Testing gravity with atomic quantum sensors

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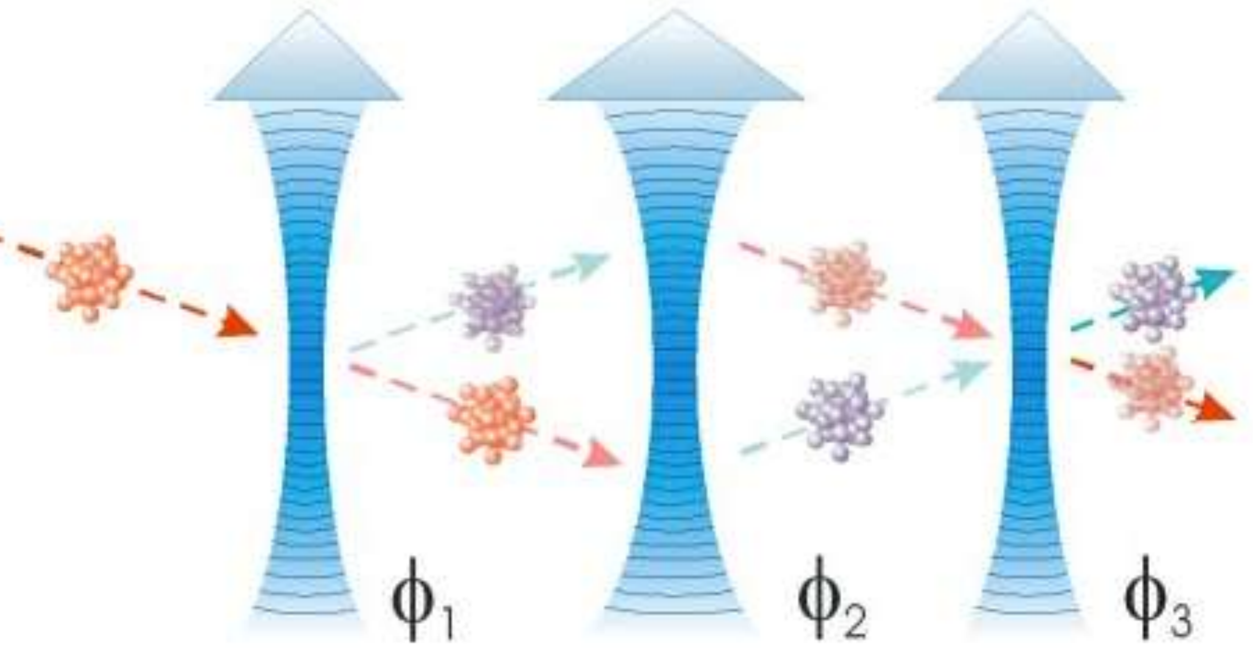
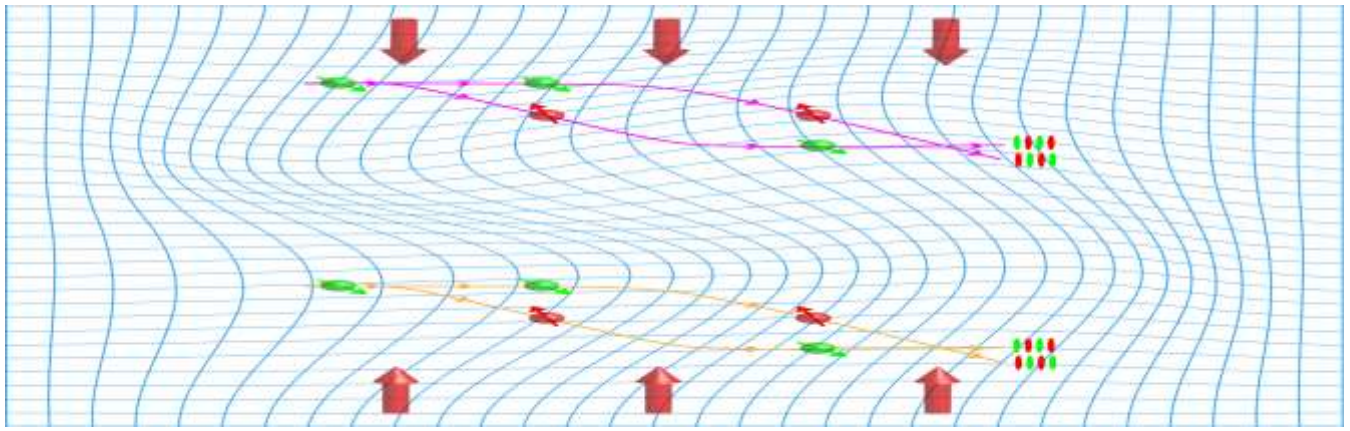
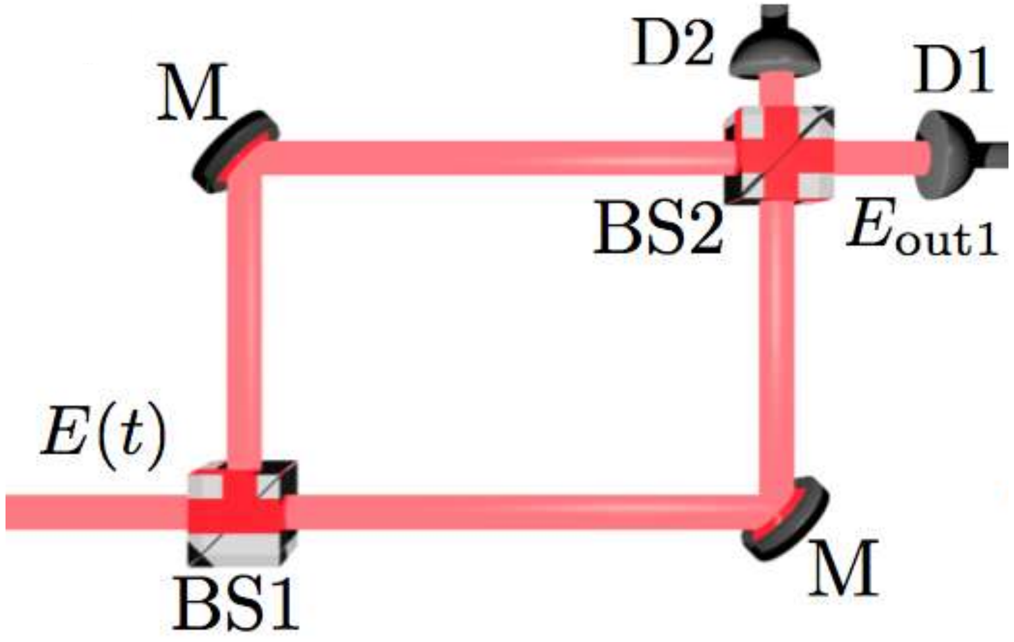
E. Wang, N. Poli, G. M. Tino

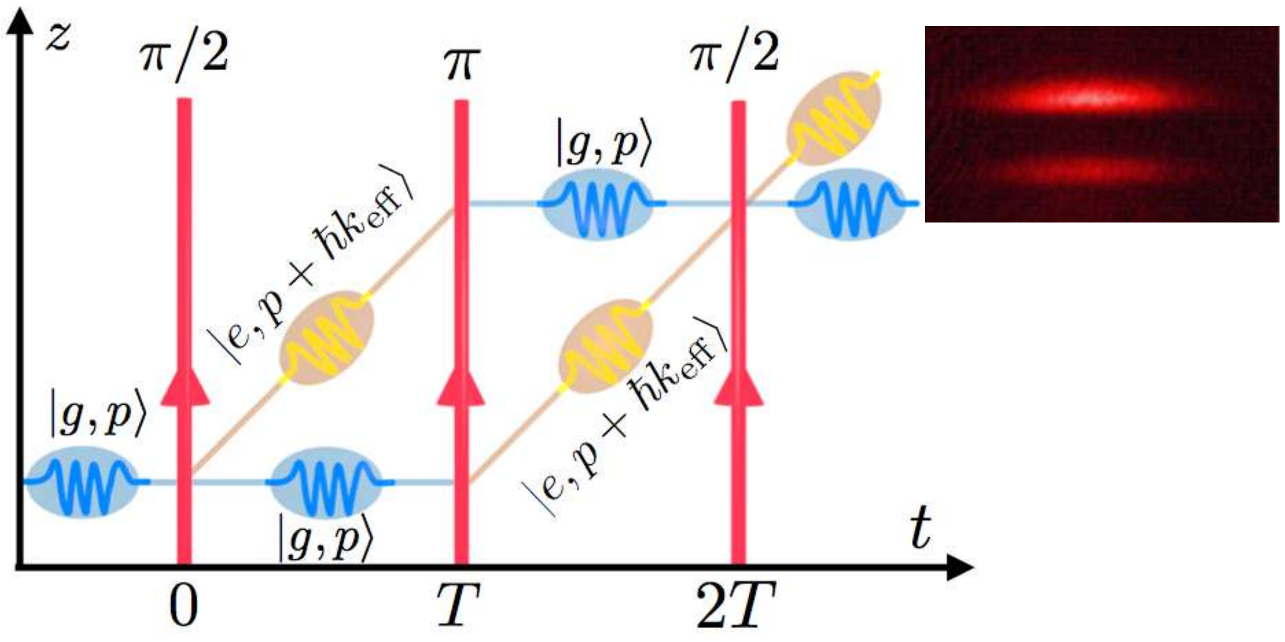
September 20, 2018

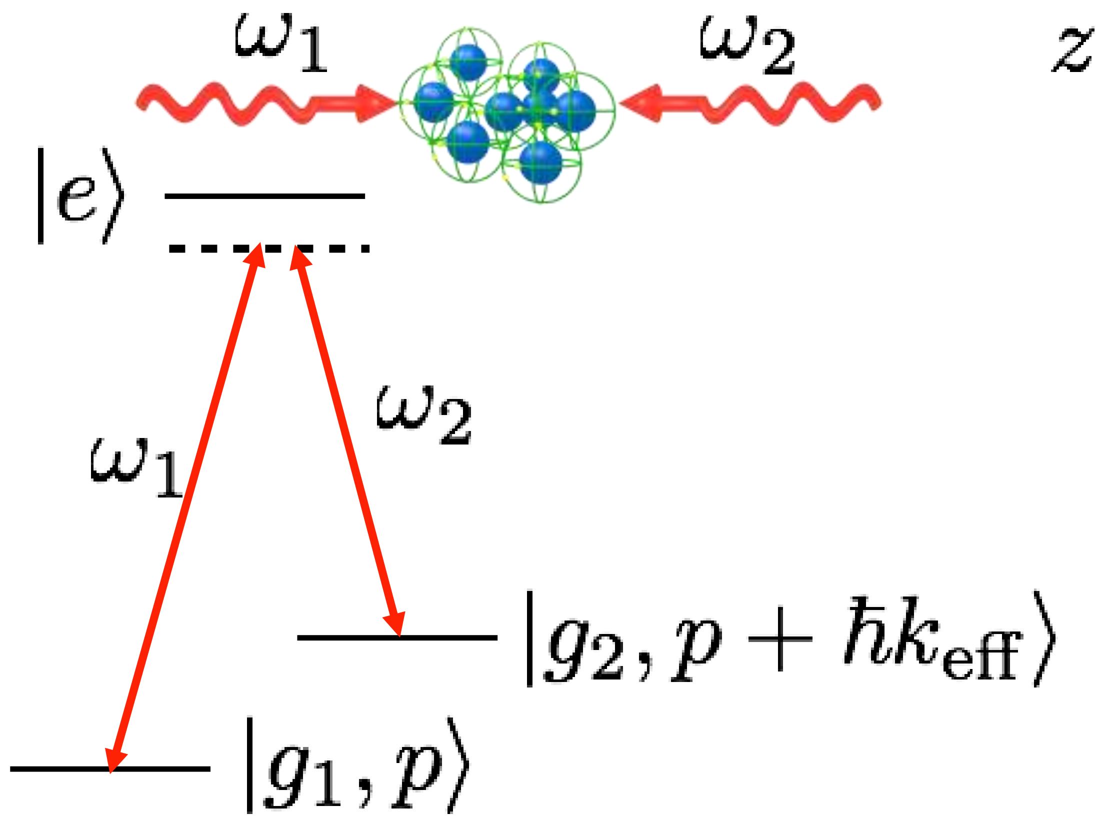


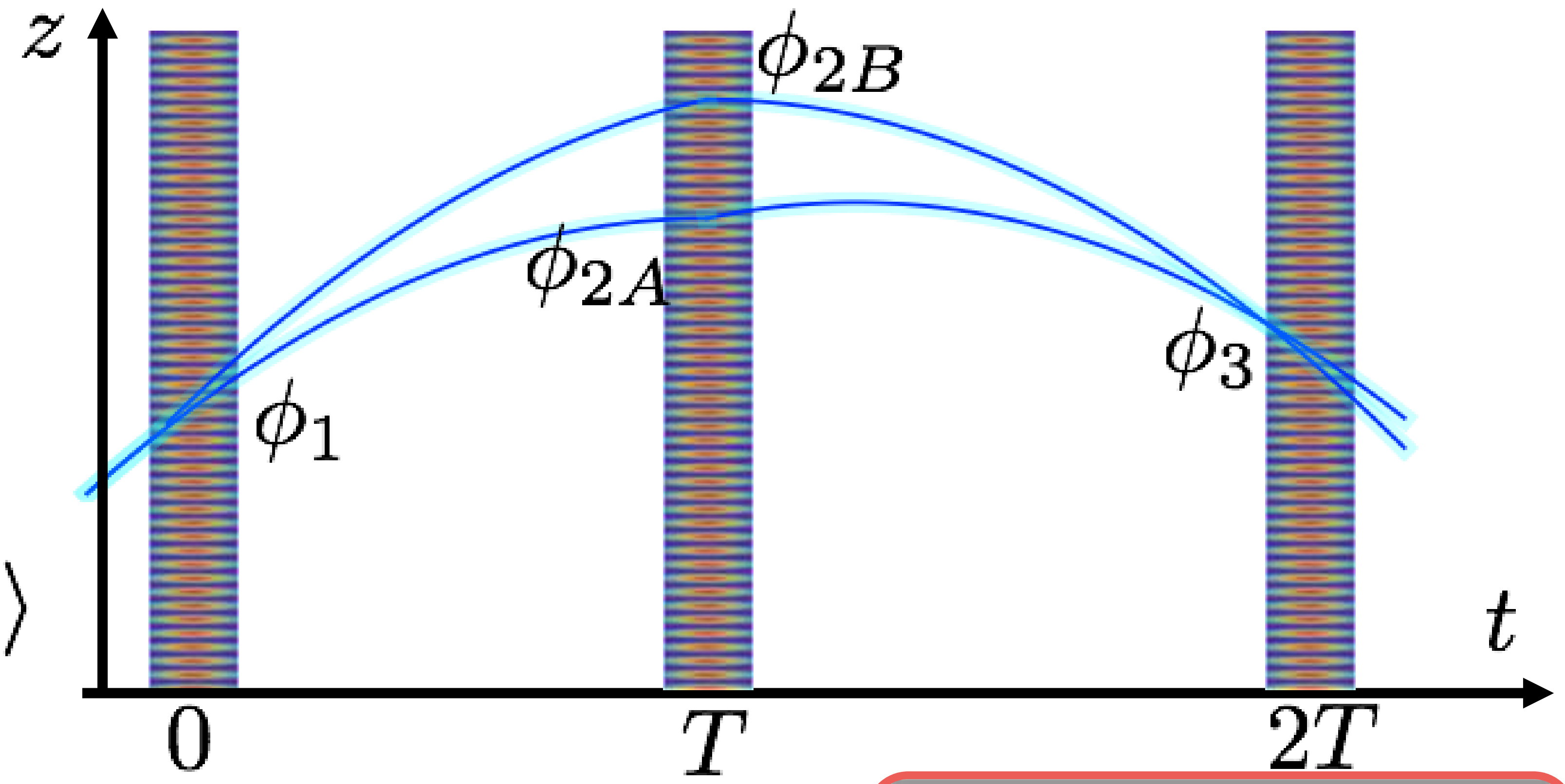


Atom Interferometry and gravity measurements



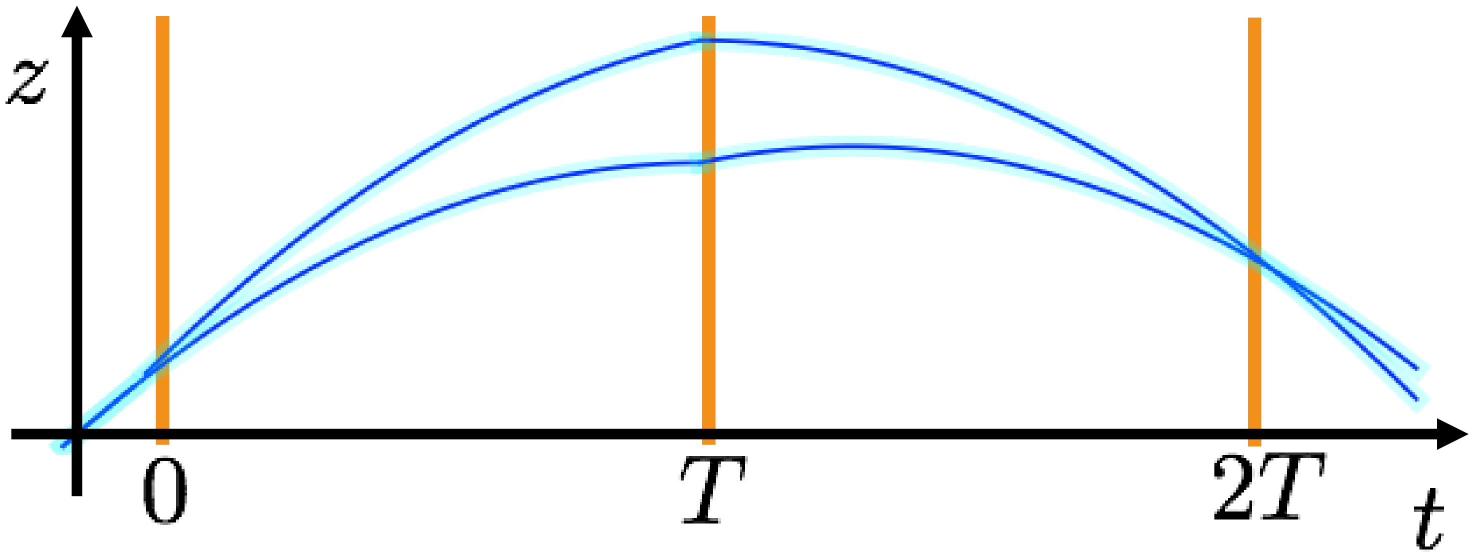


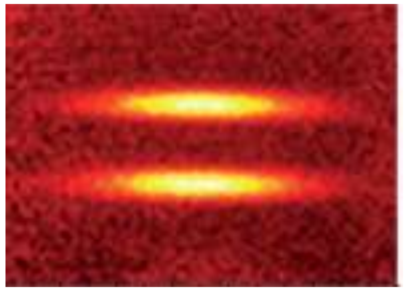


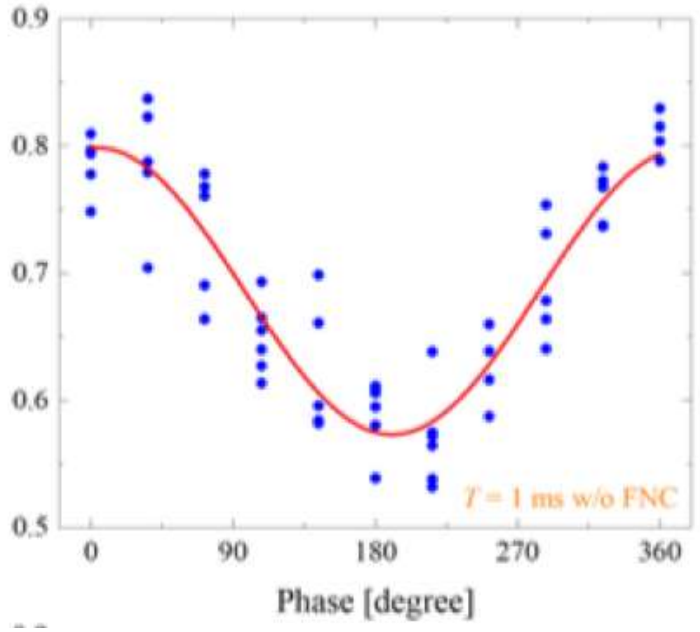


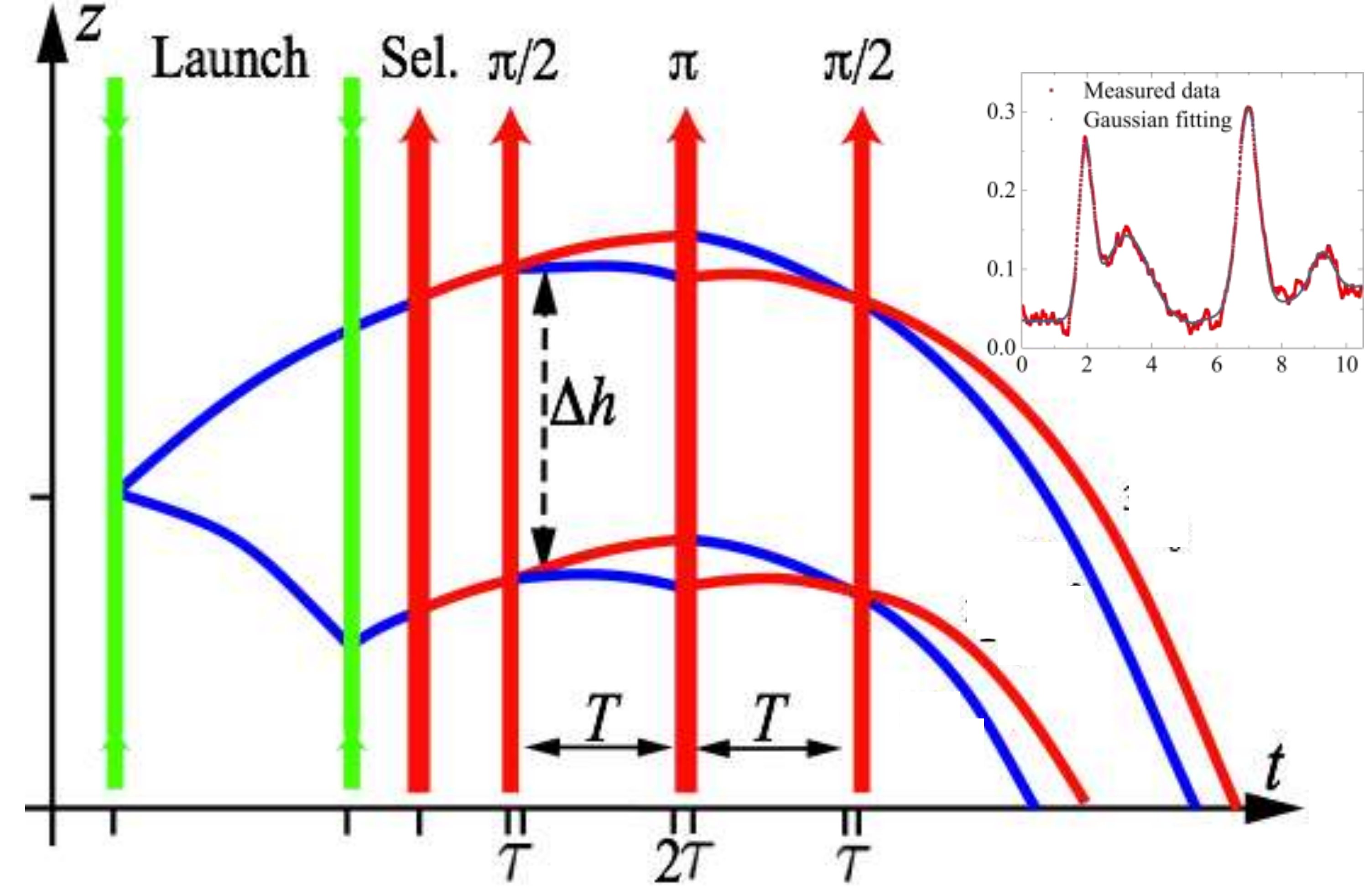
$$\Delta\phi = (\phi_1 - \phi_{2A}) - (\phi_{2B} - \phi_3) \longrightarrow \boxed{\Delta\phi = k_{\text{eff}} g T^2}$$

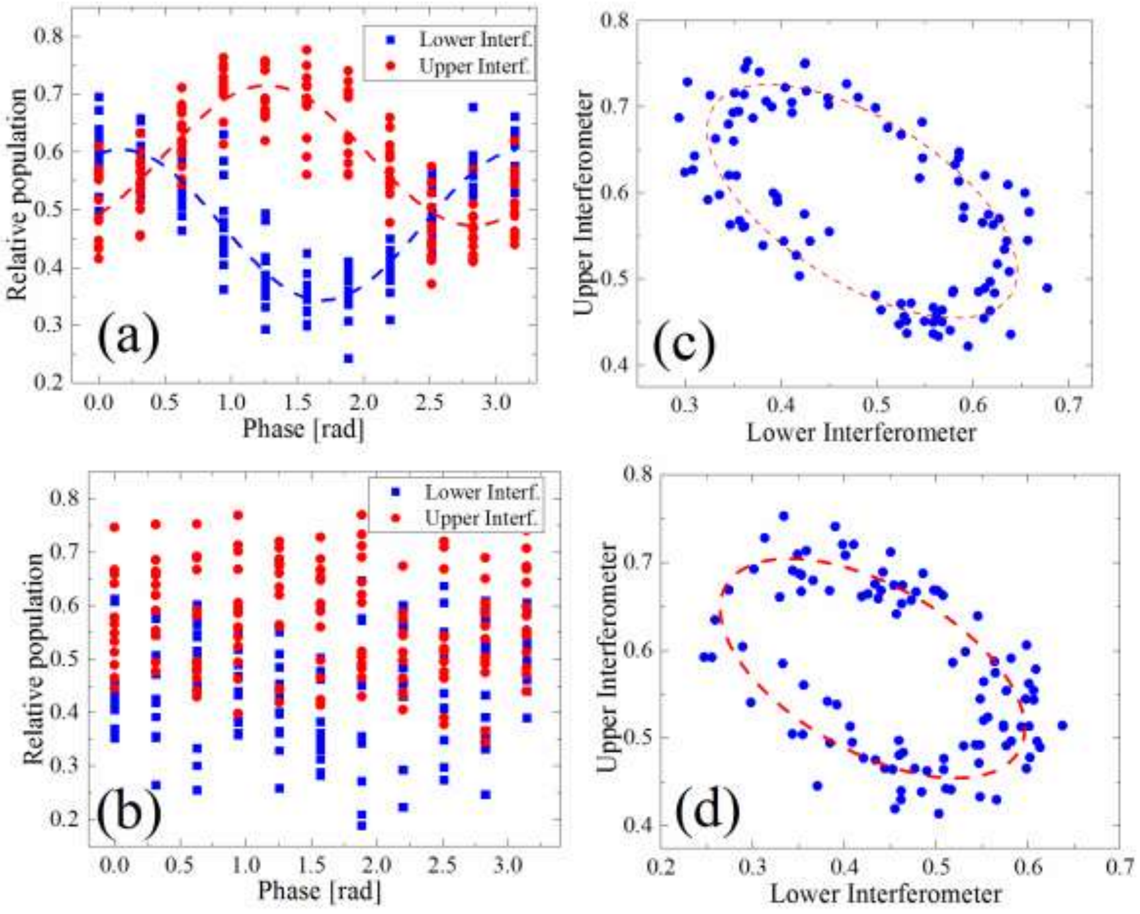
Gravity and gradient measurements





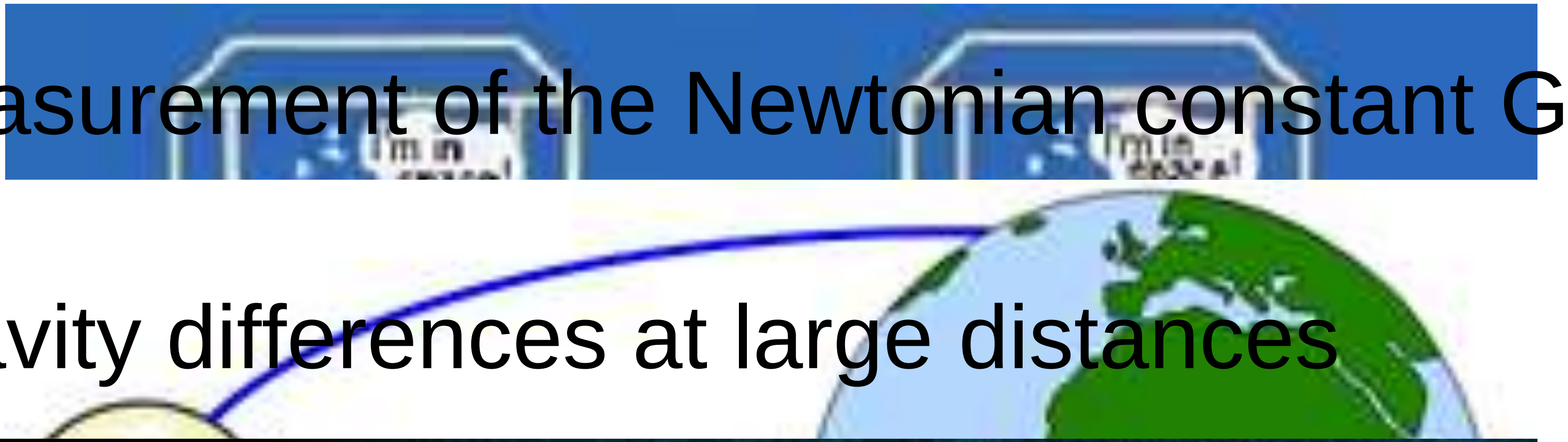




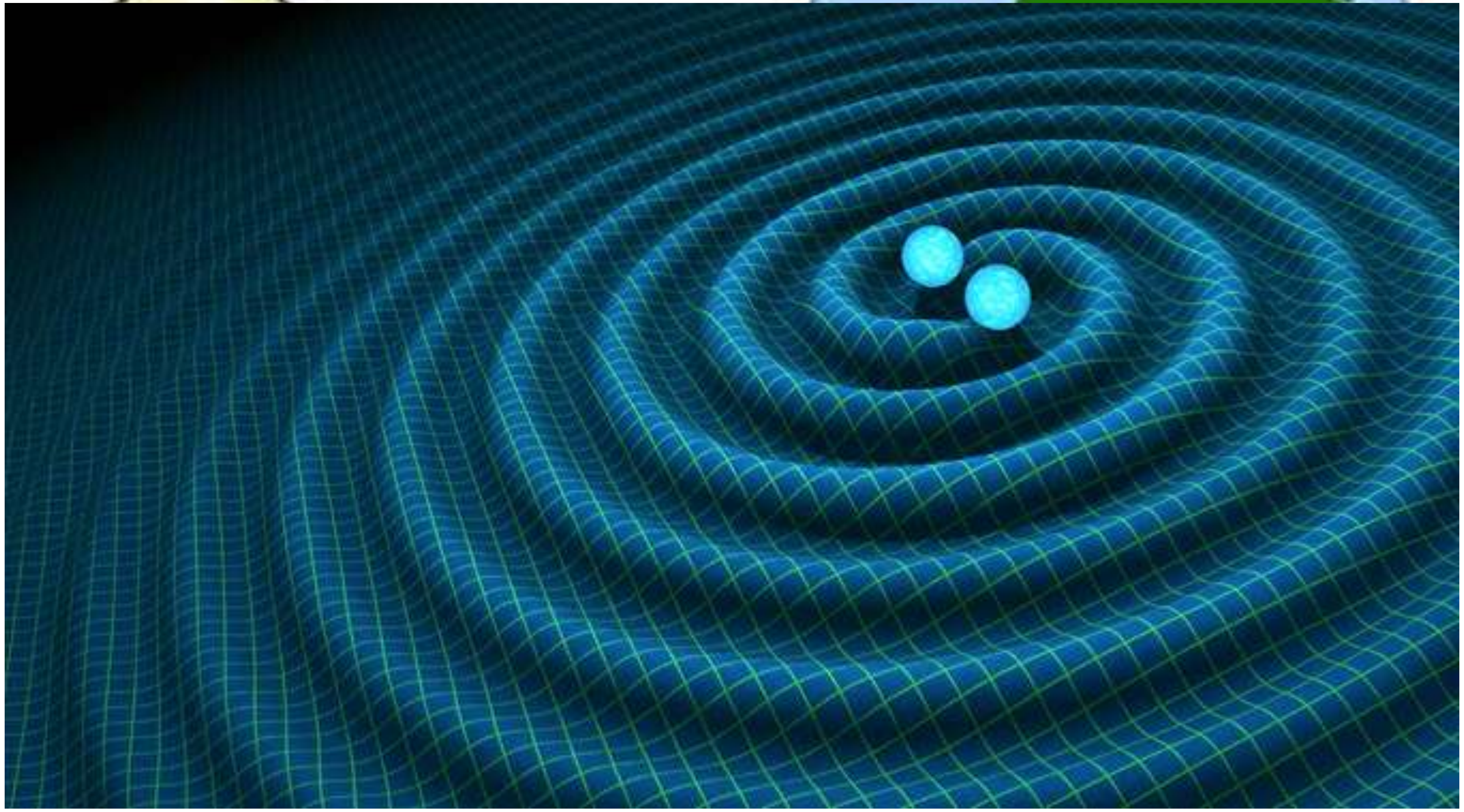


Tests of gravity with Atom Interferometry

- Equivalence principle tests at the quantum level



- Measurement of the Newtonian constant G
- Gravity differences at large distances



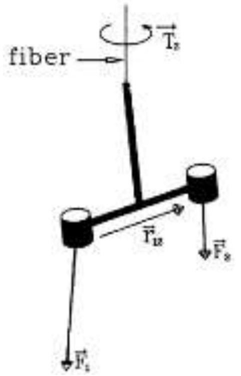
Test of the Weak Equivalence Principle

Einstein Equivalence Principle:

- **Universality of free fall or Weak Equivalence Principle** →
- **Local position invariance**
- **Local Lorentz invariance**

The trajectory of a chargeless body is independent of its internal structure and composition

$$\eta = 2\left|\frac{a_A - a_B}{a_A + a_B}\right| = 2\left|\frac{(m_i/m_g)_A - (m_i/m_g)_B}{(m_i/m_g)_A + (m_i/m_g)_B}\right|$$



Wagner et al.
CQG **29** 18 (2012)

Touboul at al.
PRL **119** 231101 (2017)

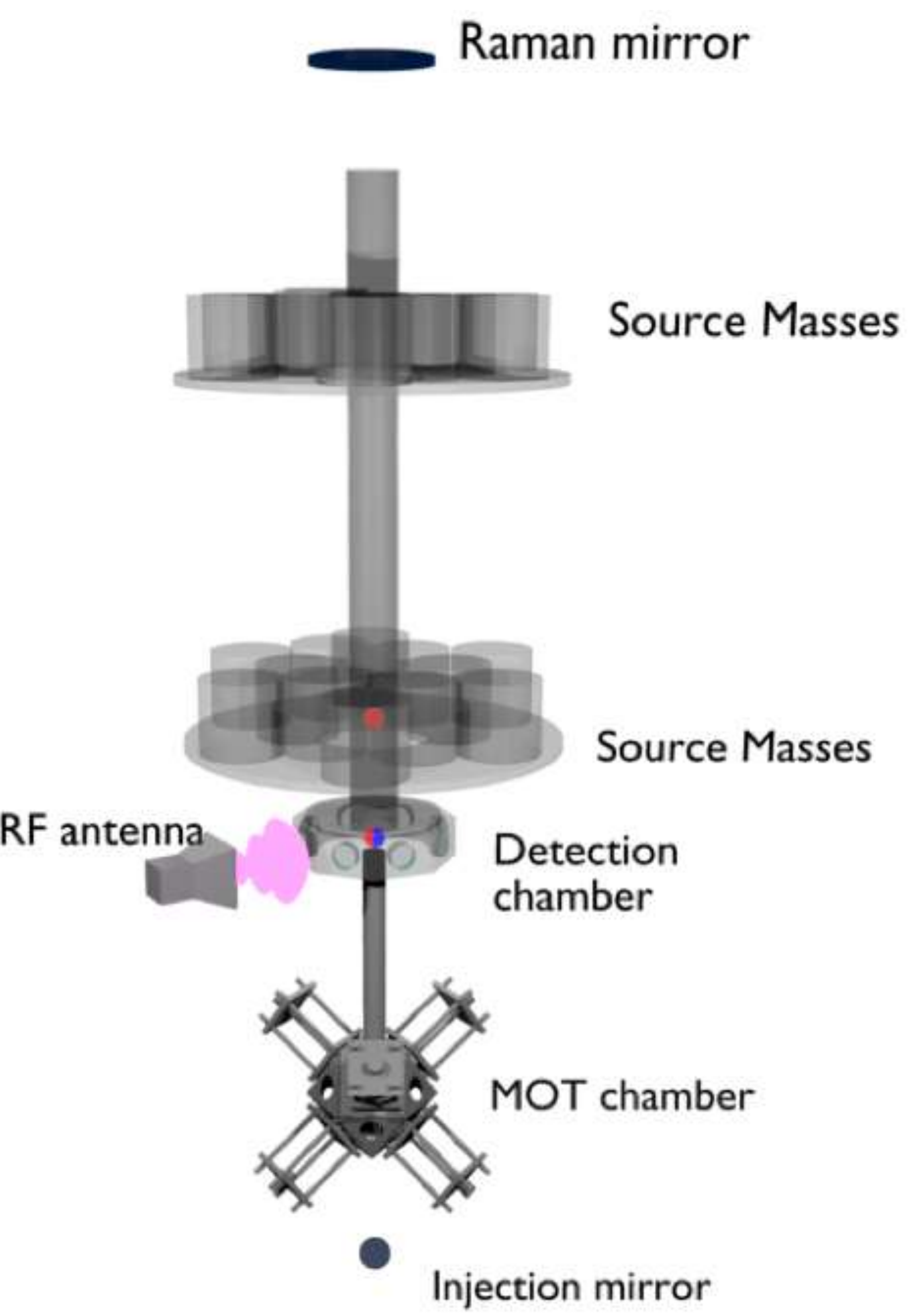
Tarallo et al.
PRL **113** 023005
(2014)

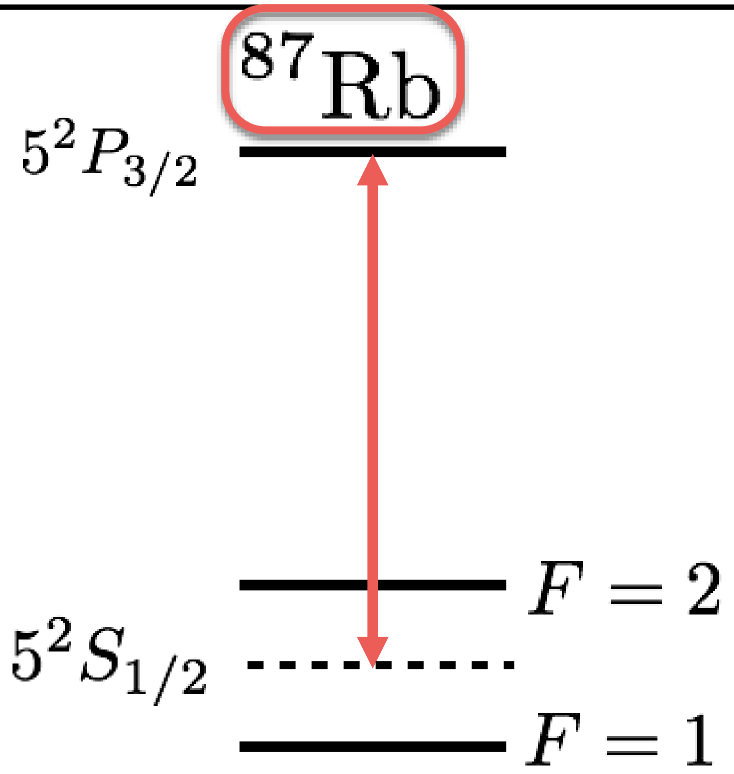
Quantum formulation of the Weak Equivalence Principle for two-level systems

$$\hat{M}_g \hat{M}_i^{-1} = \begin{pmatrix} r_1 & \boxed{r} \\ \boxed{r^*} & r_2 \end{pmatrix}$$

The off-diagonal elements can only be tested through coherent superpositions

Quantum test of WEP





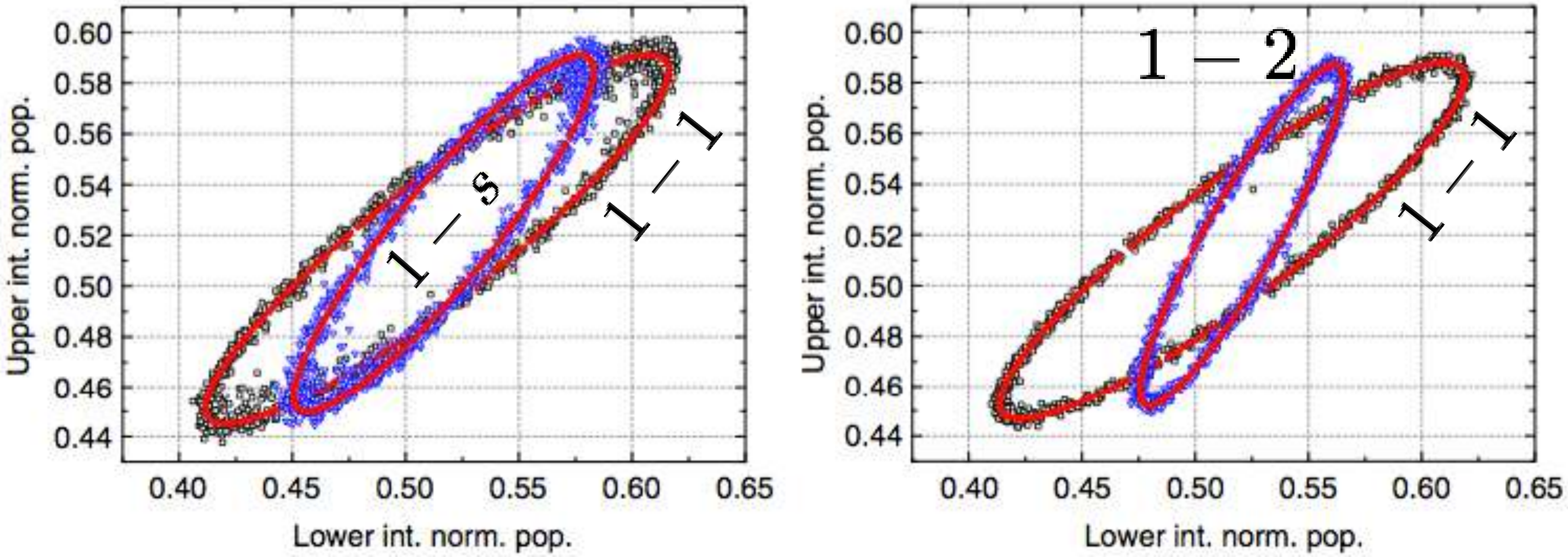
$$a_1 = g\langle 1|\hat{M}_g\hat{M}_i^{-1}|1\rangle = gr_1$$

$$a_2 = g\langle 2|\hat{M}_g\hat{M}_i^{-1}|2\rangle = gr_2$$

$$|s\rangle = \frac{1}{\sqrt{2}}(|1\rangle + e^{i\gamma}|2\rangle)$$

$$a_s = \langle s|\hat{M}_g\hat{M}_i^{-1}|s\rangle$$

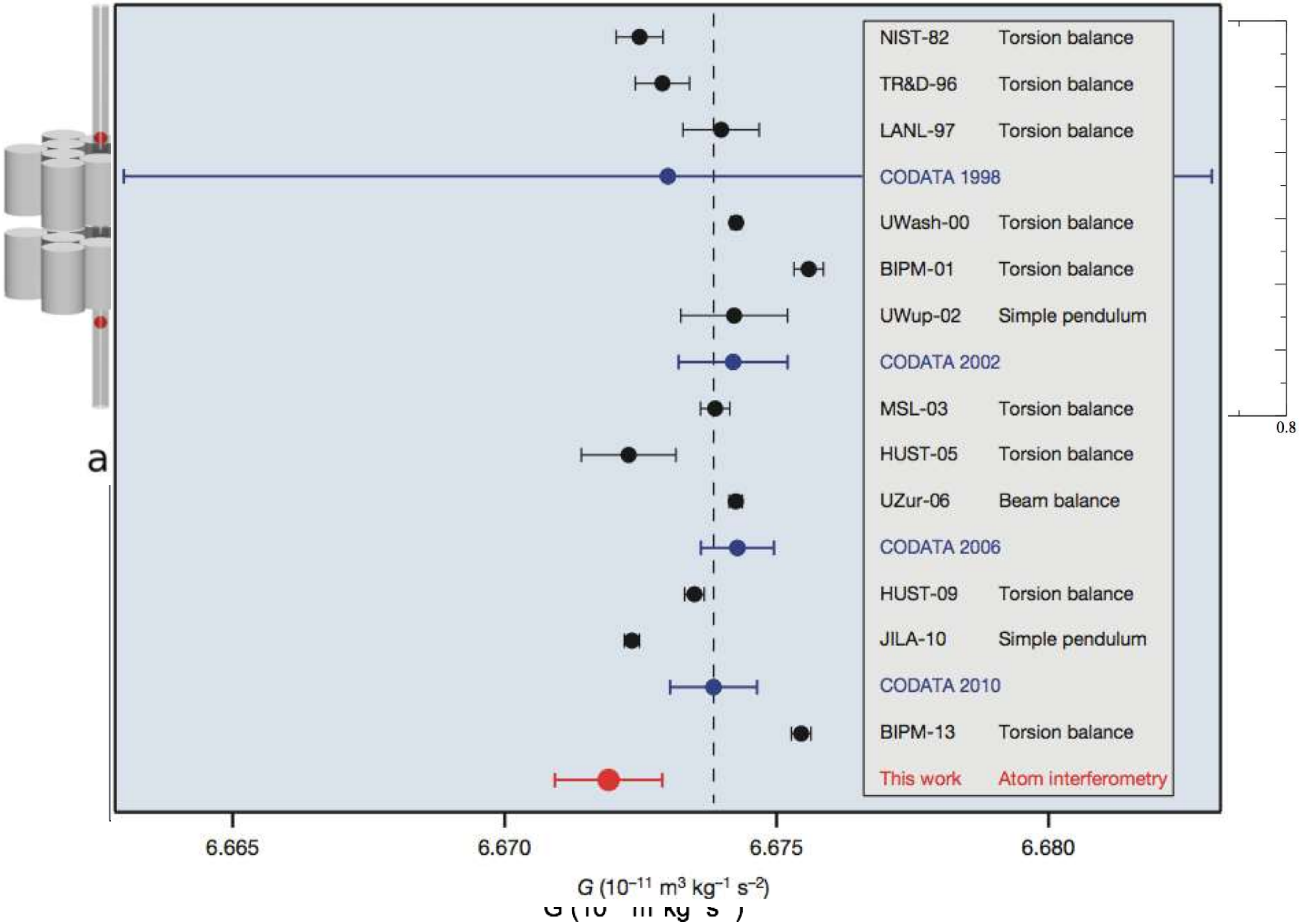
$$= g\left[\frac{r_1+r_2}{2} + |r|\cos(\phi_r+\gamma)\right]$$



$$\eta_{1-2} = (1.0 \pm 1.4)\times 10^{-9} \quad \eta_{1-s} = (3.3 \pm 2.9)\times 10^{-9} \quad |r| \le 5\times 10^{-8}$$

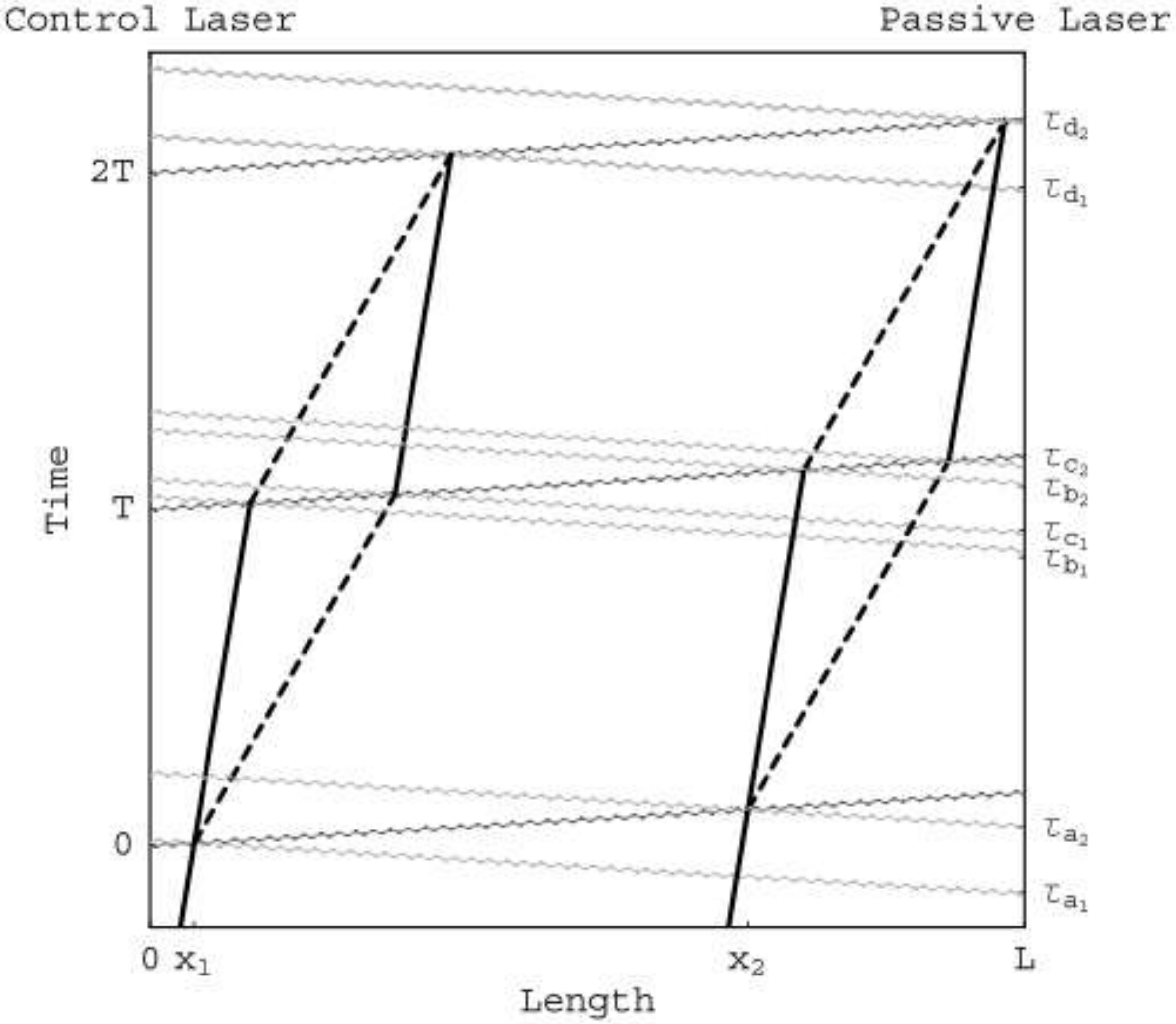
Rosi et al. Nature Communications **8,** 15529 (2017)

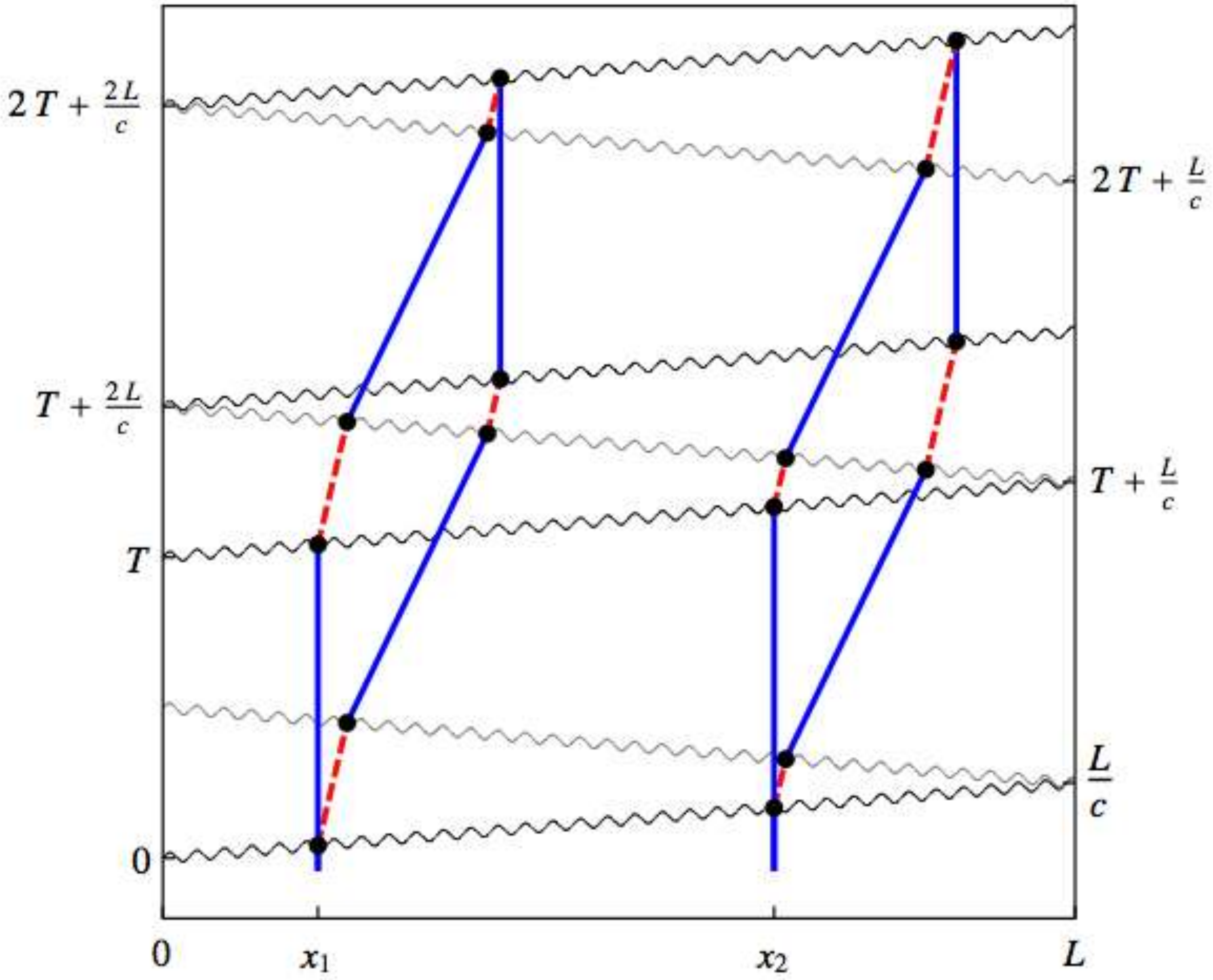
Measurement of the Newtonian constant G



G. Rosi et al., Nature **510** 518-521 (2014)

Long-baseline atom interferometry





Detector bandwidth limit:

$$\Delta\nu_{\max} \sim c/L$$

Absence of phase noise from the laser:

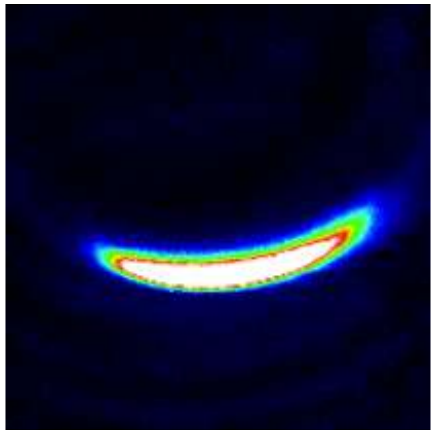
single-photon transition required

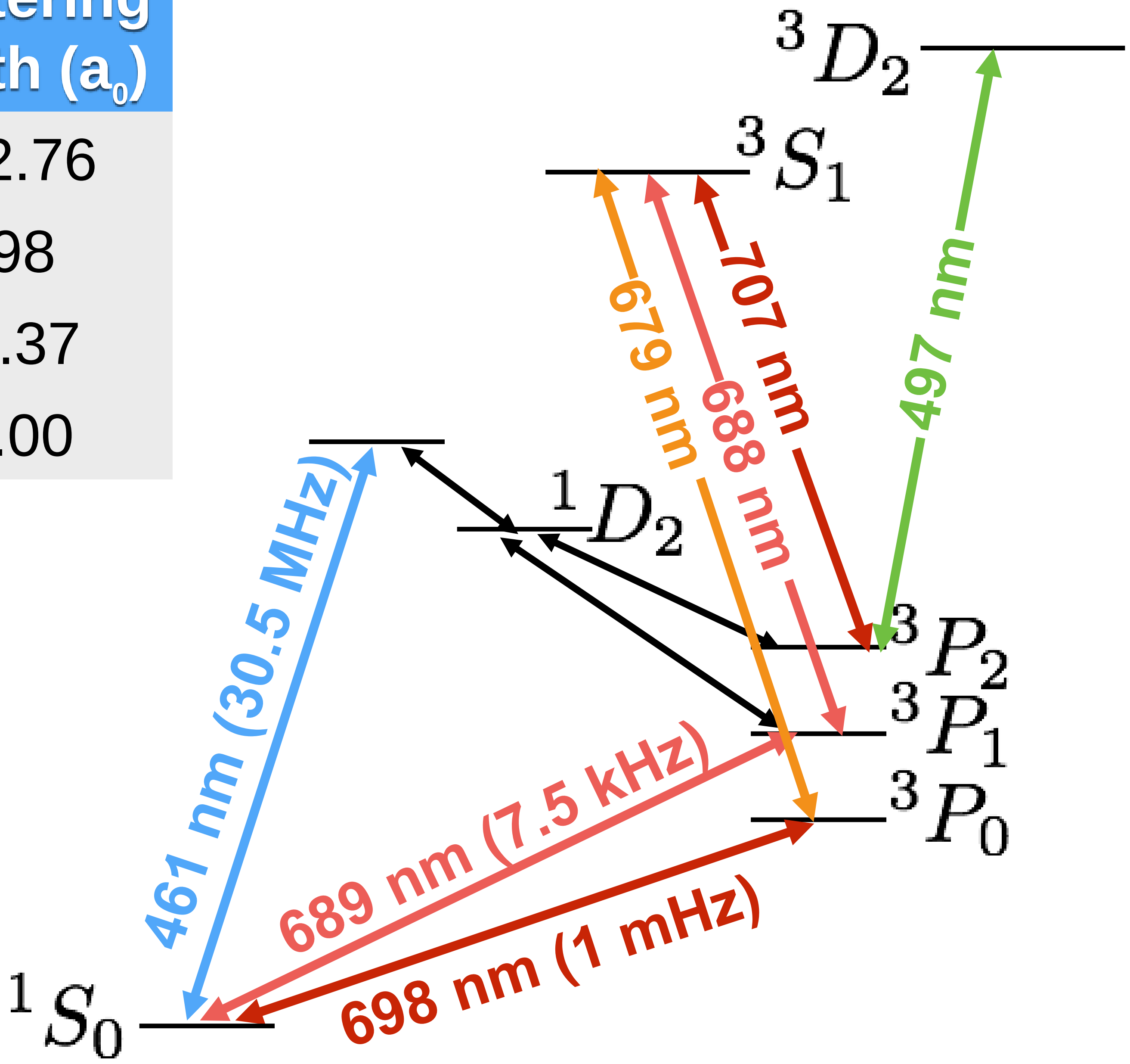
- S. Dimopoulos et al., *Phys. Lett. B* **678**, 37-40 (2009)
- P. W. Graham et al., *Phys. Rev. Lett.* **110**, 171102 (2013)

Requirements for the AI based on a single-photon transition

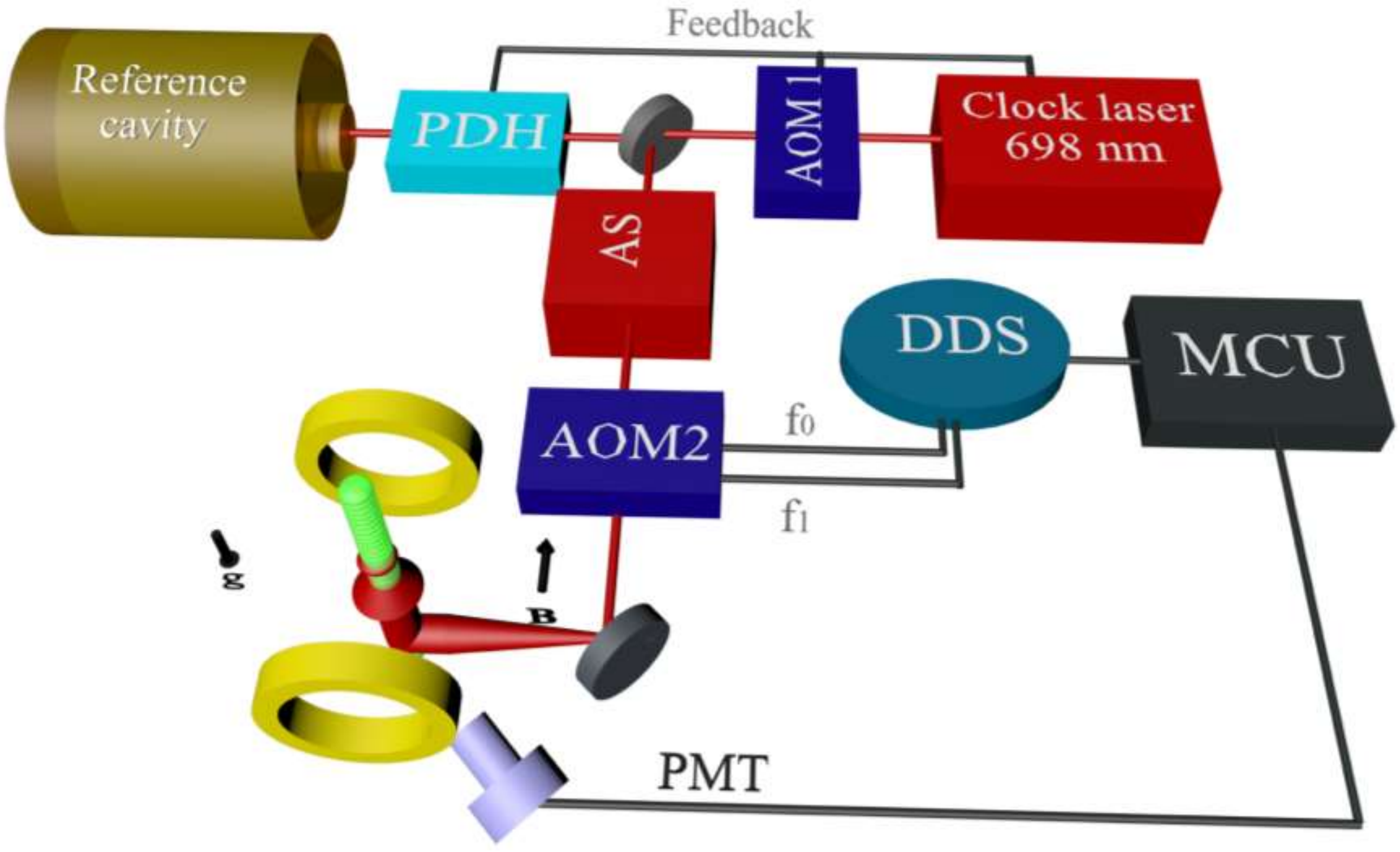
- Lifetime of the excited state longer than the interferometer time
- Ultra-stable laser to address the transition
- High-power laser to attain good transfer efficiency

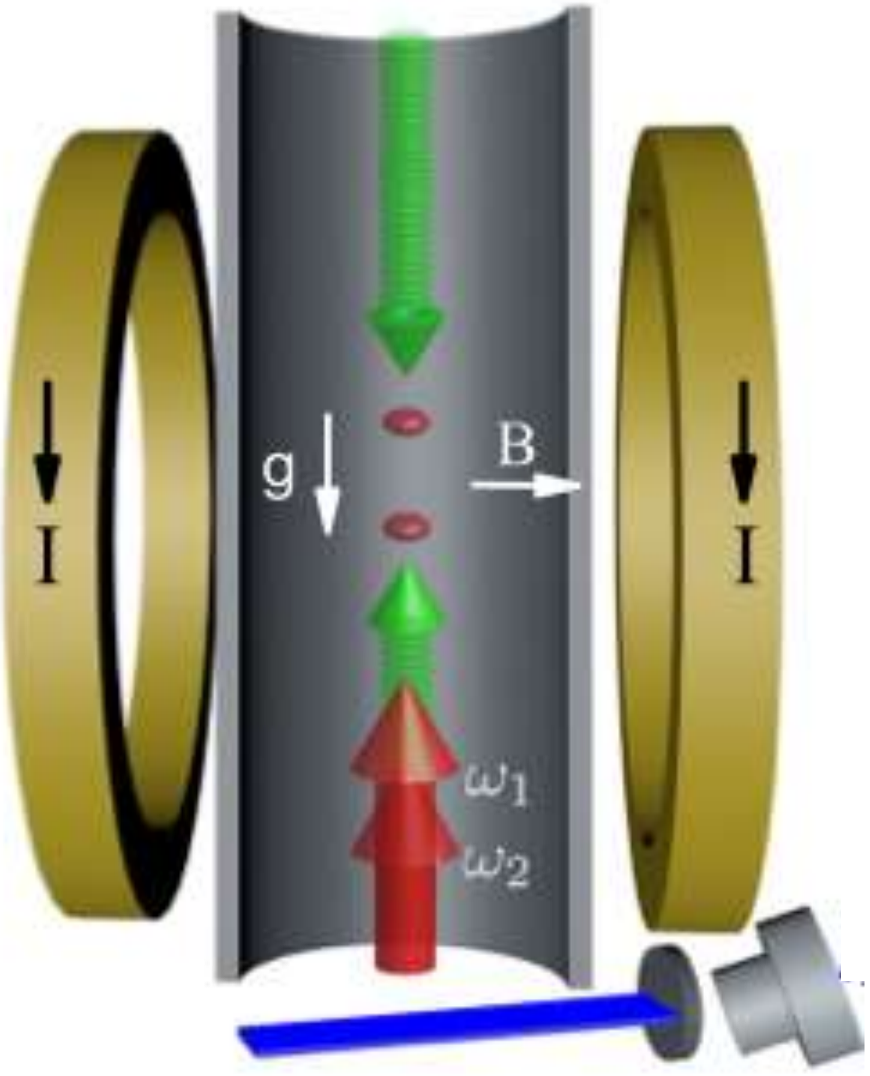
Atomic mass	Abundance	Nuclear spin	Scattering length (a_0)
84	0.56%	0	122.76
86	9.86%	0	798
87	7.00%	9/2	97.37
88	82.58%	0	-2.00



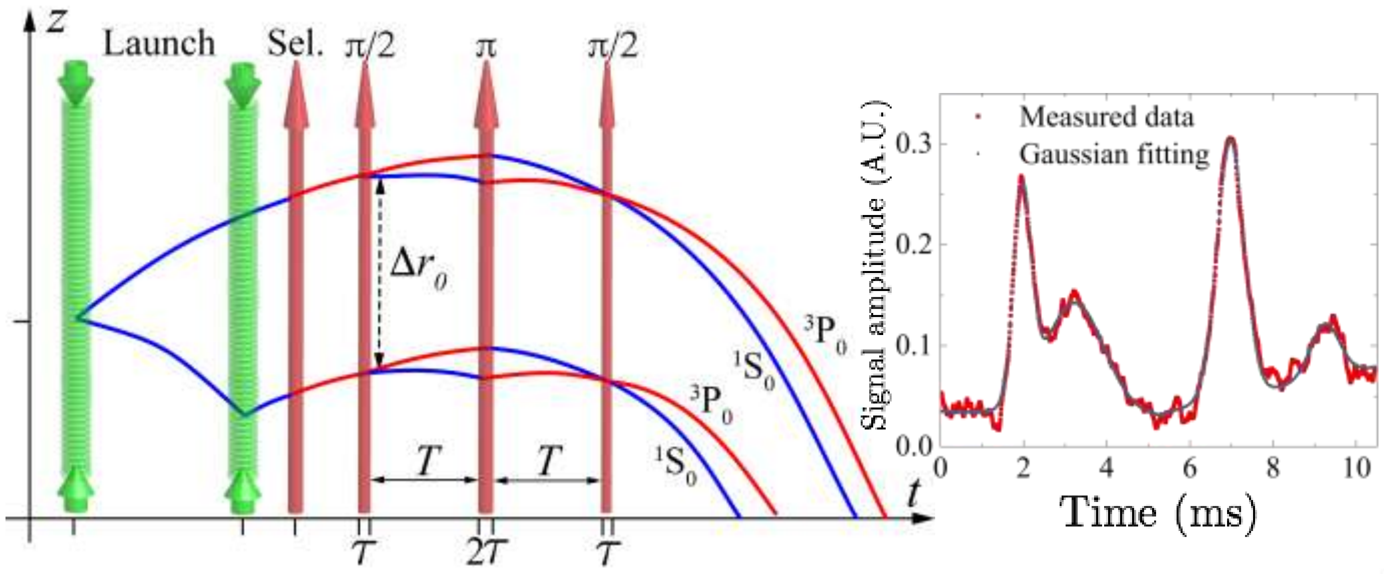


Experiment setup for proof of principle





Gradiometer setup and signal

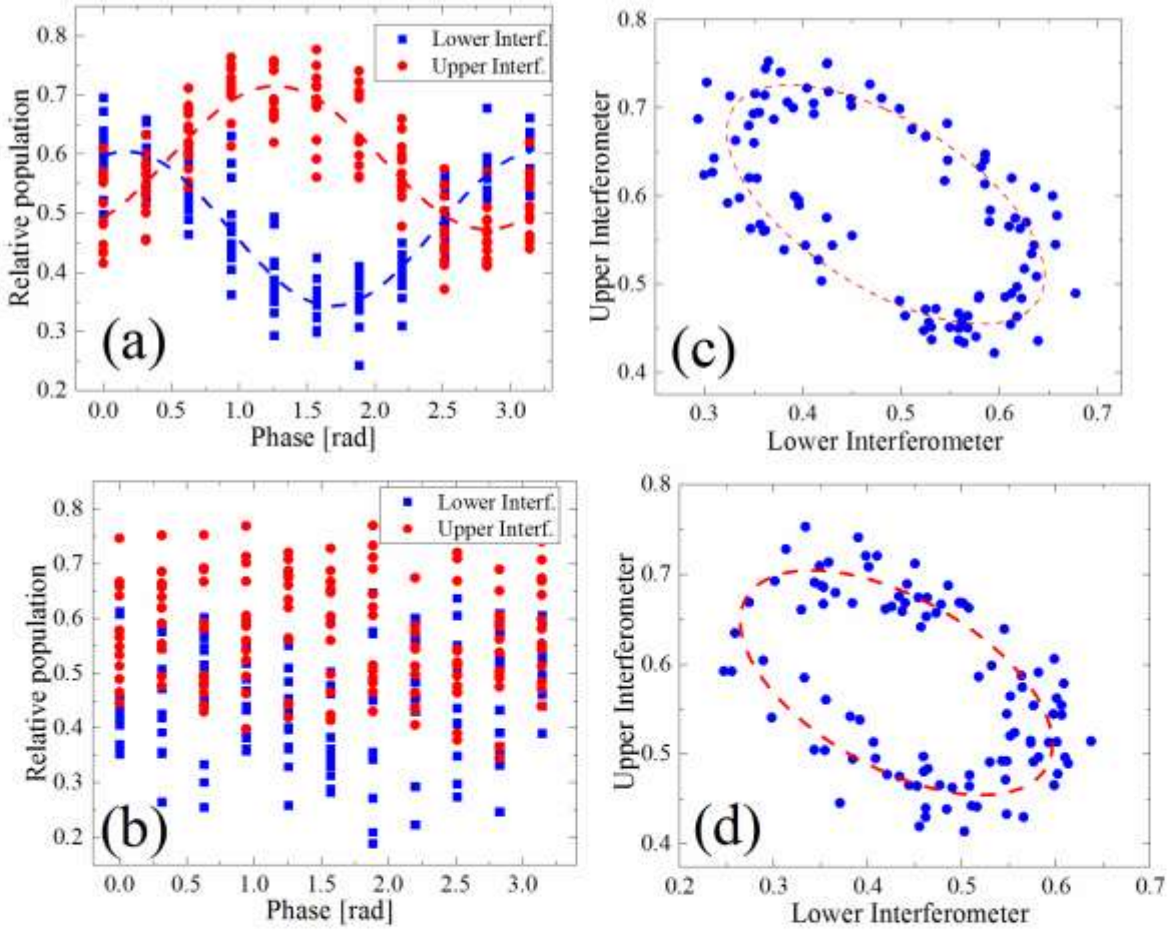


$$\Delta r_0 = 1.9 \text{ mm}$$
$$\Delta v_0 = 3.4 \text{ cm/s}$$

Because of the velocity difference, a single laser frequency cannot interact with both probes.

With two frequencies:

- both clouds addressed
- tunable artificial phase shift



Attained phase noise 5 times greater than the atom shot noise due to limited detection efficiency

Hu et al., PRL **119** 263601 (2017)

Conclusions and prospects

- Quantum test of the Equivalence principle
- Accurate measurement of G with a completely new method, **attained the atom shot noise level**
- New type of interferometer operating on a single-photon transition

Future work

- Implementation of entangled (squeezed states) to overcome the shot noise
- Quantum test of WEP with superpositions of states separated by the optical clock transition

Thank you for your attention