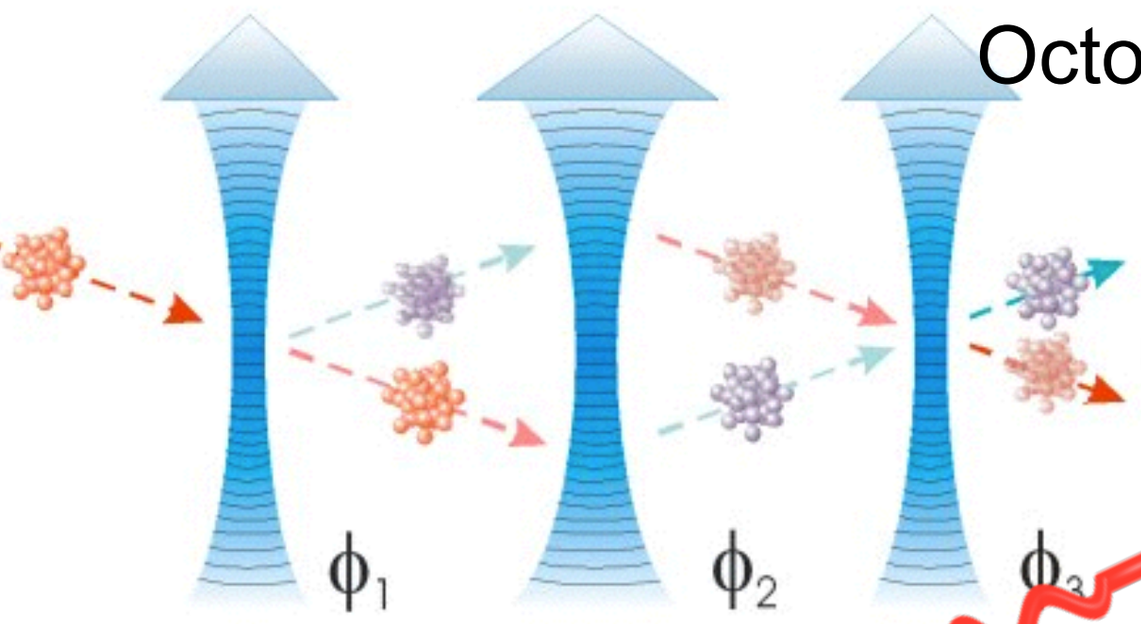
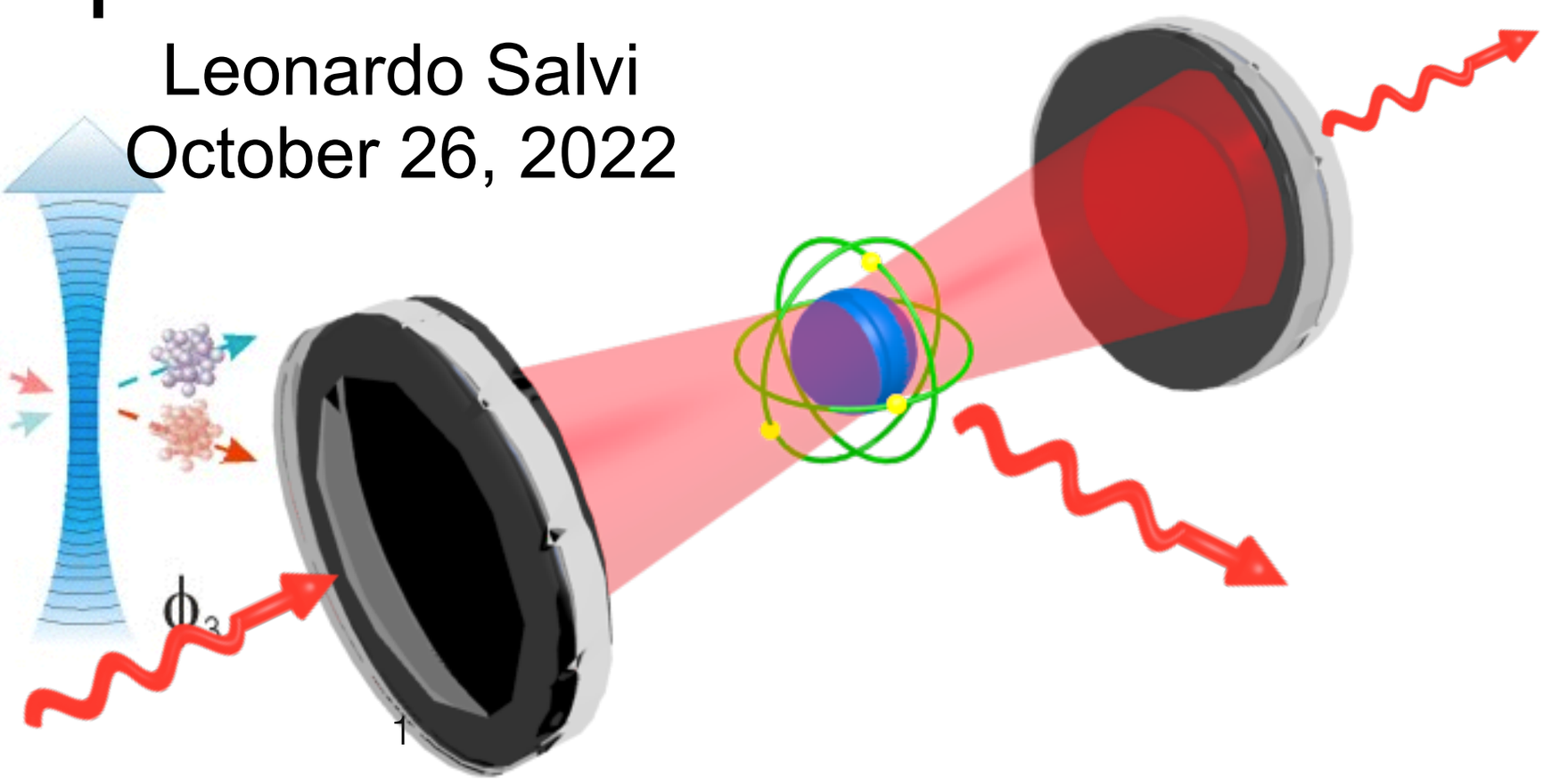
An Apparatus for Atom Interferometry on an Optical Clock Transition with Squeezed States

Leonardo Salvi

October 26, 2022

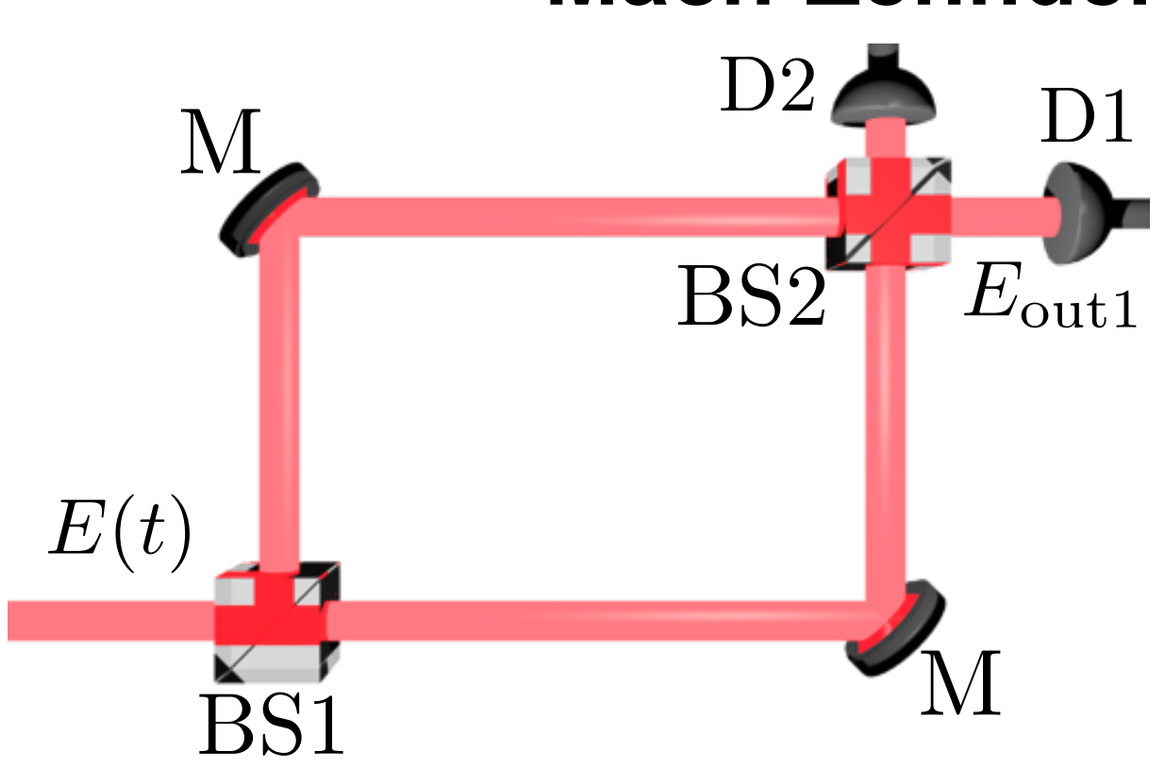


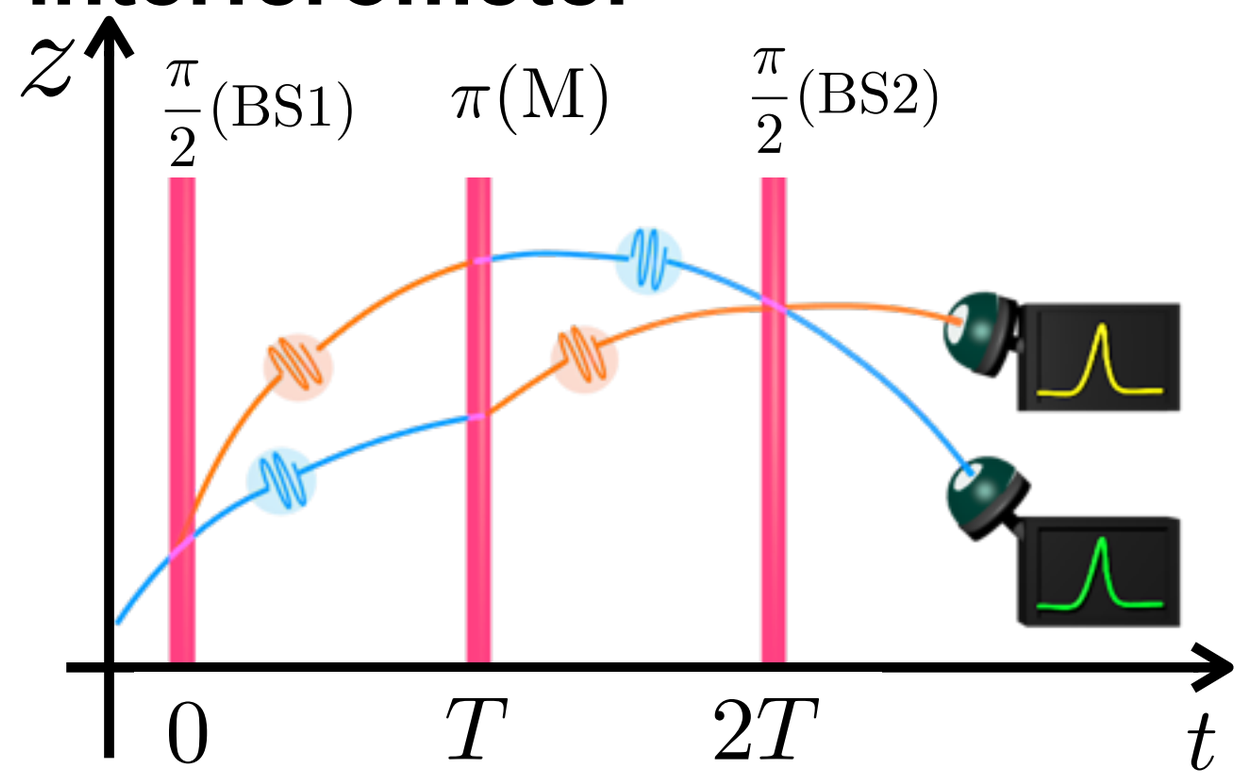


Atom Interferometers for Gravity Measurements

State preparation $|\psi_0\rangle$ → Phase accumulation $U(\Delta\phi)|\psi_0\rangle$ → Phase estimation $\mu \to \Delta\phi$

Mach-Zehnder interferometer





$$\Delta\phi = k_{\mathrm{eff}} g T^2$$

How do we improve sensitivity to gravity acceleration?

$$\Delta\phi = k_{\text{eff}} g T^2$$

Large phase resolution

Large momentum transfer

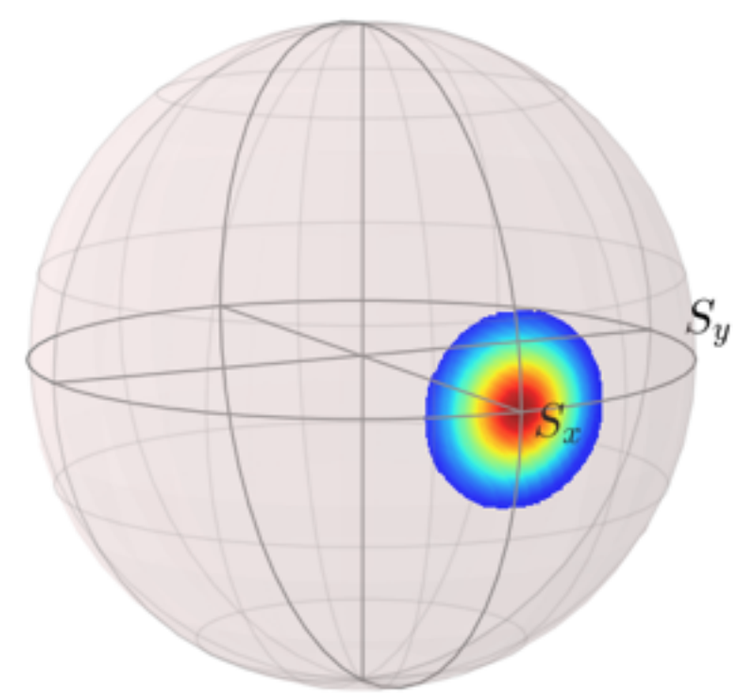
Long interrogation times

Coherent spin state

$$|\psi_{\text{CSS}}\rangle = \otimes_{i=1}^{N} \left[\cos\left(\frac{\theta}{2}\right) |\uparrow\rangle_i + \sin\left(\frac{\theta}{2}\right) e^{i\varphi} |\underset{S_z}{\downarrow}\rangle_i \right]$$

$$\delta(\Delta\phi) = \frac{1}{\sqrt{N}}$$

SQL



How do we improve sensitivity to gravity acceleration?

$$\Delta\phi = k_{\mathrm{eff}} g T^2$$

Large phase resolution

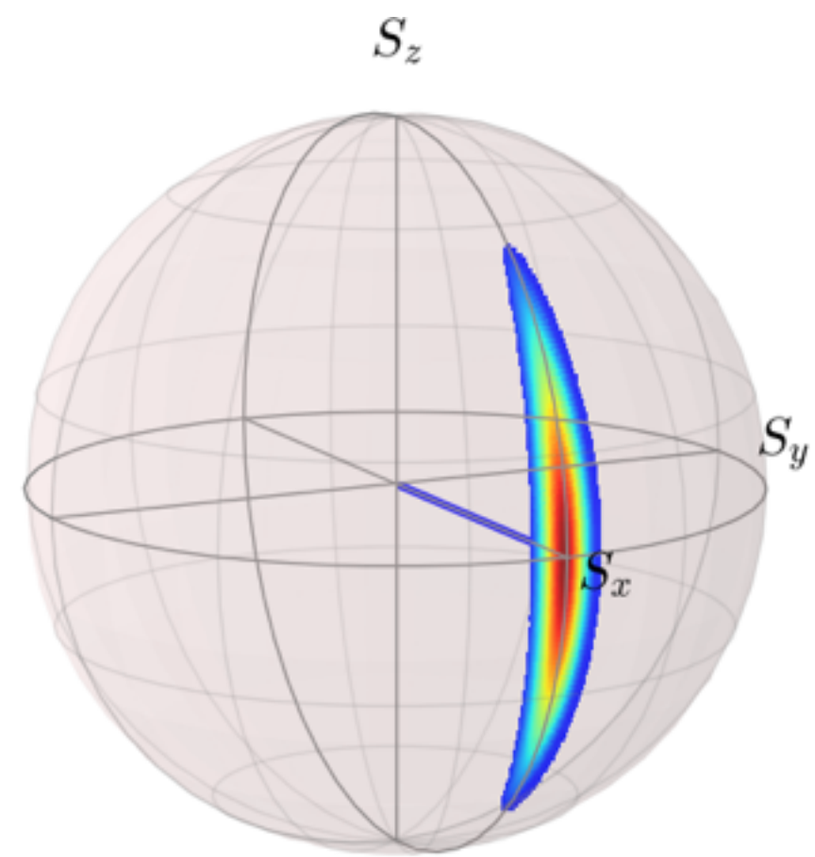
Large momentum transfer

Long interrogation times

Spin Squeezed State

$$\delta(\Delta\phi) \propto \frac{1}{N^{\alpha}}, \frac{1}{2} < \alpha < 1$$

Kitagawa & Ueda, Phys. Rev. A **47**, 5138 (1993)



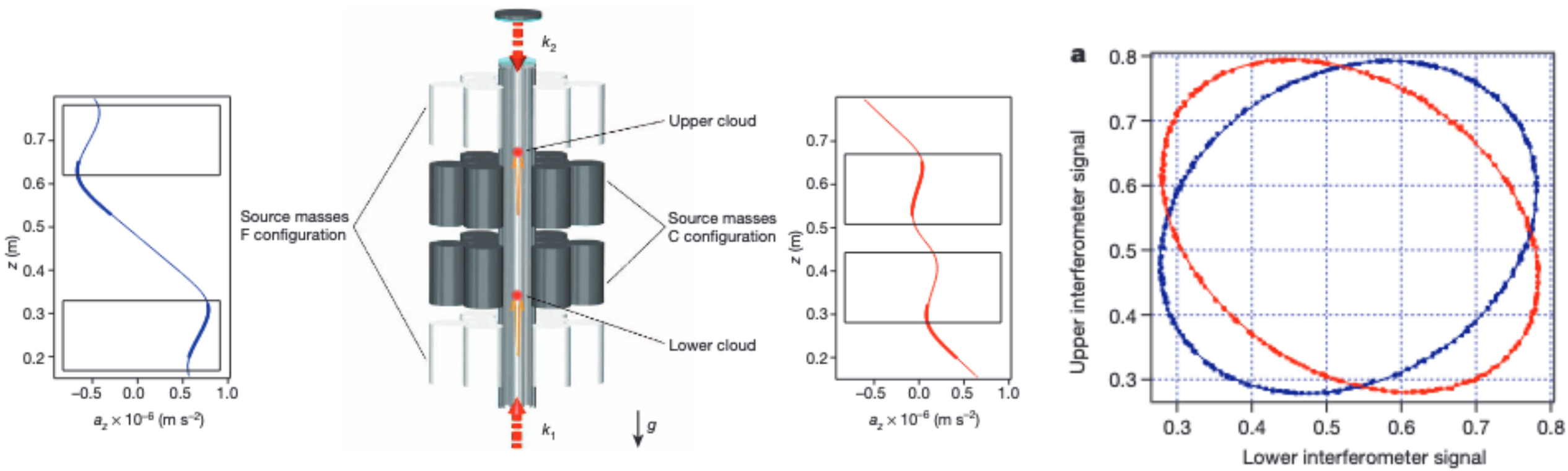
State-of-the-art AI-gradiometers do attain the SQL

LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]



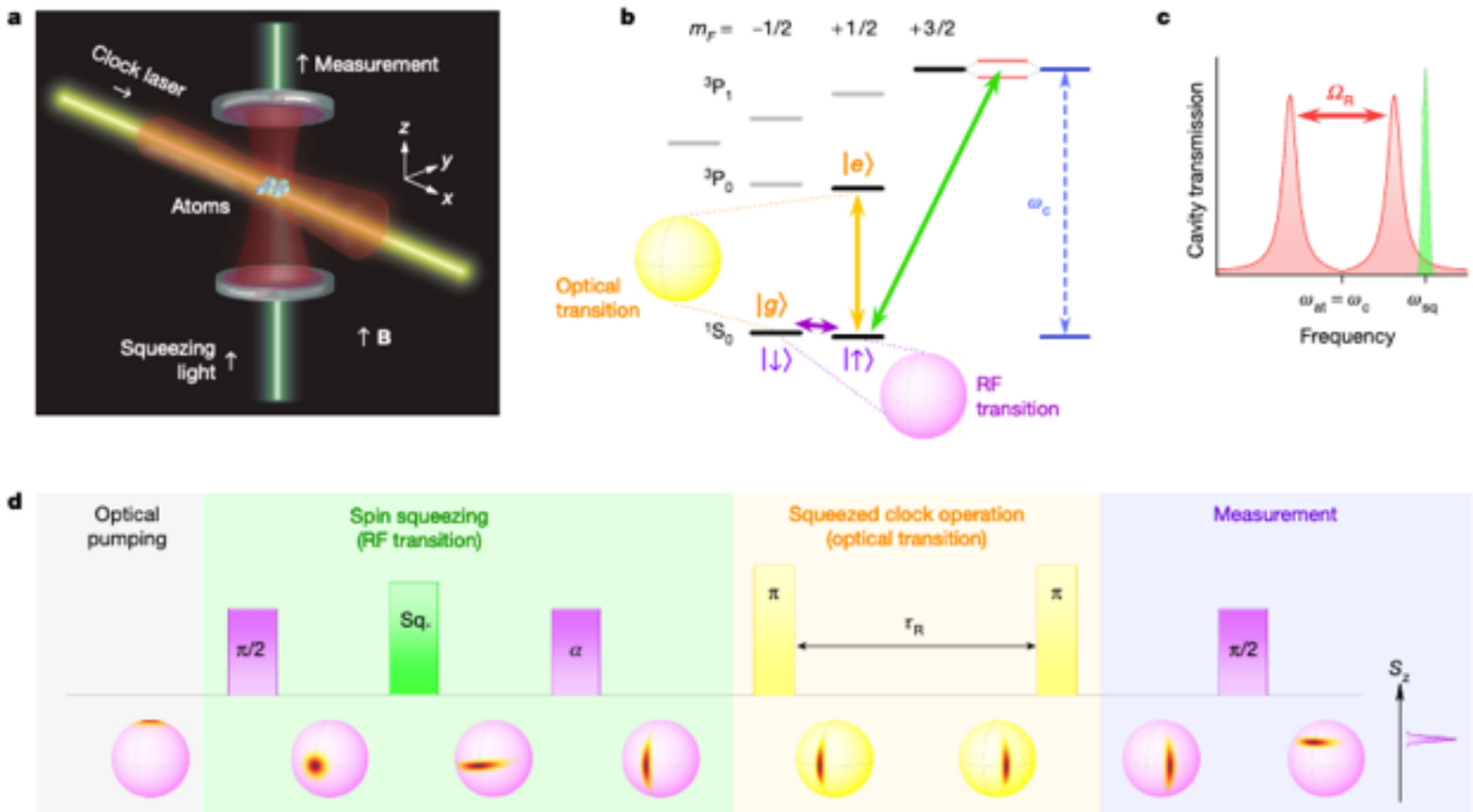
Systematic uncertainty: 92 ppm

Statistical uncertainty: 116 ppm

Article

Entanglement on an optical atomic-clock transition

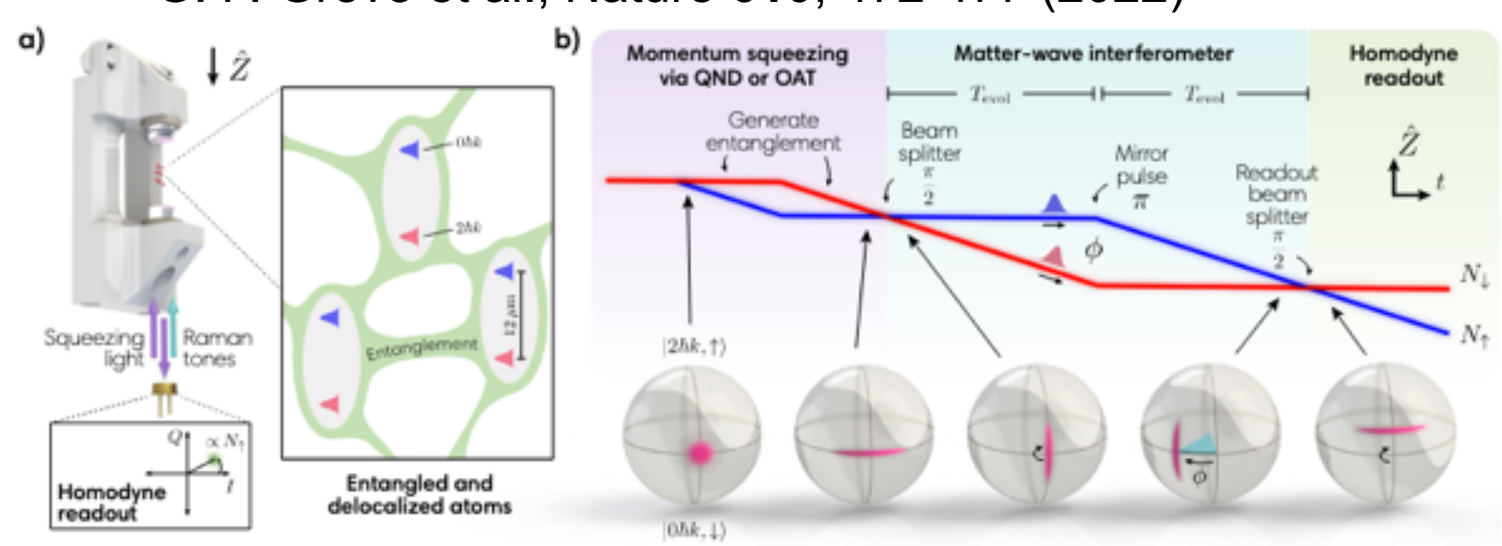
Pedrozo-Penafiel et al., Nature **588**, 414-418 (2020)



Article

Entanglement-enhanced matter-wave interferometry in a high-finesse cavity

G. P. Greve et al., Nature **610**, 472-477 (2022)

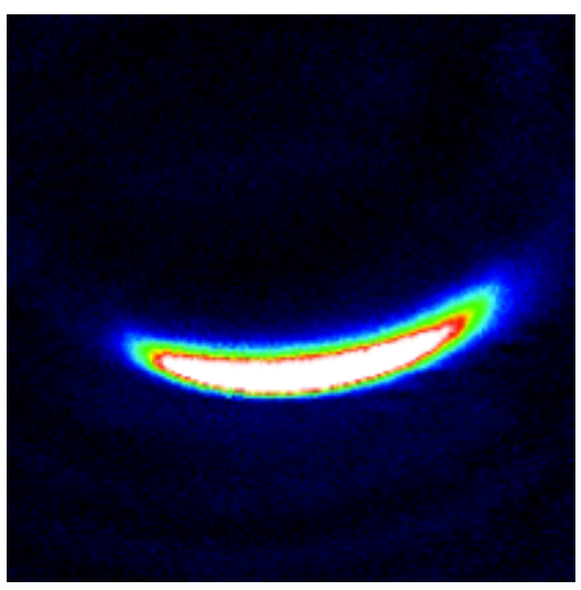


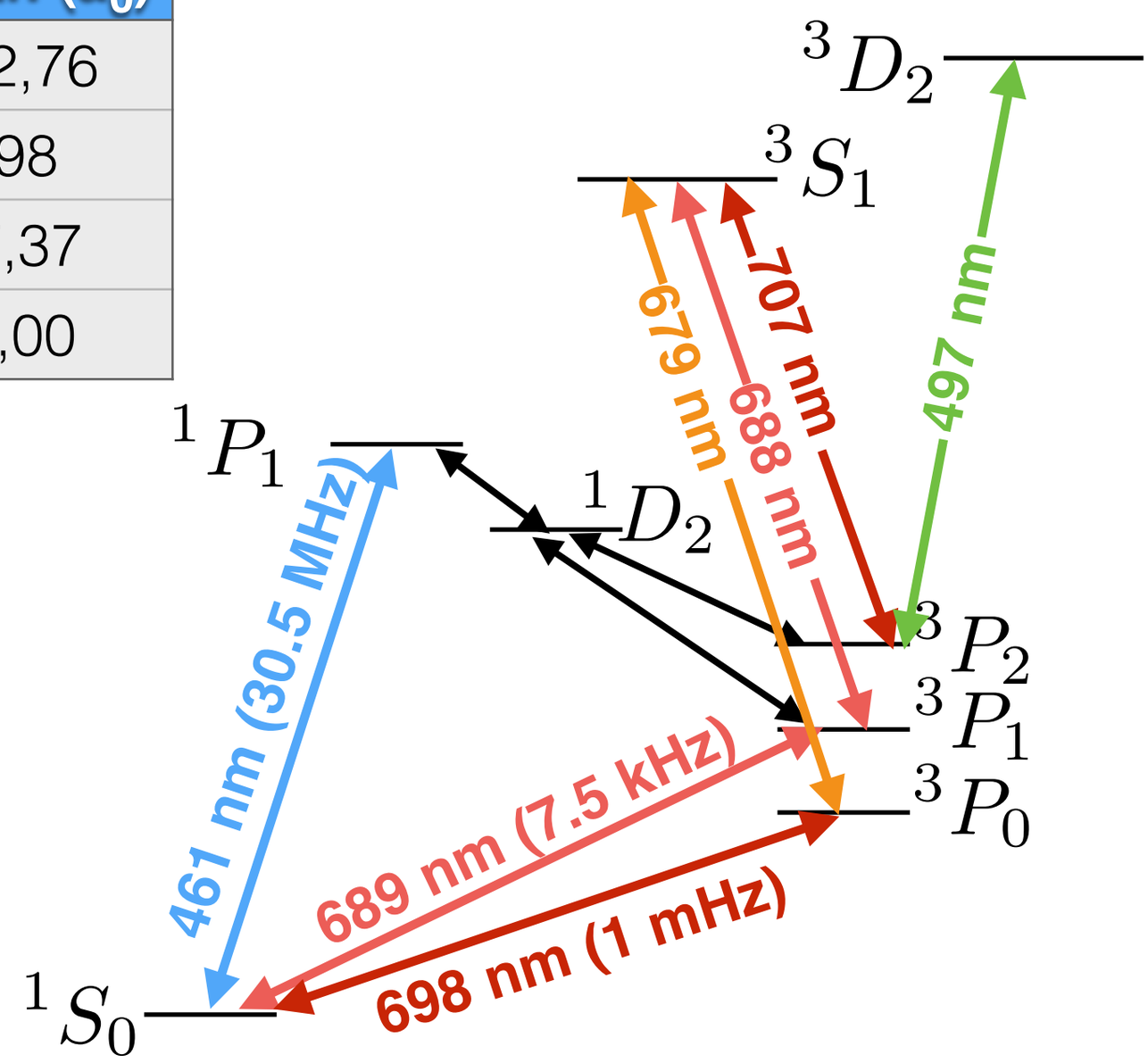
Strontium for Atom Interferometry

Atomic mass	Abundance	Nuclear spin	Scattering length (a_0)
84	0,56%	0	122,76
86	9,86%	0	798
87	7,00%	9/2	97,37
88	82,58%	0	-2,00

$^1S_0 - {}^1P_1$

$^1S_0 - {}^3P_1$

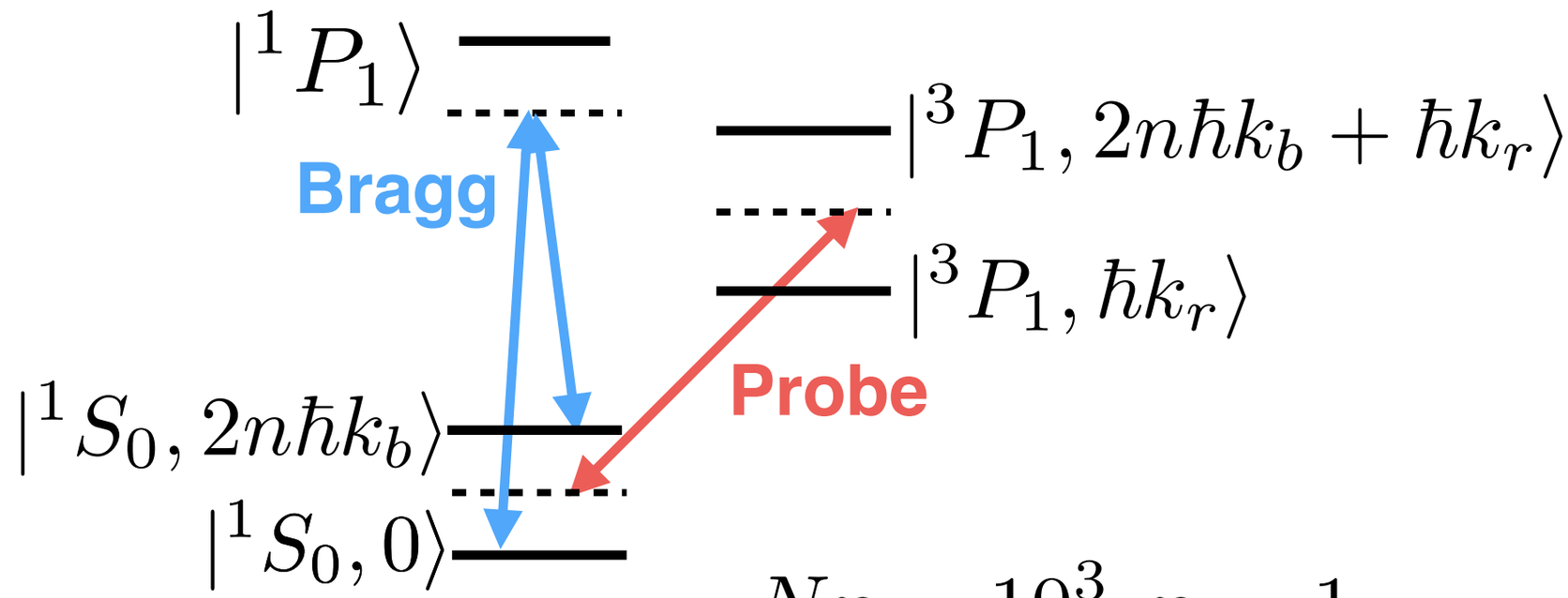


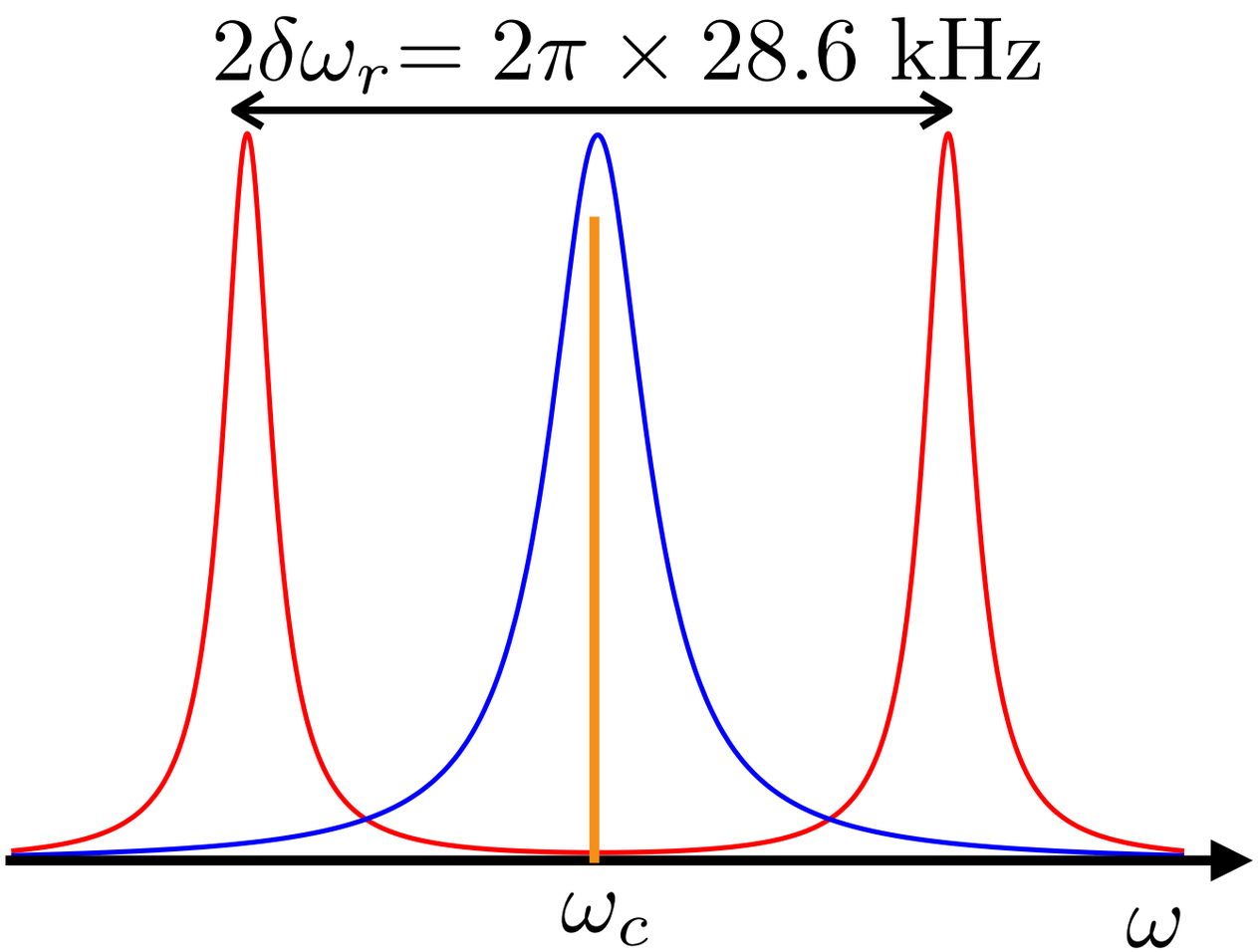


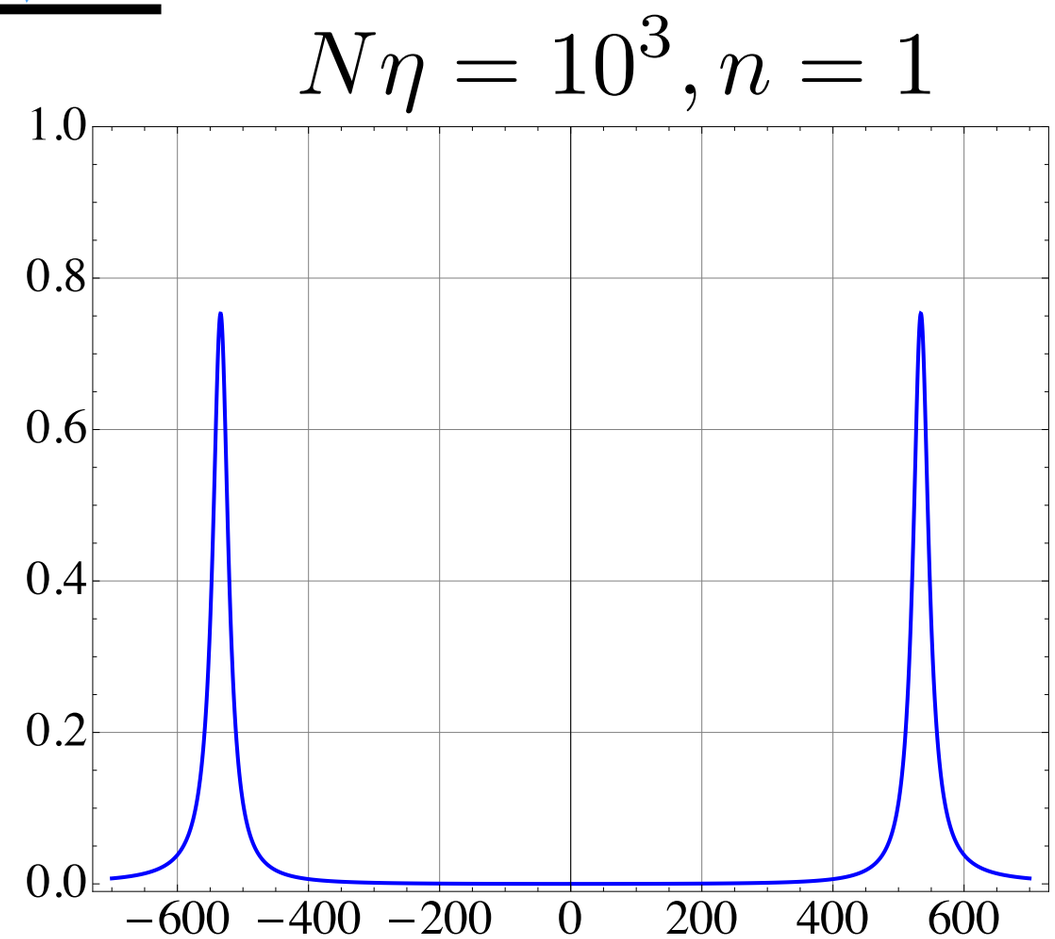
- Mazzoni et al., Phys. Rev. A **92**, 053619 (2015)
- Del Aguila et al., New J. Phys. **20,** 043002 (2018)
- Hu et al., Phys. Rev. Lett. **119**, 263601 (2017)

Probing of Sr momentum state superpositions

- With the intercombination transition, momentum states can be distinguished via the Doppler effect
- Resonant absorption can spoil the cavity finesse







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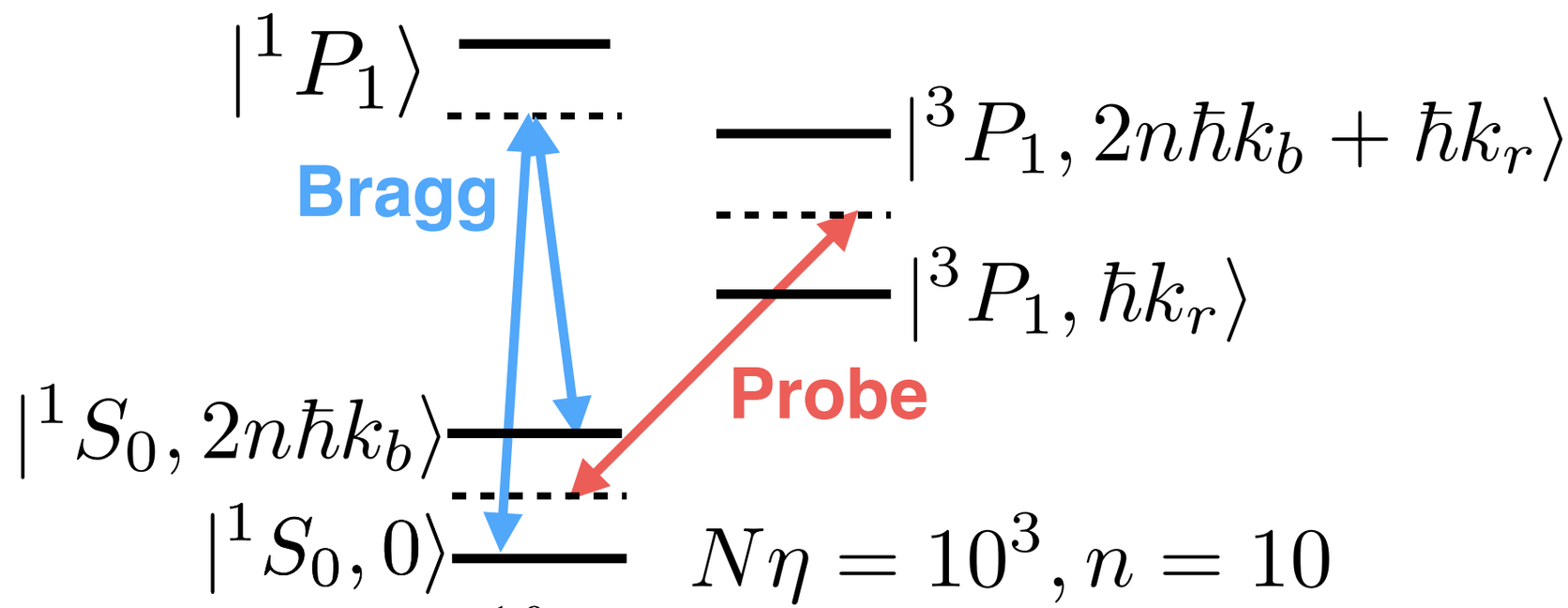

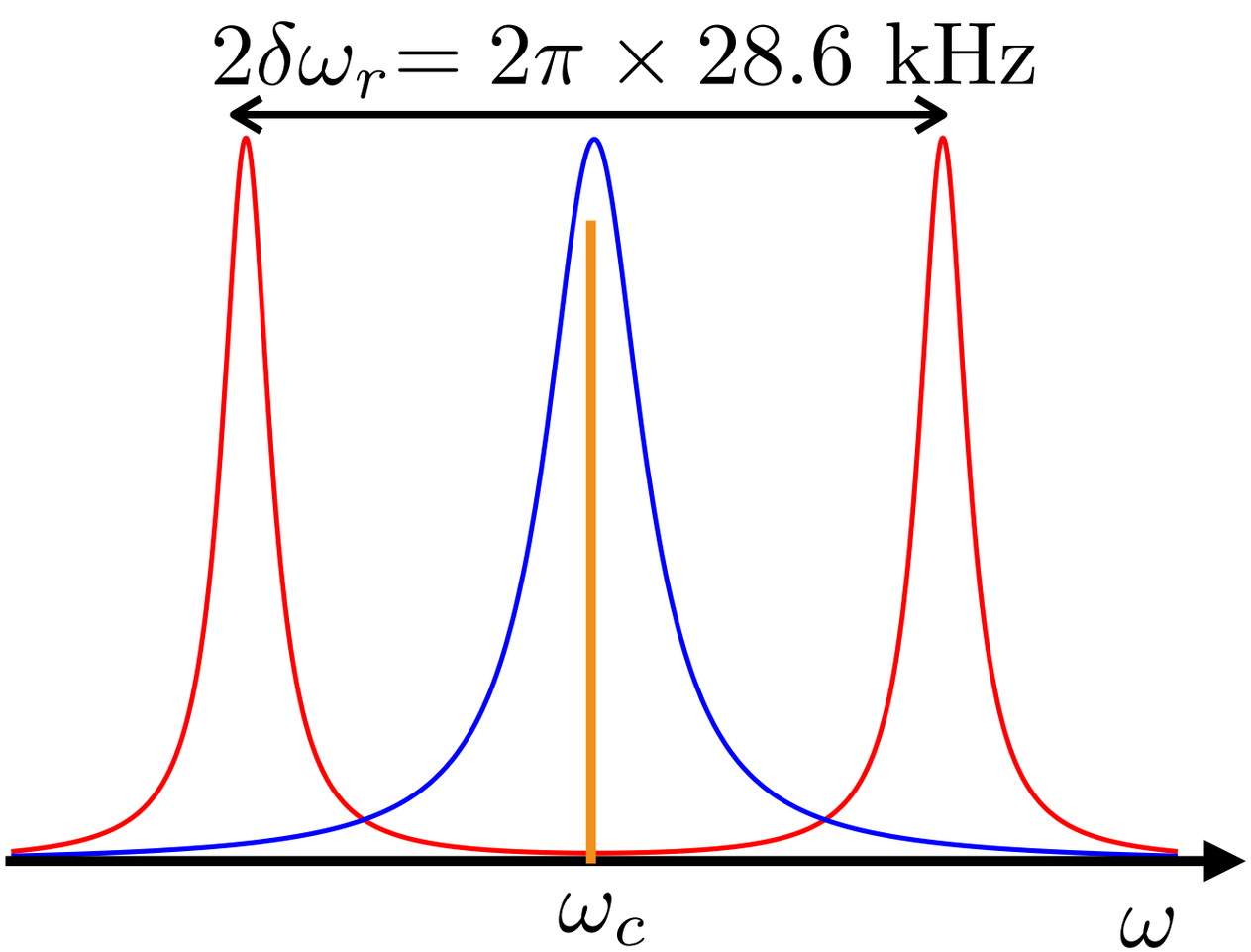

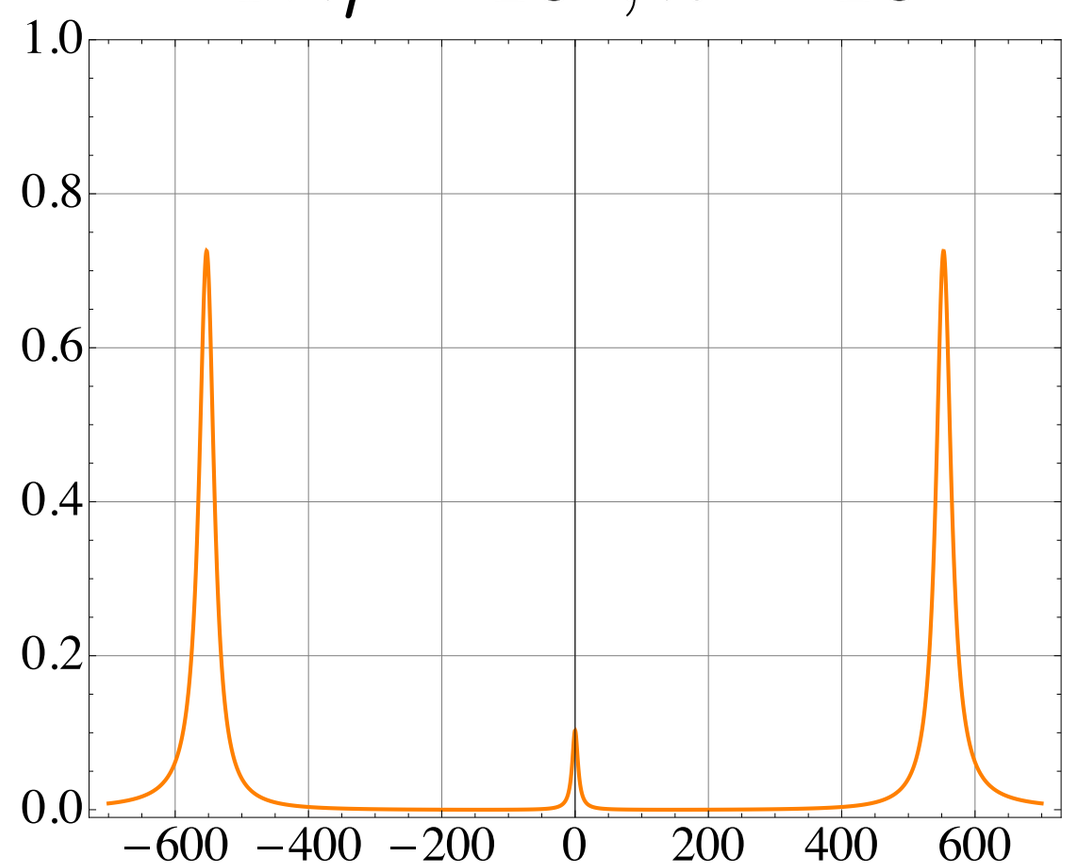

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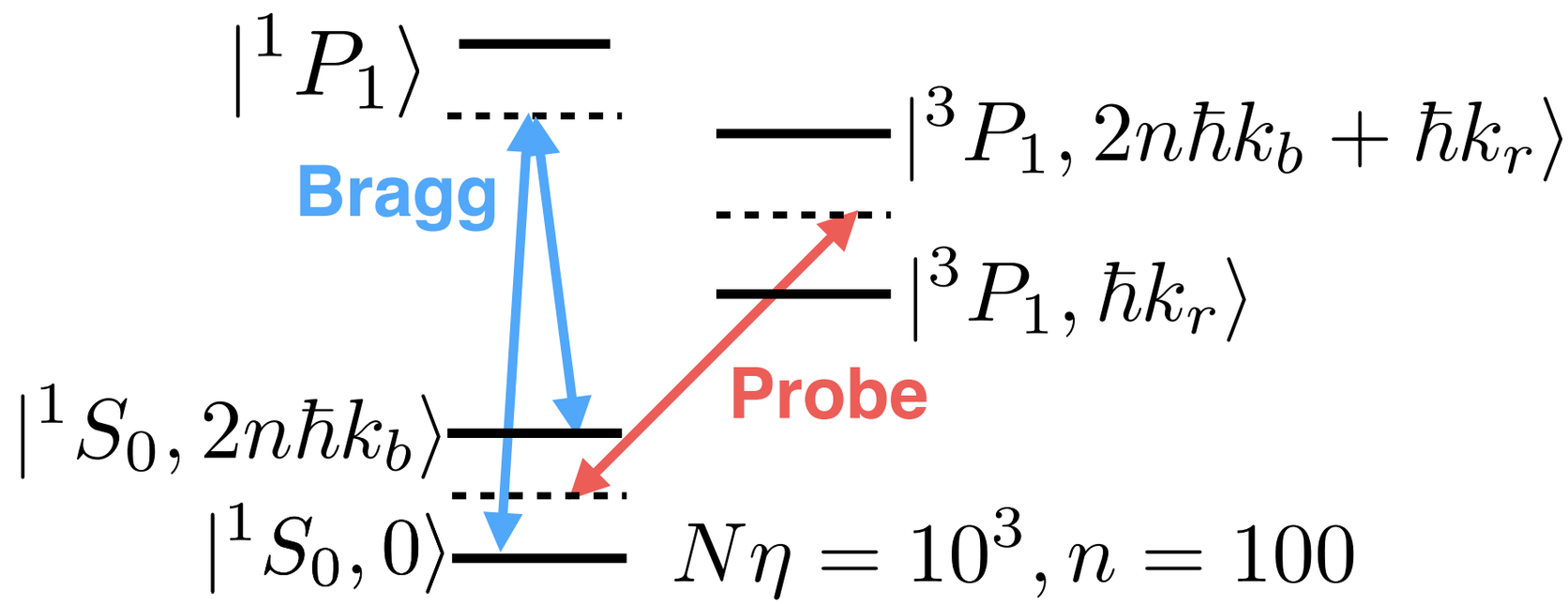
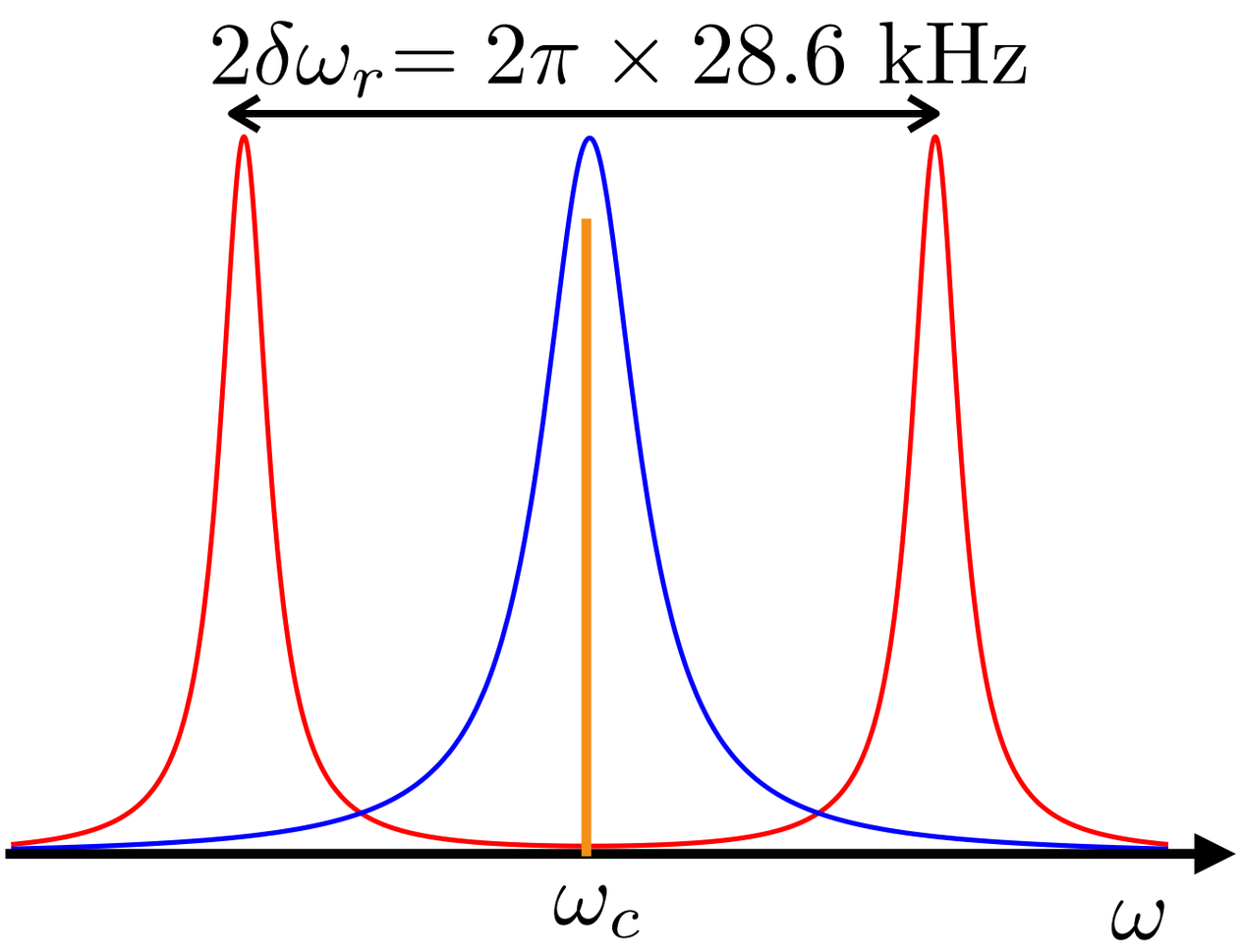
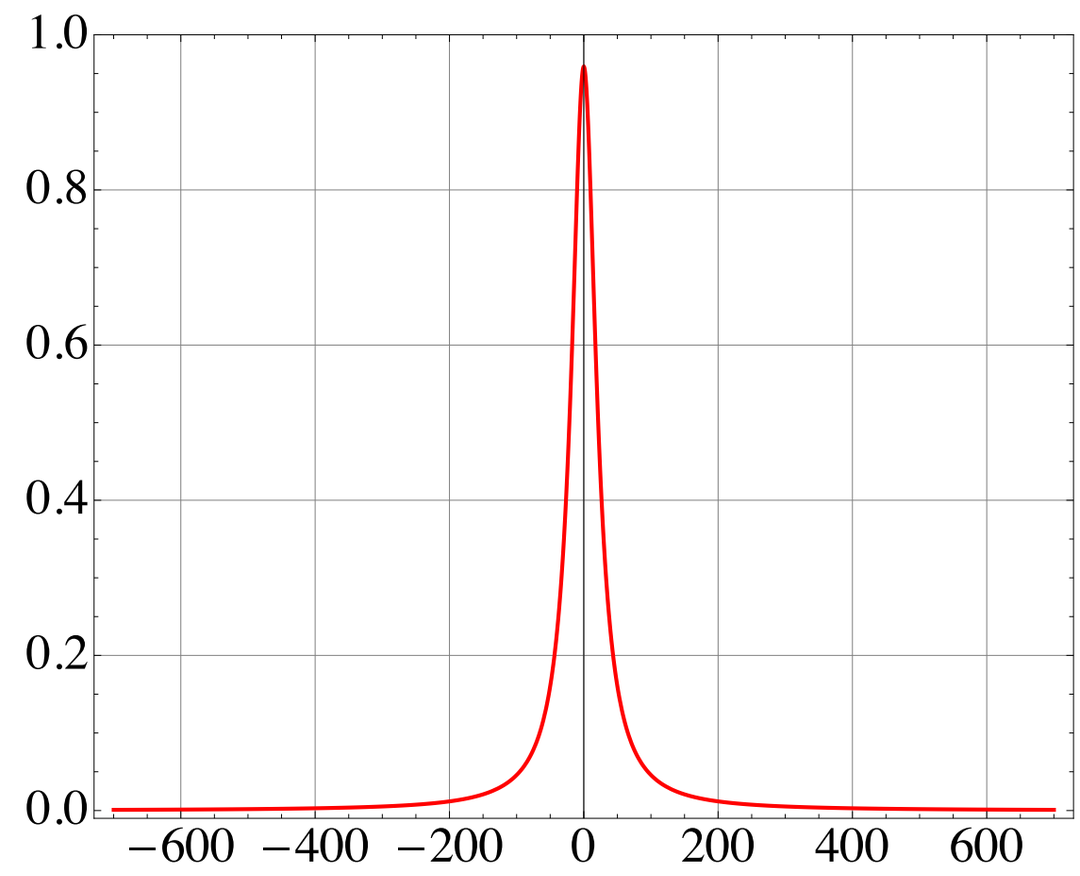
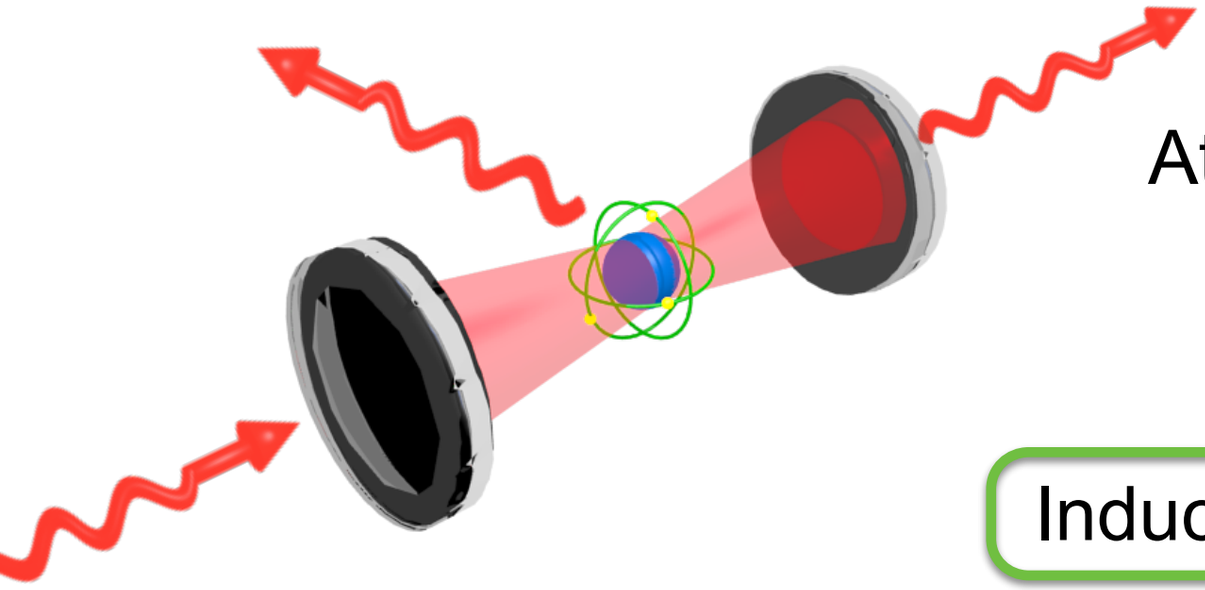






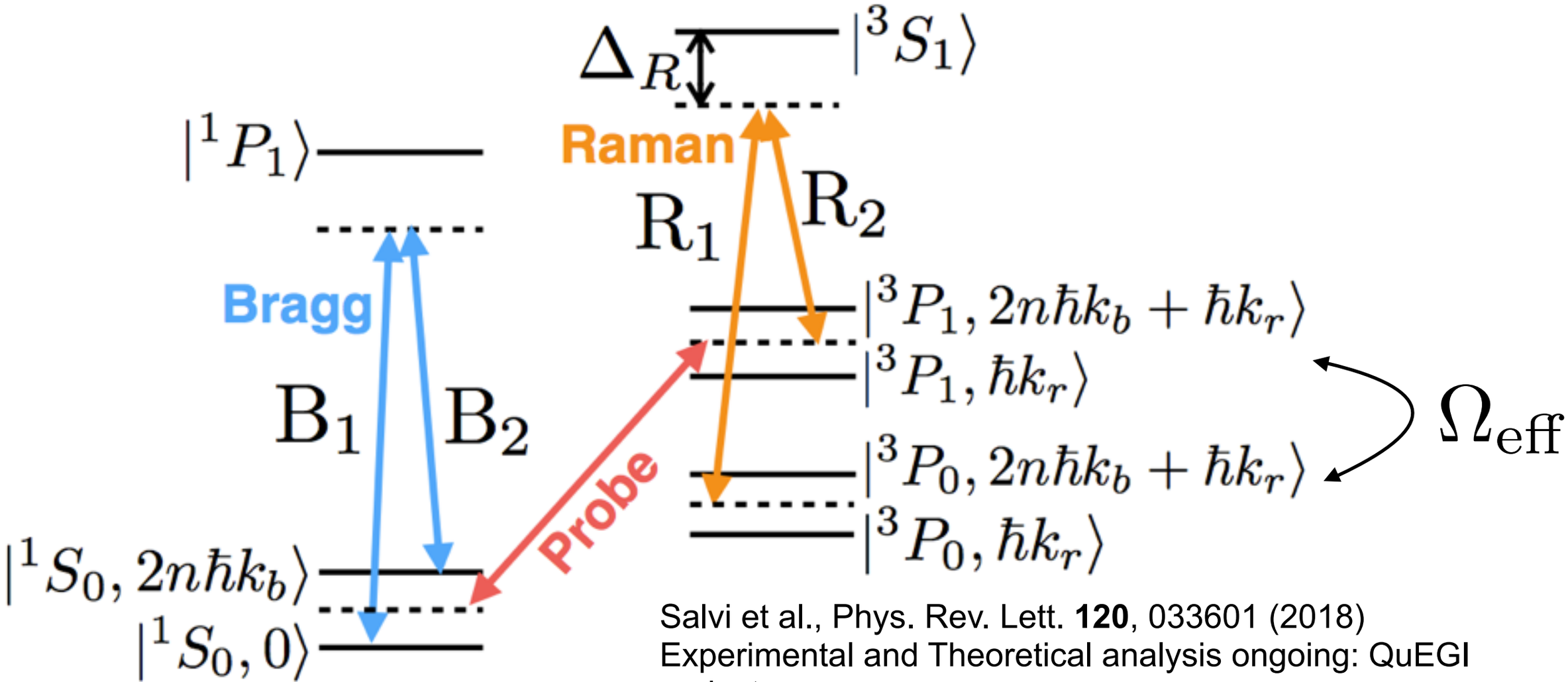
EIT-enhanced momentum squeezing



Atomic opacity at small diffraction orders

↓

Induce transparency in the medium (EIT)



Salvi et al., Phys. Rev. Lett. **120**, 033601 (2018)
Experimental and Theoretical analysis ongoing: QuEGI project

Atom Interferometry on an Optical Clock transition

PRL 119, 263601 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

Atom Interferometry with the Sr Optical Clock Transition

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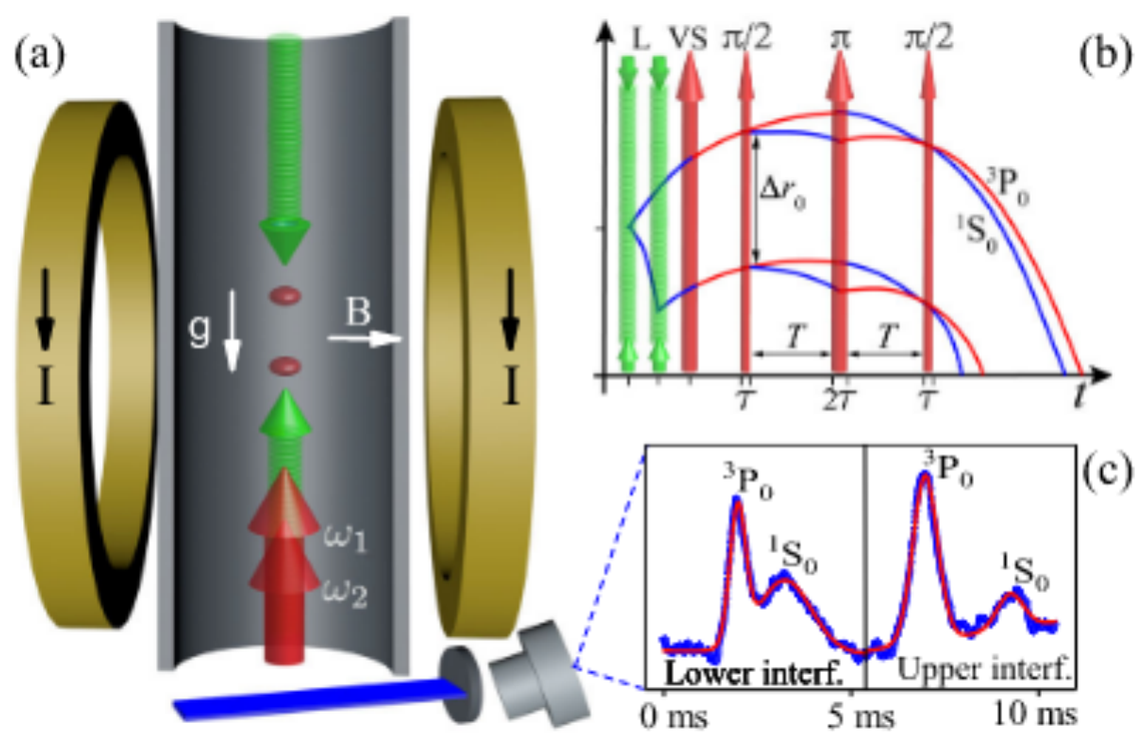
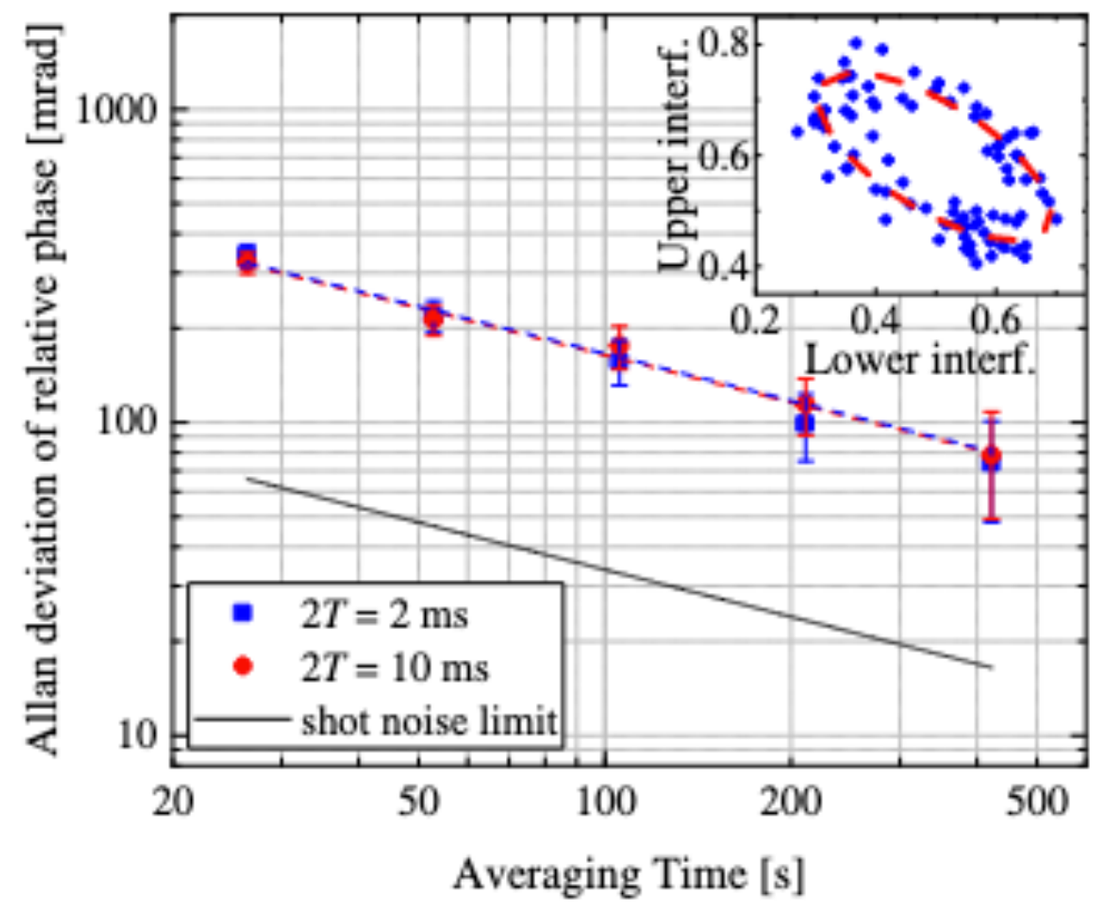
(Received 15 August 2017; published 27 December 2017)

We report on the realization of a matter-wave interferometer based on single-photon interaction on the ultranarrow optical clock transition of strontium atoms. We experimentally demonstrate its operation as a gravimeter and as a gravity gradiometer. No reduction of interferometric contrast was observed for a total interferometer time up to ~10 ms, limited by geometric constraints of the apparatus. Single-photon interferometers represent a new class of high-precision sensors that could be used for the detection of gravitational waves in so far unexplored frequency ranges and to enlighten the boundary between quantum mechanics and general relativity.

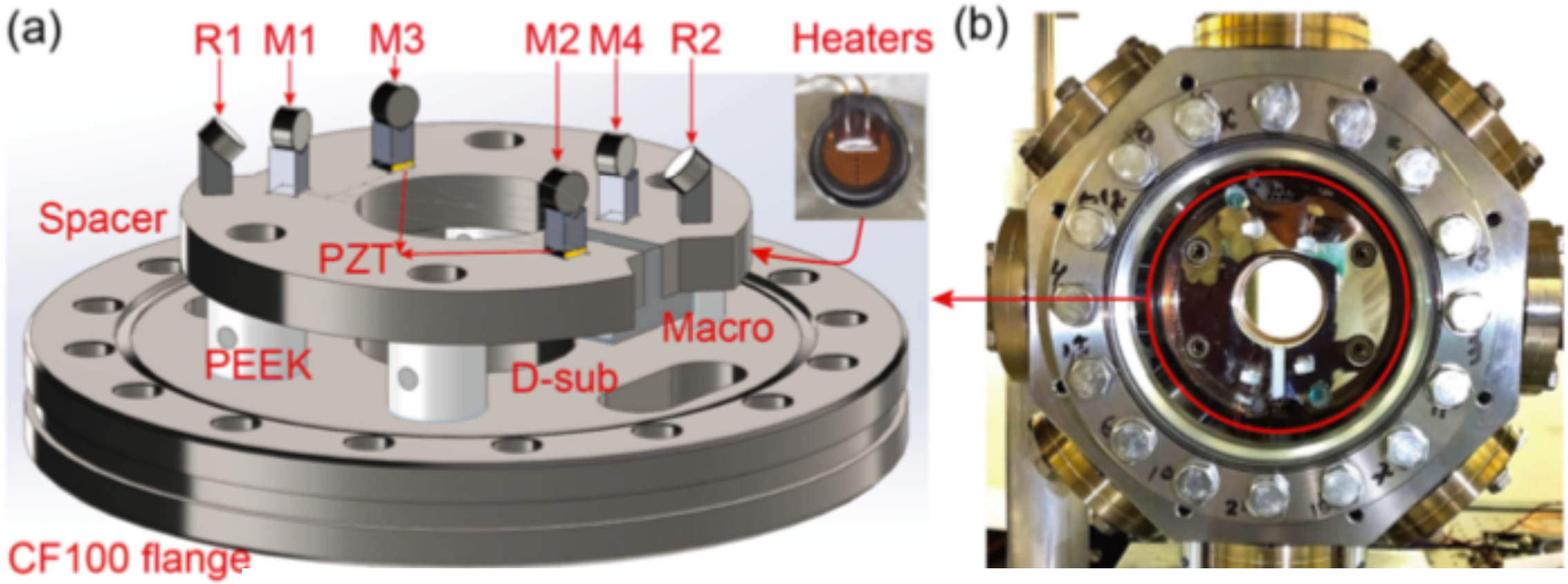
DOI: 10.1103/PhysRevLett.119.263601





See also: L. Hu et al., Class. Quantum Grav. **37**, 014001 (2020)

Optical ring cavity in the vacuum chamber



Single-atom cooperativity

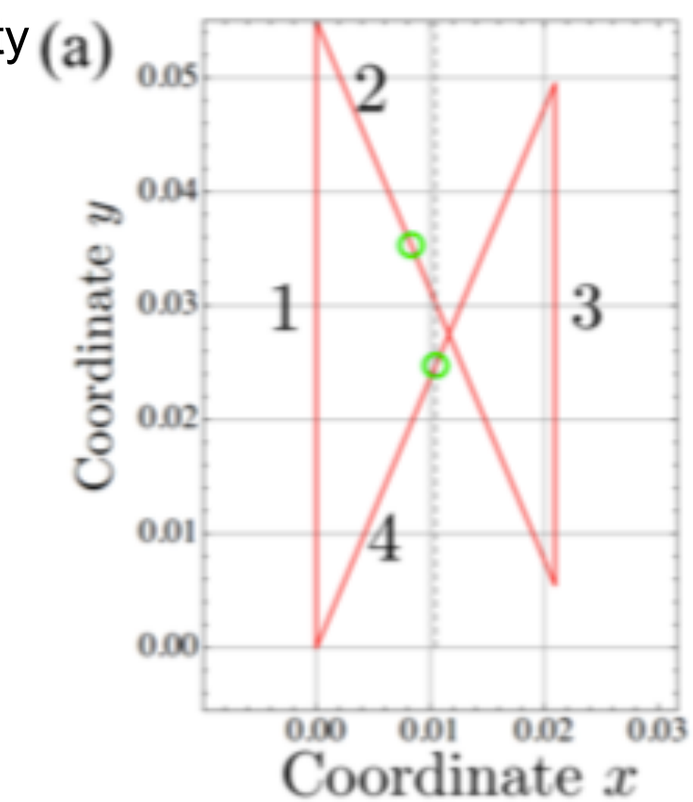
$$\eta = \frac{6F}{\pi k^2 w^2}$$

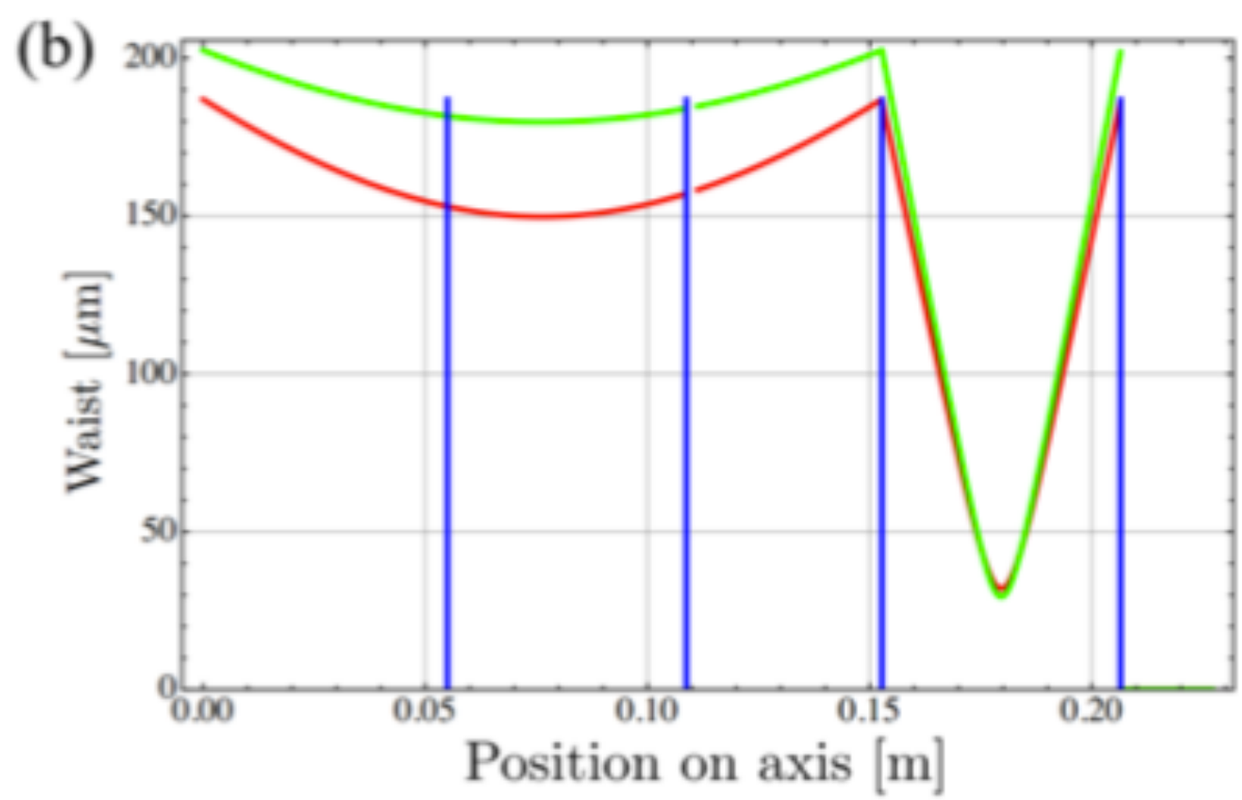
Large waist

$$\eta \simeq 0.02$$

Small waist

$$\eta \simeq 0.6$$





Measured parameters of the optical cavity

Parameters for the 689 nm probe transition

Parameter	Value	Unit
Mirror Radius of Curvature	Flat, 50, 50, Flat	mm
Mirror transmission	219.6(4),<0.2,<0.2,6.6(1)	ppm
Free spectral range	1.4475(5)	GHz
Mode linewidth	65.6(1)	kHz
Finesse	$2.2(2)\times10^{4}$	—

Measured parameters of the optical cavity

Transmissions (in ppm) for three relevant wavelengths

Magic wavelength for clock transition

Mirror	461 nm (H/V)	689 nm (H/V)	813 nm (H/V)
1	10993(4)/9573(8)	303.8(4)/219.6(4)	1926(6)/1396(5)
2	904(9)/652(5)	<0.2/<0.2	266(2)/183(8)
3	1032(3)/851(9)	<0.2/<0.2	258(8)/171(7)
4	10258(9)/9372(9)	8.8(1)/6.6(1)	1246(3)/1012(6)

PHYSICAL REVIEW A **103**, 022609 (2021)

Method for the differential measurement of phase shifts induced by atoms in an optical ring cavity

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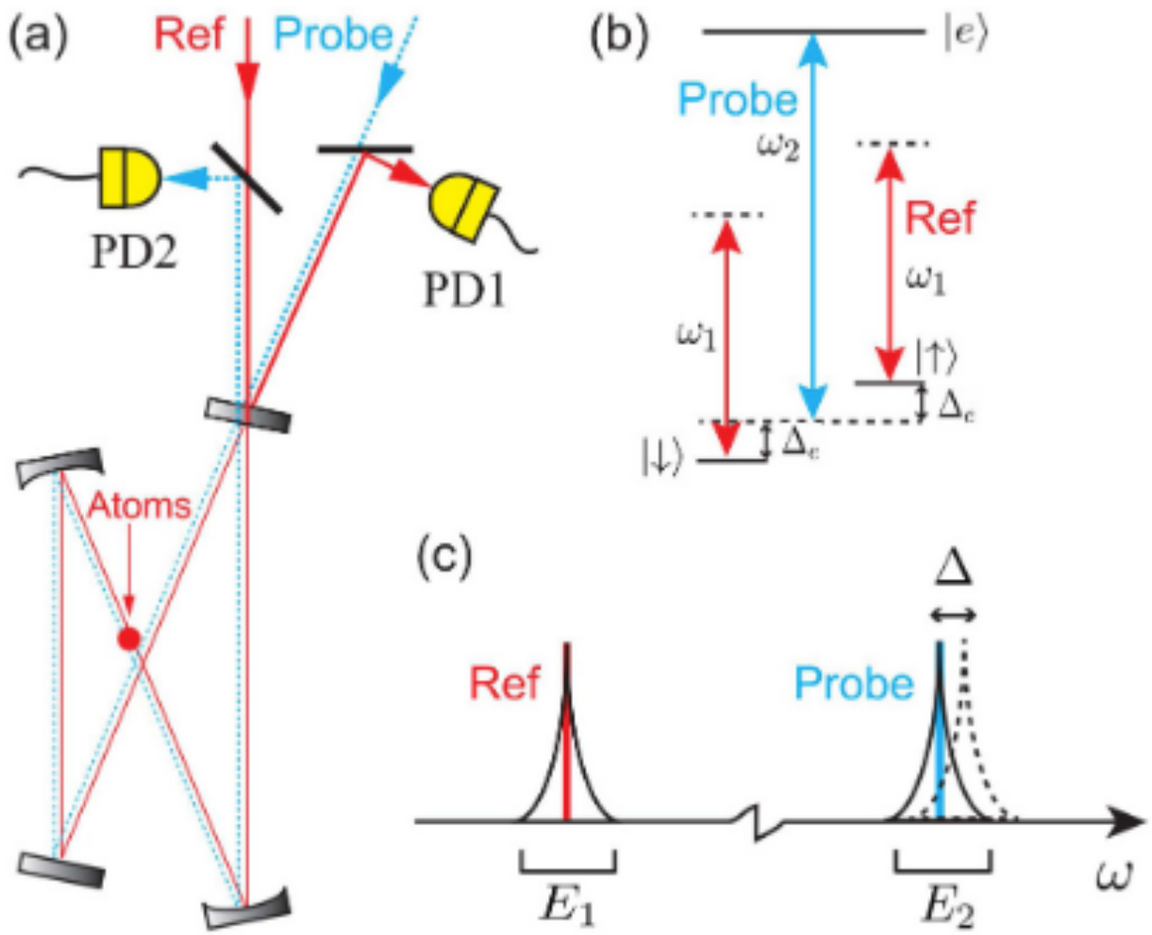
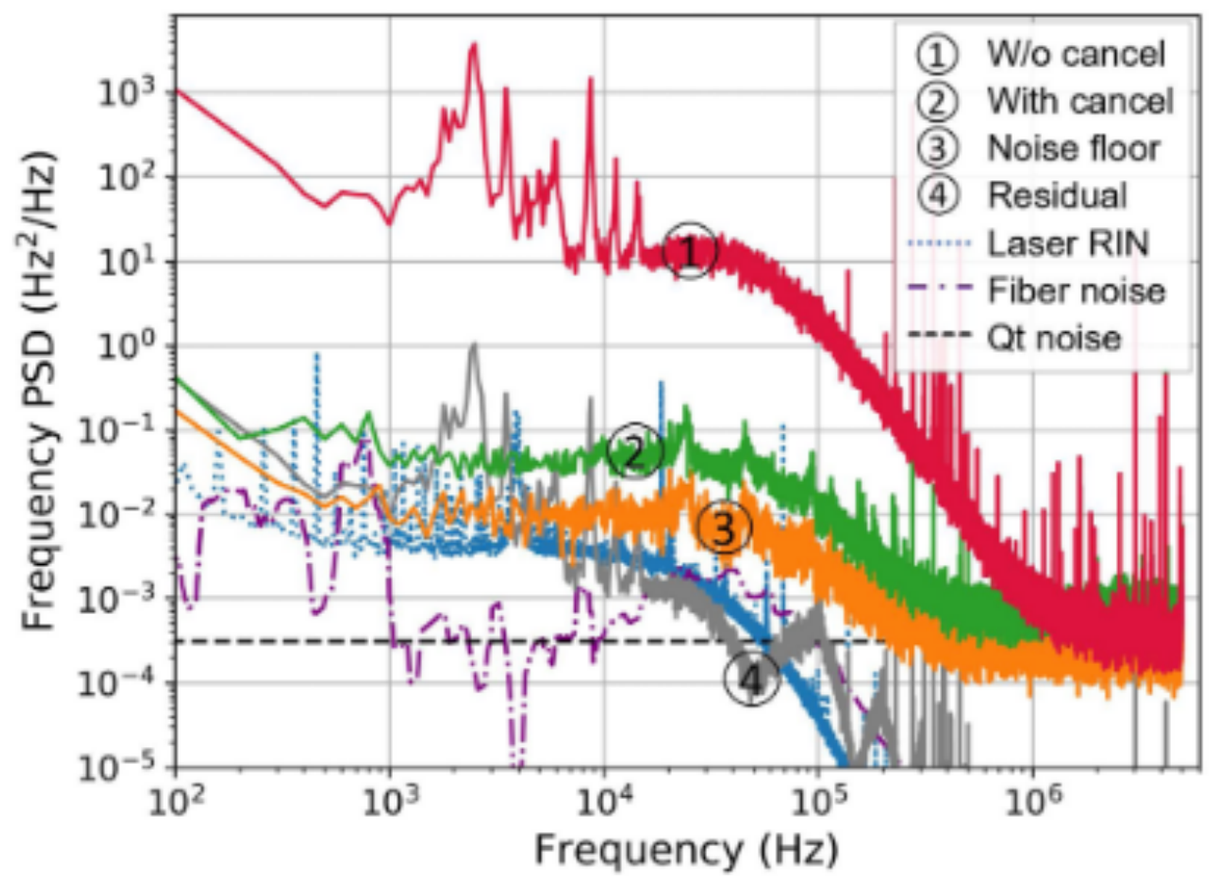
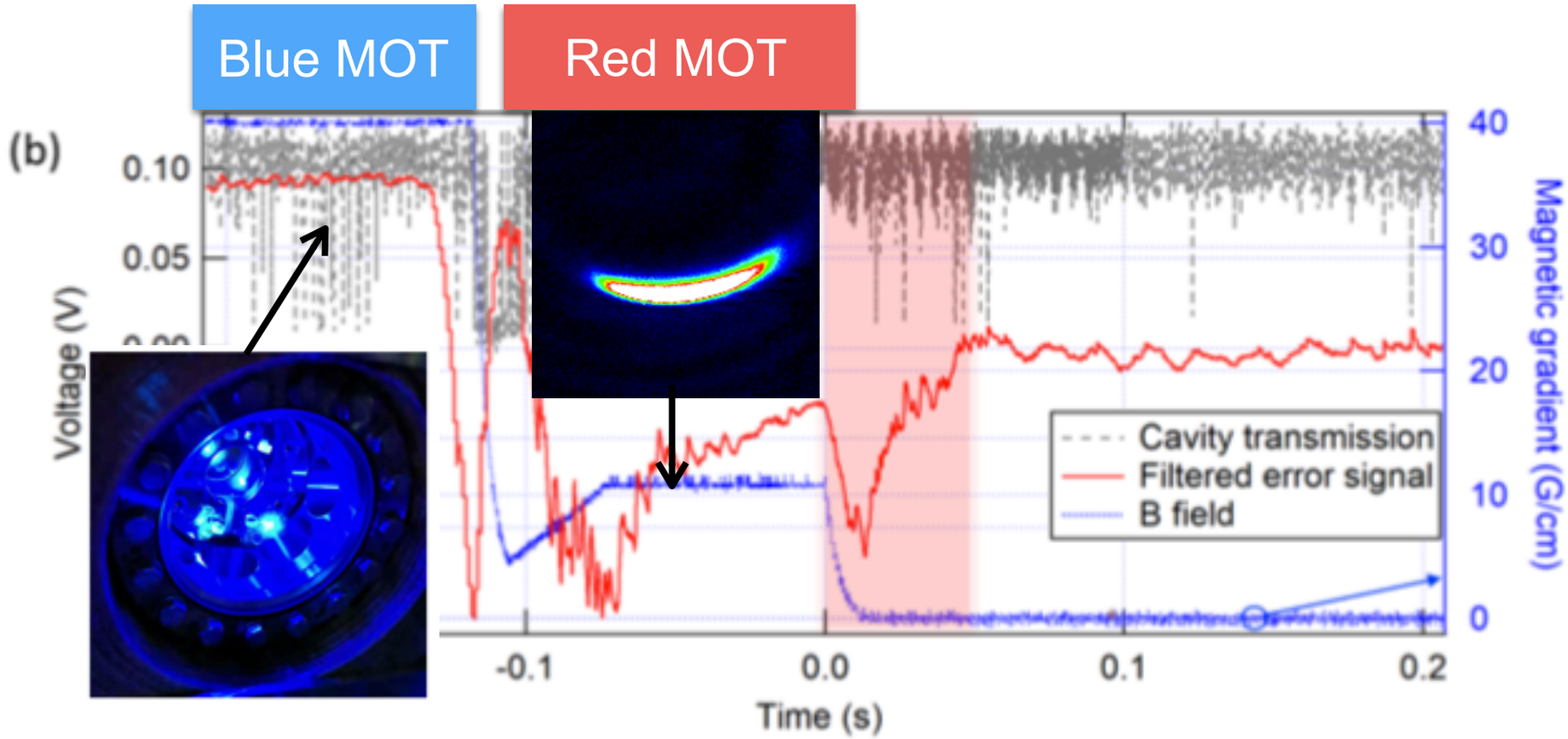
(Received 11 September 2020; accepted 14 January 2021; published 16 February 2021)





First signatures of atom-cavity coupling

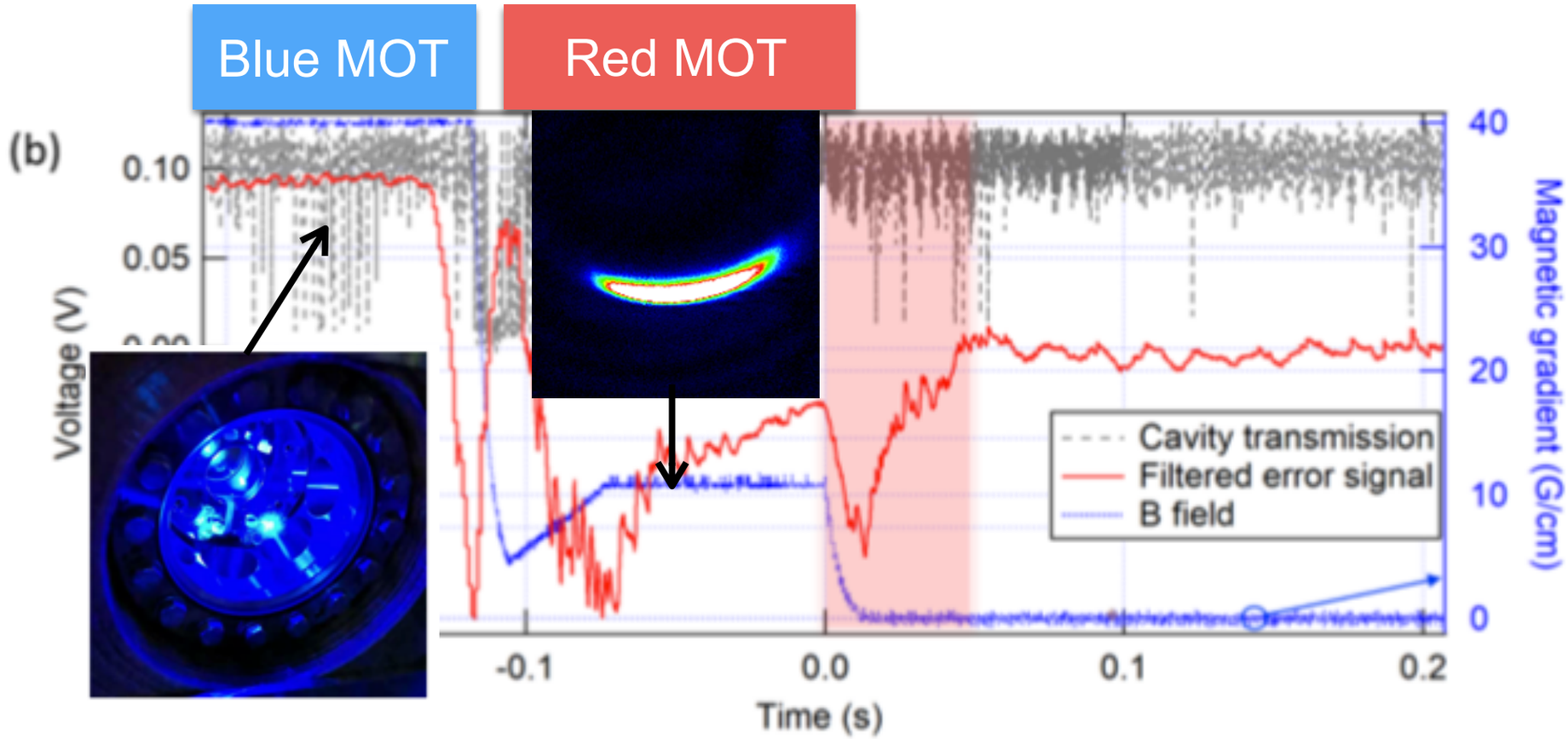


Master equation for the coupled atom-cavity system

$$\frac{d\rho}{dt} = \frac{i}{\hbar}[\rho, H] + \frac{\kappa}{2}(2c\rho c^\dagger - c^\dagger c\rho - \rho c^\dagger c) + \frac{\Gamma}{2}\sum_j (2\sigma_-^{(j)}\rho\sigma_+^{(j)} - \sigma_+^{(j)}\sigma_-^{(j)}\rho - \rho\sigma_+^{(j)}\sigma_-^{(j)})$$

$$H = \frac{\hbar\omega_0}{2}\sum_j \sigma_z^{(j)} + \hbar\omega_c c^\dagger c + i\hbar g \sum_j \left[\mathcal{E}(\vec{r}_j)\sigma_+^{(j)} c - \mathcal{E}^*(\vec{r}_j) c^\dagger \sigma_-^{(j)}\right]$$

First signatures of atom-cavity coupling



Mean-field steady-state equation for the cavity photon amplitude

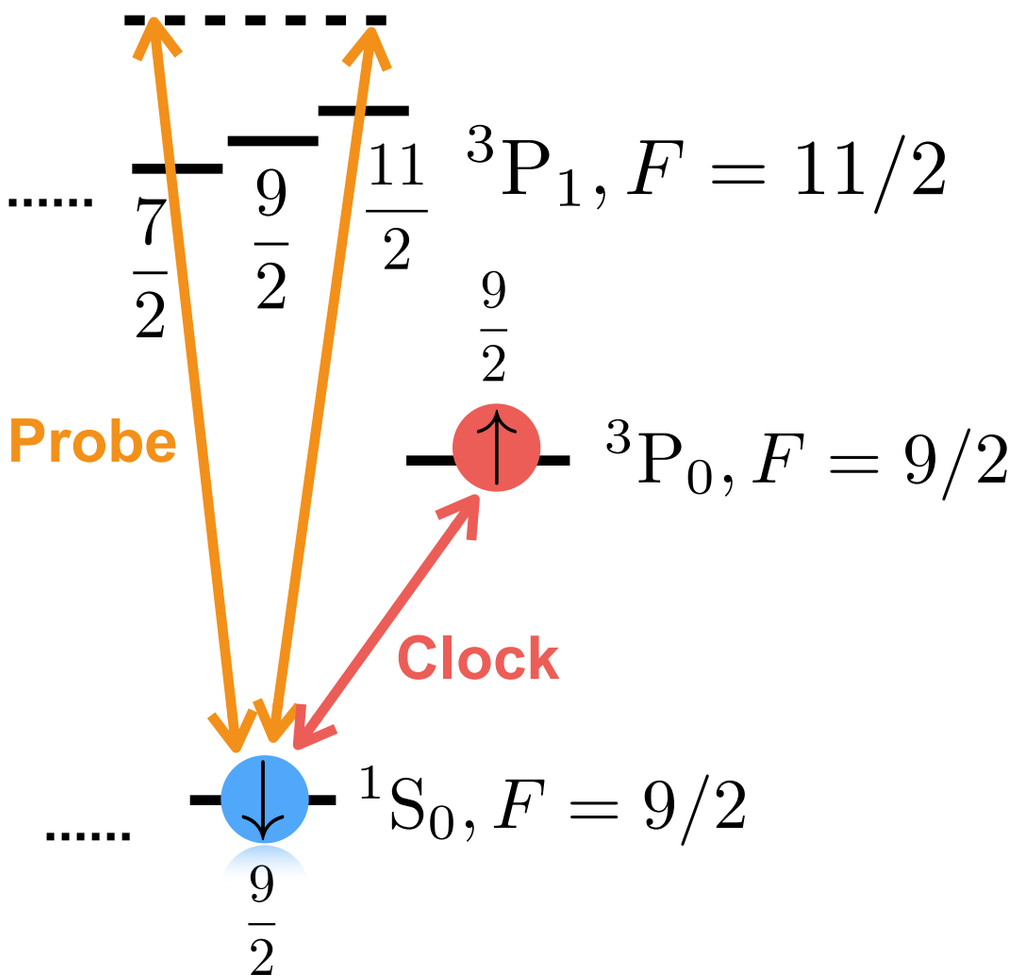
$$\left(i\delta_c - \frac{\kappa}{2}\right)\langle c\rangle - \sqrt{\kappa_{in}}\beta + \frac{g^2\langle c\rangle}{i\Delta - \Gamma/2}\sum_j \frac{|\mathcal{E}(\vec{r}_j)|^2}{1 + \frac{2g^2|\mathcal{E}(\vec{r}_j)|^2|\langle c\rangle|^2}{\Delta^2+(\Gamma/2)^2}} = 0$$

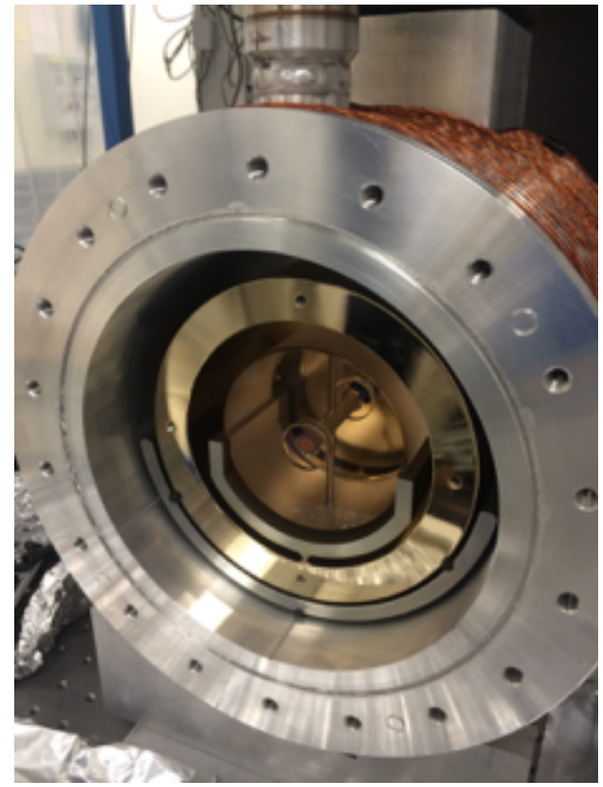
Intracavity photon number approximated by its empty cavity value (strong saturation or far detuning)

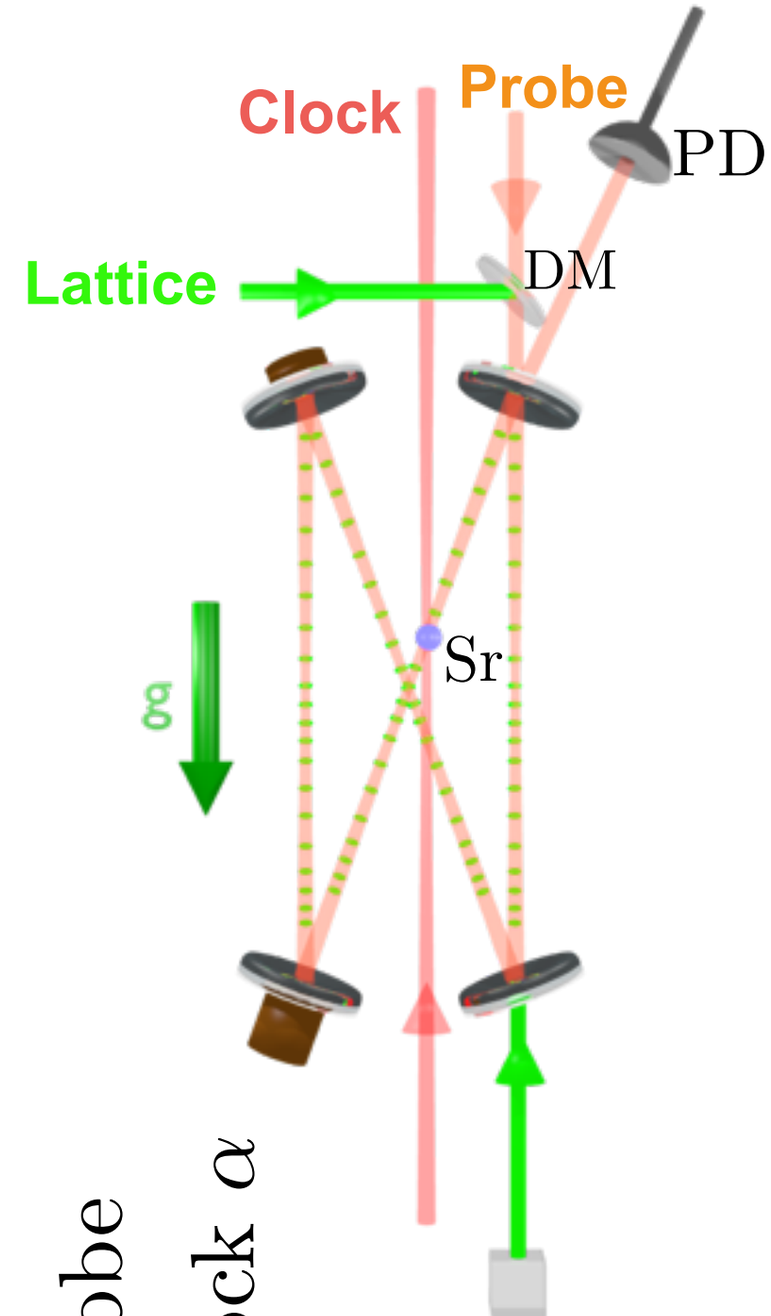
$$|\langle c\rangle|^2 \sim 4\kappa_{in}\beta^2/\kappa^2$$

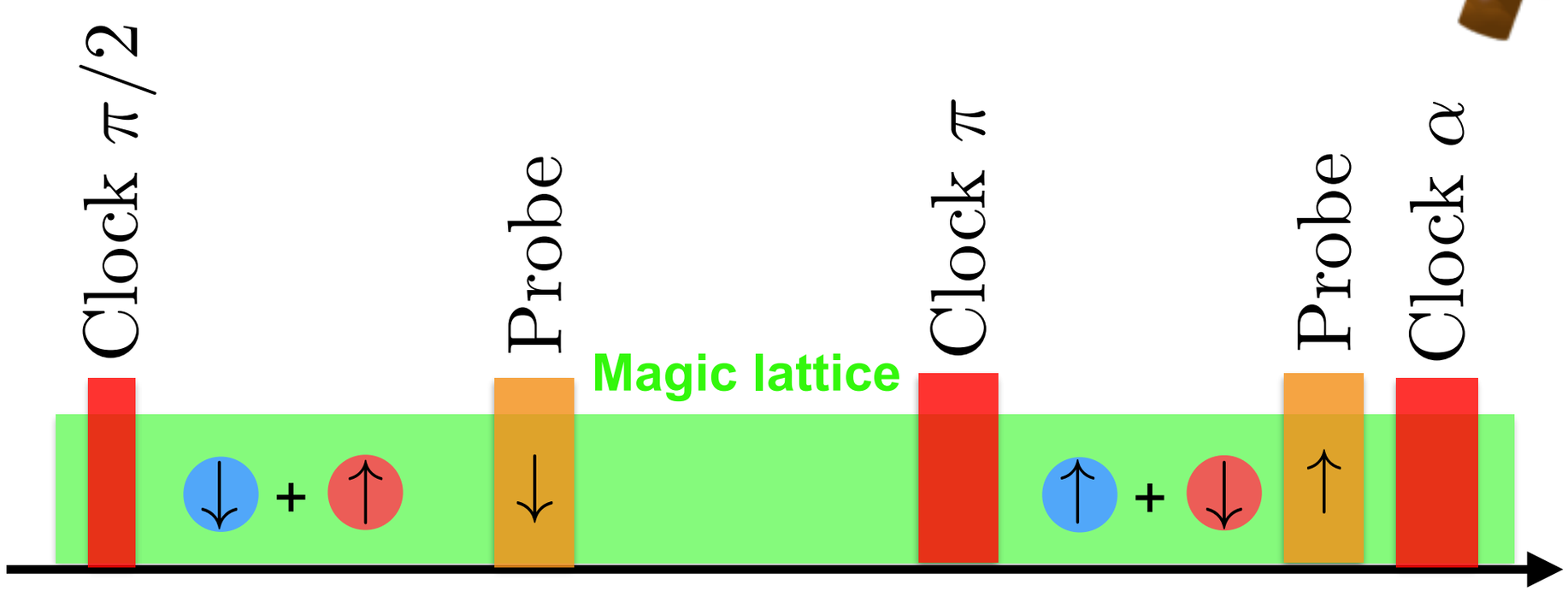
Adding the dipole and scattering forces from the probe beam one explains the long signal tail.

Towards squeezing on the optical clock transition









Conclusions

- Proposal for direct momentum squeezing scheme for strontium atoms
- Realization of a high-finesse bow-tie ring cavity allowing for homogeneous atom-cavity coupling in a vacuum apparatus
- Common-mode cavity noise cancellation for the collective probing of the atomic ensemble
- First signatures of atom-cavity coupling observed for a falling cold cloud
- Development of the apparatus for interferomerometry on the clock transition

Future work and challenges

⇒
- Study of EIT+squeezing
- EIT laser stabilization
- Explore the role of Bragg losses

⇒
- Trap atoms in magic wavelength intracavity optical lattice
- Improve locking to the reference 689 nm laser

⇒
- Homodyne detection of the atom induced shift of the cavity resonance frequency

⇒
- MOPA for atom interferometry
- Validation of the low phase noise of the clock laser