Quantum Enhanced Cavity QED Interferometer with Partially Delocalized Atoms in Lattices

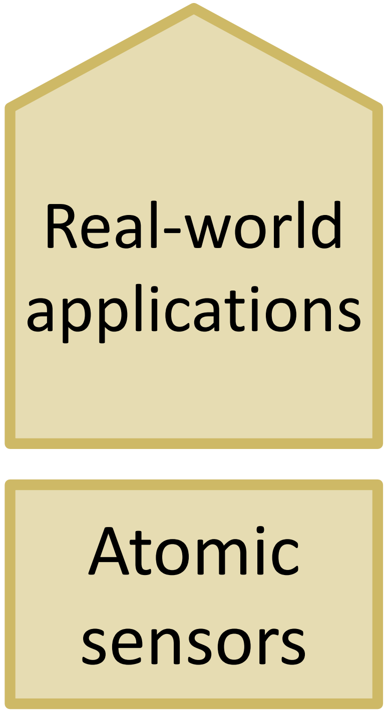
Anjun Chu

JILA, NIST and Department of Physics, University of Colorado Boulder

APS DAMOP Meeting, June 1st , 2021

arXiv:2104.04204 in collaboration with Peiru He, James K. Thompson and Ana Maria Rey

Quantum metrology with ultracold atoms



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[2]Meas. Sci. Technol. 20, 022001 (2009)
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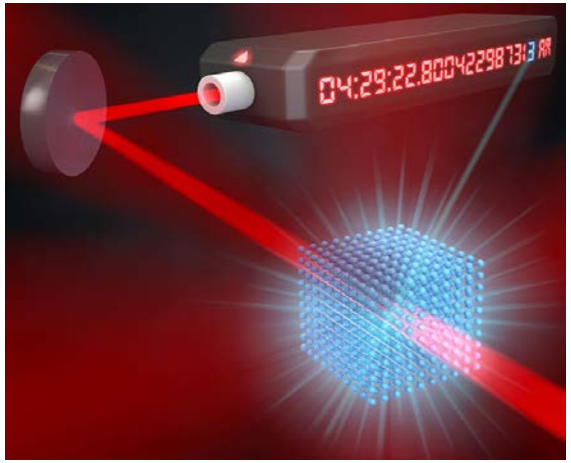
[6]Nature 588, 414 (2020)

Quantum metrology with ultracold atoms

Atomic clock[1]



JILA/Ye Lab

Real-world applications

Atomic sensors

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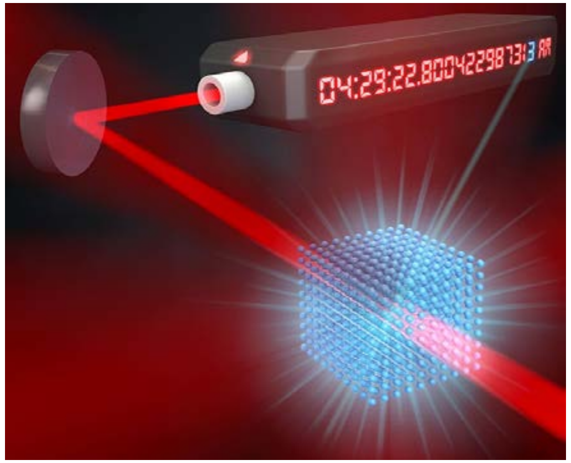

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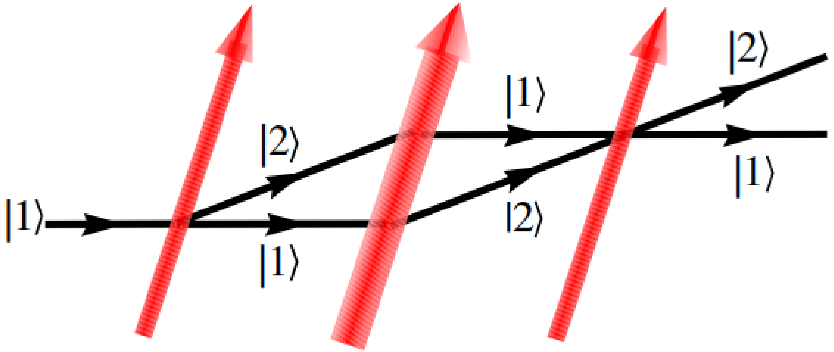
Atom interferometer[2]



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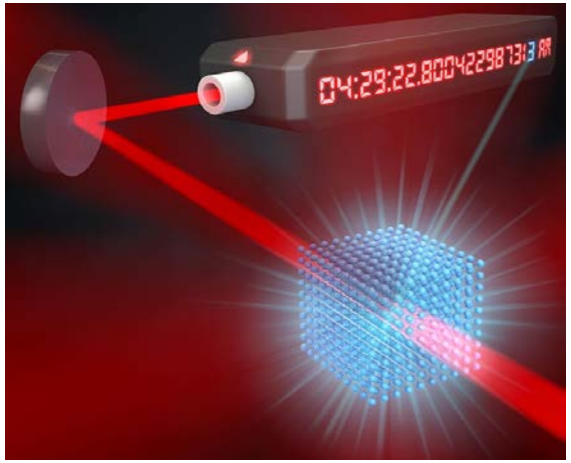

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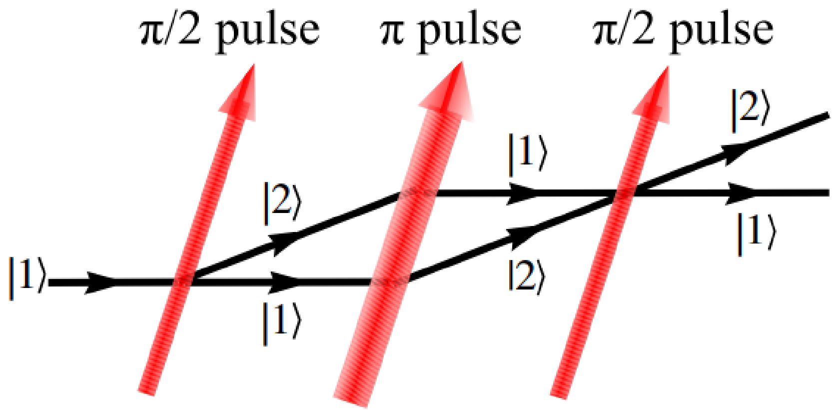

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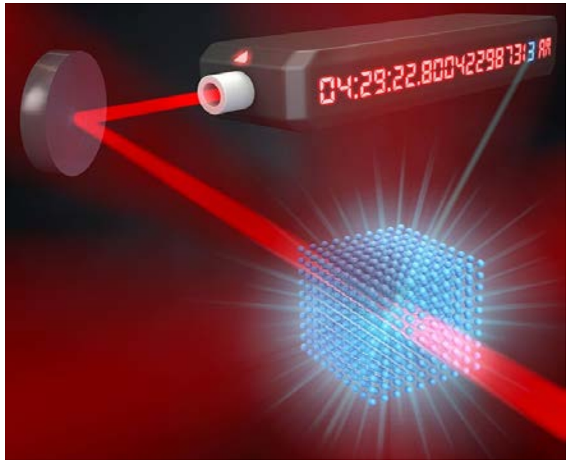

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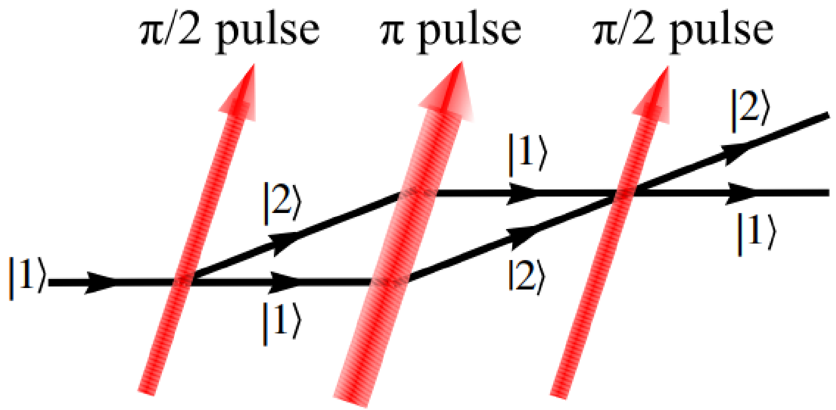
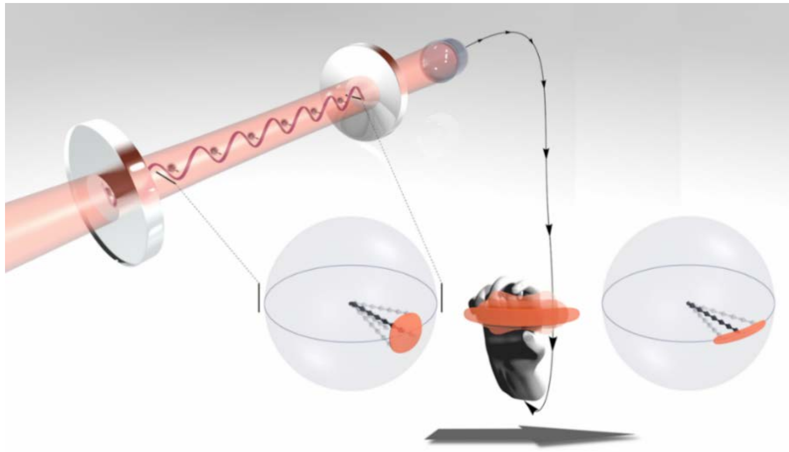


Spin squeezing[3,4,5,6]



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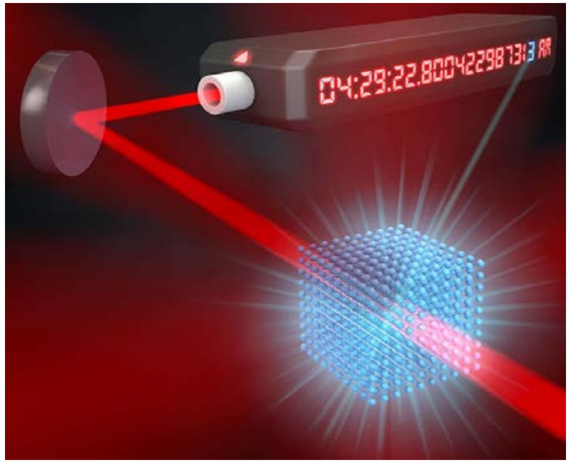

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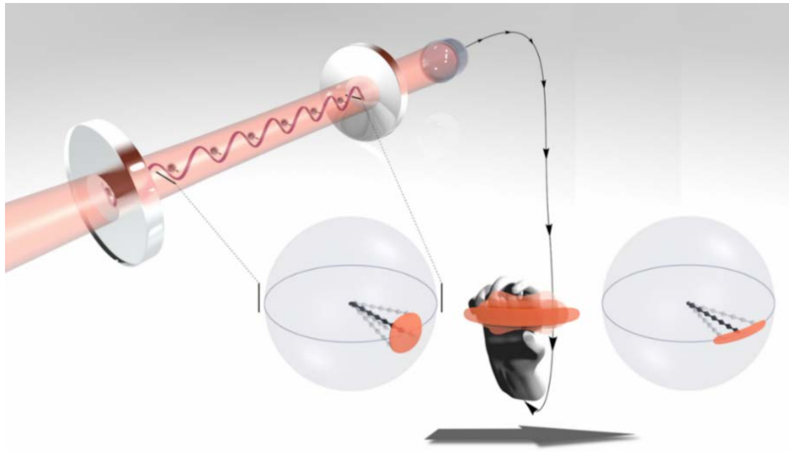

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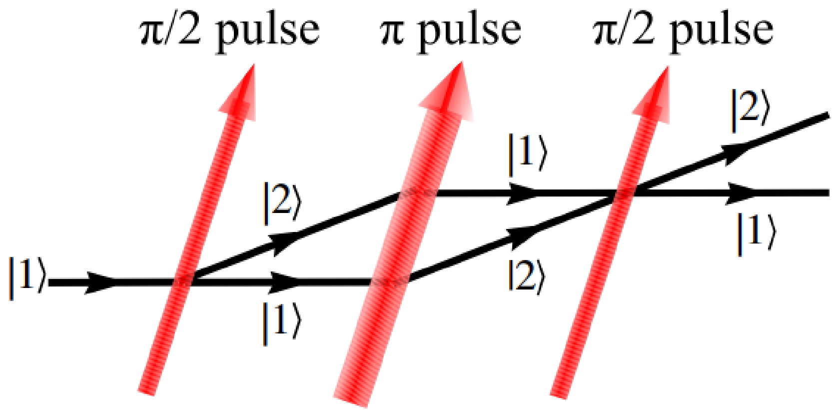

Towards quantum enhanced atom interferometer

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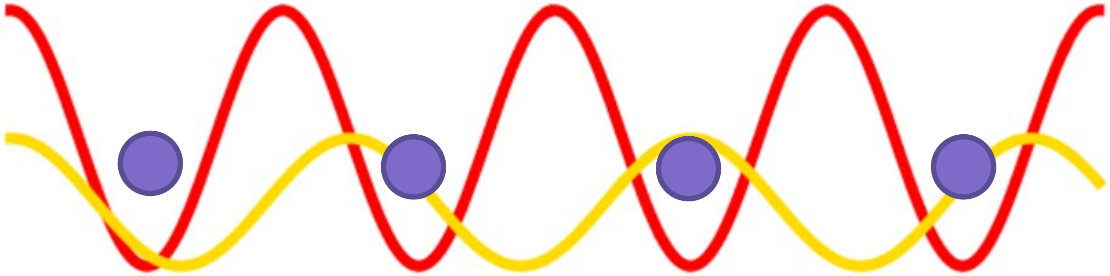
Cavity QED interferometer

- Engineering homogeneous atom-light couplings



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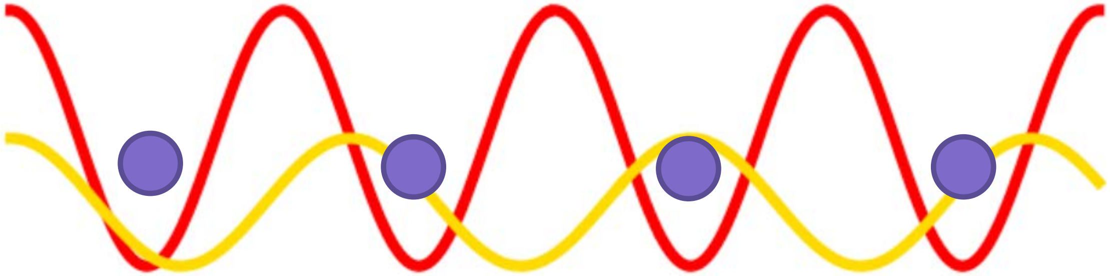

- commensurate lattices[1]
- ring cavities[2]
- time averaging[3]

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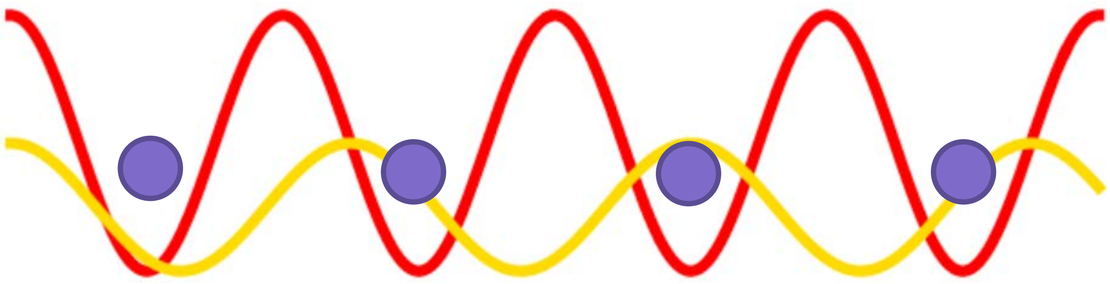

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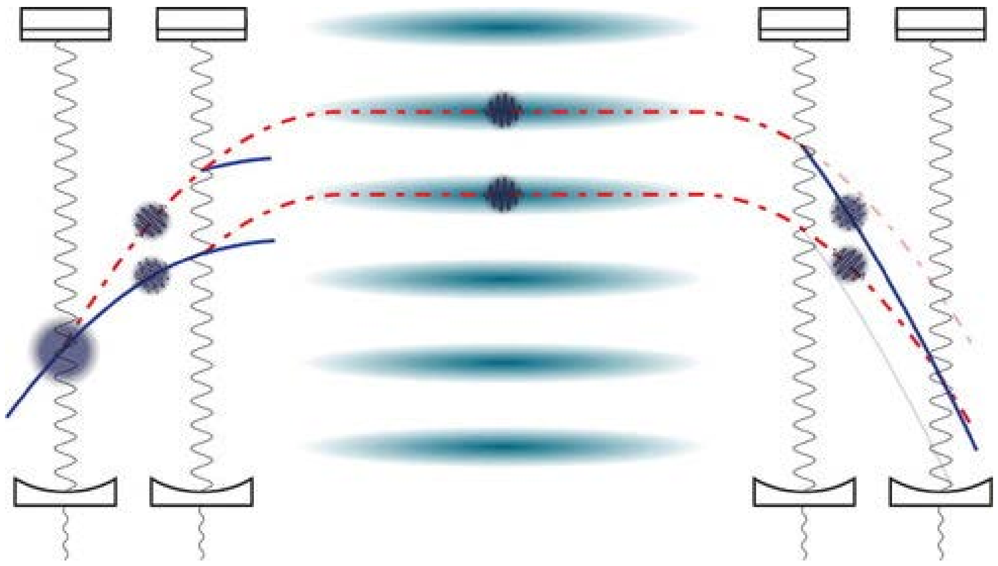
- Development of lattice-based interferometer[4,5]



Berkeley/Müller Lab

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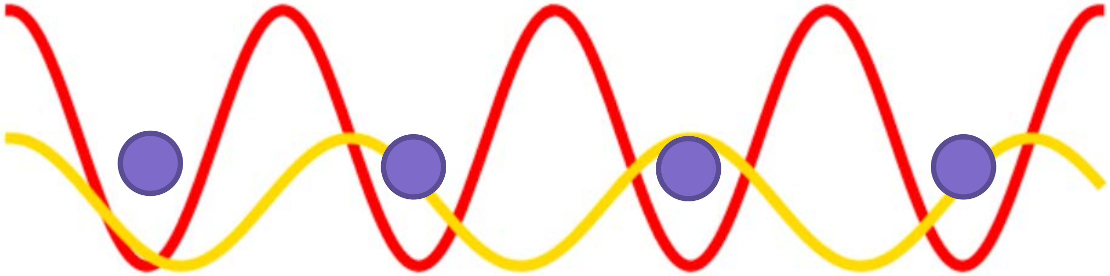

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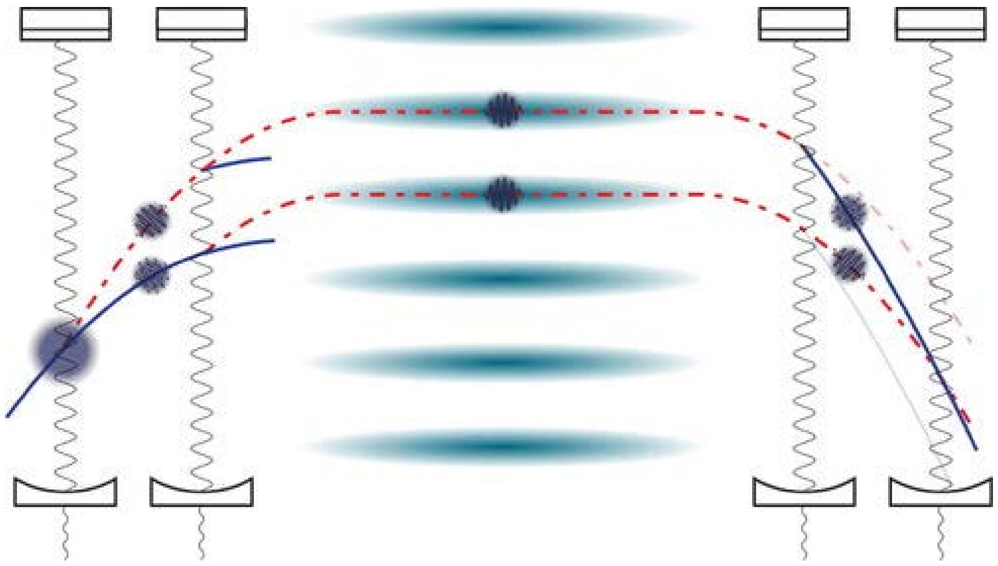

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Our protocol: quantum enhanced lattice-based interferometer using Wannier-Stark states

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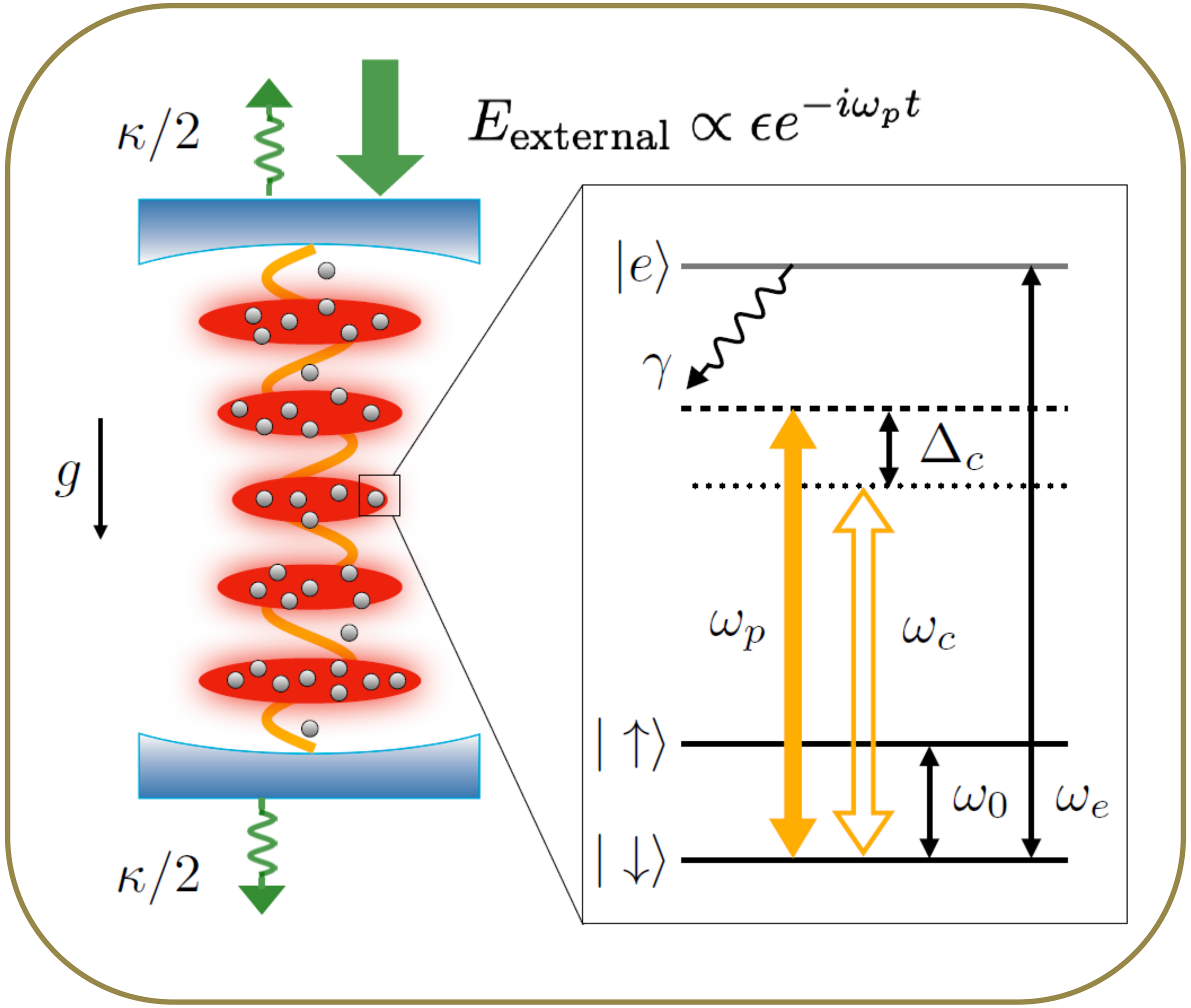
Cavity QED system with Wannier-Stark states

- Dispersive atom-light interaction

$$\hat{H} = \sum_{\beta=\uparrow,\downarrow} \int dz \hat{\psi}^\dagger_\beta(z) \Big[\frac{\hat{p}^2}{2M} + V_0 \sin^2(k_l z) + Mgz$$
$$+ \frac{\hbar |\mathcal{G}_\beta(z)|^2}{\Delta_\beta} \hat{a}^\dagger \hat{a} \Big] \hat{\psi}_\beta(z) + \hat{H}_{\mathrm{cav}} + \hat{H}_{\mathrm{drive}}$$



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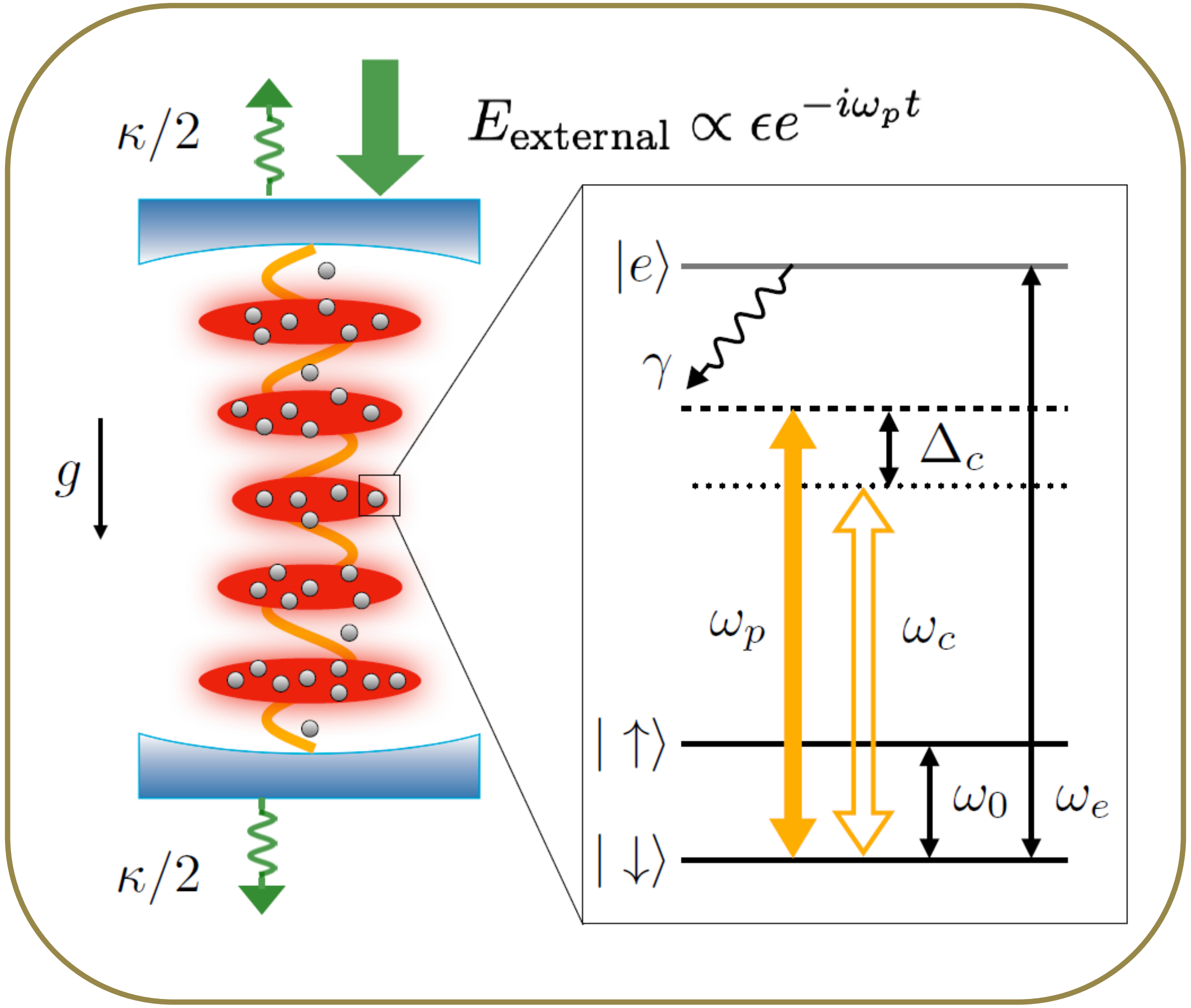

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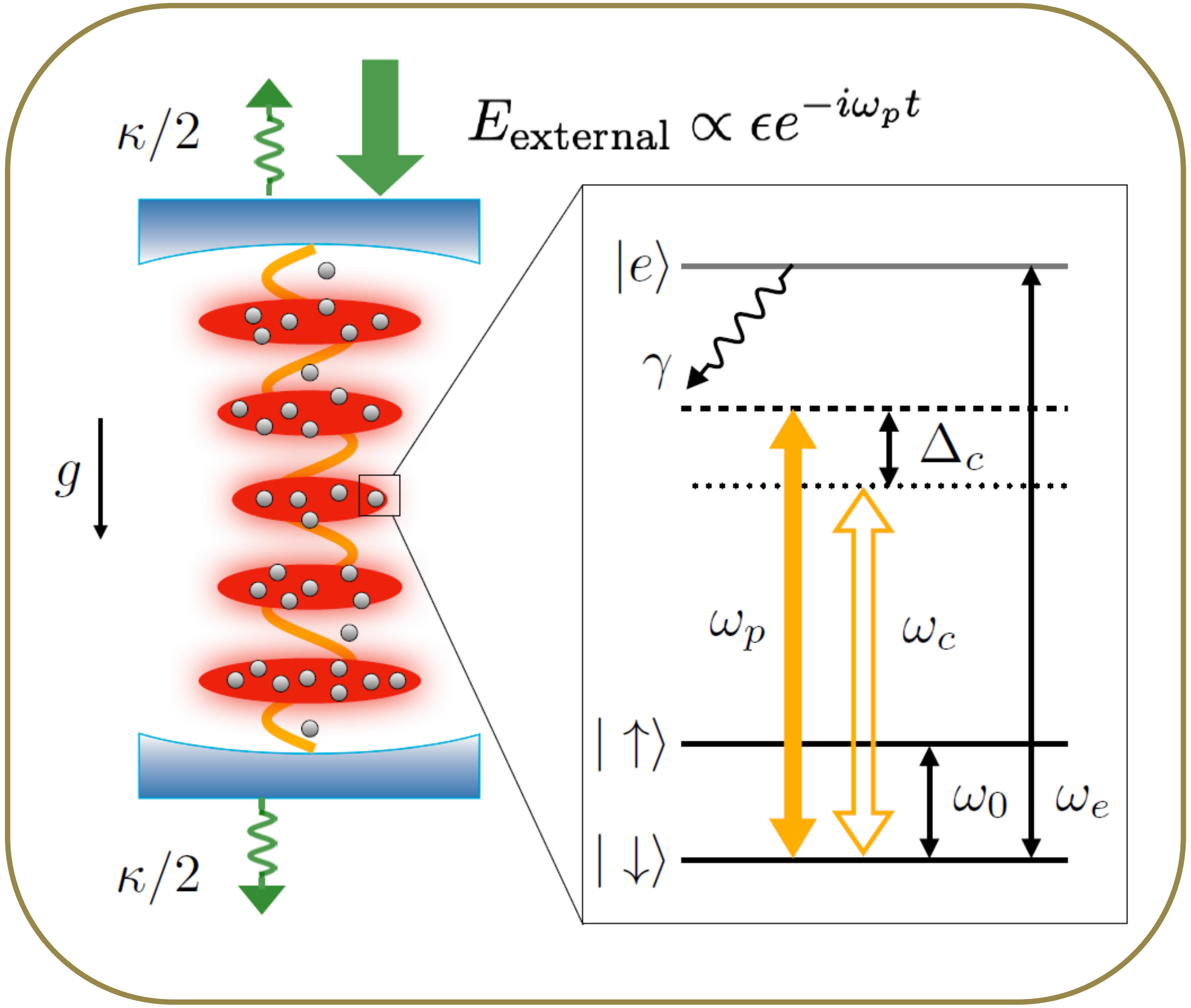

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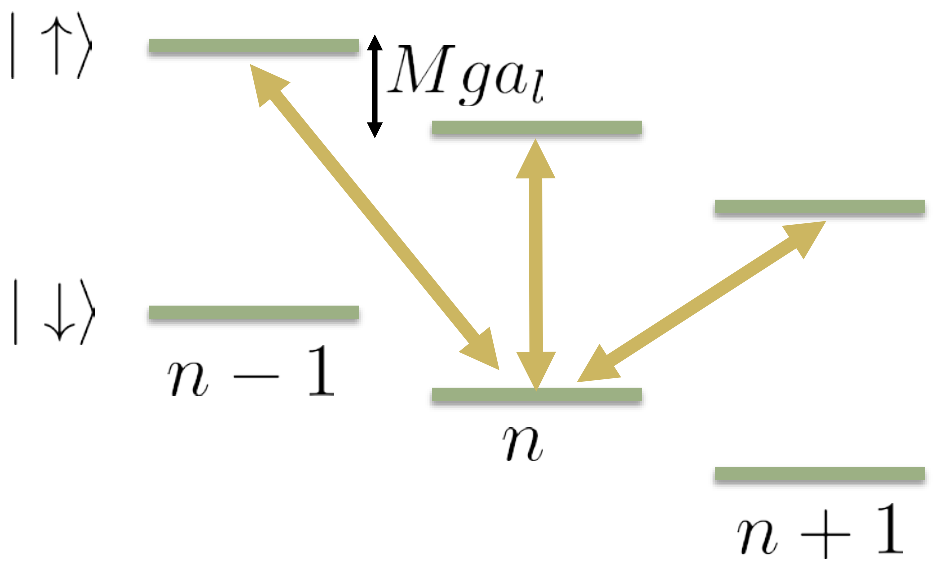

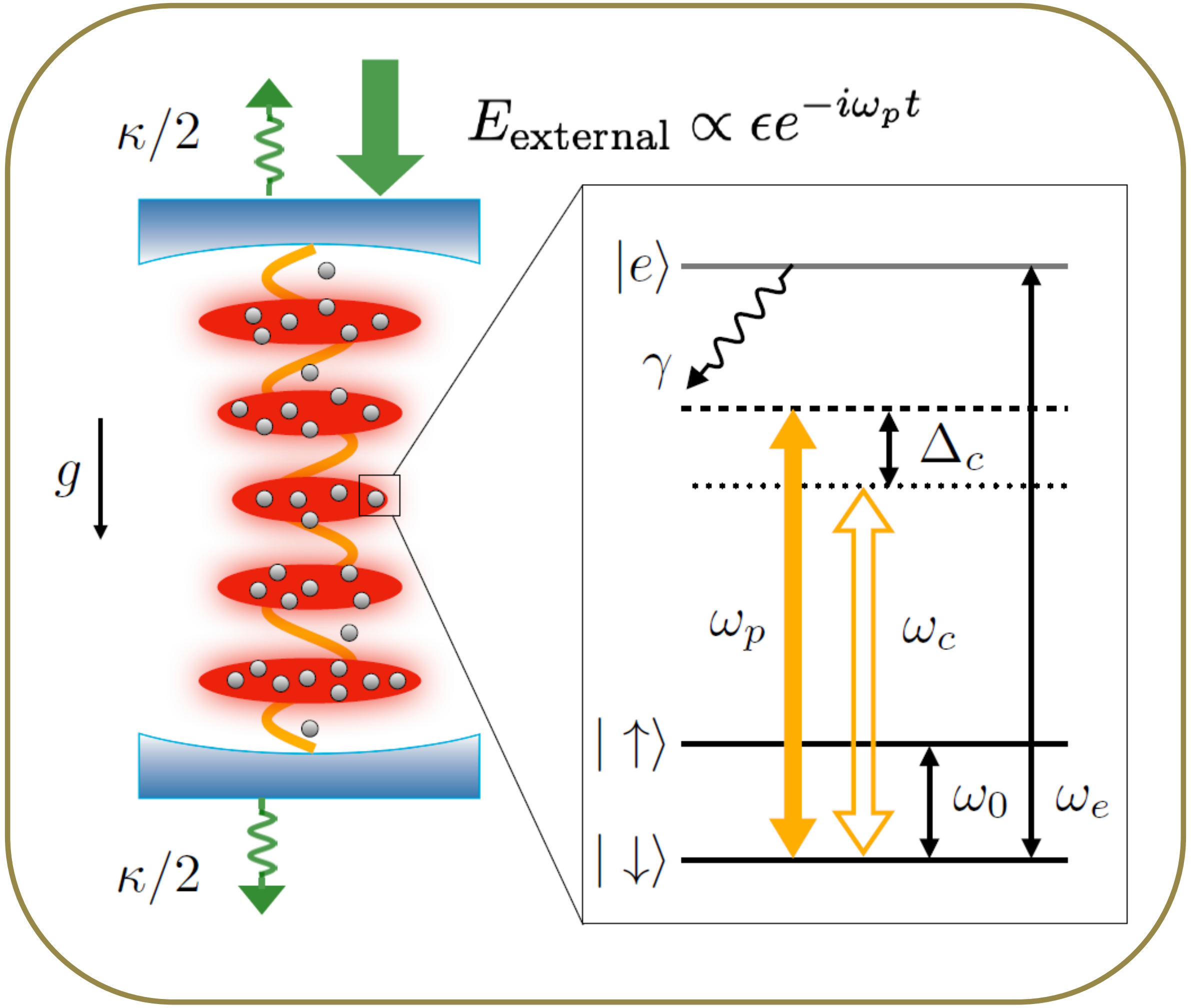

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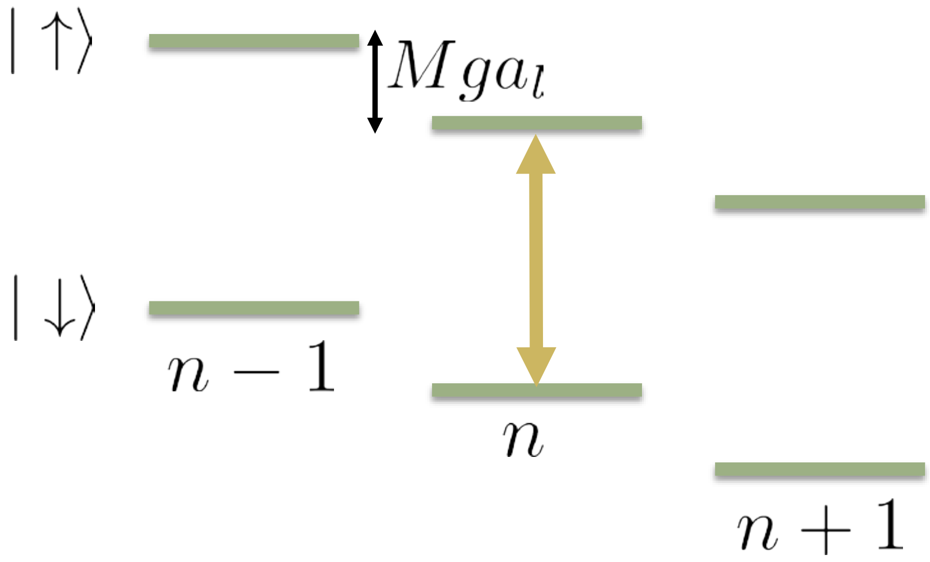

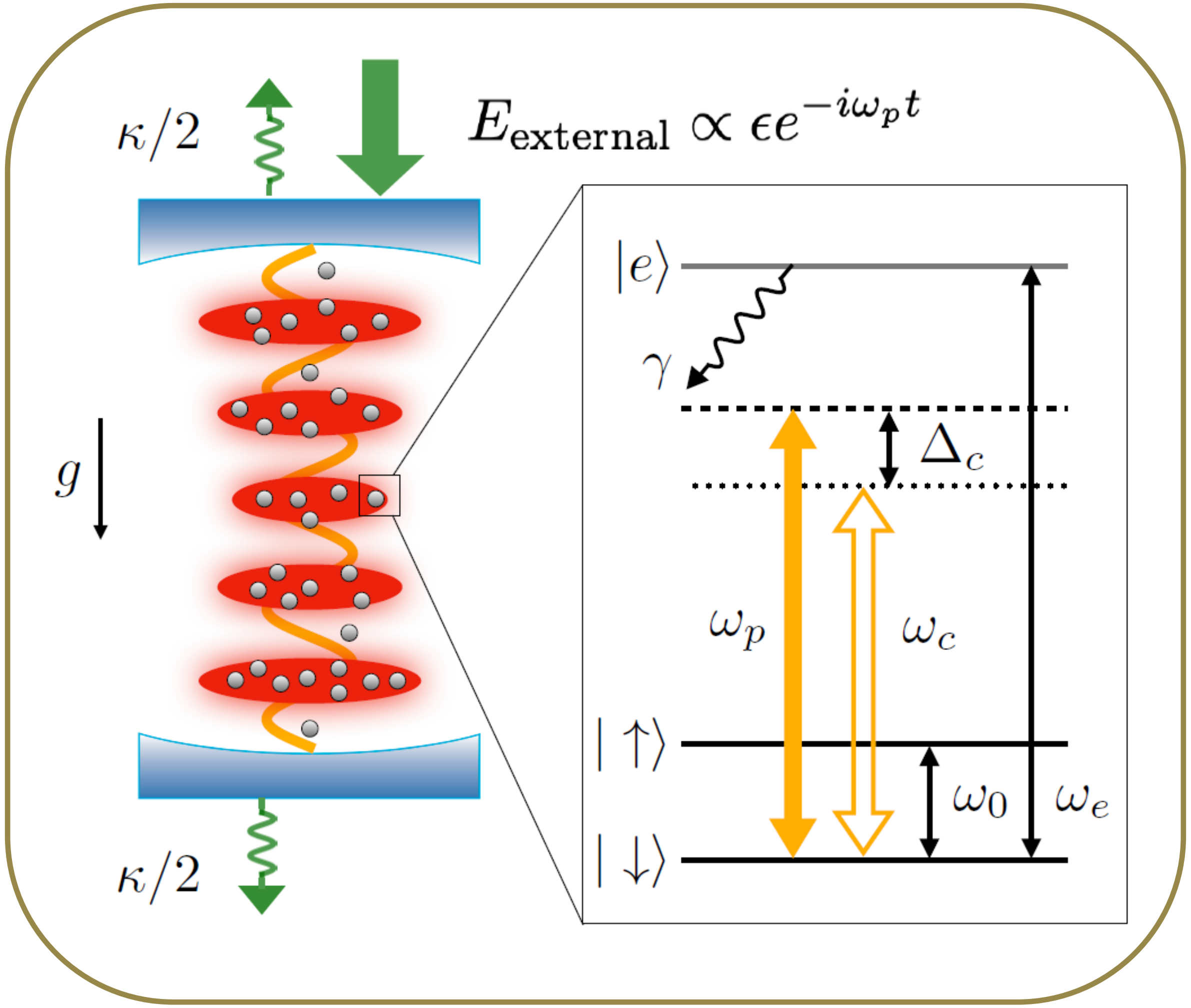

Engineering homogeneous couplings

- Adiabatic elimination of cavity photons

One-axis twisting

$$\hat{H}_{\text{eff}}/\hbar = -\sum_n (\delta - \eta_n |\alpha|^2)\hat{S}_n^z + \boxed{\sum_{nm} \chi_{nm} \hat{S}_n^z \hat{S}_m^z} + \Omega \sum_n \hat{S}_n^x$$

$$\chi_{nm} = \eta_n \eta_m |\alpha|^2 \tilde{\Delta}_c / (\tilde{\Delta}_c^2 + \kappa^2/4)$$

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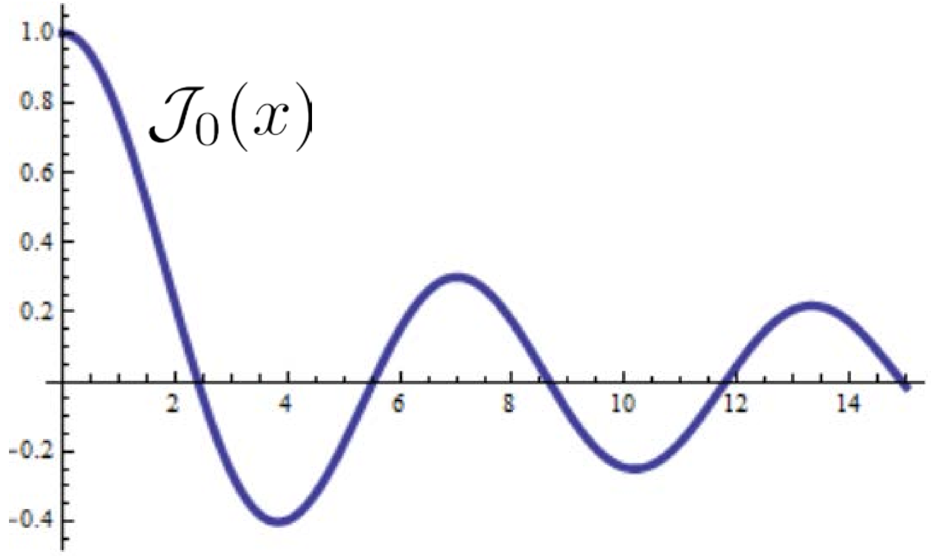
- Tuning inhomogeneity via lattice depth

$$\eta_n \propto 1 + \mathcal{C}\mathcal{J}_0\left(\frac{4J_0}{Mga_l}\sin(\varphi/2)\right)\cos(n\varphi)$$

$$\varphi = 2\pi\lambda_l/\lambda_c$$

lattice/cavity wavelength



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tunnel coupling

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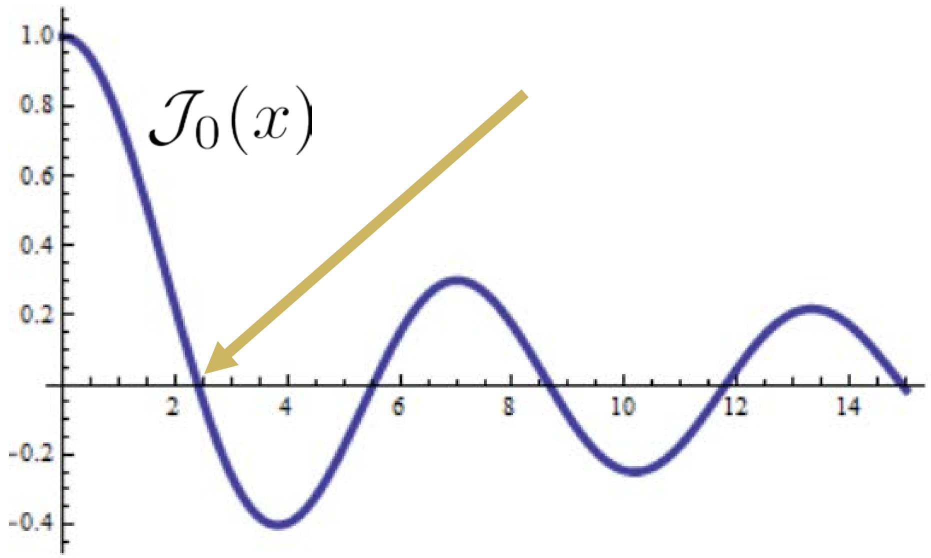

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Magic lattice depth

$$\boxed{\mathcal{J}_0\left(\frac{4J_0}{Mga_l}\sin(\varphi/2)\right) = 0}$$

Example: 6.0E_r for ^{87}Rb atoms in 532nm lattice

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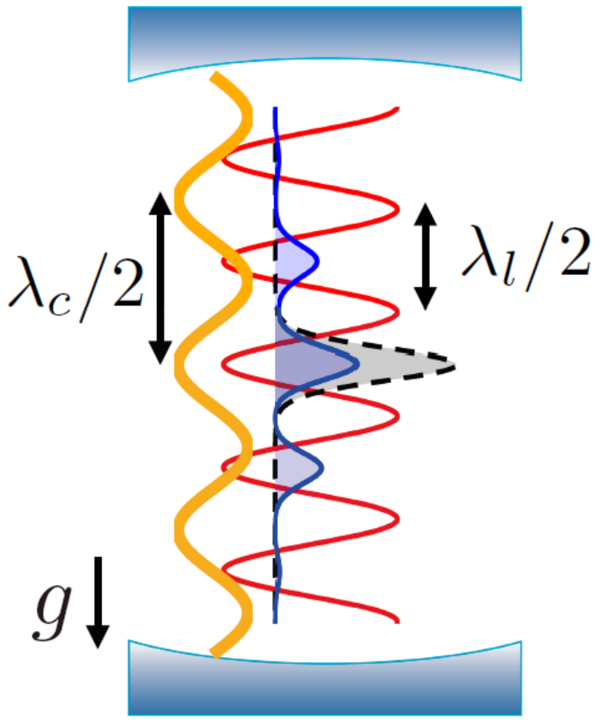

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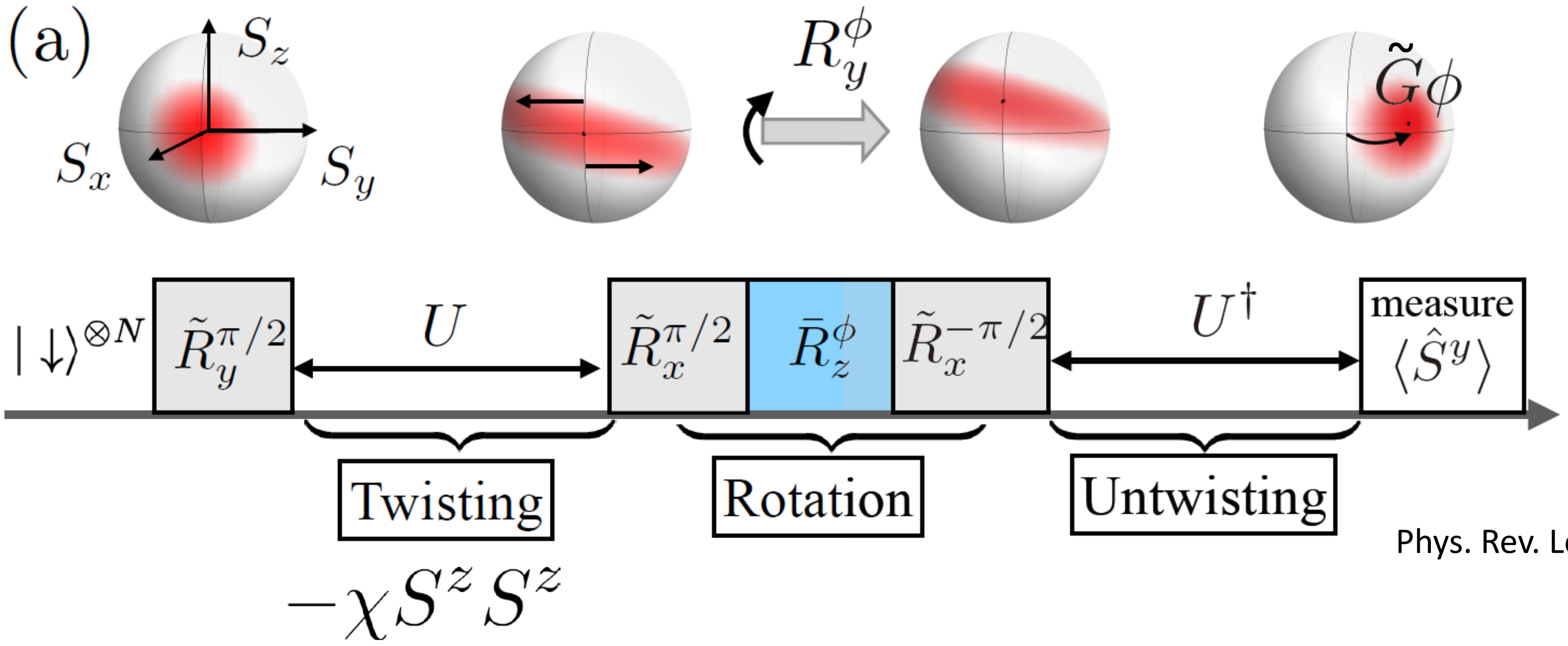
Quantum enhanced interferometric protocol



Phys. Rev. Lett. 116, 053601 (2016)

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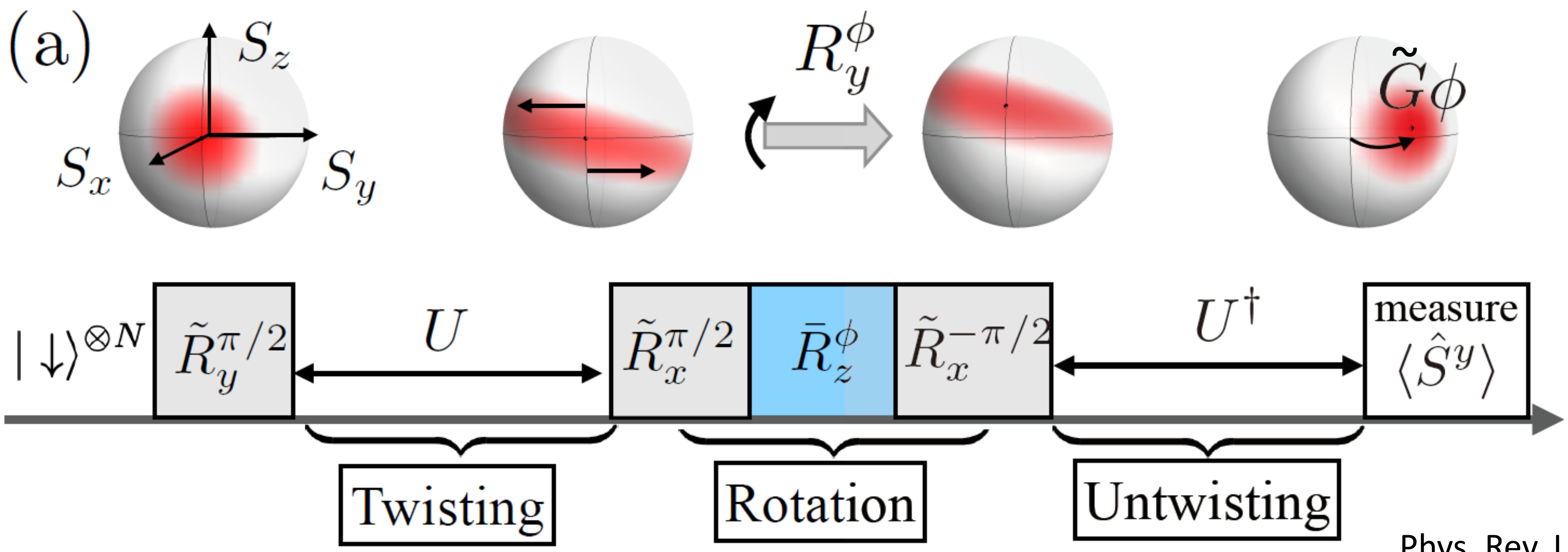

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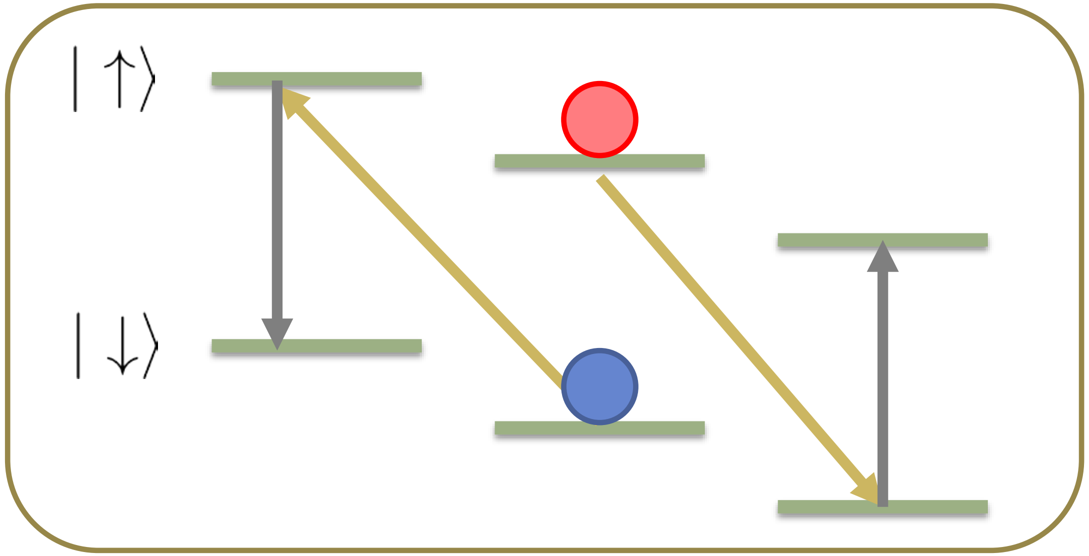

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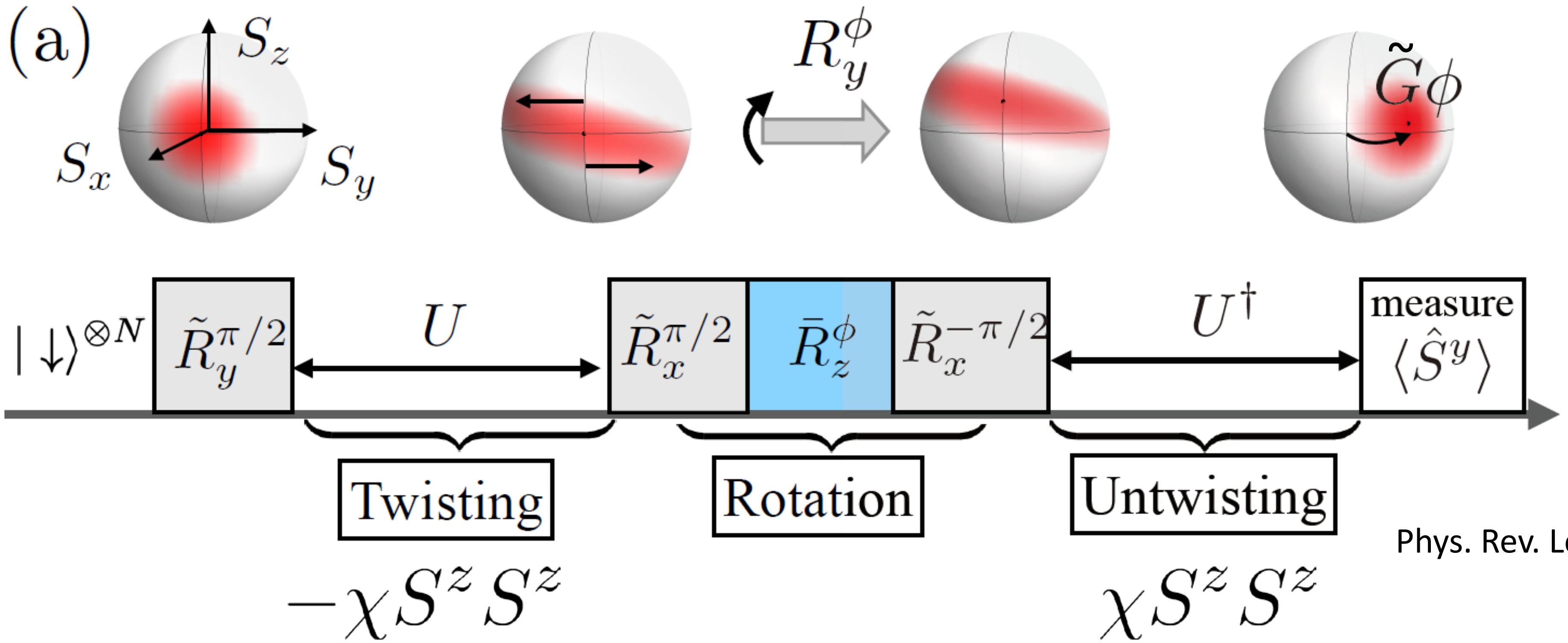

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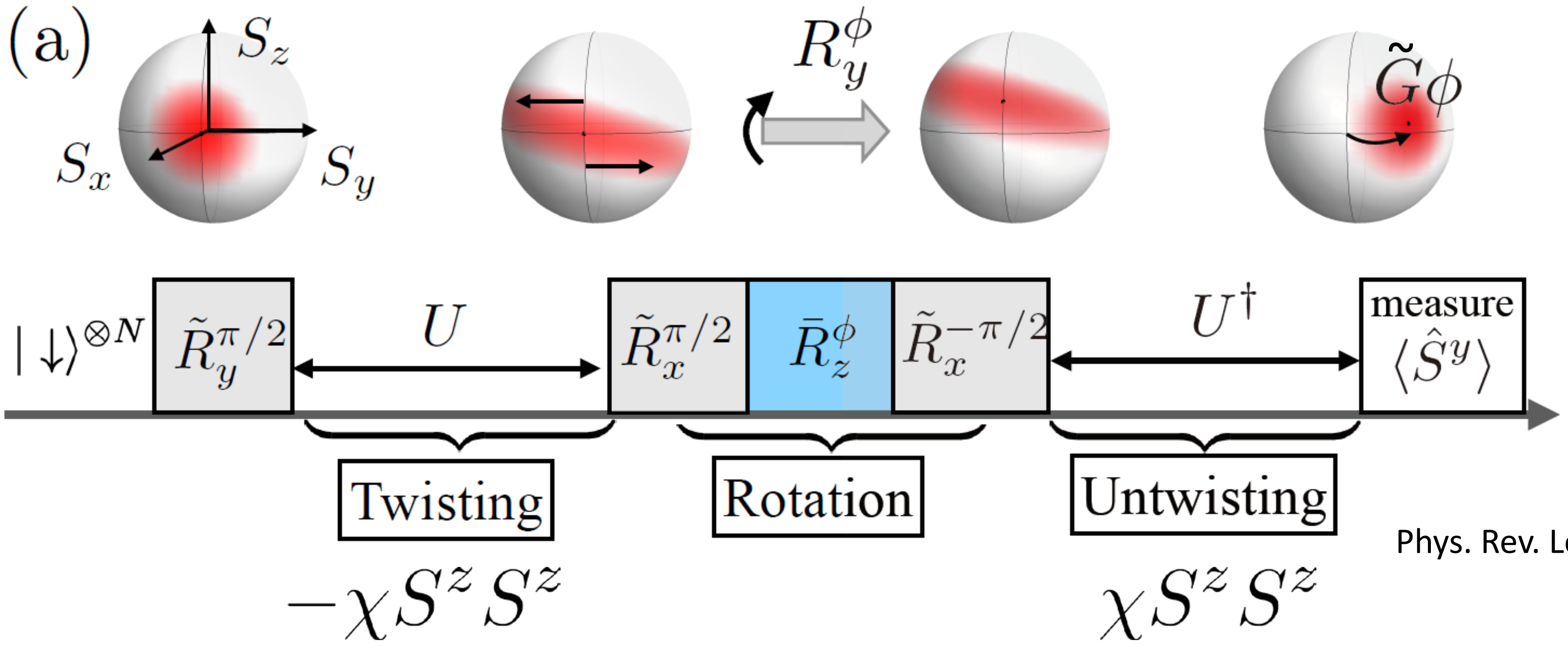

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- Phase sensitivity $\Delta\phi = (\Delta\phi)_{\mathrm{SQL}}/\tilde{G}$

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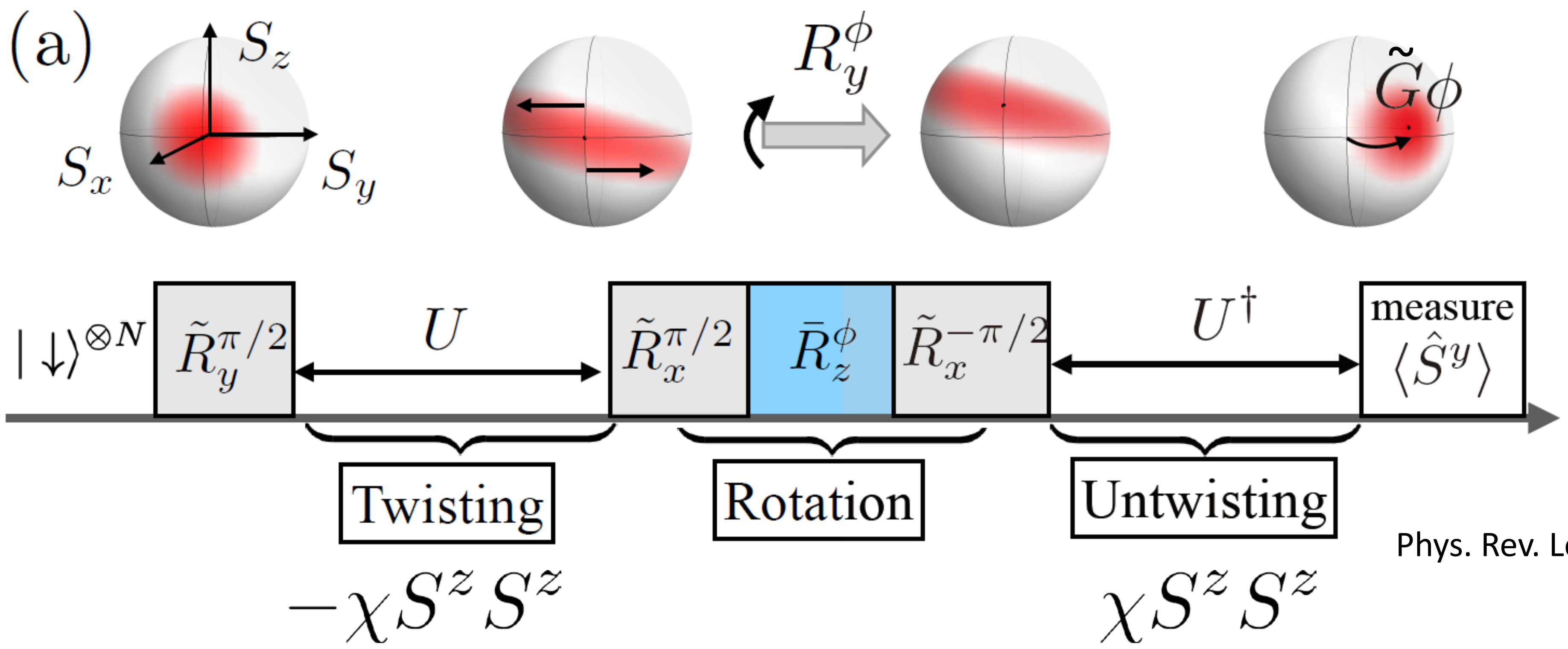

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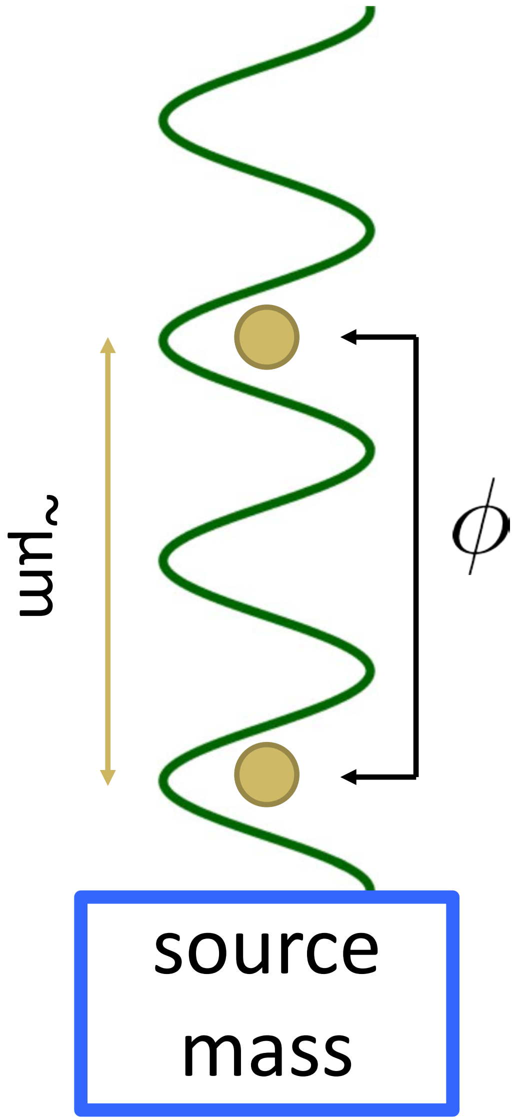
- Phase sensitivity $\Delta\phi = (\Delta\phi)_{\mathrm{SQL}}/\tilde{G}$
- Approaching Heisenberg limit with detection resolution at the atom shot noise level

Short-range force sensing



- Example: non-Newtonian deviations of gravity

$$\mathcal{U}(r) = -G\frac{m_1 m_2}{r}\left(1 + \tilde{\alpha}\mathrm{e}^{-r/\lambda}\right)$$

Phys. Rev. Lett. 107, 171101 (2011)

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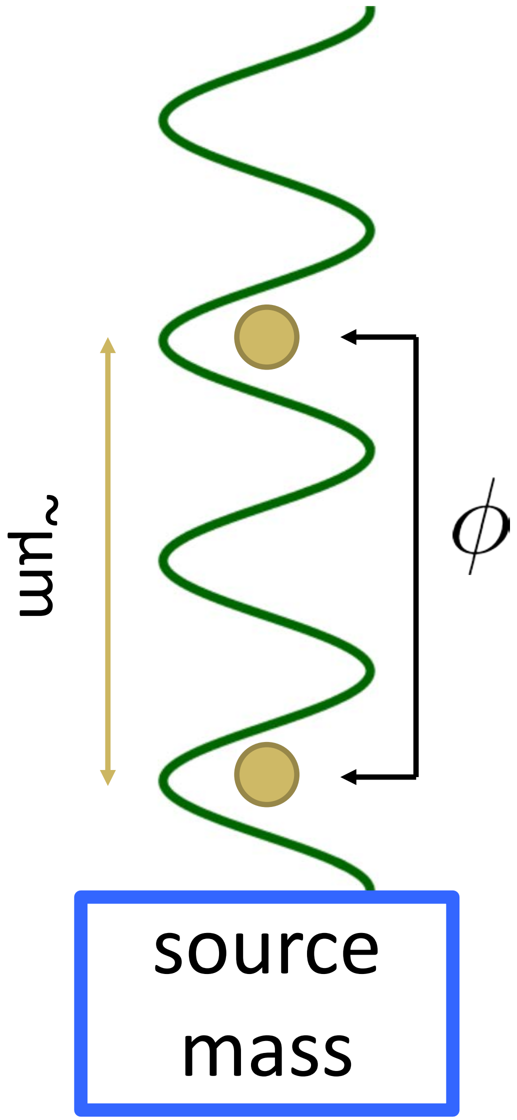

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- Protocol requirement:
- Small spatial extension of atomic cloud

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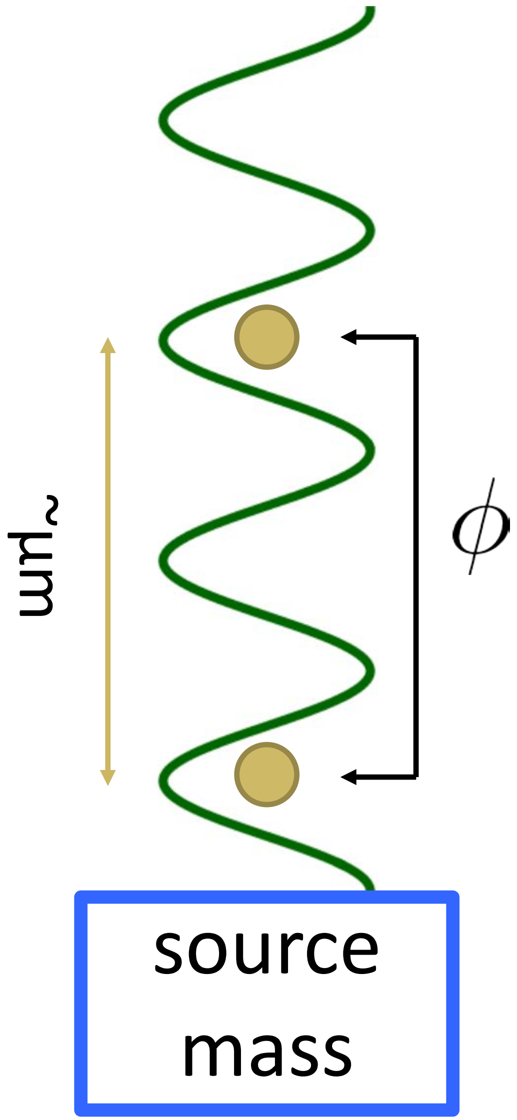

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- Small spatial extension of atomic cloud
- Homogeneous atom-light couplings for squeezing

Magic lattice depth

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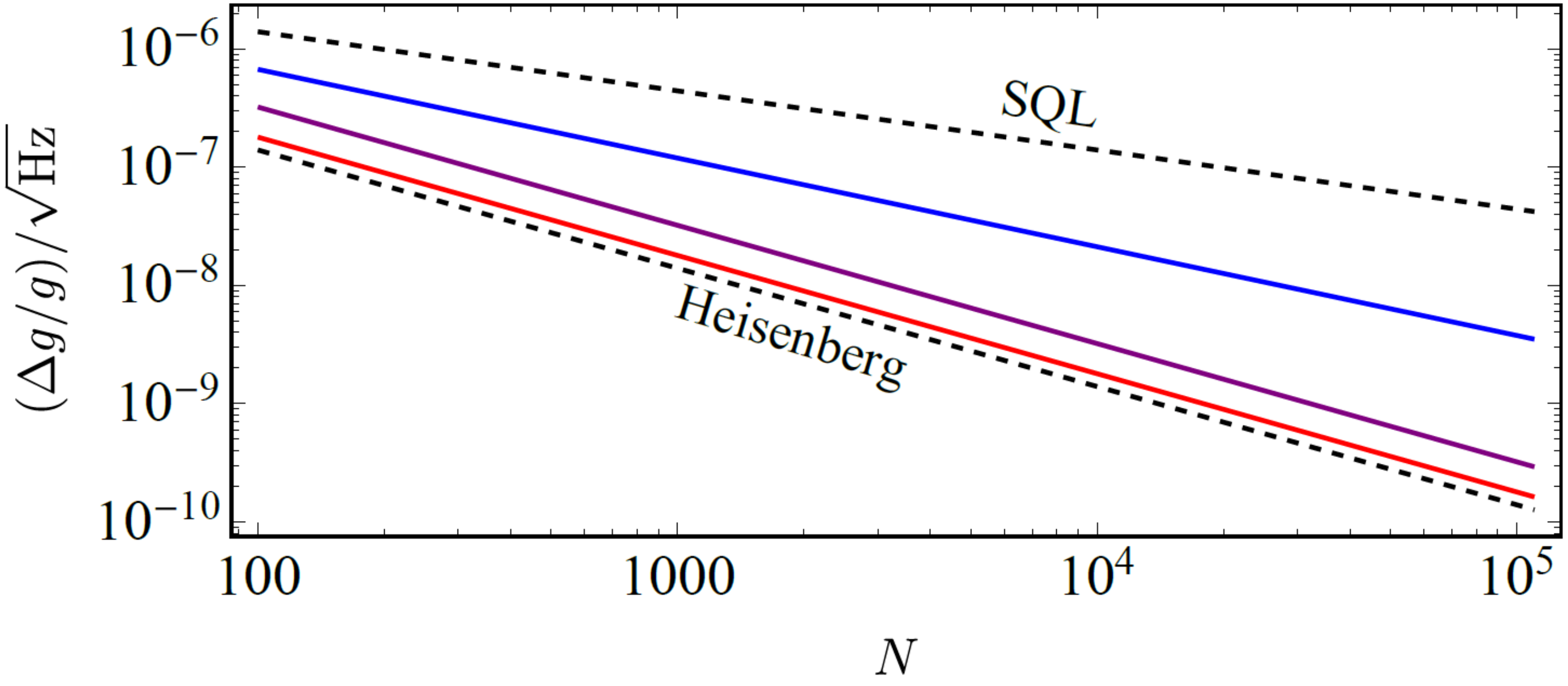
Experimental considerations

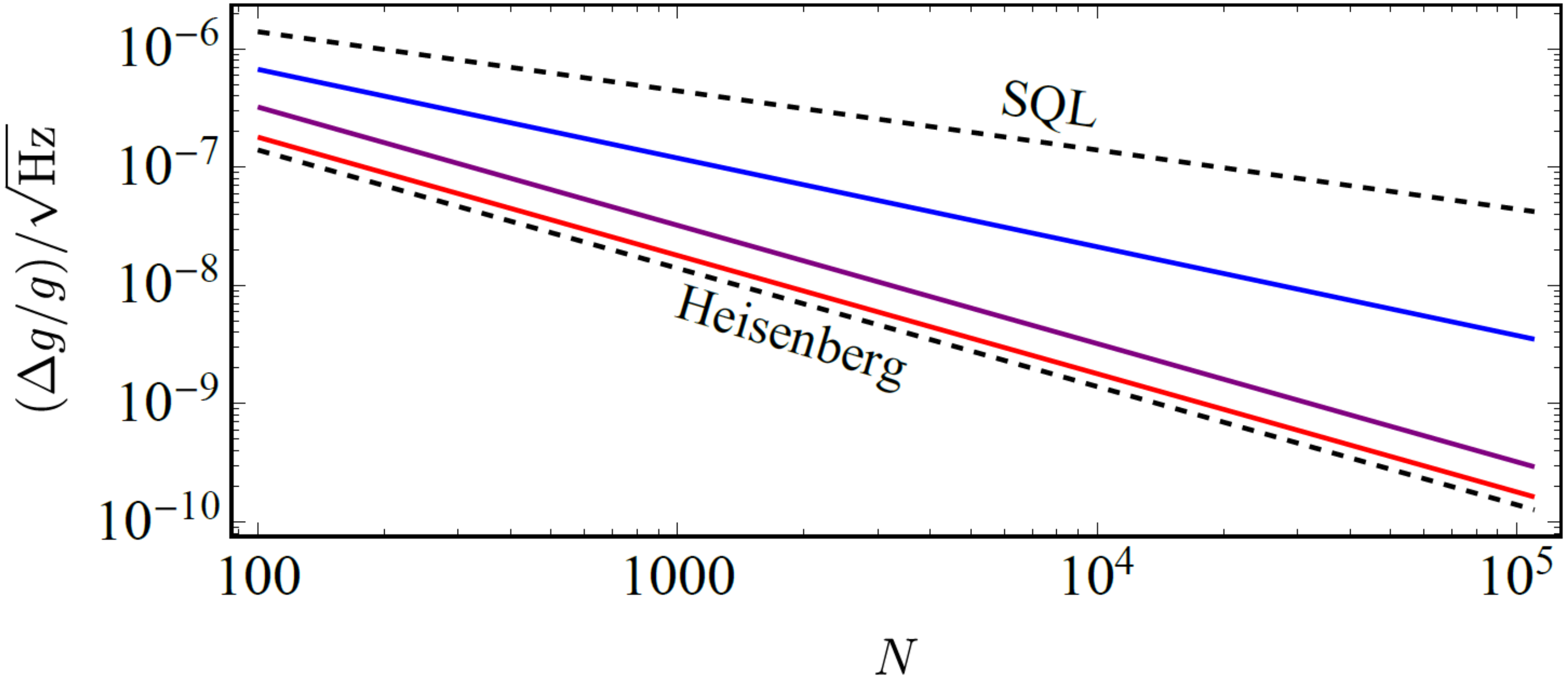


^{87}Rb atoms

5.32µm separation

1s interrogation

Experimental considerations



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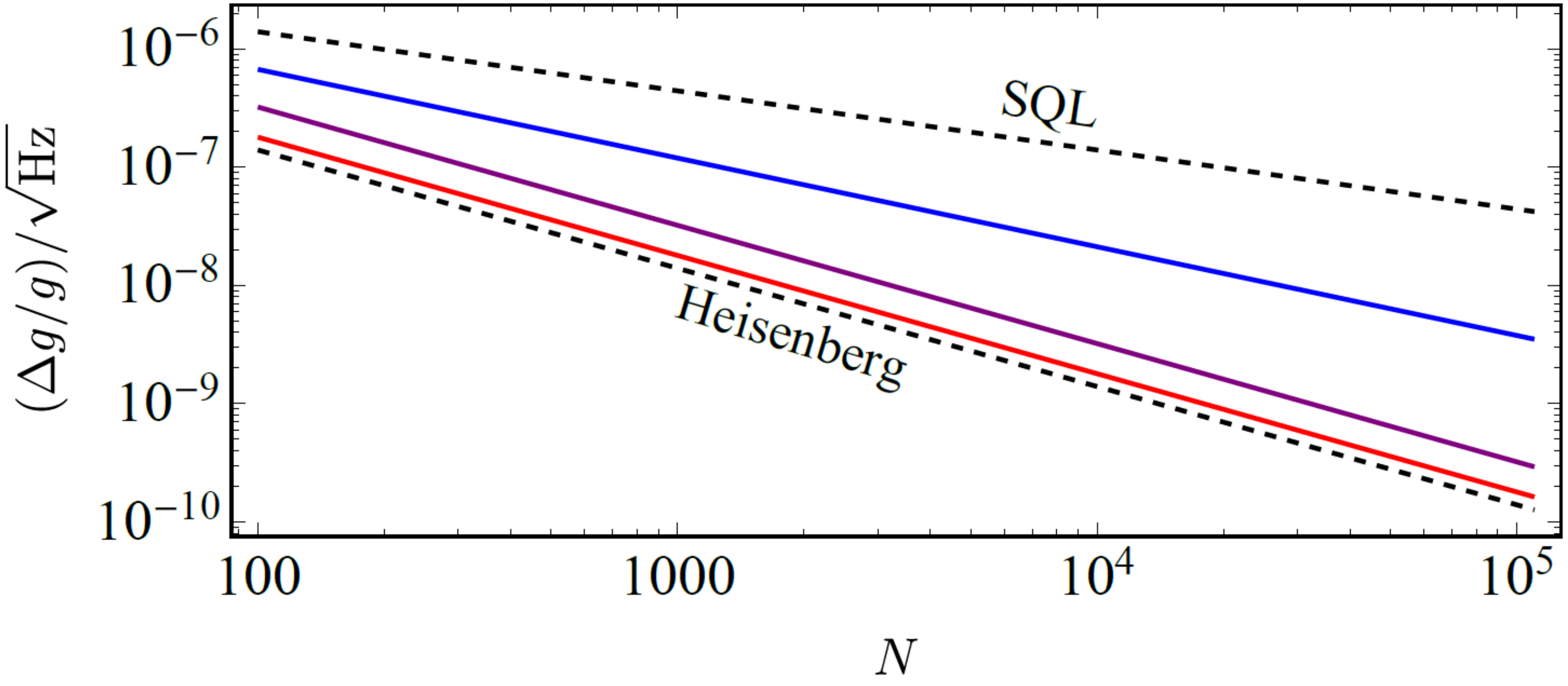
➢ Ideal case: near Heisenberg limit

$$\Delta g/g \propto N^{-1}$$

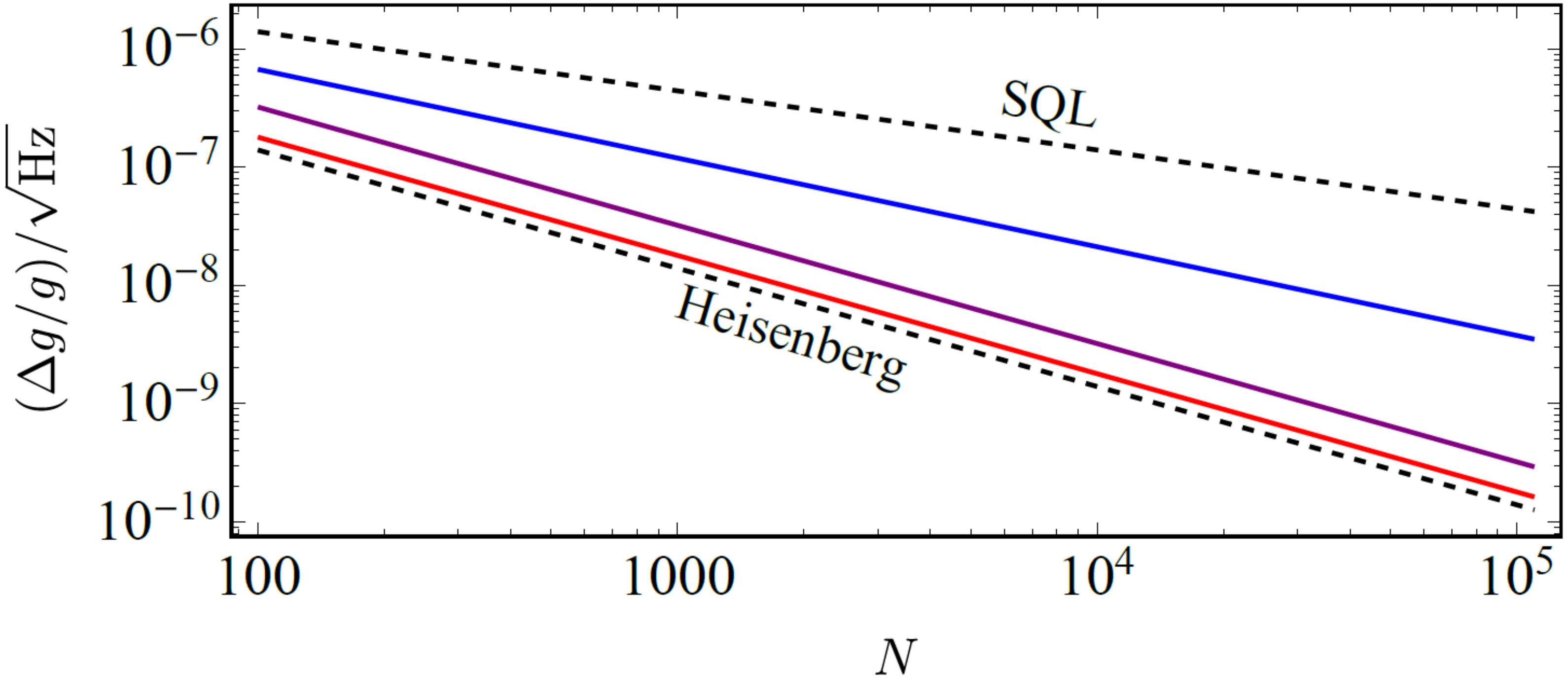
Experimental considerations



^{87}Rb atoms
5.32μm separation
1s interrogation

- Ideal case: near Heisenberg limit $\quad \Delta g/g \propto N^{-1}$
- Cavity loss and Raman scattering $\quad \Delta g/g \propto N^{-3/4}$

Experimental considerations



^{87}Rb atoms
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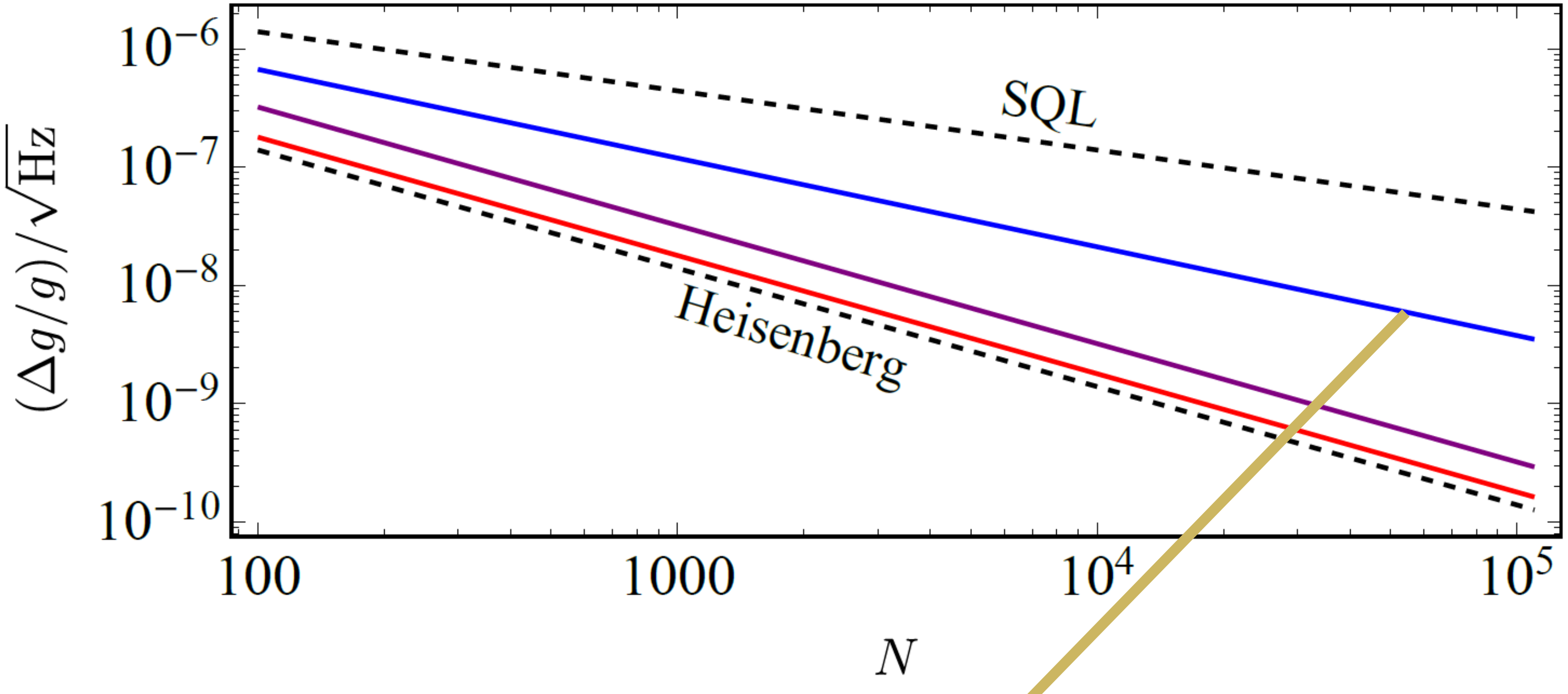
- Ideal case: near Heisenberg limit $\Delta g/g \propto N^{-1}$
- Cavity loss and Raman scattering $\Delta g/g \propto N^{-3/4}$
- Cavity loss and Rayleigh scattering $\Delta g/g \propto N^{-1}$

Experimental considerations

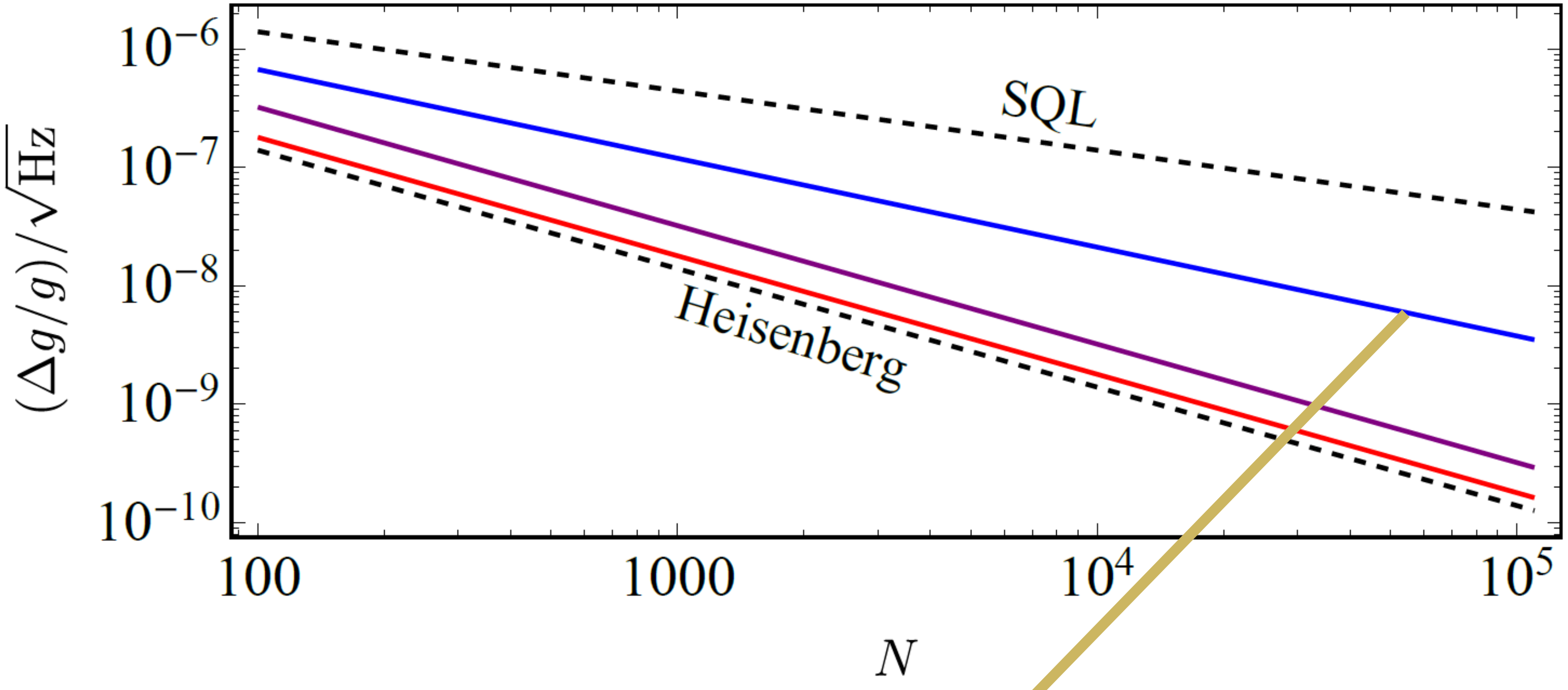


^{87}Rb atoms
5.32μm separation
1s interrogation

- ➢ 20dB beyond SQL using 50000 atoms

$$\Delta g/g \sim 6 \times 10^{-9}/\sqrt{\mathrm{Hz}}$$

Experimental considerations



^{87}Rb atoms
5.32µm separation
1s interrogation

- 20dB beyond SQL using 50000 atoms $\Delta g/g \sim 6 \times 10^{-9}/\sqrt{\mathrm{Hz}}$
- ~10dB even accounting for the fragility of spin squeezed states

Thank you for your attention!

Peiru He

James K. Thompson

Ana Maria Rey

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