The Abdus Salam
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2239-8

Workshop on Integrability and its Breaking in Strongly Correlated and Disordered Systems

23 - 27 May 2011

Dynamics of impurities in a one-dimensional bosonic gas

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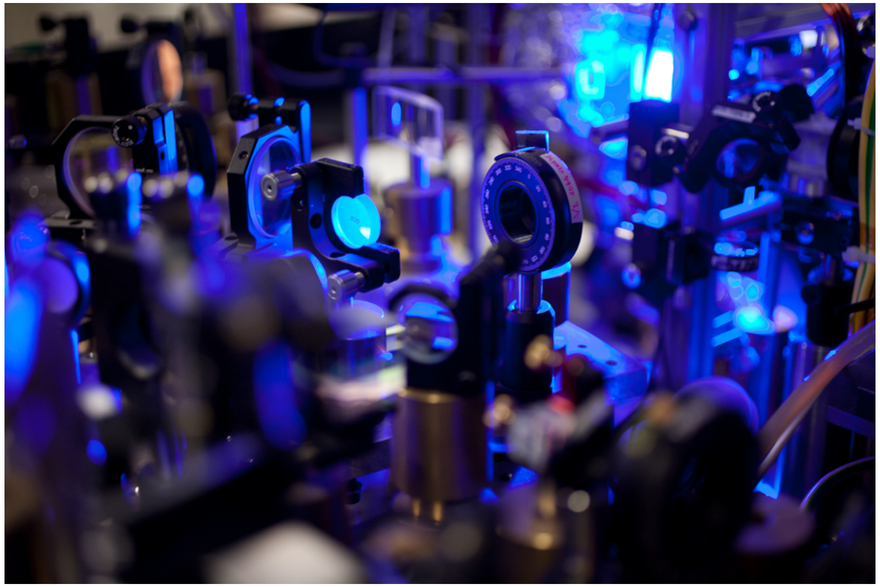
Dynamics of impurities in a one-dimensional Bose gas



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European Laboratory for Nonlinear Spectroscopy

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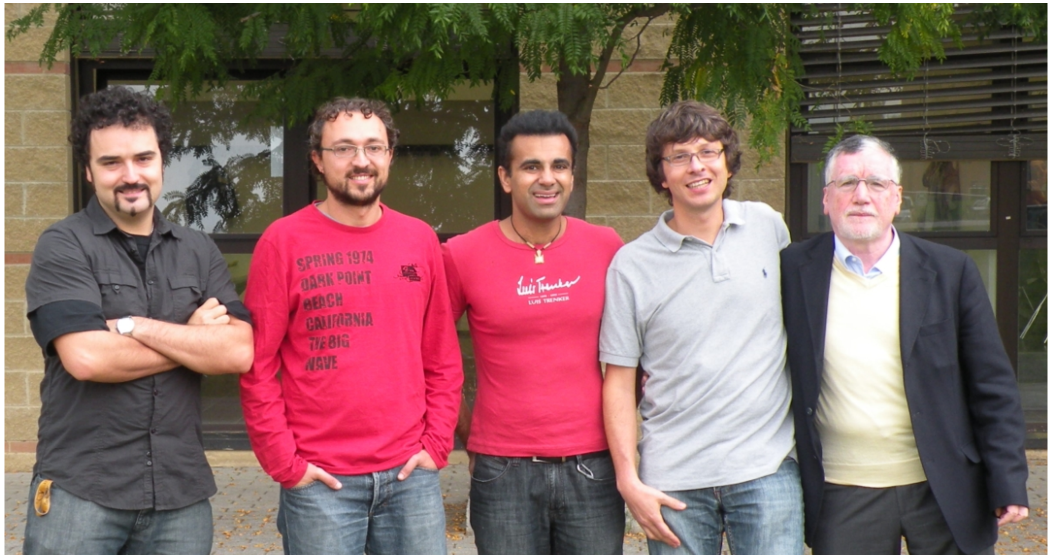
ICTP Trieste, May 25, 2010

Acknowledgements

BEC^3 group at LENS, Firenze



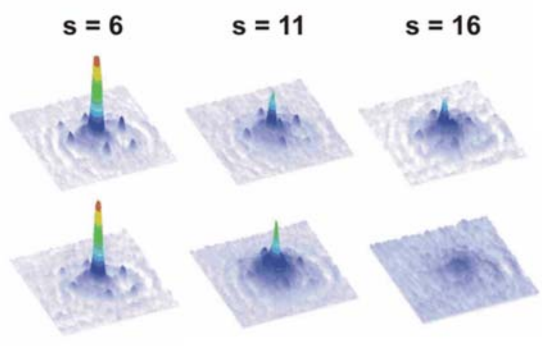
J. Catani, G. Lamporesi, D. Naik, FM, M. Inguscio

M. Gring (U. Vienna)

In collaboration with A. Kantian and T. Giamarchi (U. Geneve)

Why Bose-Bose mixtures? (Our) motivation

▷ Bose-Bose mixtures in optical lattices map to spin hamiltonians



J. Catani et al., Phys. Rev. A (2008)

▷ entropy control (and thermometry) of species A by means of a species B
[J. Catani et al., Phys. Rev. Lett. (2009)]

▷ few-body physics in ultracold collisions:
- Efimov resonances with heavy/light atoms [G. Barontini et al., Phys. Rev. Lett. (2009)]
- scattering in confined dimensions [G. Lamporesi et al., Phys. Rev. Lett. (2010)]

▷ probing fluctuations/correlations in 1D systems,
in collaboration with A. Kantian and T. Giamarchi, University of Geneve

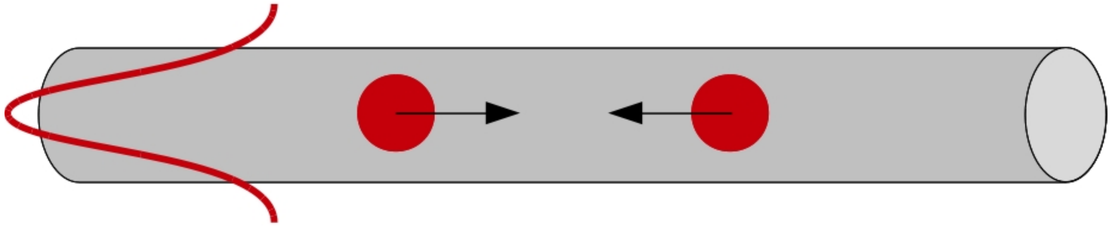
Two-body scattering in low dimensions

Scattering in a waveguide

[M. Olshanii, Phys. Rev. Lett. 81, 938 (1998)]

Quick reminder: scattering of two atoms via a pseudo-potential $U(r) = g\delta(\vec{r})(r\partial_r)$ in a tight waveguide

Strong confinement along two directions: $E \ll \omega, \quad k\,\ell \ll 1, \ell = \sqrt{\hbar/m\omega}$



- Scattering amplitude

$$f = -\frac{1}{1 + ika_{1D}}$$

- 1-dimensional scattering length

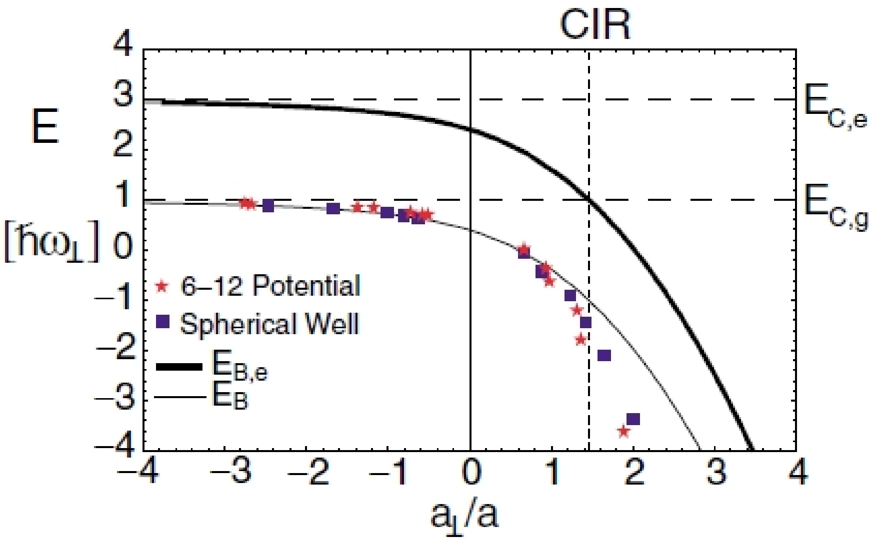
$$a_{1D} = -\frac{\ell^2}{a}(1 - C\frac{a}{\ell}), C = 1.4603/\sqrt{2}$$

- Same as 1D potential $U(z) = g_{1D}\delta(z), \quad g_{1D} = -\frac{\hbar^2}{\mu a_{1D}}$

Confinement-induced resonance (CIR): $a_{1D} \to 0$, $g_{1D} \to \infty$ for $\ell = Ca$

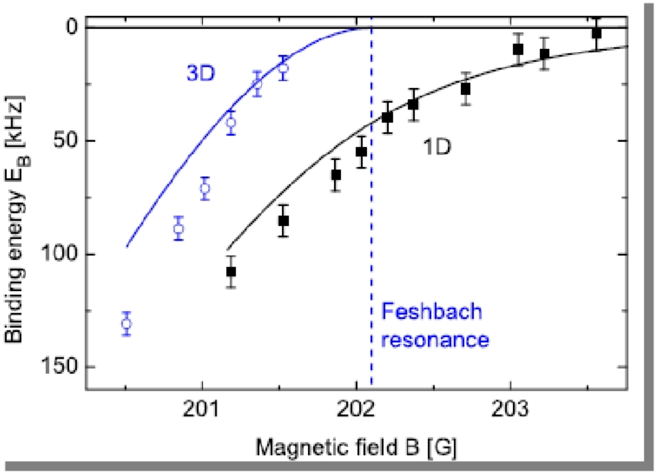
Confinement-induced resonances, interpretation

[T. Bergeman et al., Phys. Rev. Lett. 91, 163201 (2003)]



- 1D, bound state for all values of scattering length, a (vs 3D: bound state for $a > 0$)
- CIR as FR: "closed channel" = set of excited harmonic transverse levels
- only 1 CIR for all excited states
- decoupling of internal and center-of-mass motion

Confinement-induced molecules and resonances, exp

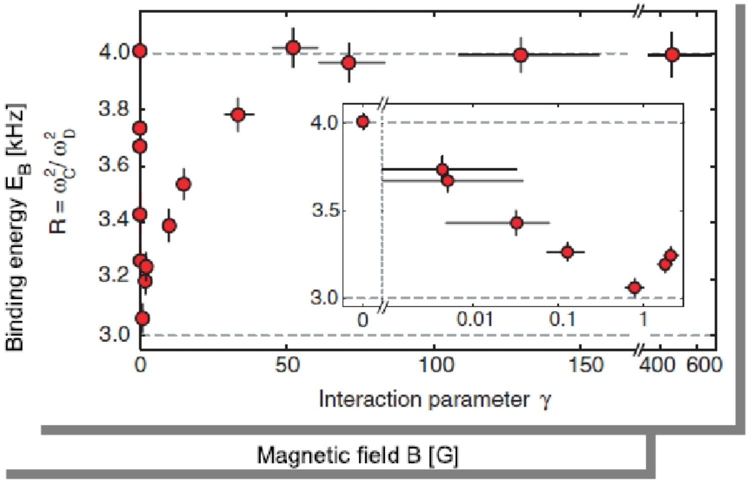


Experiments

- Confinement-induced molecules with ^{40}K atoms

  [H. Moritz et al., Phys. Rev. Lett. 94, 210401 (2005)]

Confinement-induced molecules and resonances, exp



Experiments

- Confinement-induced molecules with ^{40}K atoms
  [H. Moritz et al., Phys. Rev. Lett. 94, 210401 (2005)]
- CIR on Cs atoms
  [E. Haller et al., Science 325, 1124 (2009)]

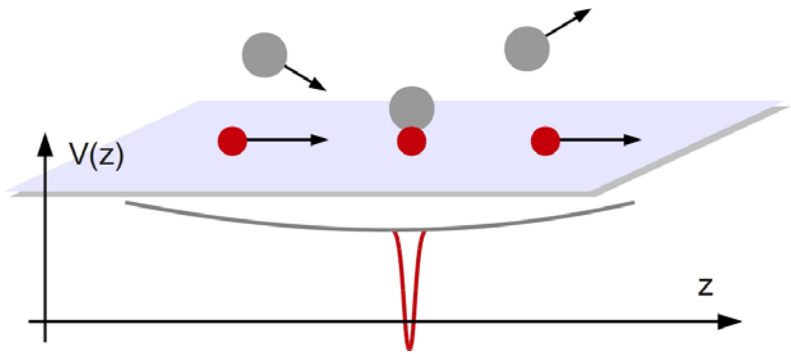
Very recently,

- CIR in elliptic waveguide [E. Haller et al., Phys. Rev. Lett. 104, 153203 (2010)]
- CIR 2D with ^{6}Li atoms [B. Fröhlich et al., Phys. Rev. Lett.106, 105301 (2011)]

Mix-dimensional configuration

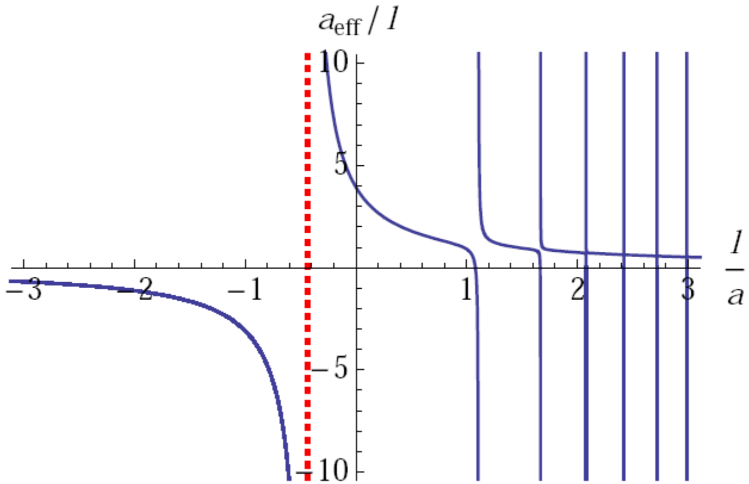
in collaboration with Y. Nishida (MIT)

Different kind of particles can live in different dimensions



$a_{eff} \to \infty$ for multiple values of a/ℓ depending only on the mass ratio m_1/m_2 (*)

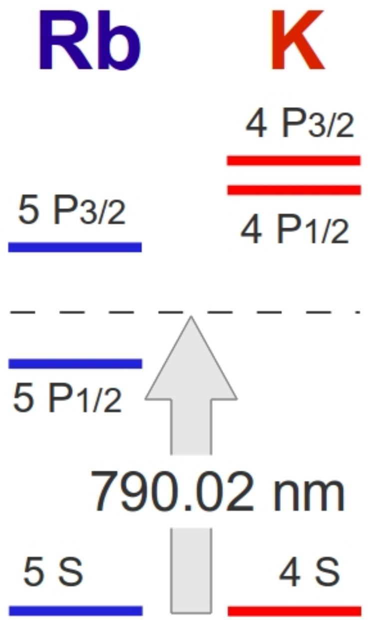
Coupling of center-of-mass and relative motion



How-to? Species-selective dipole potential

Suitable choice of laser wavelength $\rightarrow$ optical dipole potential selective on atomic species
[L. J. LeBlanc and J. H. Thywissen, Phys. Rev. A 75, 053612 (2007)]

For our particular mixture, i.e. ^{87}Rb–^{41}K, $\lambda = 790.02\,$nm.



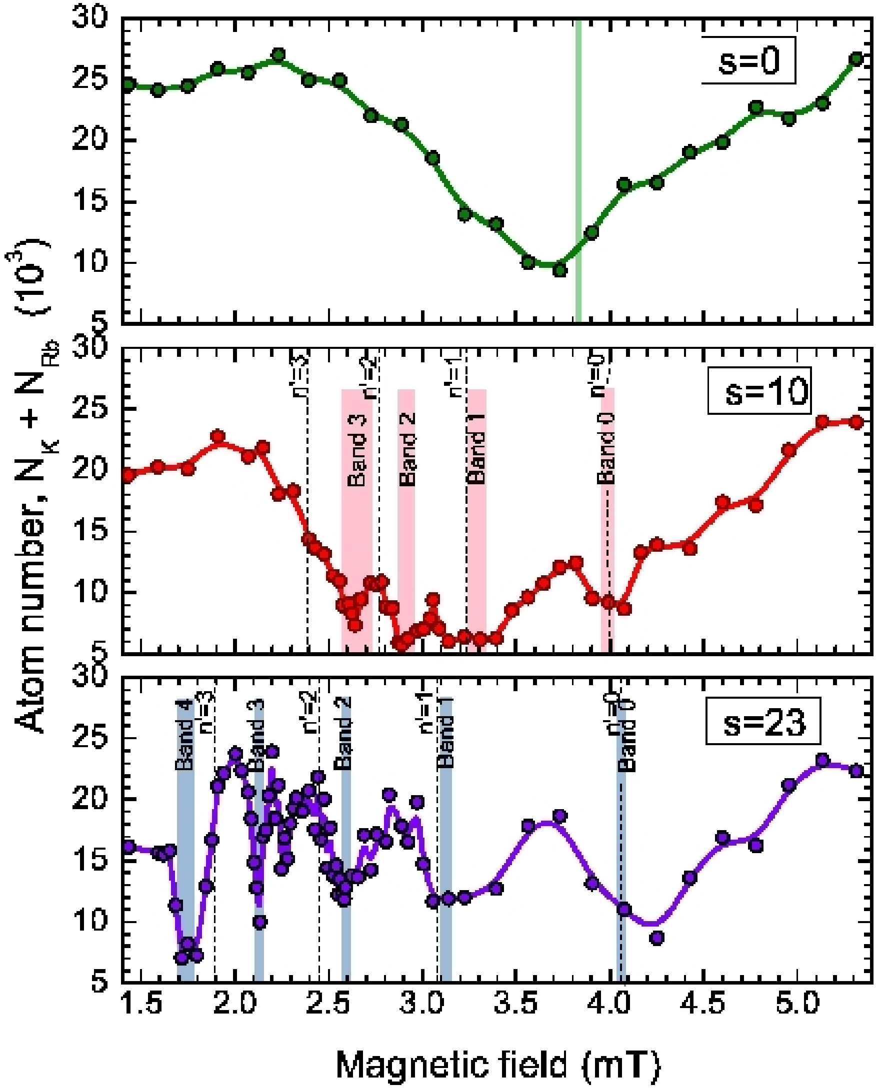
For Rb, D1 and D2 light-shifts cancel out

Tight confinement realized by 1D optical lattice
$V_0 = sE_r$
Array of 2D traps:

$$\ell = \lambda/(2\pi s^{1/4})$$

(e.g. $\ell = 1200a_0$ for $s = 15$)

Experimental observation

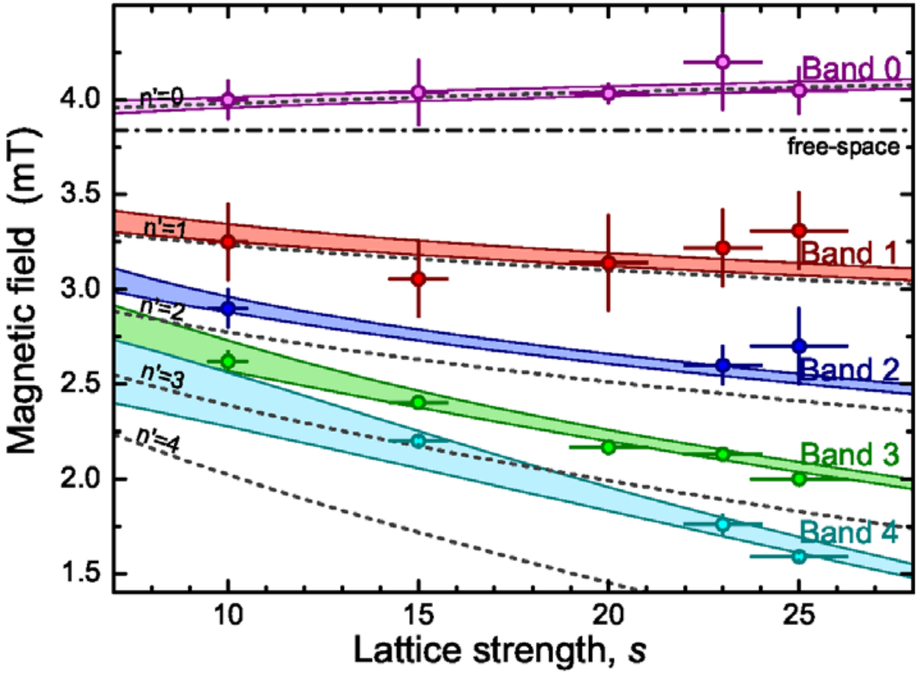


Need to account for lattice band structure

Experiment/theory comparison

Energy degeneracy

$p^2/(2m_{Rb}) + \epsilon_K(0, q; V_{\rm lat}^K) = \epsilon_{KRb}(n', q + p; V_{\rm lat}^K) - E_b$



- $\epsilon_i(n, q; V_{\rm lat}^K)$, energy of the Bloch wave of particle $i = K$, KRb
- (n, q) quasimomentum/band index
- $V_{\rm lat}^K$ lattice potential
- p initial Rb momentum
- E_b, binding energy

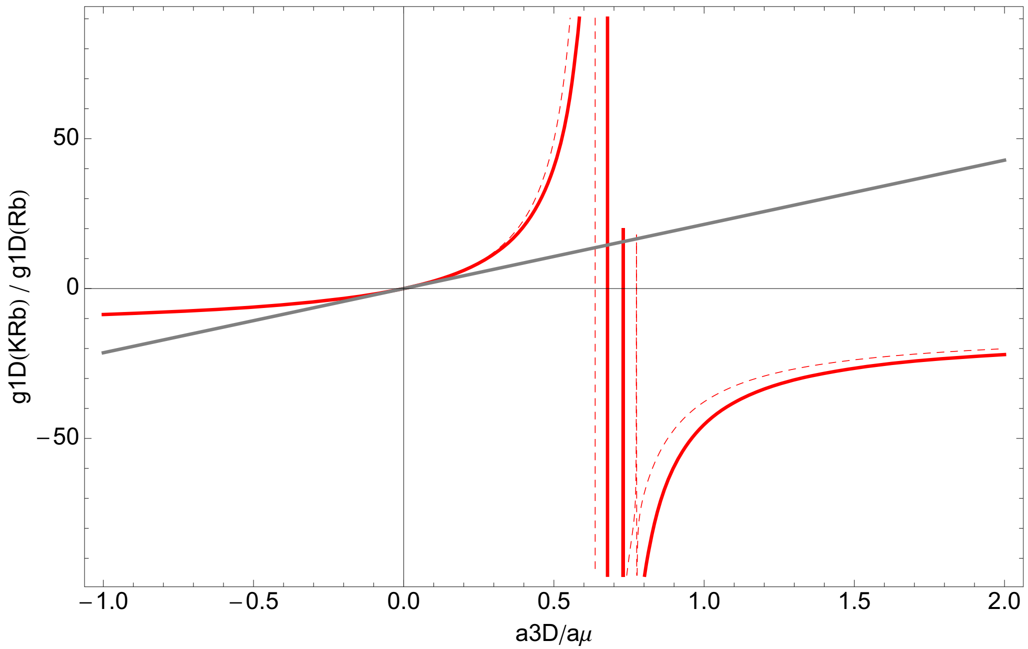
Impurities in 1D bosons

Scattering of two unequal particles in 1D

Extension of Olshanii's analysis V. Peano et al., New J. Phys.7, 192 (2005)
Central result:

$$g_{1D} = \frac{1}{2\mu\pi a_\mu^2} \sum_n \frac{|\langle 0|e_n\rangle|^2}{\lambda_n + 1/(4\pi a)} \qquad a_\mu = \sqrt{\frac{2\hbar}{\mu(\omega_1+\omega_2)}}$$

where $\lambda_n, |e_n\rangle$ eigenvalues/vectors of regular part of the Green's function



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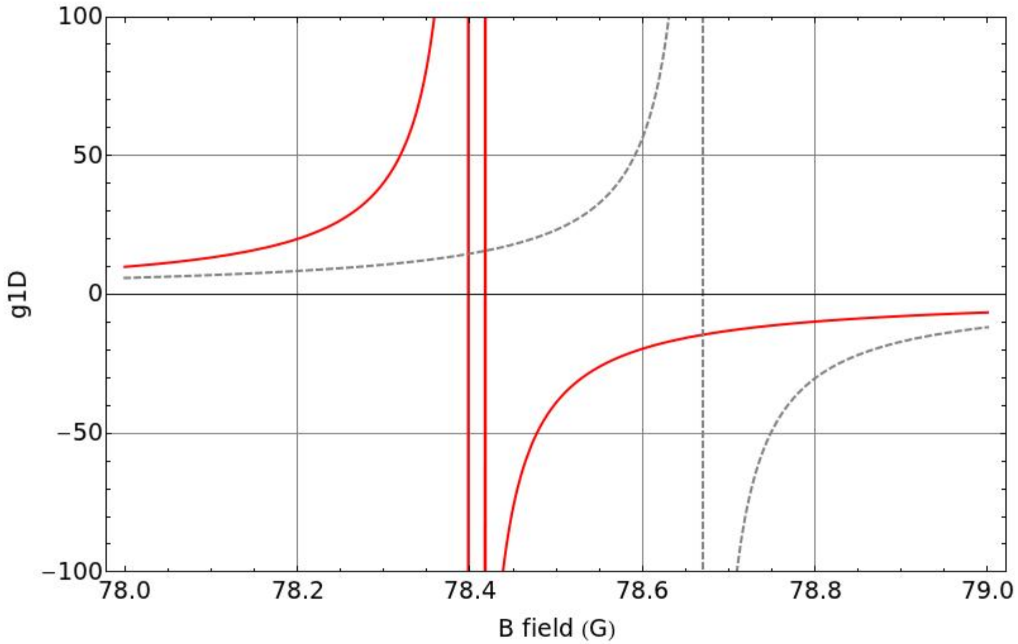
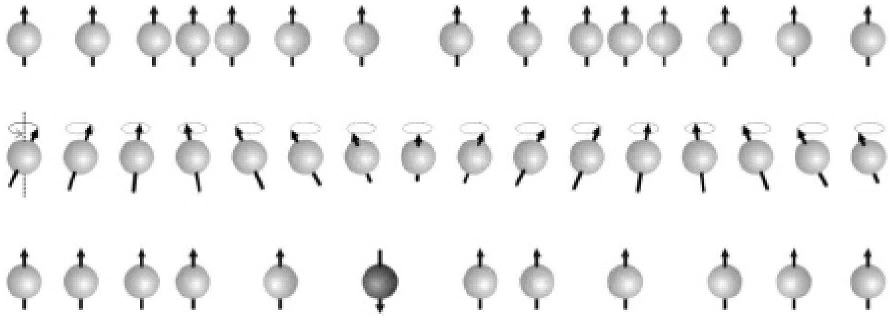


Out-of-equilibrium dynamics in a strongly correlated quantum system

Credit to T. Giamarchi

Impurity diffusion in a 1D gas of impenetrable bosons, analogy with a spin impurity in a spin chain

M. B. Zvonarev et al., Phys. Rev. Lett. 99, 240404 (2009)



Low energy excitations with quadratic dispersion relation, $\epsilon(p) = p^2$

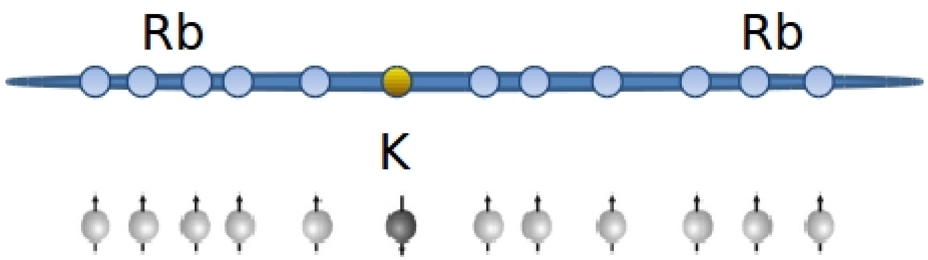
$\Rightarrow$ Luttinger liquid description not directly applicable

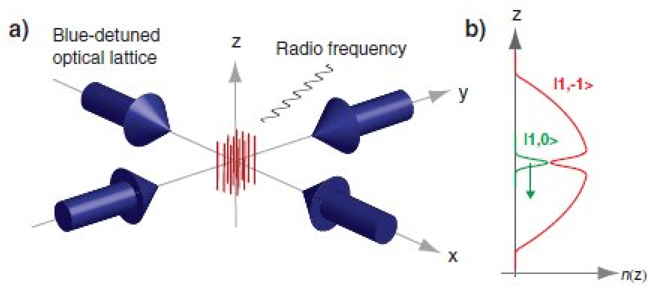
Spin chain

In strongly interacting regime, i.e. $\gamma = mg_{1D}/(\hbar^2 n_{1D}) \gg 1$, impurity diffuses very slowly, actually "subdiffuses" $\sigma^2 \sim \log(t)$

M. B. Zvonarev et al., Phys. Rev. Lett. 99, 240404 (2009)

Mimick spin chain with 2 bosonic species

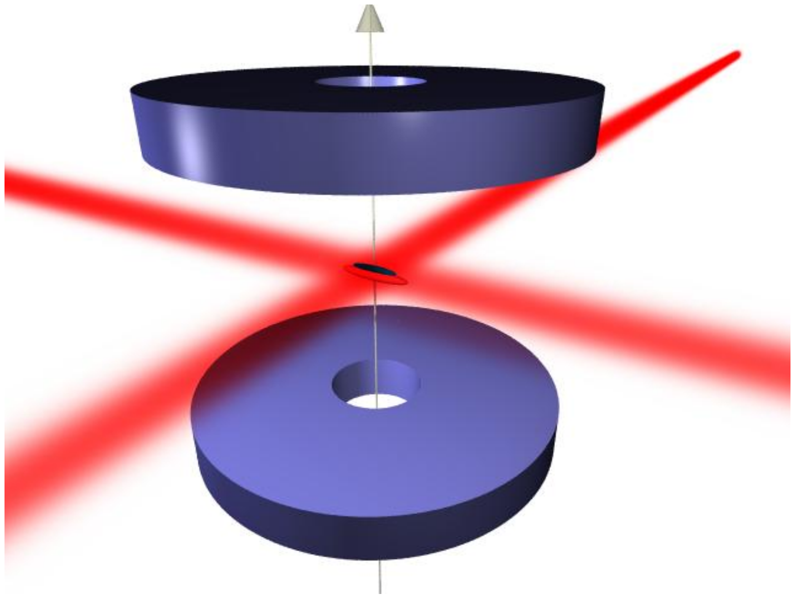




S. Palzer et al., Phys. Rev. Lett. 103, 150601 (2009)

Similar experiment with two hyperfine states of Rb atoms
here impurities fall fast under gravity

Sample preparation, harmonic trap



Evaporation, both species in lowest hyperfine state $|f=1, m_f=1\rangle$ @$B = 77$G ($a = 250a_0$)

$\omega/2\pi = (39, 87, 81)$Hz for Rb (1.47 larger for K)

At this point:

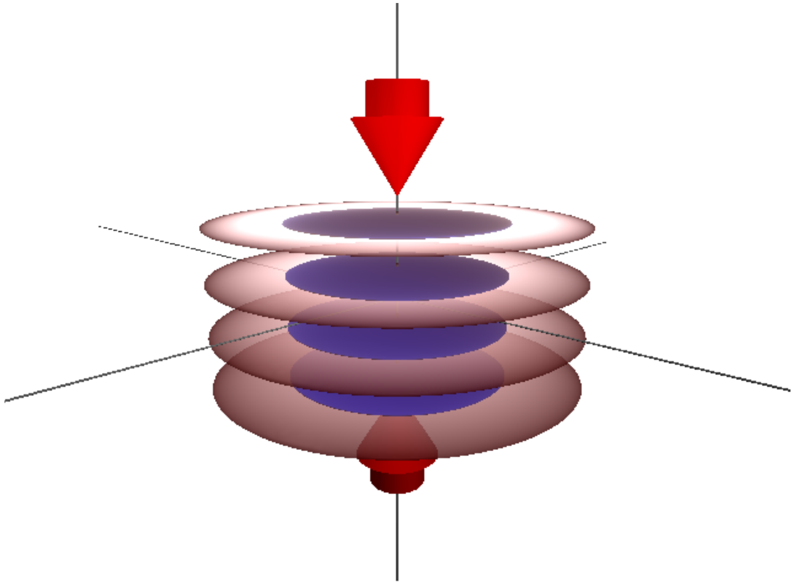
$T = 150$nK

$N_{Rb} \simeq 1.5 \times 10^5$, $N_K \simeq 5 \times 10^3$

Calculate filling factors assuming Bose density distribution $g_{3/2}(ze^{-\beta U(r)})$

Differential gravity sag 20μm

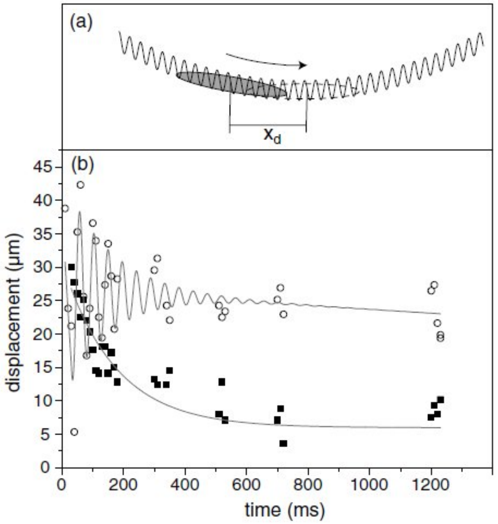
Sample preparation, vertical lattice



Vertical lattice $V = 15(6.5)E_r$ [Rb(K)]

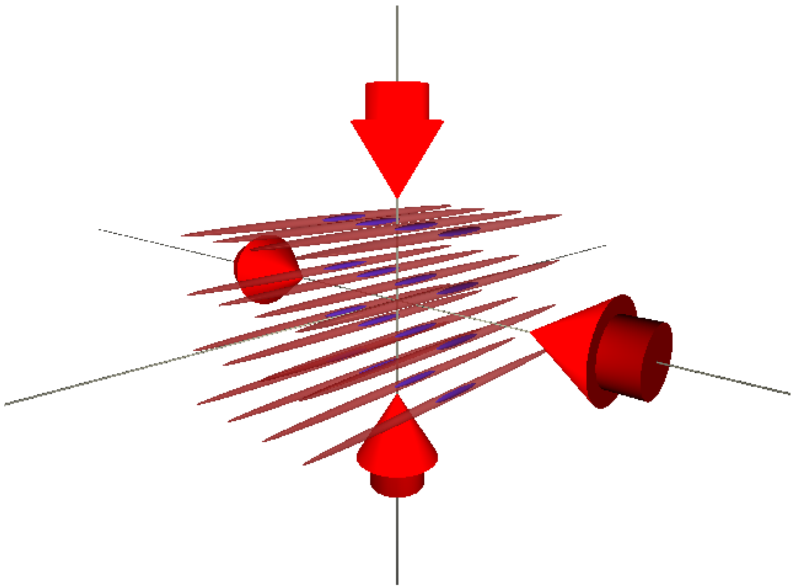
Tunneling time $\hbar/J = 80(4)$ms

Lighter K atoms fall under gravity, disrupted Bloch oscillations
similar to degenerate fermions colliding with bosons



H. Ott et al., Phys. Rev. Lett. 92, 160601 (2004)

Sample preparation, 2D lattice



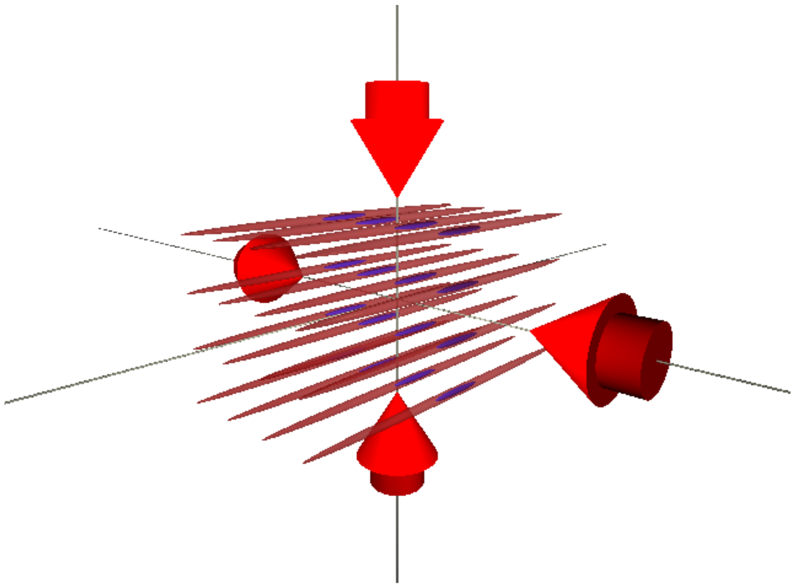
2D lattice $V = 60(26)E_r$

1st excited band gap $= 29(39)$kHz, i.e. $1.4(1.9)\mu$K

tunneling time $\hbar/J = 57(0.27)$s

$\omega_x/2\pi = 60(80)$Hz

Sample preparation, 2D lattice



Max filling = 180 (3) atoms/tube [Rb(K)]

avg filling $\langle n^2 \rangle / N$= 80 (.8) atoms/tube

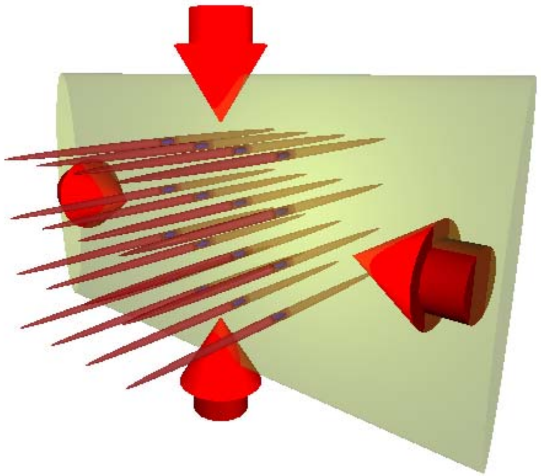
peak Rb 1D density = 7 atoms/μm

T=(350 $\pm$ 50) nK (from Rb time-of-flight images)

Rb Tonks parameter $\gamma = g_{1D,Rb} m / (\hbar^2 n_{1D}) \simeq .5$

Rb degeneracy temperature $T_d = \hbar \omega_x N = 520\text{nK} \rightarrow$ weakly interacting condensates at center

Sample preparation, 2D lattice + "light blade"

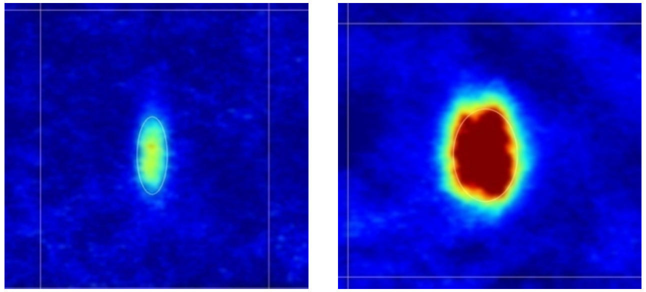


"Light blade" $\lambda = 770$nm, elliptic $75 \times 15\mu$m

Species selective:
V $\simeq 0$ on Rb, $\simeq 6\mu$K on K

$\omega_{x,LB}/2\pi \simeq 1$kHz, i.e. 50 nK

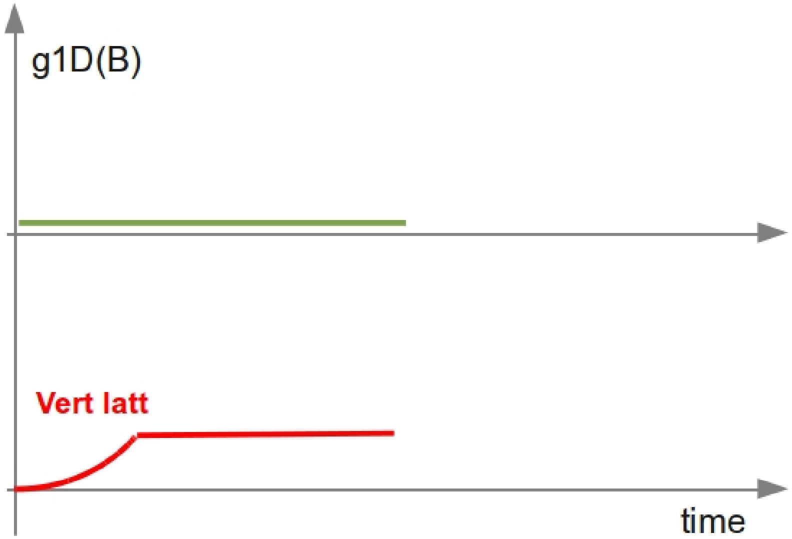
linear ramp in 50 ms



K Rb

initial K size $<$ imaging resolution (8μm)

Time sequence



- $g_{1D} \simeq 0$, vertical lattice $s_{vert} \to 15$
- horizontal lattice $s_{hor} \to 60$, then $s_{vert} \to 60$
- light blade on slowly in 50ms, g_{1D} to final value
- light blade off abruptly in 0.5ms, impurity expansion
  (then freeze+*in situ* imaging)

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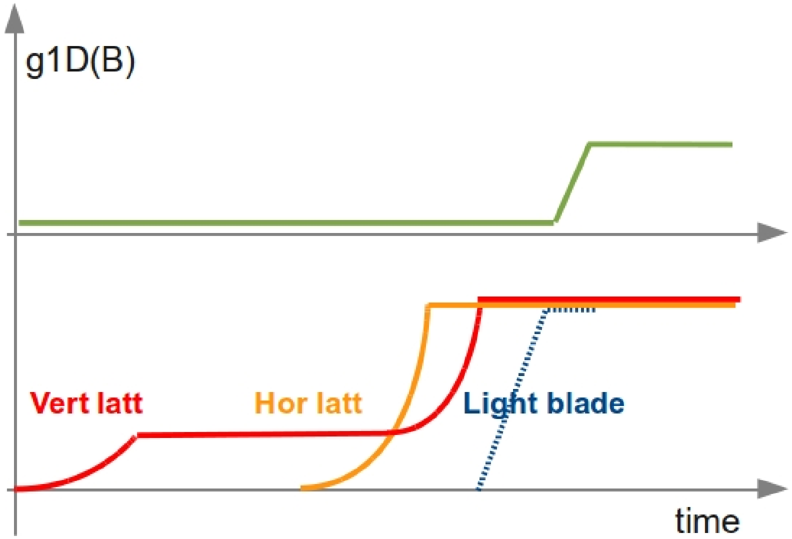

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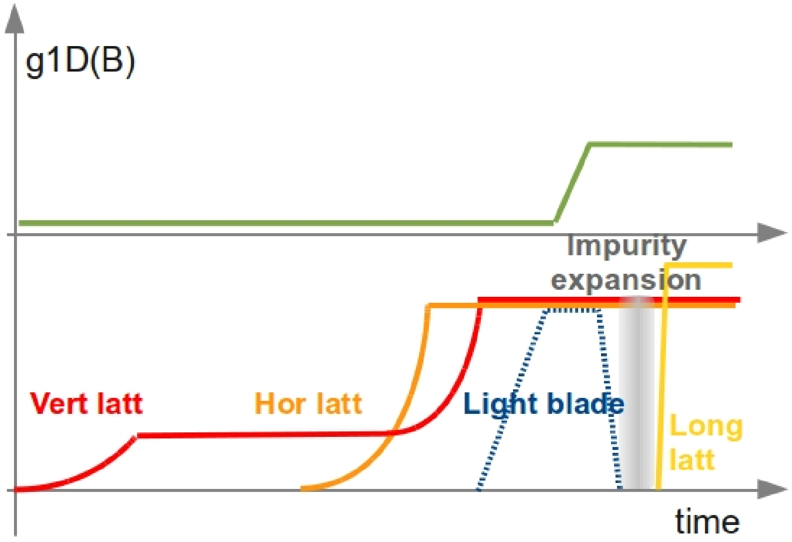

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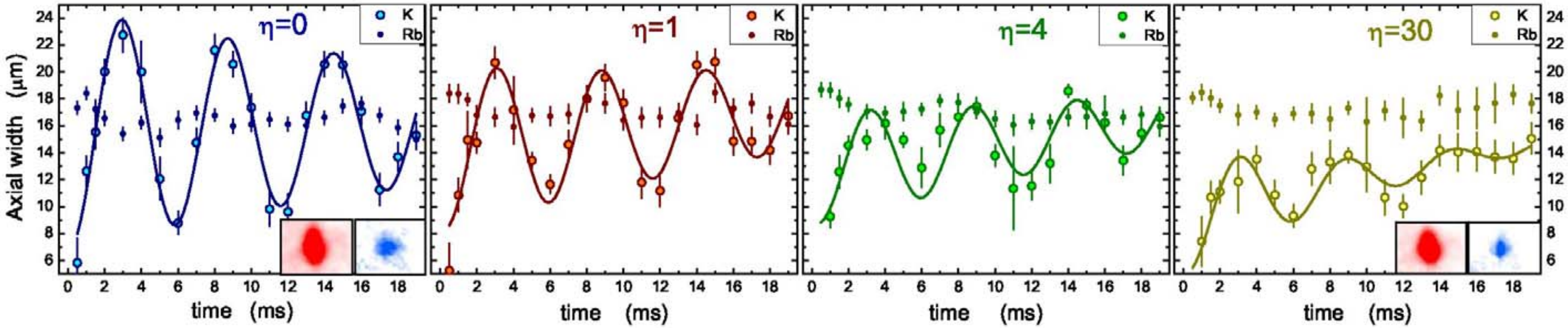
Impurity oscillations

Oscillations of K impurity size $\sigma(t)$ at different interactions $\eta \equiv g_{1D}(KRb)/g_{1D}(Rb)$



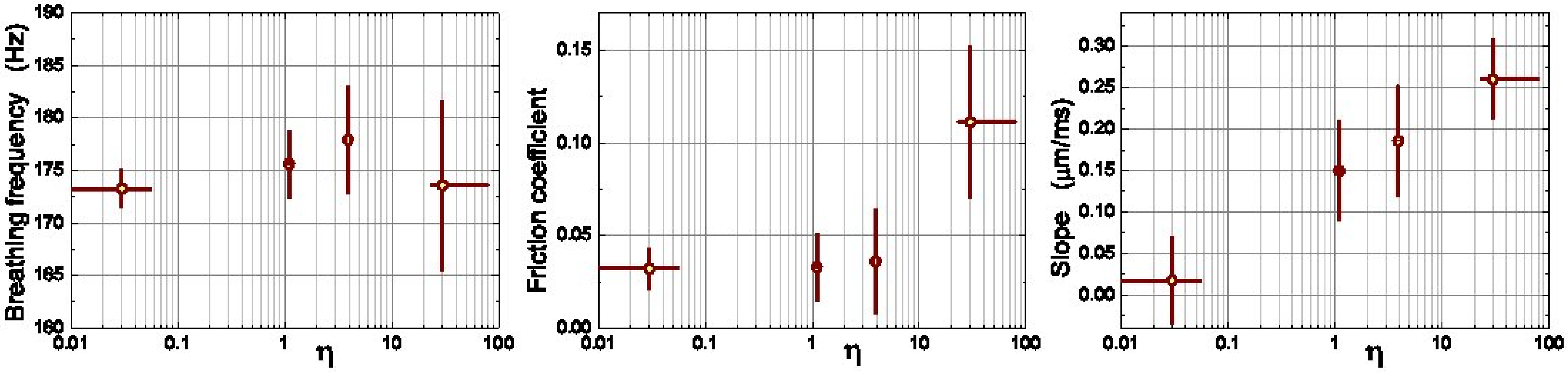
- ▷ more interactions → smaller oscillation amplitude of $\sigma(t)$
- ▷ tilted oscillations
- ▷ oscillation frequency almost constant

Oscillation frequency, damping and slope

Fitting function:

$$\sigma(t) = \sigma_1 + \beta\, t - A\, e^{-\gamma \omega t} \cos(\sqrt{1-\gamma^2}\omega\, (t - t_0))$$

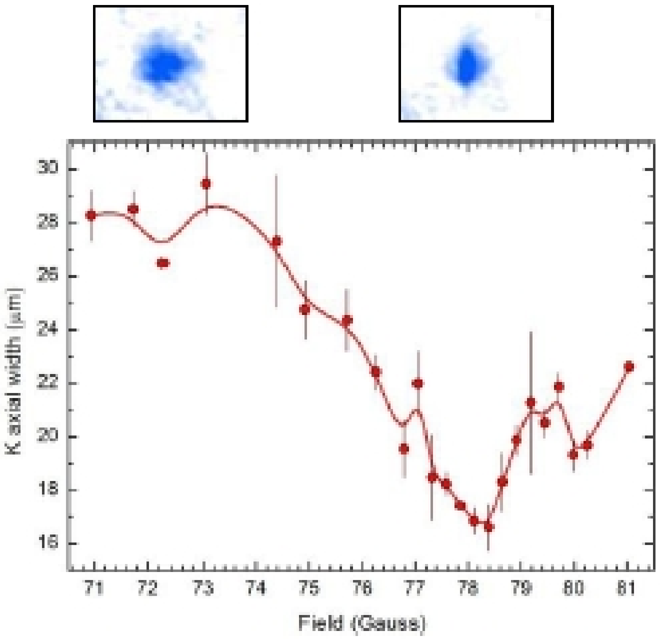
Fit results:



Amplitude of first oscillation

Focus on the quantity most sensitive to coupling with Rb bath

Peak σ of 1st oscillation versus g_{1D} (experimentally magnetic field, B)



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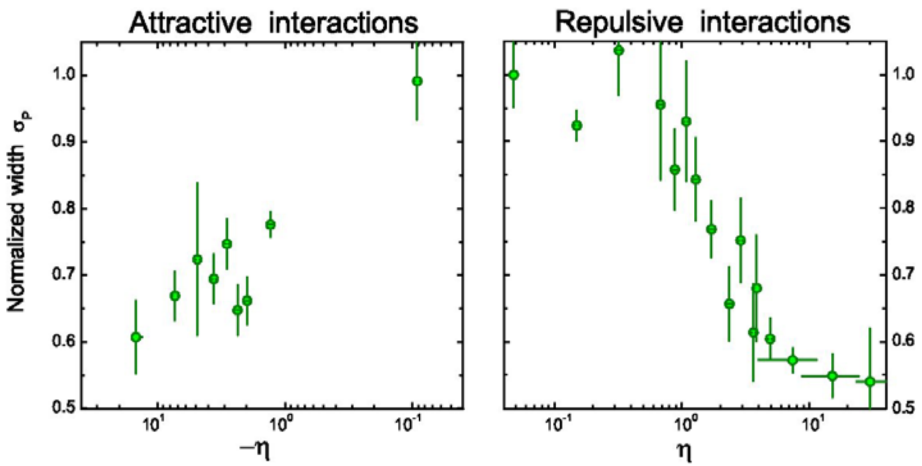


- ▷ η, i.e. g_{1D}, calculated following Peano et al.
- ▷ NOT trivial mean-field pressure of bath

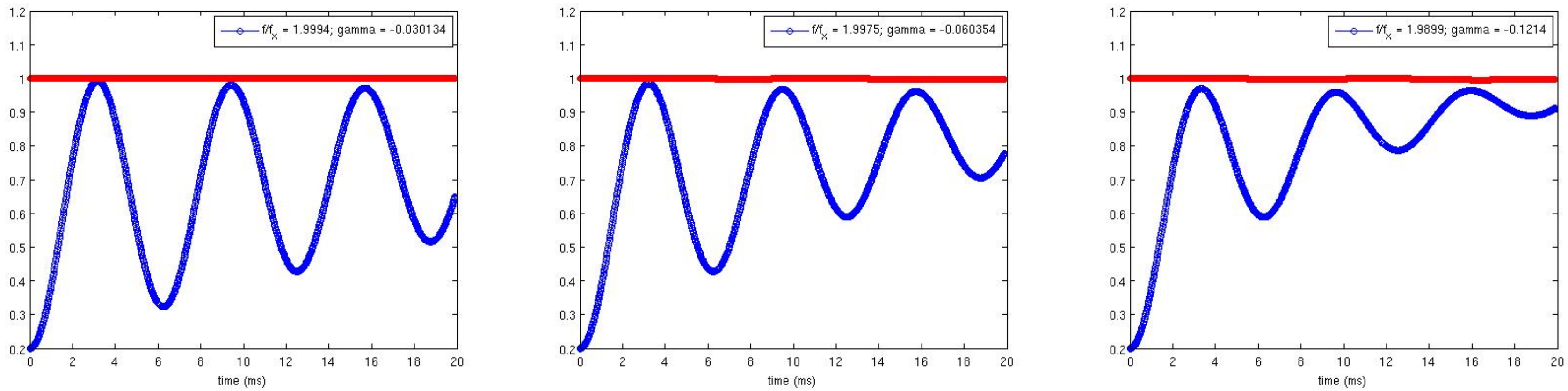
"Poor man" approach

Collective oscillations for two colliding 1D normal, ideal gases

Transition from collisionless to hydrodynamic regime

D. Guery-Odelin et al., Phys. Rev. A 60, 4851 (1999); M. Anderlini et al., Phys. Rev. A 73, 032706 (2006)

Linear differential eqns for momenta of phase-space distribution: $\langle x_i^2 \rangle, \langle x_i v_i \rangle, \langle v_i^2 \rangle$



More sophisticated analysis (A. Kantian and T. Giamarchi, U. Geneve)

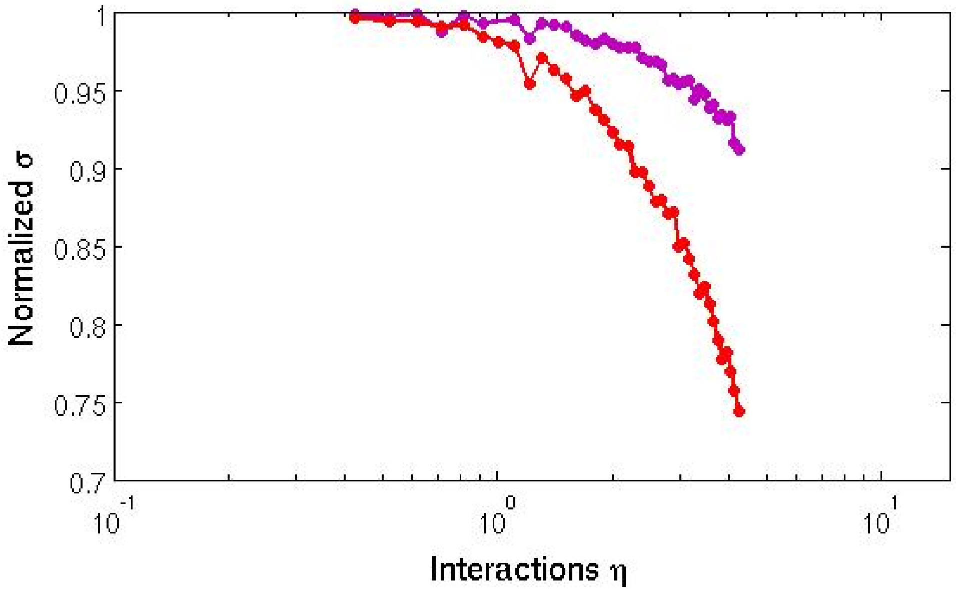
Semi-empirical model

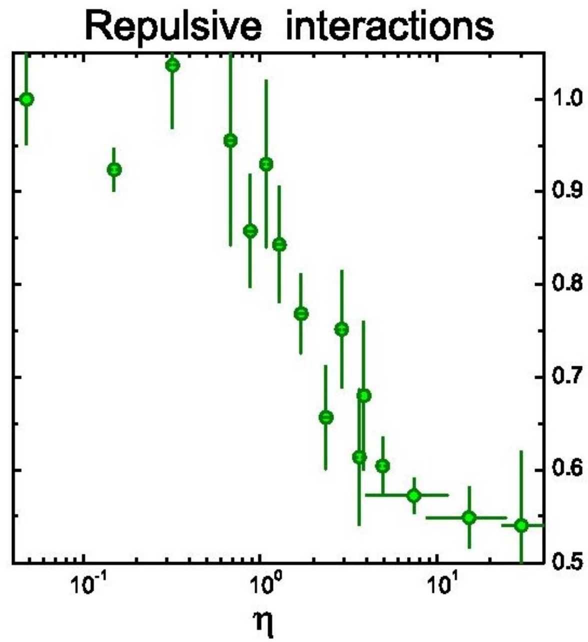
Quantum Langevin equation, damped harmonic oscillator in contact with a thermal bath

$$\begin{aligned} \dot{\hat{x}}(t) &= \hat{p}(t)/m_K^* \\ \dot{\hat{p}}(t) &= -m_K^* \omega^2 \hat{x}(t) - \tilde{\gamma}/m_K^* \dot{\hat{x}}(t) + \hat{\xi}(t) \end{aligned}$$

- ▷ frequency is fixed, according to observation
- ▷ Rb density assumed to be uniform
- ▷ mass is increased by polaronic coupling to the finite T bath
  R. P. Feyman, Phys. Rev. 97, 660 (1955)
- ▷ mass renormalization at fixed frequency → trapping potential renormalization (work in progress)

Analysis (A. Kantian and T. Giamarchi, U. Geneve)



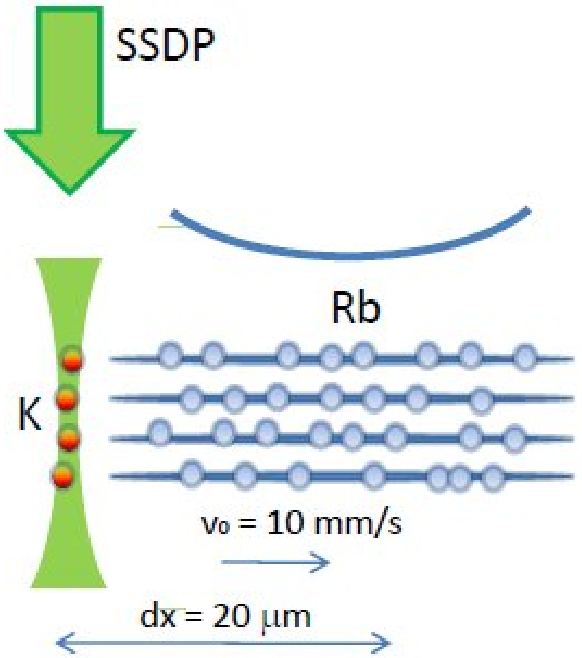


Theory

Experiment

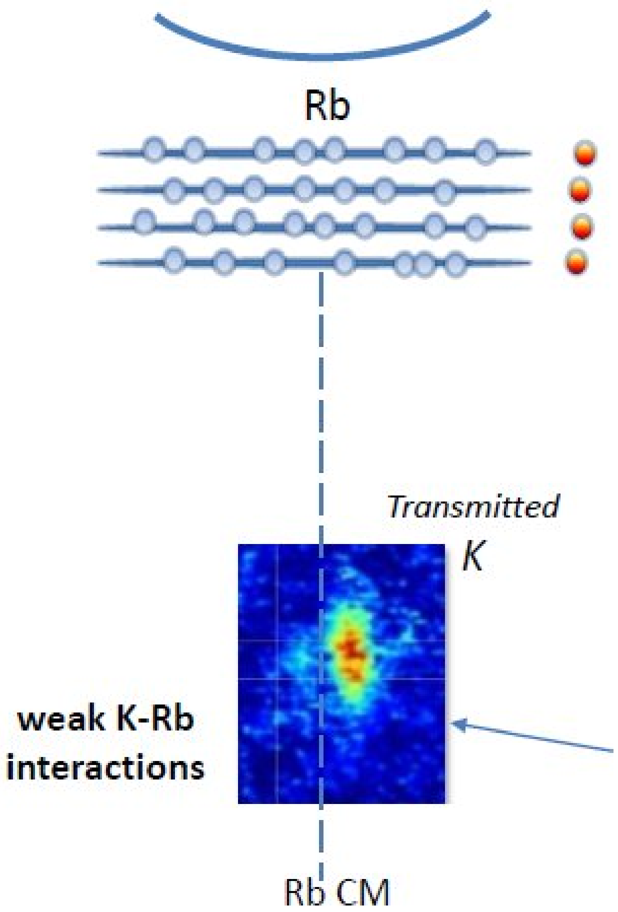
Quantum reflection in 1D

Impurity displaced



- Impurity displaced and released
- accelerated by harmonic potential

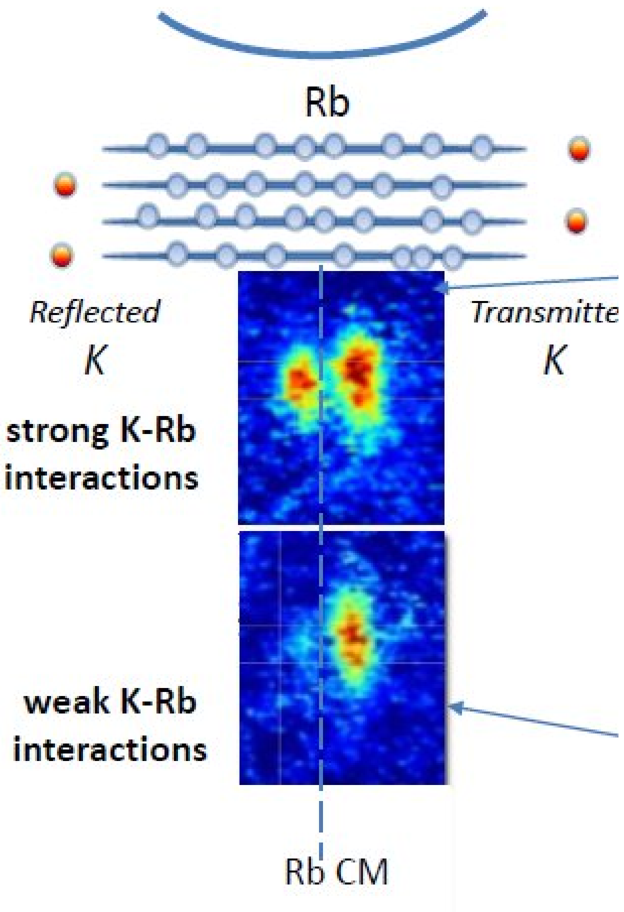
Impurity displaced



- Impurity displaced and released
- accelerated by harmonic potential

◁ at small coupling strength, impurity transmitted

Impurity displaced



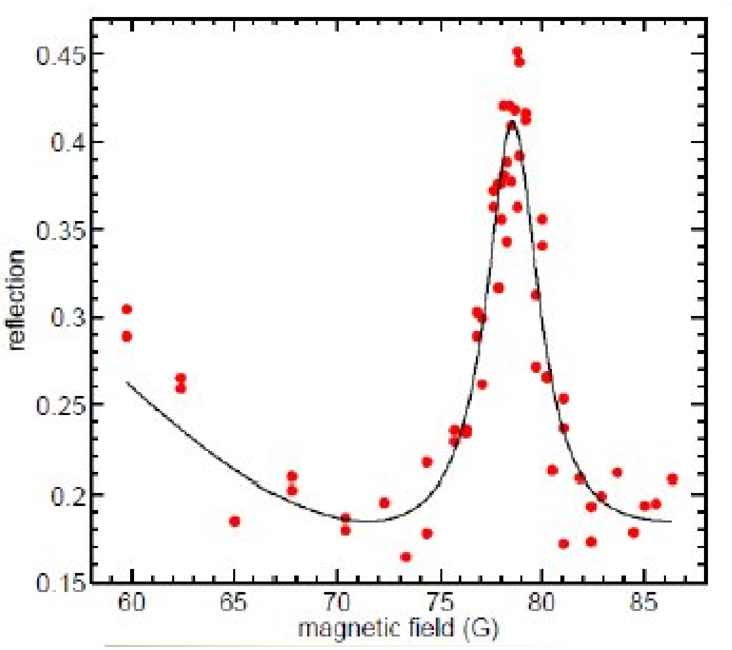
- Impurity displaced and released
- accelerated by harmonic potential

◁ at high coupling strength, partial reflection

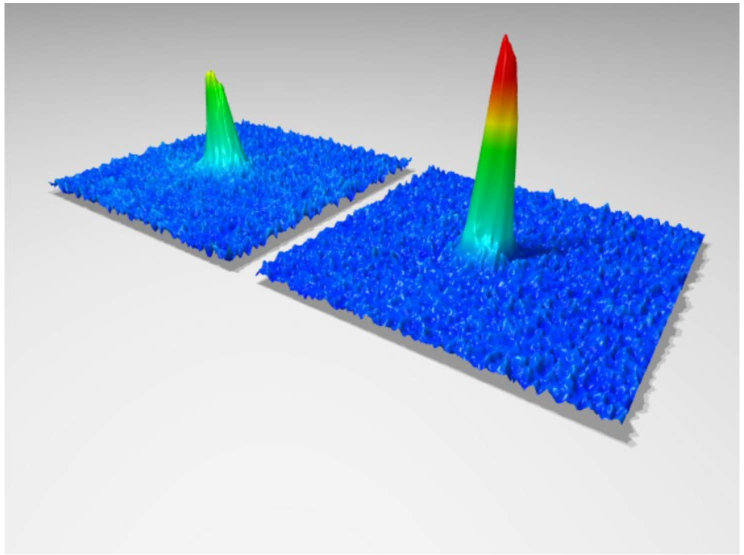
◁ at small coupling strength, impurity transmitted

Impurity reflection

Quantum reflection, also at $g_{1D} < 0$



The end



Thank you

http://quantumgases.lens.unifi.it