Atom-Light Interaction and Basic Applications

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ICTP-SAIFR Winter School 2019

Atom optics

→ powerful trapping & cooling techniques

→ focus on external degrees of freedom (atomic motion)

→ Bose-Einstein condensation

→ emulation of other complex systems

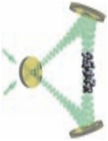
→ long-range effects

Overview

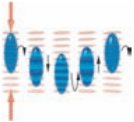
Introduction
long-range forces in atomic clouds

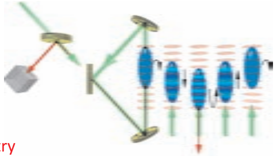
2. *CARL with Bose-condensate*
quantized motion

1. *Collectice Atomic Recoil Laser*
self-synchronization, Kuramoto



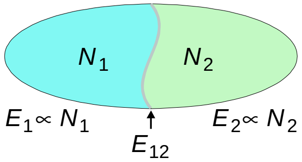
3. *Bloch oscillation*
matter wave interferometry





Conclusion
in-vivo gravimetry

Long-range interactions



Short range $\rightarrow$ additivity: $E = E_1 + E_2 \gg E_{12} \propto N^{1/3}$

Long range $\rightarrow$ non-additivity: $E \neq E_1 + E_2$

since $E_{12} \propto N^{2-\alpha/3}$ for a two-body interaction potential $V(r) \propto r^{-\alpha}$

Particularities: non-equilibrium metastable states, non-ergodicity,

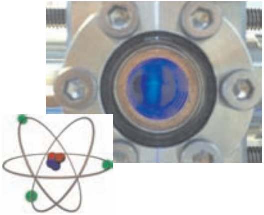
inhomogeneities at all scales

negative heat capacity, non-equivalence of ensembles

Model systems for long-range interactions

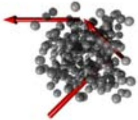
astrophysics → inaccessible, not tunable

hydrodynamics, solid state physics → too complicated



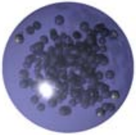
want simple, clean, tunable systems → atom optics

Advantages of ultracold atomic gases



cold atomic clouds are **micro- and macro**scopic, $N > 10^5$ e $T < 100$ nK

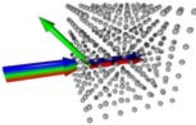
n_r



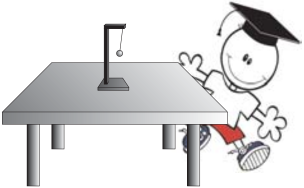
perfect isolation & control over **all** degrees of freedom

$\rightarrow$ quantum nature emerges

Bose-Einstein condensates, optical lattices (crystalline structures with cold atoms)



'table top' experiment $\rightarrow$ can be operated by a *single* medium-sized PhD student



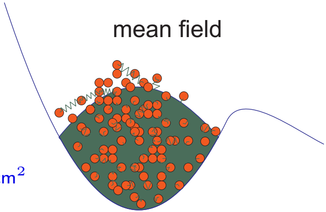
The atom optical toolbox

atoms (or ions) in dilute cloud of $N = 1...10^{10}$ atoms

trapping potentials compressing to $n = 10^{9}...10^{14}$ cm^{-3}

cooling mechanisms down to $T = 10\ \mu$K...1 nK

control of interaction force in real time $\sigma_{collision} \simeq 0...10^{-9}$ cm^{2}



		trapping	cooling	Feshbach resonances
		$\downarrow$	$\downarrow$	$\downarrow$
E	$=$	E_{pot}	$+ E_{kin}$	$+ E_{self}$

[Courteille, Freeland, Heinzen, van Abeelen, Verhaar, PRL **81**, 69 (1998)]

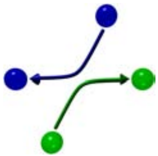
[Inouye, Ketterle *et al.*, Nature **392**, 151 (1998)]

Collisions between ground state atoms (exchange of virtual photons)

Long range forces

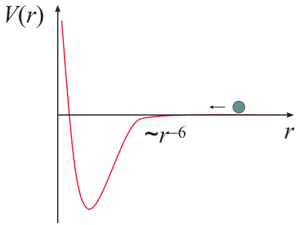
ions repelled by Coulomb forces $\longrightarrow V(r) \propto r^{-1}$

atoms with dipole-dipole interactions $\longrightarrow V(r) \propto r^{-3}$



Short range forces

neutral atoms via van der Waals $\longrightarrow V(r) \propto r^{-6}$

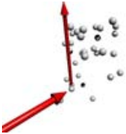


Interaction between excited atoms (exchange of real photons)

Light injected $\longrightarrow$ *interaction between excited dipoles*

super- & subradiance, diffraction, refraction, ...

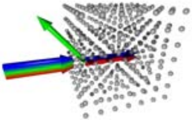
Rayleigh & Bragg scattering, ...



Multiple scattering

Mie resonances, Anderson localization in disordered clouds

forbidden photonic bands in optical lattices, ...



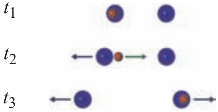
Excitation exchange between atoms

recoil of backscattered photons accelerates atoms

in 1D uniform global coupling is possible $\longrightarrow$ $F(r) \propto r^0$

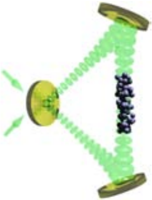
correlations between subsequent scattering events

$\longrightarrow$ instabilities $\longrightarrow$ quantum sensing



1. The Collective Atomic Recoil Laser

Atoms interacting with ring cavities

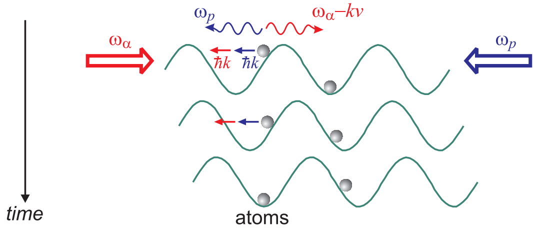


Opto-mechanical coupling

atoms in a (red-detuned) standing light waves

dipolar force via coherent photon redistribution

standing wave is shifted as well $\longrightarrow$ correlated atomic motion



detection requires 1. collective atomic behavior

2. self-determined dynamics of the standing wave

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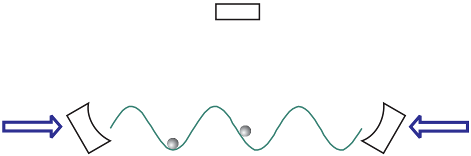
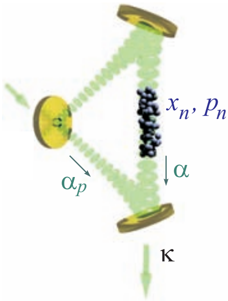


detection requires 1. collective atomic behavior

2. self-determined dynamics of the standing wave

$\longrightarrow$ *use ring cavity with ultrahigh finesse*

Ring cavities & Collectice Atomic Recoil Laser



two cavity modes with independent photon budgets $|\alpha_p|^2$ e $|\alpha|^2$

standing light wave by backscattering $\longrightarrow$ **freedom of phase**

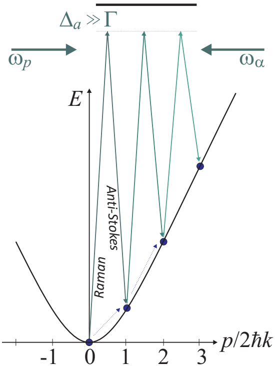
coupling strength between modes: $U_0 = \frac{g^2}{\Delta_a}$

rate equation for the modes

$$\dot{\alpha} = -\kappa\alpha + iU_0\alpha_p \sum_m e^{2ikx_m}$$

dipolar force on atoms

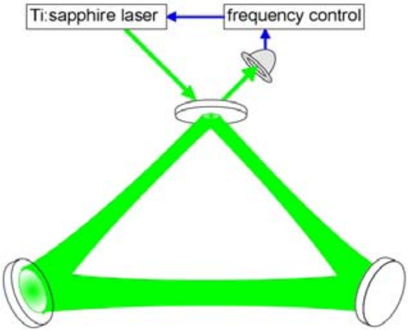
$$m\ddot{x}_n = -2i\hbar k U_0(\alpha_p \alpha^* e^{ikx_n} - \alpha_p^* \alpha e^{-ikx_n})$$



[Bonifacio *et al.*, PRA **50**, 1716 (1994)]

[Gangl and Ritsch, PRA **61**, 43405 (2000)]

Experimental sequence



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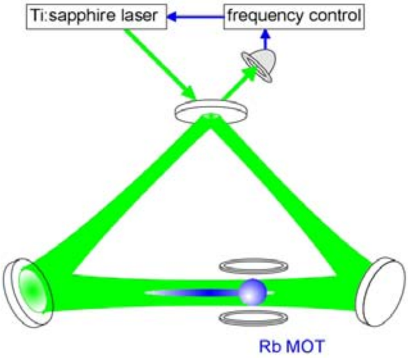

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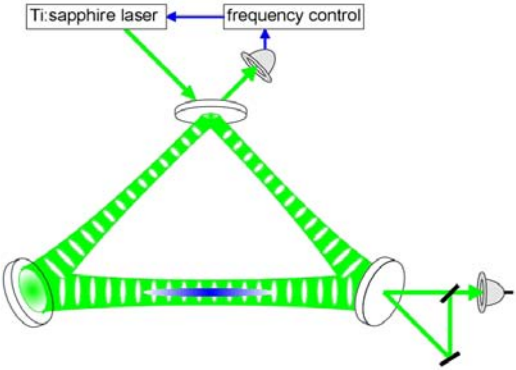

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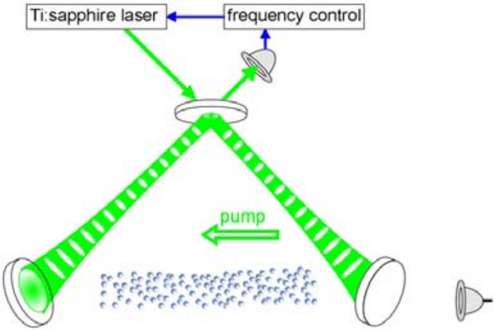

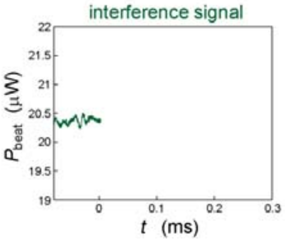

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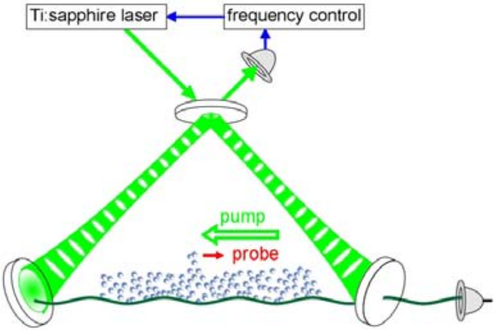

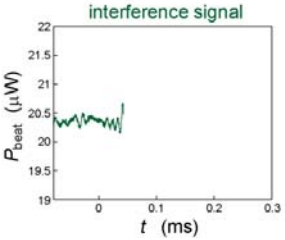

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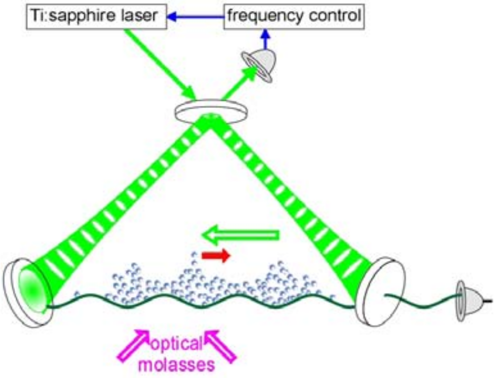

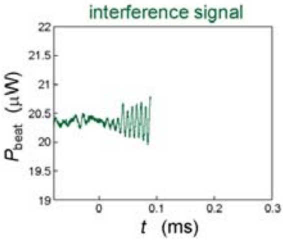

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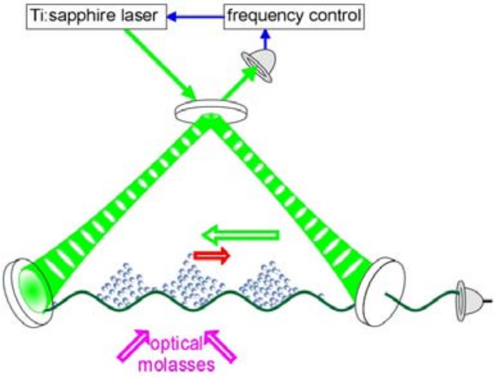

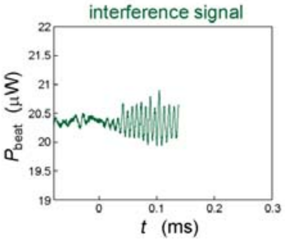

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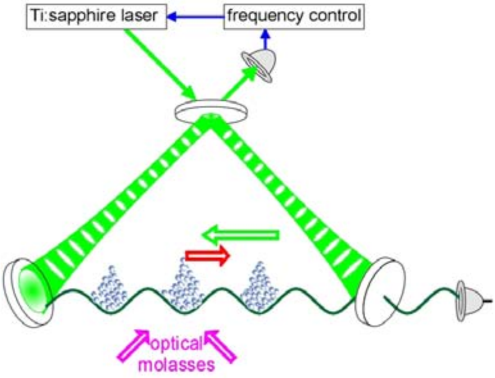

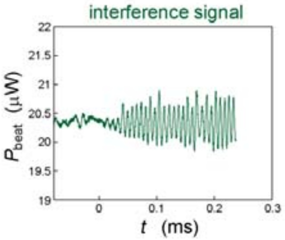

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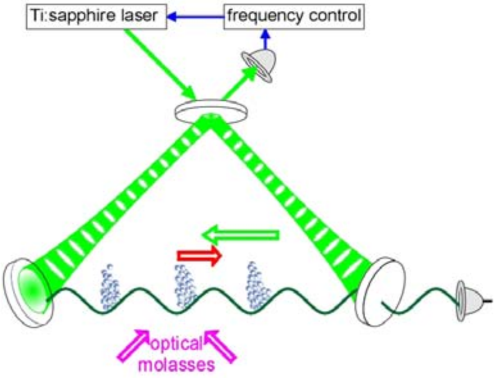

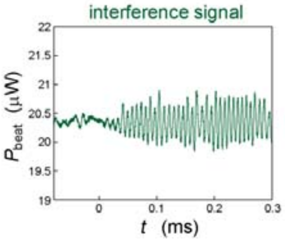

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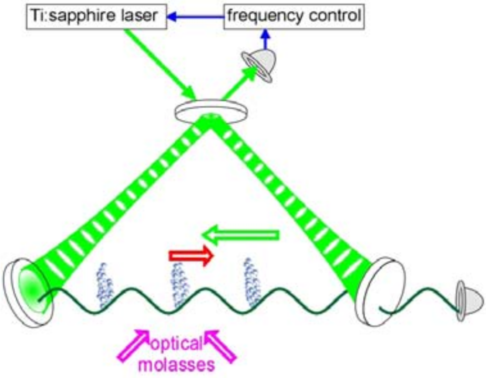

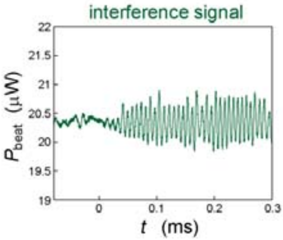

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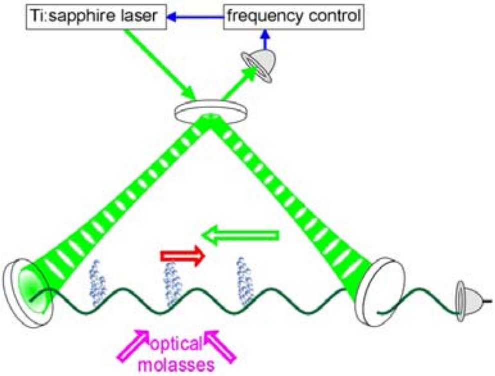

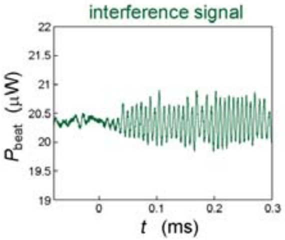

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[Bonifacio, De Salvo, Narducci, D'Angelo, PRA **50**, 1716 (1994)]

Experimental sequence

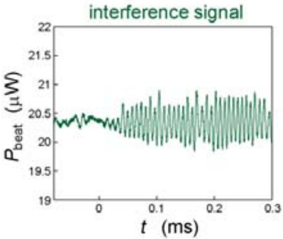
$Finesse = 80000$

$P = 10$ W

$N = 10^7$

$\Delta_a = -1 \ldots -10$ THz

$T = 50 \ldots 500$ μK



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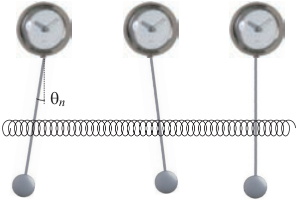
Atoms surfing on a self-generated light wave

Atomic motion acts collectively on light wave

→ laser emission by coherent backscattering → CARL

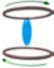
→ spontaneous synchronization of atomic ensemble

→ analogy with Huygens pendulum clocks



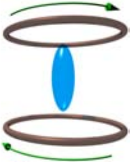
[Robb, N. Piovella, Ferraro, Bonifacio, Courteille, Zimmermann, PRA **69**, 41403(R) (2004)]

[von Cube, Slama, Kruse, Zimmermann, Courteille, Robb, Piovella, Bonifacio, PRL **93**, 83610 (2004)]

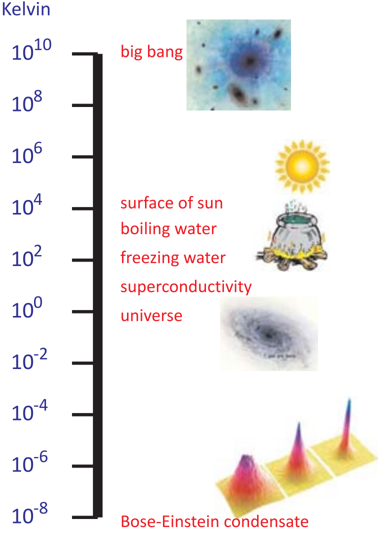


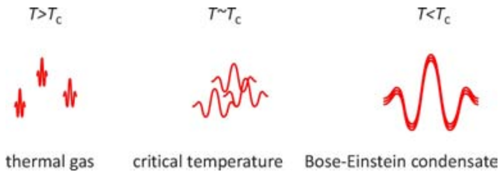
2. In vivo monitoring of Bose condensates

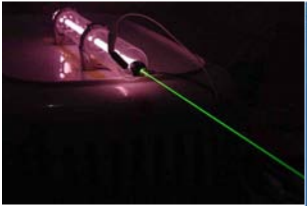
in cavities

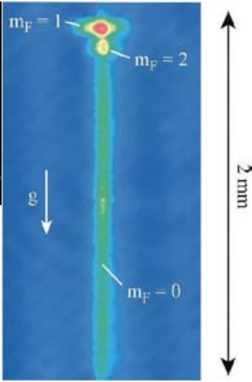


Bose-Einstein condensates





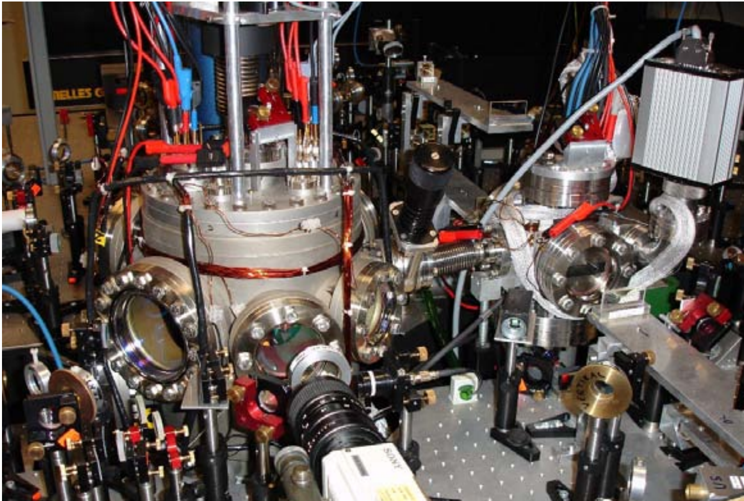




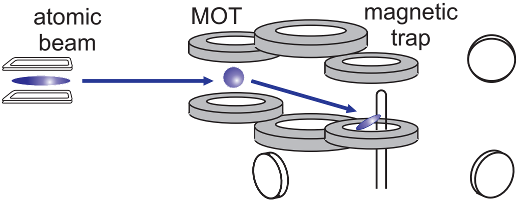
First condensate in a cavity

$\mathcal{F} = 135000$ $L = 8$ cm

$N = 10^5$ $T = 50..500$ nK

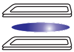


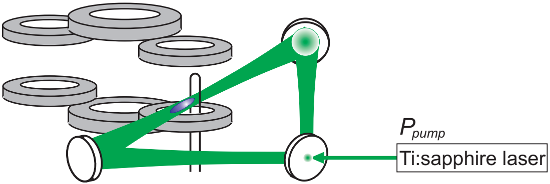
Experimental procedure



[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

Experimental procedure





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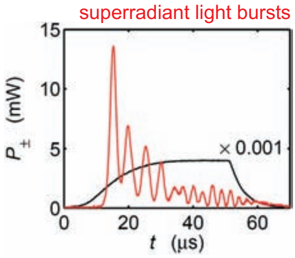

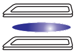

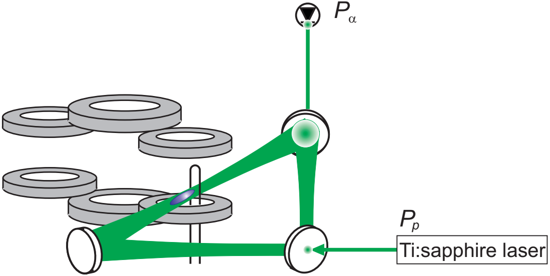

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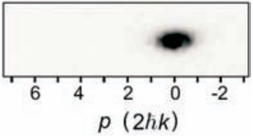
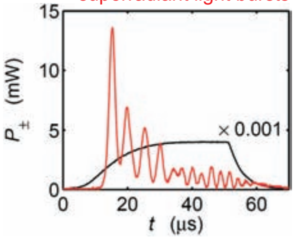
Experimental procedure

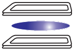
momentum distribution before pumping

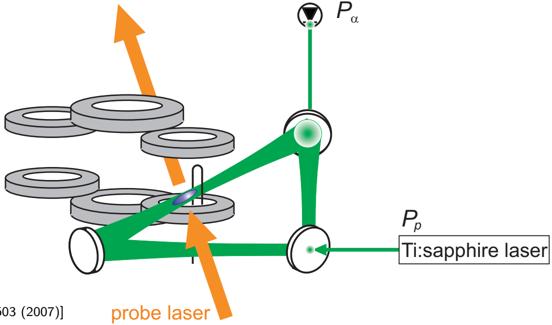
$t = 0\ \mu s$



superradiant light bursts

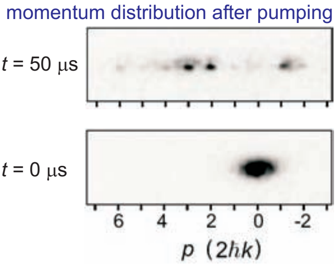


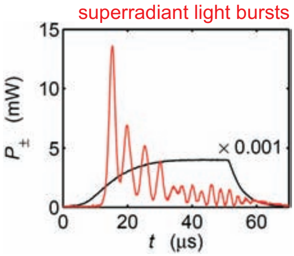


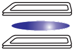


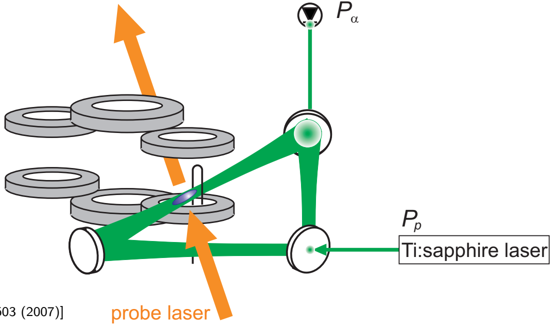
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

Experimental procedure





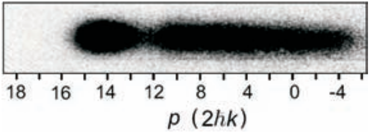




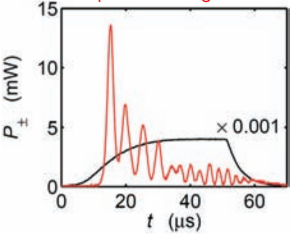
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

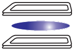
Experimental procedure

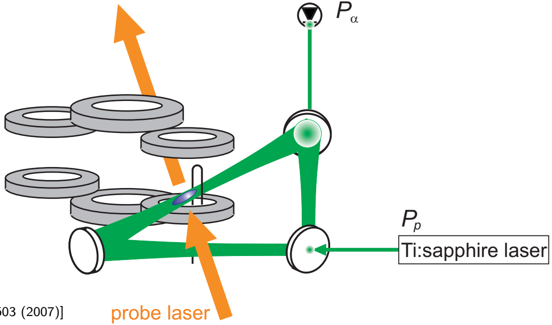
momentum distribution with hot atoms



superradiant light bursts







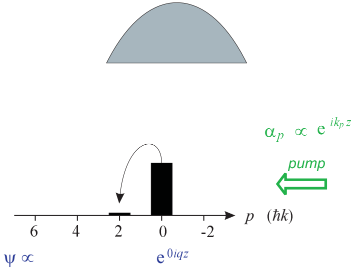
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

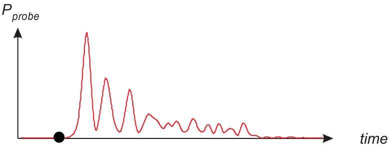
Macroscopic instability

homogeneous cloud

↓

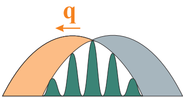
density fluctuation





[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

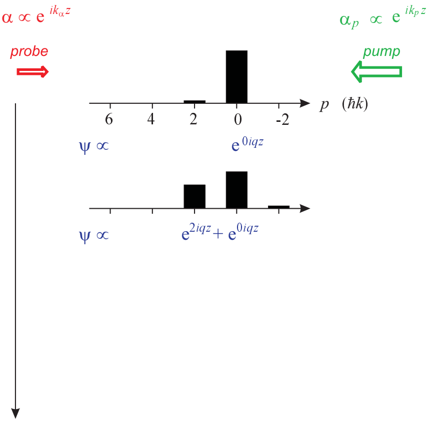
Macroscopic instability

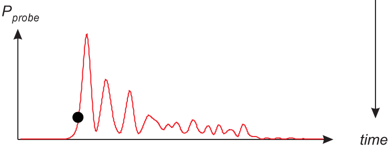


homogeneous cloud

↓

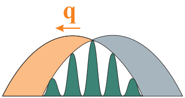
density fluctuation

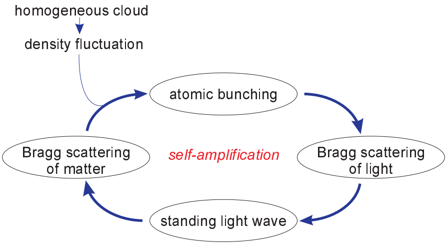


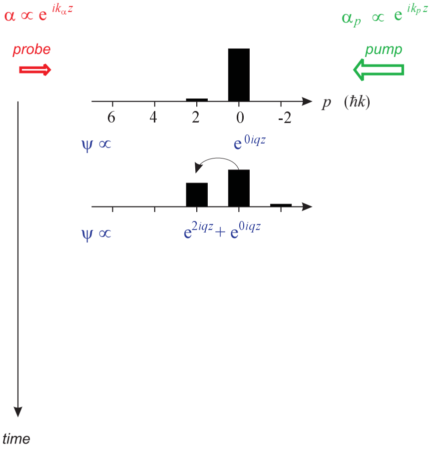


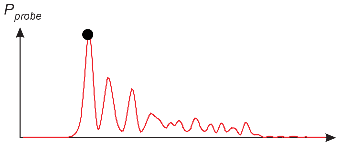
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

Macroscopic instability



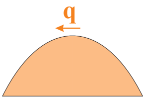


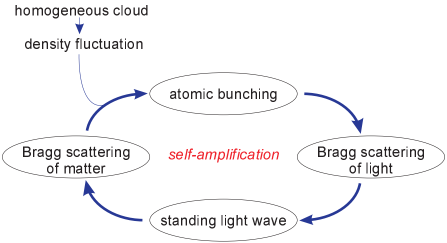


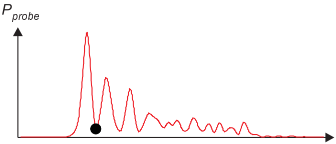


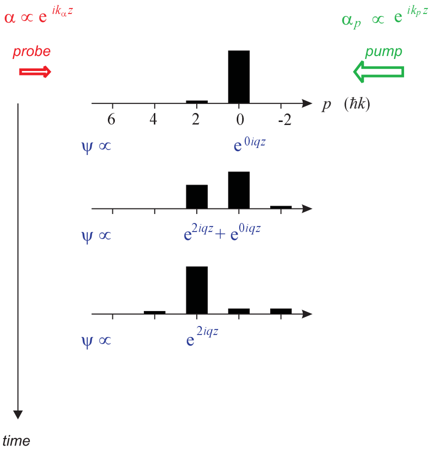
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

Macroscopic instability



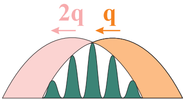


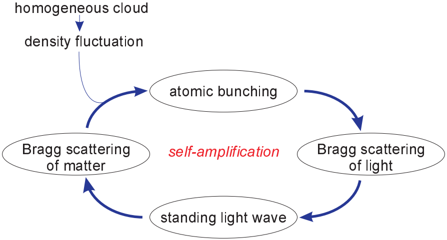


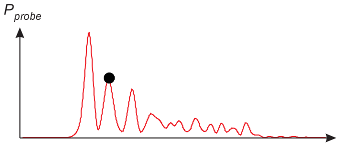


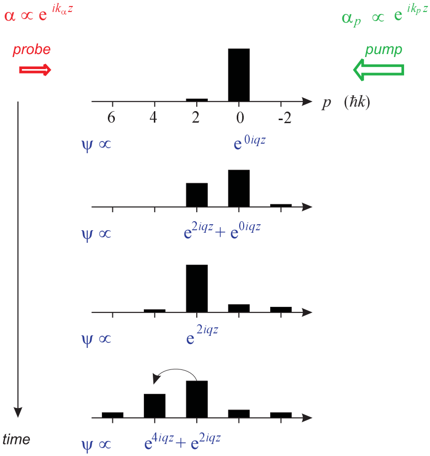
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

Macroscopic instability









[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]

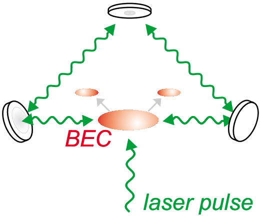
Cavity-assisted matterwave superradiance

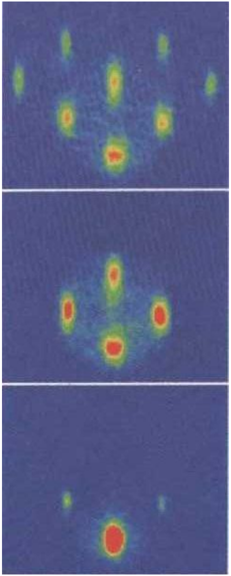
Superradiant Rayleigh scattering

- exponential gain for matter waves and optical modes
- connexion to CARL!

Condensates in cavities

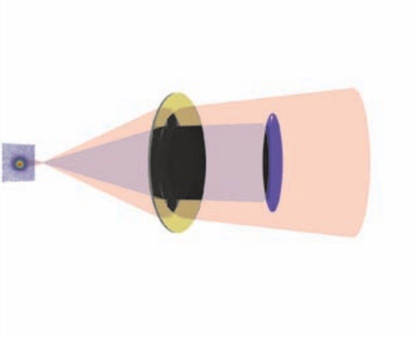
- quantized acceleration
- matterwave superradiance stimulated by the cavity





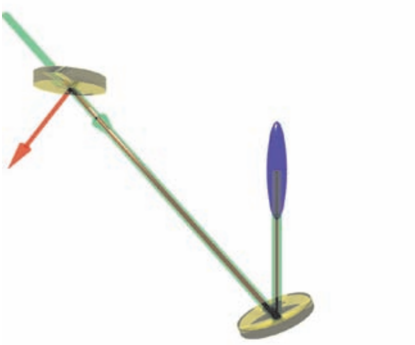
[Inouye, Chikkatur, Stamper-Kurn, Stenger, Pritchard, Ketterle, Science **285**, 571 (1999)]
[Bux, Gnahm, Maier, Zimmermann, Courteille, PRL **106**, 203601 (2011)]

3 methods of measuring matter wave trajectories



(1) take photos of the position of the matter wave

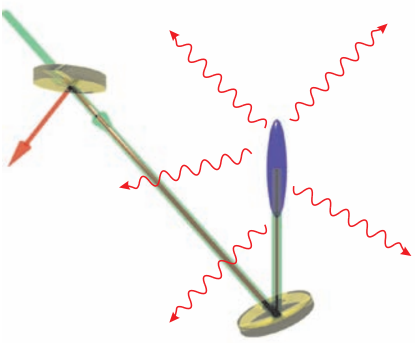
3 methods of measuring matter wave trajectories



(1) take photos of the position of the matter wave

(2) measure velocity of matter wave via Doppler shift (RIR)

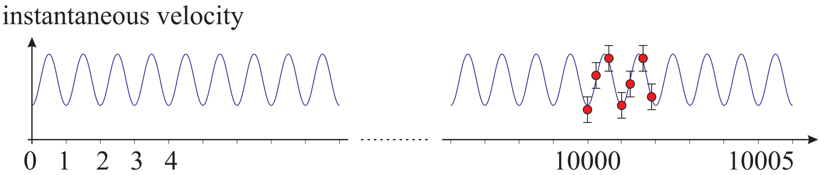
3 methods of measuring matter wave trajectories



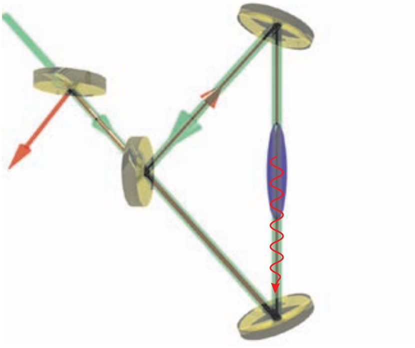
(1) take photos of the position of the matter wave

(2) measure velocity of matter wave via Doppler shift (RIR)

(3) use cavity to control backscattering (CARL)



3 methods of measuring matter wave trajectories

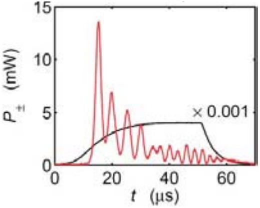


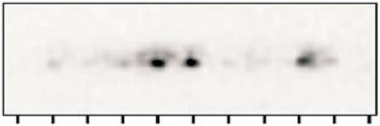
(1) take photos of the position of the matter wave

(2) measure velocity of matter wave via Doppler shift (RIR)

(3) use cavity to control backscattering (CARL)

in vivo monitoring of backscattered light ⟶ simulations ⟶ reconstructed trajectories

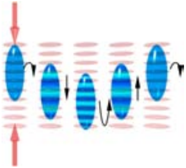




[Kruse, von Cube, Zimmermann, Courteille, PRL **91**, 183601 (2003)]
[Slama, von Cube, Deh, Ludewig, Zimmermann, Courteille, PRL 94, 193901 (2005)]
[Slama, Bux, Krenz, Zimmermann, Courteille, PRL **98**, 053603 (2007)]
[Bux, Gnahm, Maier, Zimmermann, Courteille, PRL **106**, 203601 (2011)]

3. Matter wave Bloch oscillations

for inercial sensing

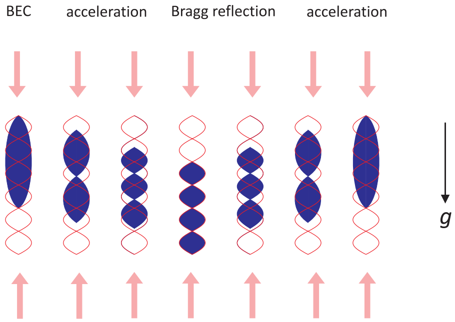


Gravimetry with Bose-Einstein condensates

matter wave Bloch oscillations in a periodic potential

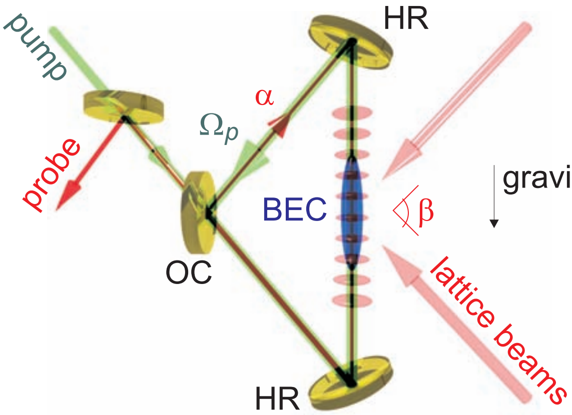
- frequency $\nu_b = \frac{mg}{2\hbar k}$

$\longrightarrow$ measure gravity g



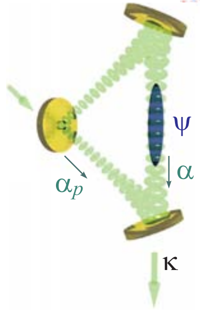
[Ben Dahan, Peik, Castin, Salomon, PRL **76**, 4508, (1996)]
[Samoylova, Piovella, Hunter, Robb, Bachelard, Courteille, Las.Phys.Lett. **11**, 126005 (2014)]

Bloch oscillations in a cavity



[Courteille, Bachelard, Patent pending, INPI, BR 10 2015 007944-3 (2015) Dispositivo e método para medida da aceleração gravitacional]
[Samoylova, Piovella, Robb, Bachelard, Courteille, Opt.Exp. **23**, 14823 (2015)]
[Samoylova, Piovella, Hunter, Robb, Bachelard, Courteille, Las.Phys.Lett. **11**, 126005 (2014)]

Model: Quantum CARL



Heisenberg equation for matter waves (2nd quantization)

$$i\hbar\frac{\partial\hat{\psi}}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\hat{\psi}}{\partial x^2} - i\hbar U_0(\alpha_p^*\alpha e^{2ik_0x} - \alpha_p\alpha^* e^{-2i\hbar k_0 x})\hat{\psi}$$

Heisenberg equation for (classical) optical fields

$$\frac{d\alpha}{dt} = -\kappa\alpha + 2k_0U_0\alpha_p^*\int N|\hat{\psi}|^2 e^{-2ik_0x}dx$$

expansion into momentum states with $|c_n(t)|^2$ momentum state populations

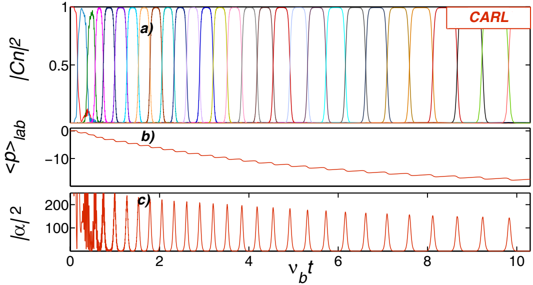
$$\hat{\psi}(x,t) = \sum_n c_n(t)e^{2ink_0x}$$

$N = 8\cdot 10^4$

$\kappa = 160\omega_r$

$U_0 = 0.04\omega_r$

$\delta = 0$



Model: Bloch band spectrum

Schrödinger equation for a particle at rest in a standing light wave (periodic 1D potential)

after adiabatic elimination of internal states

$$\hat{H}\hat{\psi} = -\frac{\hbar^2}{2m}\frac{\partial^2\hat{\psi}}{\partial x^2} + \frac{\hbar W_0}{2}\sin(2k_l x)\hat{\psi}$$

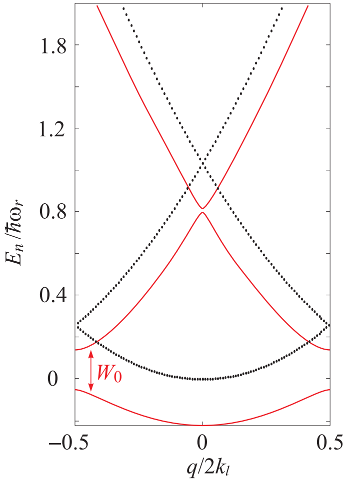
expand into Bloch waves

$$\hat{\psi}(x) = \sum_{n=-\infty}^{\infty} c_n e^{2inqx} \qquad \text{with } n \in \mathbb{N}$$

stationary solution yields band spectrum

$$E_n c_n = \frac{2n^2\hbar^2 q^2}{m} c_n + \frac{\hbar W_0}{4i}(c_{n-1} - c_{n+1})$$

confine q to 1. Brillouin zone & calculate eigenenergy spectrum



Model: Dynamics

moving particle in standing light wave

$$i\hbar\frac{\partial\hat{\psi}}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\hat{\psi}}{\partial x^2} + \frac{\hbar W_0}{2}\sin(2k_l x)\hat{\psi} \; - mgx\hat{\psi}$$

external force

expand into plane (Bloch) waves (de Bloch) with $|c_n(t)|^2$ momentum states populations

$$\hat{\psi}(x,t) = \sum_{n=-\infty}^{\infty} c_n(t) e^{2ink_l x} \cdot e^{imgxt/\hbar}$$

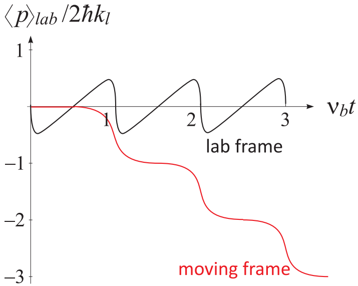
transform into moving frame

time-dependent solution with $\nu_b = \frac{g}{\omega_r}$ and $\omega_r = \frac{\hbar k_l^2}{2m}$

$$\frac{dc_n}{dt} = -4i\omega_r(n + \nu_b t)^2 c_n + \frac{W_0}{2}(c_{n+1} - c_{n-1})$$

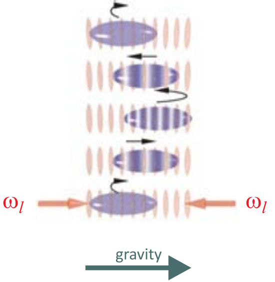
center-of-mass momentum

$$\langle p\rangle_{lab} = \sum_n n|c_n(t)|^2 + \nu_b t$$



[Samoylova, Piovella, Hunter, Robb, Bachelard, Courteille, Las.Phys.Lett. **11**, 126005 (2014)]
[Samoylova, Piovella, Robb, Bachelard, Courteille, Opt.Exp. **23**, 14823 (2015)]

2 pictures of Bloch oscillations

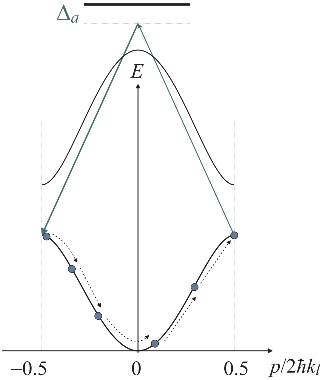


a. Bragg reflection of matter waves by a standing light wave

when $\lambda_{dB} = \frac{h}{p} \stackrel{!}{=} \frac{2\pi}{k_l} = \lambda_l$

$\Longleftrightarrow$ $p = \hbar k_l$ recoil of 1 photon

$\Longleftrightarrow$ edge of Brillouin zone



b. Light-matter interaction needs an atomic transition

$\Longrightarrow$ Raman transition between counterprop. momentum states

with photonic recoil $2\hbar k_l$

Bloch oscillations in a cavity

optical lattice + gravity + ring cavity (CARL) $\longrightarrow$ hybrid CARL-Bloch equations

$$i\hbar\frac{\partial\hat\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\hat\psi}{\partial x^2} + \frac{\hbar W_0}{2}\sin(2k_0x)\hat\psi - mgx\hat\psi - i\hbar U_0(\alpha e^{2ik_0x} - \alpha^* e^{-2i\hbar k_0x})\hat\psi$$

$$\frac{d\alpha}{dt} = -\kappa\alpha + 2k_0NU_0\int|\hat\psi|^2e^{-2ik_0x}dx$$

same numerical treatment $\longrightarrow$ continuous monitoring of Bloch oscillations via $|\alpha|^2$

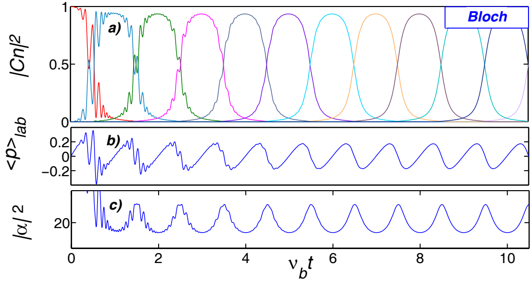
in some regimes $\longrightarrow$ we observe self-estabilization of Bloch oscillations

$N = 8\cdot 10^4$

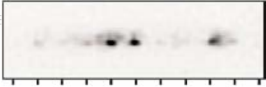
$\kappa = 160\omega_r$

$U_0 = 0.04\omega_r$

$W_0 = 80U_0$



Bloch or CARL ?



depends on relative force of CARL and Bloch

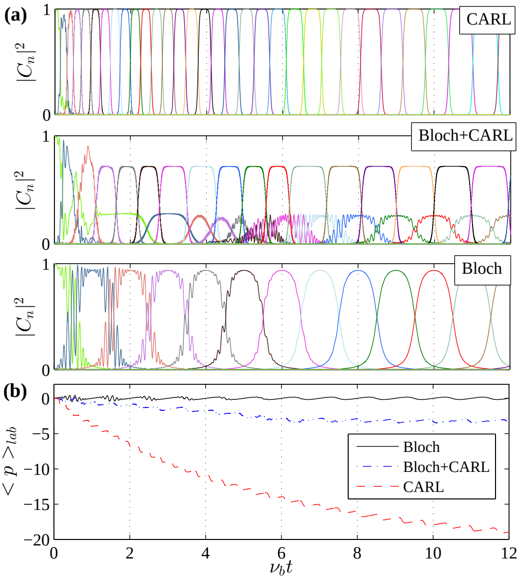
strong CARL

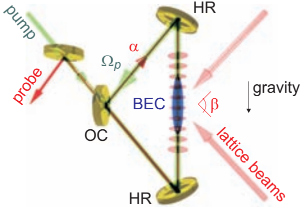
$\longrightarrow$ unlimited acceleration

weak CARL

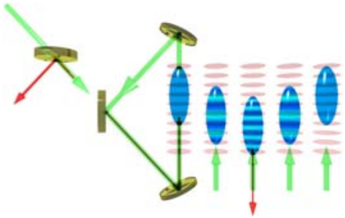
$\longrightarrow$ Bloch oscillations get robust to noise,

$\longrightarrow$ collisions, ...





Sr2 objectives

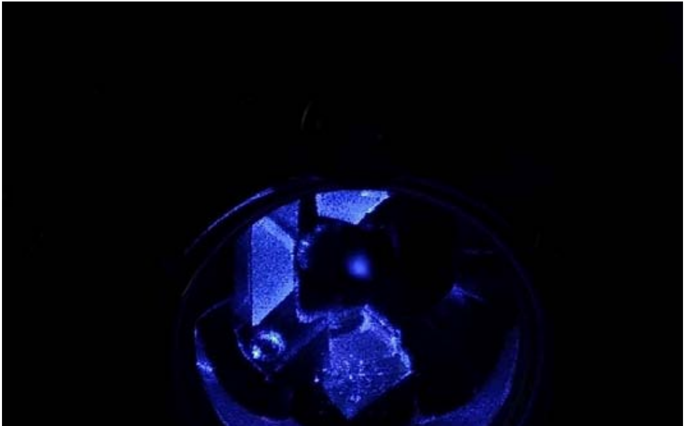


quantum synchronization of matter waves

in vivo monitoring of Bloch oscillations

quantum electrodynamics in macroscopic cavities

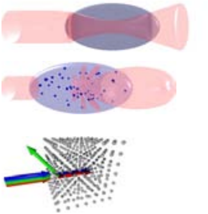
quantum sensing, metrology & gravimetry



Take-away messages

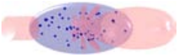
Atomic distribuition matters

forward, specular or Bragg scattering

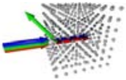


Take-away messages

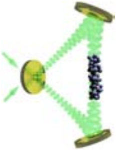
Atomic distribuition matters



forward, specular or Bragg scattering



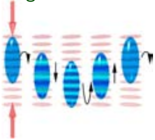
Atomic motion matters



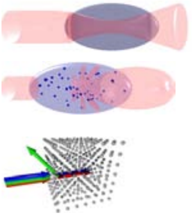
correlation between scattering events

coherence stored in spatial degrees of freedom

self-organization $\longrightarrow$ matter wave superradiance & Collective Atomic Recoil Lasing



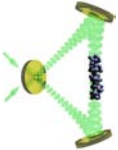
Take-away messages



Atomic distribuition matters

forward, specular or Bragg scattering

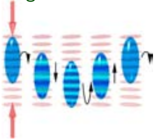
Atomic motion matters



correlation between scattering events

coherence stored in spatial degrees of freedom

self-organization $\longrightarrow$ matter wave superradiance & Collective Atomic Recoil Lasing



Structure of vacuum matters

density of states available to scattered photons

impact of cavities on the scattering process