

-100

0

Frequency [MHz]

100

-200

0

Frequency [MHz]

200

# **Cavity-Enhanced Microscope for Cold Atoms**

**T. Cantat-Moltrecht**, N. Sauerwein, N. Reiter & J.-P. Brantut

#### Working Principle of Microscope The Cavity-Microscope : high finesse & high NA **Cavity holder design** Aspheric lens **Cavity design** Cavity mirror • Combine strongly damping and (DL spot size $\sim 1 \,\mu m$ ) HR @ 671 & 1342nm ; HT @ 460 & 780 nm Spatial control of atom-• High-finesse cavity coupling • Close to concentric $\Rightarrow$ Strong atom-cav. coupling At the 460 nm beam focal focusing field light shifting dipole trap Mirror post (Silicon Carbide) Mirror (BK7) point, D2 transition is light-2P3/2 Wavele beam 460 nm peam 780 nm shifted closer to cavity Cav. le resonance $\Rightarrow$ local enhancement of Mode v cavity field cavity field Shea Lithium 6 2S1/2-Finesse 671 nm atom-cavity coupling atoms $\kappa/2\pi$ $\eta$ = $g_0/2\pi$ **Dispersive atom-cavity coupling** Super-resolution effect Top Pla Cavity light phase-shifted by $\delta\phi\propto g^2/\Delta$ non-linearity in atom-cavity coupling $\Rightarrow$ dispersive measurement of atom number $\Rightarrow$ resolution enhancement $\frac{\sigma}{2w} \sim \sqrt{\frac{\Delta(z_{\infty})}{\Delta(z=0)}}$ Lens design Dampers (PTFE) Waveler up to a factor >10 is expected Focusing beam DL bear — ideal PSF — measured PSF • 460 nm laser beam focused to $< 1 \, \mu m$ 0.8 blue intensity • High NA = 0.37 • red detuned from 2P<sub>3/2</sub> - 4D<sub>5/2</sub> transition 9.0 tensity atom-cavity detuning Optically contacted assembly $\Rightarrow$ light shifts the 2P<sub>3/2</sub> excited state by $\delta \propto I$ atom-cavity coupling int **Point spread function** $\frac{1}{2}0.4$ Micro dipole trap Aberrations lead to Strehl ratio • 780 nm laser beam focused to 1.3 μm of < 0.5 $0.2 \cdot$ • trapping frequency $\sim$ 650 kHz for 100 mW frequency (Hz) automatically aligned to cavity center => wavefront correction 0 0.0 necessary for DL operation 0.00.51.01.52.02.5z (µm) radius (µm) Vacuum setup Laser system Next steps **Future Experiments** Pumping cross Main chamber **Frequency-doubled system** Zeeman slowe Structured atom ensembes coupled 1342 nm: 671 nm: Trapping atoms in strongly confining dipole traps Oven 🖛 to the cavity (Diode + Raman fiber amp): • Laser cooling Main chambe Load atoms into intra-cavity dipole trap at Use intra-cavity ODT and microtrap Science cavity lock • Cavity probe 1342 nm (lattice structure at 671 nm) Zeéman • Cavity cooled 1D chains or 2D arrays of Intra-cavity ODT • Atom imaging Load atoms into micro-tweezer at 780 nm single atoms with $\lambda$ -spacing • 671 nm generation Shutter Load 1D chain of atoms using light-induced Structured collective atom-cavity interaction collisions [2] in the combined dipole trap Atoms loaded directly at cavity center NEG coating for improved vacuum < 2.10<sup>11</sup> mbar 460 nm laser Wavefunction microscope [5] Home-made bulk-machined MOT coils [1] Science cavity SHG Sideband-resolved cavity cooling [3,4] Single atom trapped in a Very confining harmonic trap (> 500 kHz) Two-colour MOT fluo imaging harmonic trap Narrow cavity & far-detuned transv. pump small signal focusing beam laser cooling • Enhanced atom-cavity and blue pump & imaging Cavity tuned to anti-Stokes sideband single <sup>6</sup>Li **~** narrow 461 nm beam co-propagating with coupling at center $|n=0\rangle$ atom Conservative laser cooling vertical MOT beam and retro-reflected large signal MOT effect at 461 nm Li spectro cell high collection efficiency at 461nm -2P3/2 through "cavity-lens" **Programmable Quantum Simulator Two-photon spectroscopy** at 671 nm at 671 nm • Spatial and temporal tunability of cavity- Saturated absorption single-pass absoprtion transverse cavity 10<sup>3</sup> atoms 10<sup>4</sup> atoms pump field spectroscopy for 670 nm spectroscopy for 460 nm mediated interaction and potentials • Micro-trap array • Quantum information gates at 460 nm 10<sup>3</sup> atoms absorbtion absorbtion error signal error signal [2] Y. Sortais et al. PRA 75, 013406 (2007) vertical MOT beam blue fluo beam (671 nm) (461 nm)

LQG, EPFL, Lausanne, Switzerland



ngth	$671\mathrm{nm}$	$1342\mathrm{nm}$		
ength	25.895	$25.895\mathrm{mm}$		
	(2R - 1)	$(2R - 105 \mu m)$		
vaist	$13.3\mathrm{\mu m}$	$18.8\mu\mathrm{m}$		
<b>)</b>	17950	59300		
	$322.5\mathrm{kHz}$	$97.7\mathrm{kHz}$		
	6.9			
	$2.56\mathrm{MHz}$			

ngth	$460\mathrm{nm}$	$780\mathrm{nm}$
m waist	$0.61\mu{ m m}$	1.03 µm





- high specific stiffness materials
- Non-magnetic and UHV compatible



Measured mechanical response









[3] V. Vuletic et al., PRA 64, 033405 (2001)

[4] M. Hosseini et al., PRL 118, 183601 (2017) [5] D. Yang et al. PRL 120, 133601 (2018)

ENERGY EXTERNAL SUISSE DE LA RECHERCHE SCIENTIFIQUI **Cavity-Enhanced Microscope for Cold Atoms** 

EPFL

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### Working Principle of Microscope





Spatial control of atomcavity coupling

At the 460 nm beam focal point, D2 transition is lightshifted closer to cavity resonance ⇒ local enhancement of atom-cavity coupling



#### **Dispersive atom-cavity coupling**

Cavity light phase-shifted by  $\delta\phi \propto g^2/\Delta$ 

 $\Rightarrow$  dispersive measurement of atom number



+

#### Focusing beam

- 460 nm laser beam focused to  $< 1\,\mu\text{m}$
- red detuned from 2P<sub>3/2</sub> 4D<sub>5/2</sub> transition
- $\Rightarrow$  light shifts the 2P<sub>3/2</sub> excited state by  $\delta \propto I$

#### Micro dipole trap

- 780 nm laser beam focused to 1.3  $\mu m$
- trapping frequency  $\sim\!650\,\text{kHz}\,$  for  $100\,\text{mW}$
- automatically aligned to cavity center

#### Super-resolution effect

non-linearity in atom-cavity coupling

 $\Rightarrow$  resolution enhancement  $\frac{\sigma}{2w} \sim \sqrt{\frac{\Delta(z_{\infty})}{\Delta(z=0)}}$ up to a factor >10 is expected







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## The Cavity-Microscope : high finesse & high NA

#### **Cavity design**

- High-finesse
- Close to concentric
- $\Rightarrow$  Strong atom-cav. coupling

Wavelength	$671\mathrm{nm}$	$1342\mathrm{nm}$
Cav. length	$25.895\mathrm{mm}$	
	$(2\mathrm{R}-105\mathrm{\mu m})$	
Mode waist	$13.3\mathrm{\mu m}$	$18.8\mu{ m m}$
Finesse	17950	59300
$\kappa/2\pi$	$322.5\mathrm{kHz}$	$97.7\mathrm{kHz}$
$\overline{\eta}$	6.9	
$g_0/2\pi$	$2.56\mathrm{MHz}$	



#### Lens design

Wavelength	$460\mathrm{nm}$	$780\mathrm{nm}$
DL beam waist	$0.61\mathrm{\mu m}$	$1.03\mu{ m m}$

- High NA = 0.37
- Optically contacted assembly

#### **Point spread function**

Aberrations lead to Strehl ratio of < 0.5

=> wavefront correction necessary for DL operation



#### Cavity holder design

- Combine strongly damping and high specific stiffness materials
- Non-magnetic and UHV compatible





#### Measured mechanical response



### **Cavity-Enhanced Microscope for Cold Atoms**

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### Laser system

#### **Frequency-doubled system**

#### 1342 nm:

#### **671 nm**:

- (Diode + Raman fiber amp): Laser cooling
  - Cavity probe
  - Atom imaging

single-pass absoprtion

spectroscopy for 460 nm

• 671 nm generation

Science cavity lock

Intra-cavity ODT



### Two-photon spectroscopy

- Saturated absorption spectroscopy for 670 nm
- The provided matrix of the second sec



# Two-colour MOT fluo imaging

- narrow 461 nm beam co-propagating with vertical MOT beam and retro-reflected
- MOT effect at 461 nm
- high collection efficiency at 461nm through "cavity-lens"



vertical MOT beam blue fluo beam (671 nm) (461 nm)





at <mark>671 nm</mark> 10<sup>4</sup> atoms

at 671 nm 10<sup>3</sup> atoms



[1] K. Roux et al., SciPost Phys. 6, 048 (2019)



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### **Next steps**

#### Trapping atoms in strongly confining dipole traps

- Load atoms into intra-cavity dipole trap at 1342 nm (lattice structure at 671 nm)
- Load atoms into micro-tweezer at 780 nm
- Load 1D chain of atoms using light-induced collisions [2] in the combined dipole trap

### Sideband-resolved cavity cooling [3,4]

- Very confining harmonic trap (> 500 kHz)
- Narrow cavity & far-detuned transv. pump
- Cavity tuned to anti-Stokes sideband
- Conservative laser cooling



## **Future Experiments**

# Structured atom ensembes coupled to the cavity

- Use intra-cavity ODT and microtrap
- Cavity cooled 1D chains or 2D arrays of single atoms with  $\lambda\mbox{-spacing}$
- Structured collective atom-cavity interaction



#### Wavefunction microscope [5]

- Single atom trapped in a harmonic trap
- Enhanced atom-cavity coupling at center

#### Programmable Quantum Simulator

- Spatial and temporal tunability of cavitymediated interaction and potentials
- Micro-trap array
- Quantum information gates



[2] Y. Sortais et al. PRA 75, 013406 (2007)[3] V. Vuletic et al., PRA 64, 033405 (2001)

[4] M. Hosseini et al., PRL 118, 183601 (2017)[5] D. Yang et al. PRL 120, 133601 (2018)