Quantum Ultracold Gases in Reduced Dimensions wih Tunable Interactions: from Atomtronic to Fundamental-Physics tests

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Why

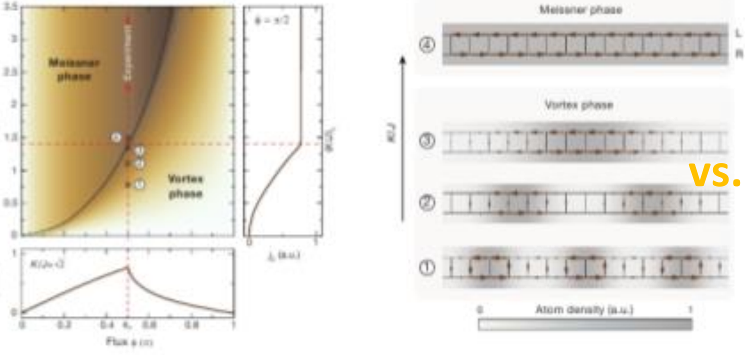
- Quantum ultracold gases are realized in labs by combined atomic-physics techs of cooling and trapping
- Extreme quantum conditions by tuning: Temperature, Interactions, Dimensions, Quantum statistics
- Controlled with high precision and amenable to modeling with no significant number of fitting parameters

For What

- Fundamental physics-Precision measurements
- Quantum information-Atomtronics- Atom litography
- Strongly correlated ground states

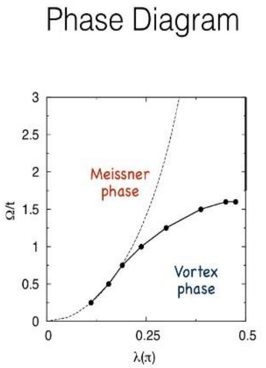
Spin& Density Structure and Transport in 1D coupled chains with artificial magnetic fields: Meissner-to-Vortex phase transitions

Lab. exp.



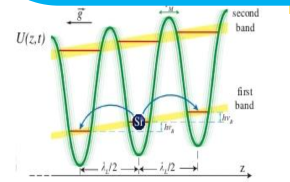
From Atala et al. Nat. Phys. (2014)

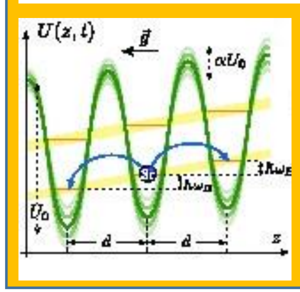
vs.



DMRG num. exp.

Precision measurements & Quantum transport in modulated optical lattices. Theo and Exp [@LENS]





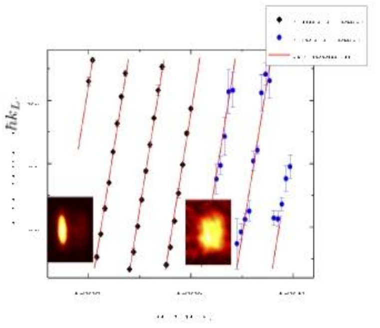
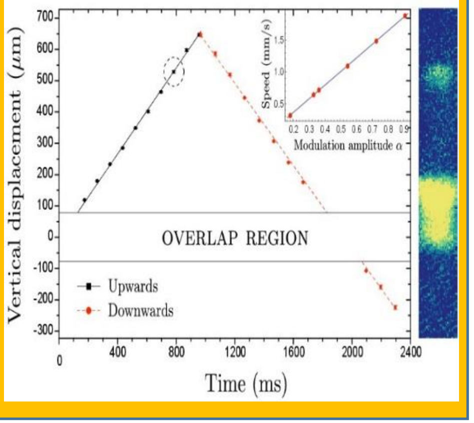


FIG. 6. Comparison between Bloch oscillation phase evolution with initial AM burst (black diamonds) and without it (blue circles). In the insets, 2D TOF atomic distributions in the two cases. The red line is obtained from the best fit with a sawtooth function.

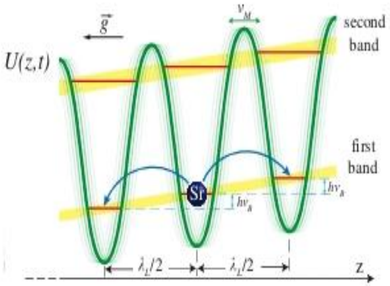


COHERENT DELOCALIZATION OF SR QUANTUM GASES IN PHASE AND AMPLITUDE MODULATED OPTICAL LATTICES [1-3]

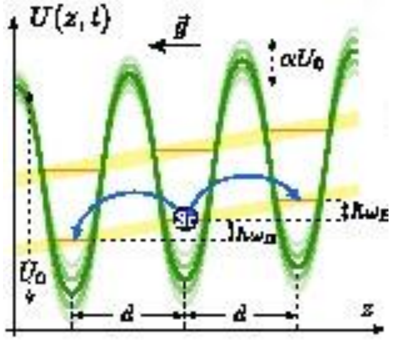
Concept

$$H(z,p,t) = \frac{p^2}{2M} + U(z)[1+\alpha f(t)] - \beta z f(t) - mgz$$

$$\boxed{\begin{aligned} U(z) &= U_0 \cos[2k_L z]/2 \\ f(t) &= \sin[\omega_M (t - t_0) - \phi] \end{aligned}}$$



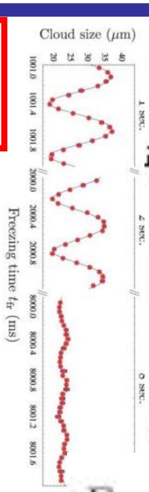
Phase Modulation

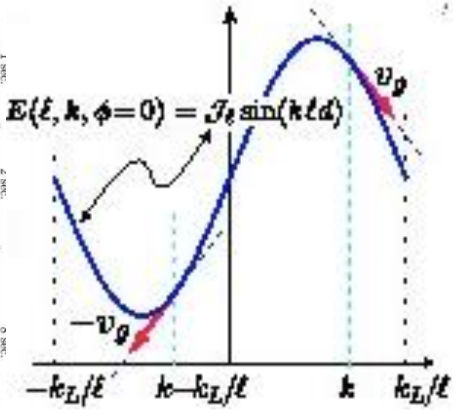


Amplitude Modulation

$$\omega_B = \frac{Fd}{\hbar}$$ **Bloch frequency**

$$\omega_M = l\omega_B$$ **Modulation frequency**





$$E_{\rm mod}(k) = |\mathcal{J}_\ell| \sin(\ell k d + \phi)$$

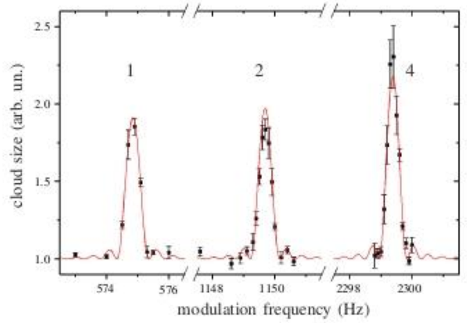
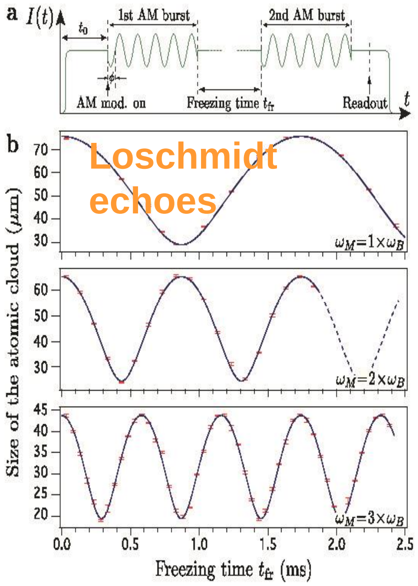


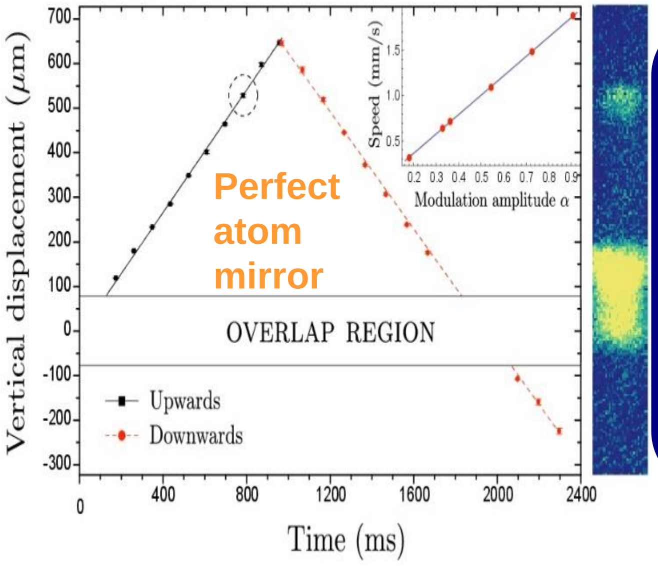
FIG. 4 (color online). Resonance spectra at the 1st, 2nd, and 4th harmonic of the Bloch frequency ν_B. The excitation time is set to 2 s. Within the error bars the fitted center line frequencies are in integer multiple ratio.

Apps

Quantum transport



Loschmidt echoes



Perfect atom mirror

Precision meas.

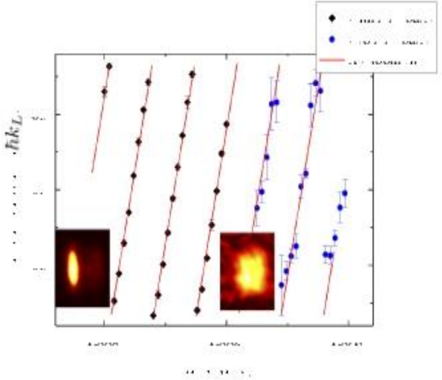


FIG. 6. Comparison between Bloch oscillation phase evolution with initial AM burst (black diamonds) and without it (blue circles). In the insets, 2D TOF atomic distributions in the two cases. The red line is obtained from the best fit with a sawtooth function.

Exceptionally long lasting Bloch oscillations

Effect	Correction (10^{-7})	Uncertainty (10^{-7})
Lattice wavelength fluctuations	0	2
Lattice beam vertical alignment	0	0.1
Inhom. Stark shift (beam geometry)	14.3 ÷ 17.3	0.4
Experiment timing	0	0.2
Tides	-1.4 ÷ 0.9	<0.1
Off-resonance tunneling	<0.01	0.01
Atomic refraction index	0	<0.01
Systematics total	17.2 ÷ 22.5	2.1
(w/o lattice wavelength fluct.)	"	0.47

1D DIPOLAR QUANTUM GASES [3]

Concept

Hamiltonian of N atoms with mass M and permanent dipolar moments, arranged on a line with density n

$$H = -\frac{1}{r_s^2}\sum_{i=1}^{N}\frac{\partial^2}{\partial x^2} + \frac{1}{r_s^3}\sum_{i<j}^{N}\frac{1}{|x_i - x_j|^3} \qquad r_s = 1/(n\, r_0) \qquad Ry^* = \frac{\hbar^2}{2Mr_0^2}$$

$$C_{dd} = \mu_0 \mu_d^2$$

Magnetic dipole

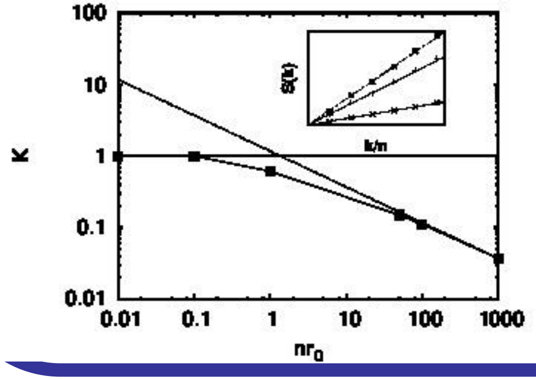
$$C_{dd} = \frac{d^2}{\varepsilon_0}$$

Electric dipole

Combine Bosonozation technique with a Numerical experiment, i.e. Reptation Quantum Monte Carlo

Results

It is a super-strongly coupled Luttinger Liquid



Momentum distribution & Dynamical Structure

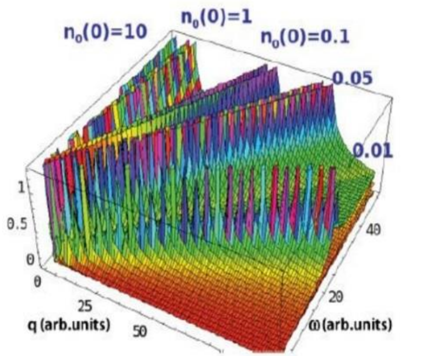


FIG. 1. (Color online) TLL model with $e(nr_0) \propto n^\gamma$ and $\gamma = 2$ in a harmonic trap. $S(q,\omega)$ in arbitrary units in the (ω,q) plane and different densities at the trap center.

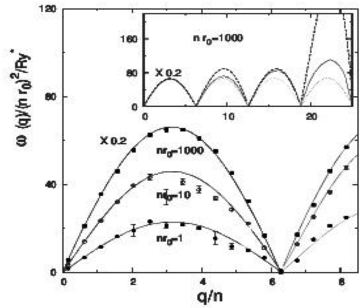


FIG. 2. Lowest excitation energies $\omega(q)$ in Ry^* units and scaled by $(nr_0)^2$ for a dipolar gas with $N=40$ and different values of $nr_0 = 1$, 10, and 1000 as in the legend. The symbols with error bars are energies extracted using Eq. (3); the solid line is a guide to the eye. The curve at $nr_0 = 1000$ is depressed by a factor of 5 for graphical reasons. Inset: zoom on the $\omega(q)$ at $nr_0 = 1000$ up to $q/n = 8\pi$ for different $F(q,\tau)$ models: multimode model (3) (solid) and Feynman (dashed) approximation. Dotted line: periodic replica of the first bump.

In conclusion:

Luttinger-liquid is a unifying theory for low-energy behavior of 1D dipolar quantum gases in the whole crossover region evolving into a Tonks-Girardeau gas at low densities and into a quasi-ordered state at high enough densities

Ongoing Work

- **Enhanced SNR via non-destructive cavity-QED methods**
- **Towards novel ground states of 1D quantum dipolar gases with spin-orbit coupling**
- **Towards novel phase diagram of Fermi gases with attractive cavity-induced interactions**
- **Superfluidity in Fermi gases with narrow Fano-Feshbach resonances**

Ongoing Work Thesis available

- **Enhanced SNR in g-meas. via non-destructive cavity-QED methods [4],** where the standing optical-lattice mode amplitude is slaved to atomic motion . **How:** Analytical and light numerical methods (+ possible experiment)

- **Towards novel phase diagram of Fermi gases with attractive cavity-induced interactions**: from superfluidity [5] to spin ferro- and antiferro-magnetic phases. **How:** Analytical+Exact diagonalization methods

- **Superfluidity in Fermi gases with narrow Fano-Feshbach resonances [6],** leading to tunable interactions and richer crossover phenomena from BCS to BEC, depending on two parameters. **How**: QMC+Analytical methods

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[4] Enhanced SNR g-meas.: Peden B, Meiser D, Chiofalo M, Holland M *PRA* **80**, 43803 (2009)

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[6] SF with narrow Feshbach resonances: De Palo S, Chiofalo M, Holland M, Kokkelmans S, *PLA* **327**, 490 (2004)