Engineering light-matter interaction for optical manipulation of atoms and dielectric microparticles

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Lights of Tuscany 2022

Outline

Introduction

1. Controlling atomic motion

    Laser cooling and trapping

    Optical lattices (OL)

    Dynamical control of tunneling in OL

2. Controlling the motion of dielectric spheres (few hundreds of nm- few micron)

    Flying particles inside photonic crystal fibers

Conclusions and outlook

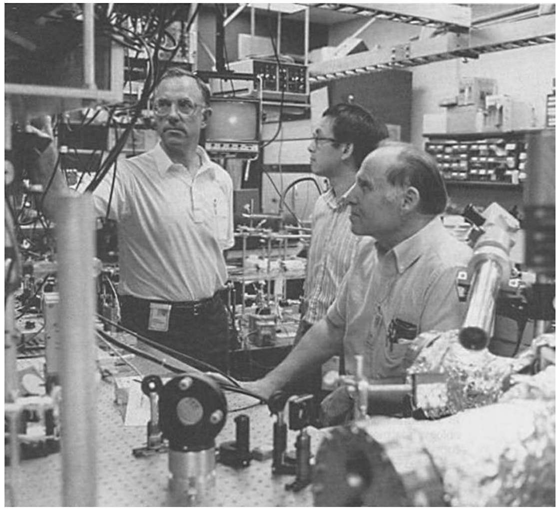
Introduction

Radiation pressure of sunlight

The tails of comets always point away from the sun.

Kepler: 17th century
Chinese astronomers: 7th century

The dawn of laser optical trapping

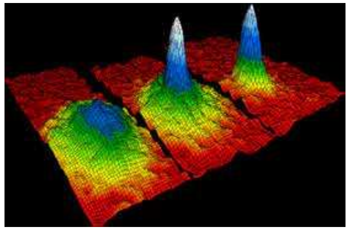


In 1970 Arthur Ashkin published the first observation that radiation pressure from lasers can “trap” transparent dielectric spheres. In the same paper, Arthur discussed how optical trapping could also be applied to atoms and molecules.

From right to left: Arthur Ashkin, Steven Chu, and John Bjorkholm in 1986, around the time of the first demonstration of atom trapping.

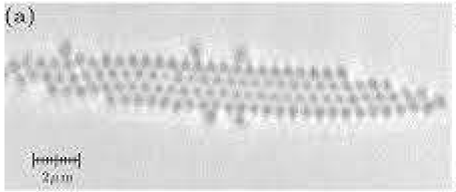
Optical manipulation

Optical manipulation (OM),
such as optical cooling, trapping

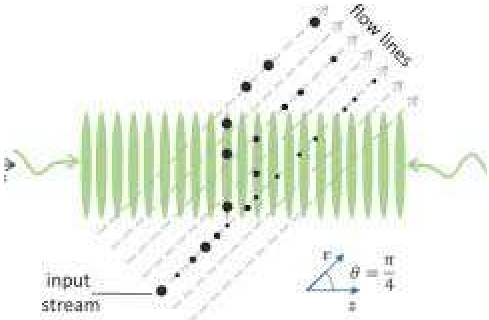


2001
all-optical
BEC

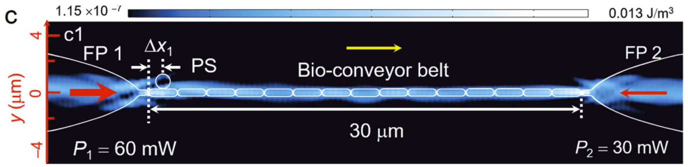
binding



sorting

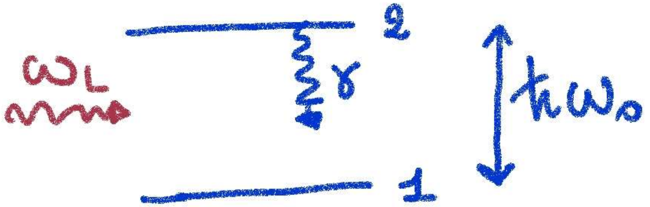


and transporting



by utilizing optical forces, has experienced intensive development in the past 40 years. OM is currently one of the most important tools in many scientific areas, including optics, atomic physics, biological science and chemistry.

Radiation pressure



$\hbar\omega$ energy

$\hbar\vec{K}_L$ momentum $K_L = \frac{\omega_L}{c}$

absorption + spontaneous emission (isotropous) rate γ

$\Downarrow$

mean velocity change of the atom is due to absorption only

$$\delta v = v_{rec} = \frac{\hbar K_L}{M}$$

Radiation pressure force

Dissipative force

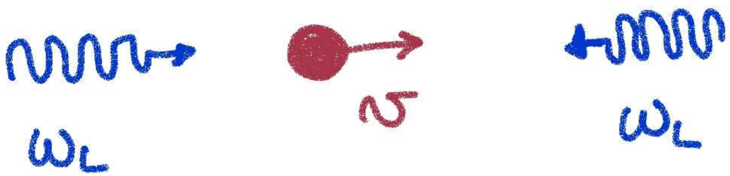
$$\mathcal{F}_{diss} \approx M \frac{\delta v}{\delta t} = M \frac{v_{rec}}{\tau} \approx \hbar K_L \gamma$$

Doppler laser cooling

$\vec{F}_{diss} = \hbar \vec{K}_L \gamma \rho_{22}$ → population excited state

$\delta = 0$ max and saturates at large laser intensities

Doppler effect: for a moving atom, the force depends on the velocity



$$F_{rad} = -a v \qquad \text{for } v < v_{max}$$

$$v_{max} \simeq \frac{\delta}{K_L}$$

for $\delta < 0 \rightarrow a > 0$

Dipolar force and optical potentials

$$\vec{\mathcal{F}}_{dip} = -\vec{\nabla} U$$

U = optical potential

CONSERVATIVE FORCE

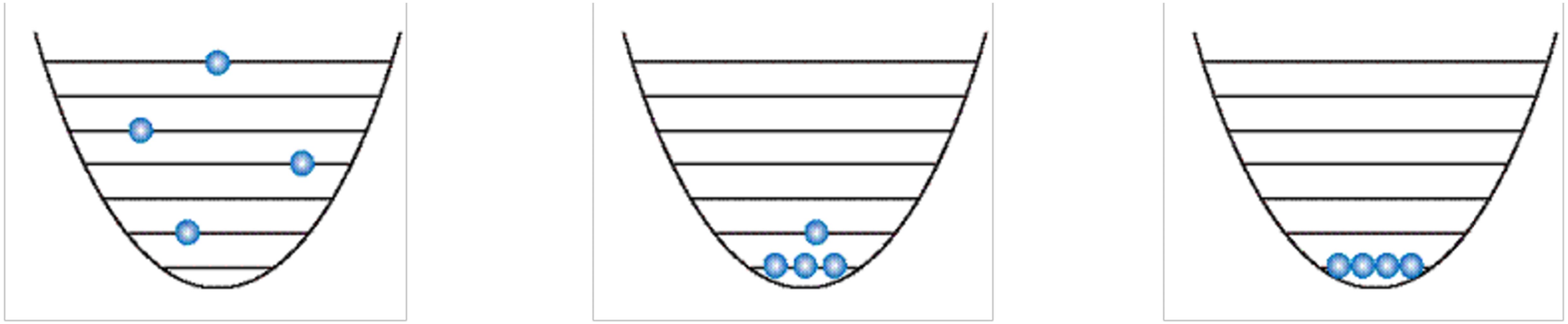
absorption + stimulated emission

$\hbar\vec{k}$ $\hbar\vec{k}'$

For $\delta = 0$, $|\delta| \to \infty$: $\vec{\mathcal{F}}_{dip} = 0$

For $\delta < 0$ $\vec{\mathcal{F}}_{dip}$ attracts the atoms towards the regions of high laser intensities.

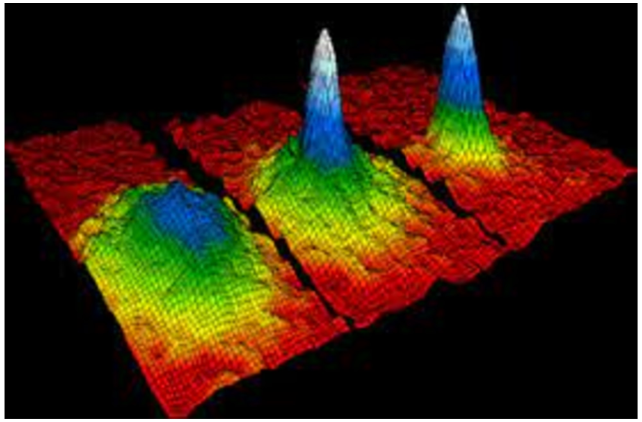
Quantum degeneracy for bosons



Thermal Bosons: $T>T_c$ | BEC+Thermal Bosons: $T\lesssim T_c$ | pure BEC: $T<<T_c$

$$k_B T_c^0 = \hbar\omega_{\rm ho}\left(\frac{N}{\zeta(3)}\right)^{1/3} = 0.94\ \hbar\omega_{\rm ho}\ N^{1/3}$$

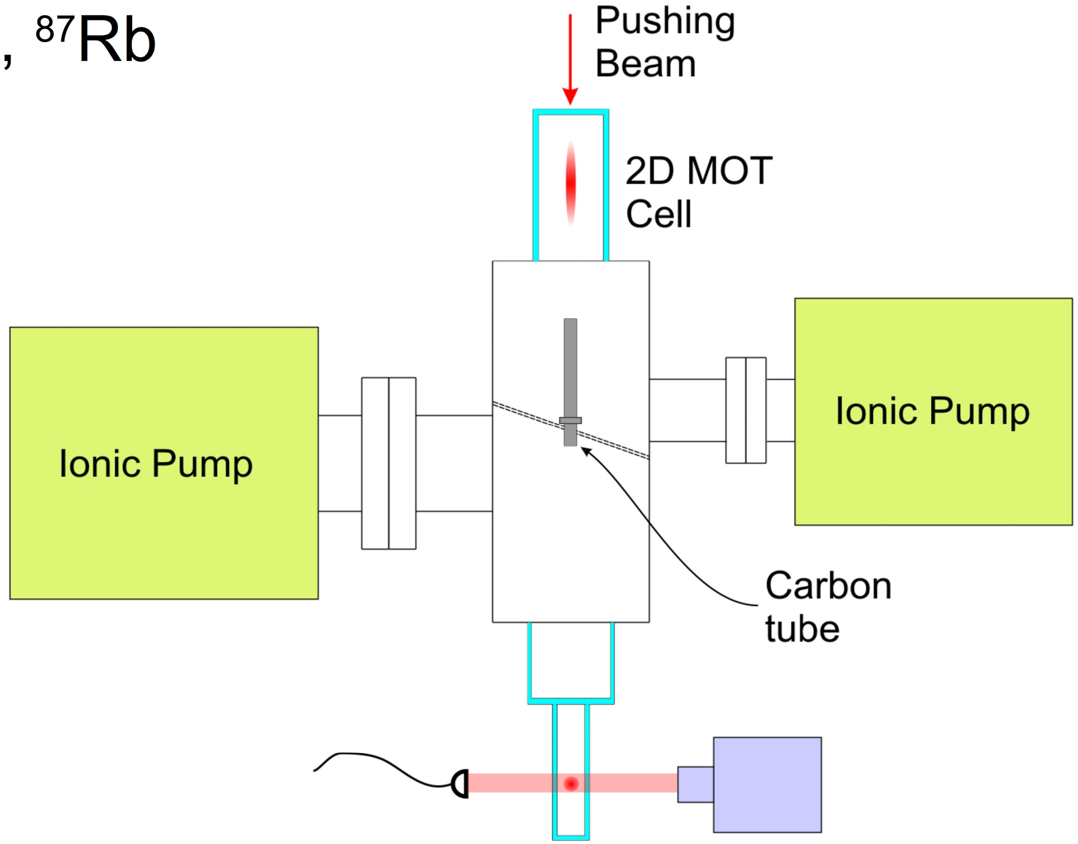
Giant matter-wave



E. Cornell, W. Ketterle
C. Wieman Nobel 2001

The Pisa cold atom machine

- Experimental setup, ^{87}Rb



- Quantum control in modulated optical lattices
- Rydberg atoms for quantum simulation

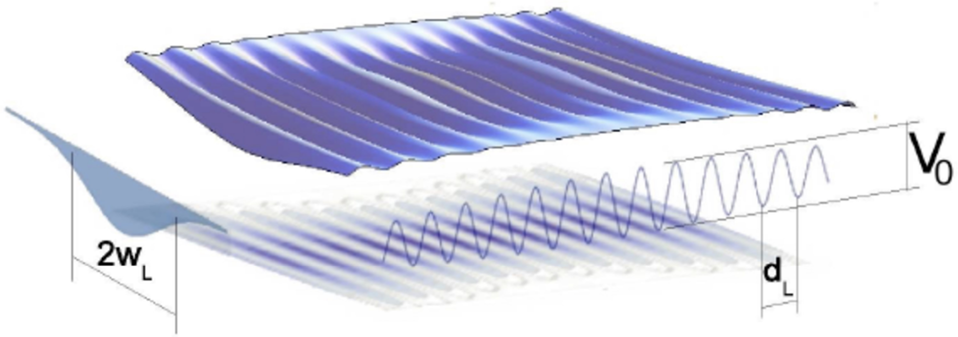
Optical lattices

- The 1D lattice:

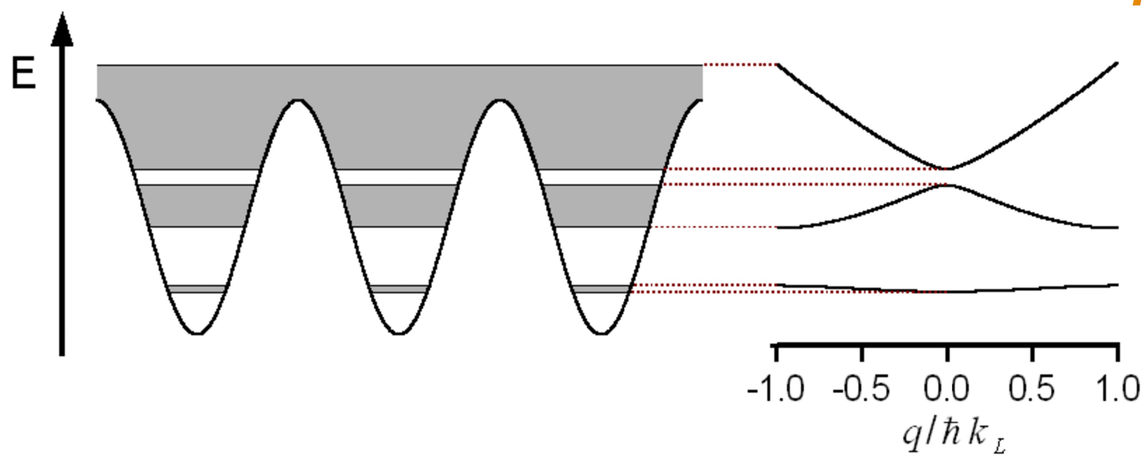
$$U(x) = V_0 \sin^2(k_L x)$$

$$k_L = \pi / d_L$$

$$E_{rec} = \frac{\hbar^2 k_L^2}{2m}$$



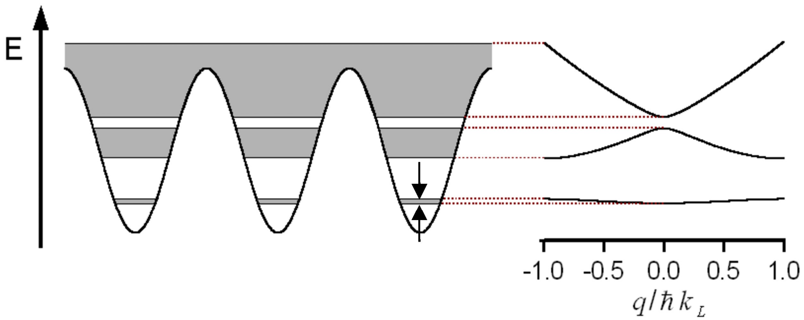
"Crystal of quantum matter"

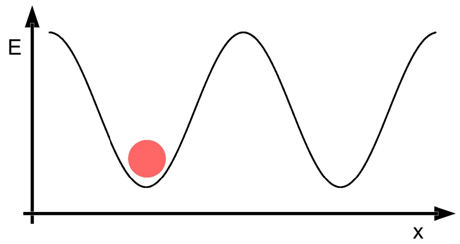


Solid state physics explored in a different framework

Quantum tunneling in an OL

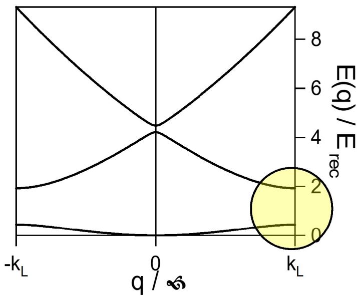
- Intra-band tunneling

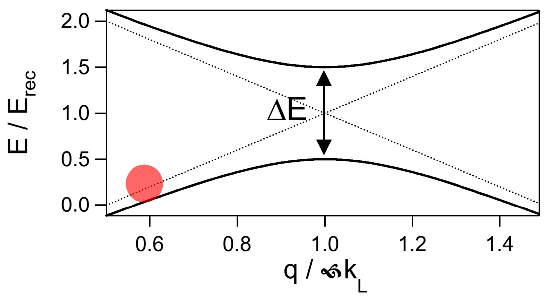


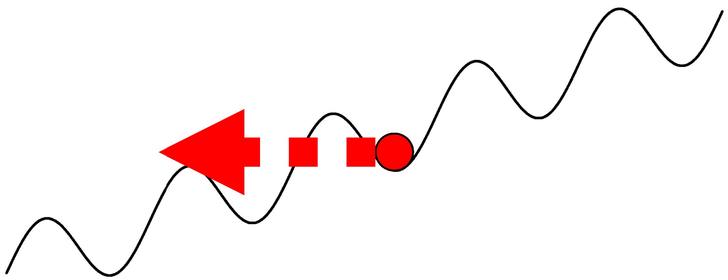


- Inter-band tunneling

$$q(t) = Ft$$







The Bose-Hubbard model

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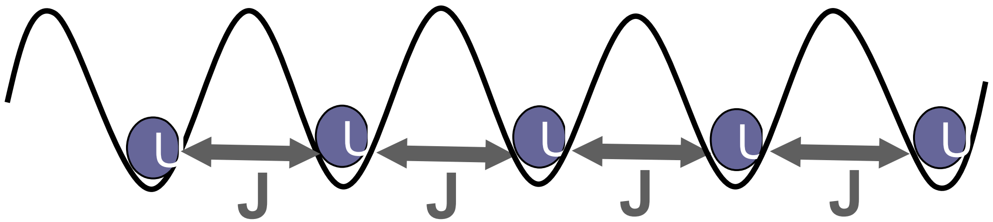
Tunneling term — On-site interaction term



Ratio U/J : a key parameter

$U/J < (U/J)_C$: Super fluid regime

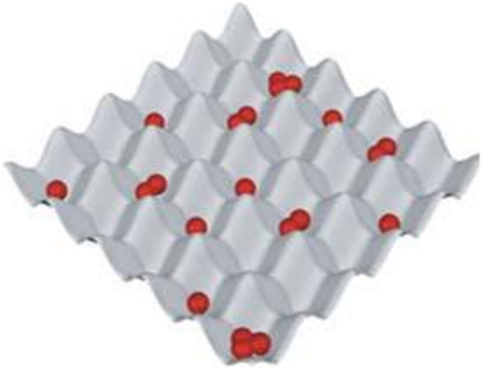
$U/J > (U/J)_C$: Mott insulator regime

$$J = \frac{4}{\sqrt{\pi}} E_{rec} \left(\frac{V_0}{E_{rec}}\right) \exp\left(-2\sqrt{\frac{V_0}{E_{rec}}}\right)$$

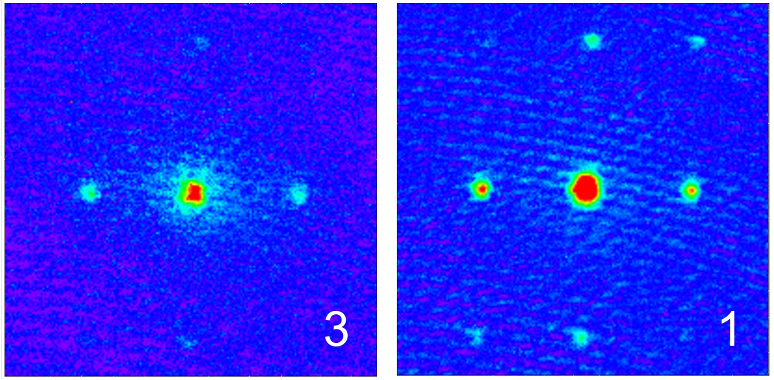
$$U = \frac{8}{\sqrt{\pi}} k a_s E_{rec} \left(\frac{V_0}{E_{rec}}\right)^{1/4}$$

Mott-insulator transition

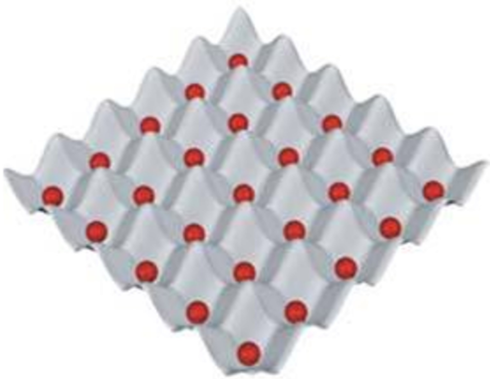
Super-fluid



Atom delocalization → Phase coherence



Adiabatic transformation



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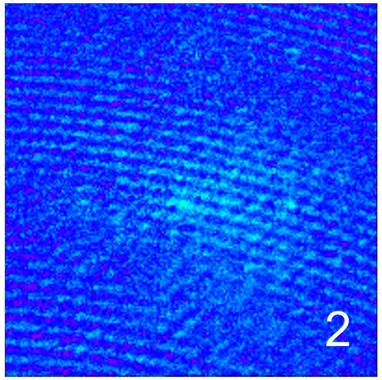
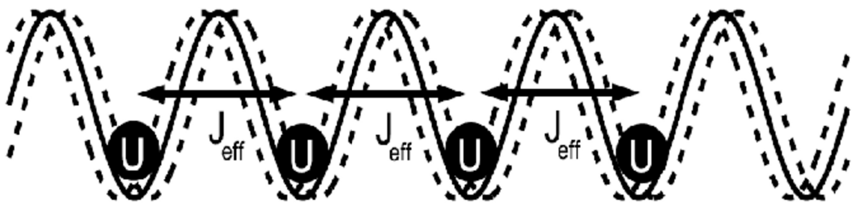


quantum register

The driven optical lattice

$$H_{tot} = H_{BH} + K\cos(\omega t)\sum_j j n_j$$



Periodicity in time $\rightarrow$ Floquet theory

$$H_{tot} = -J_{eff}\sum_{<i,j>}\left(a_i^+ a_j + a_j^+ a\right) + \frac{U}{2}\sum_j n_j\left(n_j - 1\right)$$

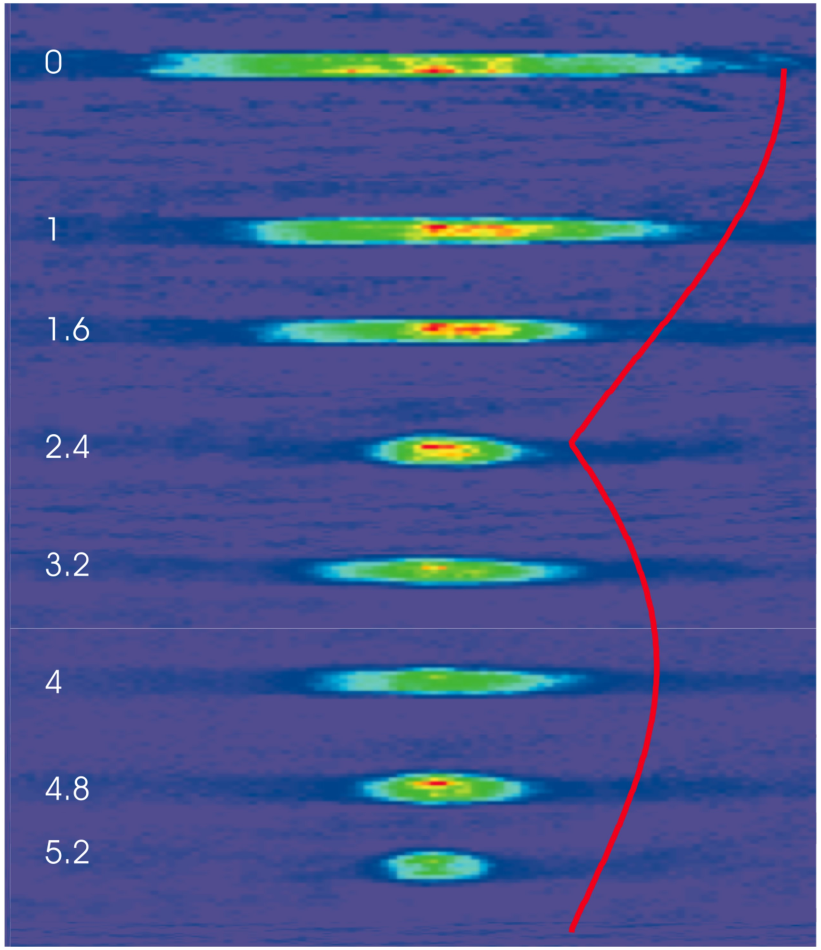
For $\hbar\omega \gg J$:

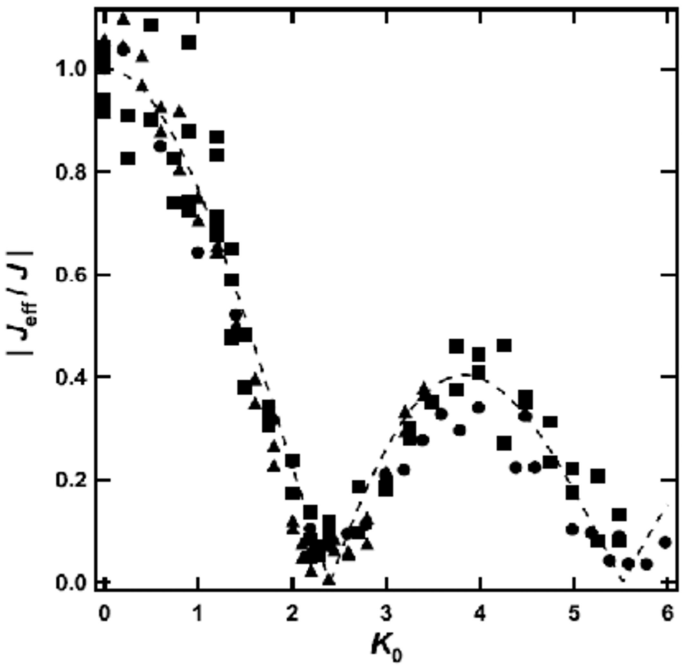
$$J \rightarrow J_{eff} = J_0\left(\frac{K}{\hbar\omega}\right)\cdot J = \mathrm{J}_0\left(K_0\right)\cdot J$$

D. H. Dunlop, V. M Kenkre, Phys. Lett. A, 131 231 (1988)
A. Eckardt, C. Weiss, and M. Holthaus, PRL 95, 260404 (2005)

Control of tunneling

In situ measurement of the expansion

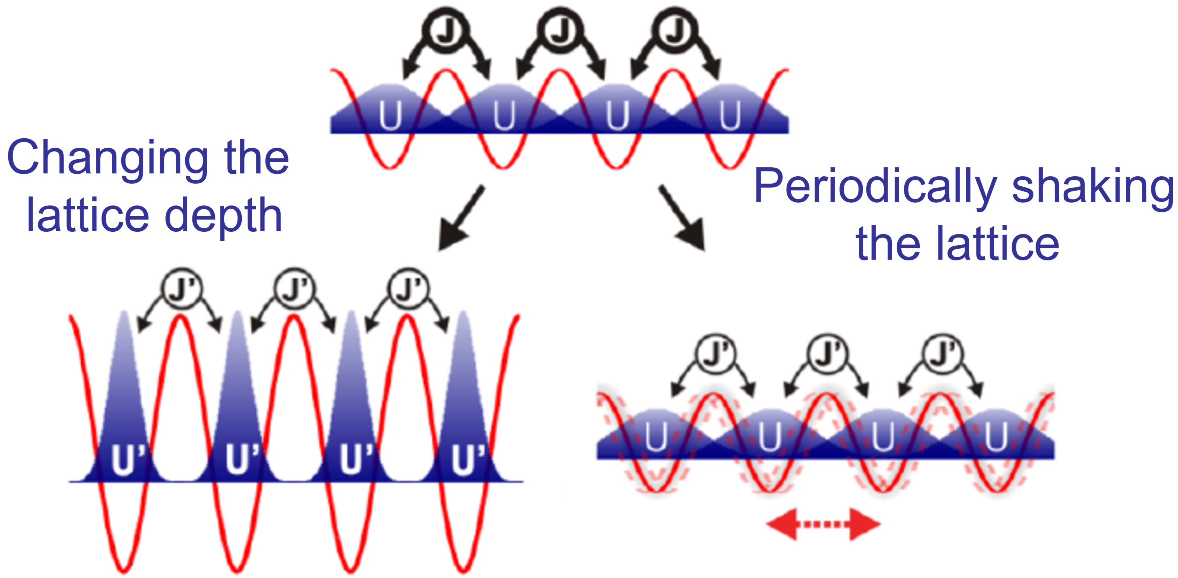




typical parameters:
V_0= 3-8 Erec
J/h ~ 100-500 Hz

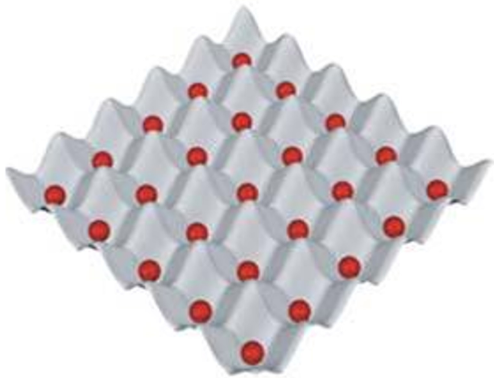
Hans Lignier, Donatella Ciampini, Carlo Sias, Yesphal Singh, Alessandro Zenesini, Oliver Morsch, and Ennio Arimondo, *Dynamical Control of Matter-Wave Tunneling in Periodic Potentials,* Phys. Rev. Lett. **99**, 220403 (2007)

Coherent control of tunneling



Preservation of the quantum coherence

driving-induced superfluid-Mott insulator transition
effected through an adiabatic variation of K_0



Alessandro Zenesini, Hans Lignier, Donatella Ciampini, Oliver Morsch, and Ennio Arimondo, *Coherent Control of Dressed Matter Waves,* Phys. Rev. Lett. **102**, 100403 (2009)

Environmental decoherence

	d=10 μm	d= 10 nm
Environment	Dust grain	Large molecule
Cosmic background radiation	1	10^{24}
Photons at room temperature	10^{-18}	10^{6}
Best laboratory vacuum	10^{-14}	10^{-2}
Air at normal pressure	10^{-31}	10^{-19}

Timescales (in s) for the suppression of spatial interference over a distance equal to the size *d* of the object [1].

Silica microspheres with *d* in the range few hundreds of nm – few μm are decribed by classical physics laws.

[1] M. Schlosshauer, *Decoherence and the Quantum to Classical Transition*, Springer, New York, 2007

Motivation

Flashback in hydrogen combustors.

For temperature measurement, Hollow Core Photonic Crystal Fiber (HCPCF) with particle as temperature probe.

Non intrusive and high resolution, temporal resolution ms scale, spatial resolution µm scale.

System remotely controlled, lasers used for position control and temperature measurement (T $\simeq$ 1500 K).

MARIE CURIE ACTIONS

POLKA

UNIONE EUROPEA
Fondo Sociale Europeo

Ministero dell'Università e della Ricerca

PON RICERCA E INNOVAZIONE 2014 - 2020

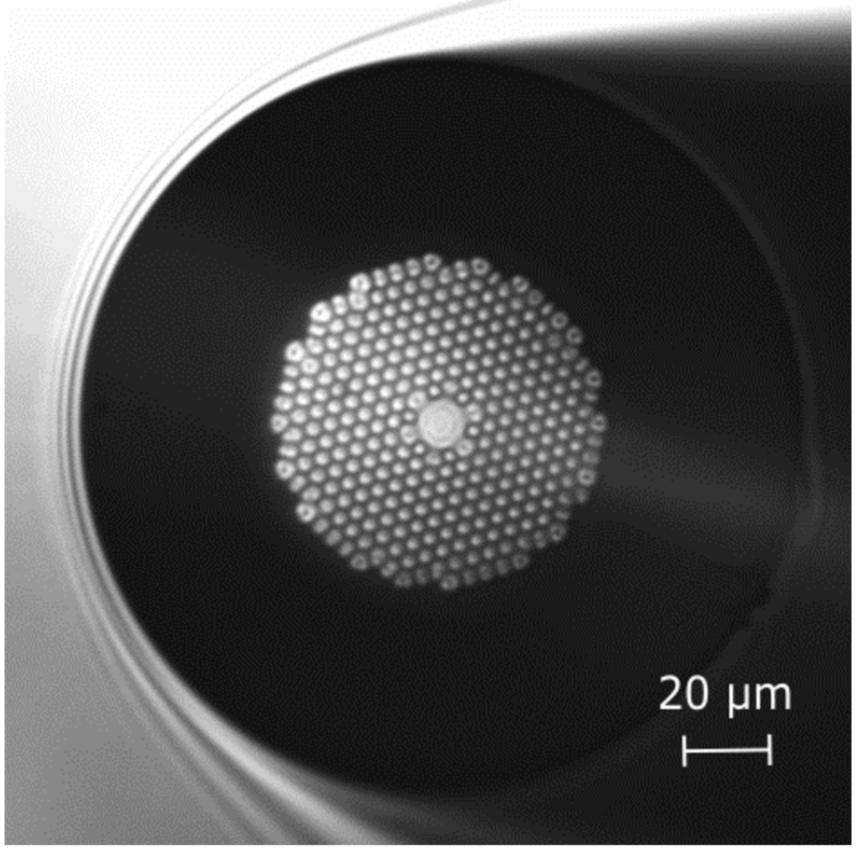
Hollow core photonic crystal fiber

Light confined to the hollow core by diffraction.

Silica microparticle can be guided inside hollow core.

Silica HCPCF minimum softening and melting points of 1948 K and 2063 K respectively.
Sapphire could be used with a melting point of 2327 K.

Silica, working wavelength 1064 nm
Core diameter 10 μm

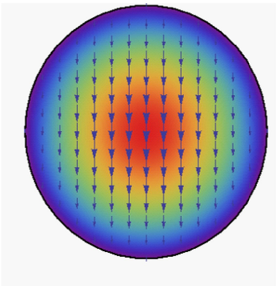


HC-1060-02 by NKT Photonics

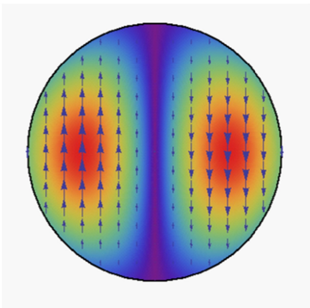
Guided modes

Allowed modes inside the fiber are similar to those that propagate inside hollow, cylindrical dielectric waveguides.

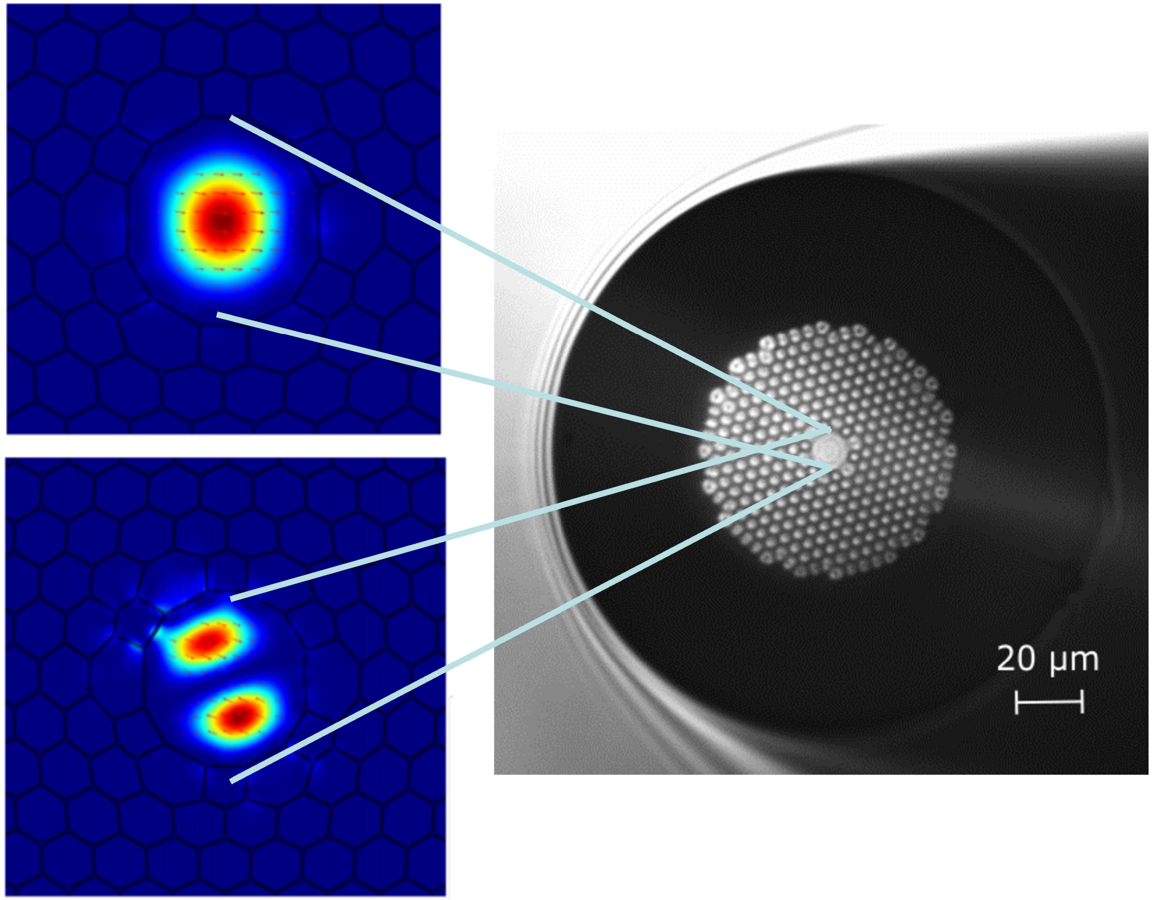
Two lowest modes are LP_{01} and LP_{11}



LP_{01}

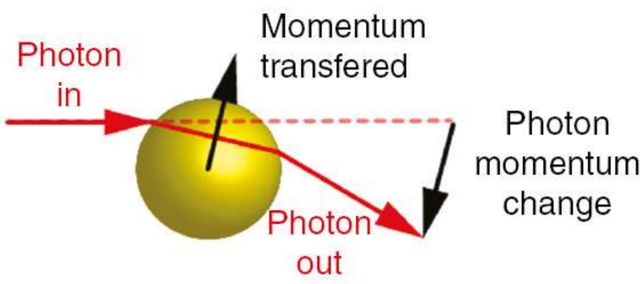


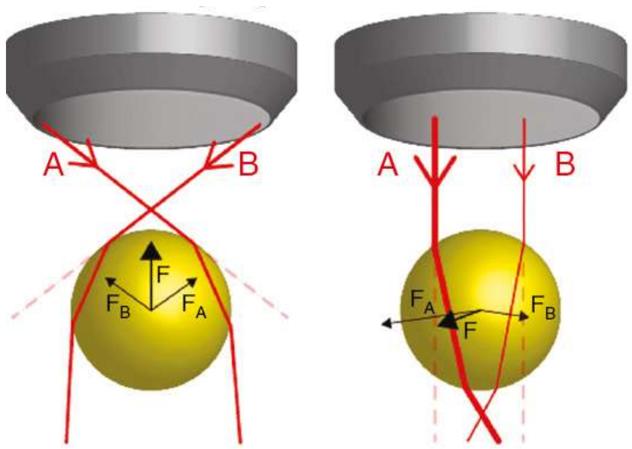
LP_{11}



Optical forces

Ray Optics Model





inaccurate when size of microsphere similar to wavelength of laser!

Lorenz-Mie Optical Force Model

We performed full electromagnetic calculation using the generalized Lorenz-Mie theory method, to determine the optical forces for dielectric particles in HC-PCFs.

Mie resonances

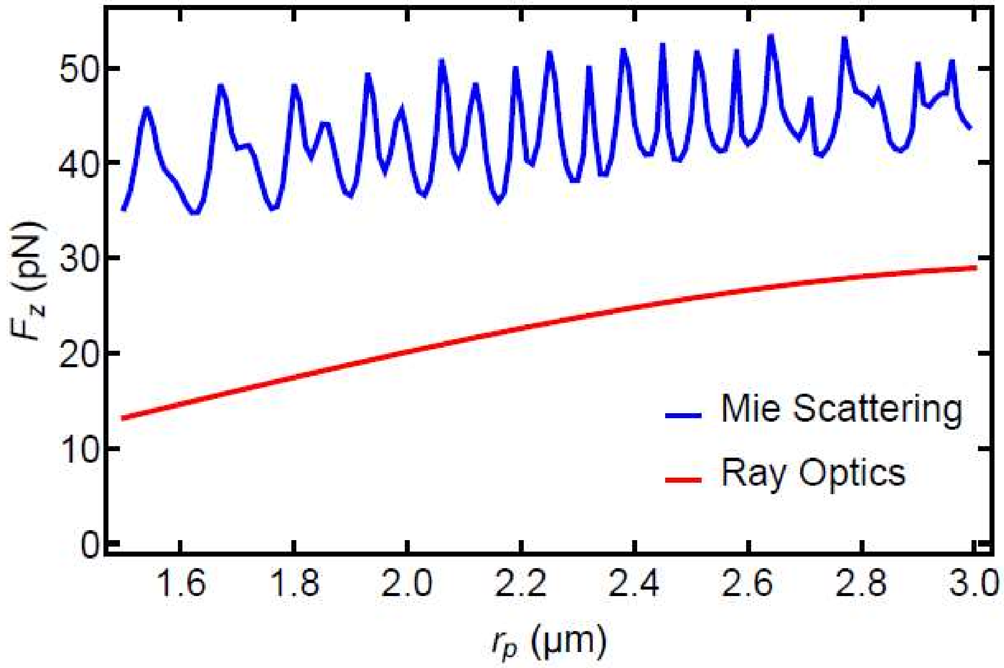
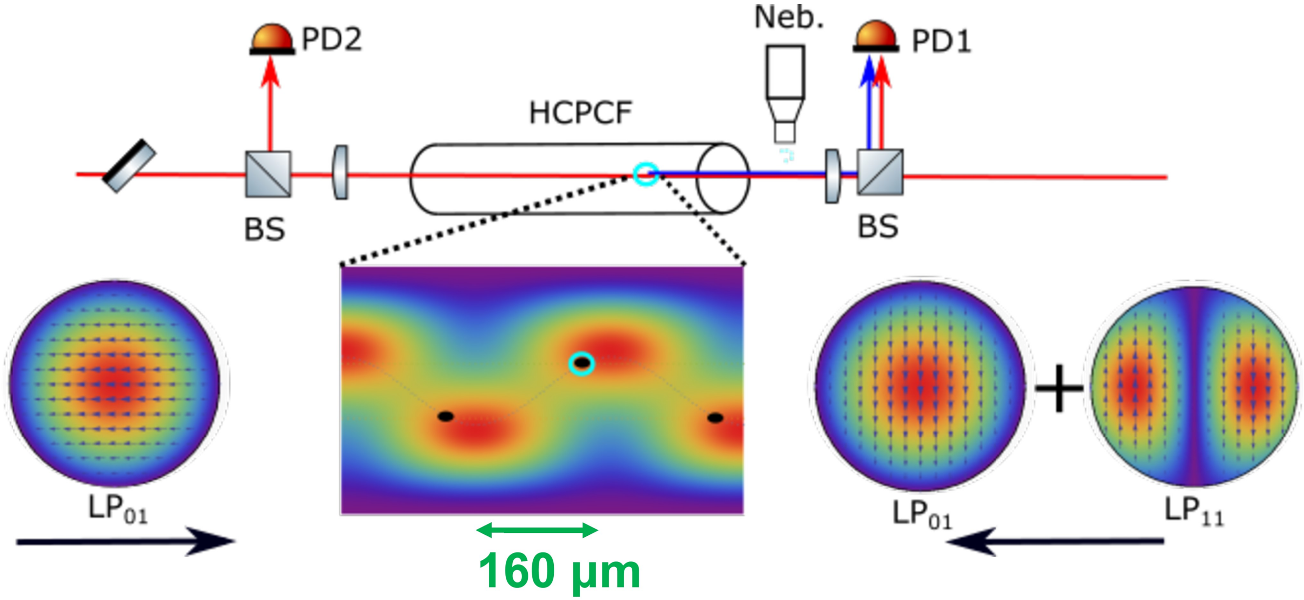


Fig. 3. Calculated radiation pressure force, F_z, exerted on silica microspheres of different radii as computed through the ray optics approximation (red curve) and through Mie scattering (blue curve). $P = 50$ mW, $\lambda = 1064$ nm, $a = 4.7$ μm, $n_m = 1$, $n_p = 1.45$.

Mixed modes optical trap



❖The LP_{01} and LP_{11} modes have a different longitudinal wave vector component

❖This generates a beating-interference intensity pattern along the fiber

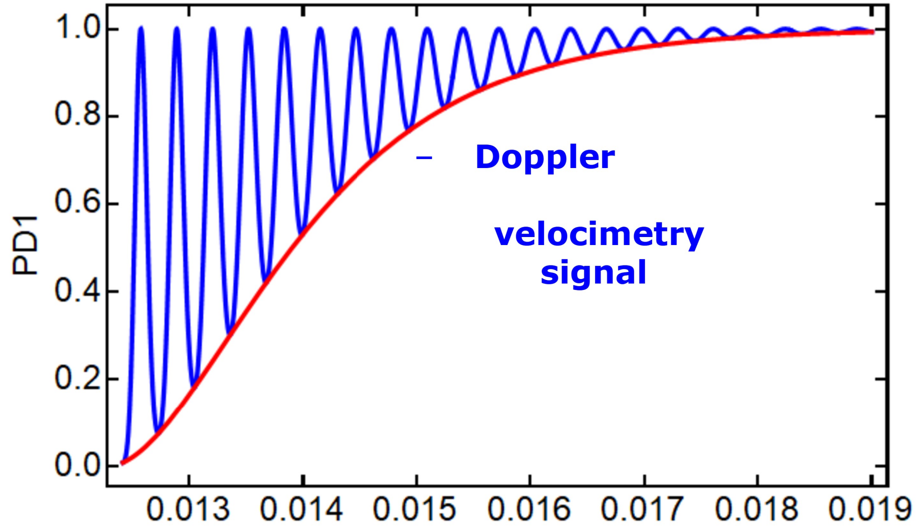
❖A particle (blue circle) may be flying along the fiber (force imbalance) or trapped at equilibrium positions (black dots)

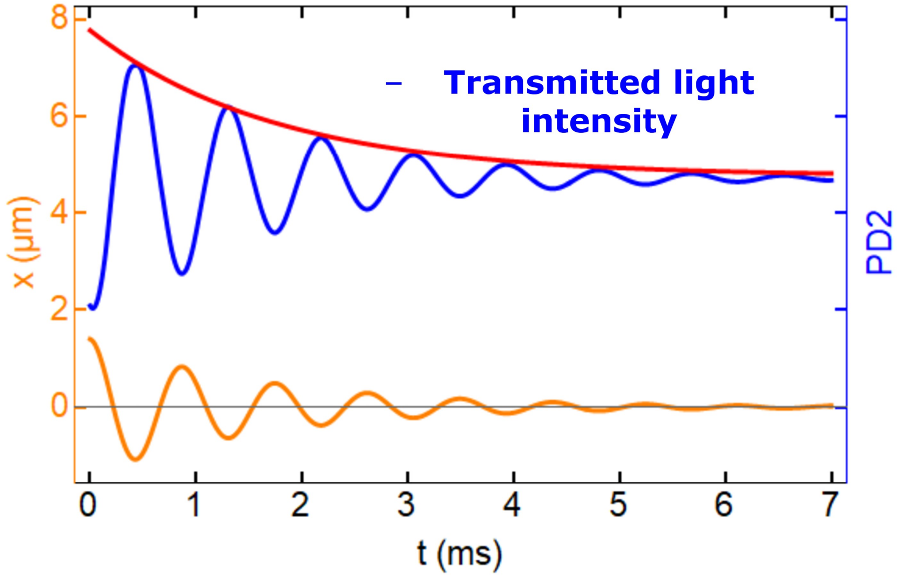
❖The interference pattern may be shifted by controlling the relative phase betwen the LP_{01} and LP_{11} modes

Temperature measurements

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = 0$$

$$\gamma(p,T) = \frac{K6\pi r_p \mu(p,T)}{m}$$





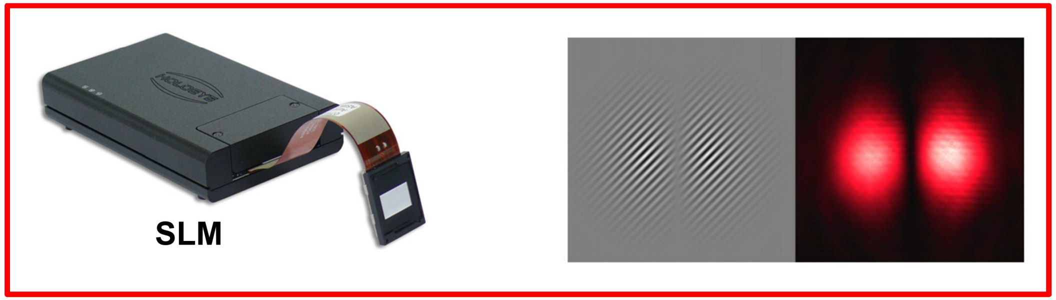
❖Consider a sudden change in particle equilibrium position, which causes it to oscillate.

❖Particle may be modelled as a simple harmonic oscillator.

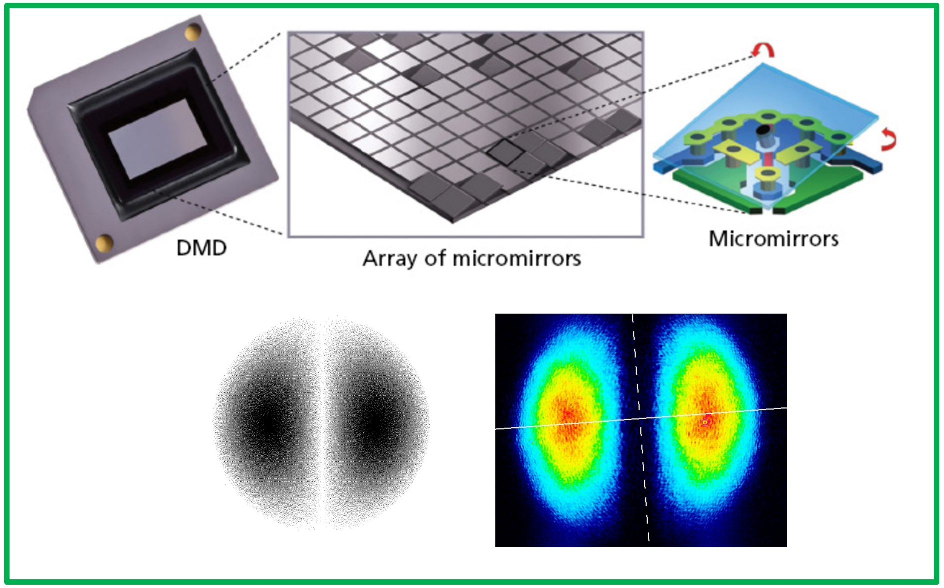
❖Temperature may be extracted from γ*(p,T).*

Mode generation

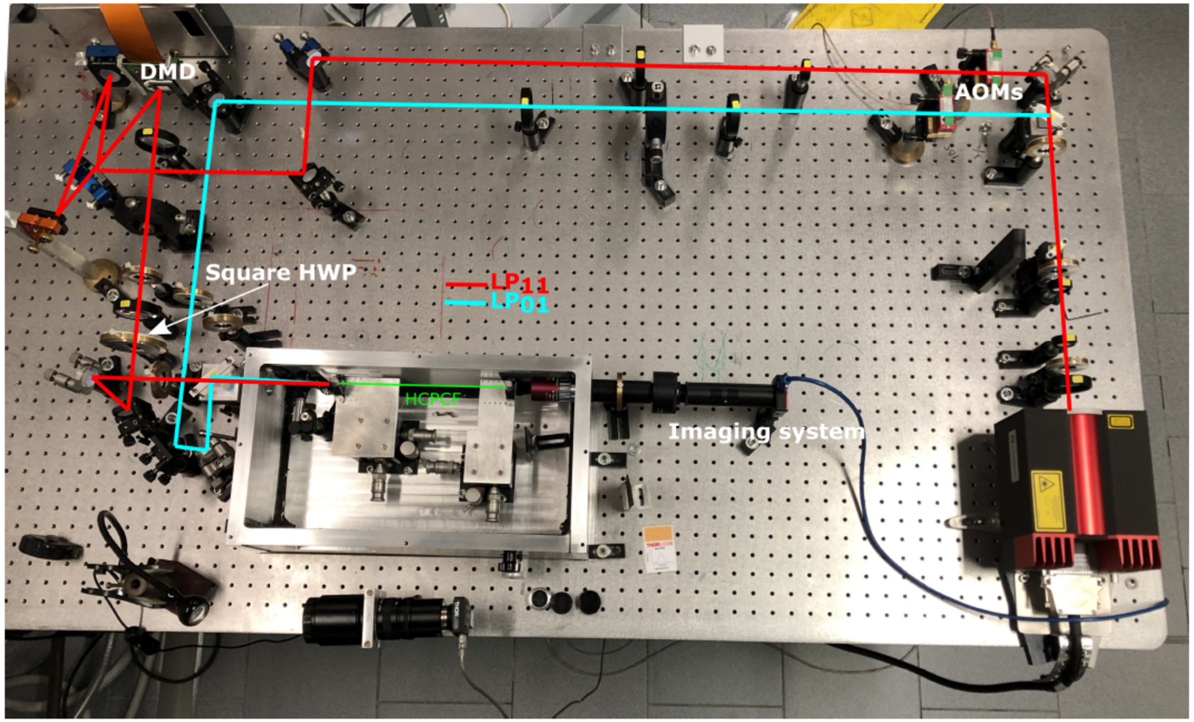
- Spatial Light Modulator (SLM) uses phase-only hologram projected onto screen, to encode the desired amplitude and polarisation.



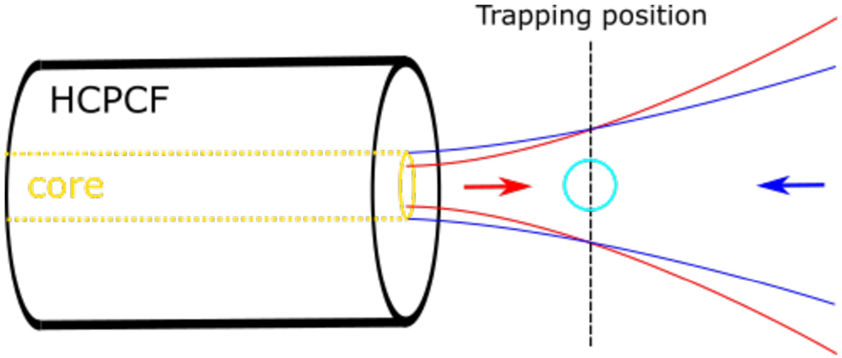
- Digital micromirror (DMD) device modulates only the amplitude using a dithering algorithm to reproduce intensity.
- DMD higher efficiency and no 60 Hz refresh rate.



The Pisa HCPCF setup

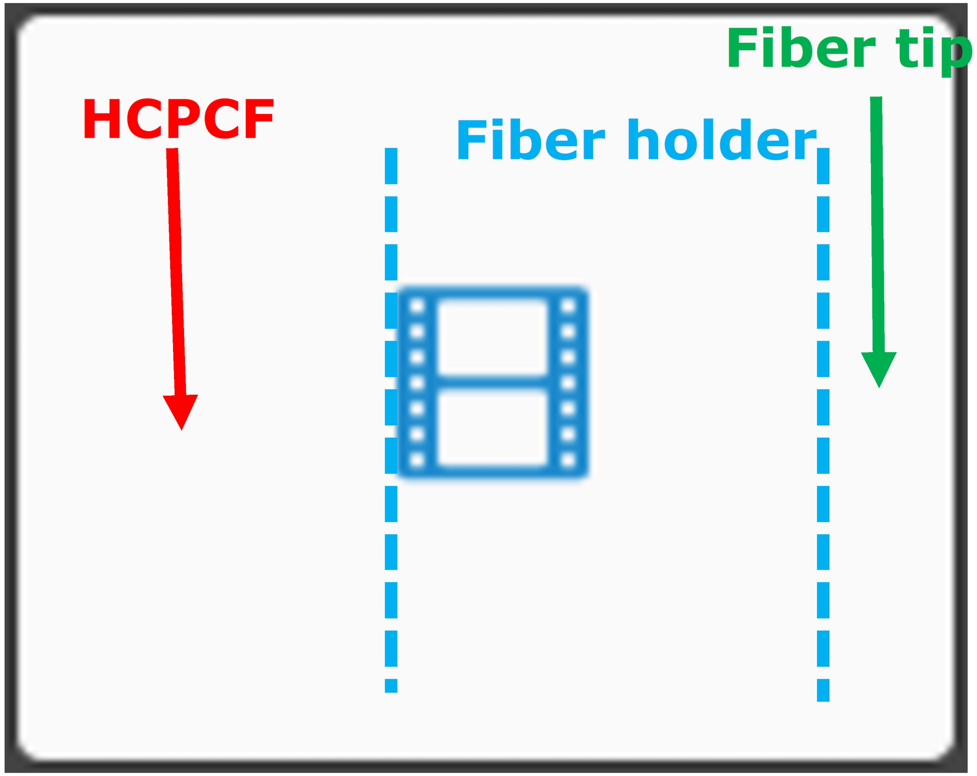


Particle load



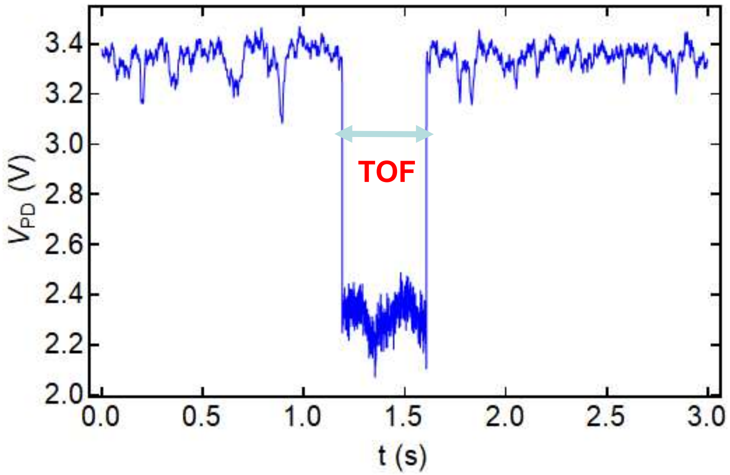
Particle load…and launch

Particle launched by changing power balance in counterpropagating beams



Time of flight experiment

Microspheres with Gaussian radial distribution with *r* = 1.585±0.162 µm



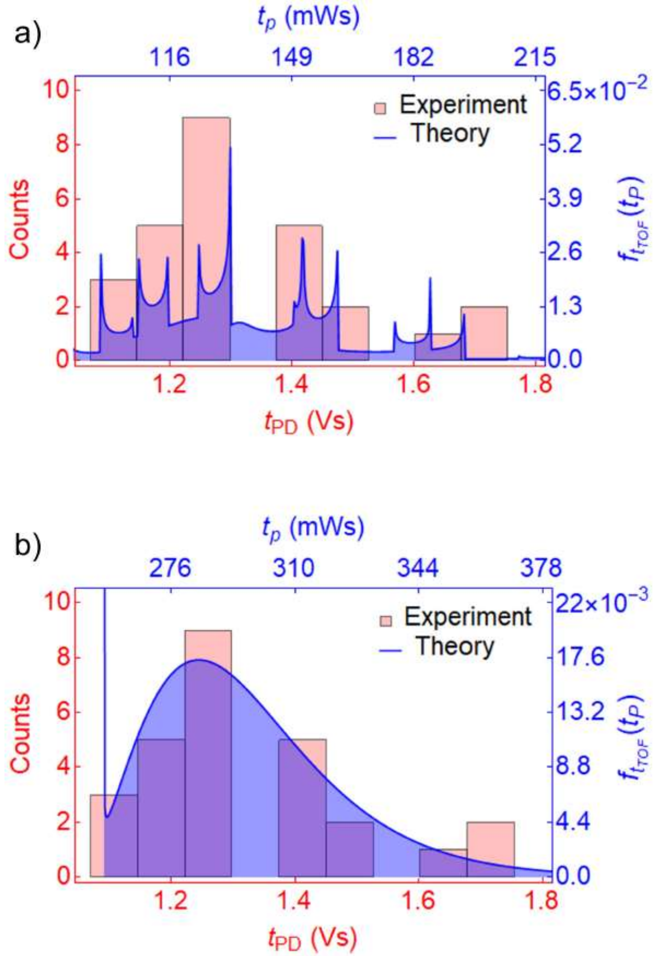
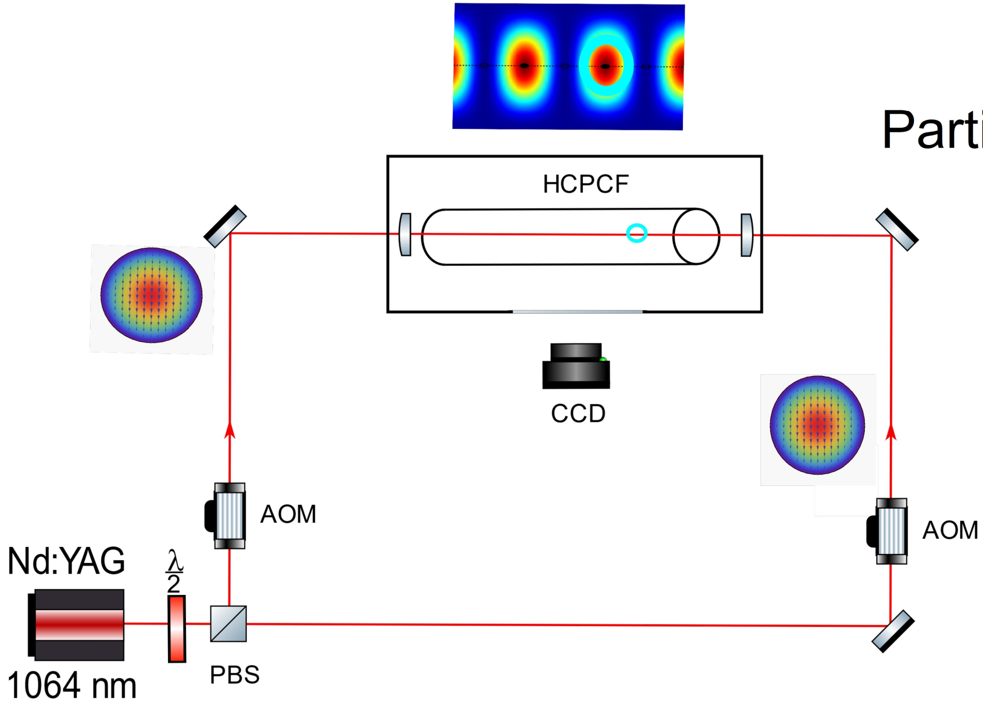


Fig. 8. Histogram of time of flight multiplied by average voltage reading on the photodiode before the launch event for 3.17 µm particles. Fiber length, 70.4 mm, 26 data points, 9 bins. Experimental data in pink with the theoretical probability distribution function overlayed in blue for a) Lorenz-Mie and b) ray optics models.

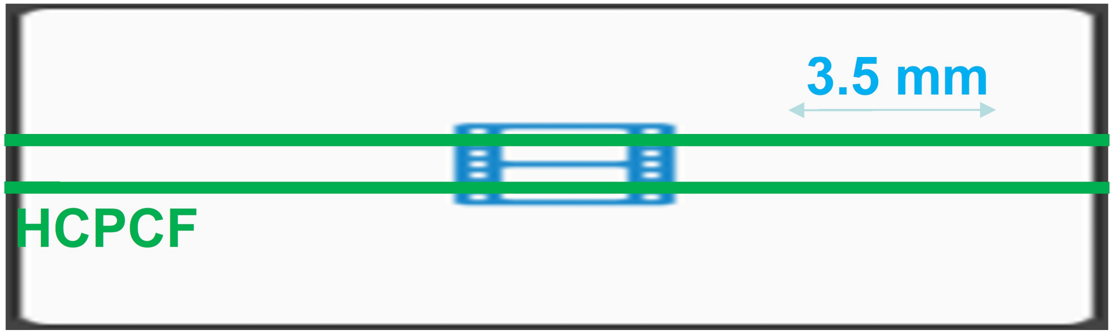
"Size-dependent optical forces on dielectric microspheres in hollow core photonic crystal fibers", Peter Seigo Kincaid, Alessandro Porcelli, Antonio Alvaro Ranha Neves, Ennio Arimondo, Andrea Camposeo, Dario Pisignano, Donatella Ciampini

Standing-wave conveyor belt

Particles: 353 nm

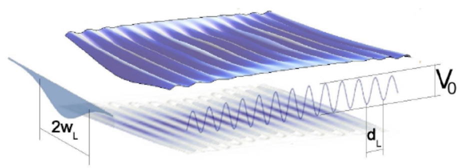


"Brownian Surfer"

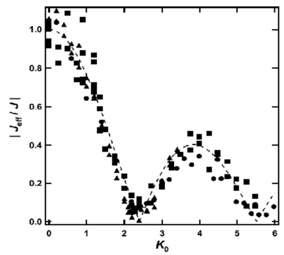


Conclusions and outlook

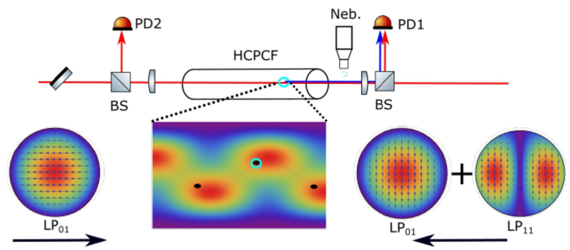
- Optical manipulation of atoms



- Coherent control of intra-band tunneling



- Optical manipulation of dielectric microspheres in HCPCF



- Towards the realization of the temperature probe: low pressure,heater,…