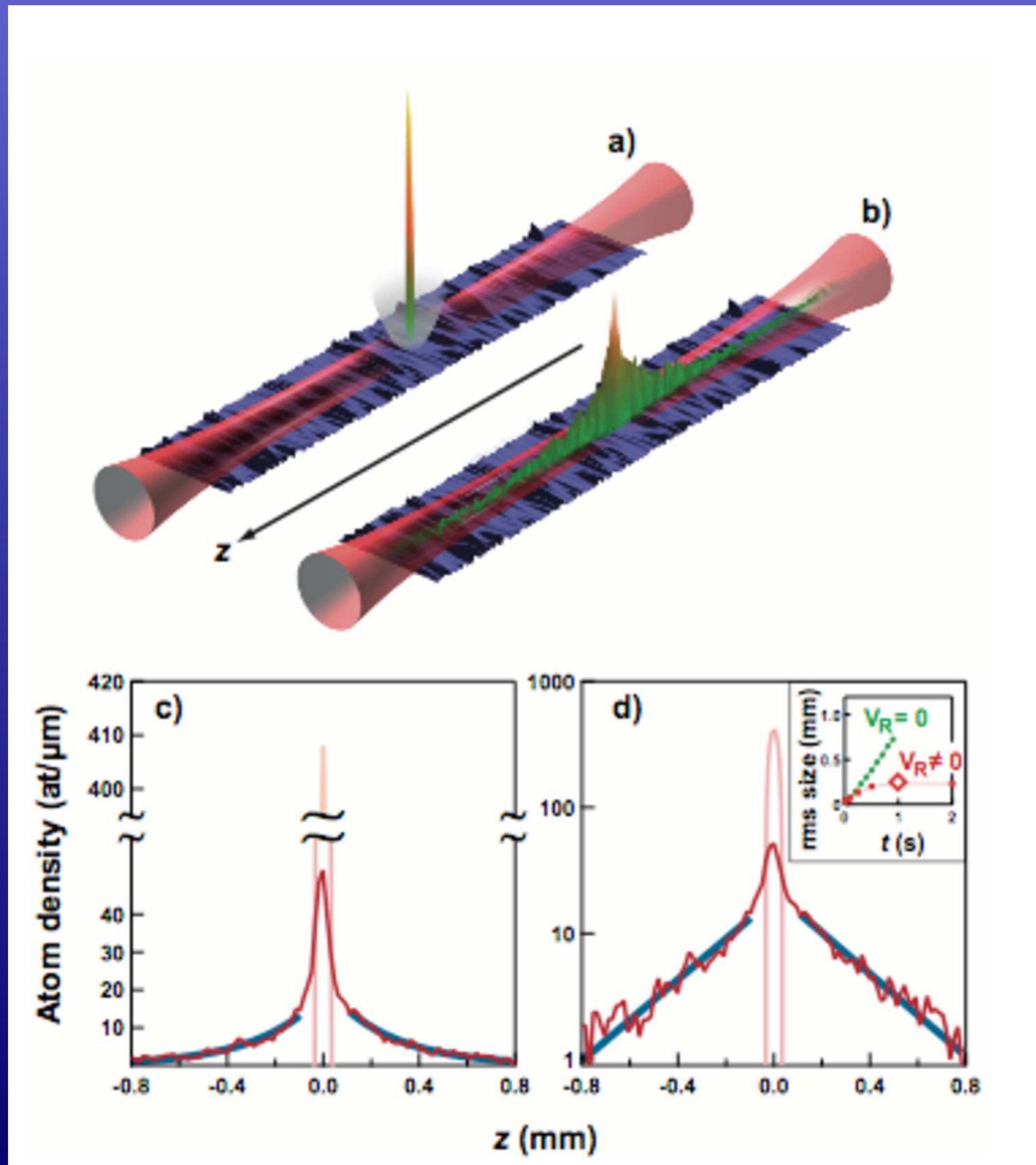
G. Roati, C. D'Errico, L. Fallani, M. Fattori[1], C. Fort, M. Zaccanti, G. Modugno, M. Modugno[2] & M. Inguscio

LENS and Physics Department,Università di Firenze, and INFM-CNR, Via Nello Carrara 1,50019 Sesto Fiorentino, Italy

[1]Museo Storico della Fisica e Centro Studi e Ricerche "E. Fermi", Roma, Italy
[2]Dipartimento di Matematica Applicata, Università di Firenze, Italy – BEC-INFM Center, Univ. Trento, Italy

Nature, **453**, 895 (12 June 2008)

Billy, *et al.*,



a)
b)
z
c)
d)
Atom density (at/µm)
420
410
400
40
30
20
10
1000
100
10
1
-0.8
-0.4
0.0
0.4
0.8
z (mm)
rms size (mm)
t (s)
V_R = 0
V_R ≠ 0

Smoking gun

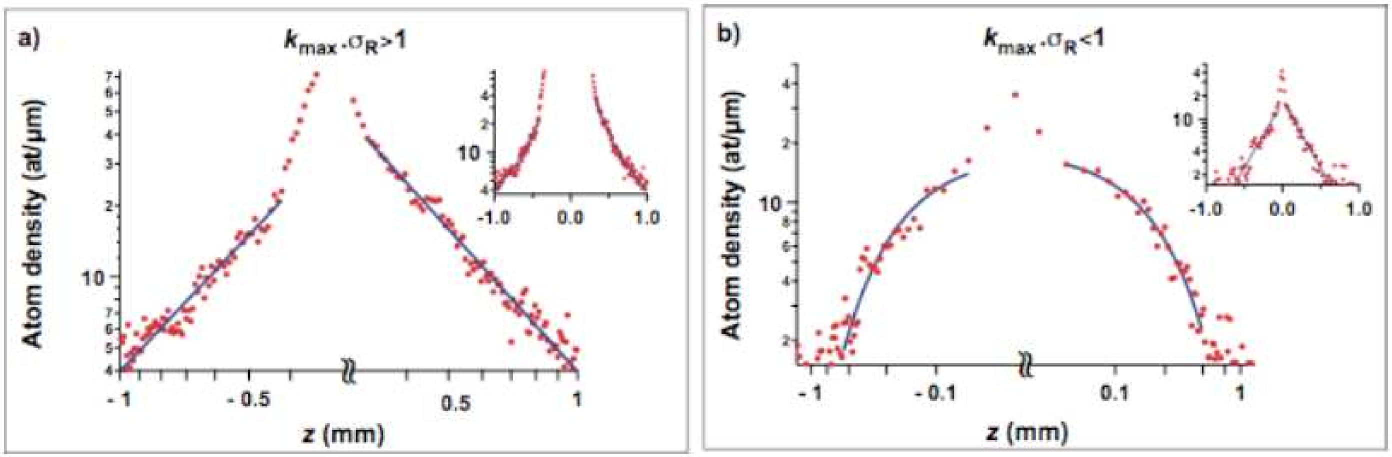


Figure 4. Algebraic *vs* exponential regimes in a 1D speckle potential. Log-log and semi-log plots of the stationary atom density profiles showing the difference between the algebraic ($k_{max}\,\sigma_R>1$) and the exponential ($k_{max}\,\sigma_R<1$) regimes. **a)** Density profile for $V_R/\mu_{in} = 0.15$ and $k_{max}\,\sigma_R = 1.16\pm0.14$ (±2 s.e.m.). The momentum distribution of the released BEC has components beyond the effective mobility edge $1/\sigma_R$. The fit to the wings with a power law decay $1/|z|^{\beta}$ yields β=1.92 +/- 0.06 (±2 s.e.m.) for the left wing and β=2.01 +/- 0.03 (±2 s.e.m.) for the right wing. The inset shows the same data in semi-log plot, and confirms the non-exponential decay. **b)** For comparison, similar set of plots (log-log and semi-log) in the exponential regime with the same $V_R/\mu_{in} = 0.15$ and $k_{max}\,\sigma_R = 0.65 \pm0.09$ (±2 s.e.m.).

Roati, *et al.*

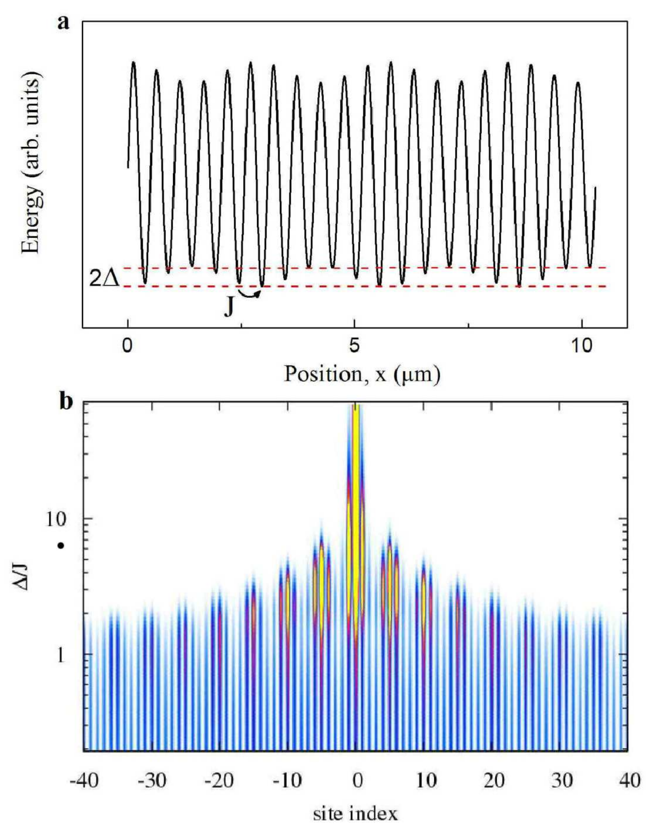


Figure 1 | The quasi-periodic optical lattice. **a**, Sketch of the quasi-periodic potential realized in the experiment. The hopping energy J describes the tunnelling between different sites of the primary lattice and 2Δ is the maximum shift of the on-site energy induced by the secondary lattice. The lattice constant is 516 nm. **b**, Typical density plot of an eigenstate of the bichromatic potential, as a function of Δ/J (vertical axis). For small values of Δ/J the state is delocalized over many lattice sites. For $\Delta/J \geq 7$ the state becomes exponentially localized on lengths smaller than the lattice constant.

Their smoking gun

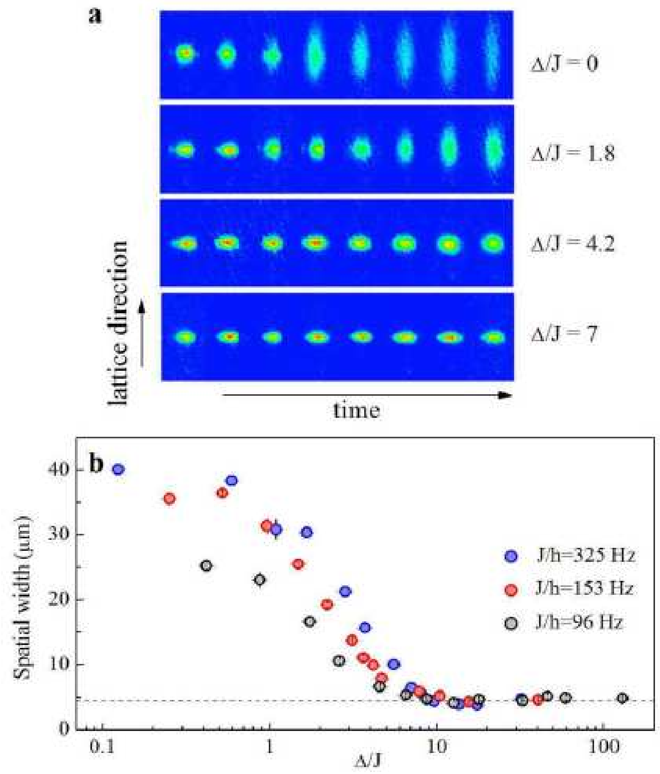


Figure 2 | Probing the localization with transport. a, In-situ absorption images of the BEC diffusing along the quasi-periodic lattice for different values of Δ and J/h=153 Hz. For Δ/J≥7 the size of the BEC remains stacked to its original value, reflecting the onset of localization. **b**, Rms size of the condensate for three different values of J, at a fixed diffusion time of τ=750 ms, vs the rescaled disorder strength Δ/J. The dashed line indicates the initial size of the condensate. The onset of localization appears in all three cases in the same range of values of Δ/J.

Incommensurate lattice experiments

- Disorder introduced with additional light field.
- Use Bose-Hubbard Hamiltonian

$$\hat{H} = \sum_{i=1}^{N} \hat{n}_i \epsilon_i - J \sum_{i=1}^{N} (\hat{a}_{i+1}^{\dagger} \hat{a}_i + \hat{a}_i^{\dagger} \hat{a}_{i+1}) + \frac{U}{2} \sum_{i=1}^{N} \hat{n}_i (\hat{n}_i - 1)$$

Quasiperiodic disorder from potential

$$V_\alpha \cos^2(\alpha x)$$

$$\alpha = \frac{\lambda_{\text{lattice}}}{\lambda_\alpha}$$

Simplest possible picture

Simplest possible picture: zero temperature

$$-i\frac{\partial z_i}{\partial t} = \epsilon_i z_i - J\left(z_{i+1} + z_{i-1}\right) + U n_{c,i} z_i,$$

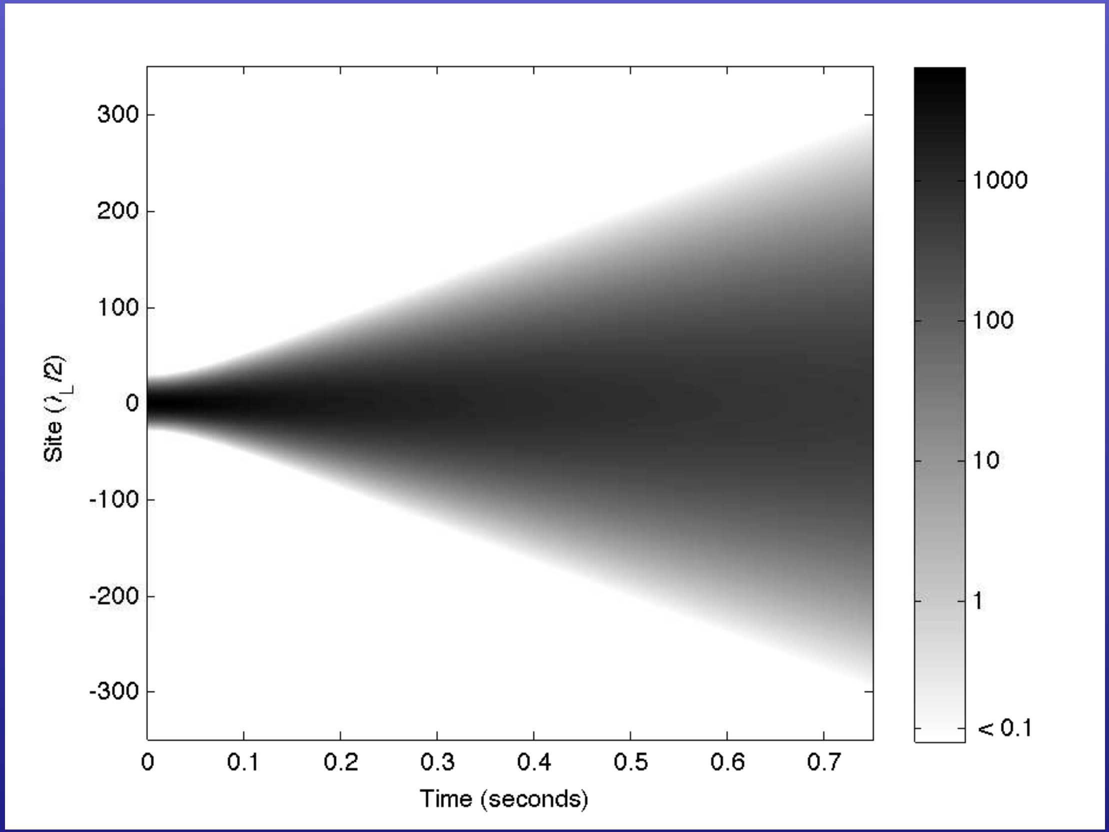
where

$$\epsilon_i = \frac{V_{\rm dis}^0}{2}\left[1 + e^{-\alpha^2\sqrt{\frac{E_R}{V_0}}}\cos\left[2\pi\alpha\left(i - \frac{1}{2}\right)\right]\right],$$

and we define

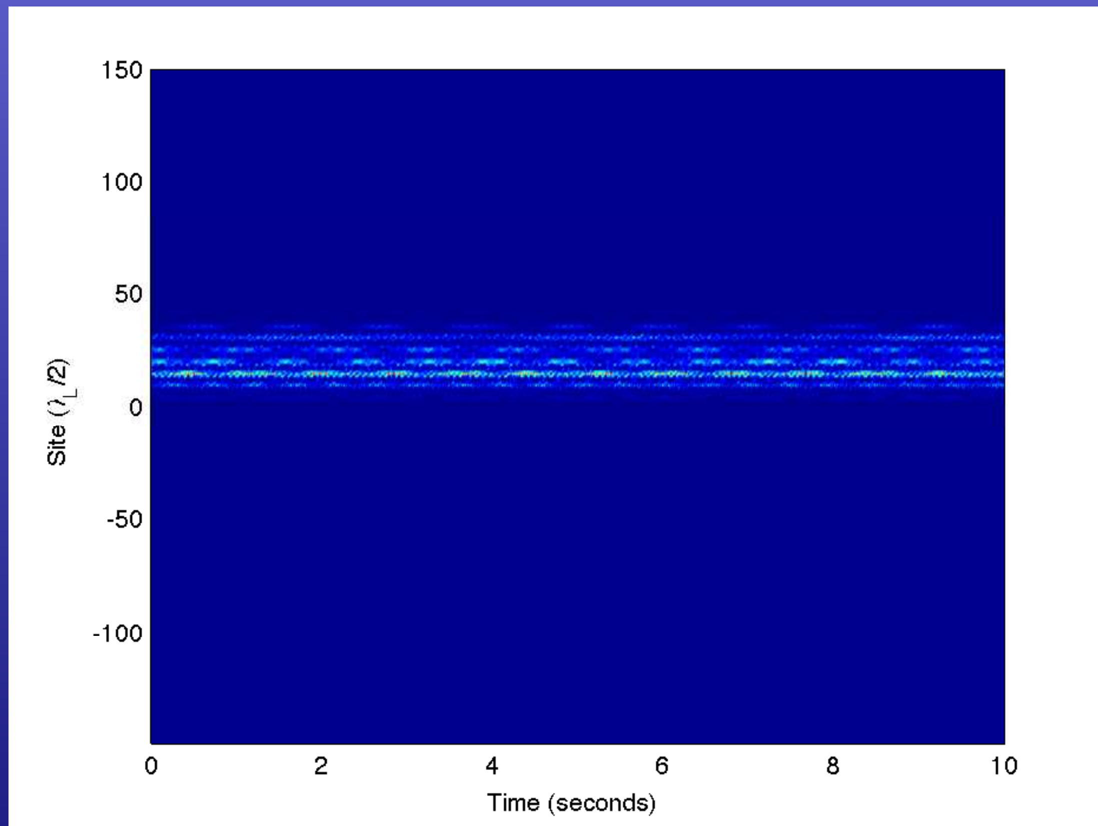
$$\frac{V_{\rm dis}}{J} \equiv \Delta.$$

Results



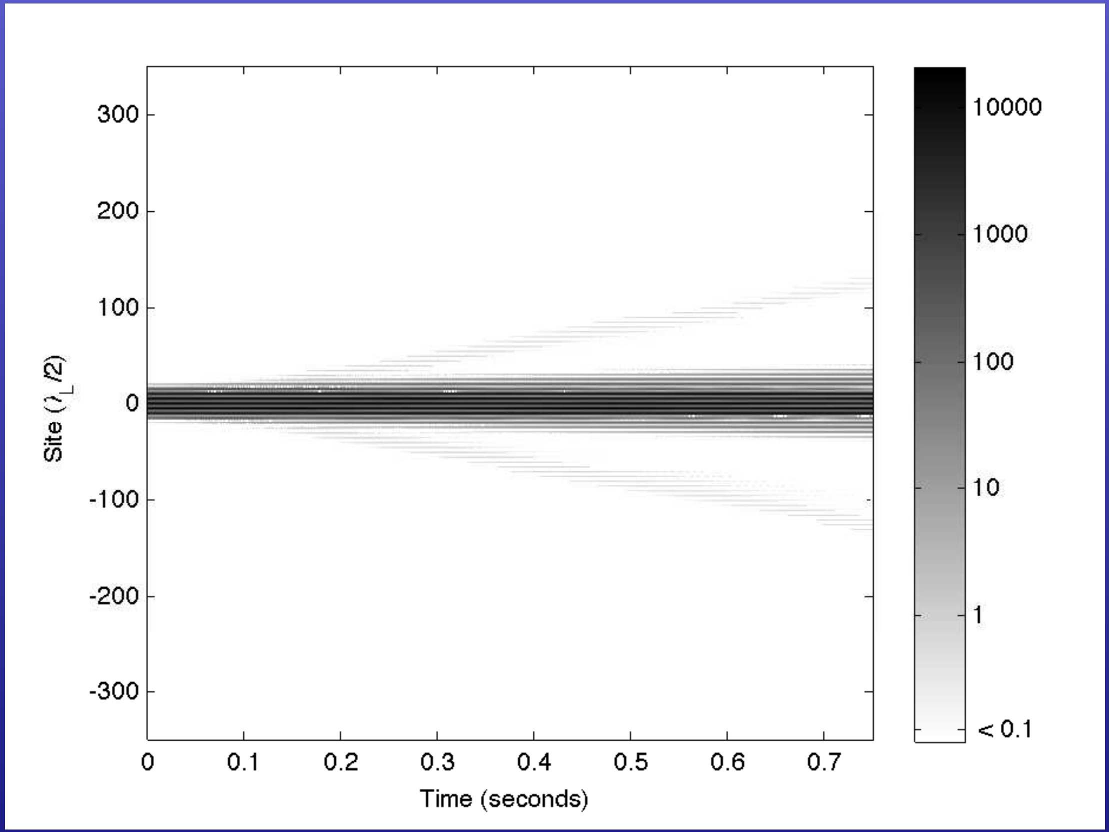
$$\Delta = 0$$

Results



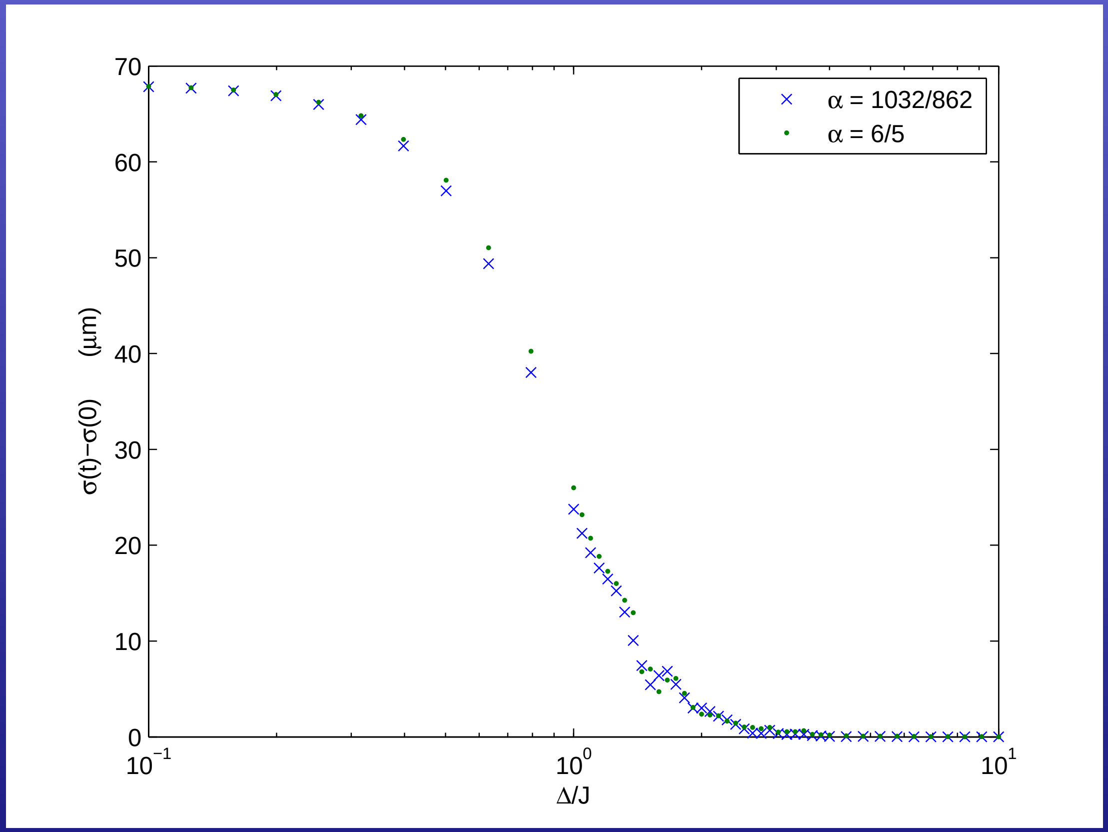
$$\Delta = 3$$

Commensurate Lattice



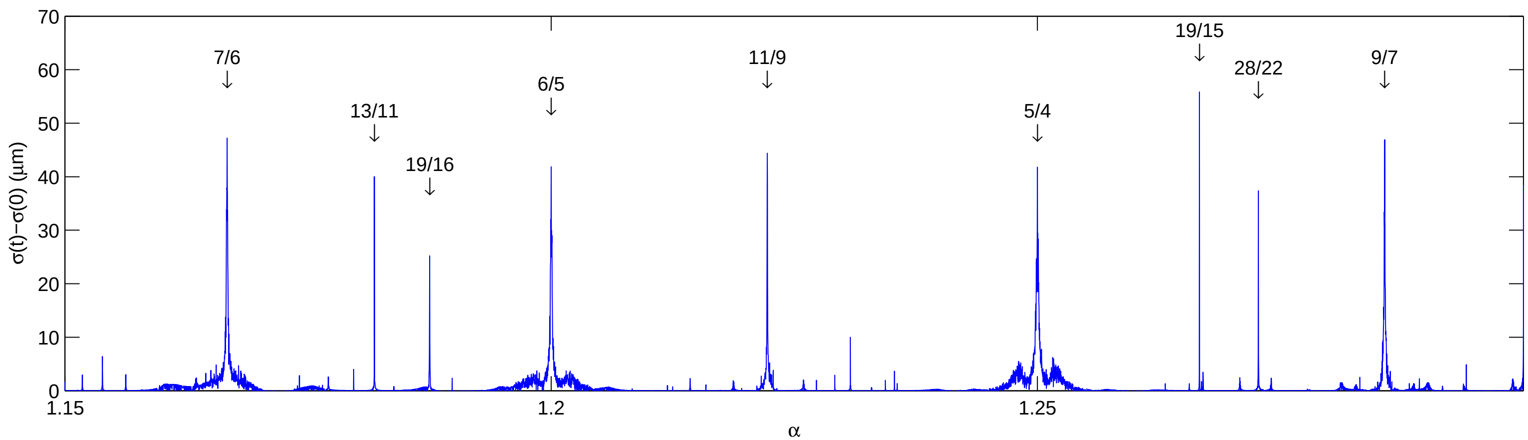
$$\Delta = 3$$

Our version of the smoking gun

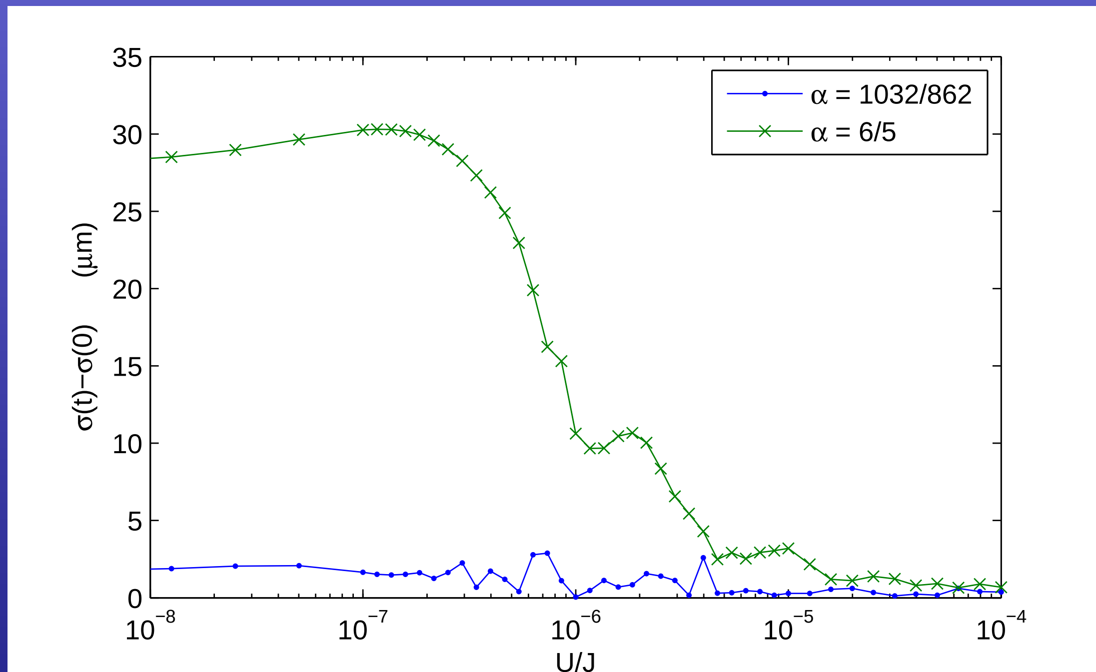


$$U/J = 10$$

Counting rational numbers

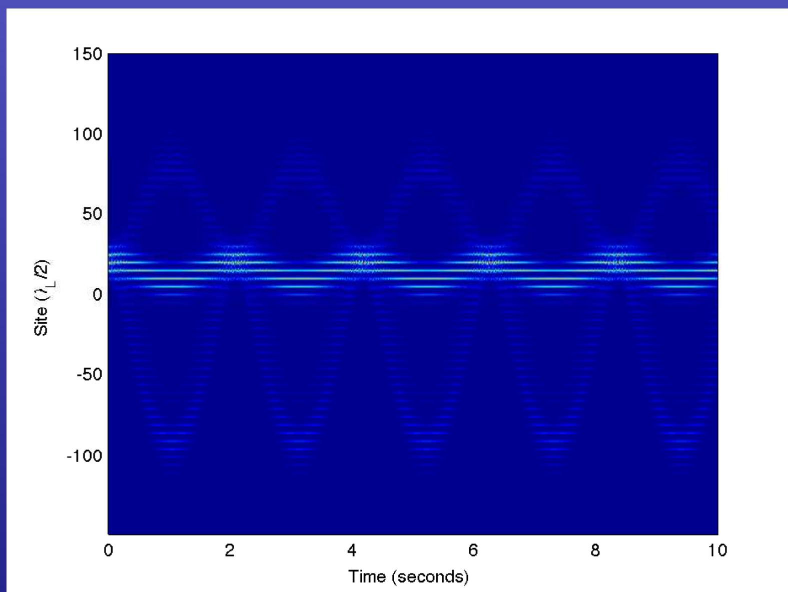


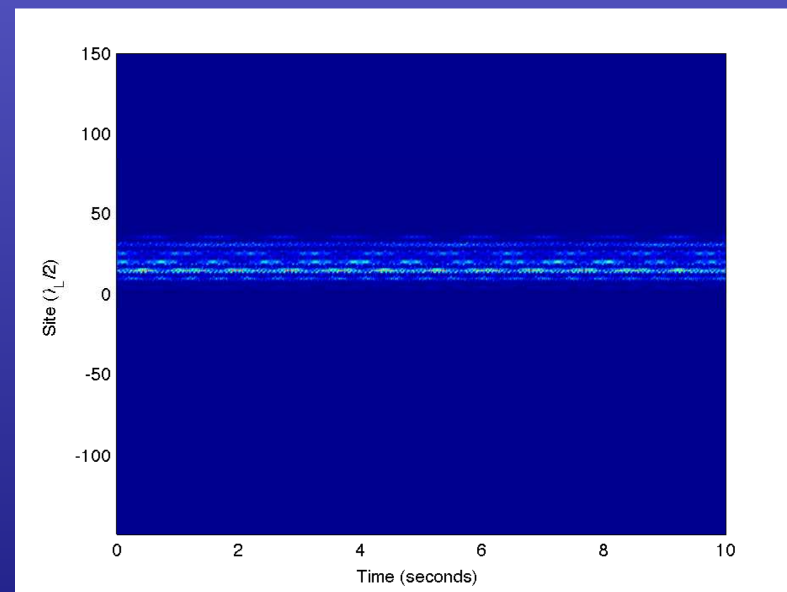
Effect of interactions



Bloch Oscillations

Commensurate

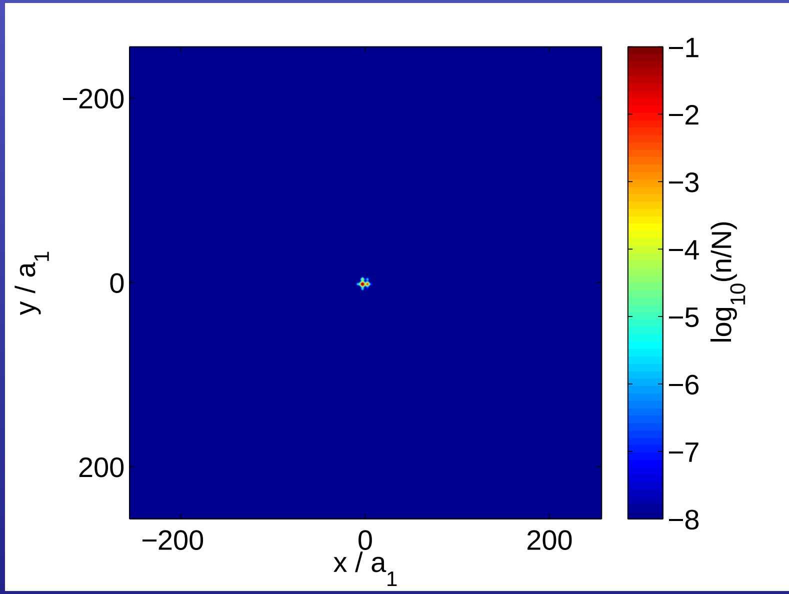


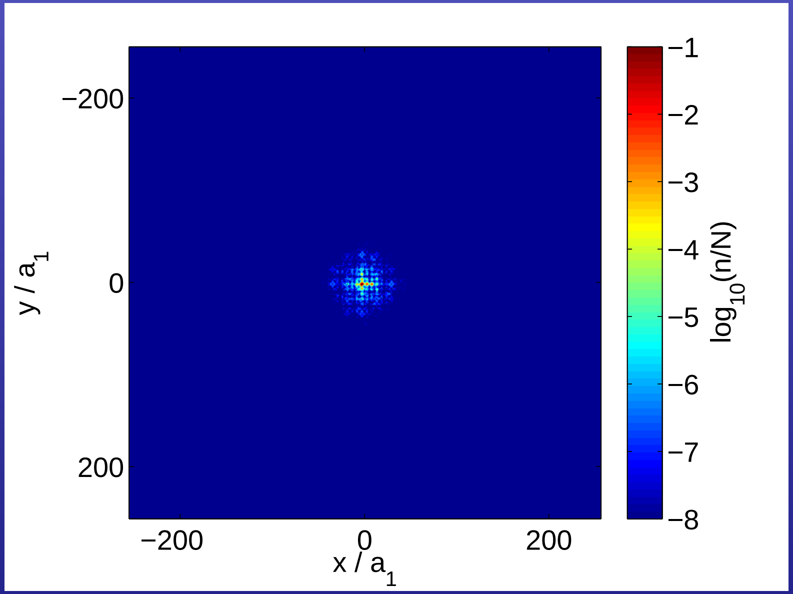


Quasi-periodic

Two dimensions

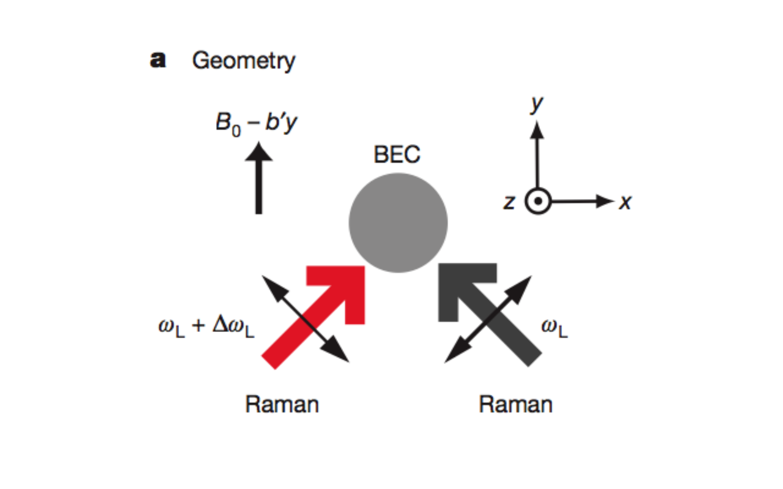
time zero

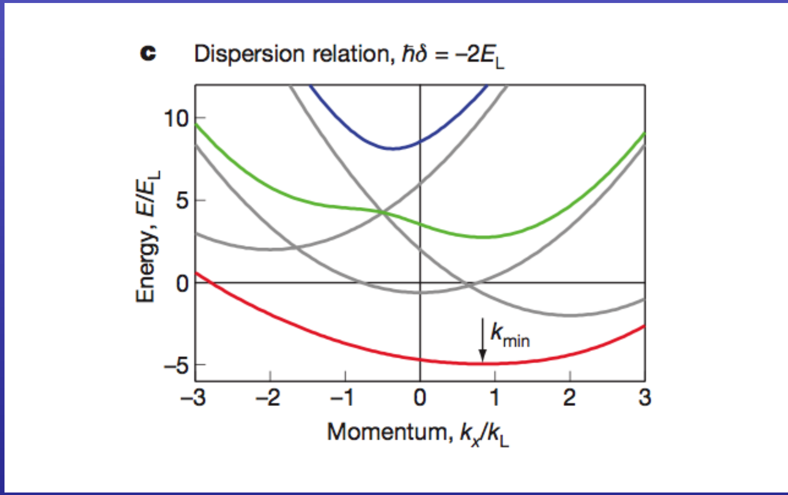




t=1000 ms

Geometry

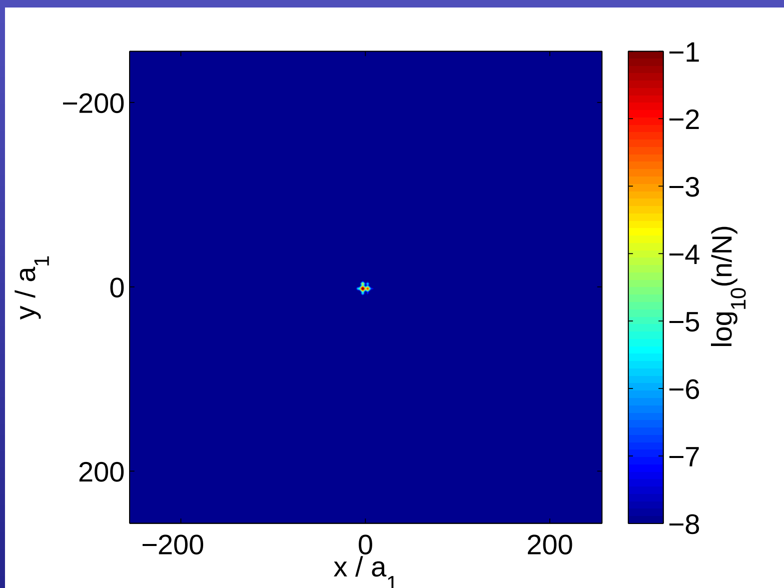


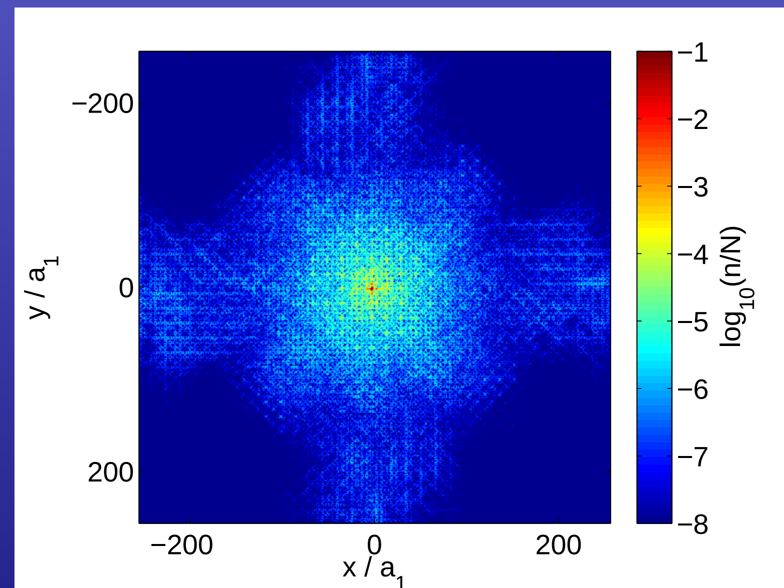


$$\mathbf{p} \rightarrow \mathbf{p} - e\mathbf{A}$$

Breaking time-reversal symmetry

time zero

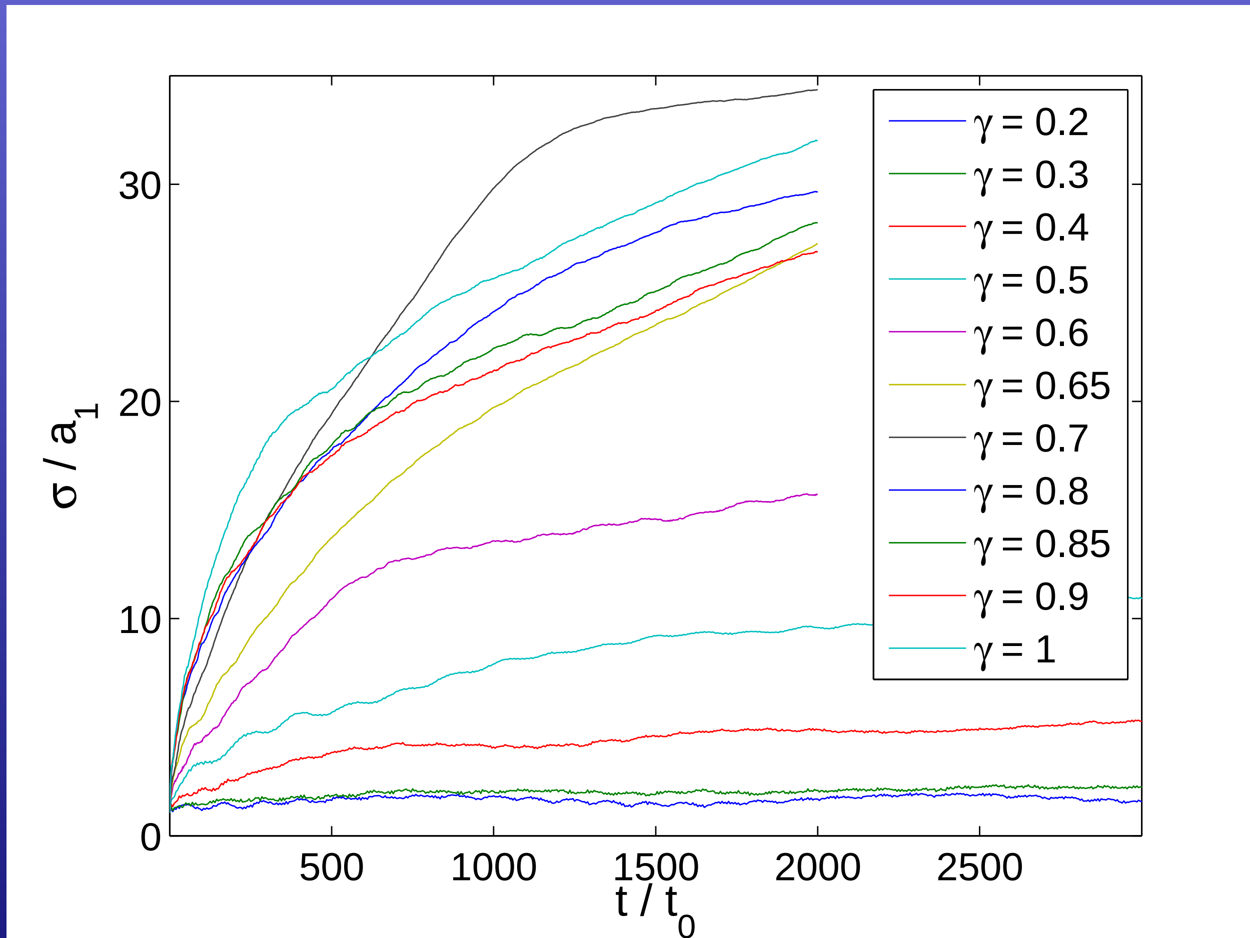




t=1000 ms,

$$\gamma \sim e\mathbf{B} = 0.7$$

A resonance...



σ / a1
t / t0
γ = 0.2
γ = 0.3
γ = 0.4
γ = 0.5
γ = 0.6
γ = 0.65
γ = 0.7
γ = 0.8
γ = 0.85
γ = 0.9
γ = 1
0
10
20
30
500
1000
1500
2000
2500

Experiments in semiconductors - the 2DEG

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Possible metal-insulator transition at $B = 0$ in two dimensions

S. V. Kravchenko, G. V. Kravchenko,* and J. E. Furneaux
Laboratory for Electronic Properties of Materials and Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019

V. M. Pudalov† and M. D'Iorio
National Research Council of Canada, Institute for Microstructural Science, Ottawa, Ontario, Canada K1A OR6
(Received 18 April 1994)

- Study resistivity of 2DEG in Si MOSFETs.
- *Very* high mobility samples.
- Low electron densities.
- Identify critical electron density for metal-insulator transition.

Kravchenko data

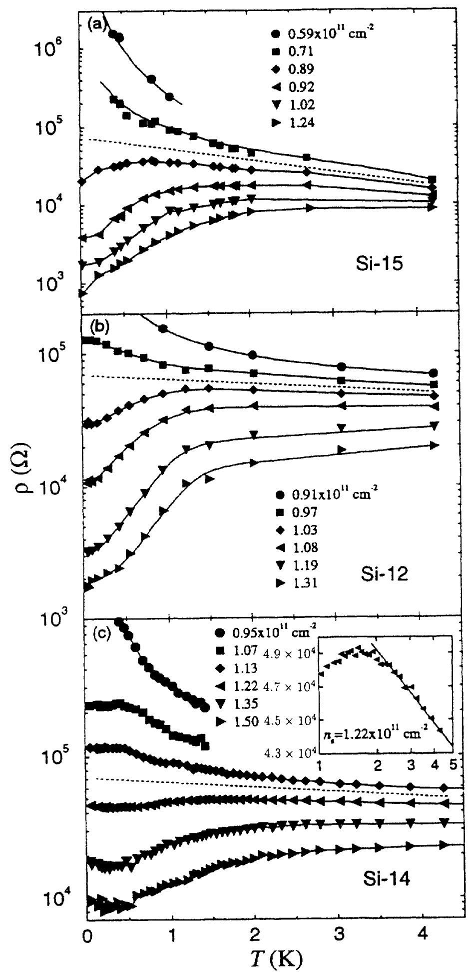
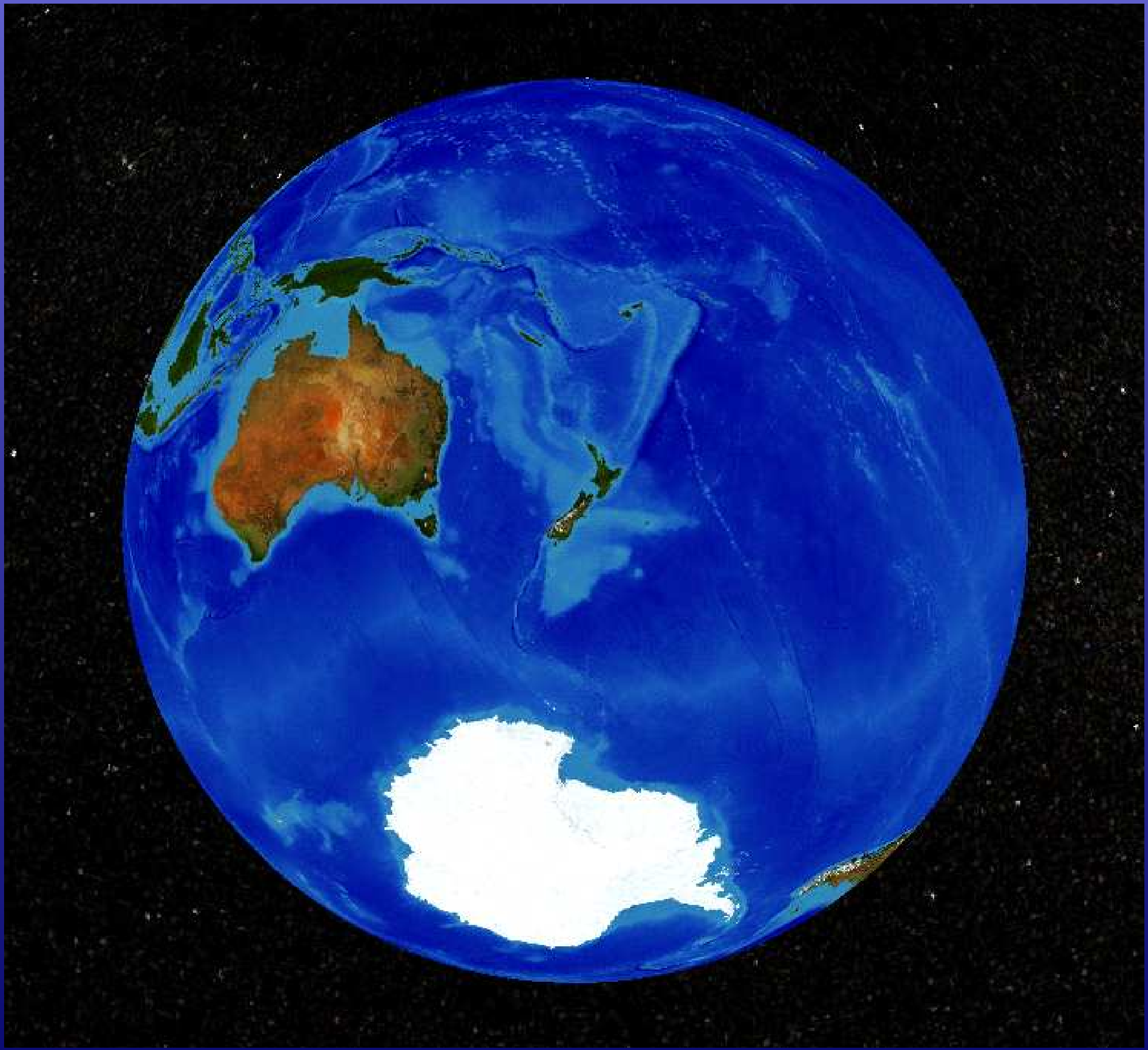


FIG. 2. Resistivity vs T for electron densities near n_{cr} for Si-15 (a), Si-12 (b), and Si-14 (c). Inset shows a temperature dependence of ρ consistent with weak localization ($\Delta\rho \propto \log T$) at temperatures above the drop of ρ.

Open questions - Interactions? Quantum phase transition? Cross-over?

A thank you...



A localised state...