Nonlinear matter wave dynamics in periodic and double-well potentials

Quantum engineering of the dynamics of interacting atoms

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www.kip.uni-heidelberg.de/matterwaveoptics/

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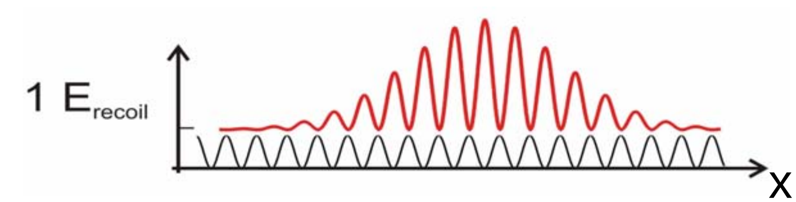
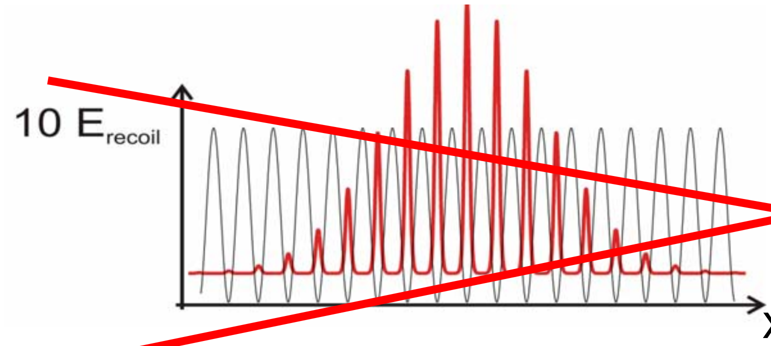
Dynamics

of interacting matter waves

Propagation in periodic potentials



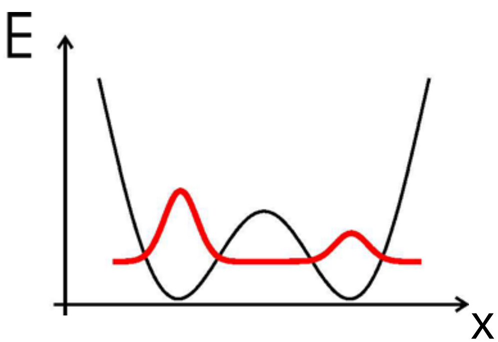
⇨ Time evolution ?



⇨ Time evolution ?

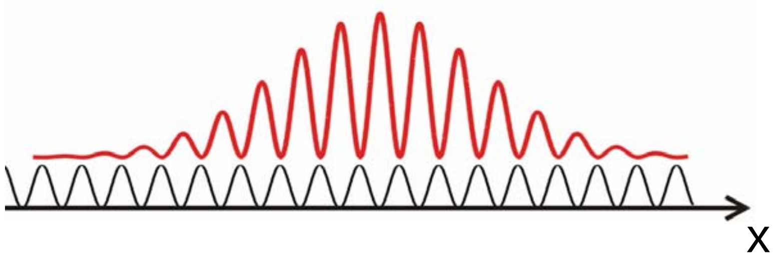
Phys. Rev. Lett. 94, 020403 (2005)

Dynamics in a double well potential



⇨ Time evolution ?

effective mass & BEC



For small momentum distribution and weak nonlinearity:

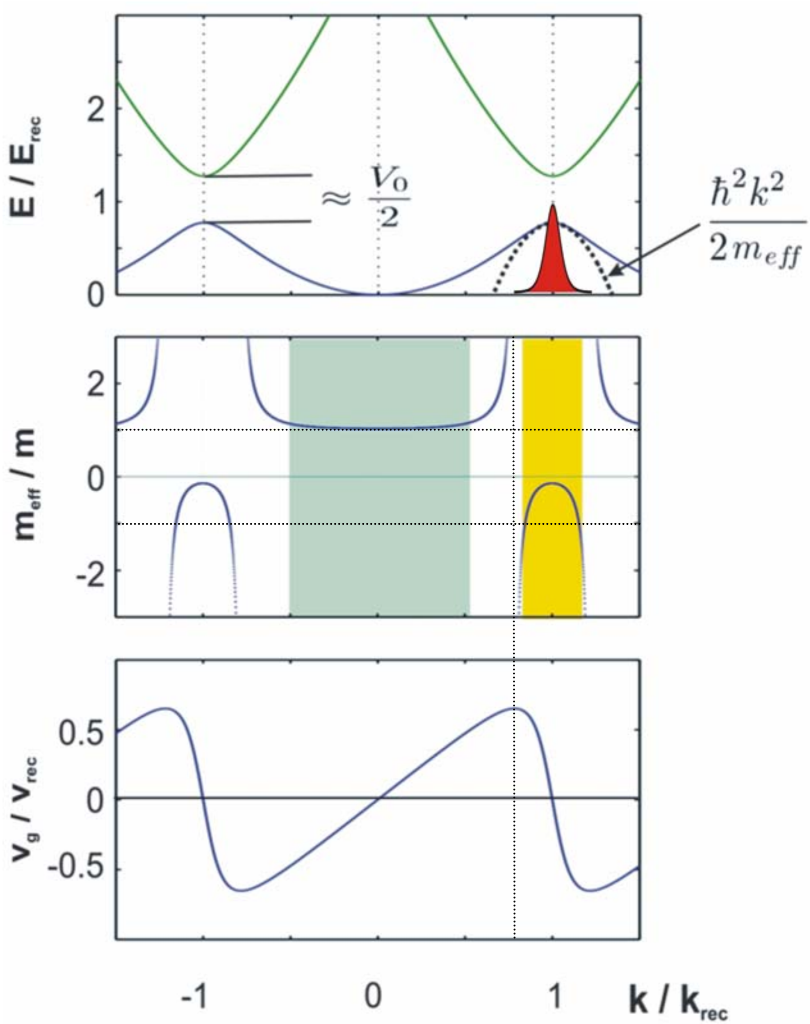
$$\Psi_{\|}(x,t) = A(x,t)\ \Phi_{n,k_0}(x)\ e^{-\frac{i}{\hbar}E_n(k_0)t}$$

Nonlinear Schrödinger-Equation:

$$i\hbar\left[\frac{\partial}{\partial t} + v_g\frac{\partial}{\partial x}\right]A(x,t) = \left[-\frac{\hbar^2}{2m_{eff}}\frac{\partial^2}{\partial x^2} + \alpha_{NL}g_{1d}|A(x,t)|^2\right]A(x,t)$$

$$g_{1d} = 2a\hbar\omega_{\perp}$$

linear density is limited to n_{1D} ~ 100 atoms/μm

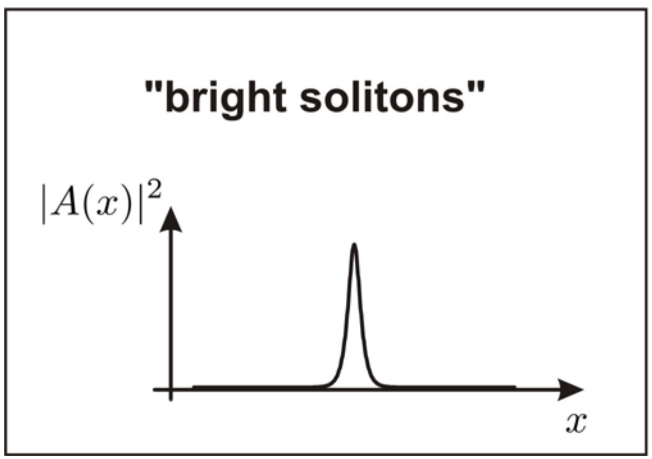


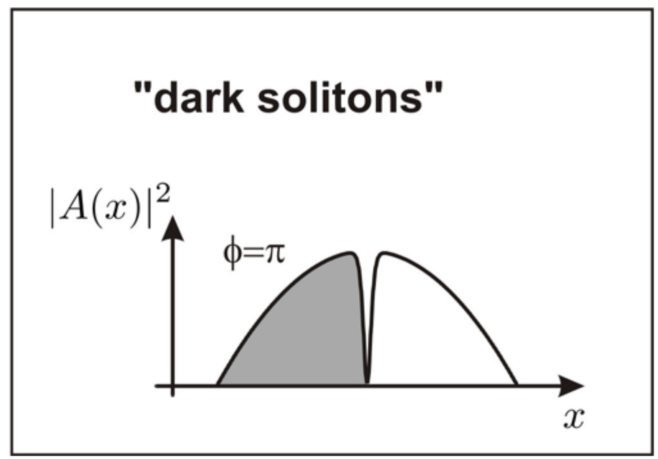
solitonic propagation

1D-Gross-Pitaevskii Equation:

$$i\hbar\left[\frac{\partial}{\partial t}+v_g\frac{\partial}{\partial x}\right]A(x,t)=\left[-\frac{\hbar^2}{2m_{eff}}\frac{\partial^2}{\partial x^2}+\alpha_{NL}g_{1d}|A(x,t)|^2\right]A(x,t) \qquad g_{1d}=2a\hbar\omega_\perp$$

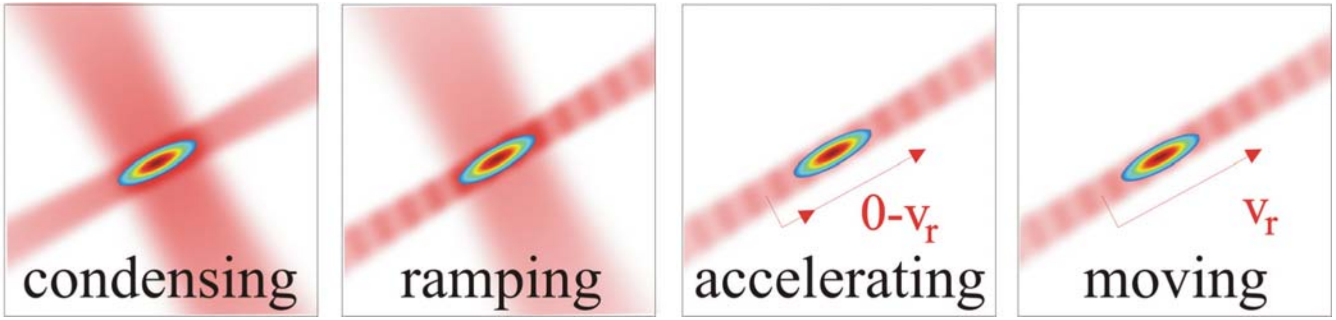
$a \cdot m < 0$ $\qquad$ $a \cdot m > 0$

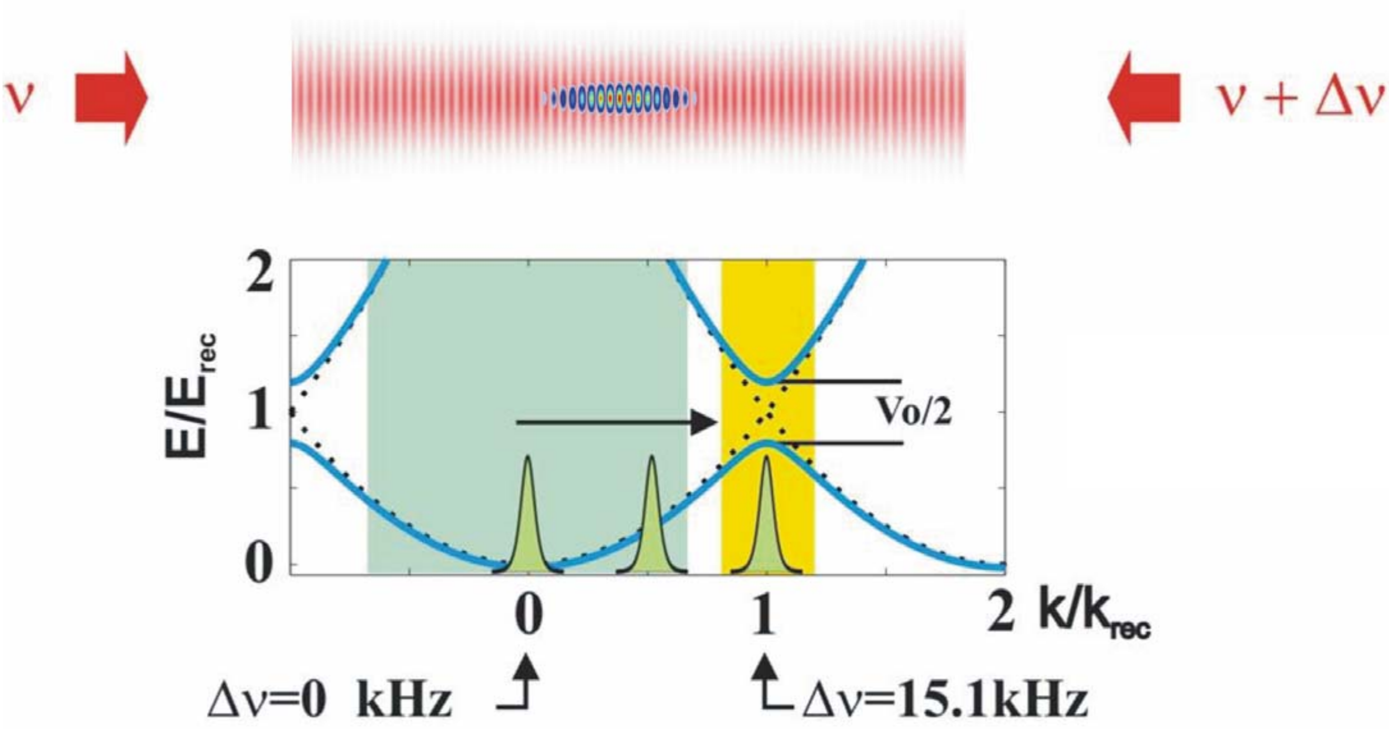




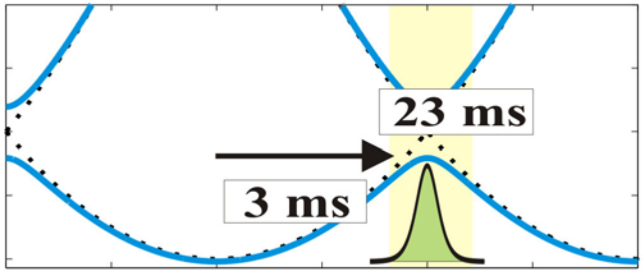
Paris / Houston $\qquad$ Hannover / Nist

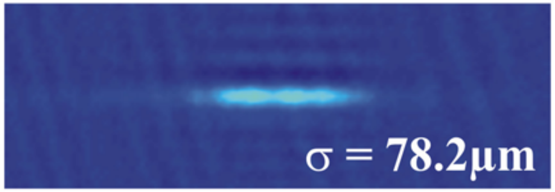
realization of m_{eff}



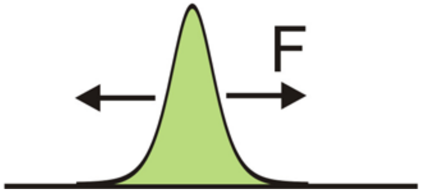


dynamics at m_{eff}<0

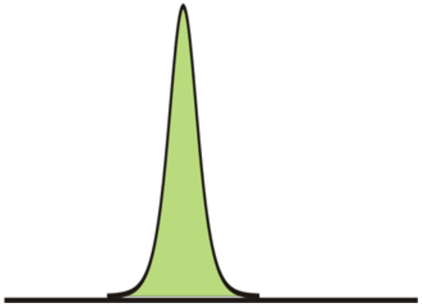




repulsive interaction

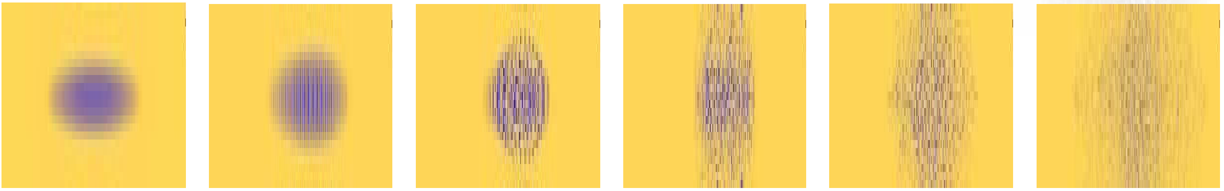


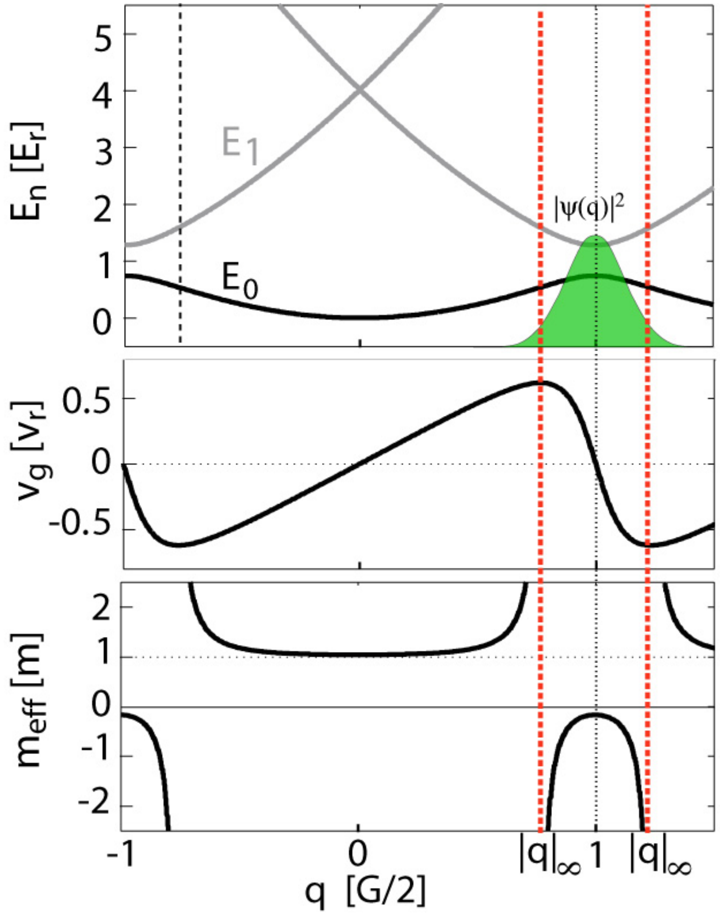
but F=m_{eff} a

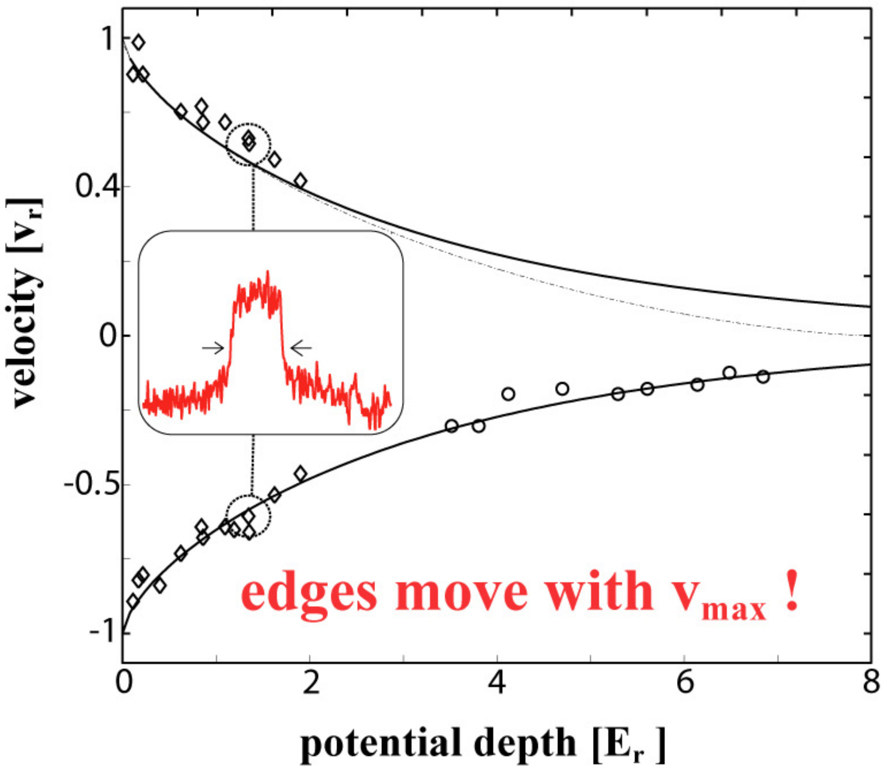


linear wave packet dynamics

Phys. Rev. Lett. 91, 060402 (2003)







soliton condition

$$i\hbar\left[\frac{\partial}{\partial t}+v_g\frac{\partial}{\partial x}\right]A(x,t)=\left[\left(-\frac{\hbar^2}{2m_{eff}}\frac{\partial^2}{\partial x^2}\right)+\left(\alpha_{NL}g_{1d}|A(x,t)|^2\right)\right]A(x,t)$$

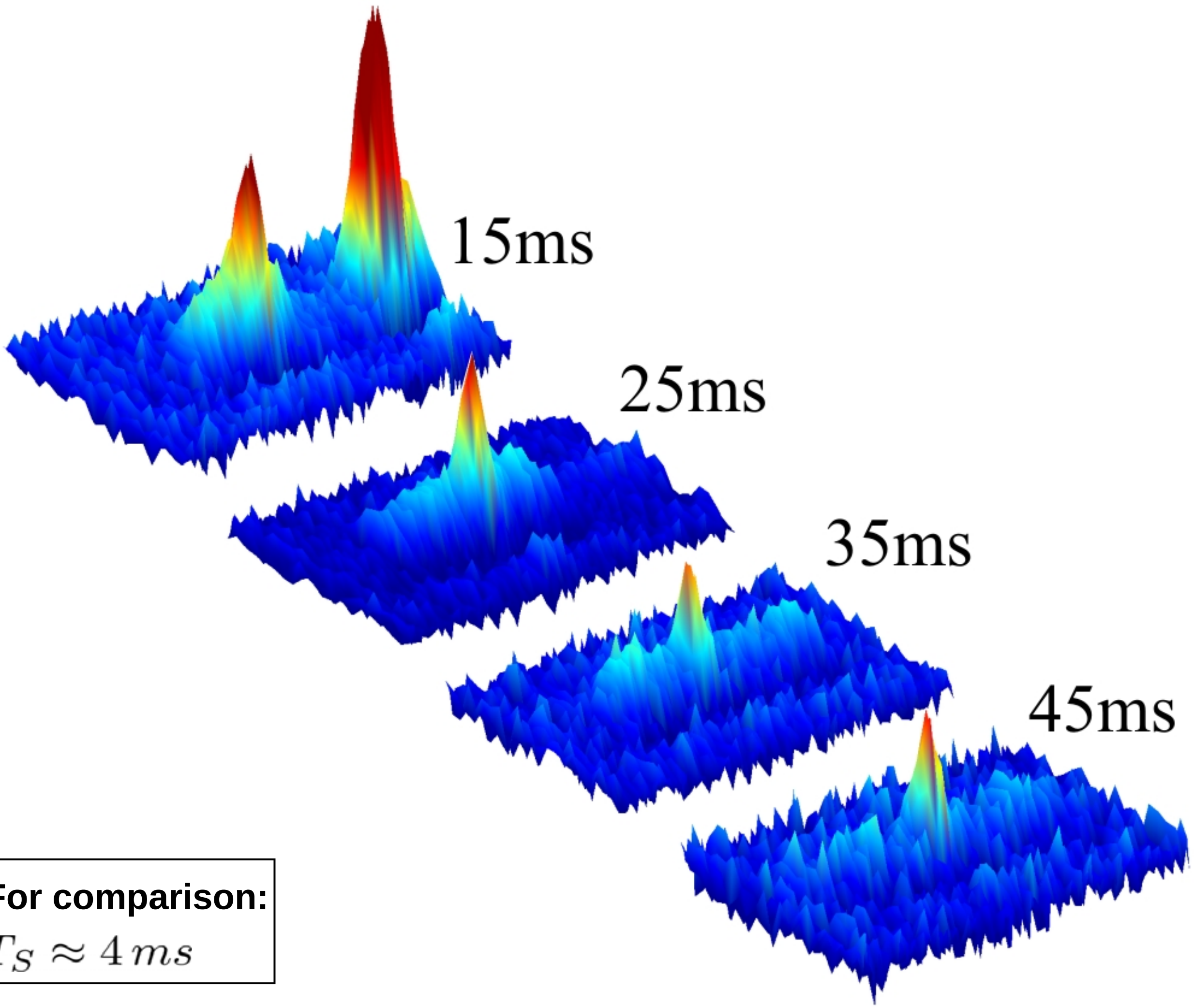
dispersion ⟷ nonlinearity

$$N=\underbrace{\frac{\hbar}{\alpha_{NL}\,a\,m}}\;\underbrace{\frac{m}{m_{eff}}}\;\underbrace{\frac{1}{\omega_\perp}}\;\underbrace{\frac{1}{x_0}}$$

0,09 x 10 x 0,002 x 2 10^5 = 350 atoms

observation of solitons

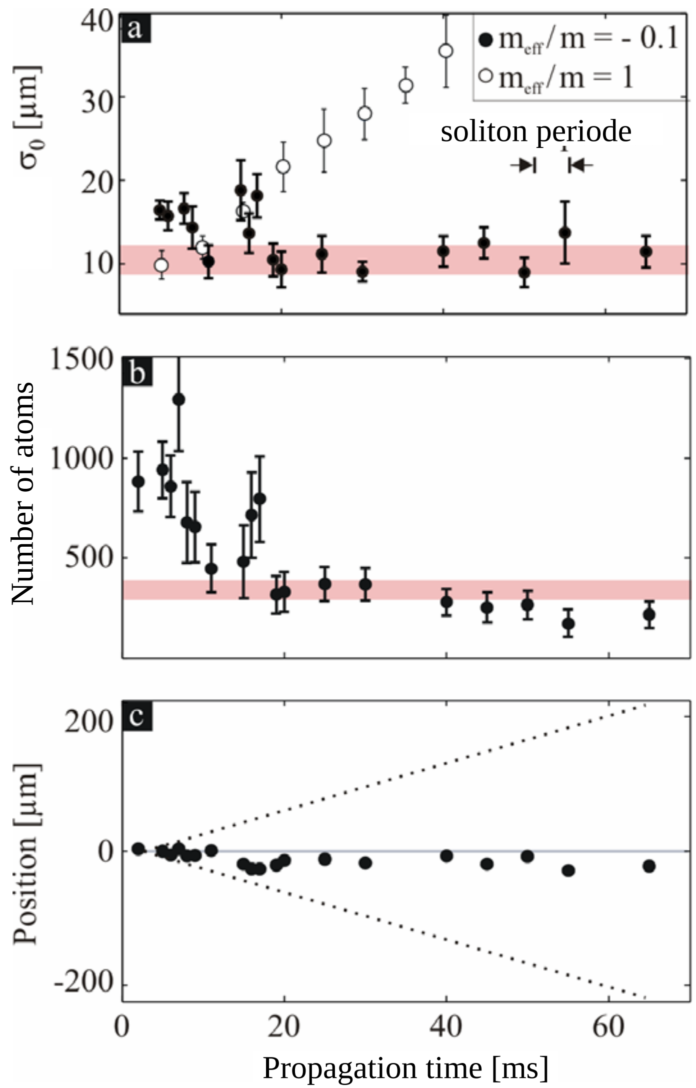
Phys. Rev. Lett. 92, 230401(2004)



For comparison:

$T_S \approx 4\, ms$

characteristics of solitons

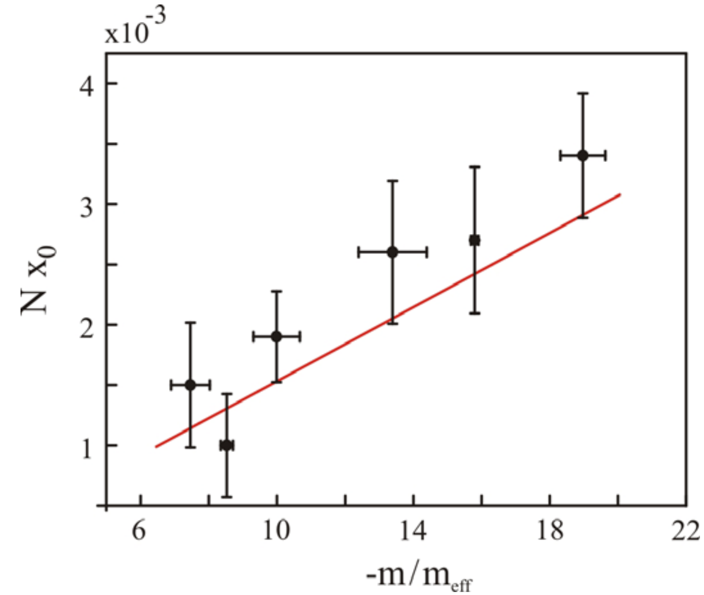


X_0=const.

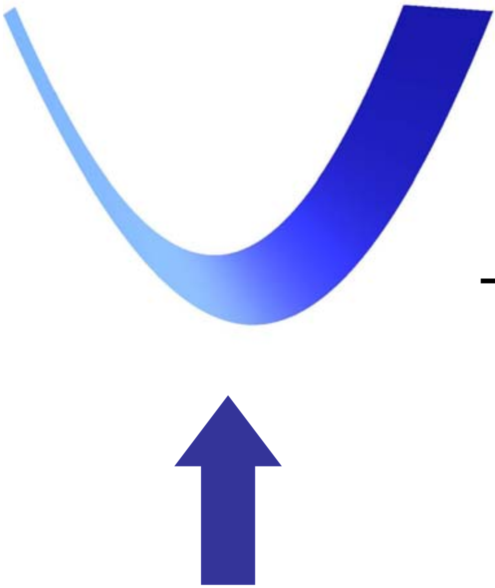
N = consistent

V_g=0

$$N\,x_0 = \frac{\hbar}{\alpha_{NL}\,a\,\omega_\perp\,m}\;\frac{m}{m_{eff}}$$

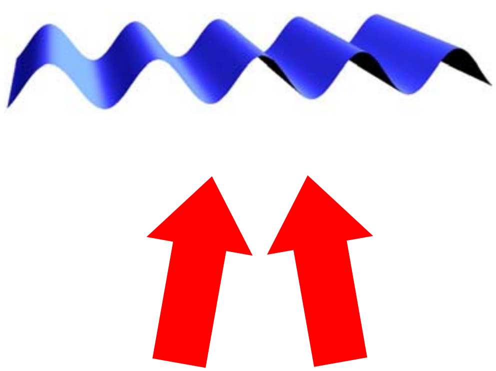


latest results

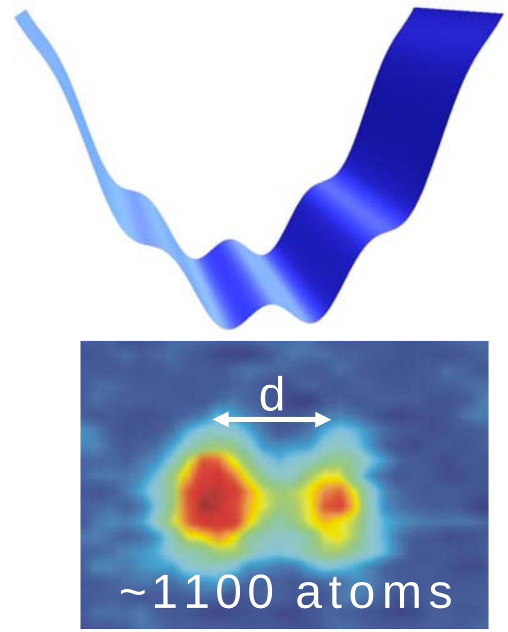


dipole trap beam,
harmonic
confinement

+



standing light wave with
relative angle of 9° between
beams

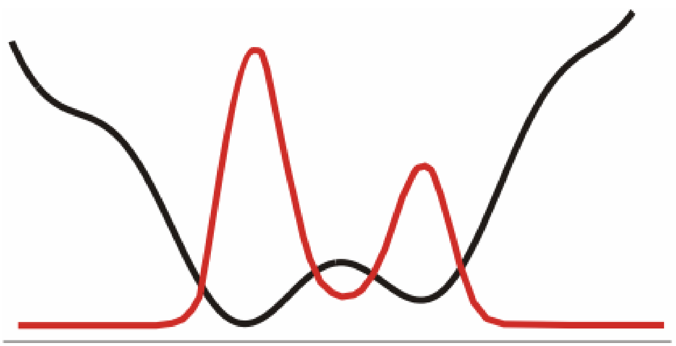


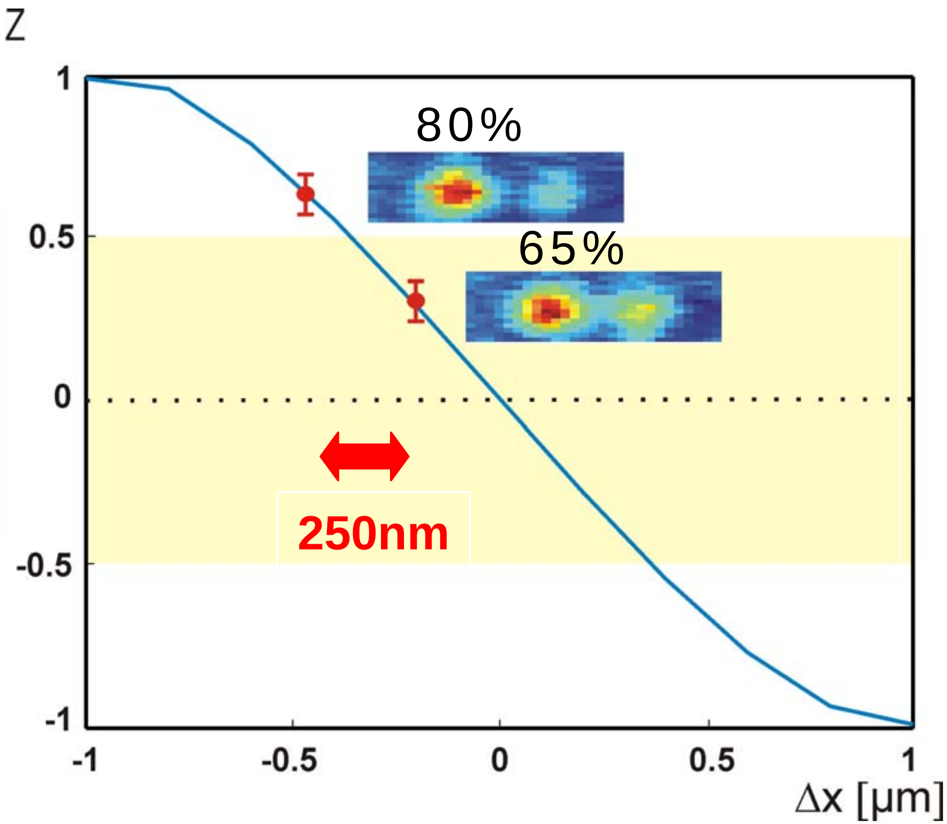
effective
double well
d = 4.4 μm

preparation

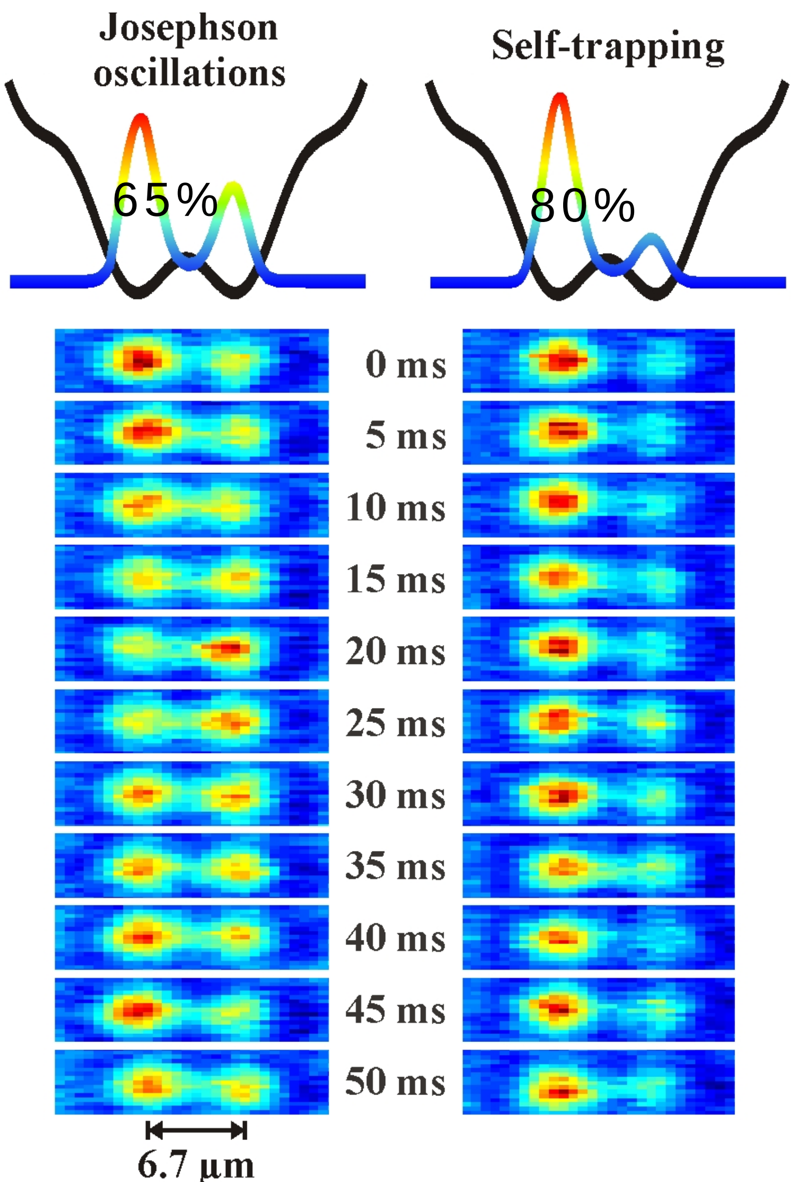
t < 0 : asymmetric double-well

$$V(x) = \frac{1}{2} m\omega_x^2 (x - \Delta_x)^2 + \frac{V_0}{2} \cos(\frac{2\pi}{d} x)$$





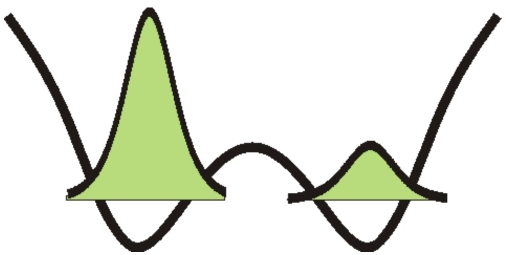
experimental results I



bosonic Josephson junction

two mode theory

double well ⟶ **two mode approximation**



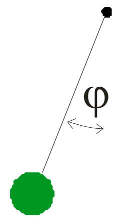
$$\Psi(x,t) = \psi_l(t)\Phi_l(r) + \psi_r(t)\Phi_r(r)$$

$$\psi_i(t) = \sqrt{N_i} e^{i\phi}$$

dynamical variables $z = \frac{N_L - N_R}{N_L + N_R}$ and $\varphi = \varphi_L - \varphi_R$

$$\dot{z}(t) = -\sqrt{1 - z(t)^2}\,\sin(\varphi(t))$$

$$\dot{\varphi}(t) = \Lambda z(t) + \frac{z(t)}{\sqrt{1 - z(t)^2}}\cos(\varphi(t))$$

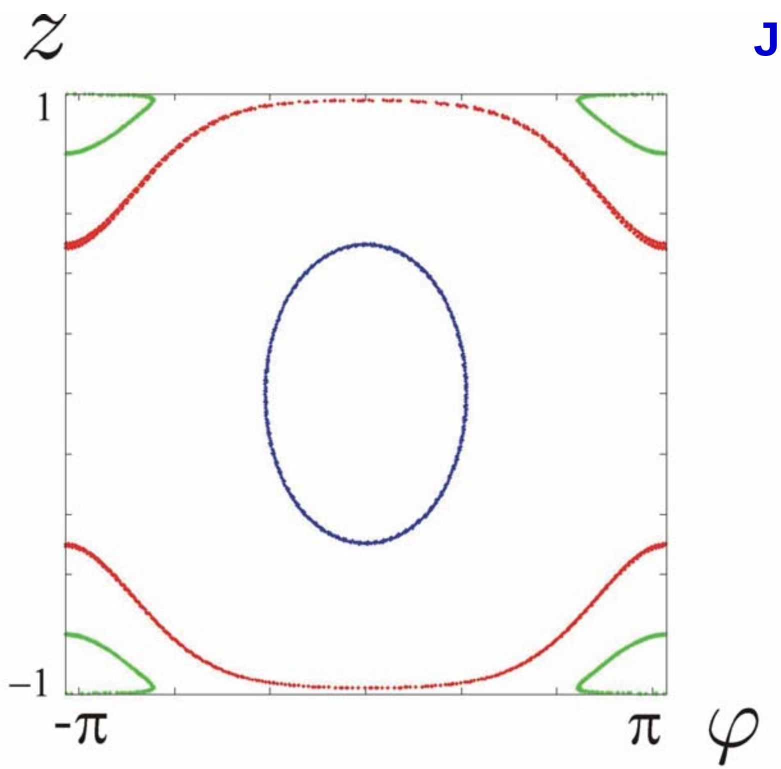


angular momentum: z

bosonic Josephson junction

mechanical analog

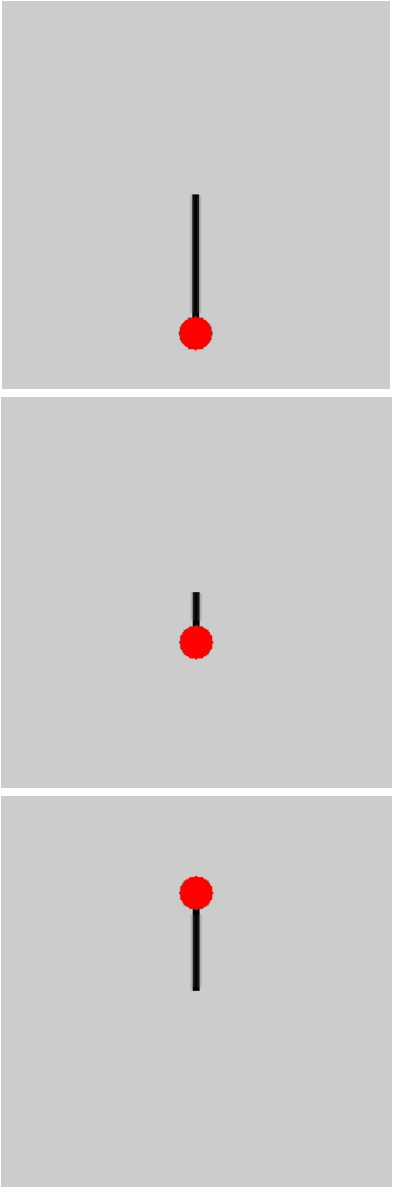
Non-rigid pendulum dynamics



Josephson-Oscillations

Self-Trapping

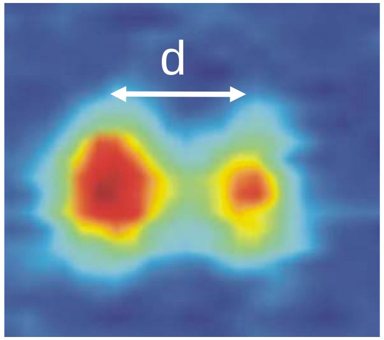
π-Oscillations



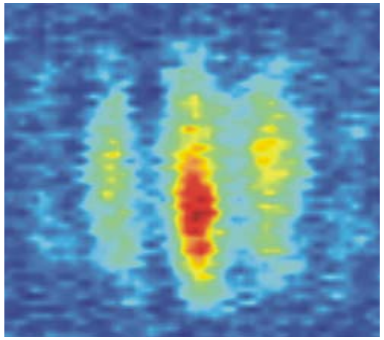
phase measurement

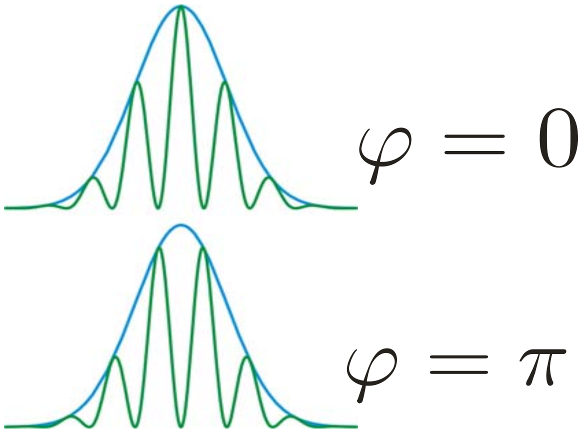
double-slit experiment

trapped BECs

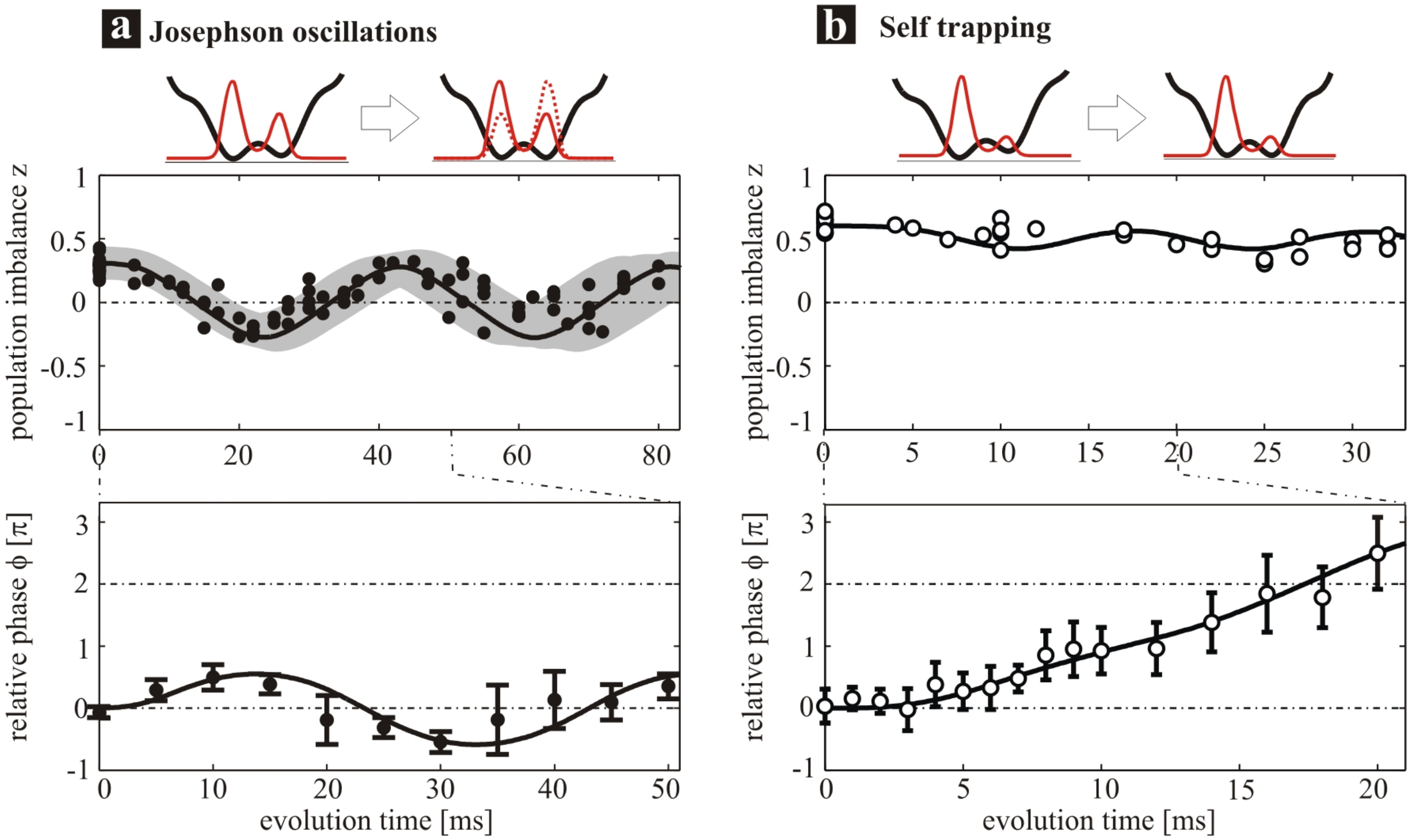


BECs after time of flight



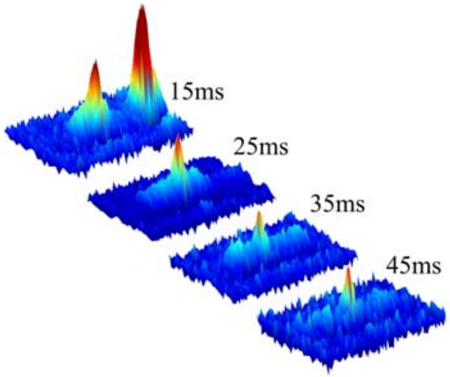


experimental results II

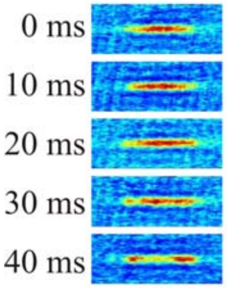


summary/outlook

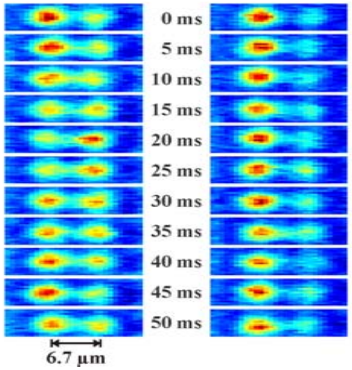
GAP SOLITON



SELF-TRAPPING



WEAK LINK



What's next:

Temperature measurement utilizing phase fluctuations in a double well potential
PRL 87, 180402 (2001)

Single site manipulation
(phase & amplitude)