Ultracold atoms under an artifical gauge field : persistent currents

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Frank Hekking Memorial Workshop

cnrs dépasser les frontières

LPMMC laboratoire de physique et de modélisation des milieux condensés

UNIVERSITÉ Grenoble Alpes

Funding from
ANR SuperRing

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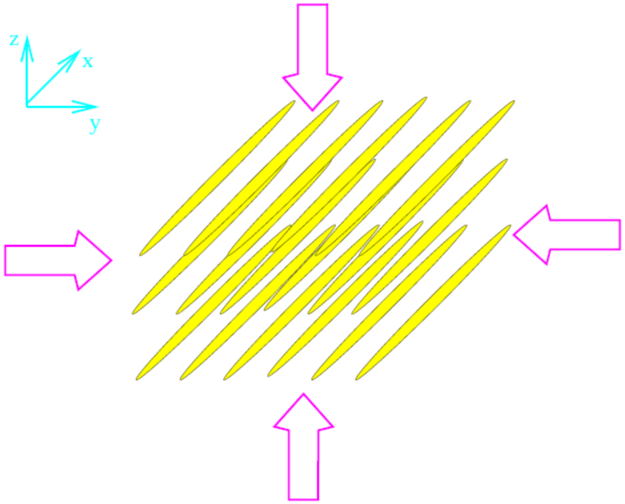
One-dimensional quantum systems with ultracold atoms

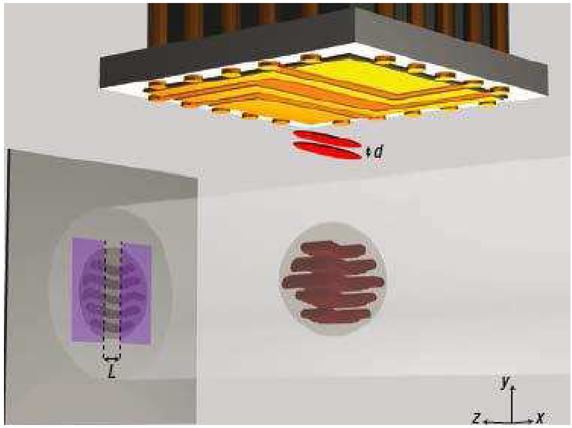
- Cylindrical geometry
- Very large transverse confinement

- All energy scales smaller than transverse energy

$$\mu, k_B T \ll \hbar\omega_\perp$$

Realization : 2D optical lattices or chip traps





Interactions in 1D quantum gases

- Interactions due to atom-atom collisions

  (short range, s-wave scattering length)

- Effective 1D interactions

$$v(x) = g\delta(x)$$

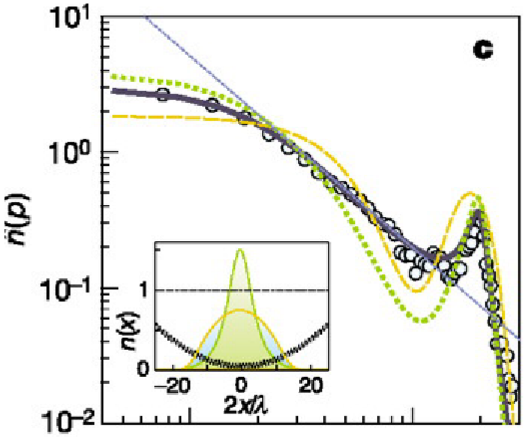
- Hamiltonian (Lieb-Liniger model with external potential)

$$\mathcal{H} = \sum_i -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_i^2} + V(x_i) + g\sum_{i<j}\delta(x_i - x_j)$$

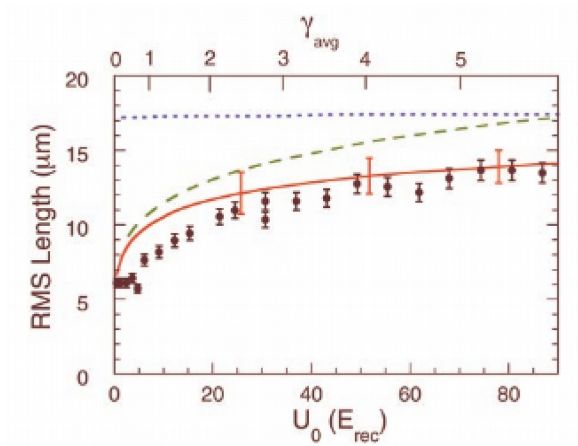
- Dimensionless interaction strength :

$$\gamma = gn/(\hbar^2 n^2/m)$$

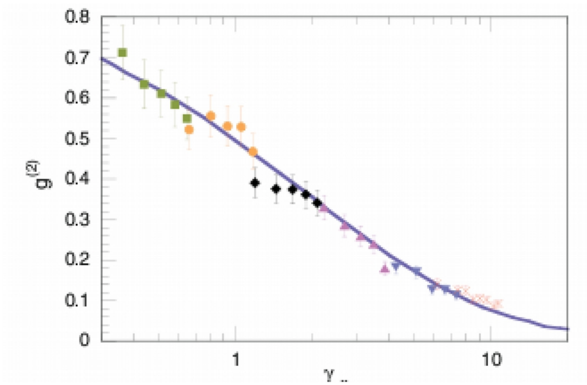
One-dimensional quantum gases : experiments



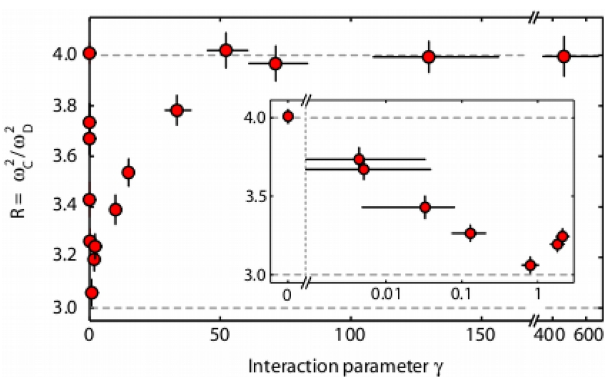
B. Paredes et al (2004)



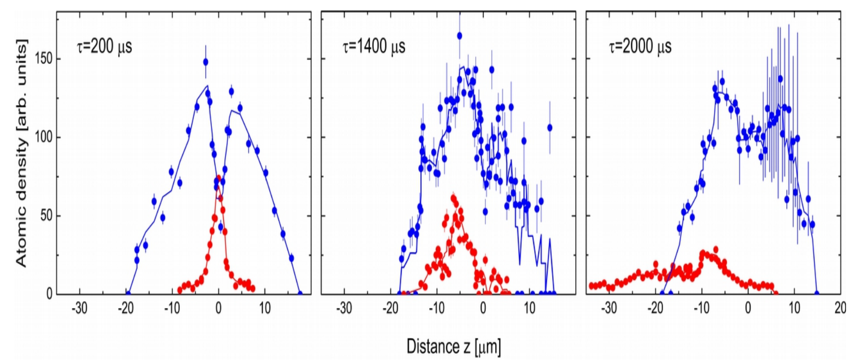
T. Kinoshita et al (2004)



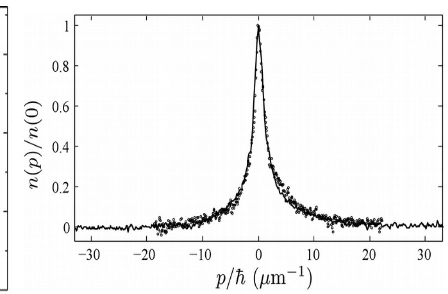
T. Kinoshita et al (2005)



E. Haller et al (2009)



S. Palzer et al (2009)



T. Jacqmin et al (2011)

Strongly interacting regime reached in the experiment

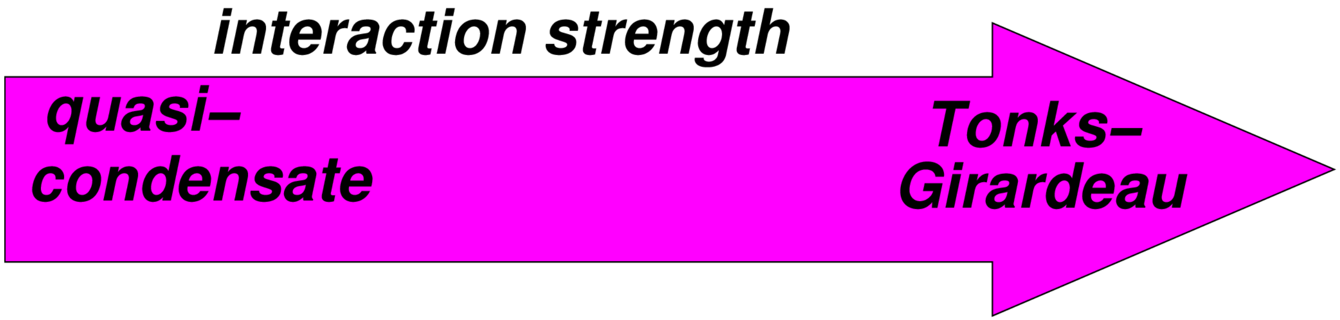
Line diagram for 1D bosons

- Weak interactions:

  a condensate with fluctuating phase

- Strong interactions:

  fermionization



- No phase transition in uniform wires
- But very different behaviour from weak to strong interactions

The weakly interacting regime : Gross-Pitaevskii equation

- Mean-field description of a Bose gas

  with 'condensate wavefunction' $\Phi(x,t)$

$$i\hbar\partial_t\Phi = -\frac{\hbar^2\nabla^2}{2m}\Phi + V_{ext}\Phi + g|\Phi|^2\Phi$$

External confinement　　　interactions

- Nonlinear Schroedinger equation: superfluidity, solitons...
- Even in the dilute regime $E_{int} \ll E_{kin}$, under external confinement/disorder the interactions are important *[Baym-Pethick, Stringari]*

Intermediate interactions : bosonizing the bosons with Luttinger liquid theory

- Quantum hydrodynamics, low-energy theory

  for the *superfluid phase* ϕ

  and the *density fluctuation* $\partial_x \theta$

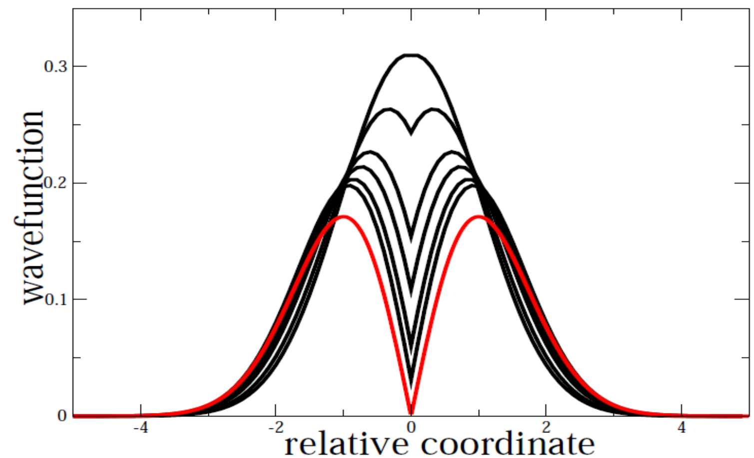
$$\mathcal{H} = \frac{\hbar v_s}{2\pi} \int dx K (\partial_x \phi)^2 + \frac{1}{K} (\partial_x \theta)^2$$

- Sound velocity and Luttinger parameter (compressibility) from the microscopic theory
- Phonon excitation spectrum: valid at intermediate and large interactions

Strong interactions : the Tonks-Girardeau gas

- Infinitely strong repulsions mimick Pauli principle

- Exact solution *[Girardeau, 1960]* mapping onto a Fermi gas



$$\Psi_B(x_1, ..., x_N) = \mathcal{A}\,\det[\phi_j(x_\ell)]$$

with

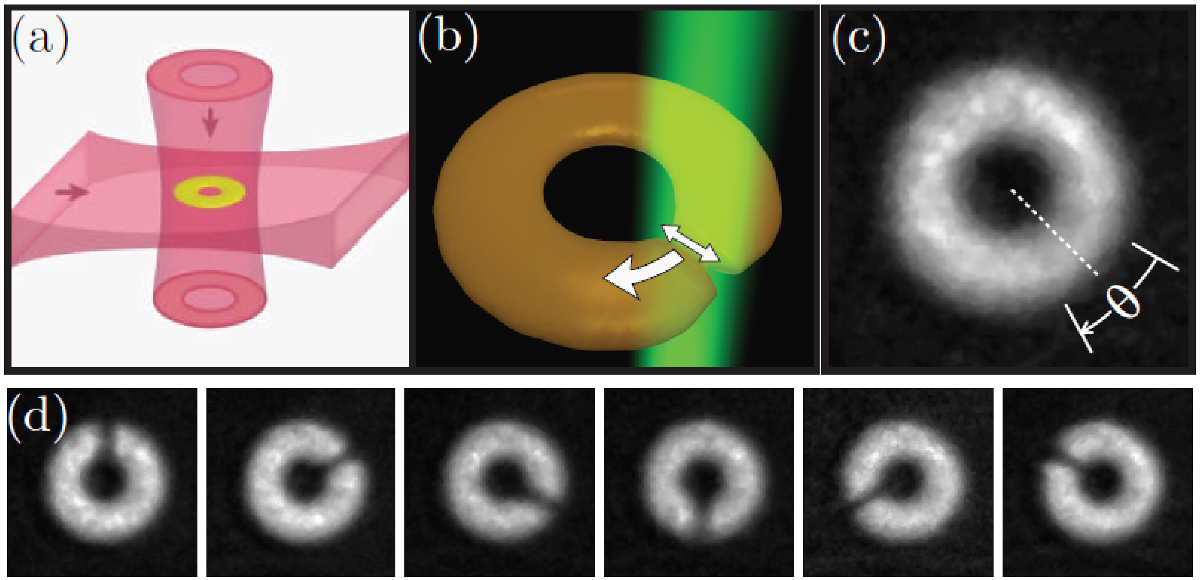
$$\mathcal{A} = \Pi_{1\leq j\leq \ell\leq N}\mathrm{sign}(x_j - x_\ell)$$

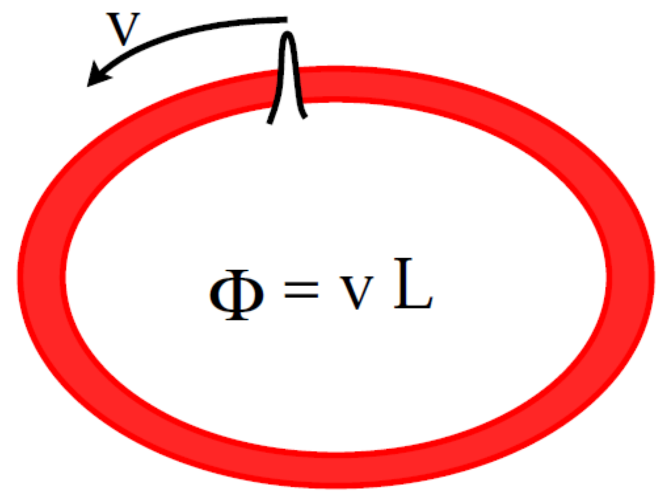
….also valid for:

- inhomogeneous systems
- finite-temperature properties
- out-of-equilibrium dynamics

No length scale associated to interactions : scale invariance

Strongly interacting bosons on a ring under a gauge field





- Barrier rotation : a way to create an artificial gauge field for neutral atoms

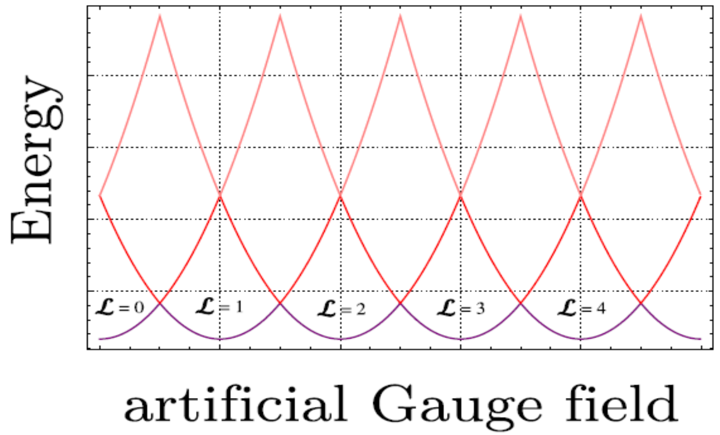
$$\mathcal{H} = \frac{1}{2m}(p - A)^2 + V_{ext} + U_{int}$$

Persistent currents

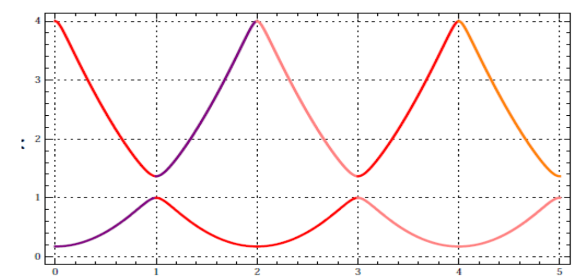
- Ground state energy in presence of gauge field ?

  → periodicity of energy levels

no barrier : Leggett's theorem

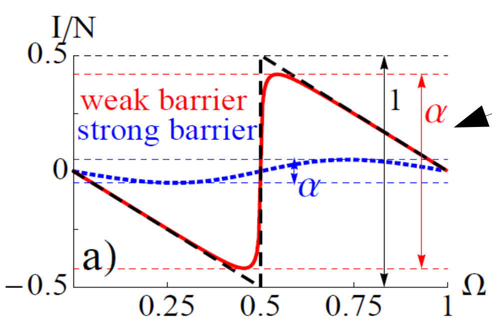


with barrier : coherent mixing of angular momentum states



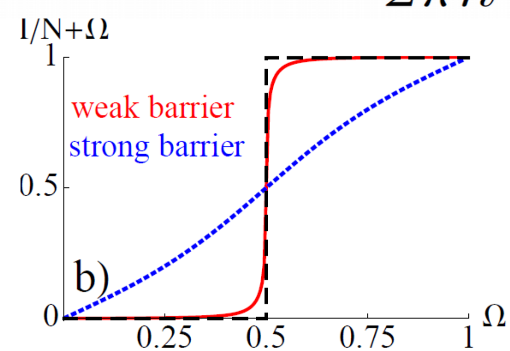
- Persistent currents : definition

$$I(\Omega) = -\frac{1}{2\pi\hbar}\frac{\partial E_0(\Omega)}{\partial \Omega}$$



moving frame

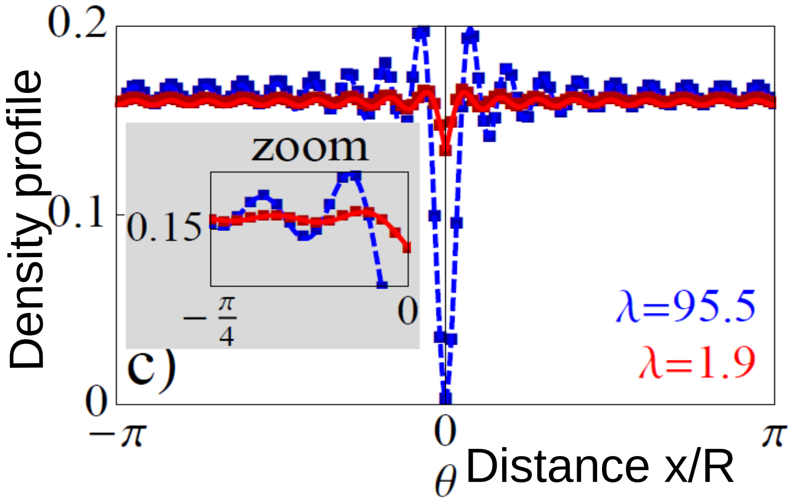
lab frame



Exact results at zero and infinite interactions

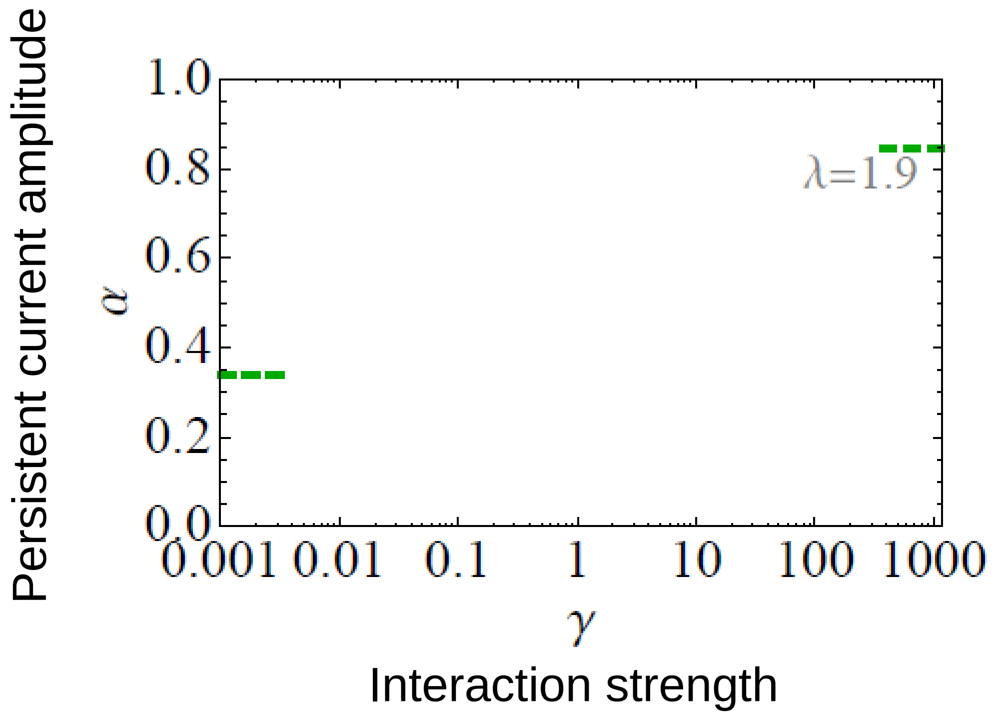
- Density profiles along the ring : Friedel oscillations at strong interactions

  a signature of the strongly correlated regime



- Amplitude of persistent currents : at large interactions, effective barrier

$$U_{eff} = U_0/N$$



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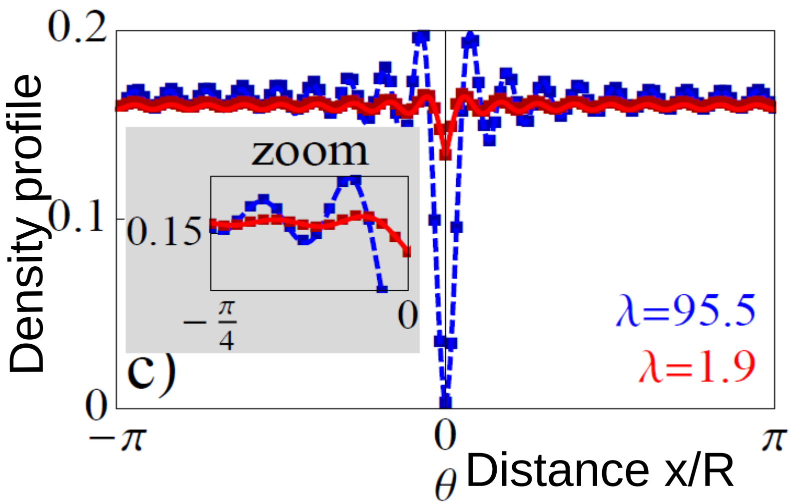

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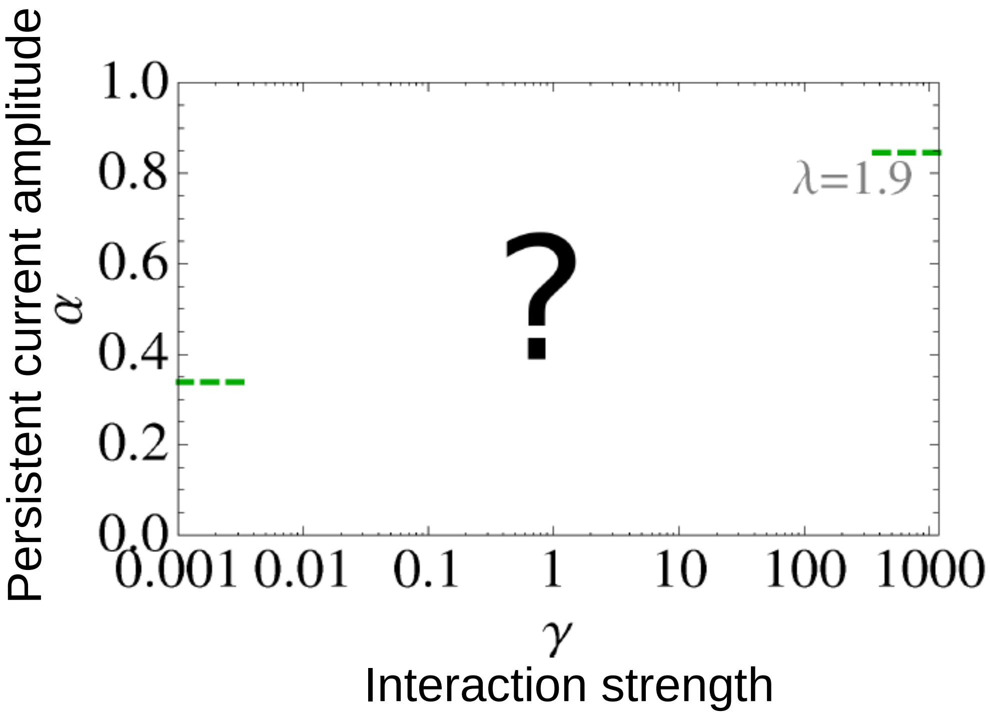
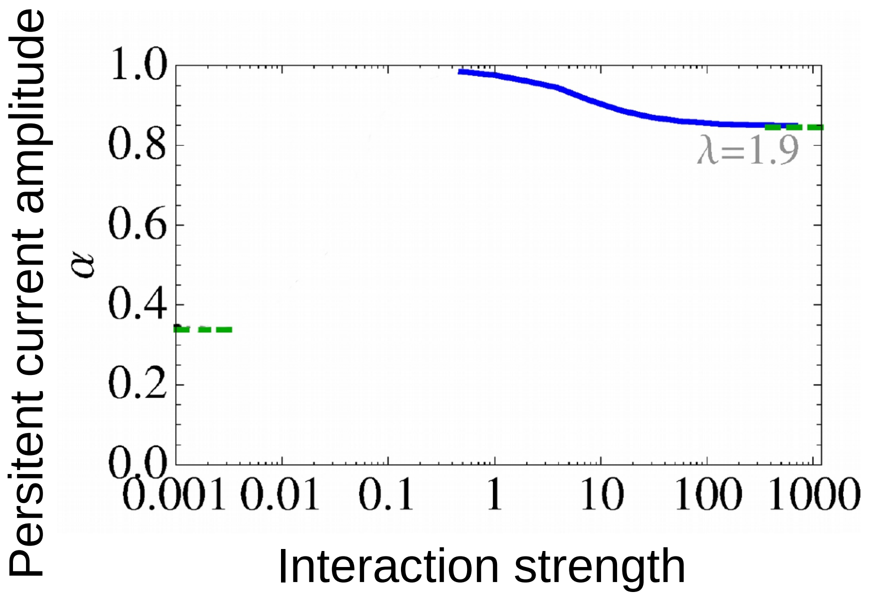


Strongly interacting limit

- Luttinger liquid theory : quantum fluctuations renormalize the barrier strength $U_{\rm eff} = U_0(d/L)^K$



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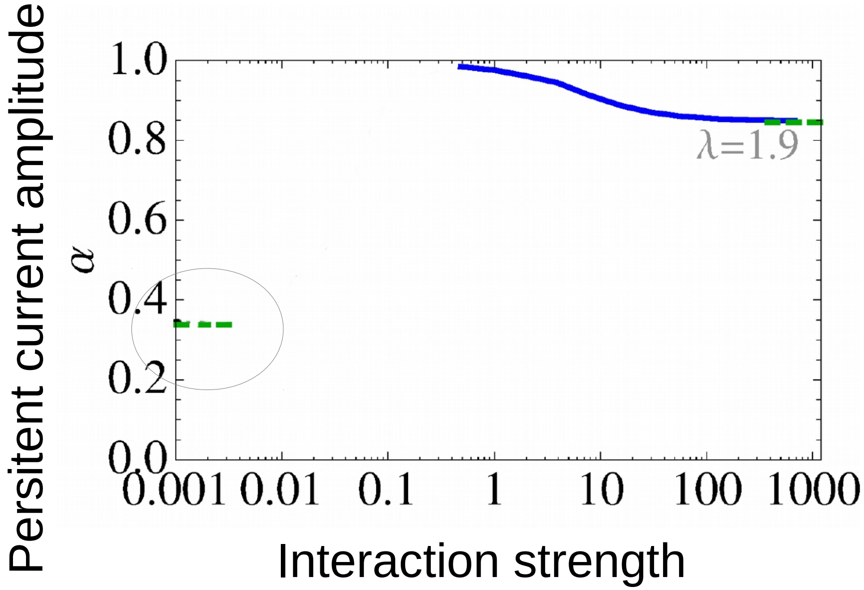

??? Wrong trend ???

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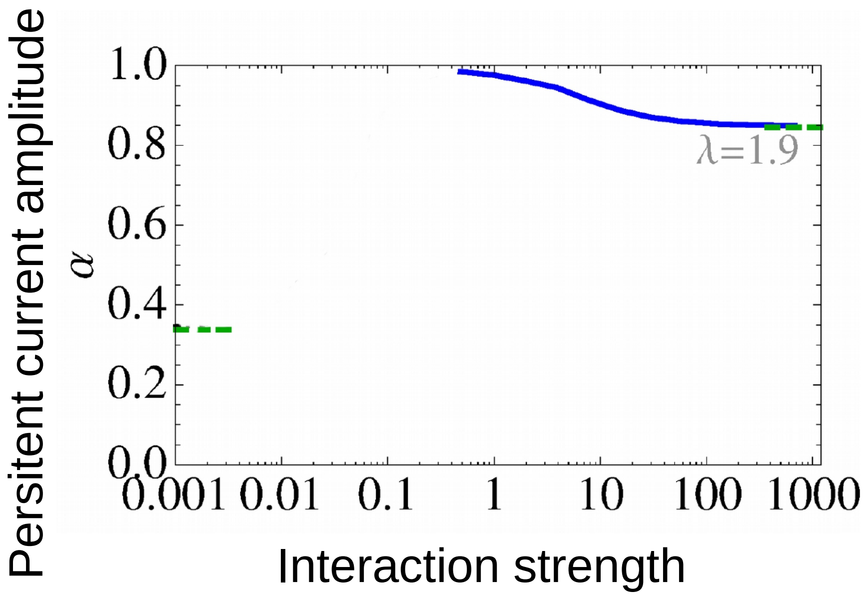


- At increasing interactions, density fluctuations renormalize the barrier less and less
  - *(duality) : phase fluctuations are more and more important at increasing interactions*

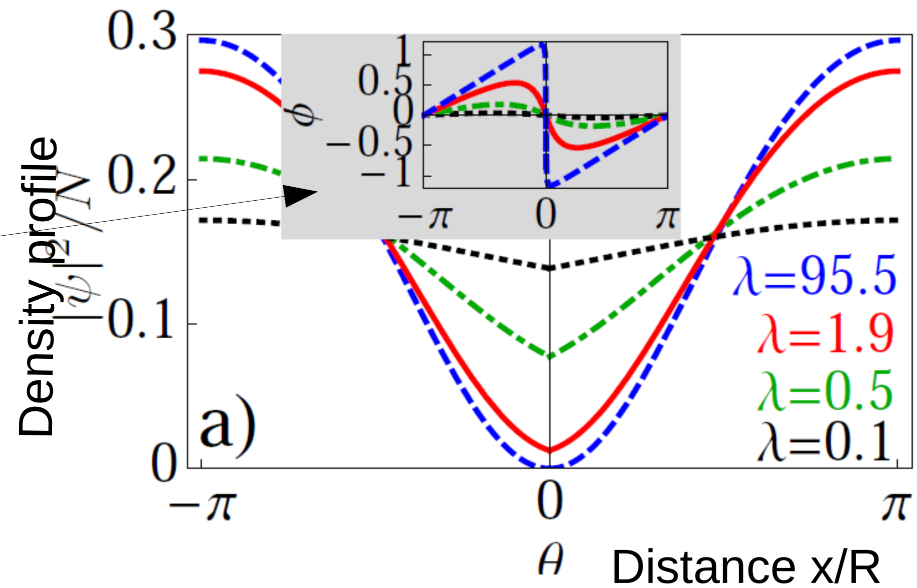
Weakly interacting limit

- Neglect quantum fluctuations : Gross-Pitaevskii equation

$$\frac{\hbar^2}{2m}\left(-i\frac{\partial}{\partial x}+\frac{2\pi}{L}\Omega\right)^2\Phi+U_0\delta(x)\Phi+g|\Phi|^2\Phi=\mu\Phi$$

(*new soliton solution with Jacobi elliptic functions)*

- The soliton is pinned by the barrier → ground state
- Phase slips at the position of the barrier



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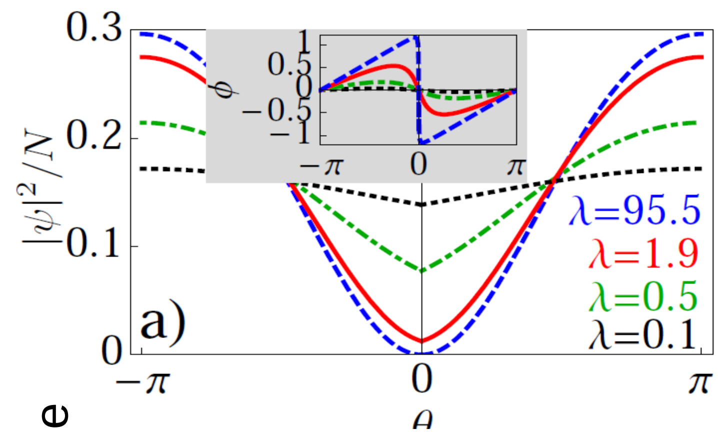
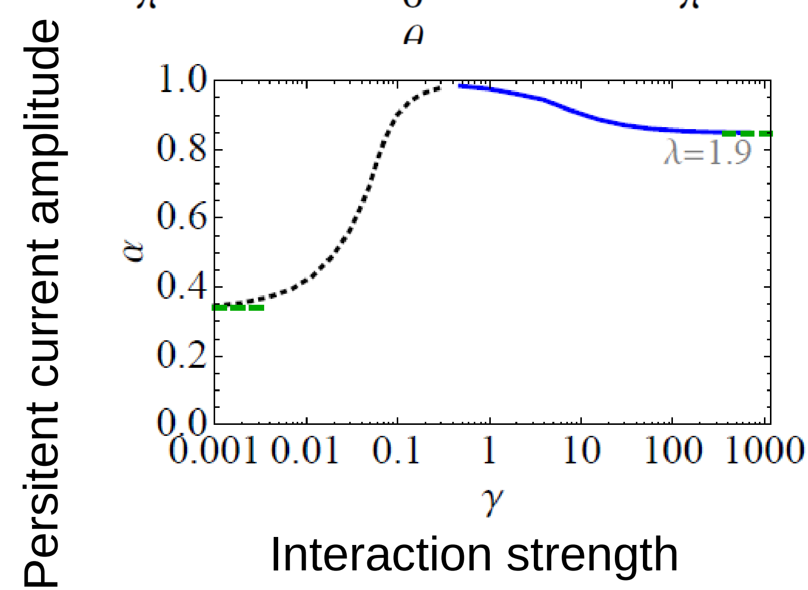
Optimal persistent current at intermediate interactions :

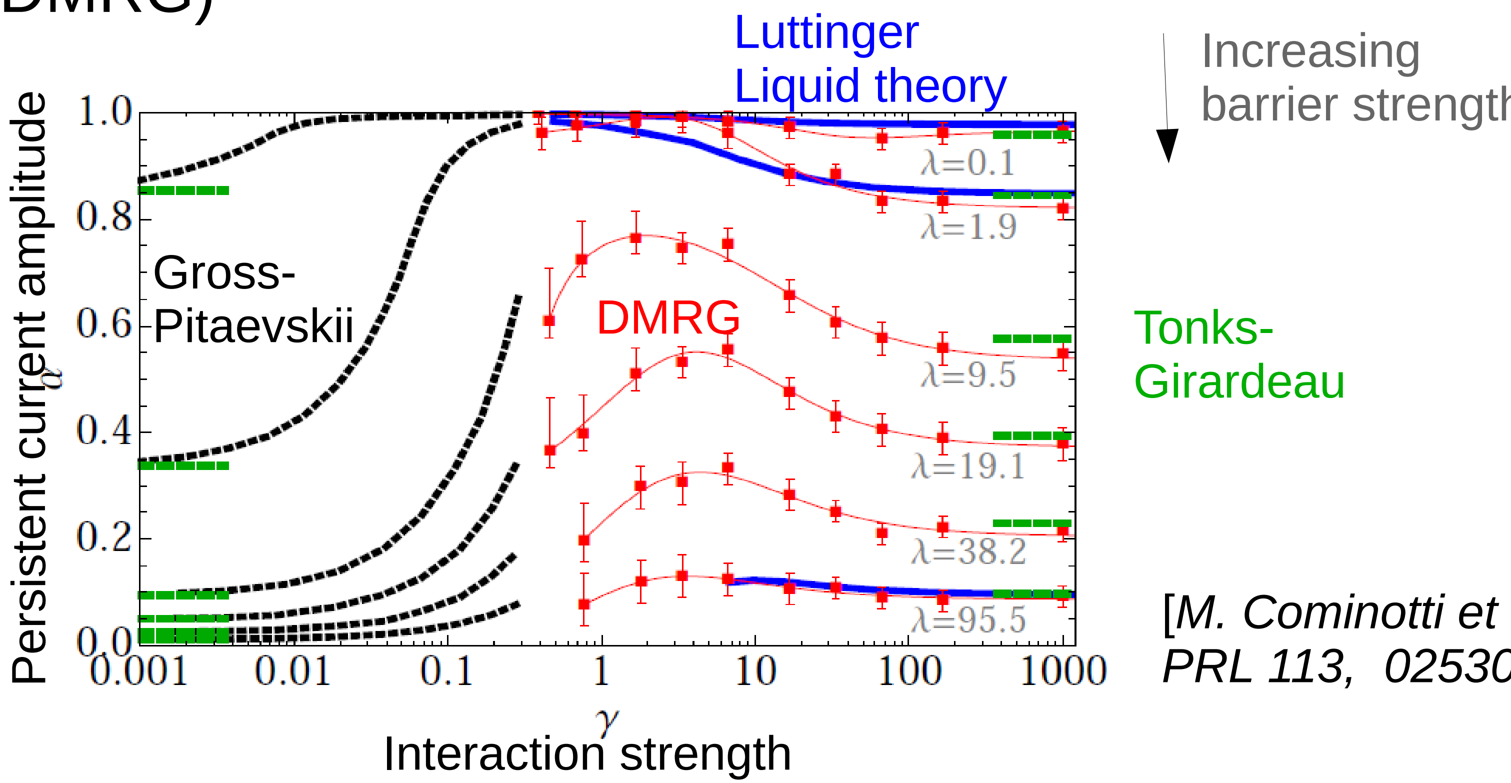
competition of classical screening and quantum fluctuations





Arbitrary interactions and barrier strengths

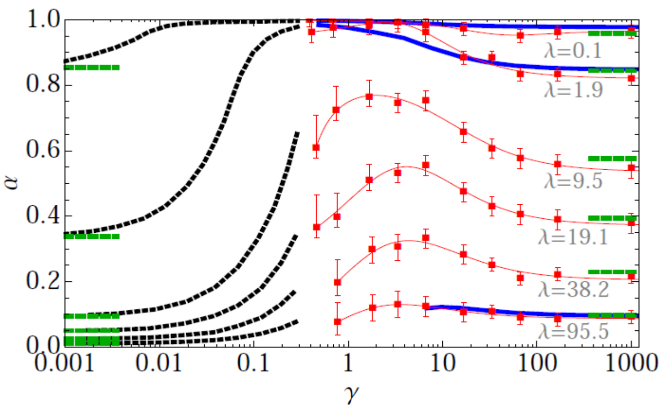
- Persistent current amplitude : all the analytical results + numerical (DMRG)



[*M. Cominotti et al, PRL 113, 025301*]

- *Interactions can turn a strong barrier into a weak one* → quantum state manipulation, transport across a barrier, analog of Hawking effect, ...

Conclusions and perspectives



Non-monotonous behaviour of persistent currents for bosons on a ring : competition of classical screening and barrier renormalisation *[Cominotti et al, PRL 2014]*

I

Seminal idea on barrier renormalisation : Talk by Roberta Citro

Consequence of barrier renormalisation : dipole modes in a split trap *[Cominotti et al, PRA 2015]*

Applications for atomtronics : Talk by Luigi Amico

Beyond 1D rings : Poster by Nicolas Victorin

Dynamics of currents after a quench : Poster by Juan Polo

Atomtronics for bosons with attractive interactions : Poster by Piero Naldesi

Experiments with ultracold atoms on a ring : Talk by Hélène Perrin

Thank you Frank !!