Matter waves in traps, beam-splitters and optical circuits

Teaching old tricks with time-dependent control to new Things

Dr Seuss, The cat in the hat
https://www.youtube.com/watch?v=yJFlSYQn9kk

Thing 1
&
Thing 2

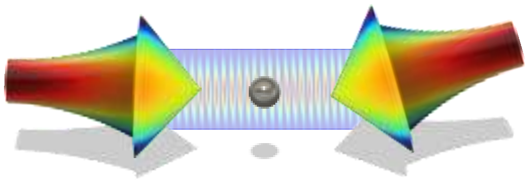
M. Sturm, A. Neumann, Reinhold Walser
Collaboration: G. Birkl, M.Schlosser, D. Pfeiffer

Contents

- **Pulsed Bragg beam-splitters**

  Good old Demkov-Kunike $Sech(t)$ analytical model

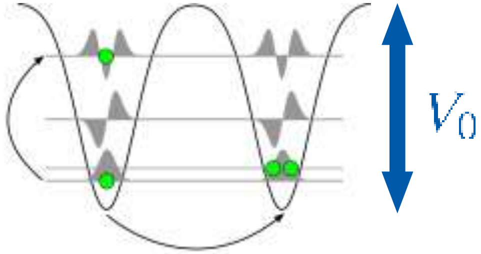
  A. Neumann *et al.,* Phys. Rev. A **103**, 043306 (2021)



- **Rapid generation** of Mott insulator states

  Good old NMR fast pulse ramps

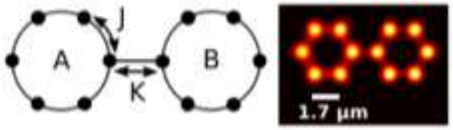
  M. Sturm, et al. , Phys. Rev. A **97**, 063608 (2018)



- **Exciting multiparticle resonances in Josephson junctions** of coupled BH rings

  Good old sudden switching

  M. Sturm, et al., Phys. Rev. A **95**, 063625 (2017)



From idealised to ‘realistic’ atomic beamsplitters

Theoretical studies in (3+1)D

Antje Neumann, Reinhold Walser & QUANTUS collaboration

TECHNISCHE UNIVERSITÄT DARMSTADT

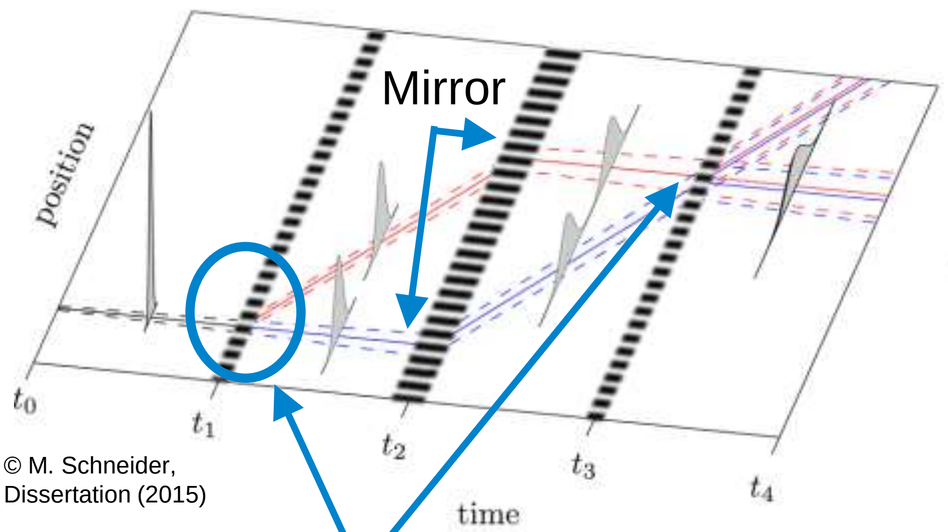
QUANTUM MATTER
GRANADA
1st-5th September 2019

theweathernetwork.com (Susan Cipriano, Creative Commons)

livestockoftheworld.com/Donkeys (Imgur/ButtersTheCat)

Why atomic beamsplitters?

Matter-wave interferometer



© M. Schneider, Dissertation (2015)

BeamSplitter

→ coherent superposition of atomic wave packets

[PRL **82** 871 (1999)]

High-precision rotation & acceleration sensing

Sensitivity $\propto \; T^2, \Delta k$

Applications:

- Fundamental physics:

  e.g. universality of free fall

- Inertial navigation, …

QUANTUS

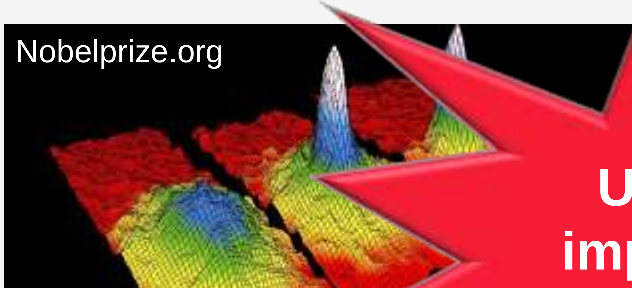
Quanten Gase Unter

microg vity

Experiments need reliable predictions!

ultracold
Quantum gases

BEC as macroscopic quantum matter

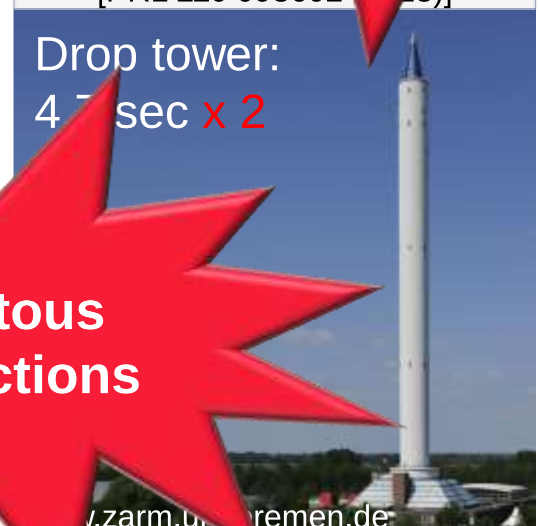


Ubiquitous imperfections

→ Long coherence le gth
→ Slow expansion
→ Narrow momentum widt

QU
free fa expe ents
[PRL **110** 093602 3)]

Drop tower:
4 sec x 2



AIU
st BEC
n space
[Nature **562** 391-395 (2018)]

Sounding rocket:
6 min

Space station:
Cold **A**toms **L**ab
[coldatomlab.jpl.nasa.gov]

Parabolic flights
[Nature comm. **7** 13786 (2016)]

Satellites

Bragg diffraction
of atoms by an optical standing wave

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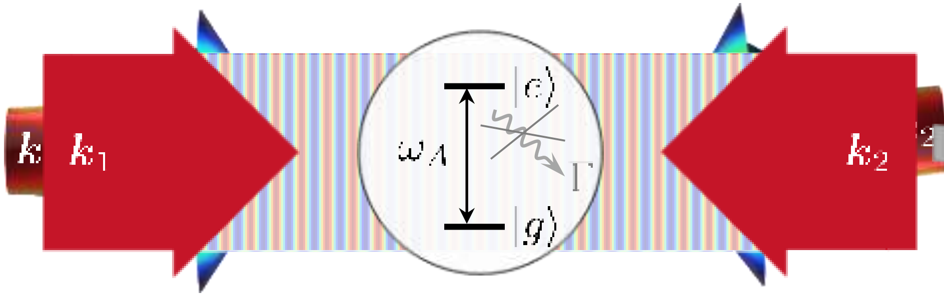


$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{\hbar\Delta}{2}(|e\rangle\langle e| - |g\rangle\langle g|) + \hat{H}_I$$

$$\hat{H}_I = \frac{\hbar}{2}\Omega(t)\left(e^{i\boldsymbol{k}_L\hat{\boldsymbol{x}}} + e^{-i\boldsymbol{k}_L\hat{\boldsymbol{x}}}\right)|e\rangle\langle g| + h.c.$$

absorb / emit 1 photon:

$$e^{\pm i\boldsymbol{k}_L\hat{\boldsymbol{x}}} = \int d^3p\,|\boldsymbol{p} \pm \hbar\boldsymbol{k}_L\rangle\langle\boldsymbol{p}|$$

coupling:

$$|g, \boldsymbol{k}\rangle \leftrightarrow |g, \boldsymbol{k} \pm 2N\boldsymbol{k}_L\rangle$$

Bragg order

S

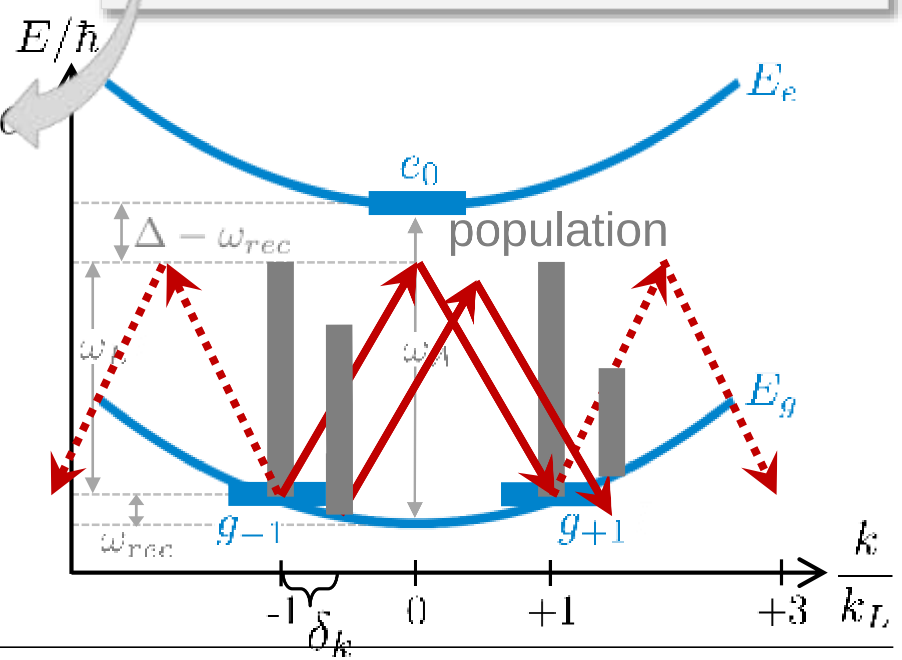
- V
- L
-
- Spatial envelopes

Frame transformation:

atoms at rest & moving grating

grating at rest & moving atoms

$|\boldsymbol{k}_L| = (|\boldsymbol{k}_1| + |\boldsymbol{k}_2|)/2$



Velocity dispersion for box pulses

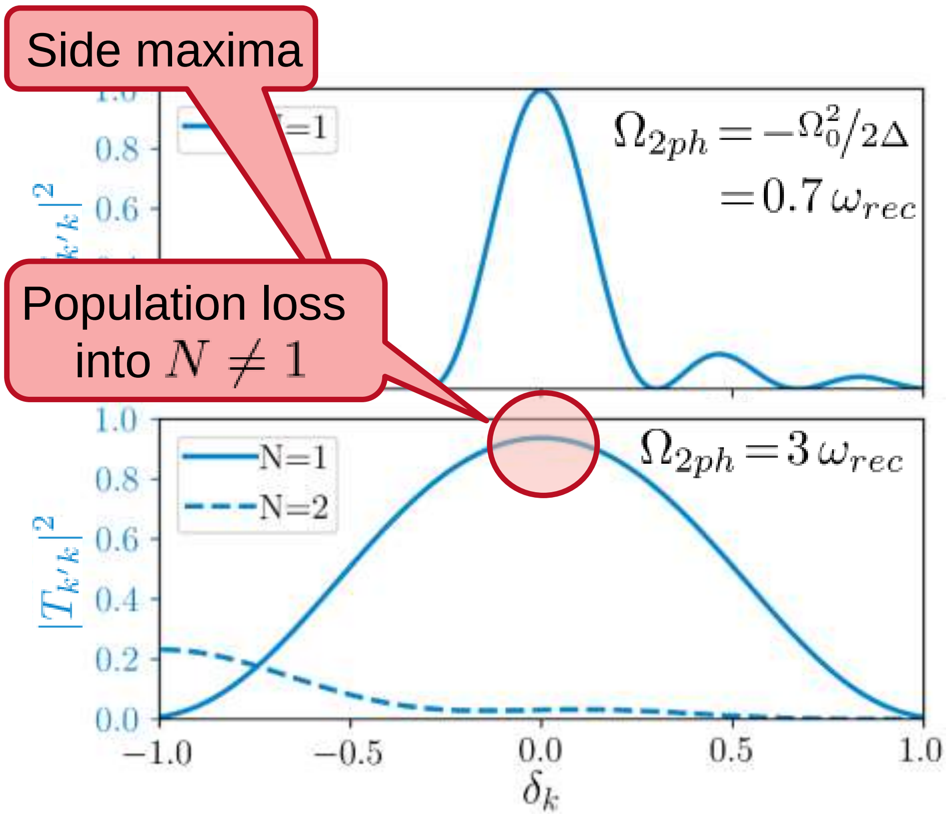
$$|\Psi(t)\rangle = \sum_{\delta_k \in (-1,1)} \sum_{m=-\mathcal{N}}^{\mathcal{N}} g_{m,\delta_k} |g,(m+\delta_k)k_L\rangle + e_{m',\delta_k} |e,(m'+\delta_k)k_L\rangle$$

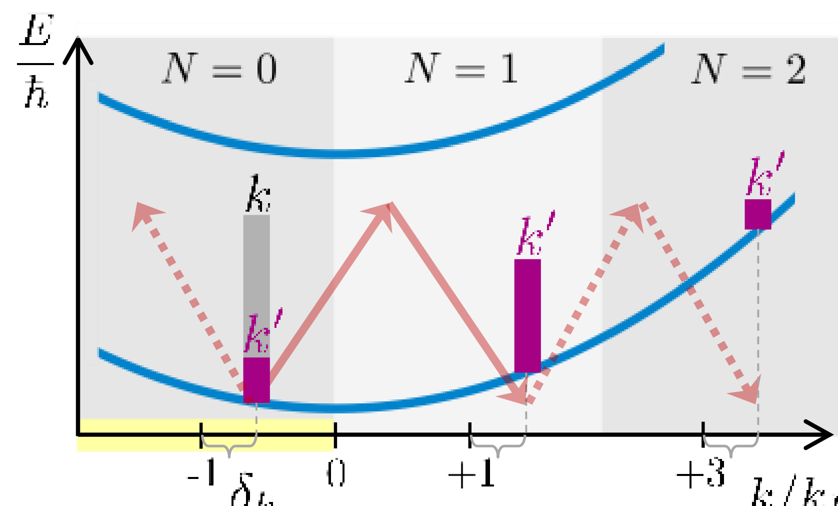
$$|\Psi(t)\rangle = e^{-i/\hbar \hat{H} t} |\Psi(0)\rangle = \hat{U} |\Psi(0)\rangle$$

Transition amplitude between initial k and final $k' = k + 2Nk_L$

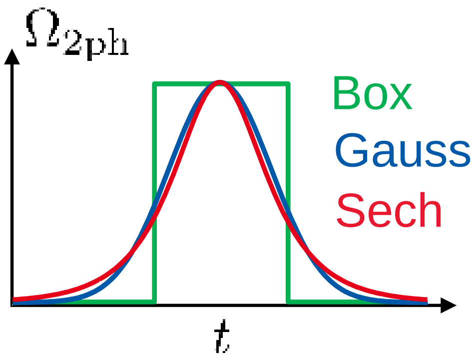
$$T_{k'k} = \langle k' | \hat{U} | k \rangle$$

→ diffraction efficiency $|T_{k'k}|^2$





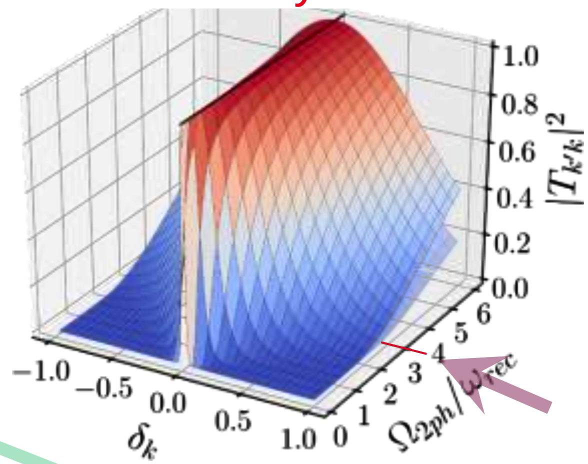
Various pulse envelopes, …

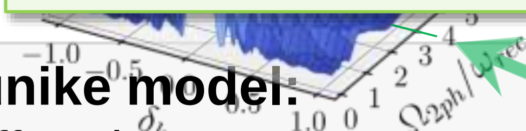


Box: analytical

- suppressed side maxima
- less population loss into higher diffraction orders
- analytic model (DK) for *sech* - pulses

DK: analytical





Analytic Demkov-Kunike model:
1D, 1st order Bragg diffraction

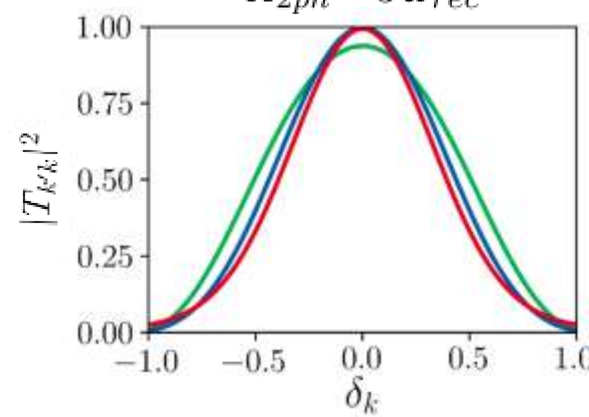
$\Omega_{2ph}(t) = \Omega_{2ph}\cdot\text{sec}$

$$T^{N=1}_{k'k} = \frac{\sigma\Omega_{2ph}\sqrt{\text{se}}}{i\sqrt{2\pi} - 8\omega_{rec}\delta_k\sigma}$$

- suppressed side maxima
- less population loss into higher diffraction orders

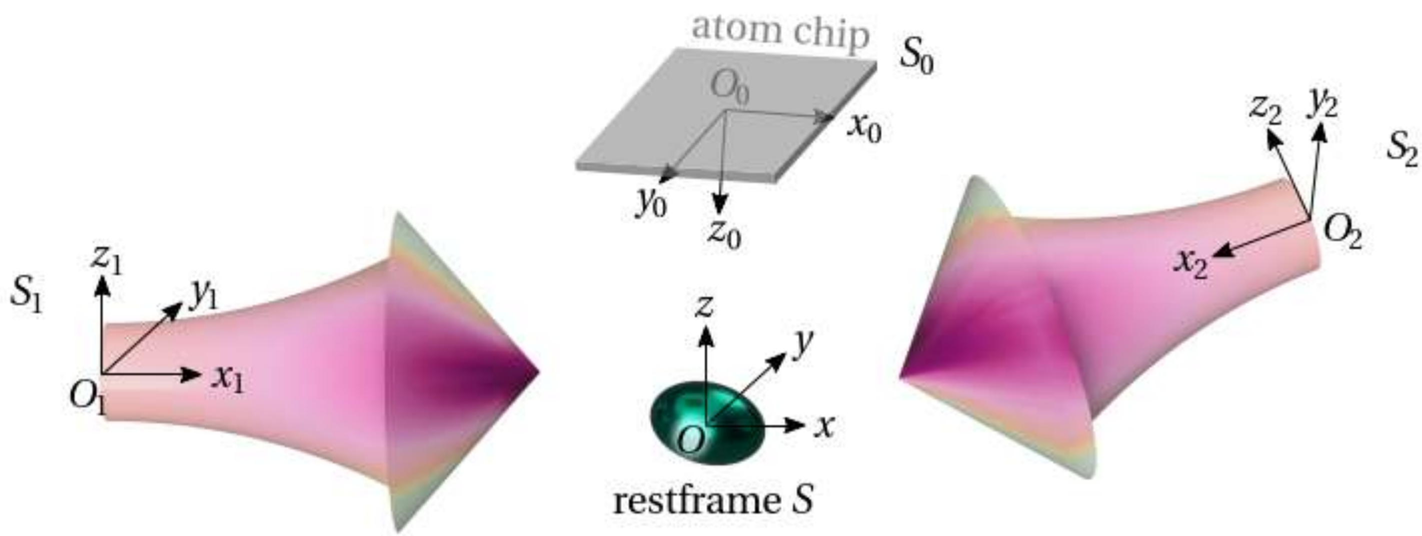
$a/b = 1 -/+ \frac{\sigma\Omega_{2ph}}{\sqrt{2\pi}},\ c = \frac{3}{2} + 2i\sqrt{\frac{2}{\pi}}\omega_{rec}\delta_k\sigma,\ z(t) = \frac{1}{2}\left(1+\tanh\left(\sqrt{\frac{\pi}{2}}\frac{t}{\sigma}\right)\right)$

$\Omega_{2ph} = 3\,\omega_{rec}$



Experiment on ground

- Prepare BEC
- Drop with variable time
- Apply Bragg pulse



Comparison with experiment*

* M. Gebbe (ZARM, University Bremen)

Laser:
- spatial dependence: ~ plane waves
- temporal: Gaussian
- Laser frequency detuned to resonance $\delta_f \longrightarrow \delta_k$

Frame transformation:

Diffraction **E**fficiency:

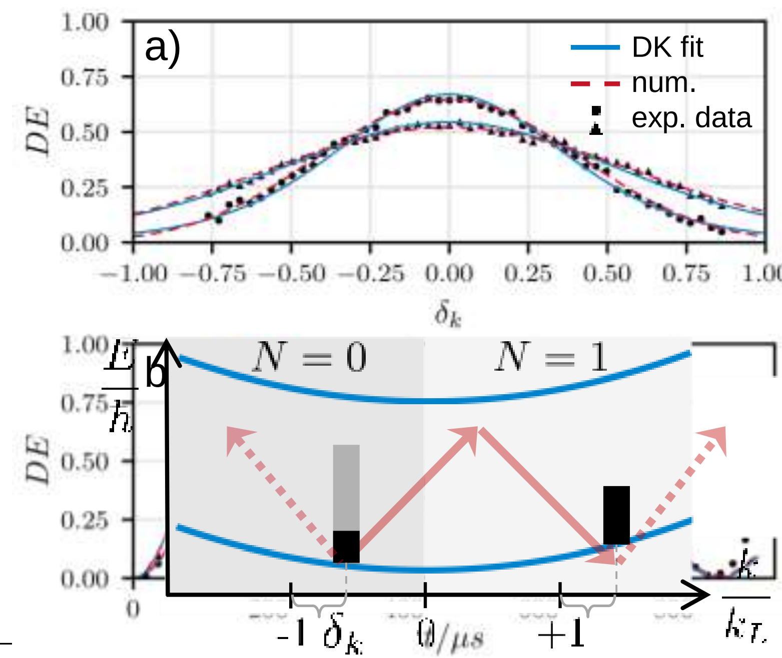
$$DE = \frac{P_{+k_L}}{P_{-k_L} + P_{+k_L}}$$

Atoms: BEC @ 50 nK ~ Thomas Fermi, momentum width $\ll k_L$

a)

	•	▲
P	$(20 \pm 2)\,\mathrm{mW}$	$(30 \pm 3)\,\mathrm{mW}$
$\Omega_{2\mathrm{ph}}^{\mathrm{exp}}$	$(1.7 \pm 0.3)\,\omega_{\mathrm{rec}}$	$(2.6 \pm 0.4)\,\omega_{\mathrm{rec}}$
t	$138.75\,\mu s$	$92.5\,\mu s$
pulse area	$0.67\,\pi$	$0.67\,\pi$
$\Omega_{2\mathrm{ph}}^{\mathrm{DK}}$	$1.87\,\omega_{\mathrm{rec}}$	$2.42\,\omega_{\mathrm{rec}}$
$\Omega_{2\mathrm{ph}}^{\mathrm{num}}$	$1.83\,\omega_{\mathrm{rec}}$	$2.40\,\omega_{\mathrm{rec}}$

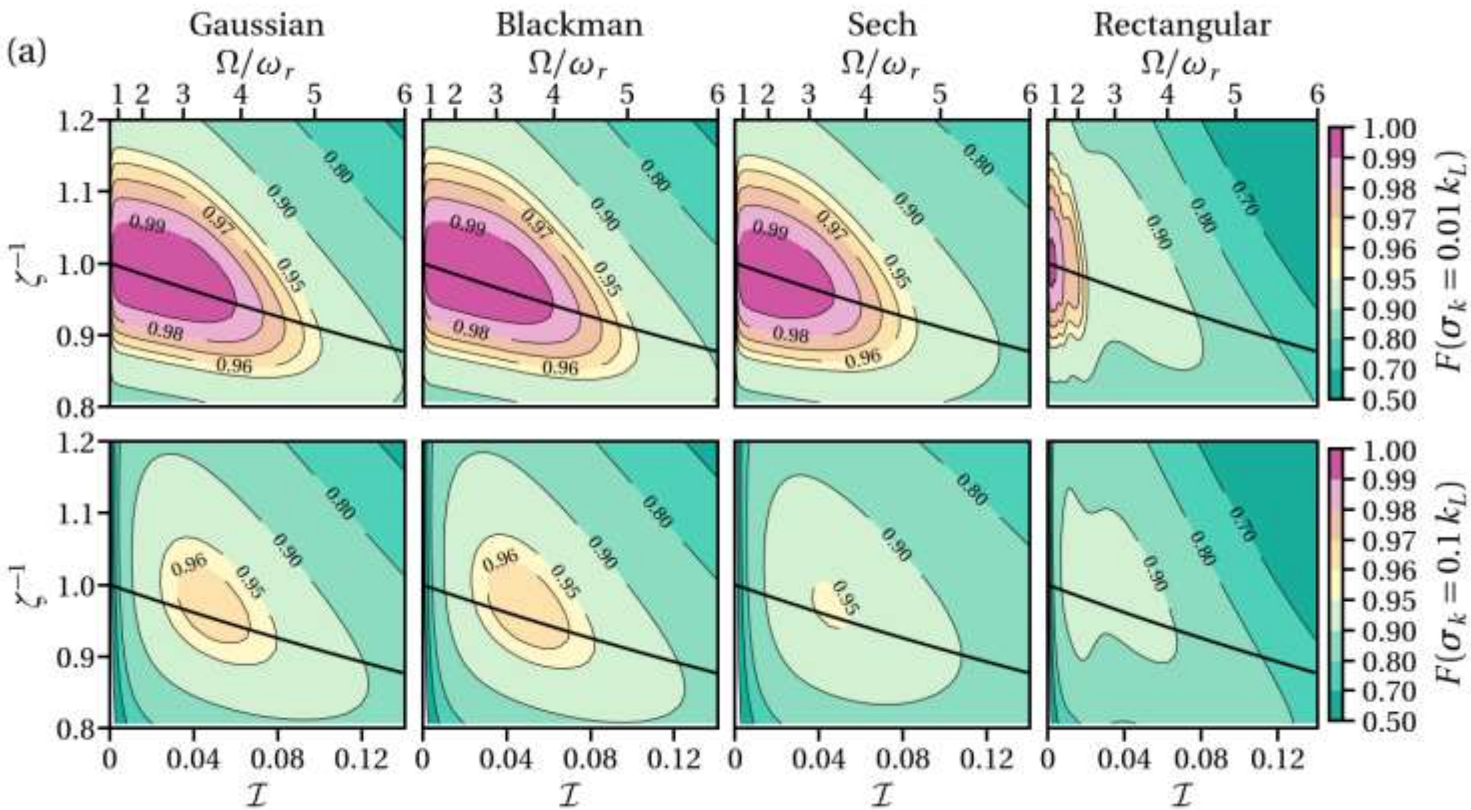
b)



Optimal π-pulse intensities for „bs-mirrors“

- Optimal π-pulse time stretching factor
- Universal rule: Kato deg. perturbation theory

$$\zeta_\pi \equiv \zeta_\pi^{\kappa=0} = \frac{1}{1-\mathcal{I}} (\approx 1+\mathcal{I}).$$



K. E. McAlpine, D. Gochnauer, and S. Gupta, Excited-band Bloch oscillations for precision atom interferometry,
Phys. Rev. A 101, 023614 (2020)

Ultracold atoms in reconfigurable arrays ot tunnel coupled traps

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Martin Sturm

Collaboration: Gerhard Birkl, Malte Schlosser

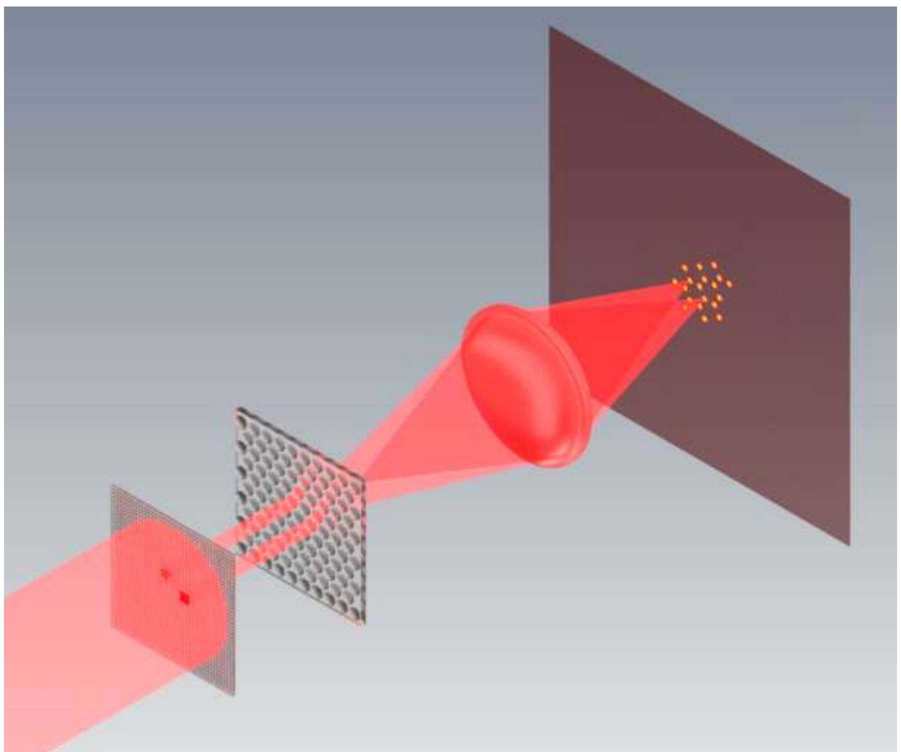
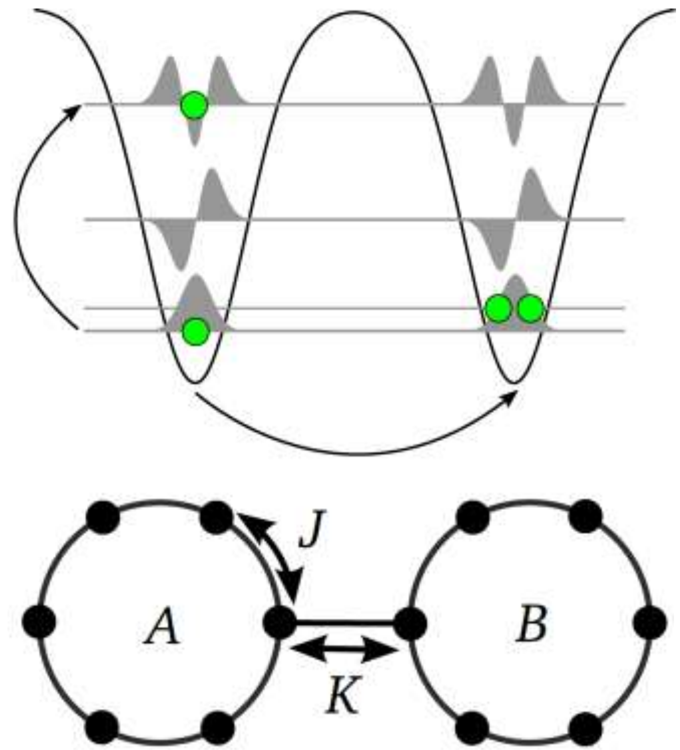


Abbildung erstellt von Malte Schlosser



Design of light potential surfaces

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- **Pinboard for atomtronics**

  implement atomtronic devices

  like diodes and transistors

- **Designable lattices**

  Exotic lattice geometries

  quasi crystals

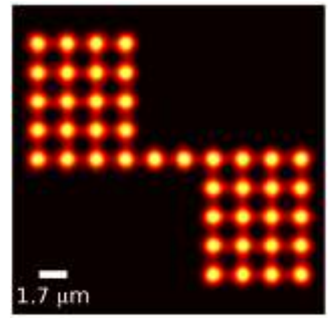
  point/line defects

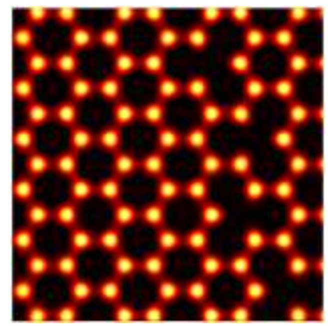
  controllable disorder

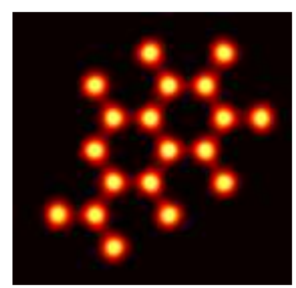
- **Molecular structures**

  mimick electronic structure

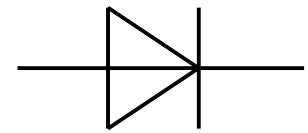
  of molecules

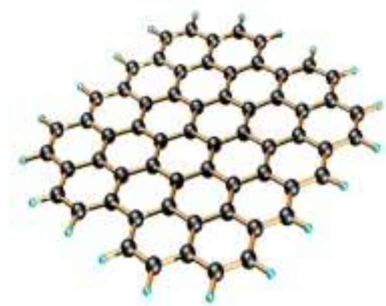




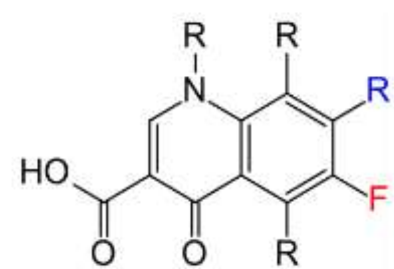


diode





Copyright: Chris Ewels



https://en.wikipedia.org/wiki/Quinolone

R. A. Pepino, J. Cooper, D. Z. Anderson, and M. J. Holland, „Atomtronic circuits of diodes and transistors“, Phys. Rev. Lett. 103, 140405 (2009).

Key parameters

- **Micro lense array**
  - Lense separation: 110 µm
  - Lense diameter: 106 µm
  - # Lenses: 100 × 100
- **Relais optics**
  - NA=0.68
  - Magnification: 1/65
  - Trap separation: **1.7 µm**
- **Spatial light modulator or DMD‘s**

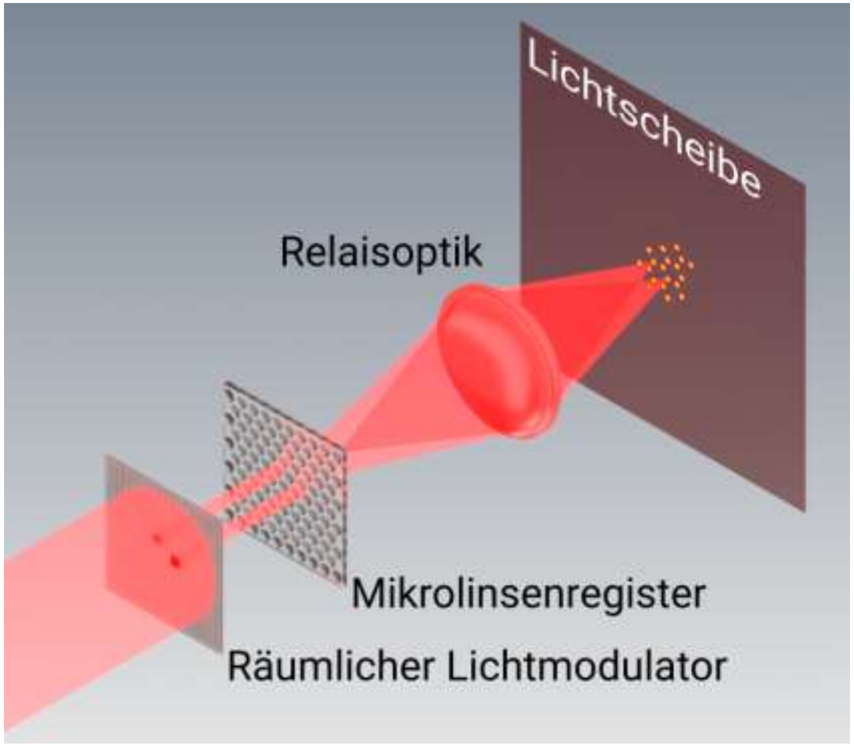


Abbildung erstellt von Malte Schlosser

Intensity distribution/optical potentials

- Register of Gauss-shaped micro traps

$$V_\perp(x,y) = \sum_{i=1}^{M} V_{0\perp}^{(i)} e^{-\frac{(x-X_i)^2+(y-Y_i)^2}{w_{0\perp}^2/2}}$$

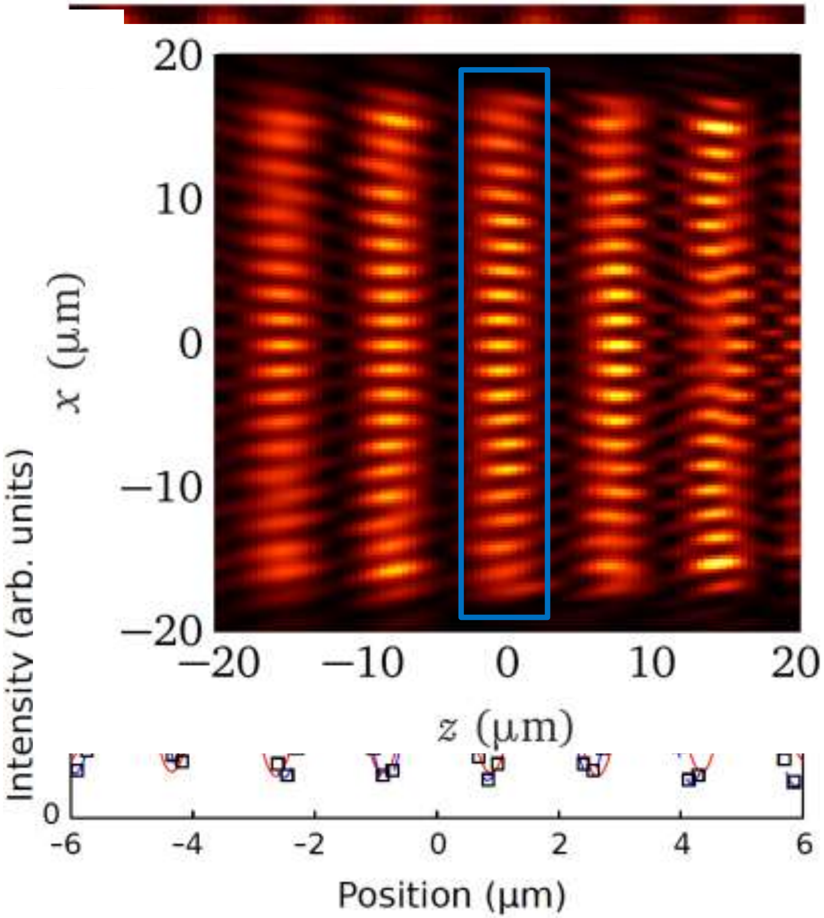
$$w_{0\perp} = 0.7\ \mu\text{m} \qquad d = 1.7\ \mu\text{m}$$

- Talbot-effect (length: 7 µm)

- Select with sheet of light

$$V_{||}(z) = -V_{0||} e^{-\frac{z^2}{w_{0||}^2/2}} \qquad w_{0||} = 2.5\ \mu\text{m}$$

Sturm et al. PRA 95, 063625 (2017)



Bose-Hubbard model

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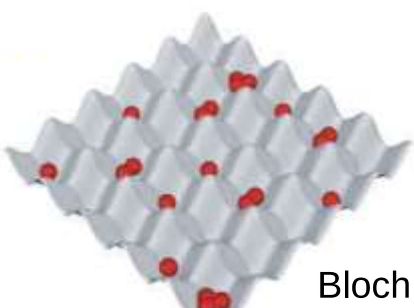
- Bosons on a lattice

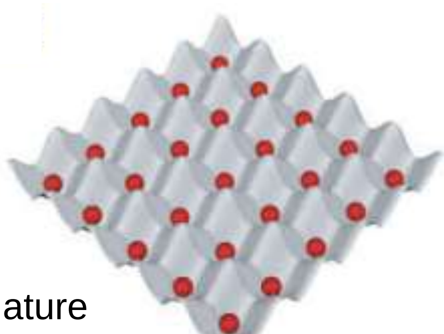
$$\hat{H} = -J \sum_{\langle ij \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_{i=1}^{M} \hat{a}_i^\dagger \hat{a}_i^\dagger \hat{a}_i \hat{a}_i$$

- Phase transition

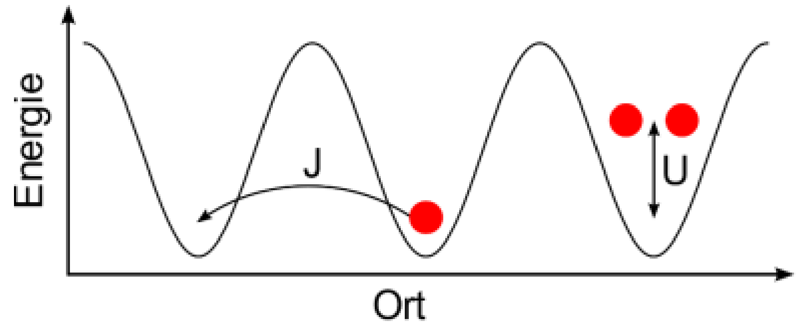
Superfluid

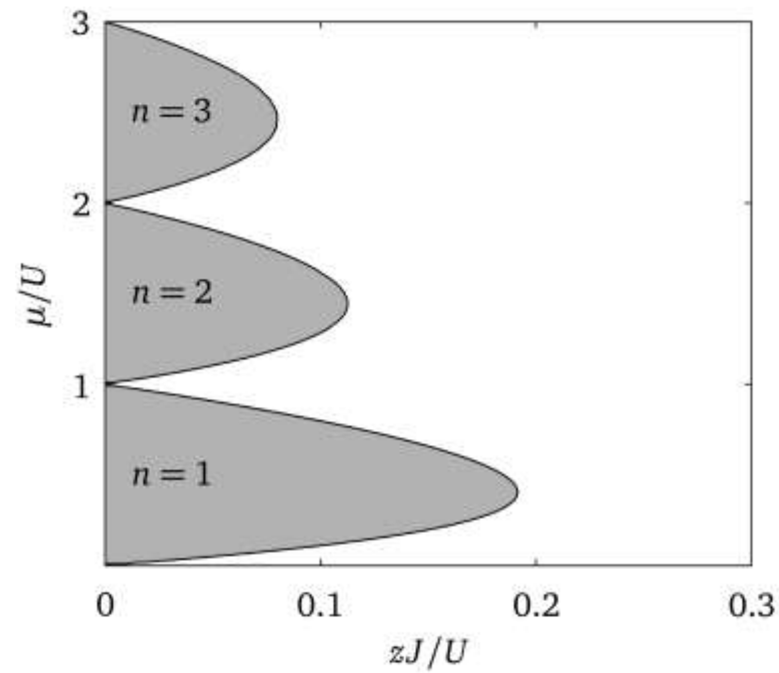


Mott-Isolator



Bloch, Nature **453**, 1016 (2008)





Bose-Hubbard parameters for 1D & 2D lattices

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- Periodic potentials V(r+R)=V(r): Bloch/ Wannier-functions

$$\psi_{\boldsymbol{k}}(\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} u_{\boldsymbol{k}}(\boldsymbol{r}) \qquad u_{\boldsymbol{k}}(\boldsymbol{r}+\boldsymbol{R}) = u_{\boldsymbol{k}}(\boldsymbol{r})$$

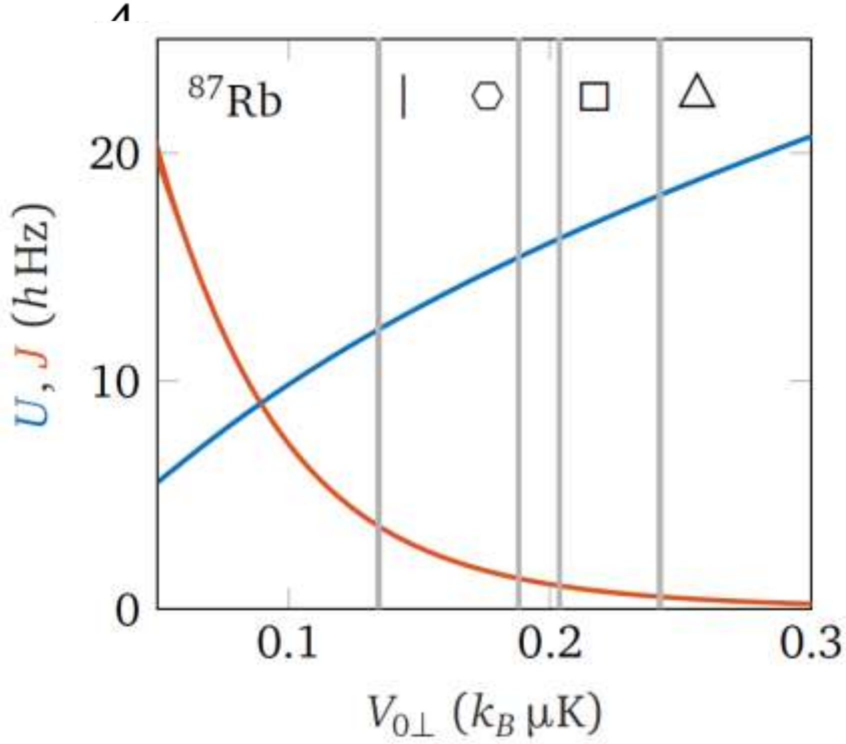
$$w_i(\boldsymbol{r}) = \frac{\Upsilon}{(2\pi)^D} \int_{\mathrm{BZ}} e^{-i\boldsymbol{k}\cdot\boldsymbol{R}_i} \psi_{\boldsymbol{k}}(\boldsymbol{r}) \, \mathrm{d}^D k$$

- Self-interation

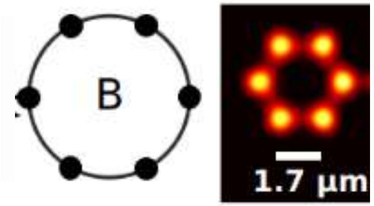
$$U = \frac{4\pi\hbar^2 a_s}{m} \int w_i^4(\boldsymbol{r}) \, \mathrm{d}^3 r$$

- Hopping strength: nearest neighbour

$$J = \int w_i(\boldsymbol{r}) \left(-\frac{\hbar^2 \Delta}{2m} + V(\boldsymbol{r}) \right) w_j(\boldsymbol{r}) \, \mathrm{d}$$



Loading atoms into the trap arrays



- Loading from BEC
  1. Preparation of an oblate BEC
  2. Adiabatic turn on of trap array
  3. Analogous to experiments in optical lattices

     Sherson et al., Nature **467**, 68–72 (2010)

- Loading in the atomic limit
  1. Deterministic preparation of one atom/trap

     Endres et al., Science **354**, 1024 (2016) & Barredo et al., Science **354**, 1021 (2016)
  2. Raman-sideband-cooling

     Kaufman et al., PRX **2**, 041014 (2012) & Thompson et al., PRL **110**, 133001 (2013)
  3. Adiabatic decrease of trap depth

     M. R. Sturm, et al. , Phys. Rev. A 97, 063608 (2018)

Optimal adiabatic parameter ramps $\gamma(t)$

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- Conditions for adiabaticity

$$\max_{0\leq t\leq\tau}\left|\frac{\alpha_{ij}(\gamma,\dot\gamma)}{\hbar\omega_{ij}^2(\gamma)}\right|^2 \ll 1 \quad \forall j\neq i$$

- Lagrange-error functional

$$\mathcal{L}(\gamma,\dot\gamma)=\sum_{j\neq i}\left|\frac{\alpha_{ij}(\gamma,\dot\gamma)}{\hbar\omega_{ij}^2(\gamma)}\right|^2=\frac{1}{2}\mathcal{M}(\gamma)\dot\gamma^2$$

$$\mathbb{E}_\infty[\gamma,\dot\gamma]=\max_{0\leq t\leq\tau}\mathcal{L}(\gamma(t),\dot\gamma(t))$$

$$\mathbb{E}_1[\gamma,\dot\gamma]=\frac{1}{\tau}\int_0^\tau\mathcal{L}(\gamma(t),\dot\gamma(t))\,\mathrm{d}t$$

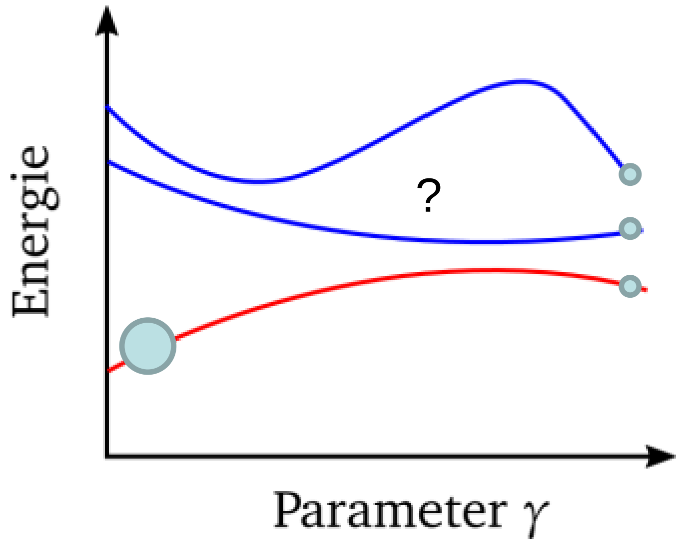
- Euler-Lagrange-equation for optimal ramp

$$\frac{\mathrm{d}}{\mathrm{d}t}\partial_{\dot\gamma}\mathcal{L}=\partial_\gamma\mathcal{L}$$

$$\hat H(\gamma)|i(\gamma)\rangle=E_i(\gamma)|i(\gamma)\rangle$$

$$\omega_{ij}(\gamma)=\frac{E_j(\gamma)-E_i(\gamma)}{\hbar}$$

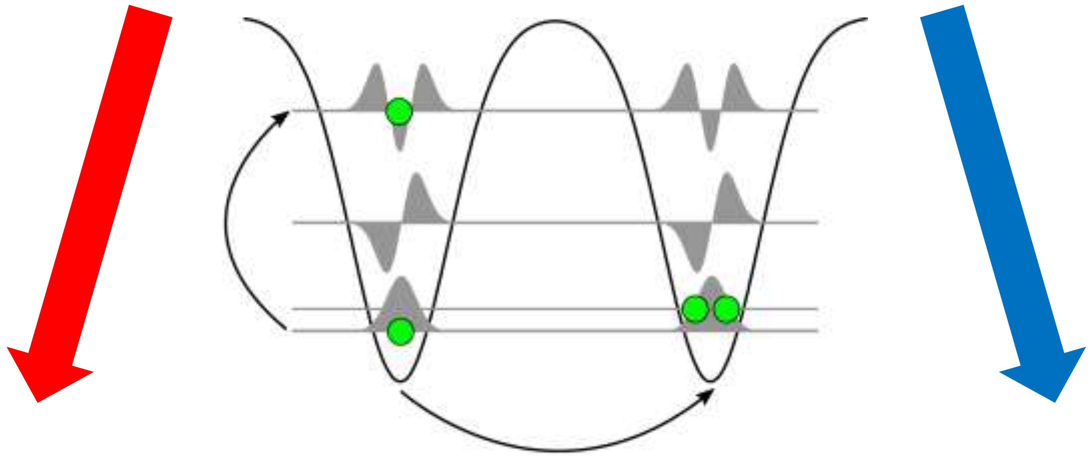
$$\alpha_{ij}(\gamma,\dot\gamma)=\langle j|\partial_t\hat H|i\rangle$$



S. McCall, E. Hahn, PRA, 183, 457 (1969), J. Baum et al, PRA, 32, 3435 (1985),
A. Rezakhani et al. PRL,103, 080502 (2009)

Multiband-Bose-Hubbard model

$$\hat H(\gamma) = \sum_{n,i} \epsilon_i^n(\gamma)\hat a_i^{n\dagger}\hat a_i^n - \sum_{n,i\neq j} J_{ij}^n(\gamma)\hat a_i^{n\dagger}\hat a_j^n + \frac{1}{2}\sum_{nopq}\sum_{ijkl} U_{ijkl}^{nopq}\hat a_i^{n\dagger}\hat a_j^{o\dagger}\hat a_k^p\hat a_l^q$$



Atomic limit

- Local interband excitations
- Disregard tunneling
- one atom/trap → no self interation

Mott-insulator

- Intraband excitations
- Disregard higher bands
- Interaction dominated (U≫J)

Atomic limit

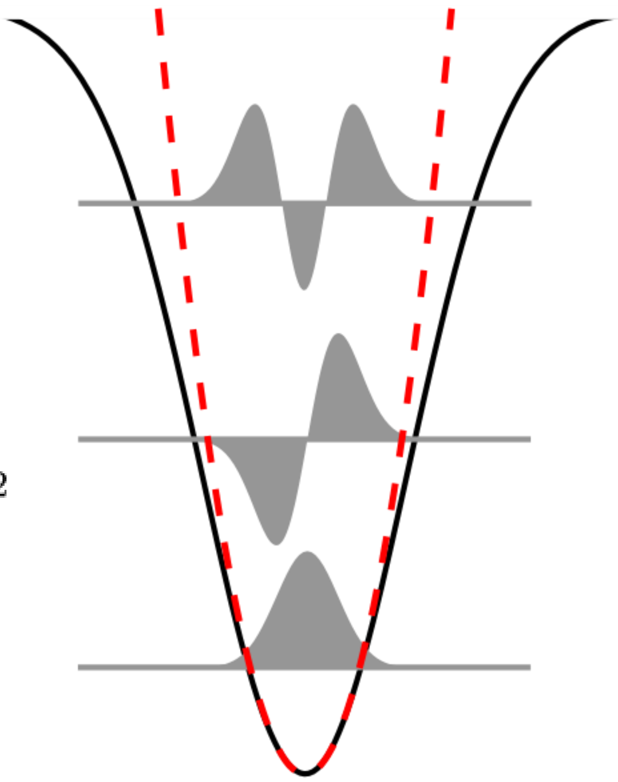
- Hamilton operator $\hat{H}_{\mathrm{al}} = \sum_{n,i} \epsilon_i^n(\gamma) \hat{a}_i^{n\dagger} \hat{a}_i^n$
- Harmonic oscillator

$$\gamma = (\Omega_x, \Omega_y, \Omega_z)$$

$$\epsilon_i^n(\gamma) = \sum_{l=x,y,z} \hbar\Omega_l \, (n_l + \frac{1}{2})$$

$$w_i^n(\boldsymbol{r}) = \langle \boldsymbol{r} - \boldsymbol{R}_i | n_x n_y n_z \rangle$$

- Lagrange-functional $\mathcal{L}_{\mathrm{al}}(\gamma, \dot{\gamma}) = \sum_{l=1}^{3} \frac{1}{2} \frac{M}{(2\gamma_l)^4} \dot{\gamma}_l^2$



- Hyperbolic ramp shape

$$\gamma_l^{-1}(t) = \Omega_{l0}^{-1} + (\Omega_{l\tau}^{-1} - \Omega_{l0}^{-1}) \frac{t}{\tau}$$

Mott-insulator

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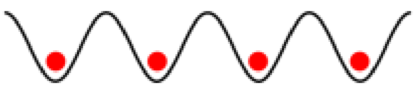
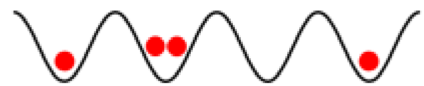
- Hamilton operator $$\hat{H}_{\mathrm{bh}} = \epsilon N + \frac{U}{2}\sum_i \hat{a}_i^\dagger \hat{a}_i^\dagger \hat{a}_i \hat{a}_i - J\sum_{\langle i,j\rangle} \hat{a}_i^\dagger \hat{a}_j$$

- Perturbation theory in J/U

$|g^0\rangle =$  $|e^0\rangle =$ 

$$E_g^1 = U + \langle g^0|\hat{H}_J|g^0\rangle \qquad |g^1\rangle = |g^0\rangle + \sum_e \frac{\langle e^0|\hat{H}_J|g^0\rangle}{E_g^0 - E_e^0}|e^0\rangle$$

- Lagrange-function $\gamma = (J, U)$

$$\mathcal{L}_{\mathrm{bh}}(\gamma, \dot{\gamma}) = \frac{1}{2}\sum_{k,l=1}^{2} \dot{\gamma}_k \mathcal{M}_{kl}(\gamma)\dot{\gamma}_l \qquad \mathcal{M}(J,U) = \frac{4Mz\hbar^2}{U^6}\begin{pmatrix} U^2 & -JU \\ -JU & J^2 \end{pmatrix}$$

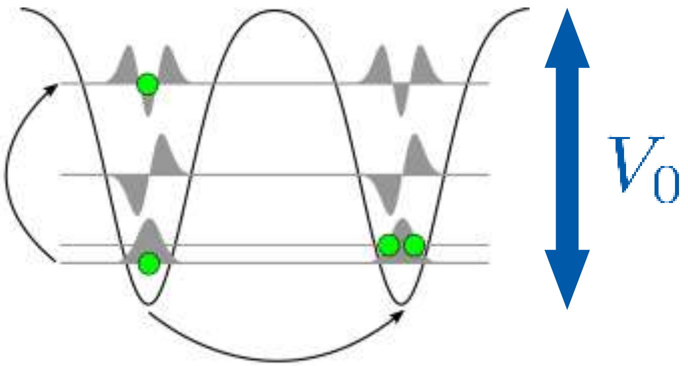
Optimal adiabatic parameter ramps

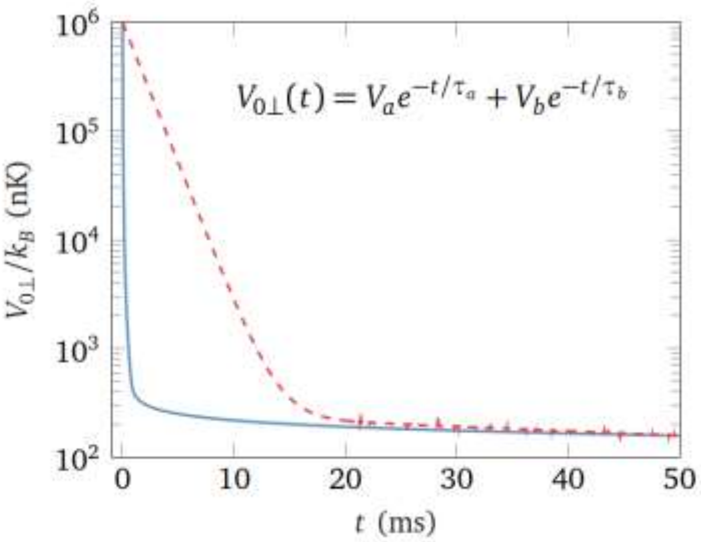
- Experimental control-parameter: $I_0 \propto V_0$

$$\Omega_l(V_0) \quad J(V_0) \quad U(V_0)$$

- Additivity of errors

$$\mathcal{L}(V_0, \dot{V}_0) = \mathcal{L}_{\mathrm{al}}(V_0, \dot{V}_0) + \mathcal{L}_{\mathrm{bh}}(V_0, \dot{V}_0)$$





Größe	Wert
Isotop	^{87}Rb
Fallenabstand	1.7 µm
Fallengröße	0.7 µm
Fallentiefe ($t = 0$)	1 k_B mK
Fallentiefe ($t = \tau$)	158 k_B nK

Constant adiabaticity

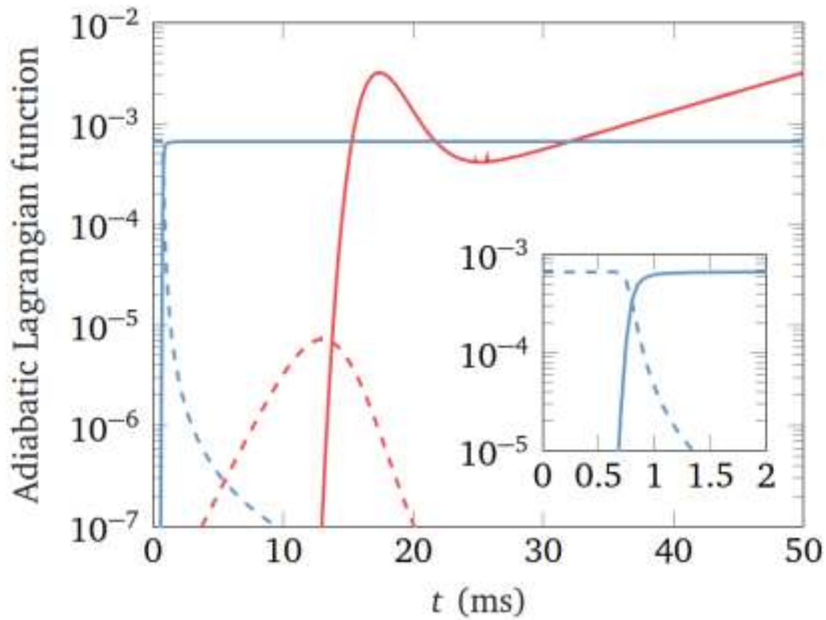
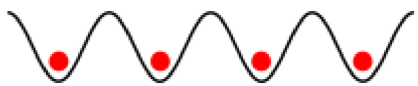


Figure 6.5: The adiabatic Lagrangian functions per site $\mathcal{L}_{\mathrm{al}}/M$ (dashed) and $\mathcal{L}_{\mathrm{bh}}/M$ (solid) are plotted versus time t for a bi-exponential (red) and an optimal adiabatic (blue) transfer sequence of duration $\tau = 50$ ms.

Fidelity and spontaneous light scattering

- Fidelity of time evolved state

$$i\hbar\partial_t|\psi(t)\rangle = \hat{H}_{\mathrm{bh}}(t)|\psi(t)\rangle$$

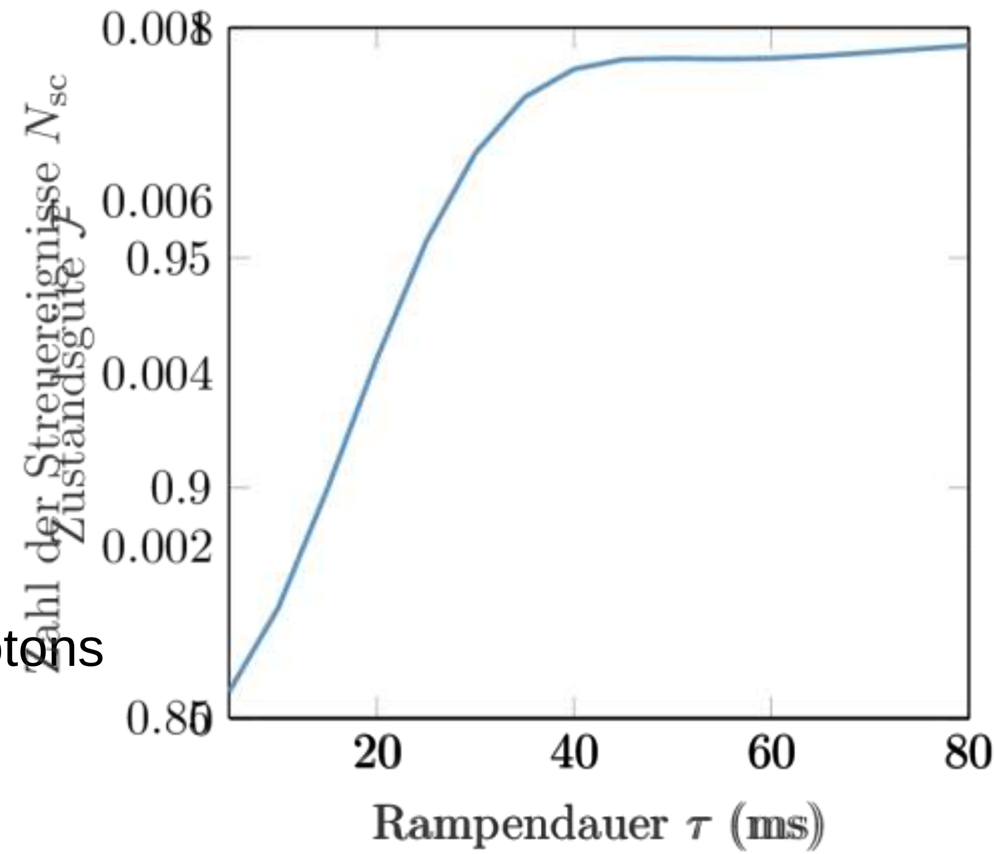
$|\psi(0)\rangle =$ 

$$\hat{H}_{\mathrm{bh}}(\tau)|g\rangle = E_g(\tau)|g\rangle$$

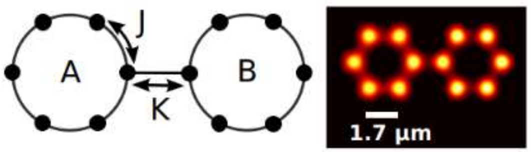
$$\mathcal{F} = |\langle g|\psi(\tau)\rangle|$$

- # sponateneous scattered photons

$$N_{\mathrm{sc}} = \int_0^{\tau} \Gamma_{\mathrm{sc}}(t)\,\mathrm{d}t$$



Coupled Josephson rings



- Extension of double well by rings
  cf. q-dots, artifical atoms

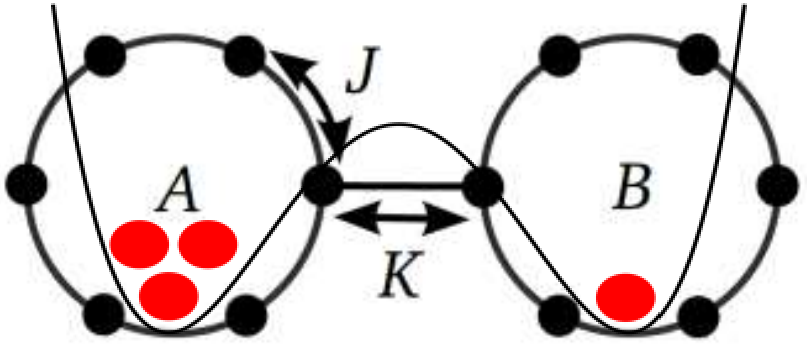
- Weak coupling between rings

$$K \ll J$$

- Tunnel dynamics after sudden turn on

$$N_A(0) = N \qquad N_B(0) = 0$$

$$\zeta(t) = \frac{N_A(t) - N_B(t)}{N}$$



$$\hat{H} = \hat{H}_A + \hat{H}_B + \hat{H}_{AB}$$

$$\hat{H}_A = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_{i=1}^{M} \hat{a}_i^\dagger \hat{a}_i^\dagger \hat{a}_i \hat{a}_i$$

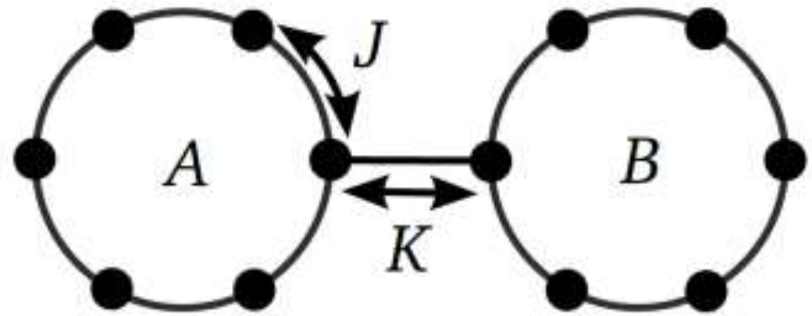
$$\hat{H}_B = -J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j + \frac{U}{2} \sum_{i=1}^{M} \hat{b}_i^\dagger \hat{b}_i^\dagger \hat{b}_i \hat{b}_i$$

$$\hat{H}_{AB} = -K(\hat{a}_1^\dagger \hat{b}_1 + \hat{b}_1^\dagger \hat{a}_1)$$

Two mode approximation

- Vortex-states quasi momentum k_l

  for K=0 & U=0



$$\hat{\alpha}_\ell = \sum_{m=1}^{M} \frac{e^{-ik_\ell m d}}{\sqrt{M}} \hat{a}_m \qquad k_\ell = \frac{2\pi\ell}{Md}$$

$$\hat{\beta}_\ell = \sum_{m=1}^{M} \frac{e^{-ik_\ell m d}}{\sqrt{M}} \hat{b}_m \qquad -\frac{M}{2} < \ell \leq \frac{M}{2}$$

- Projection to groundstate manifold

$$\hat{H}_0 = \hat{\mathcal{P}}\hat{H}\hat{\mathcal{P}} = -k(\hat{\alpha}_0^\dagger\hat{\beta}_0 + \hat{\beta}_0^\dagger\hat{\alpha}_0) + \frac{u}{2}(\hat{\alpha}_0^\dagger\hat{\alpha}_0^\dagger\hat{\alpha}_0\hat{\alpha}_0 + \hat{\beta}_0^\dagger\hat{\beta}_0^\dagger\hat{\beta}_0\hat{\beta}_0)$$

- Effective double-well for $J \gg U, K$

$$k = K/M \qquad u = U/M$$

2018_04_24_PhD_Sturm_eingereicht.pdf - Verknüpfung (2).lnk

Josephson-Oscillations: sudden turn on

- No selfinteration (U=0) $K(t)$

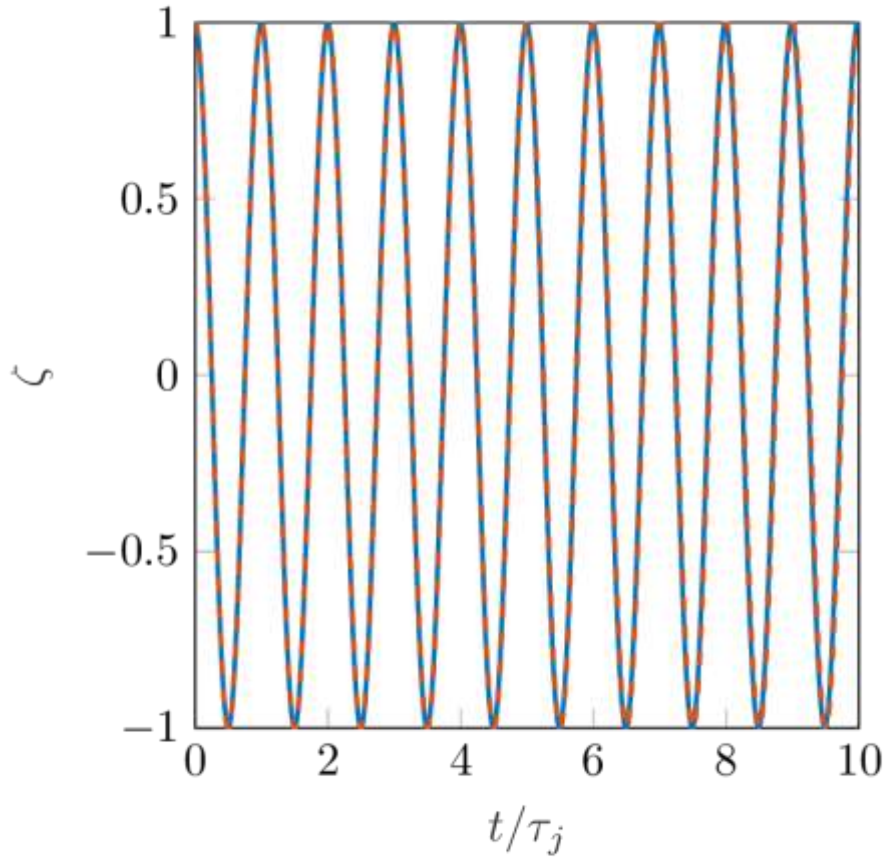
- Collective oscillations

$$\zeta(t) = \cos(2\pi t/\tau_j) \qquad \tau_j = \frac{h}{2k}$$

- Parameters

$$K = 0.1\,J \quad M = 6 \quad N = 4$$

- See JJ‘s in Supra conductors



Semifluxons in Superconductivity and Cold Atomic Gases”, R. Walser, E. Goldobin, O. Crasser, D. Koelle, R. Kleiner and W. P. Schleich, N. J. Phys. **10**, 45020 (2008)

Collapse and revival

- Weak selfinteraction (U<K)

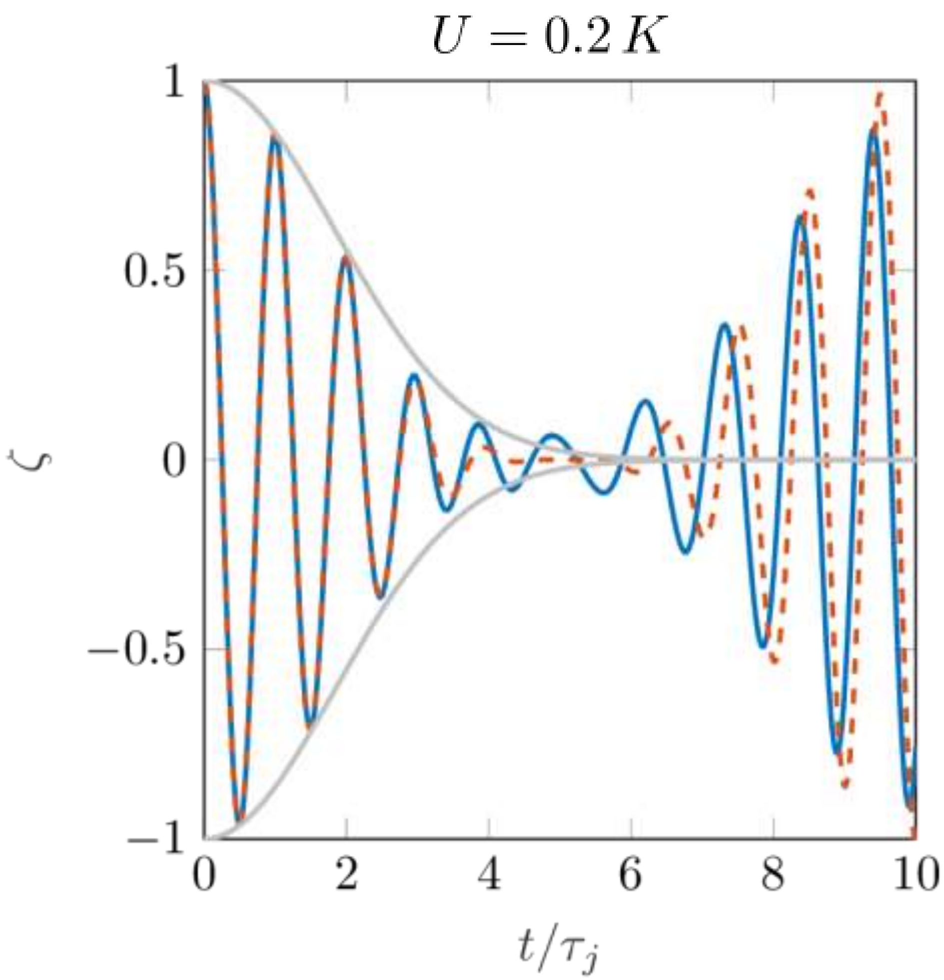
$$\zeta(t) = \cos(2\pi t/\tau_j)\cos(\pi t/\tau_r)^{N-1}$$
$$\approx \cos(2\pi t/\tau_j)e^{-t^2/\tau_c^2}$$

- Gaußscher Zerfall

$$\tau_c = \frac{h}{u}\sqrt{\frac{2}{\pi^2(N-1)}}$$

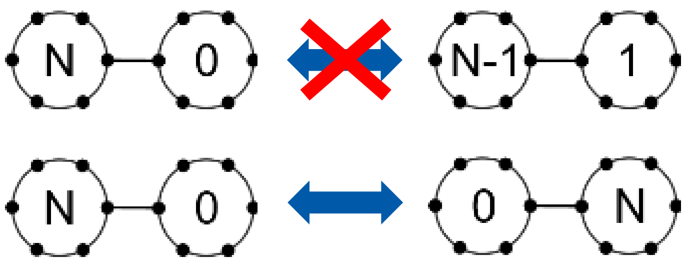
- Wiederkehr

$$\tau_r = \frac{h}{u}$$



Self-Trapping

- Strong selfinteration (U>K)



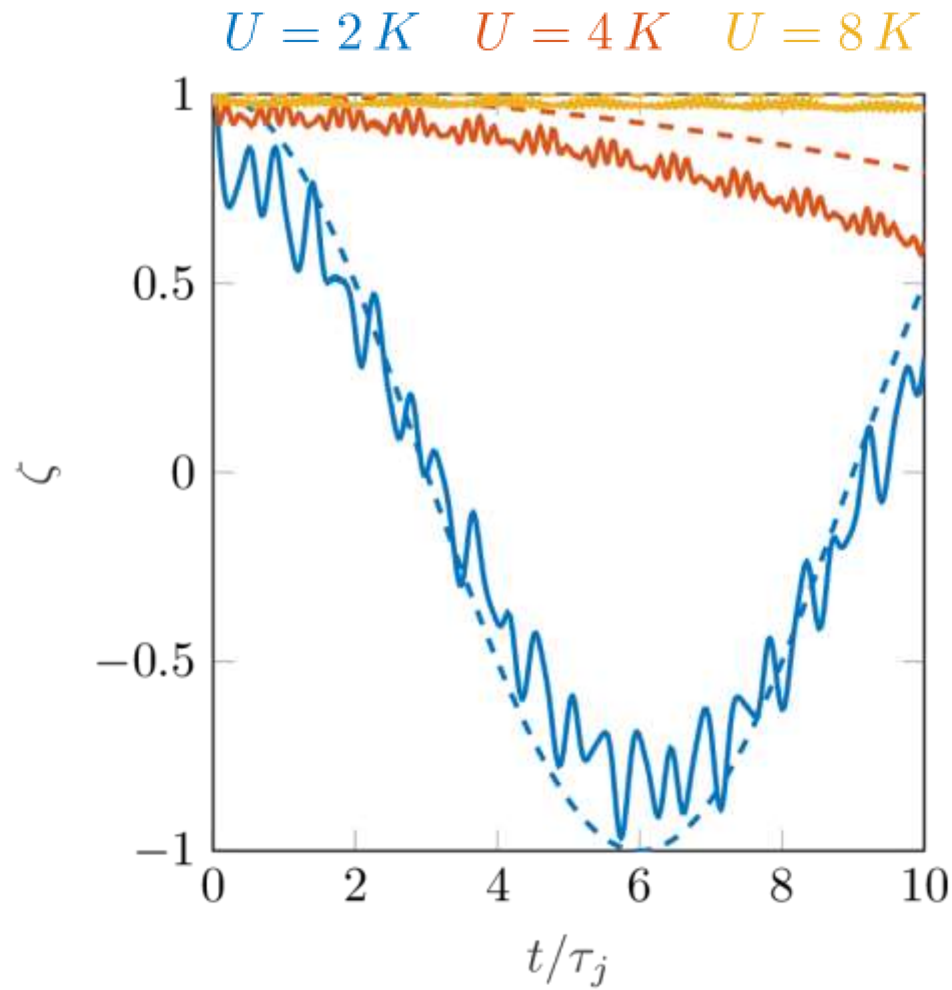
- Adiabatic elimination

  effective 2level system

$$\tau_{\text{eff}} = \frac{(N-1)!hu^{N-1}}{2Nk^{N}}$$

- „Self-Trapping“ experimentally

  realzable time scales

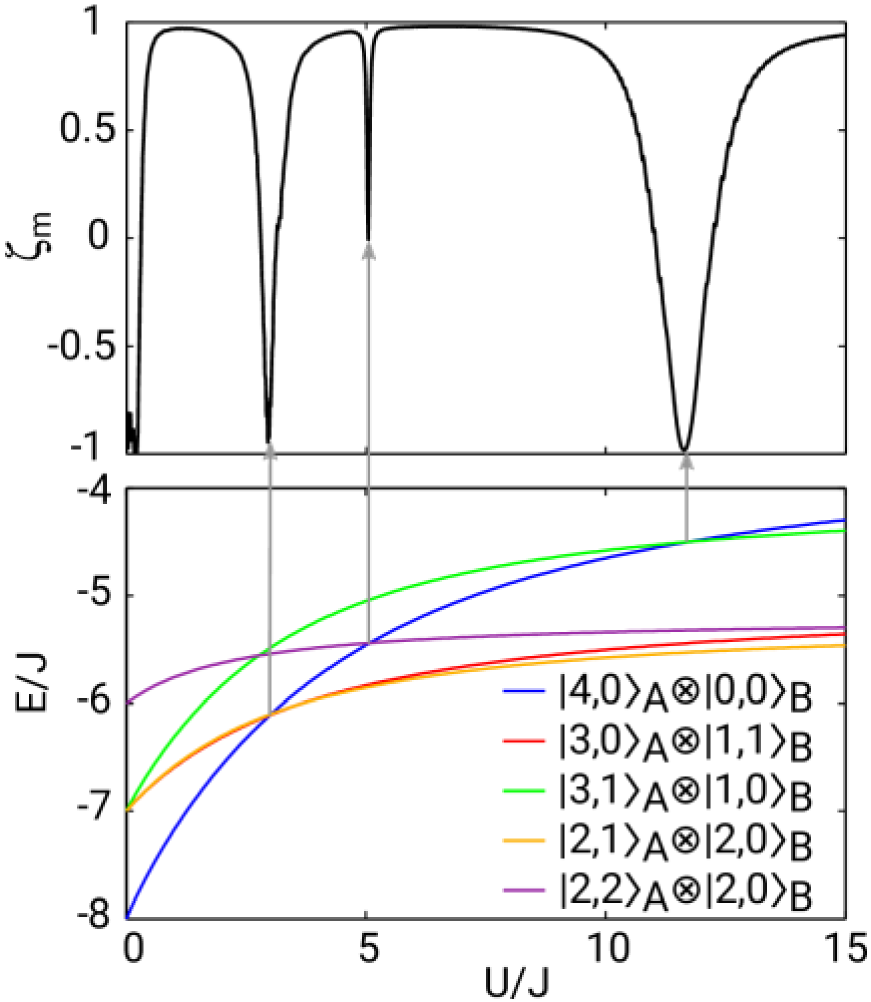


Many-body tunneling resonances

- Amplitude of population osciullations

$$\zeta_m = \min_{0 \leq t \leq 10\tau_j} \zeta(t)$$

- Tunneling resonances in self-trapping regime
- Coupling to higher k-states
- Spectroscopic information

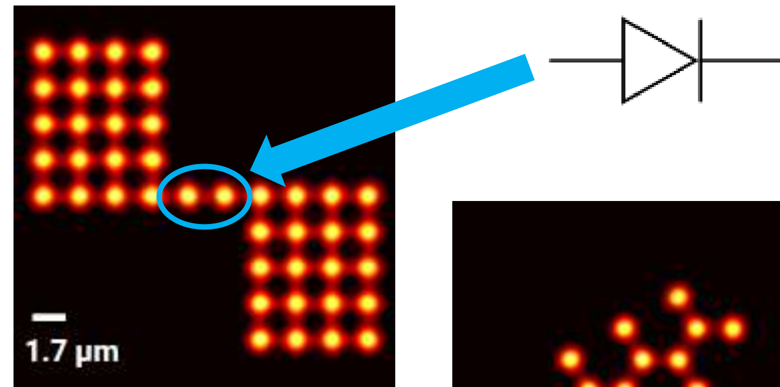


Weitere Anwendungen

- Atomtronics

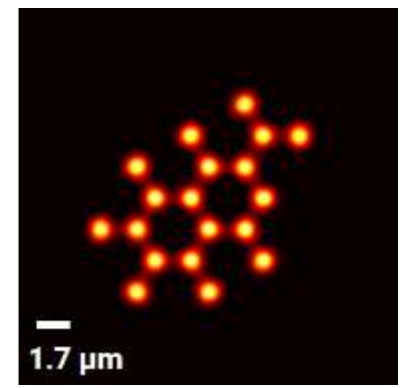
  Seaman et al., PRA **75**, 023615 (2007)

  Amico et al., NJP **19**, 020201 (2017)



- Moleküle

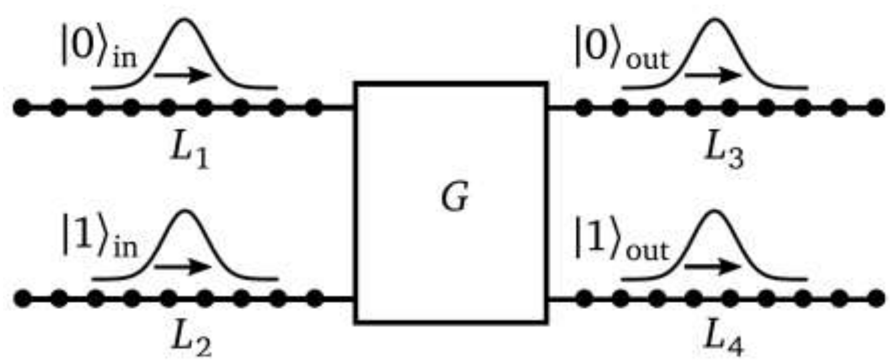
  Lühmann et al., PRX 5, 031016 (2015)



- Unordnung und Defekte

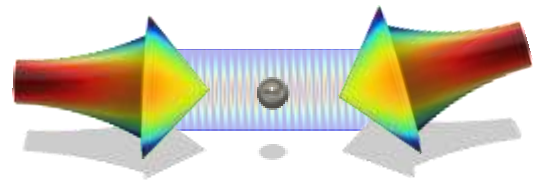
- Quantum-Walks

  Childs et al., Science **339**, 791 (2013)



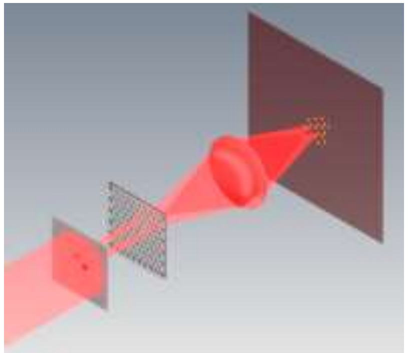
Summary

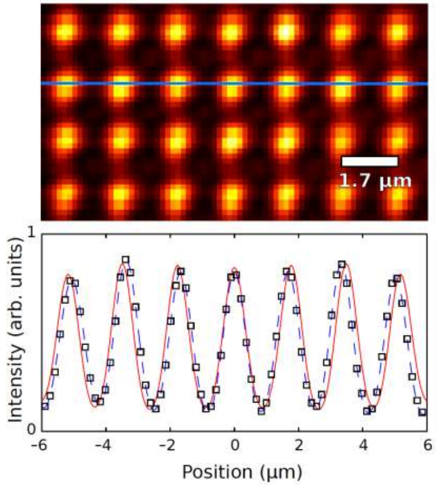
- Pulsed Bragg beam-splitters
- Alternative to optical lattices



Sturm et al., PRA **95**, 603625 (2017)

- Optical potential



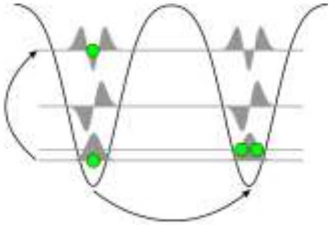


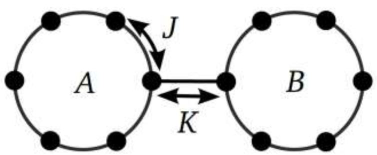
- Bose-Hubbard parameter
- Mott state preparation

M. R. Sturm, et al. , Phys. Rev. A 97, 063608 (2018)

- Application: rotation sensing

Josephson-rings





Thank you very much for the attention!

http://www.iap.tu-darmstadt.de/tqd/