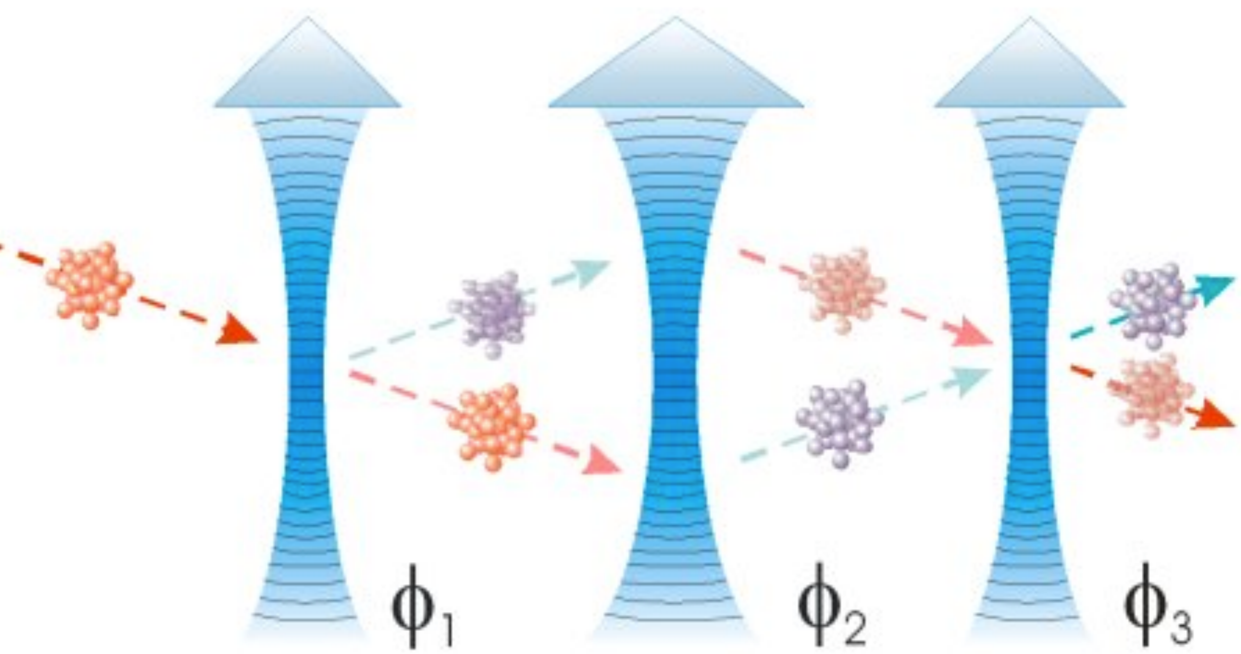
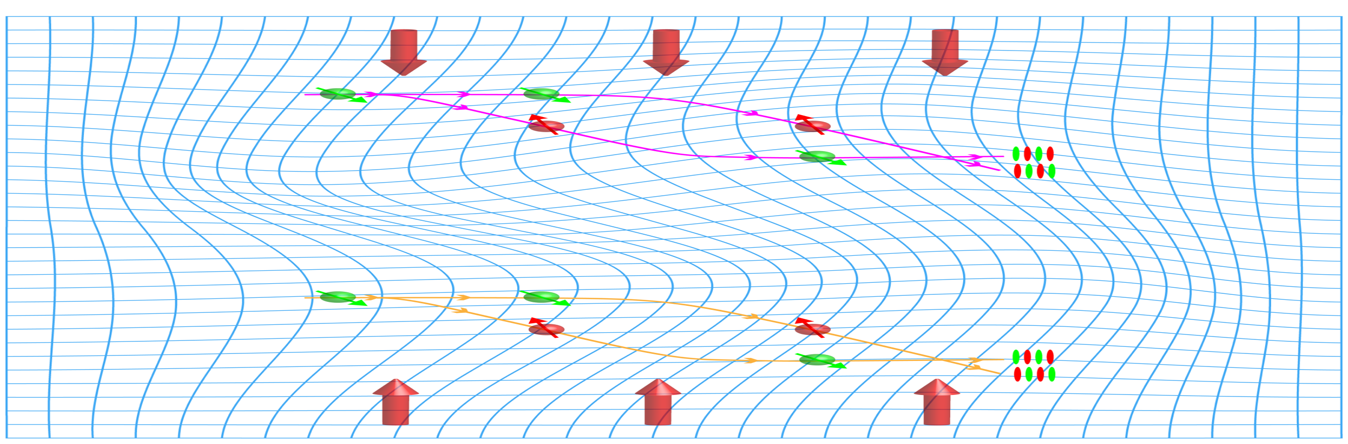
General relativity tests and precision measurements

Leonardo Salvi

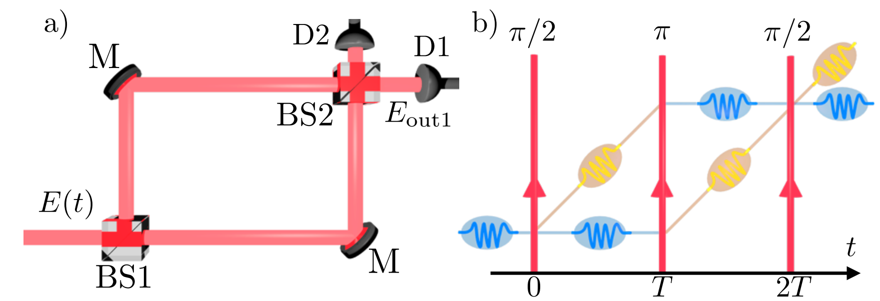
October 23, 2019



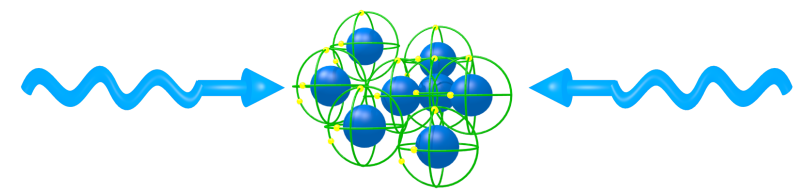


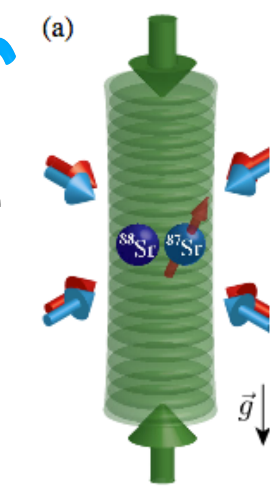
Outline

- **Atom Interferometry for gravity measurements**



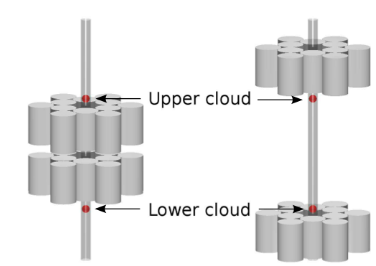
- **Technology for the implementation of atom interferometers**



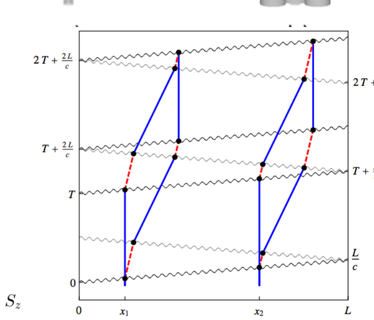


- **Classical and quantum tests of the Weak Equivalence Principle**

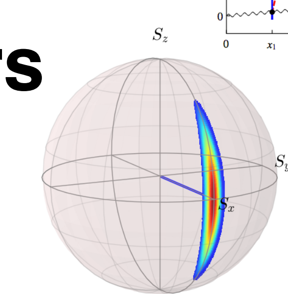
- **Measurement of the Newtonian constant G towards the 10 ppm level**



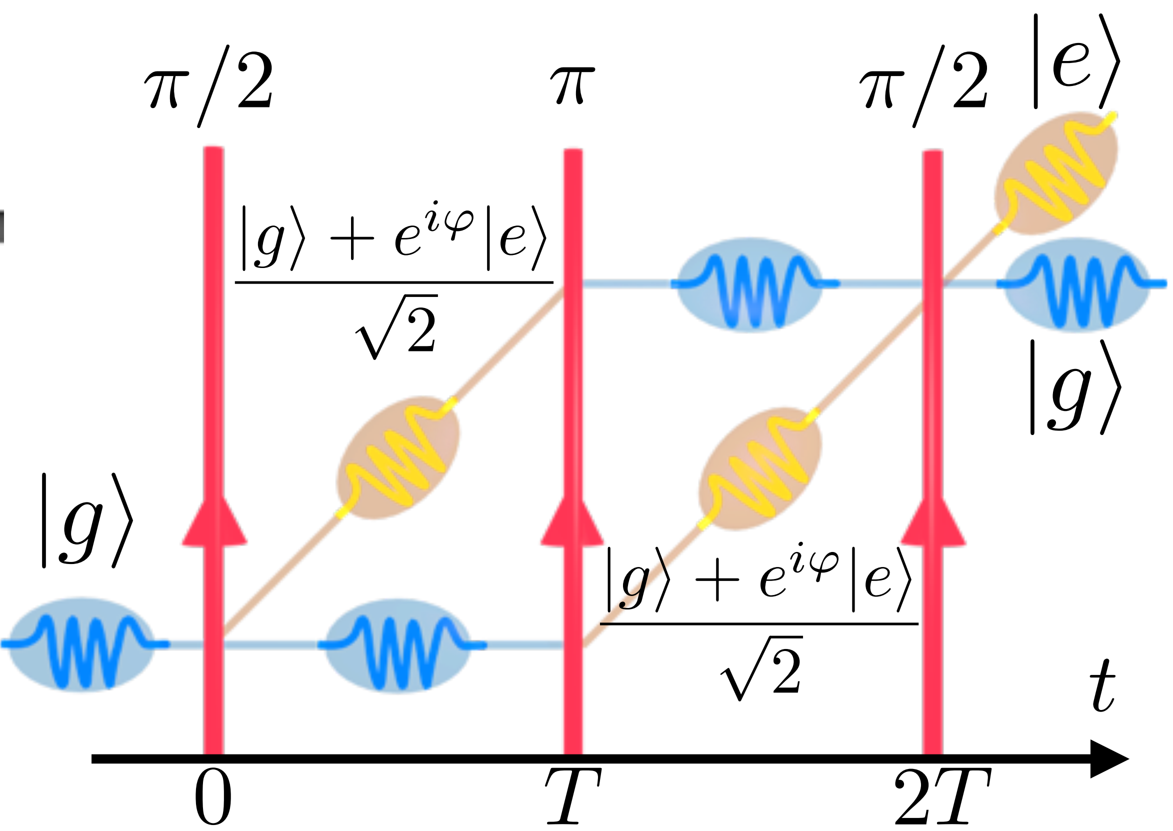
- **Atom Interferometry on a single-photon transition**



- **Towards spin squeezing in Atom Interferometers**



Atom Interferometry for gravity measurements



$$S_z = \frac{N(|e\rangle) - N(|g\rangle)}{2}$$

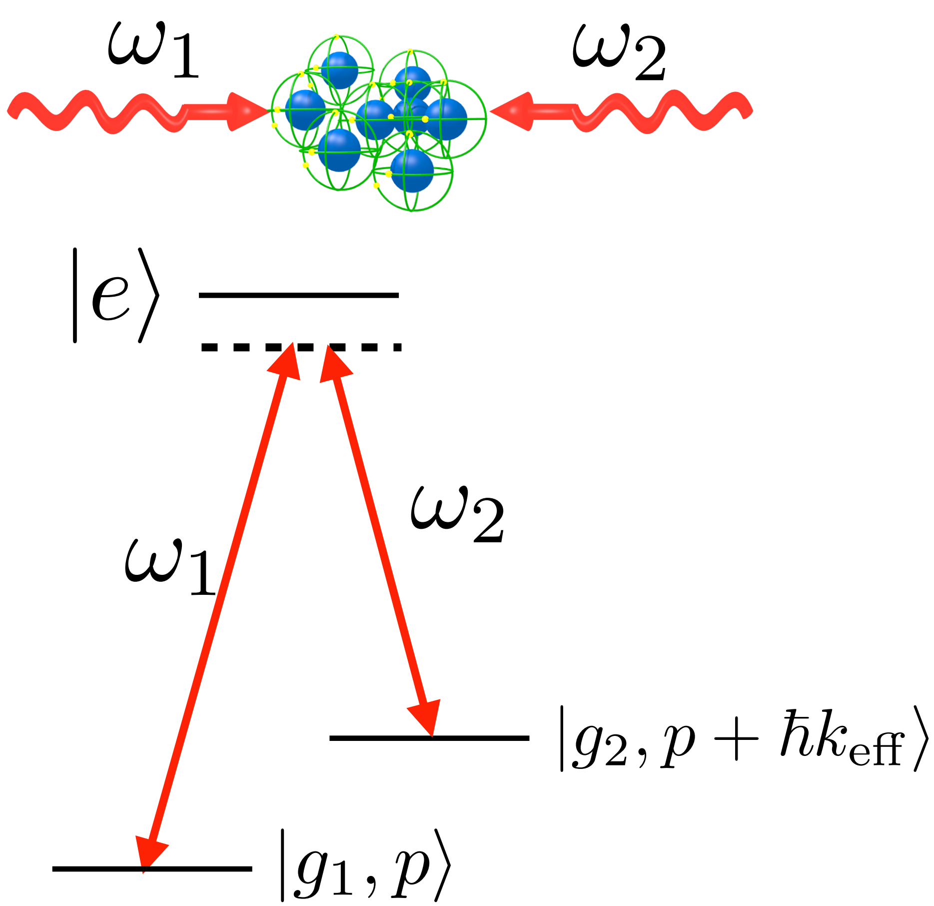
- State preparation $|\psi_0\rangle$
- Phase accumulation $U(\Delta\phi)|\psi_0\rangle$
- Phase estimation $S_z \rightarrow \Delta\phi$

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

- $\Delta\phi$ → Large phase resolution
- k_{eff} → Large Momentum Transfer
- T^2 → Long coherence times

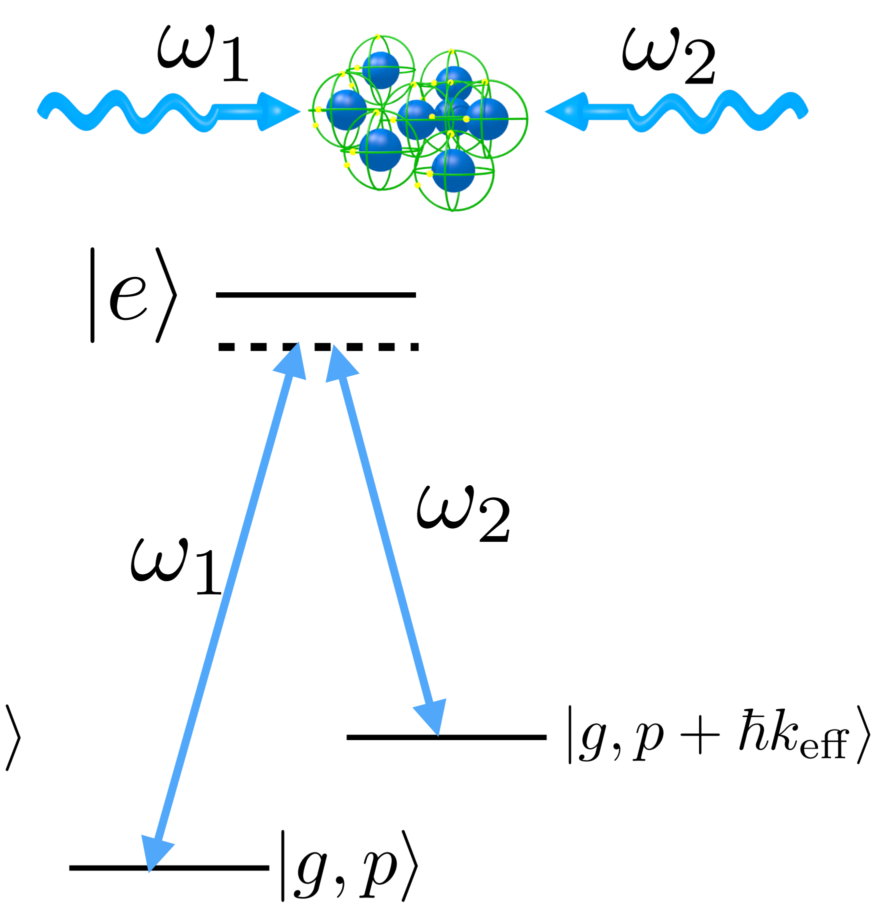
Beam splitters and mirrors for atom interferometry

Raman transition



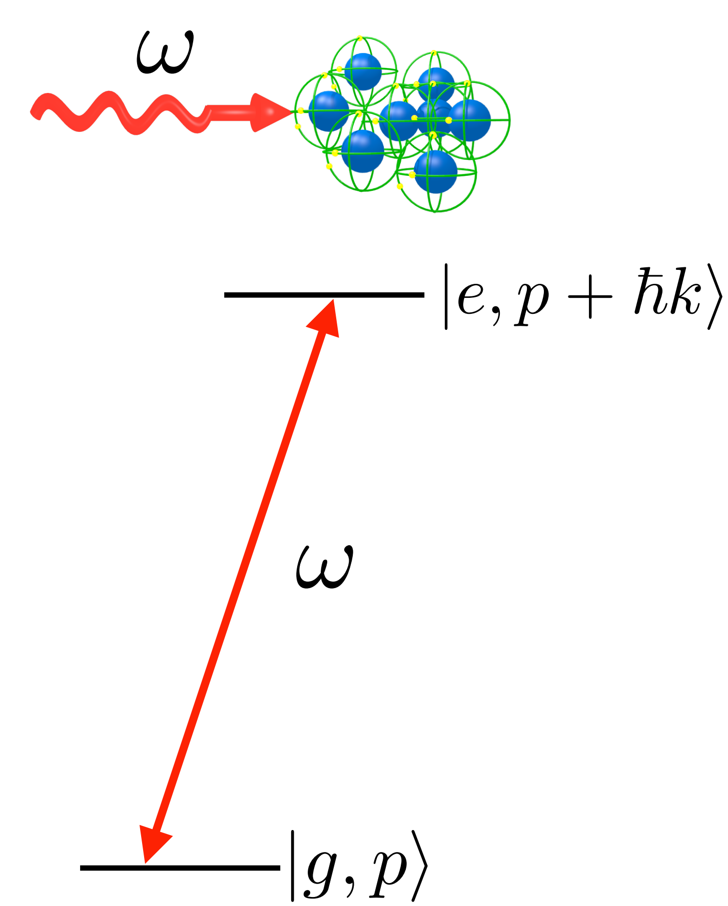
- Internal state labeling
- Light shifts
- Sensitivity to external fields

Bragg transition



- Same internal state
- Negligible light shifts
- Large momentum transfer

Single-photon transition



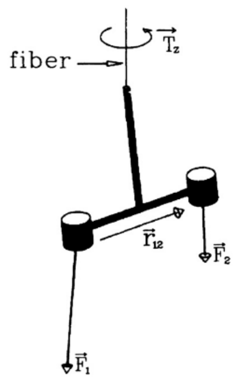
- Long-lived state required
- Negligible light shifts
- eV separation
- Laser noise-insensitive gradiometry

Test of the Weak Equivalence Principle

Einstein Equivalence Principle:

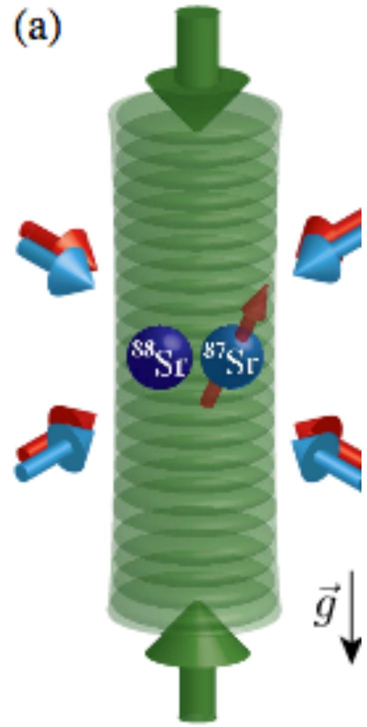
- Universality of free fall or Weak Equivalence Principle → **The trajectory of a chargeless body is independent of its internal structure and composition**

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



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

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

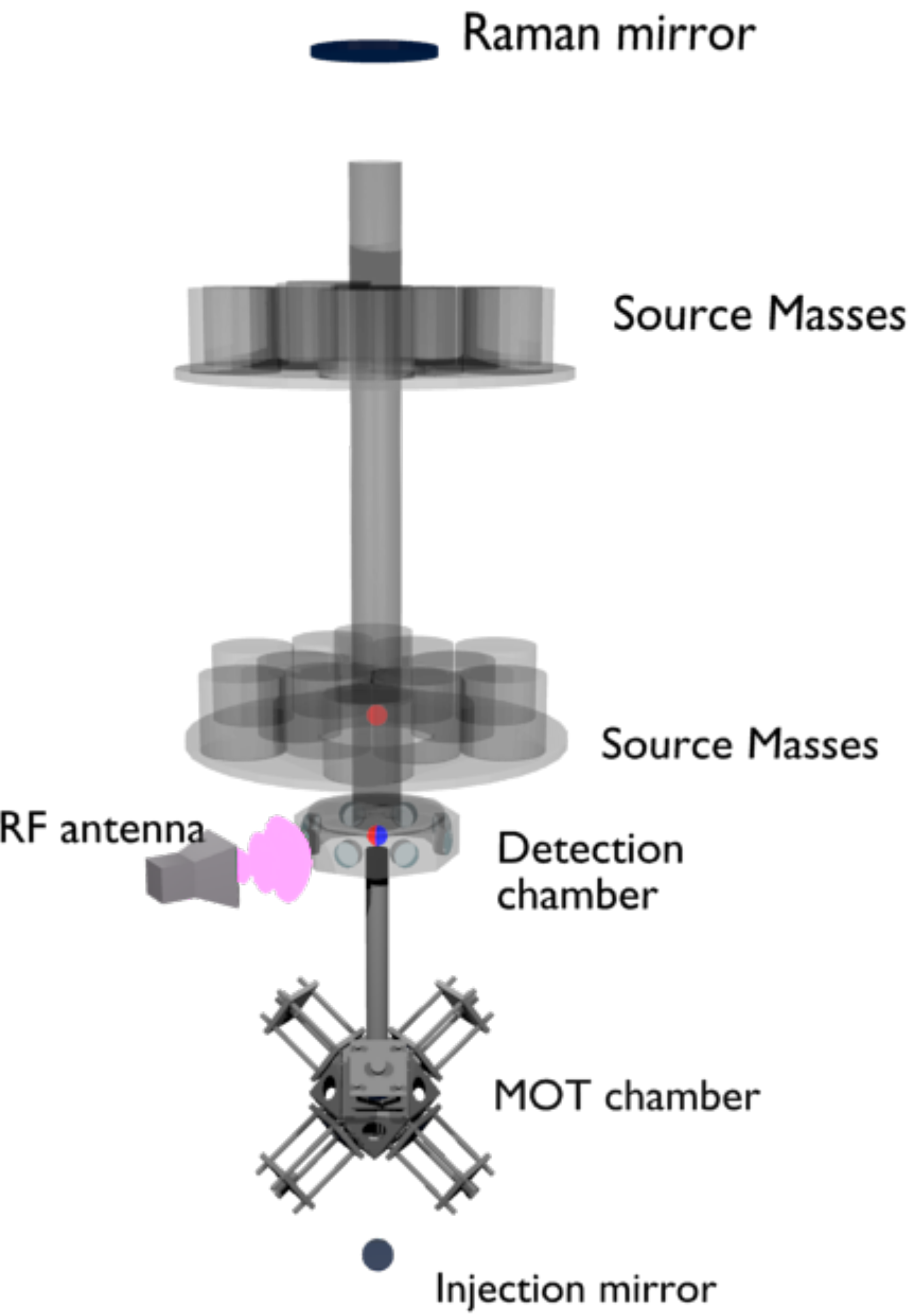


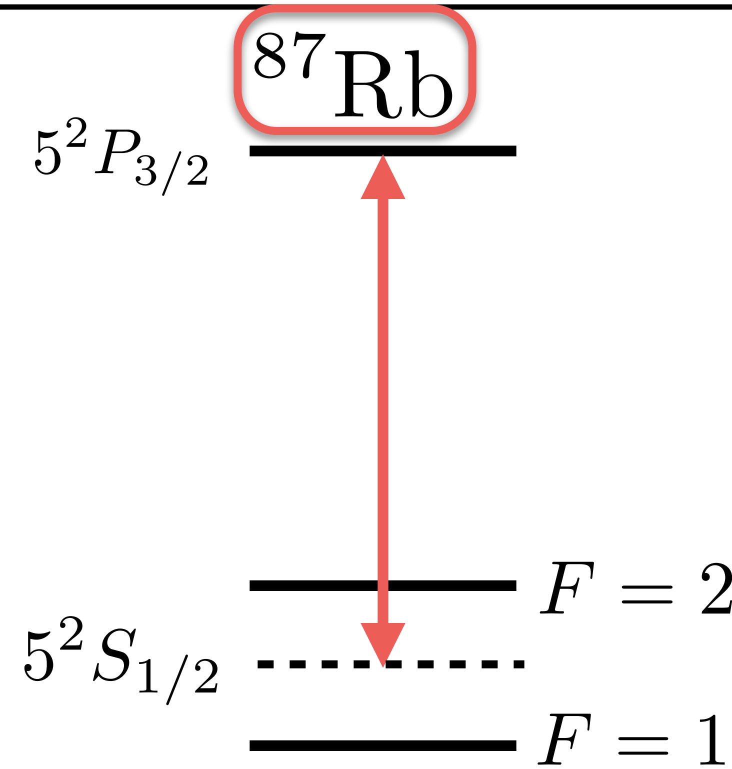
Quantum formulation of the Weak Equivalence Principle for two-level systems

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

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

Quantum test of WEP





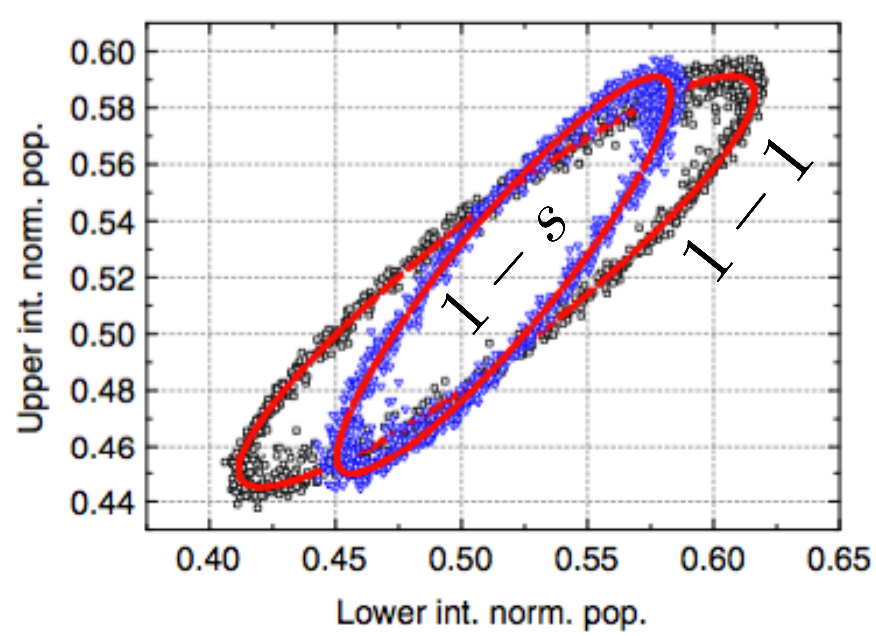
$$a_1 = g\langle 1|\hat{M}_g\hat{M}_i^{-1}|1\rangle = gr_1$$

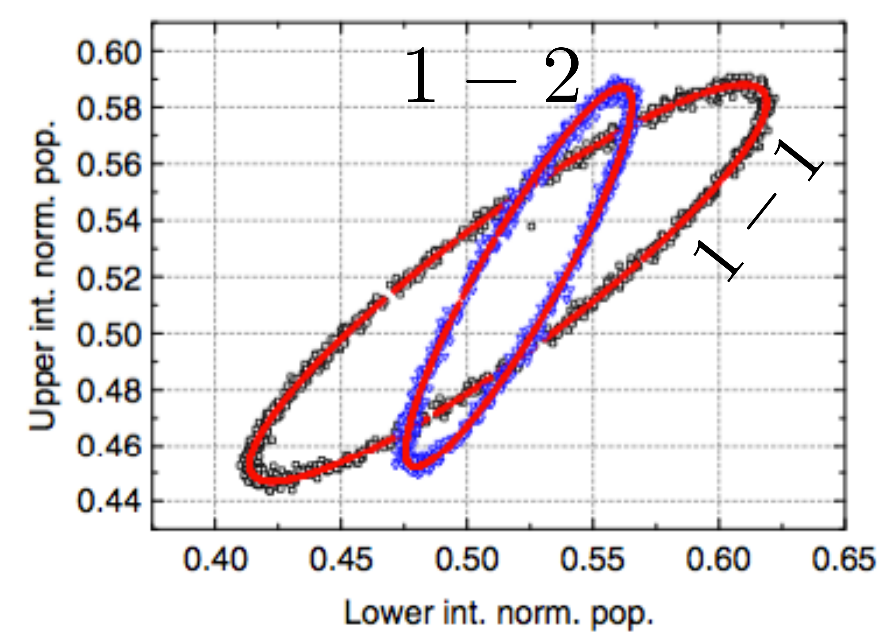
$$a_2 = g\langle 2|\hat{M}_g\hat{M}_i^{-1}|2\rangle = gr_2$$

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

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

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



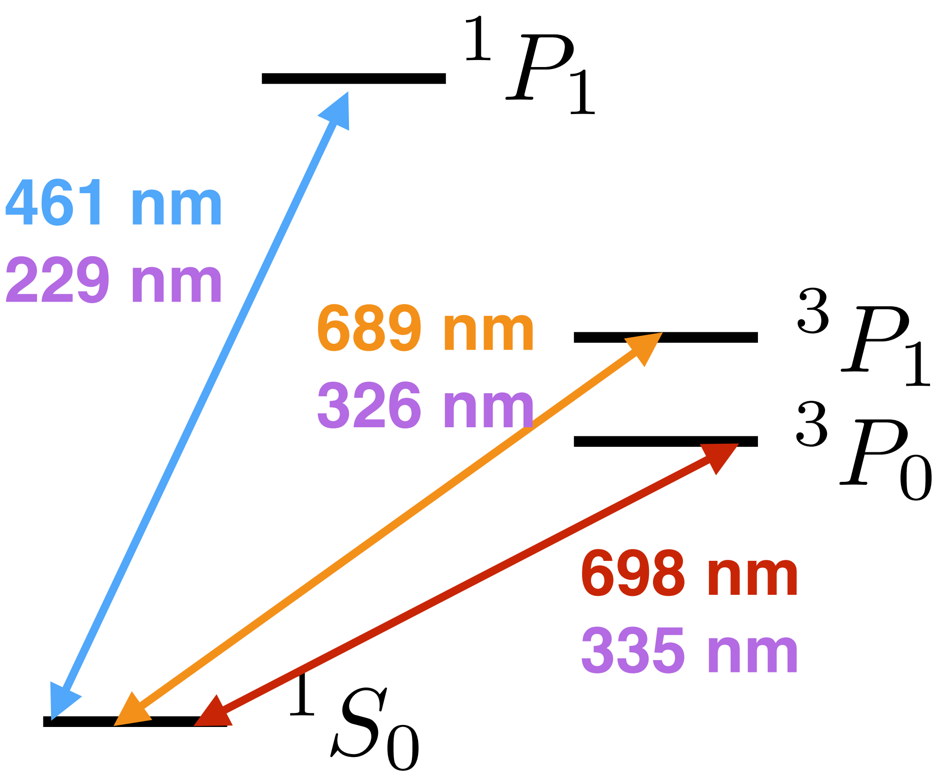


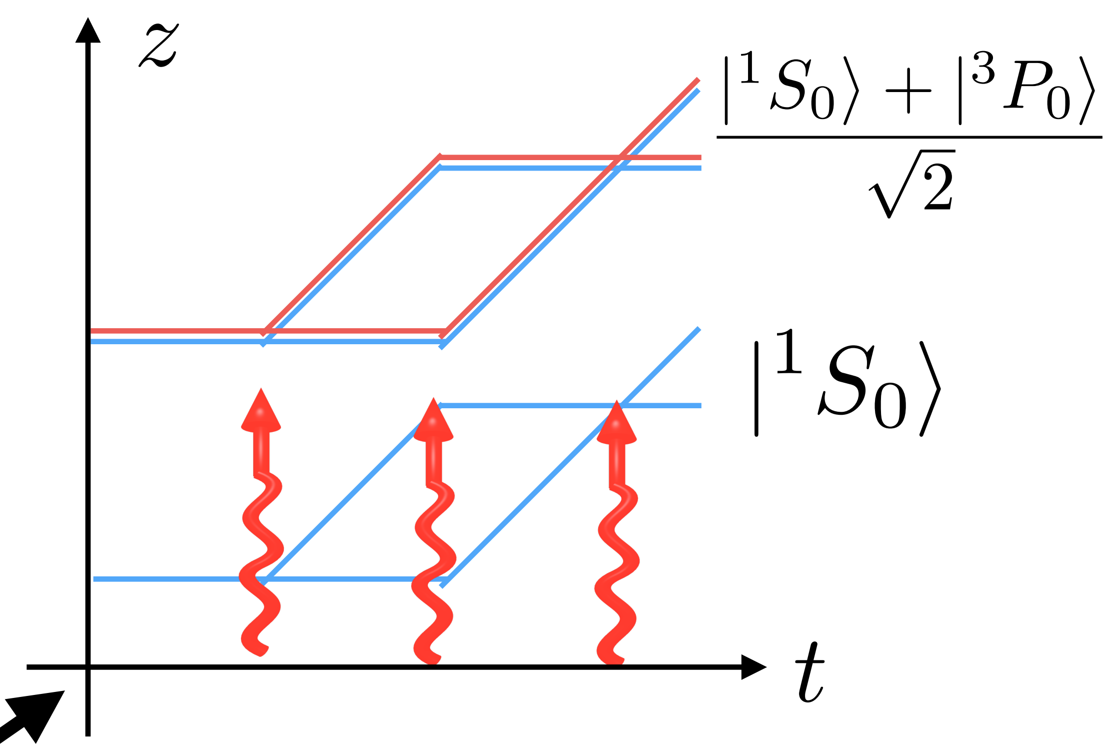
$$\eta_{1-2} = (1.0 \pm 1.4)\times 10^{-9} \quad \eta_{1-s} = (3.3 \pm 2.9)\times 10^{-9} \quad |r| \leq 5\times 10^{-8}$$

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

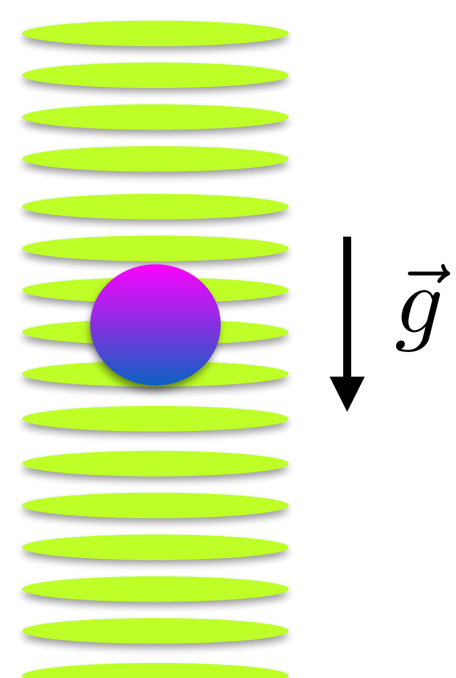
Prospects for quantum WEP tests with optical separation

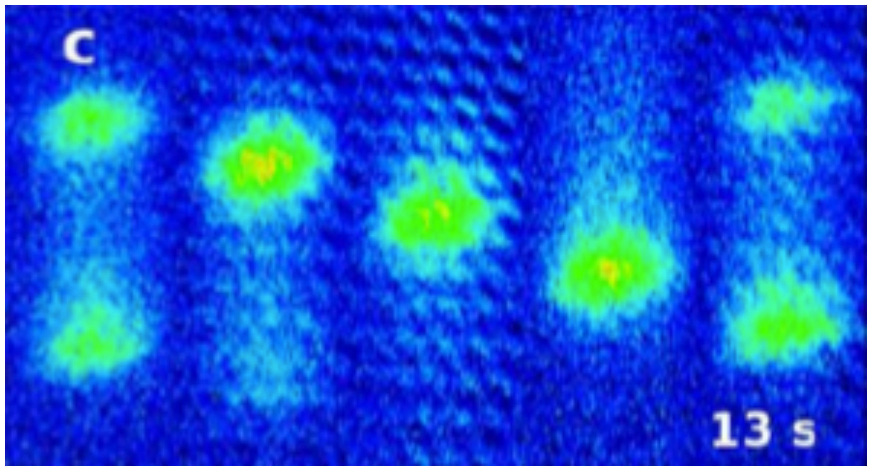
Sr and Cd AIs, TICTOCGRAV ERC project



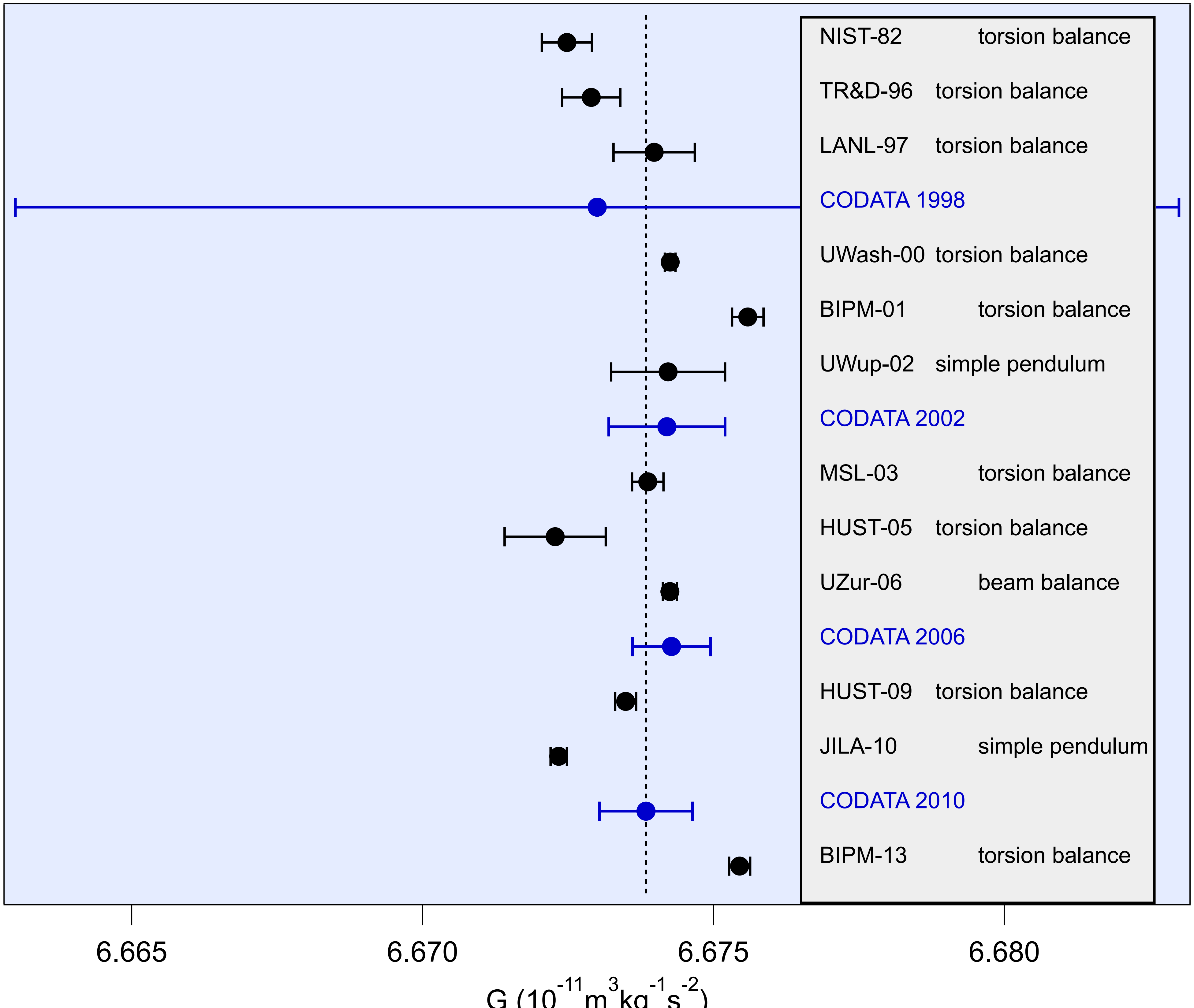


Quantum WEP test with optical separation





Measurement of the Newtonian gravitational constant



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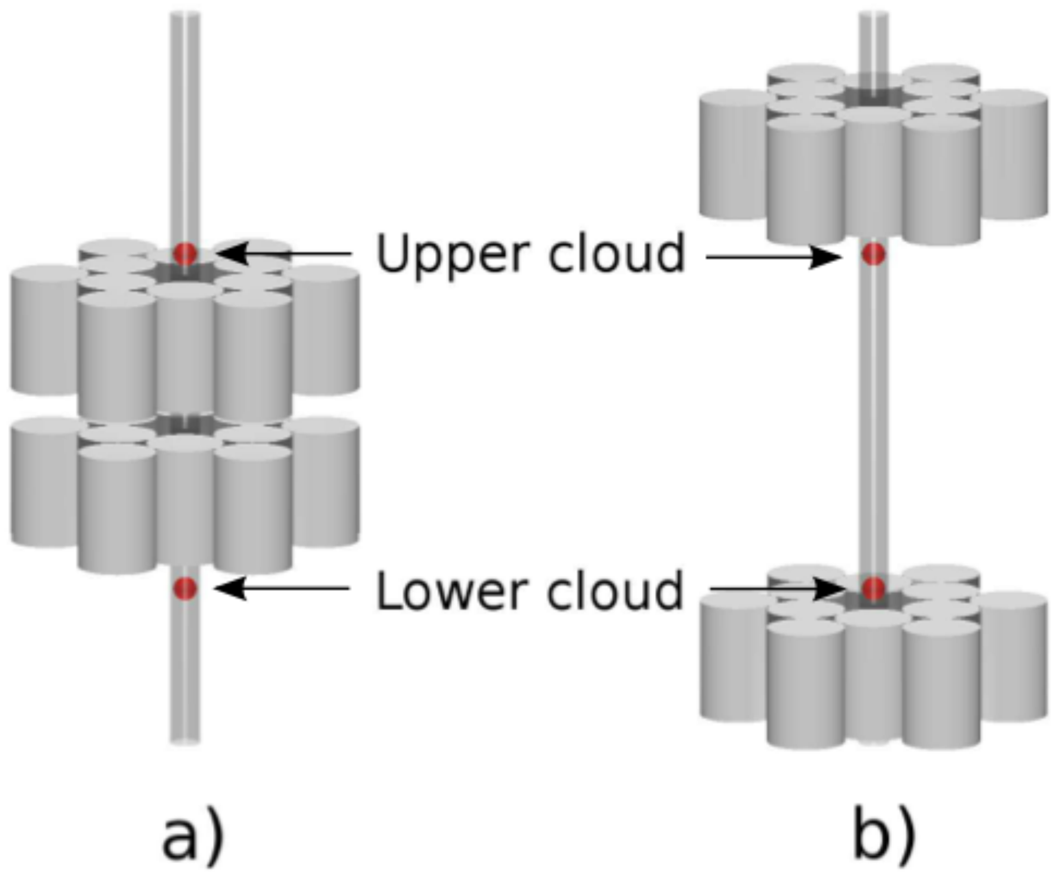
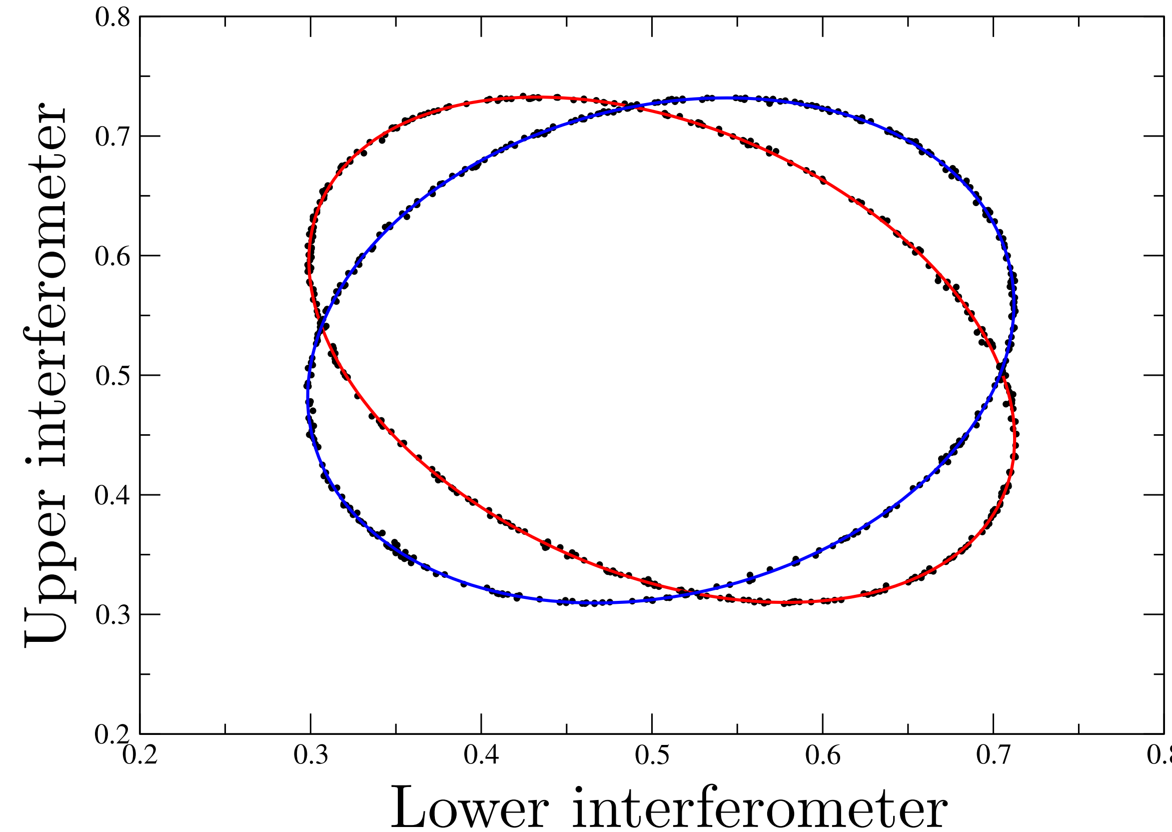




$$G = 6.67191(99) \times 10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}}$$

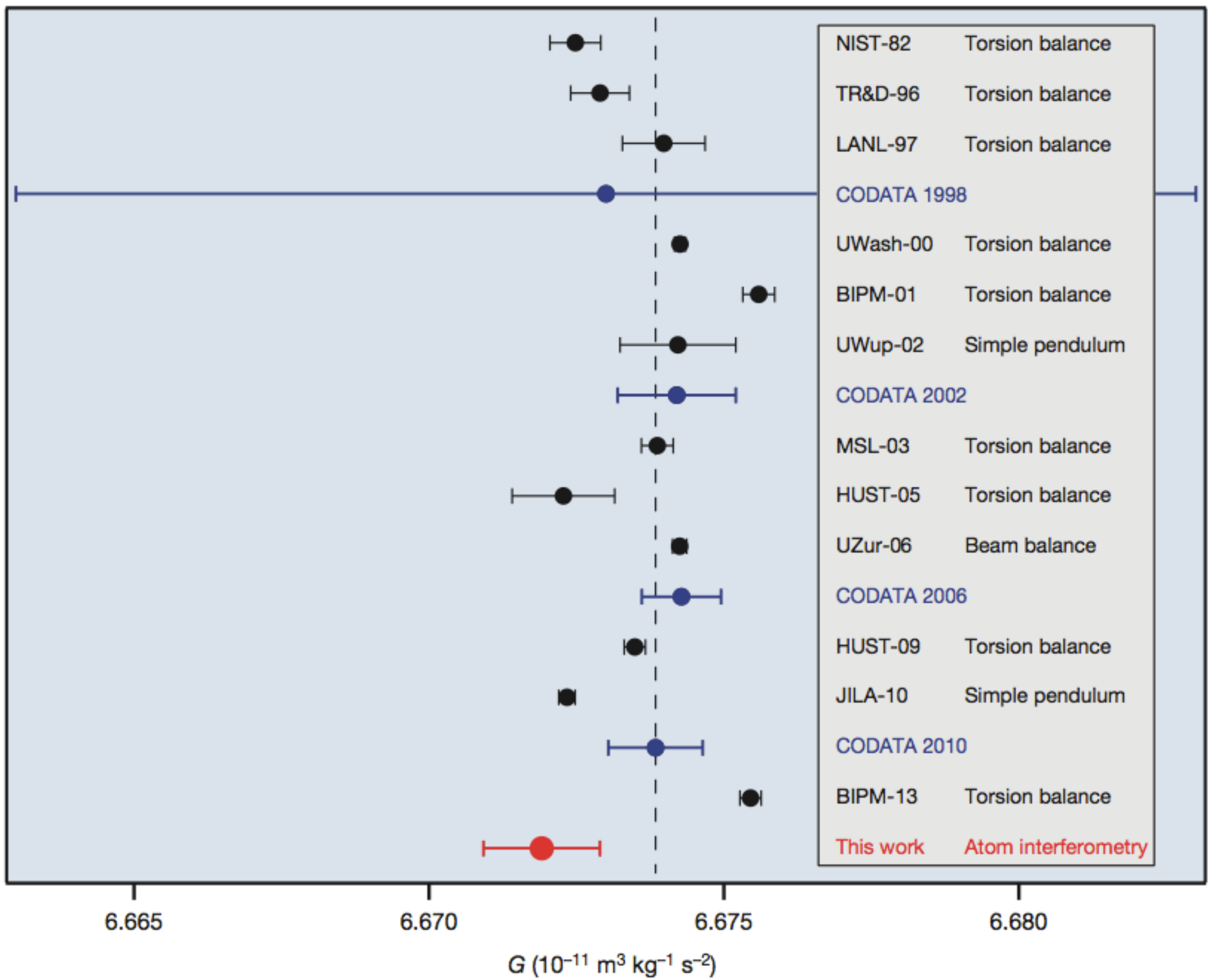
Systematic uncertainty: 92 ppm

Statistical uncertainty: 116 ppm

Total: 148 ppm

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

Measurement of the Newtonian gravitational constant



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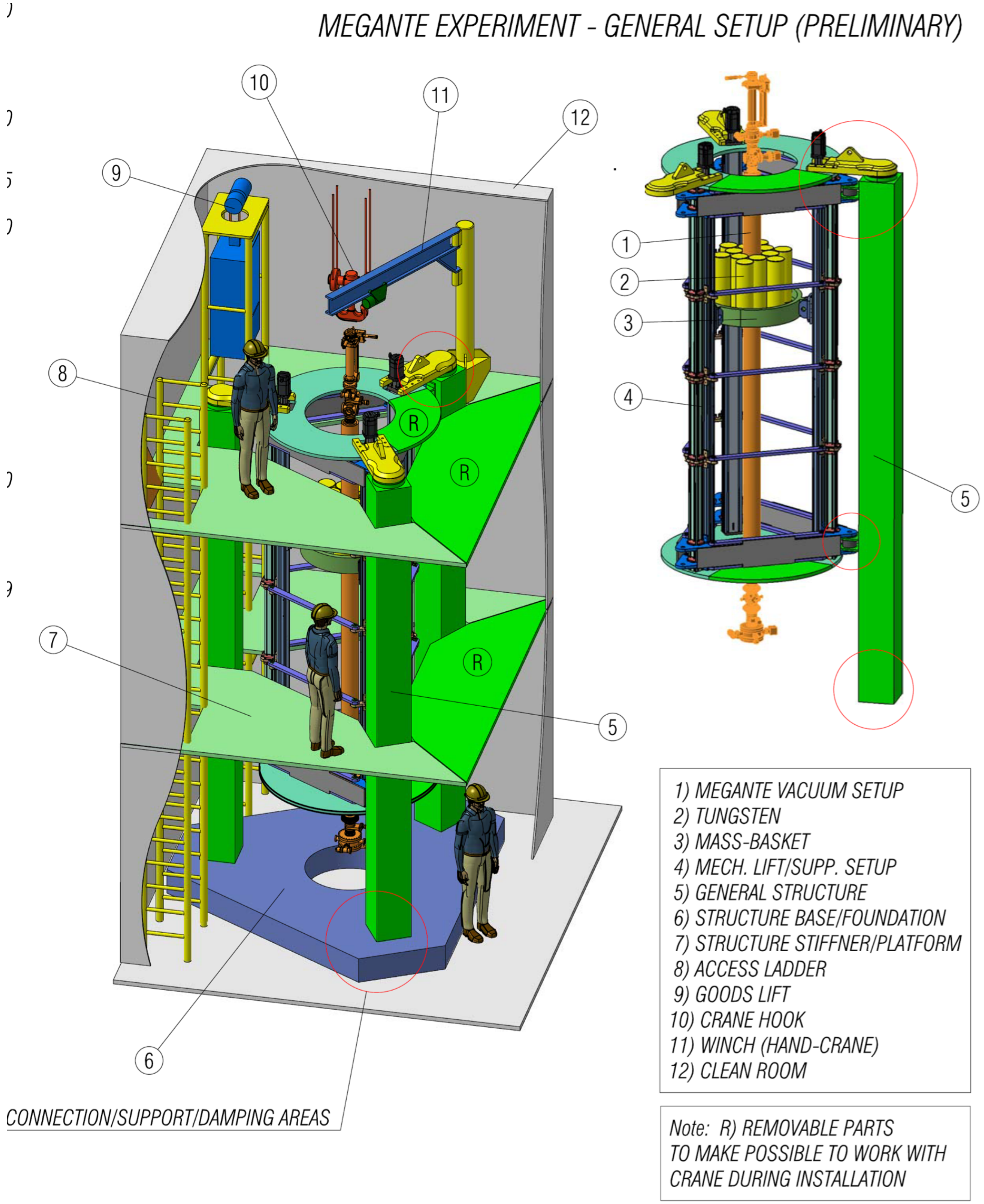


Main Features:
- Rb UltraCold atom gradiometer
- Apparatus size: 6 m (large scale)
- Source mass: 4 tons of Tungsten
- Location: Experimental Physics building
- Expected Integration time: 200 hours
- Expected Systematic error: <10 ppm*

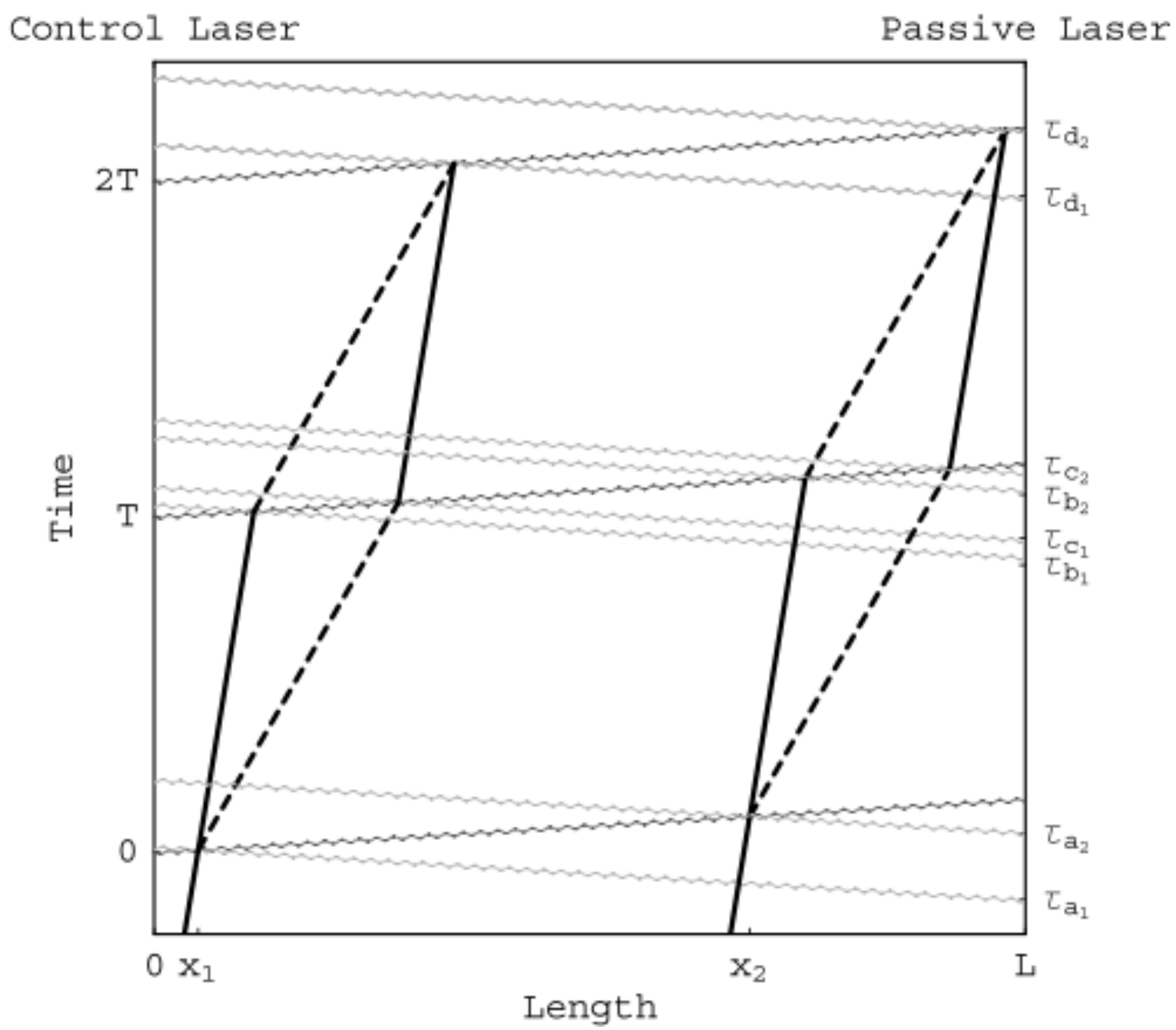
Infrastructure/Source mass handling system design in collaboration with

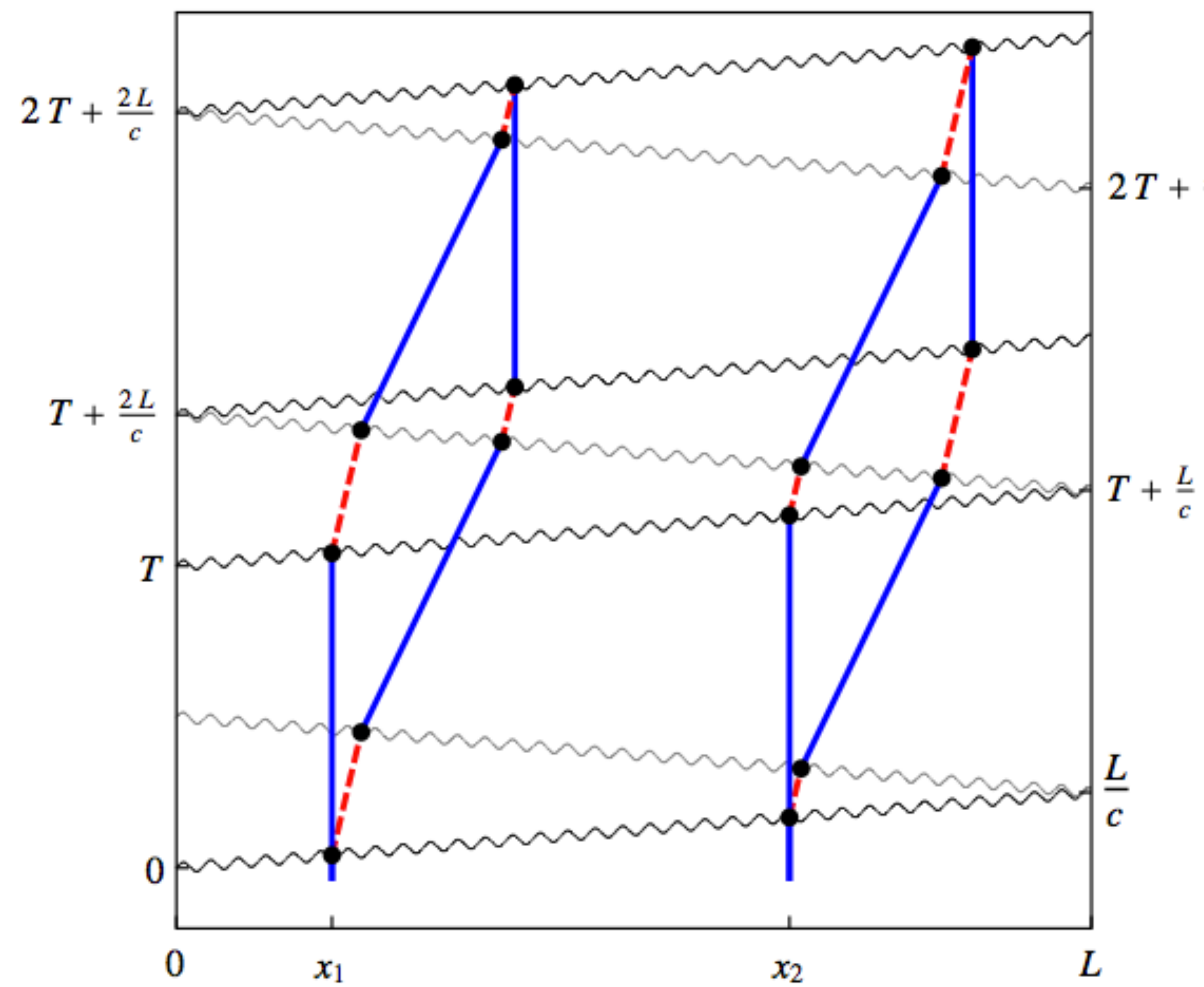
INFN LNF

PhD/Postdoc position available!

*G. Rosi, "*A proposed atom interferometry determination of G at 10^{-5} using a cold atomic fountain*" **55** 1 Metrologia (2018)

Long-baseline atom interferometry





Detector bandwidth limit:

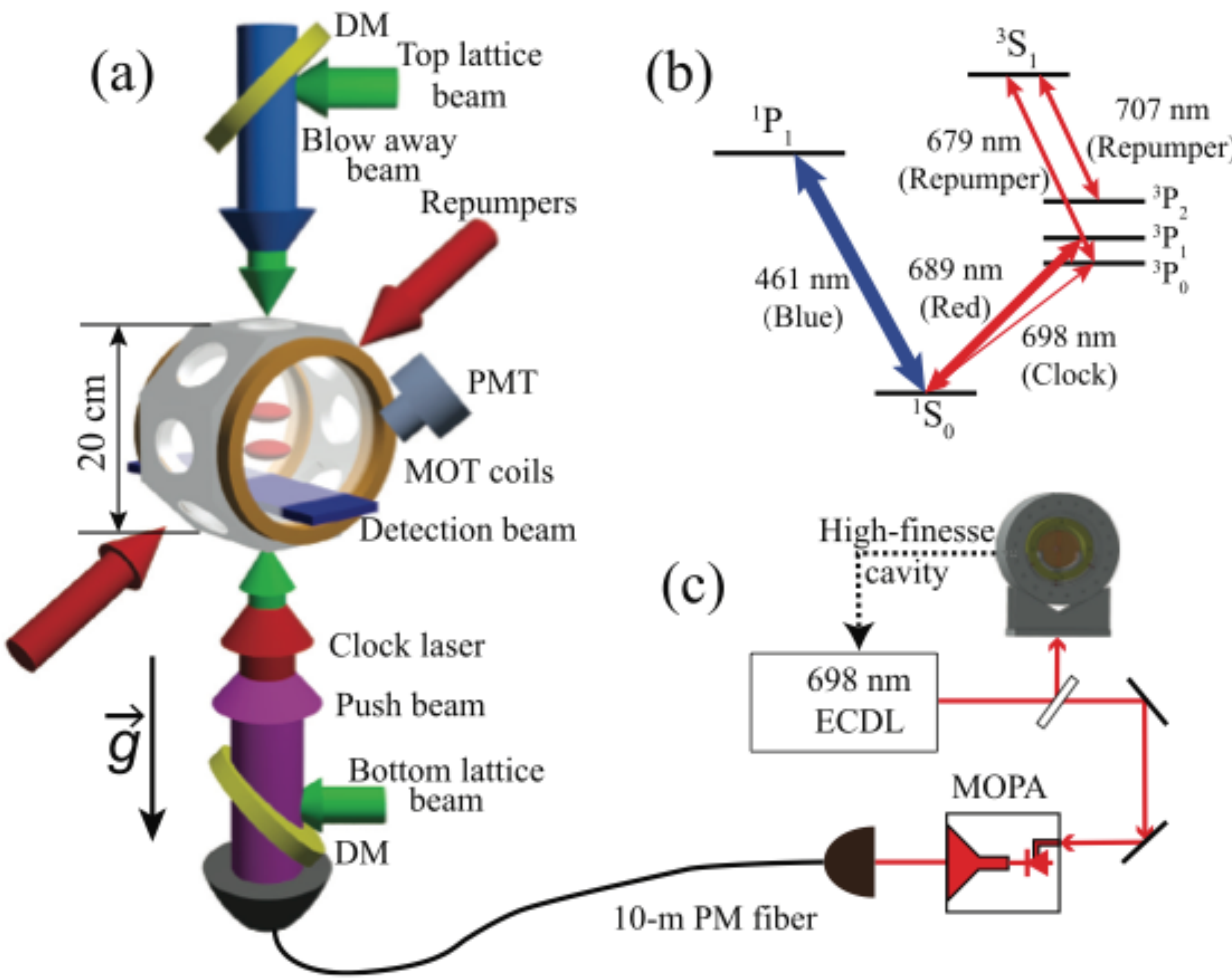
$$\Delta\nu_{\mathrm{max}} \sim c/L$$

Absence of phase noise from the laser:

single-photon transition required

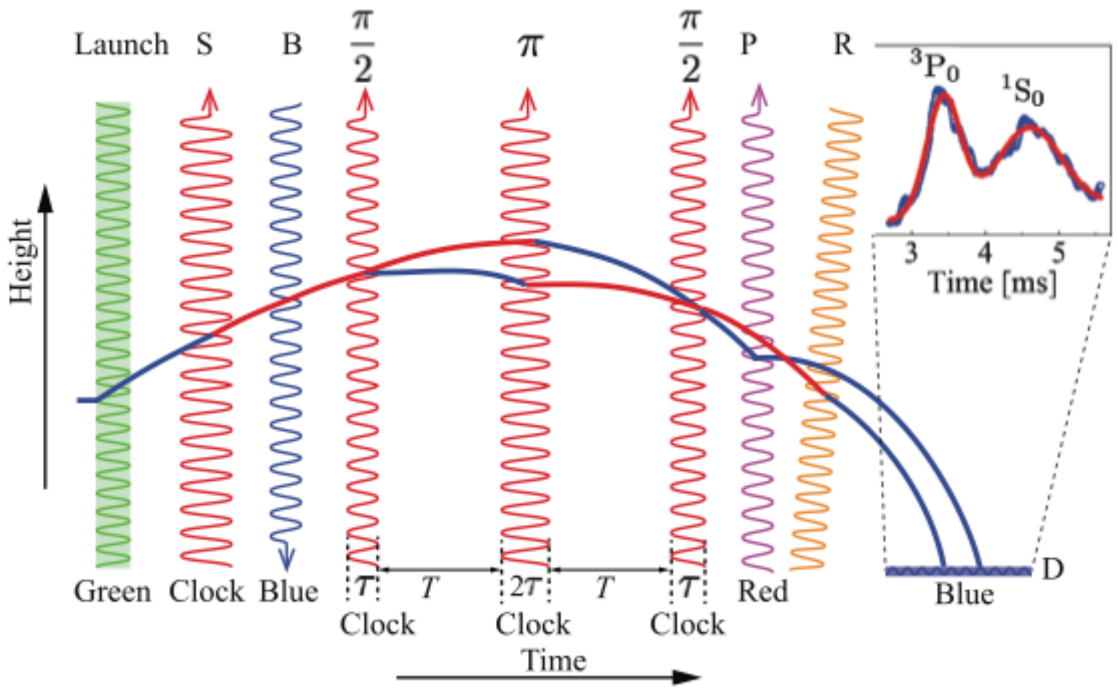
- S. Dimopoulos et al., *Phys. Lett. B* **678**, 37-40 (2009)
- P. W. Graham et al., *Phys. Rev. Lett.* **110**, 171102 (2013)

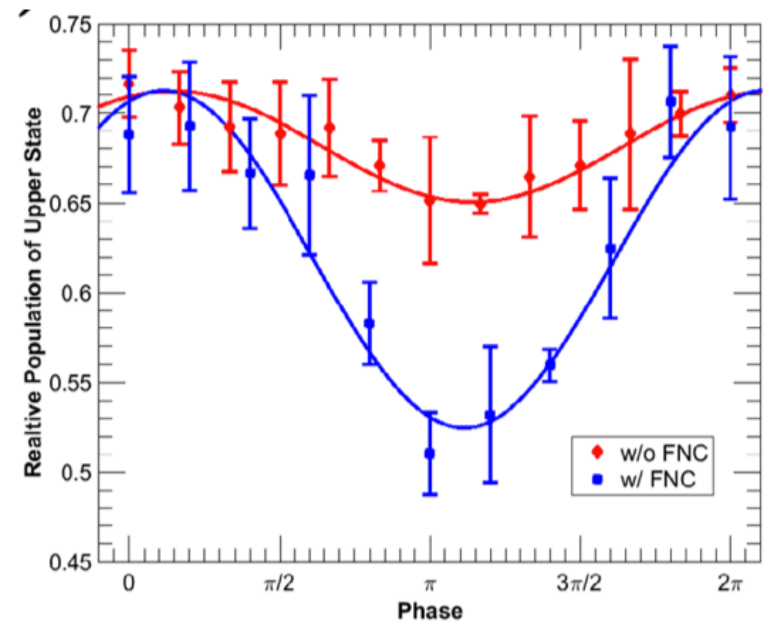
Atom Interferometry on the clock transition - setup



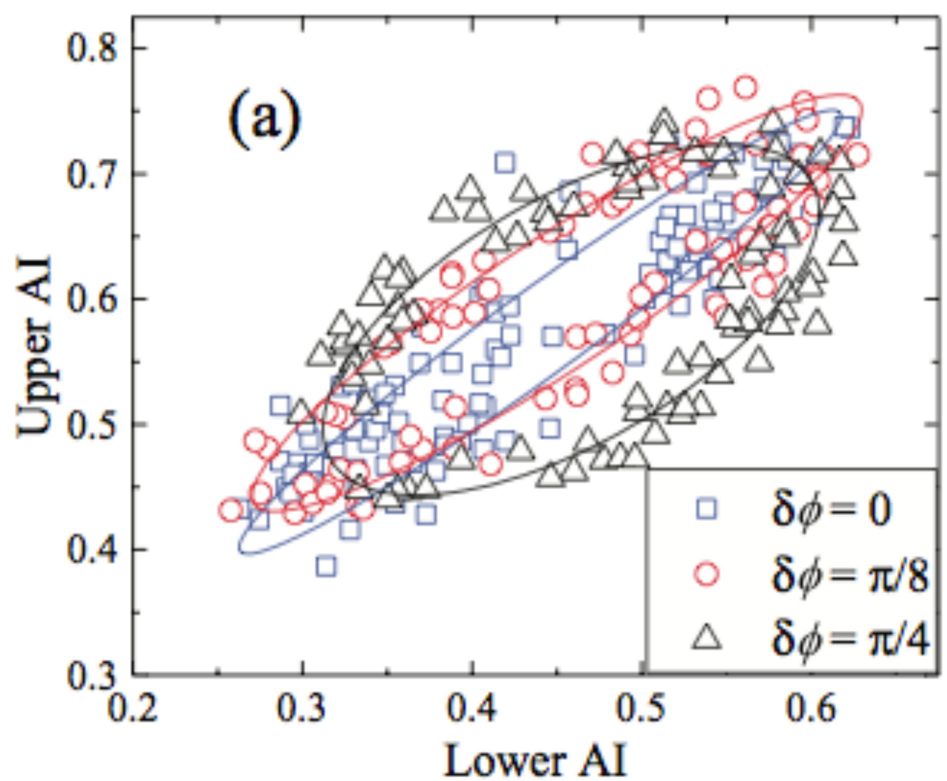
Atom Interferometry on the clock transition - results

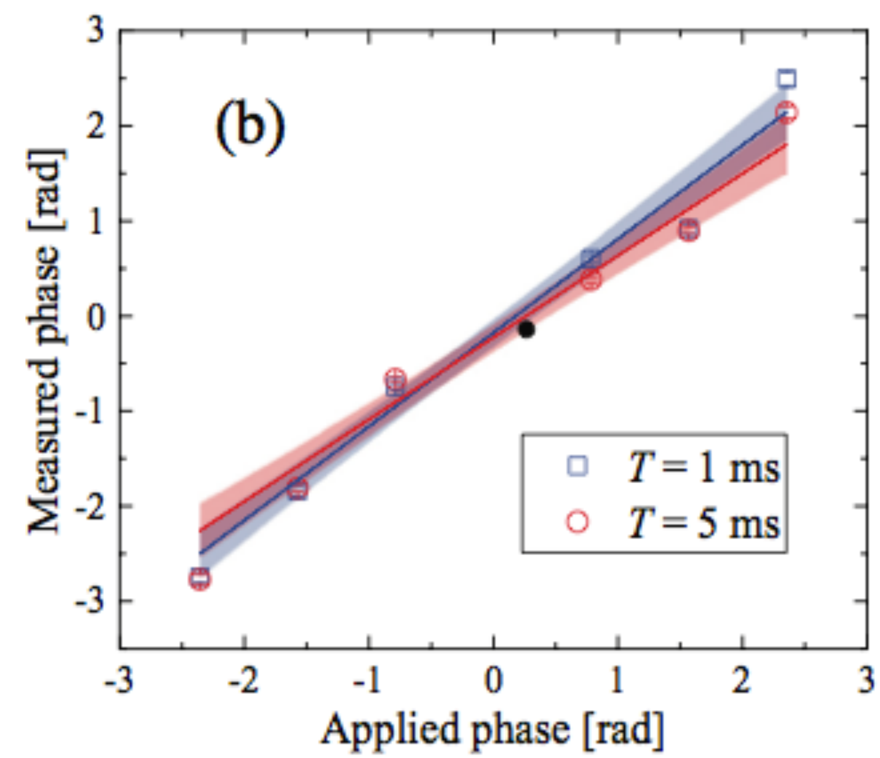
Gravimeter





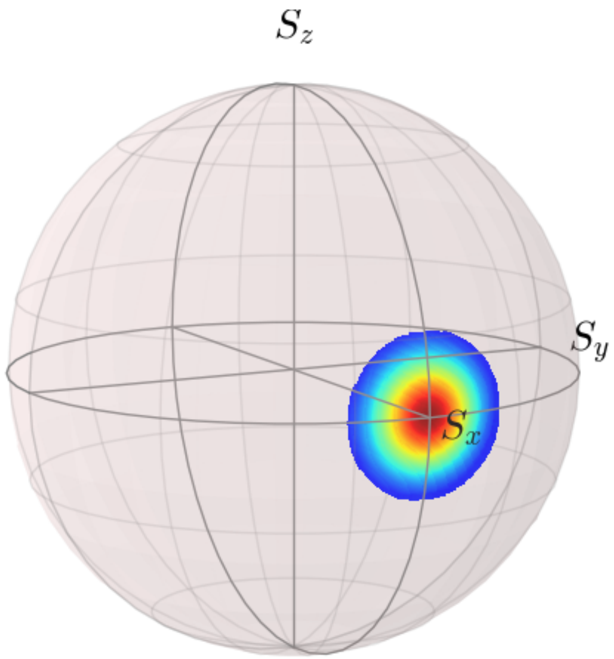
Gravity gradiometer





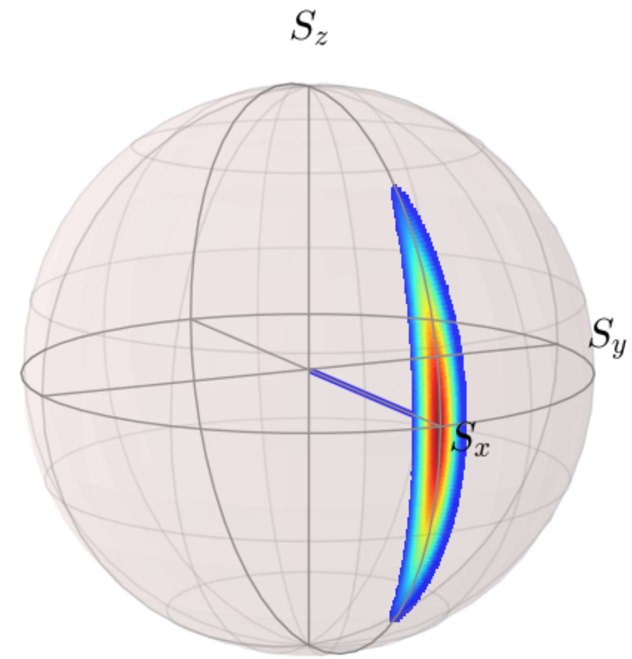
- Hu et al., PRL **119**, 263601 (2017)
- Hu et al., arXiv:1907.10537 (2019)

Squeezing the uncertainty in atom interferometry



Standard Quantum Limit

$$\Delta\phi = \frac{1}{\sqrt{N}}$$



Spin Squeezing

$$\Delta\phi \to \frac{1}{N}$$

Measurement-induced squeezing

2-1/2 spins: $\mathbf{S} = \mathbf{s}_1 + \mathbf{s}_2$

$$S = 1$$

$|\uparrow\rangle_1|\uparrow\rangle_2$ $\quad m = +1$

$\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2)$ $\quad m = 0$

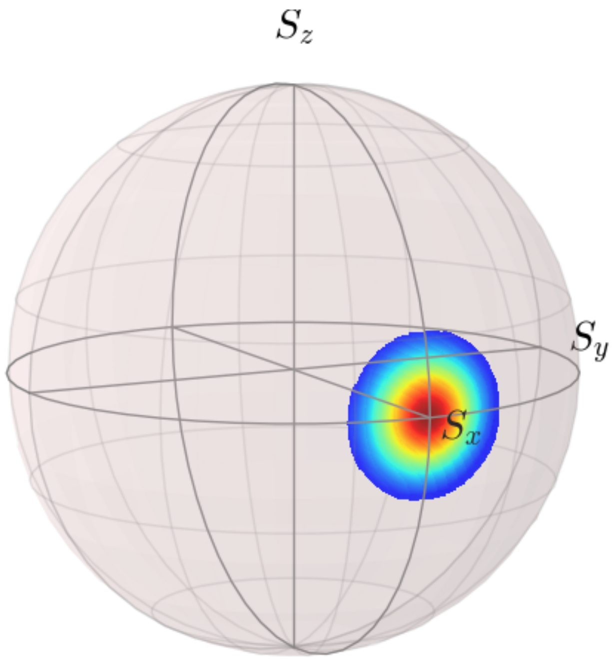
$|\downarrow\rangle_1|\downarrow\rangle_2$ $\quad m = -1$

One atom is spin up and the other one is spin down (but we do not know which one…)

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2)$$

Pezzè et al., *Rev. Mod. Phys.* **90**, 035005 (2018)

Squeezing the uncertainty in atom interferometry



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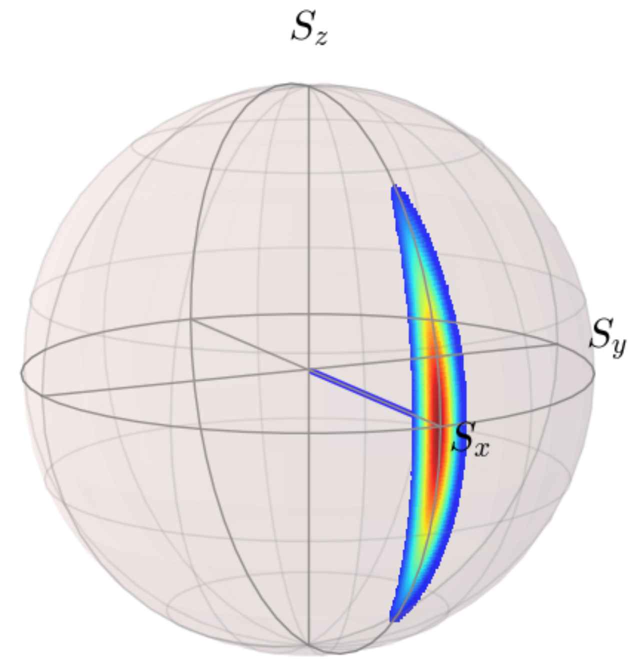


Spin Squeezing

$$\Delta\phi \to \frac{1}{N}$$

Measurement-induced squeezing

$$(\Delta S_z)^2_M = \frac{\mathrm{Var}(S_z)(\Delta M_{out})^2_{S_z}}{\mathrm{Var}(S_z) + (\Delta M_{out})^2_{S_z}}$$

Weak measurement

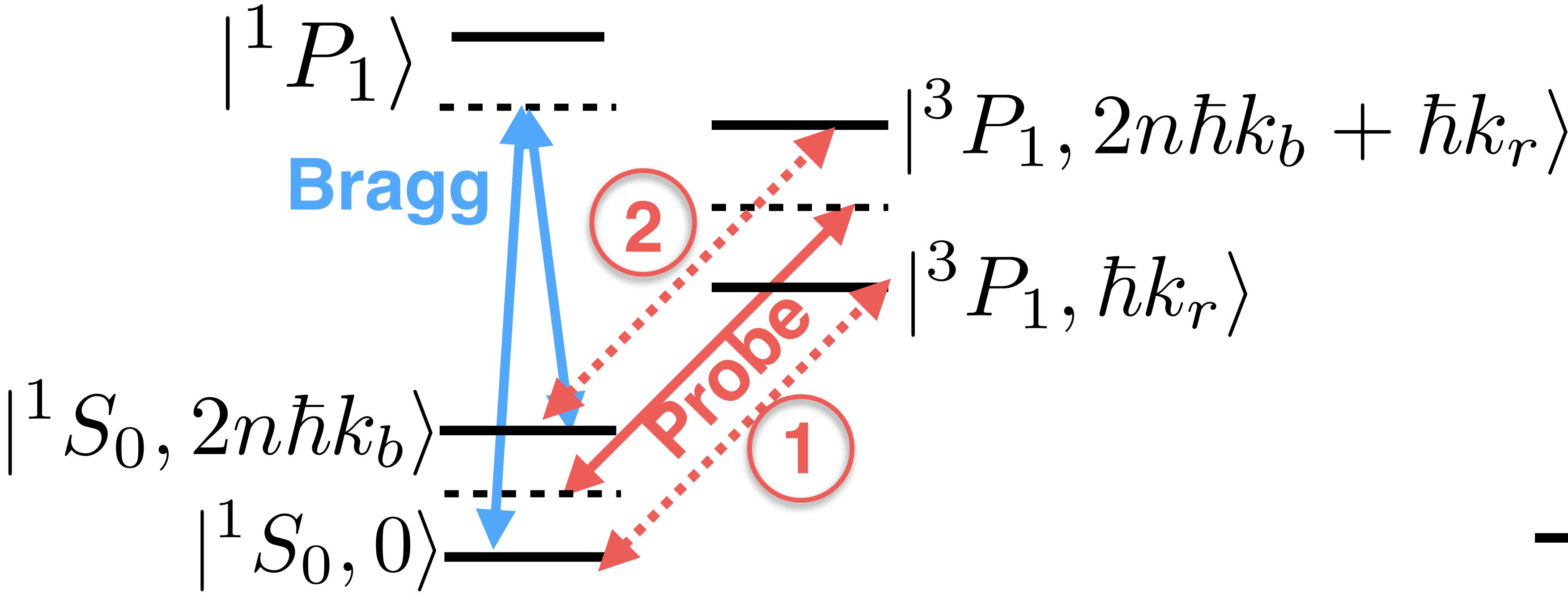
$$(\Delta S_z)^2_M \to \mathrm{Var}(S_z)$$

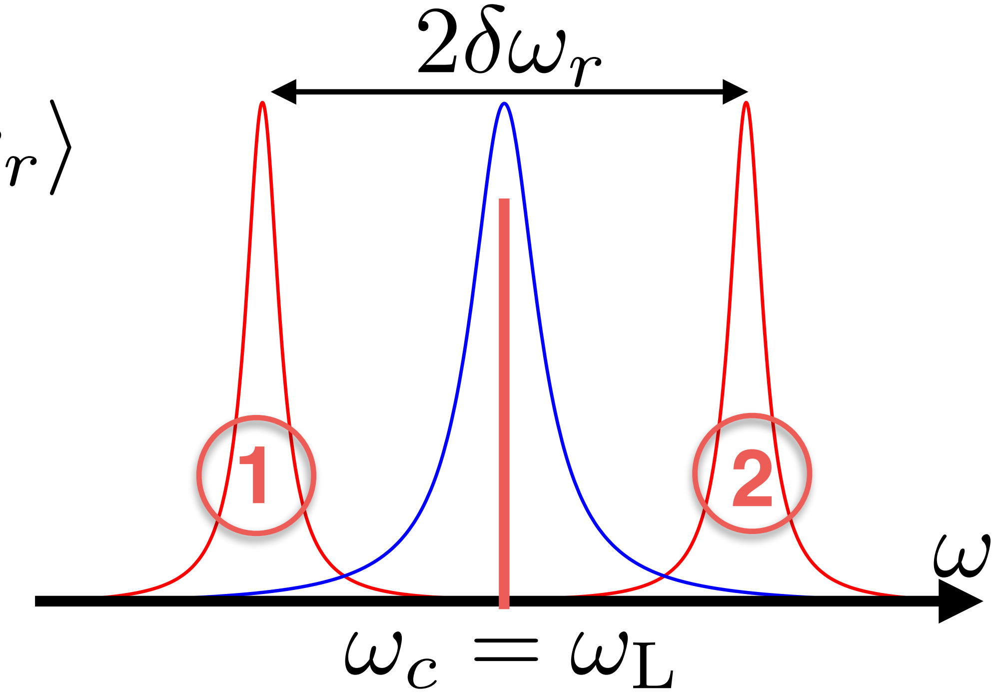
Strong measurement

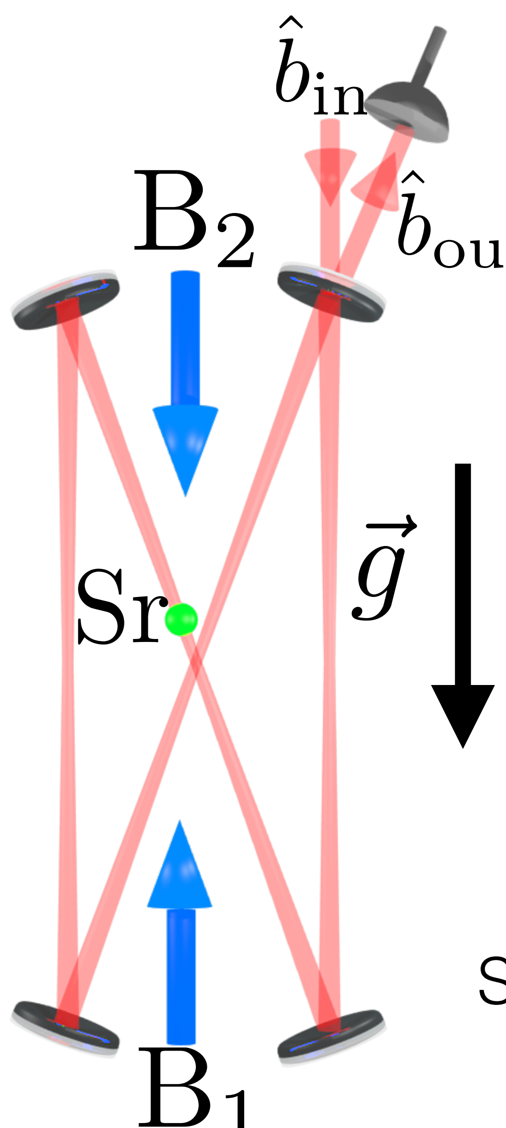
$$(\Delta S_z)^2_M \to (\Delta M)^2_{S_z}$$

Pezzè et al., *Rev. Mod. Phys.* **90**, 035005 (2018)

Implementation of squeezing in interferometry

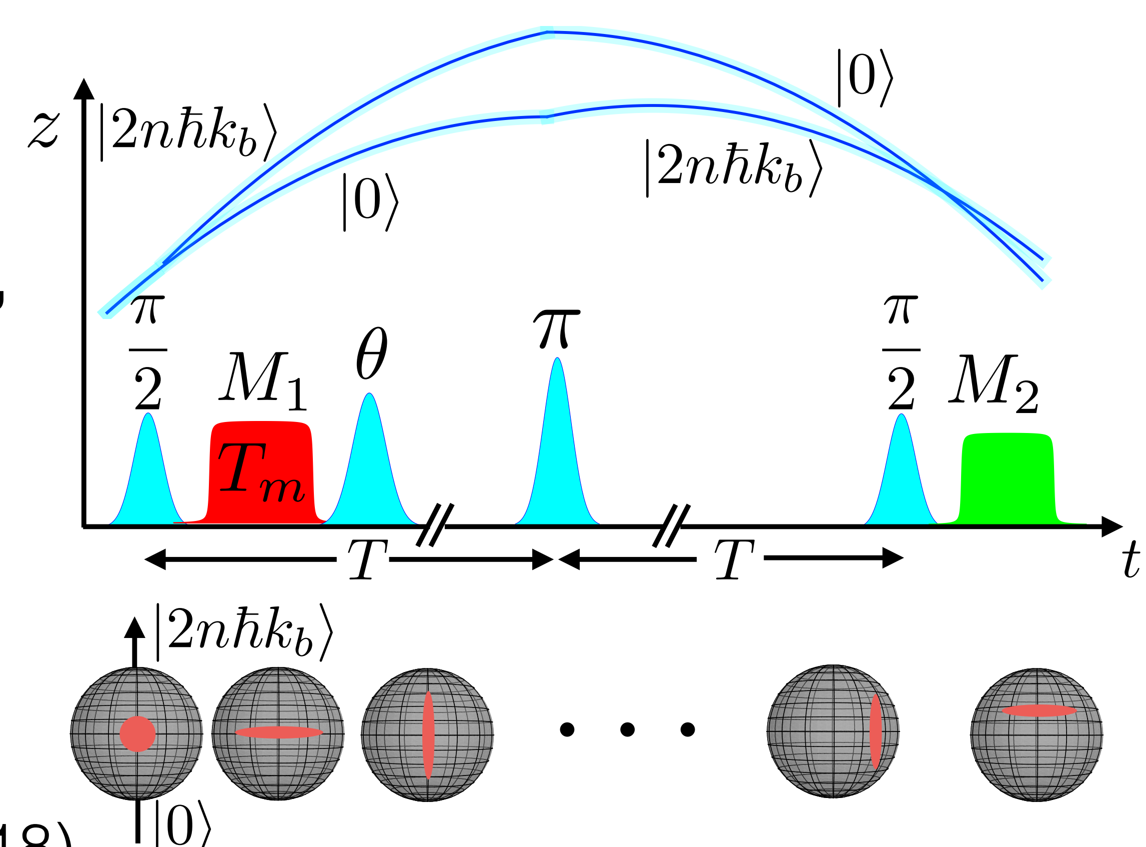






Single-atom cooperativity, effective solid angle

$$\eta = \frac{4g^2}{\Gamma\kappa} = \frac{24F}{\pi k^2 w^2}$$



Salvi et al., PRL **120**, 033601 (2018)

People and collaborations

Firenze:

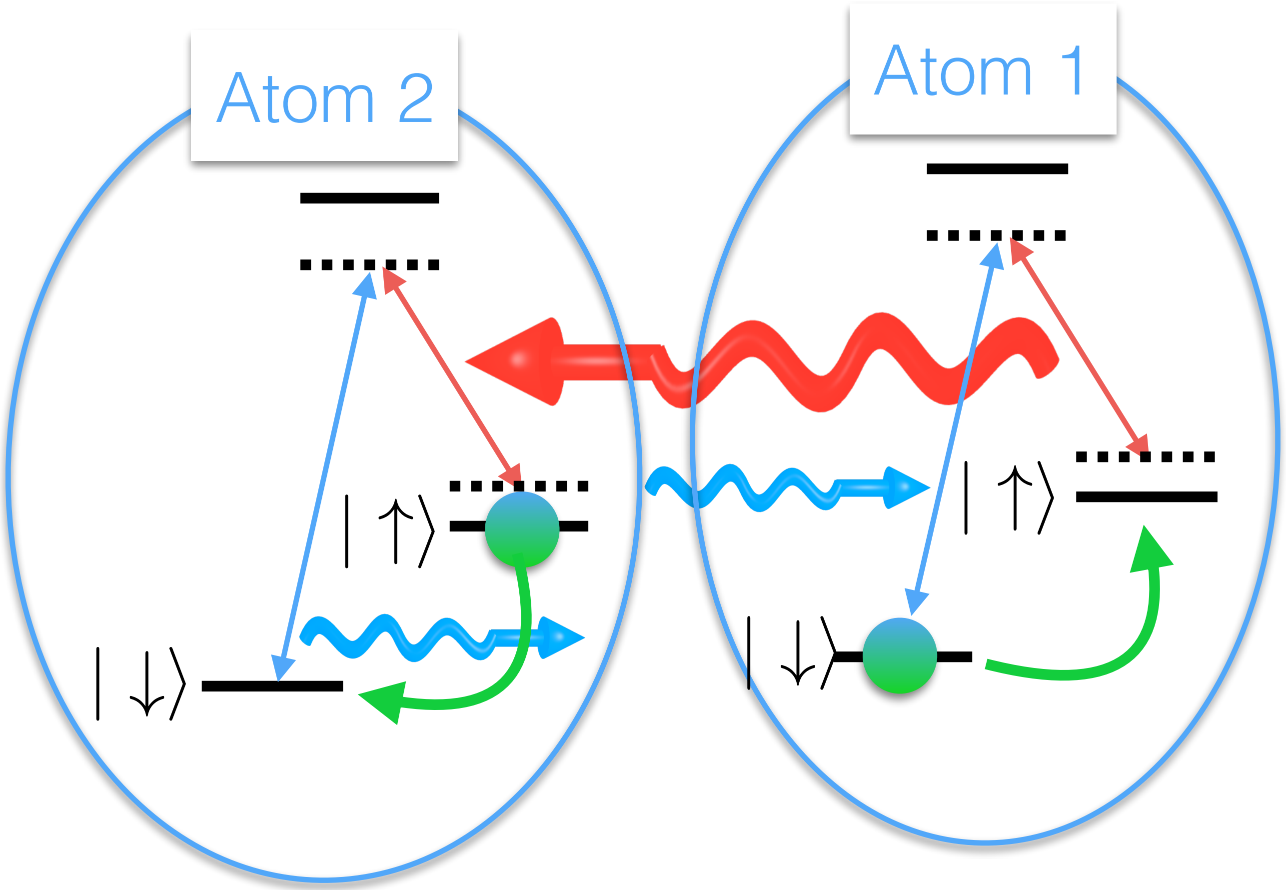
- Enlong Wang
- Gunjan Verma
- Jonathan Tinsley
- Nicola Poli
- Manan Jain
- Gabriele Rosi
- Guglielmo M. Tino

MIT:

Vladan Vuletic

Boulder-Pisa:

- Athreya Shankar
- Maria Luisa Chiofalo
- Murray Holland



$$H \propto J_- J_+ = J^2 - J_z^2 - J_z$$

Shankar et al., arXiv: 1907.10174v1

Conclusions

WEP tests and G measurement

- Quantum WEP tests on hyperfine and optical transitions
- G measurements towards the 10 ppm level

Interferometry on the clock transition

- A single-photon transition can cancel laser phase noise in atomic gradiometers
- Proof-of-principle of an atomic gradiometer based on the optical clock transition

Spin Squeezing in Atom Interferometry

- Presented scheme suitable for Sr Bragg atom interferometers
- With realistic experimental parameters, the scheme can provide significant noise reduction