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Non-Linear Spectroscopy

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Measurement of the gravitational constant *G* by atom interferometry

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MAGIA

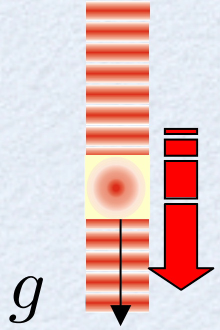
Misura Accurata di G mediante Interferometria Atomica

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA

Misura Accurata di G mediante Interferometria Atomica

- Measure g by atom interferometry

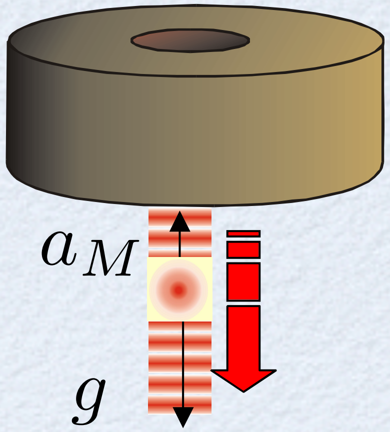


http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA

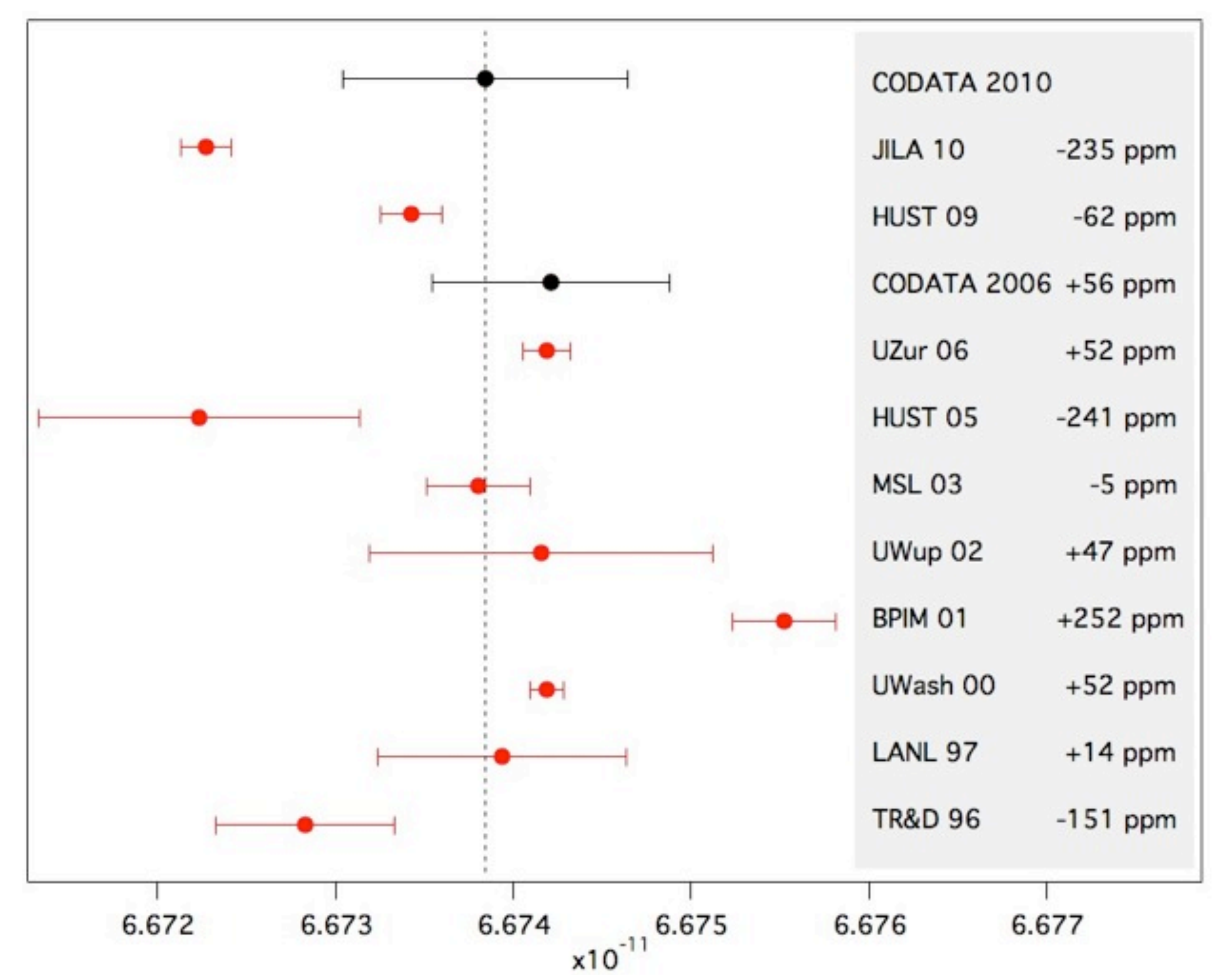
Misura Accurata di G mediante Interferometria Atomica

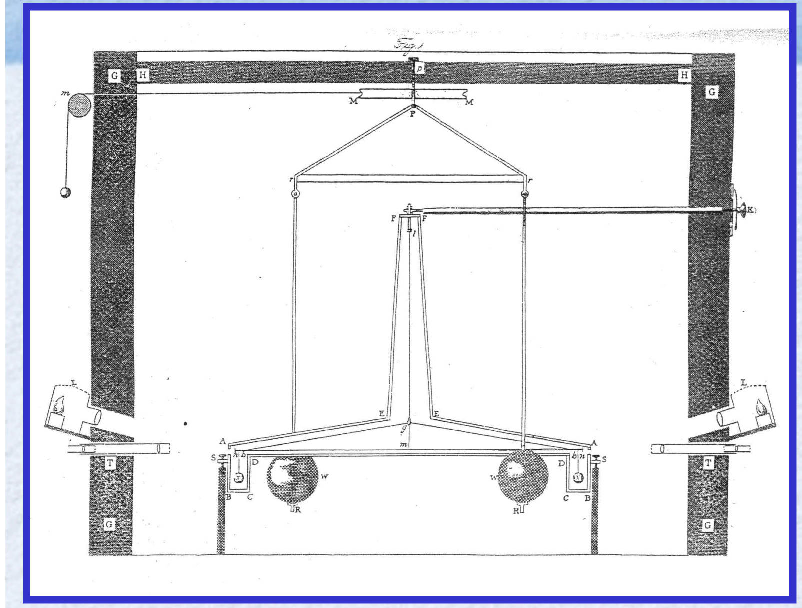
- Measure g by atom interferometry
- Add source masses
- Measure change of g



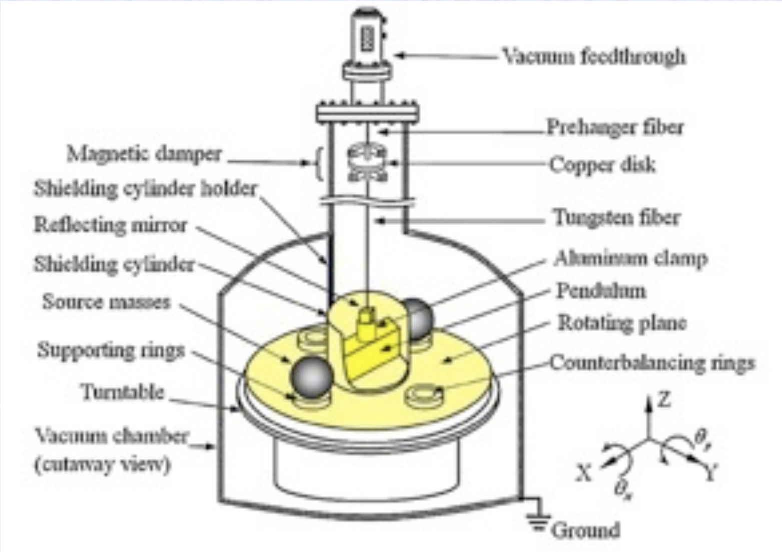
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Motivation





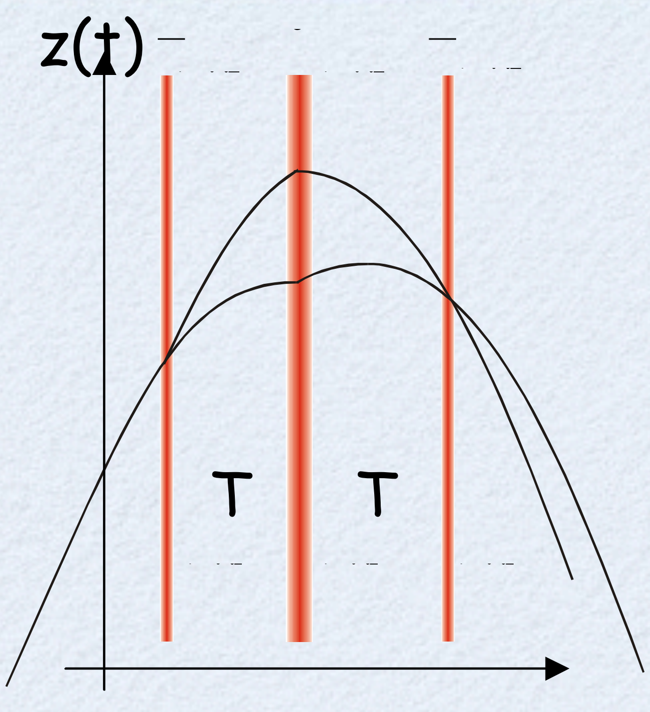
Cavendish 1798



Zang 2009

- Atomic probes
  - point-like test masses in free fall
  - virtually insensitive to stray fields
  - well know and reproducible properties
  - different states, isotopes

Raman interferometry in a ^{87}Rb atomic fountain



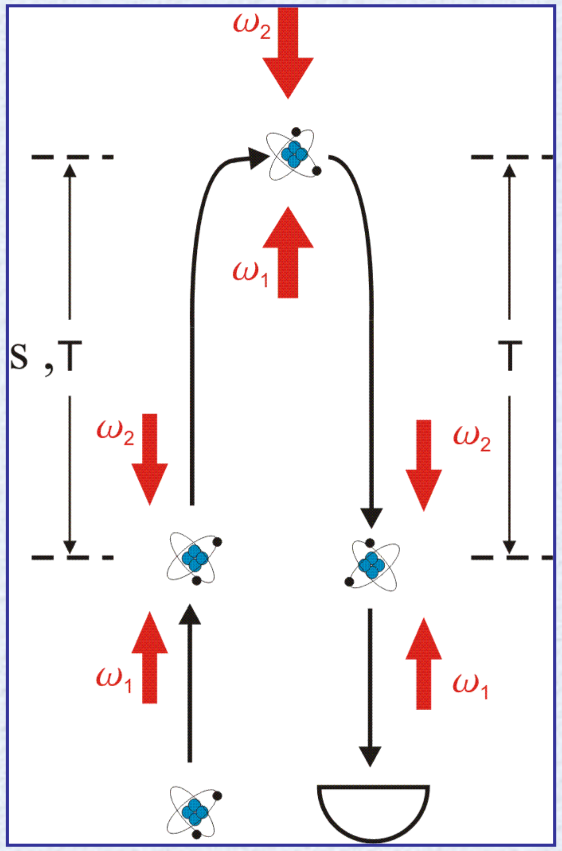
Phase difference between the paths:

$\Delta\Phi = k_c[z(0)]2z(T)] + \Phi_e$

$k_e = k_1 - k_2$

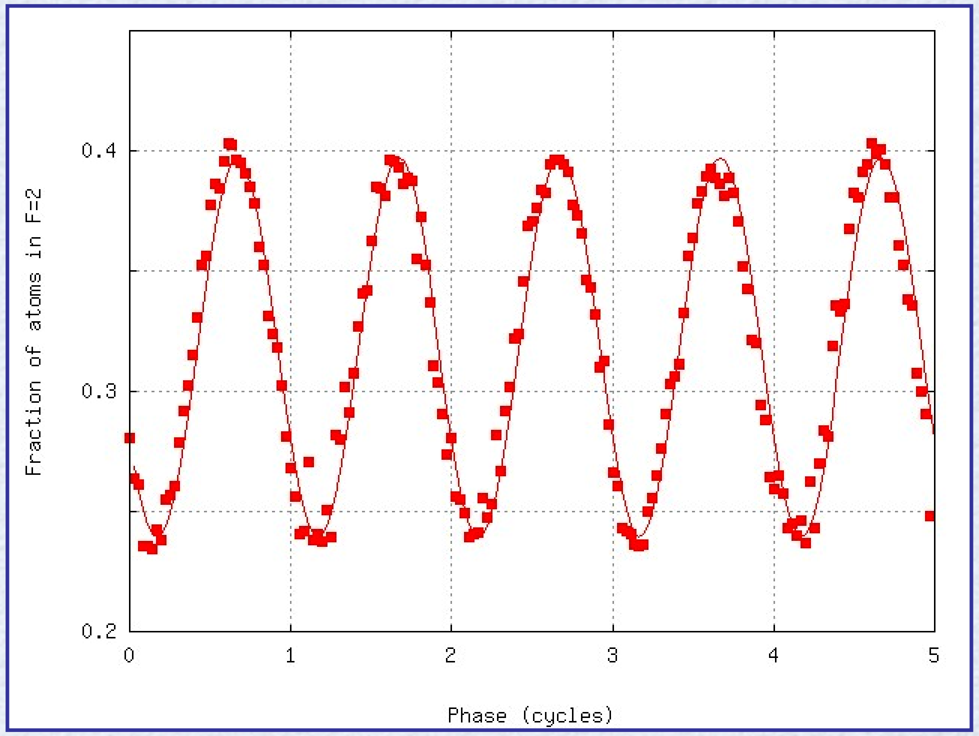
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

$\rightarrow \Delta\Phi = k_e g T^2$



Final population:

$N_a = N/2(1 + cos[\Delta\Phi])$

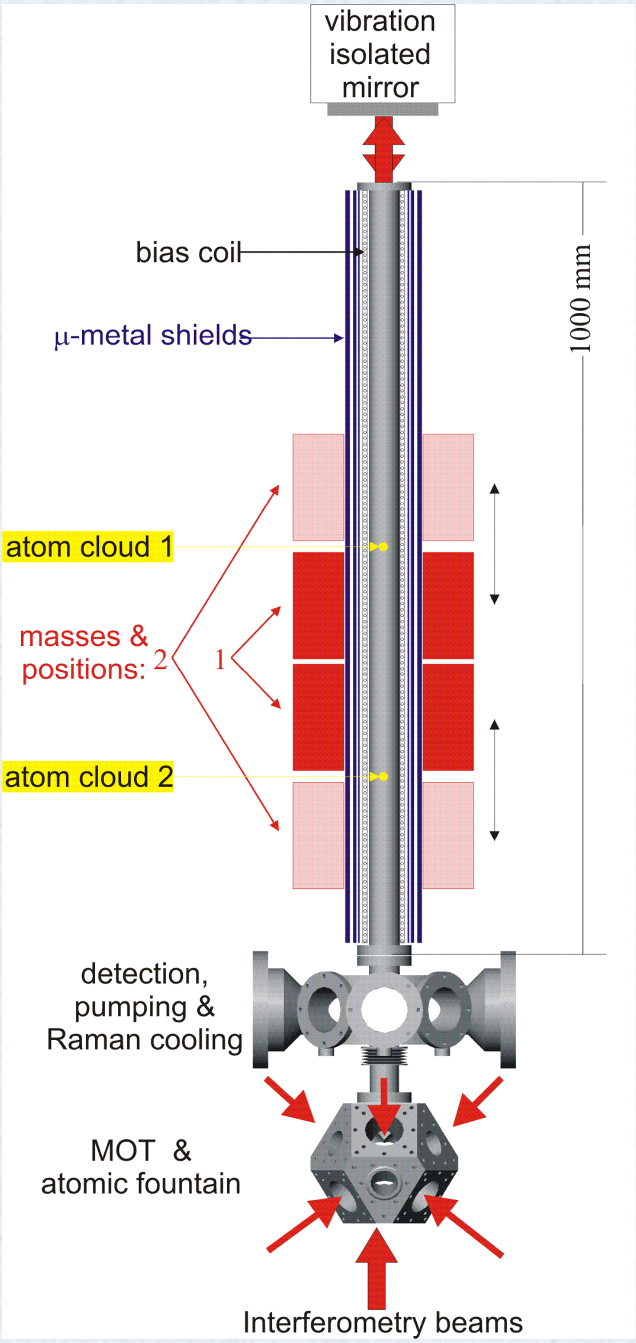


$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

S/N=1000 $\rightarrow$ Sensitivity 10^{-9} g/shot

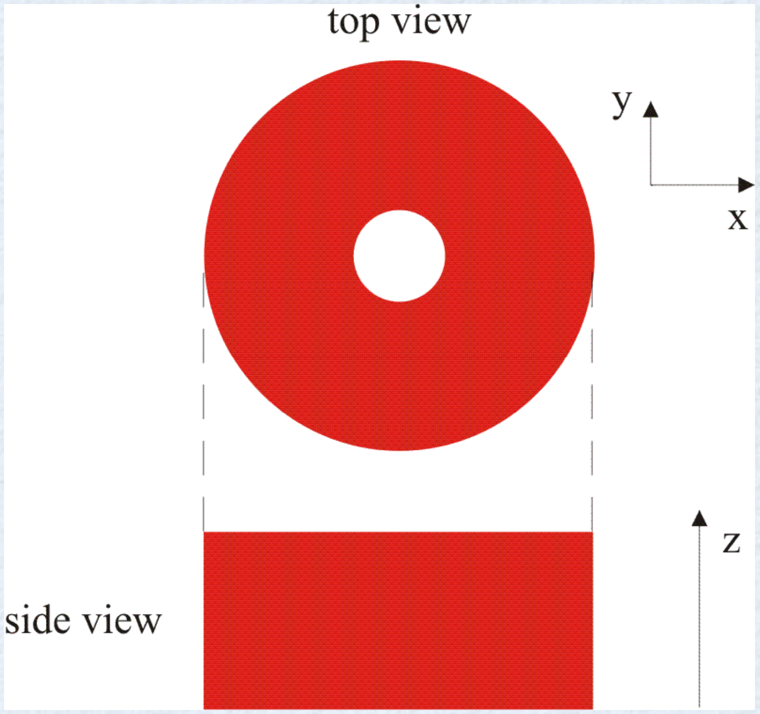
A. Peters et al., Nature **400**, 849 (1999)

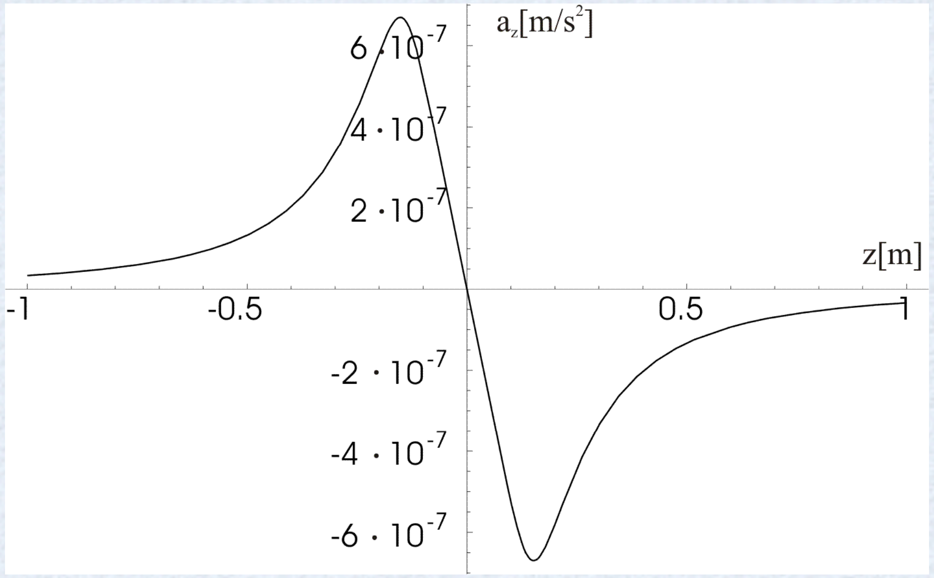
Atom gravimeter + source masses



Sensitivity 10^{-9} g/shot

one shot $\rightarrow \Delta G/G \sim 10^{-2}$





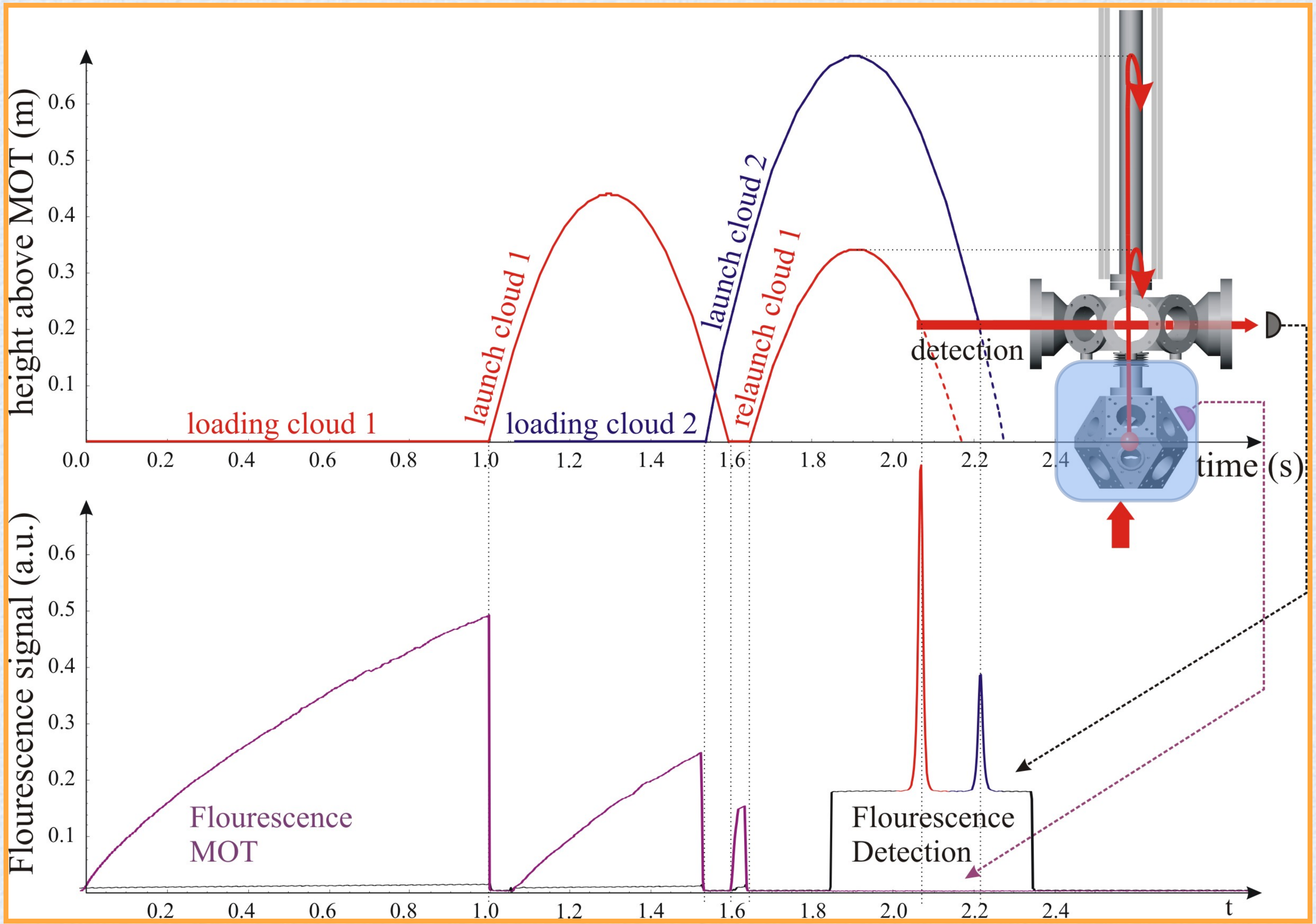
500 Kg tungsten mass

Peak mass acceleration $a_g \sim 10^{-7}$ g

10000 shots $\rightarrow \Delta G/G \sim 10^{-4}$

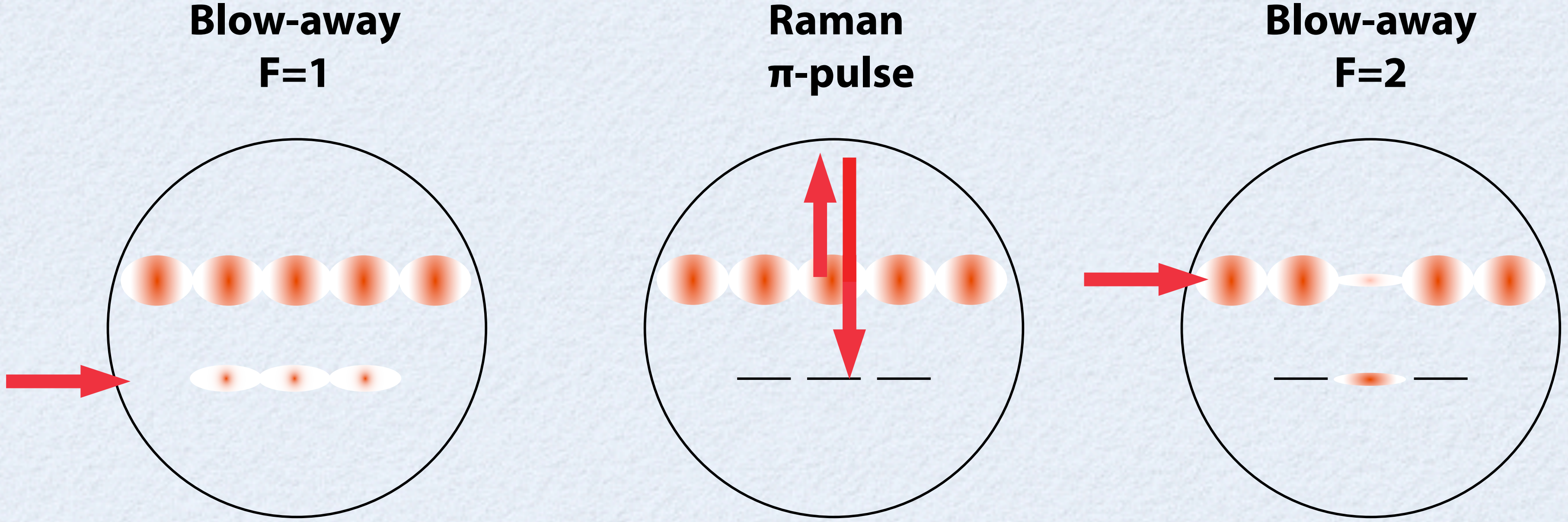
Experimental sequence

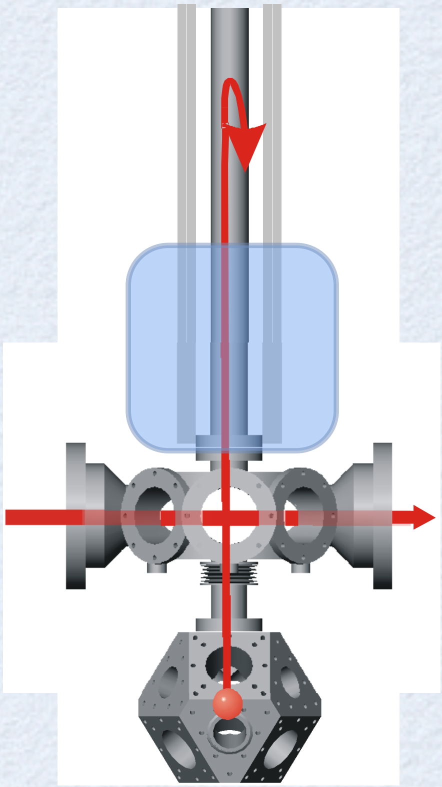
- MOT + launch via moving molasses
  - juggling the two clouds for larger n. of atoms

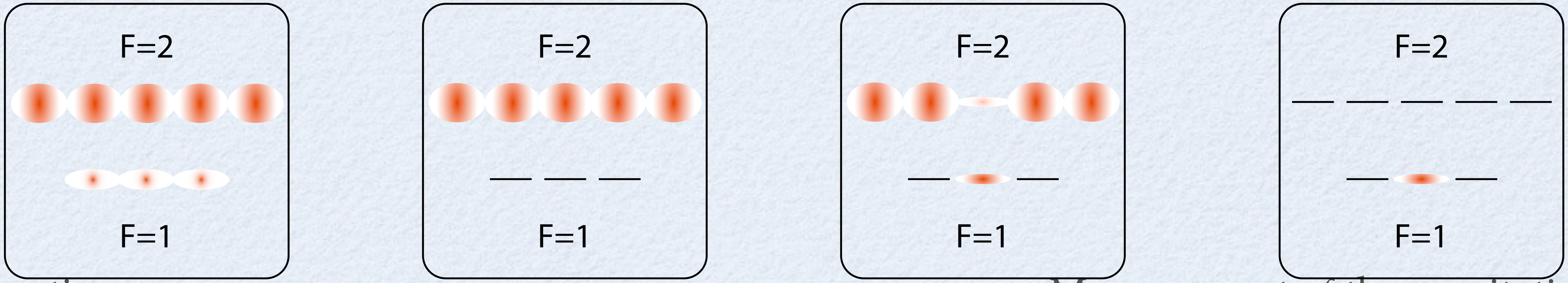


Experimental sequence

- MOT + launch via moving molasses
  - juggling the two clouds for larger n. of atoms
- selection of internal state & velocity class
  - from unpolarized to $m_F=0$, from 3.5 v_{rec} to 0.3 v_{rec}
  - via Raman pulses + resonant blow-away pulses







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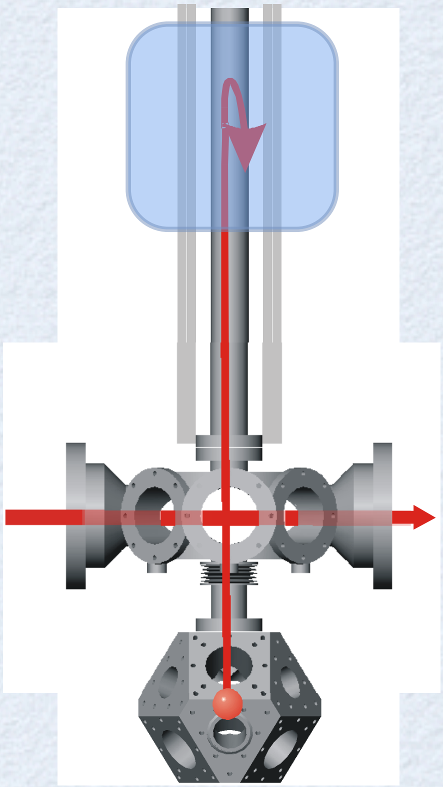
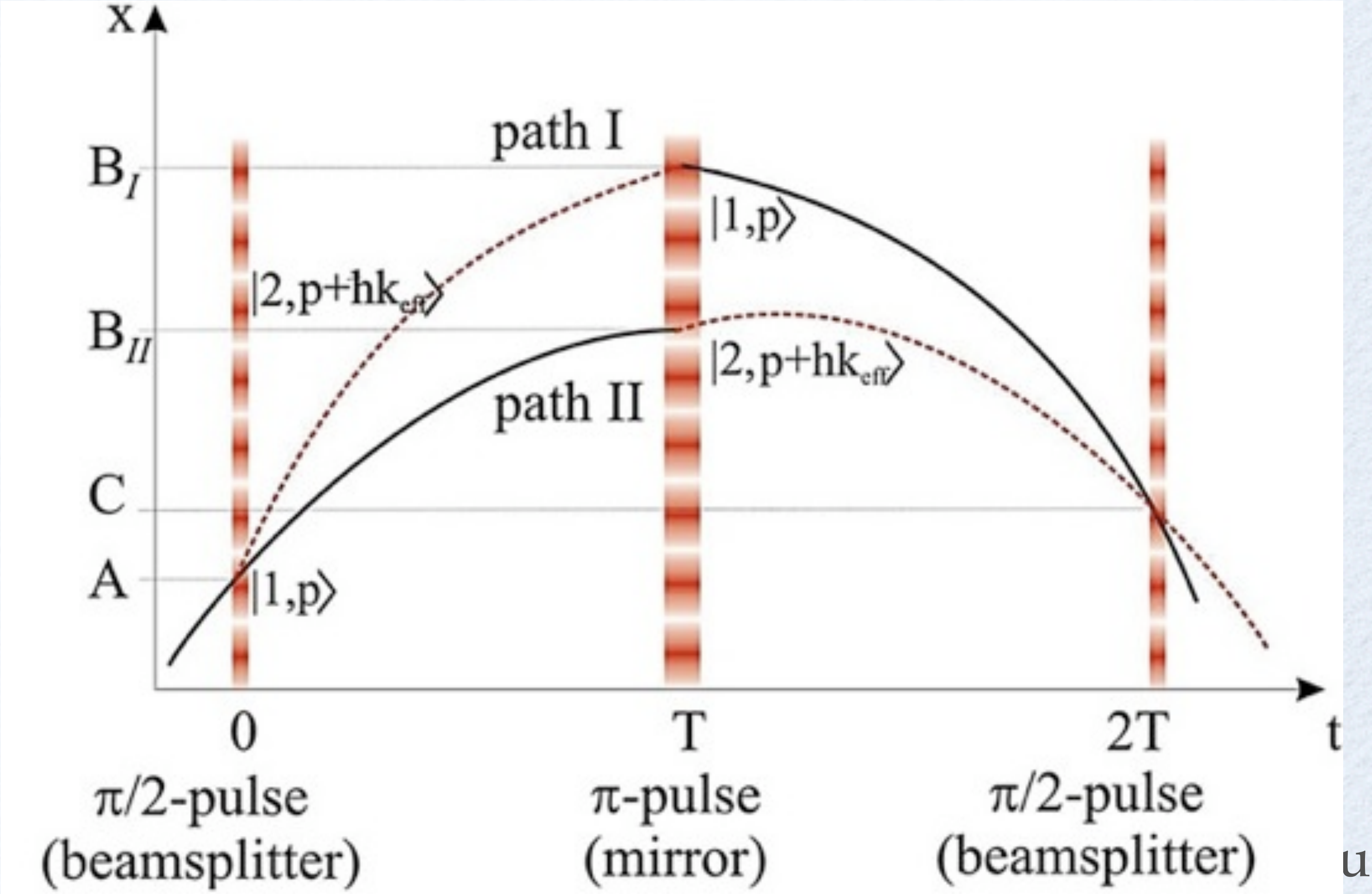
- Raman interferometry sequence around apogee





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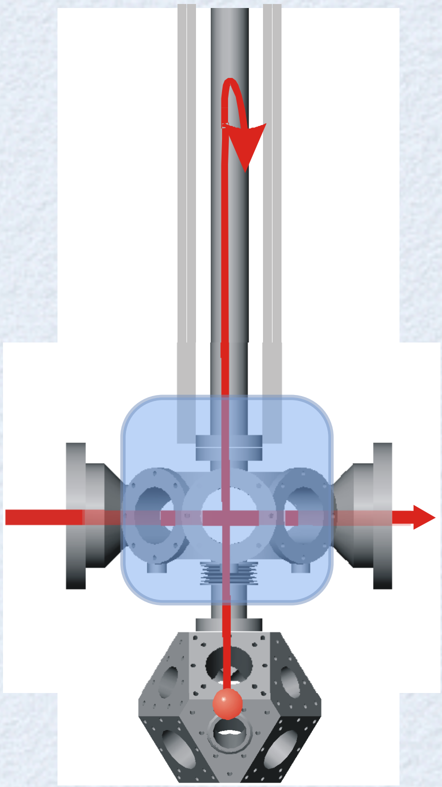
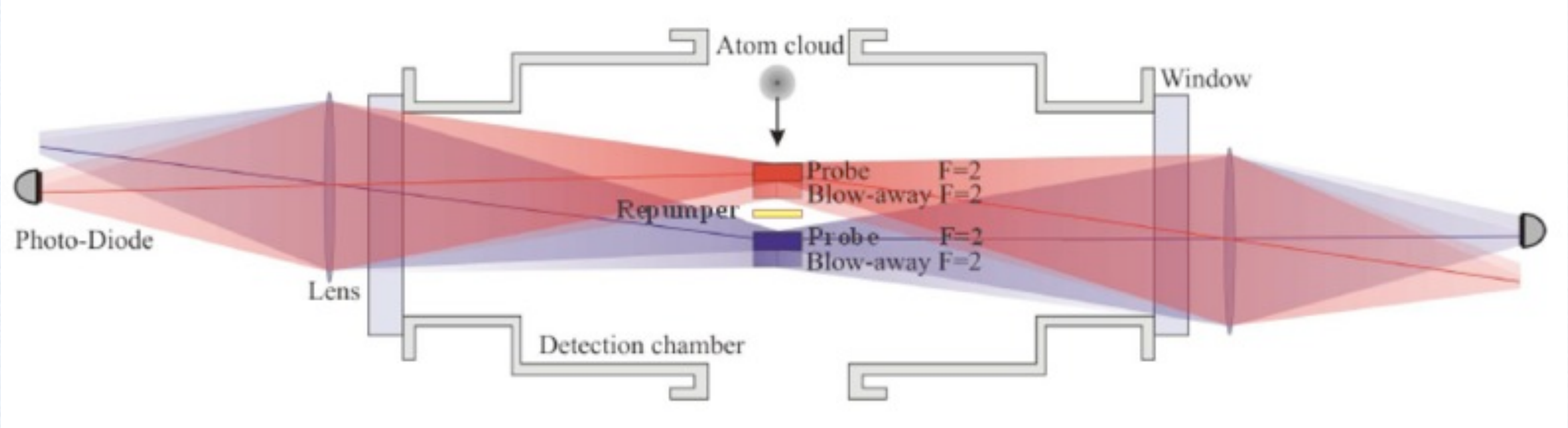
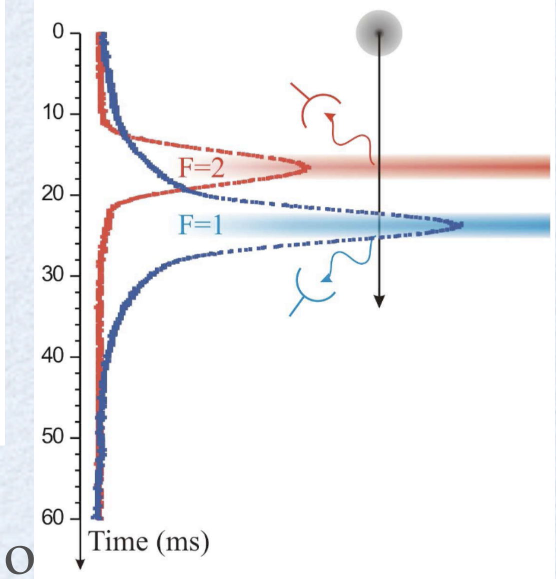
  - from unpolarized to $m_F=0$, from 3.5 v_{rec} to 0.3 v_{rec}
  - via Raman pulses + resonant blow-away pulses
- Raman interferometry sequence around apogee
- fluorescence detection of F=1 and F=2 populations



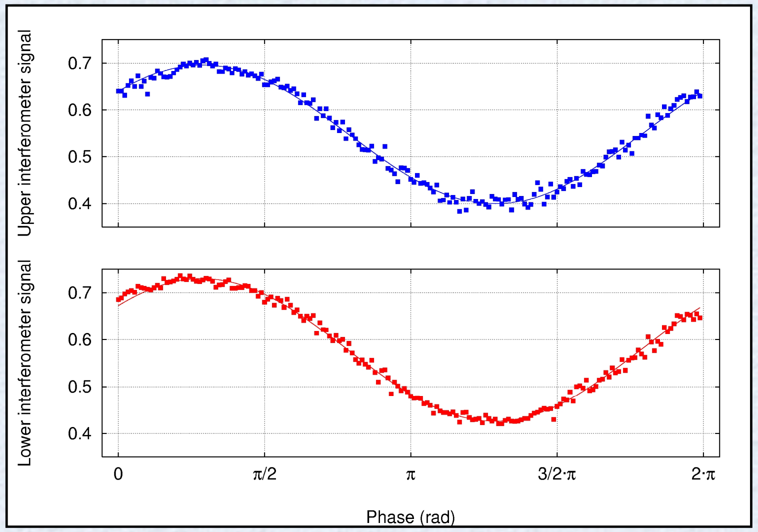




Raman gravity gradiometer

$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer

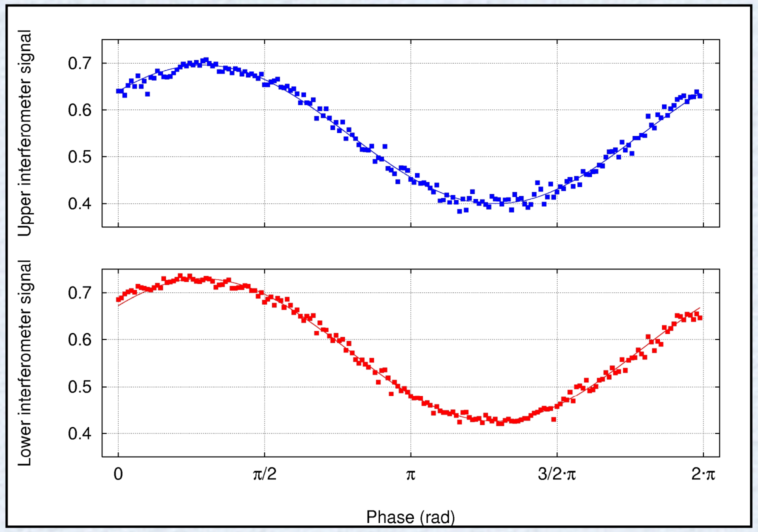


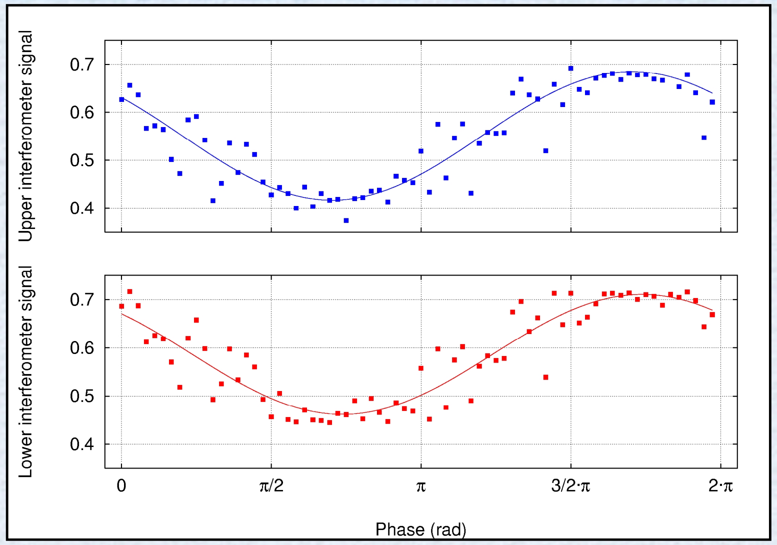
T=5 ms

$$\text{resol.} = 2.3 \times 10^{-5} \text{g/shot}$$

$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer



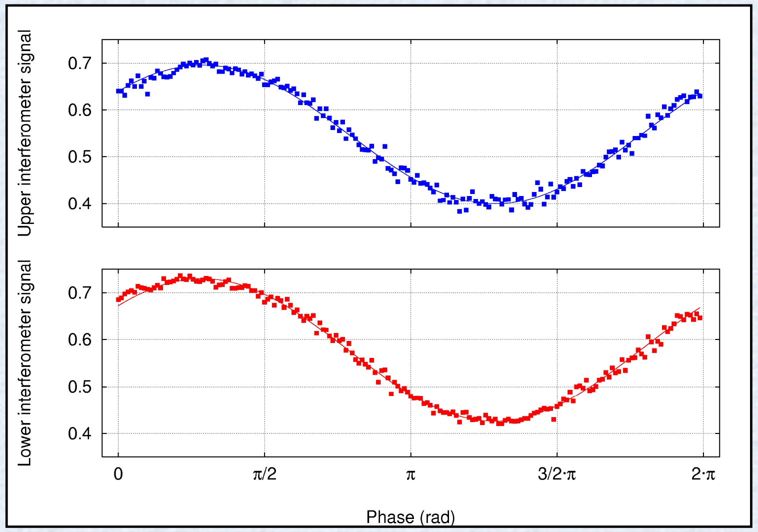


T=5 ms
$\text{resol.} = 2.3 \times 10^{-5}\text{g/shot}$

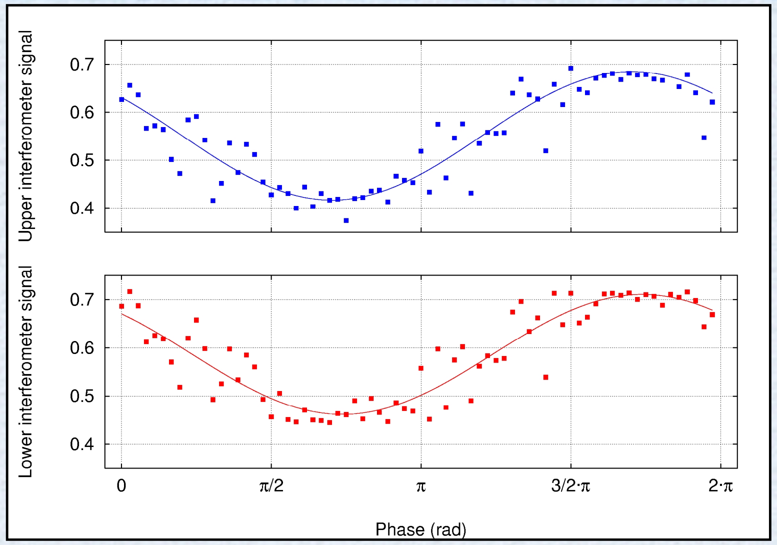
T=50 ms
$\text{resol.} = 1.0 \times 10^{-6}\text{g/shot}$

$$\Delta\Phi = k_e g T^2$$

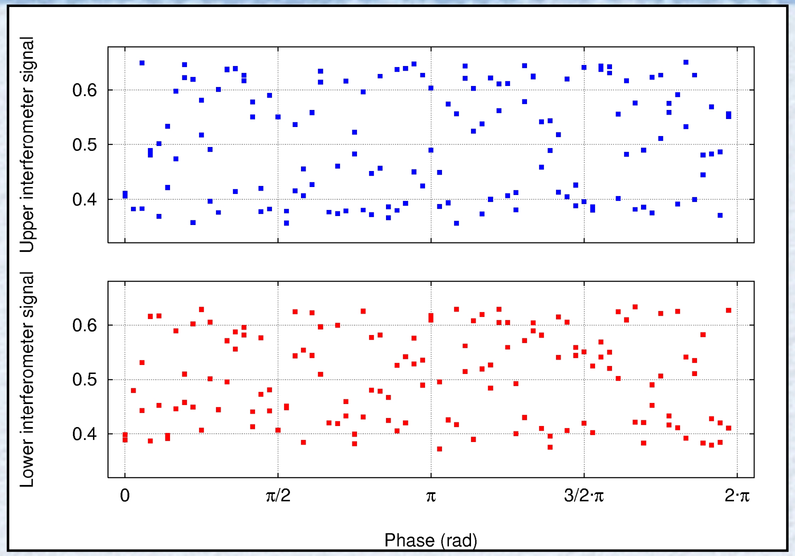
Raman gravity gradiometer



$$T=5\ \mathrm{ms}$$
$$\mathrm{resol.}\ = 2.3 \times 10^{-5}\mathrm{g/shot}$$



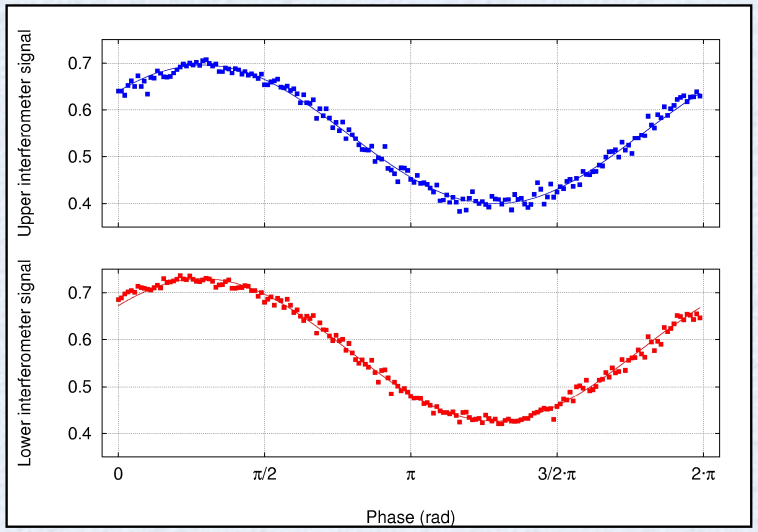
$$T=50\ \mathrm{ms}$$
$$\mathrm{resol.}\ = 1.0 \times 10^{-6}\mathrm{g/shot}$$



$$T=150\ \mathrm{ms}$$
$$\mathrm{resol.}\ = 3.2 \times 10^{-8}\mathrm{g/shot}$$

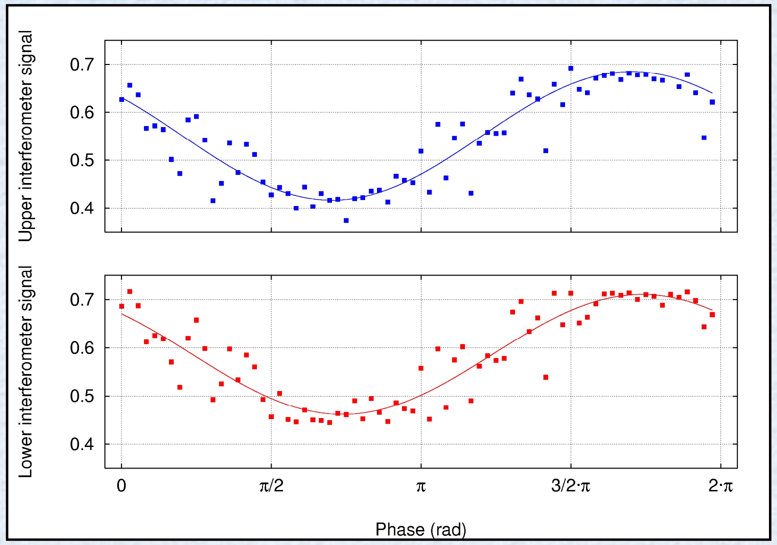
$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer



$T=5$ ms

$\text{resol.} = 2.3\times10^{-5}\text{g/shot}$



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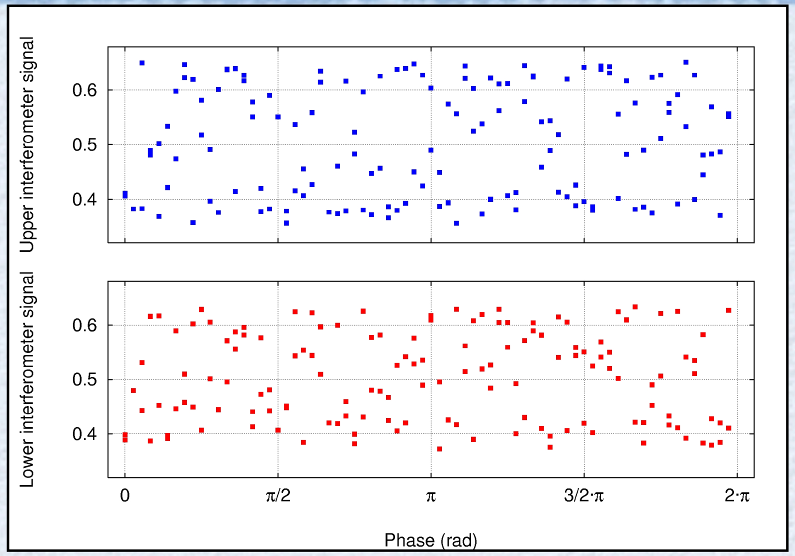

$T=150$ ms

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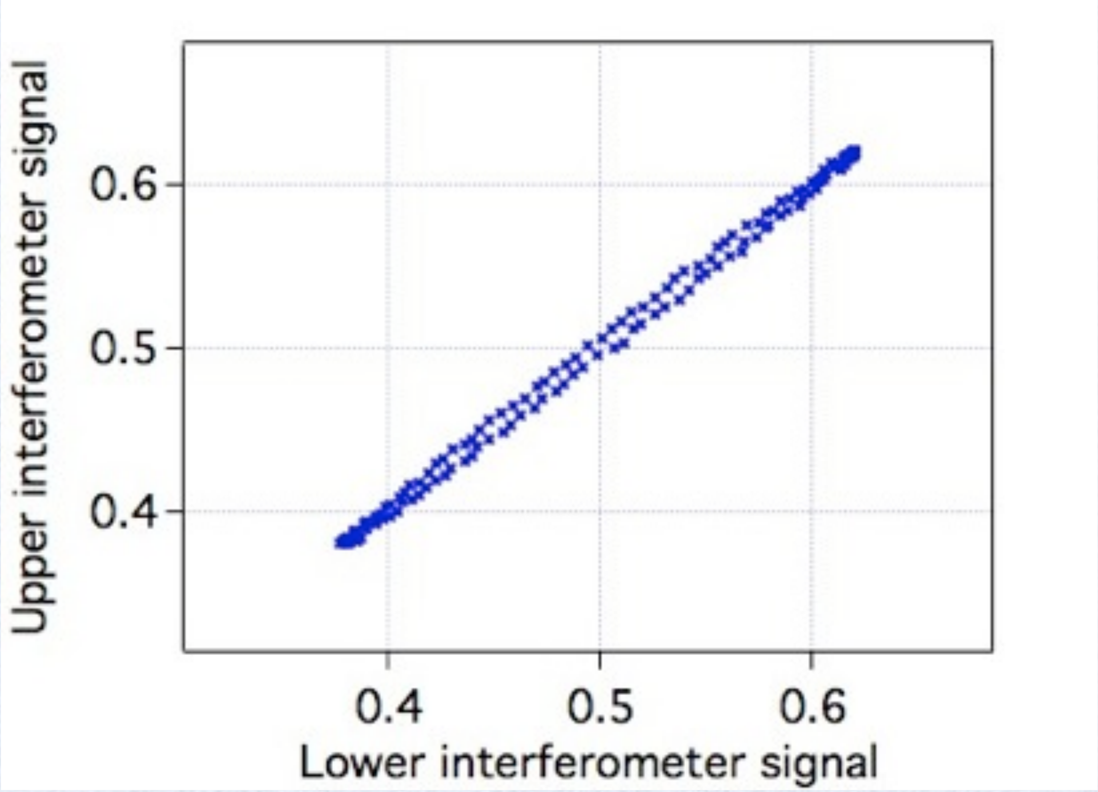
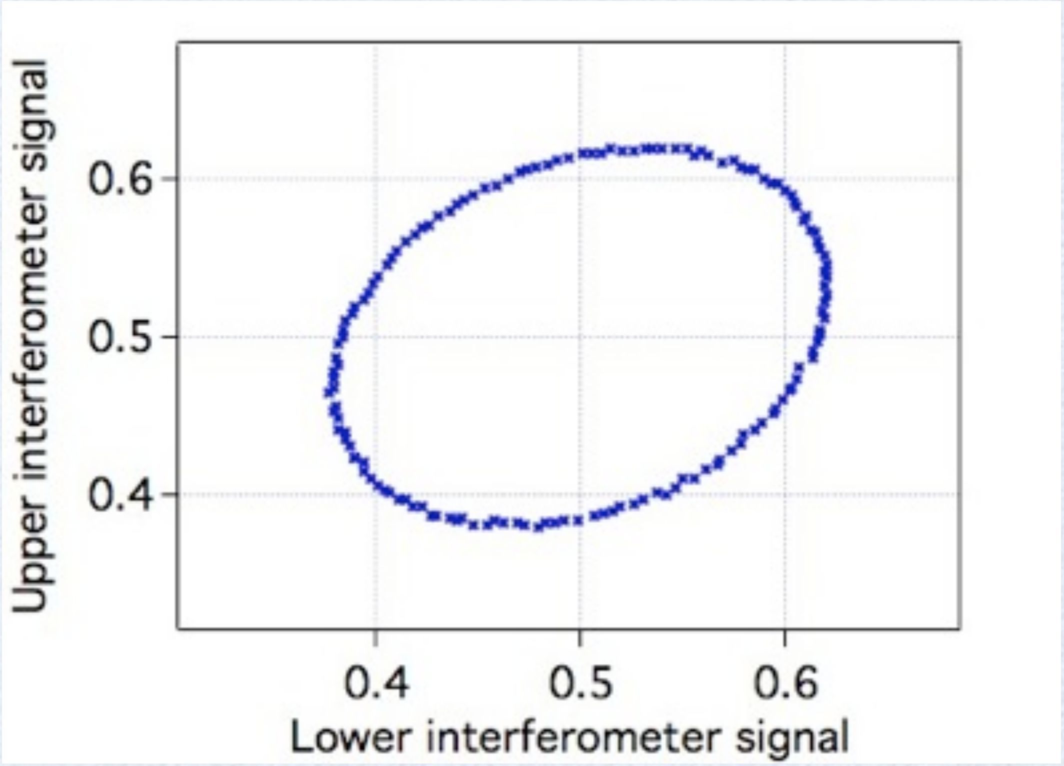


$$\Delta\Phi = k_e g T^2$$



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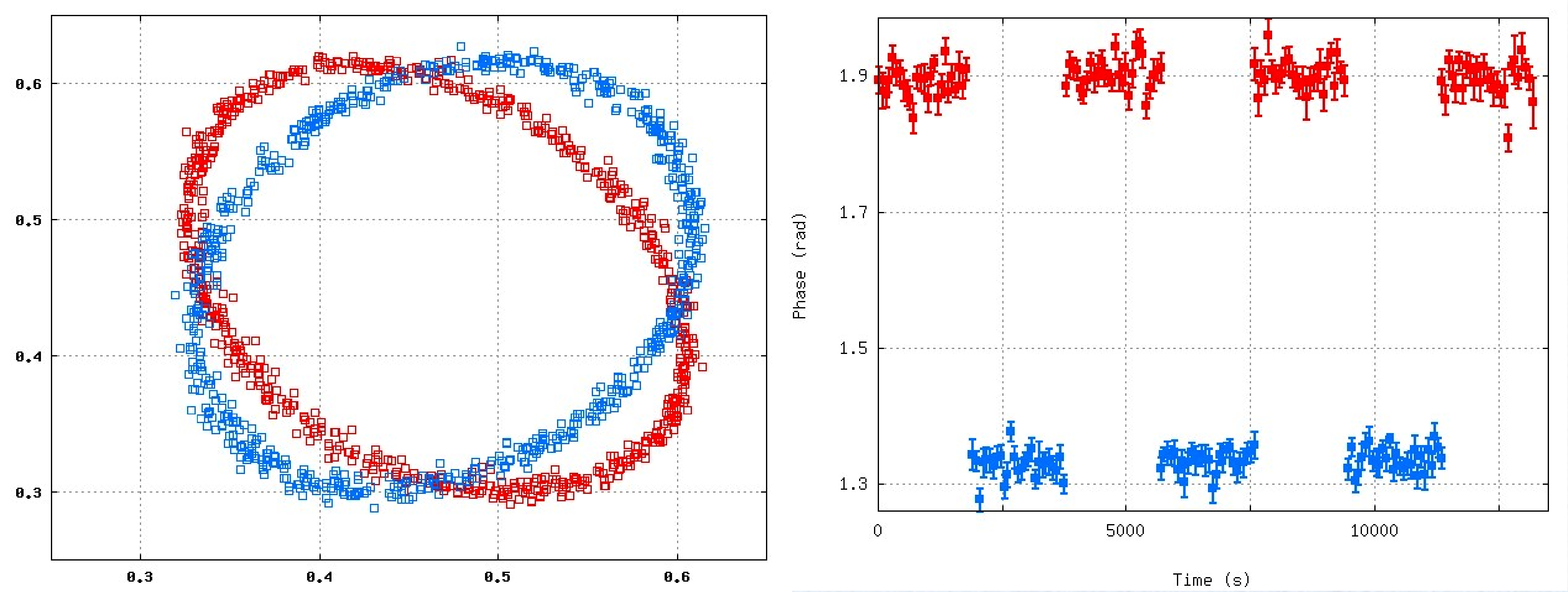
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

Measurement of the gravitational...

2007÷2008: proof-of-principle



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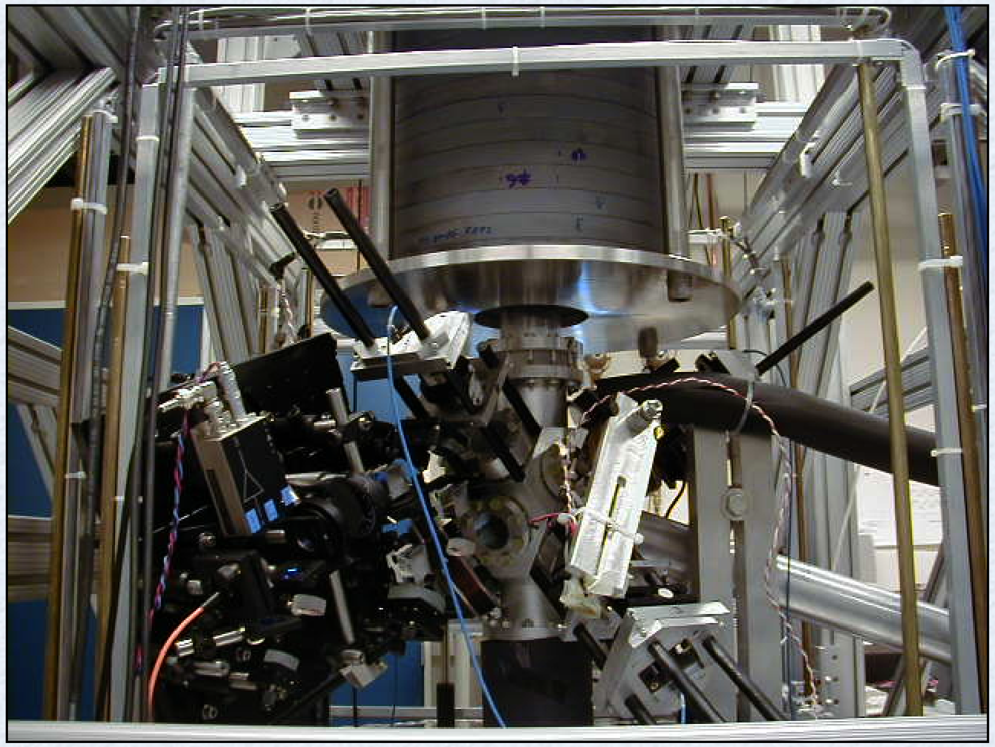
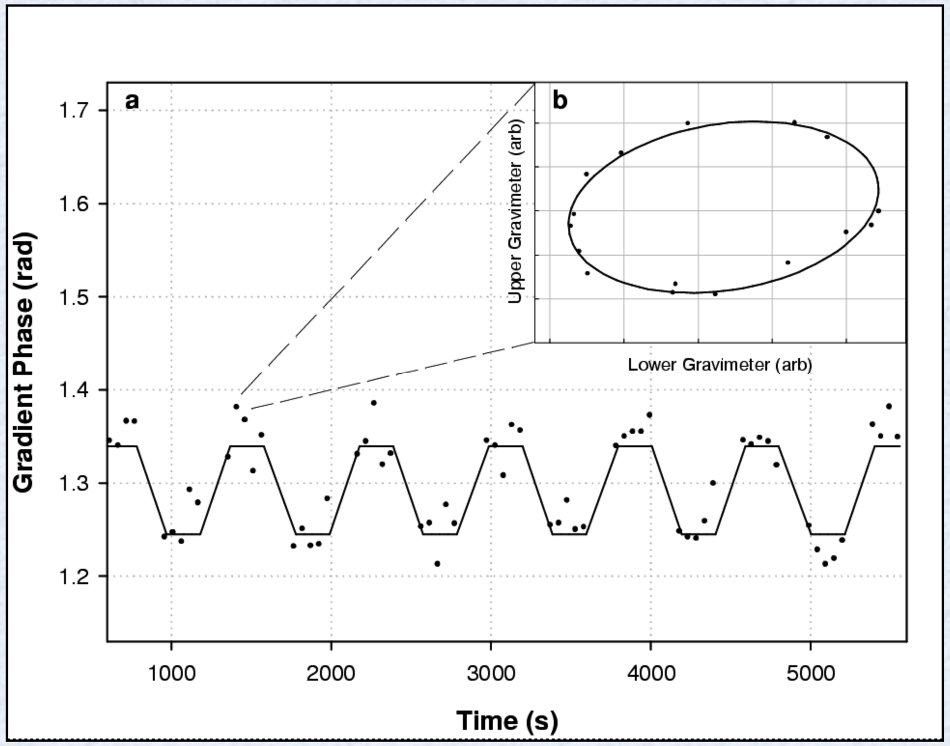
$G = 6.667\ (11)\ (3)\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$

G. Lamporesi et al., Phys. Rev. Lett **100**, 050801 (2008)





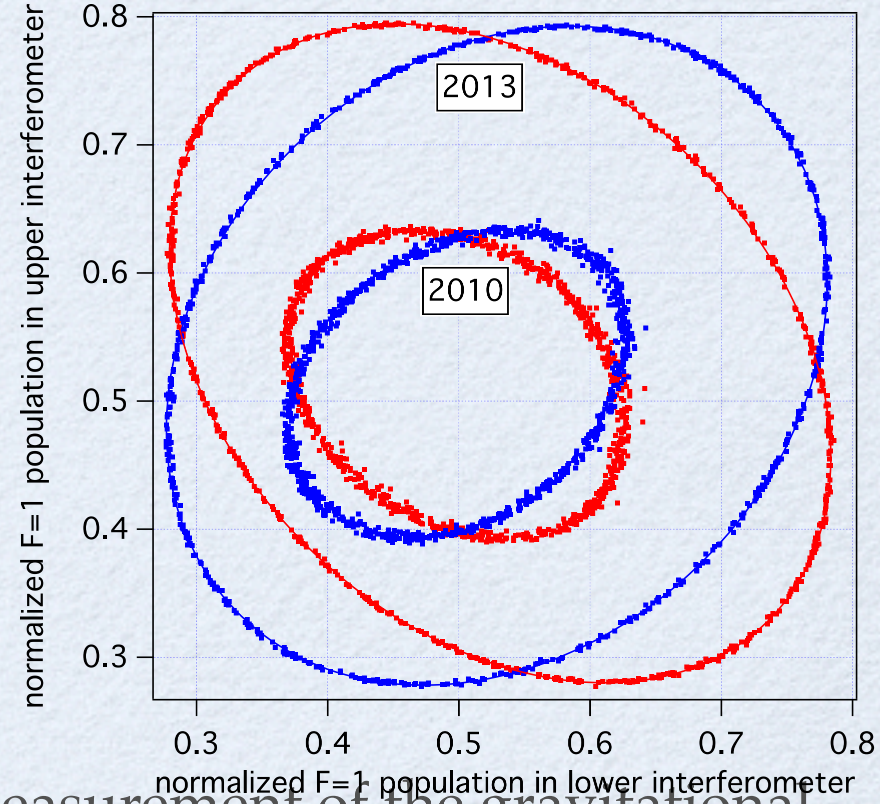
Stanford

$G = 6.693\ (27)\ (21) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$

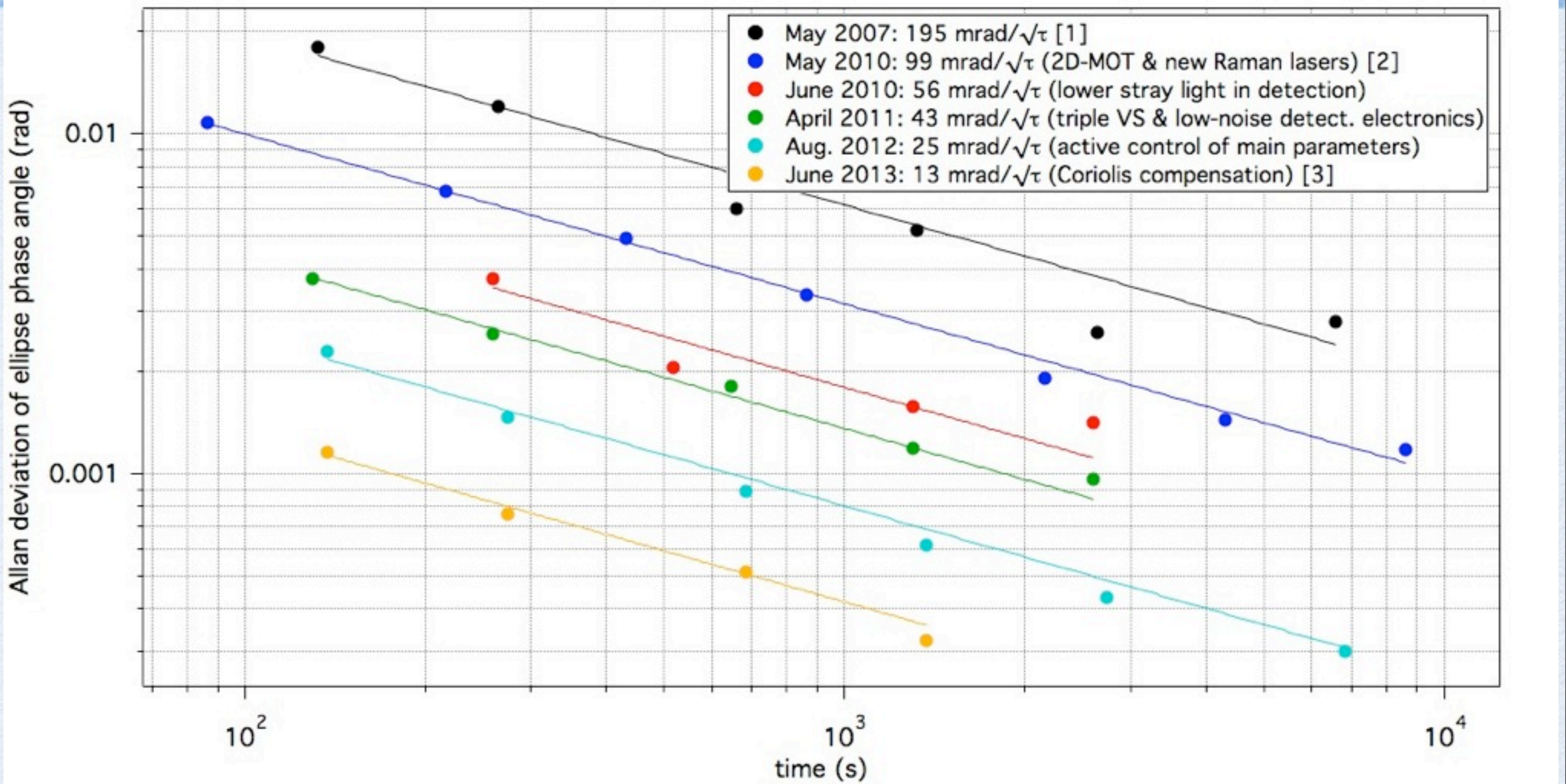
J. B. Fixler et al., Science **315**, 74 (2007)

From proof-of-principle to G measure

- Sensitivity
  - 15-fold improvement of the instrument sensitivity from 2008 to 2013
  - integration time for the target 100 ppm reduced by more than a factor 200
- Accuracy
  - systematic uncertainty had been reduced by a factor ~10 since 2008, mostly due to
    - better characterization of source masses
    - control & mitigation of Coriolis acceleration
    - excellent control of atomic trajectories
- Data analysis
  - we developed a reliable model accounting for all of the relevant effects
    - gravitational potential from source masses
    - quantum mechanical phase shift of atomic probes
    - detection efficiency
  - measurement are compared with a Montecarlo simulation
- MAGIA @ EGAS
  - EGAS 41 (2009): F. Sorrentino
  - EGAS 43 (2011): M. Prevedelli
  - EGAS 44 (2012): G. Rosi



Improving the sensitivity



Current sensitivity to differential acceleration: 3×10^{-9} g @ 1s (=QPN for 4×10^{5} atoms)

[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)

[2] F. Sorrentino et al., New J. Phys. **12**, 095009 (2010)

[3] F. Sorrentino et al., Phys. Rev. A **89**, 023607 (2014)

Pursuing the accuracy limits

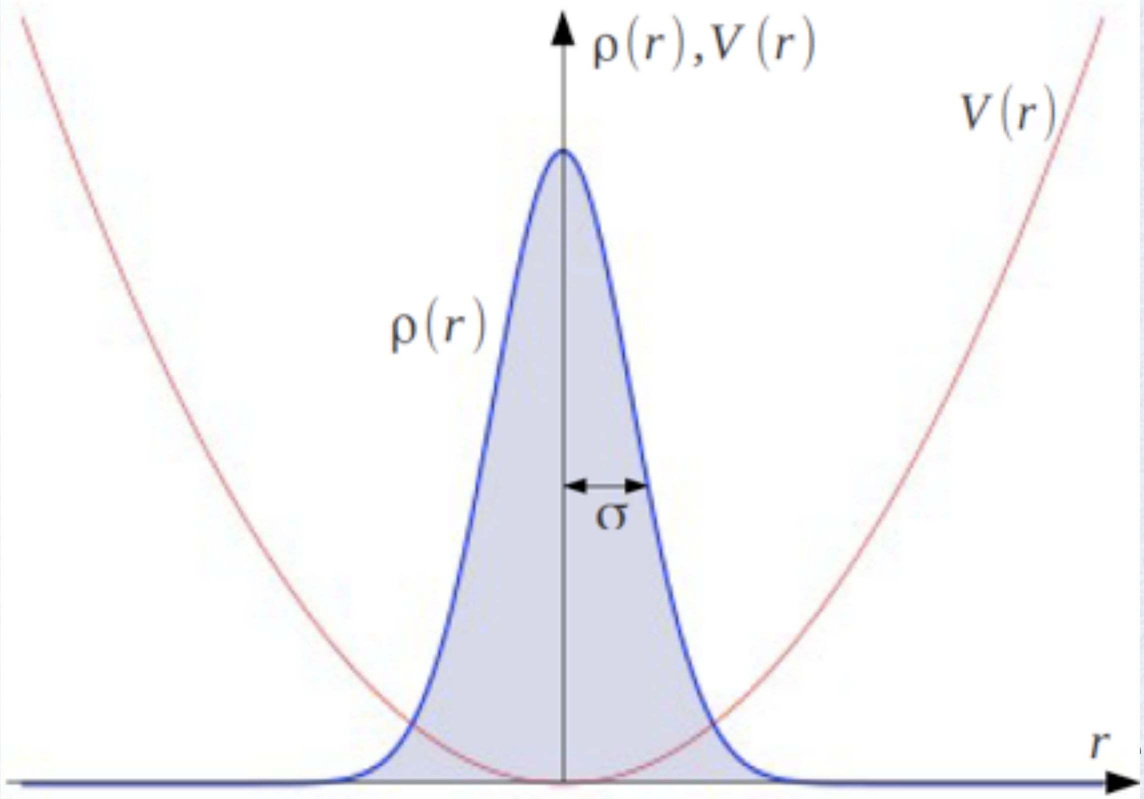
- Precise characterization of source masses (weight, density homogeneity, shape, position)
- Precise characterization of atomic trajectories
- Calibration of relative detection efficiency in the two interferometer outputs
- Removal of k-independent biases (Zeeman shift)
- Removal of k-dependent biases (Coriolis acceleration)

Pursuing the accuracy limits

- Precise characterization of source masses (weight, density homogeneity, shape, position)
- **Precise characterization of atomic trajectories**
- Calibration of relative detection efficiency in the two interferometer outputs
- Removal of k-independent biases (Zeeman shift)
- **Removal of k-dependent biases (Coriolis acceleration)**

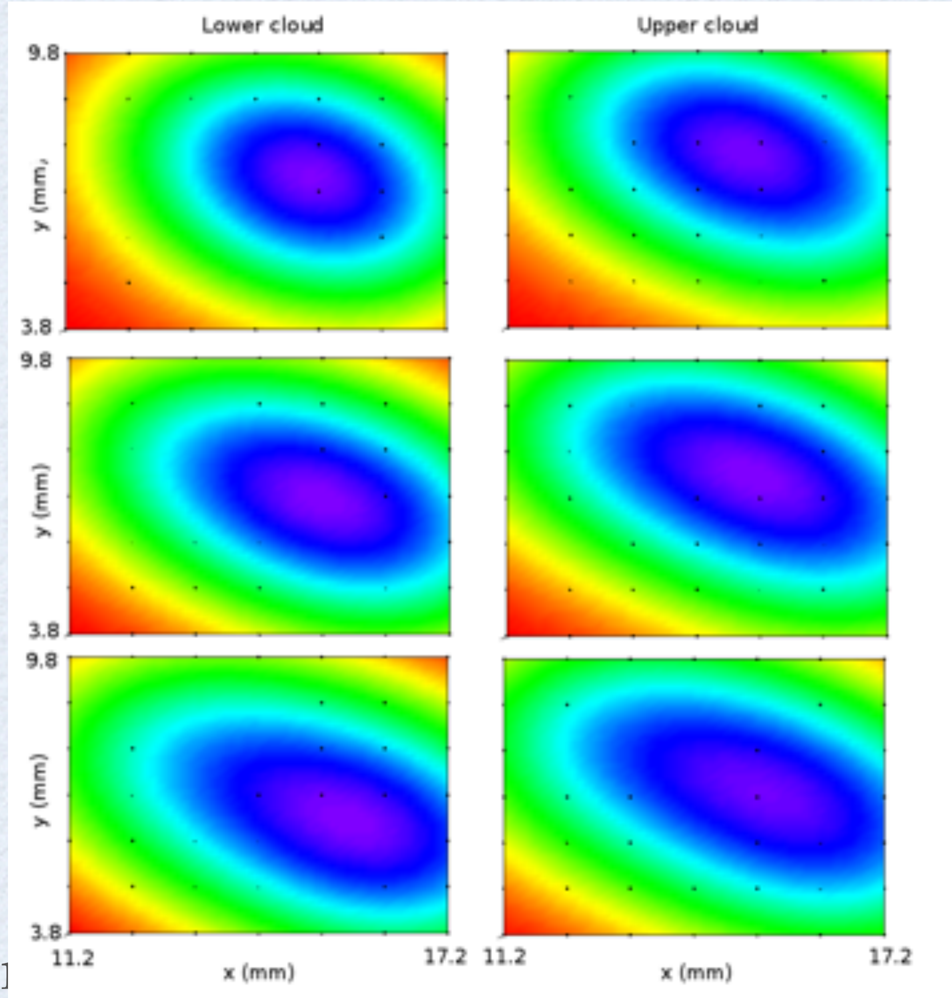
Effect of atomic trajectories

- Finite size of atomic clouds yields a bias on G due to the curvature of gravitational potential
  - curvature has opposite sign on horizontal plane and vertical direction
  - partial compensation of bias on G for finite cloud size
- Correcting for the bias requires:
  - a precise knowledge of atomic clouds density distribution along the atom interferometry sequence
  - a precise knowledge of the spatial distribution of detection efficiency
  - a Montecarlo simulation to calculate the corresponding phase shift



Measurement of atomic trajectories

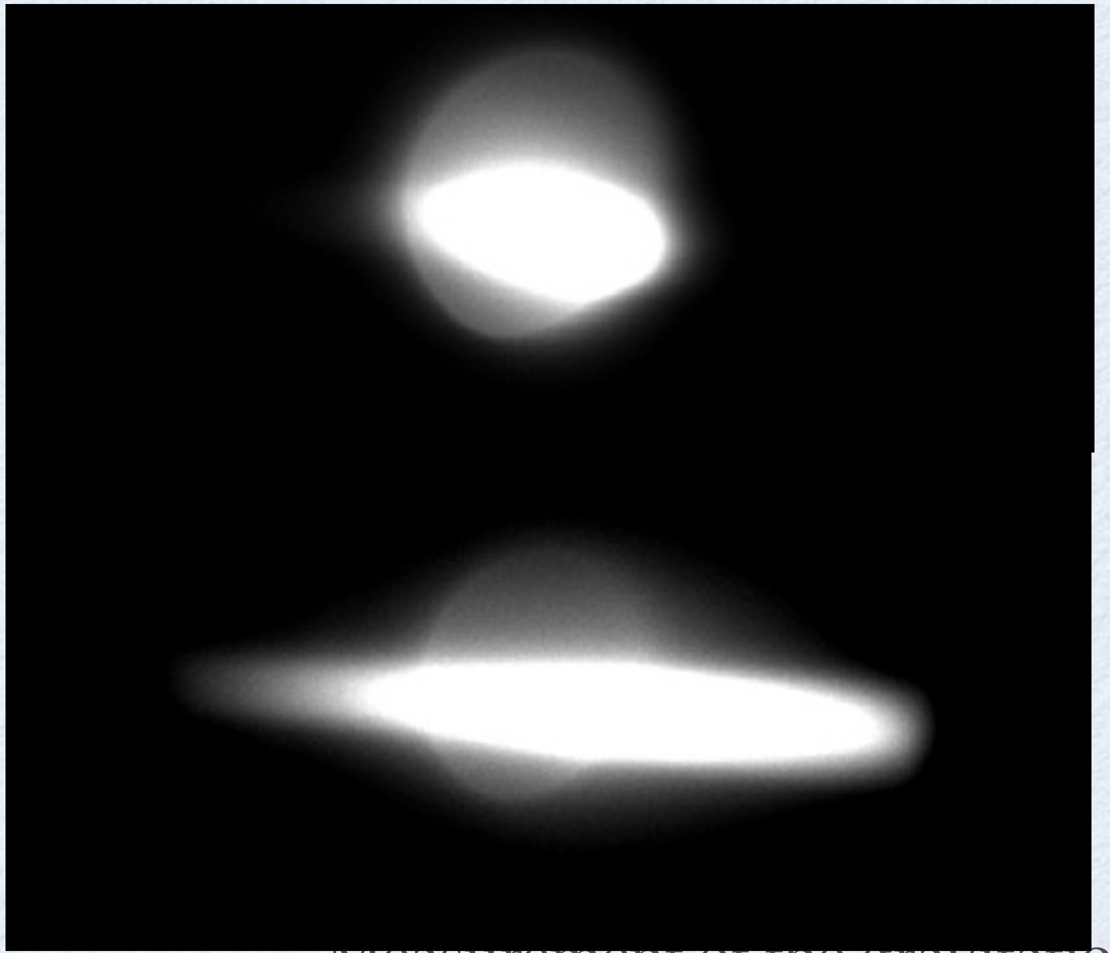
- Vertical coordinates measured within 0.1 mm from TOF + double diffraction
    - **corresponding error on *G*: 57 ppm**
- Transverse density distribution measured by different methods:
    - 2D scanning of a thin portion of Raman laser beams
    - fluorescence imaging of clouds at the two passages in the detection chamber
    - Raman velocimetry
    - barycenter and width measured within 1 mm
    - **corresponding error on *G*: 38 ppm**



T = 0 ms

T = 62.5 ms

T = 125 ms

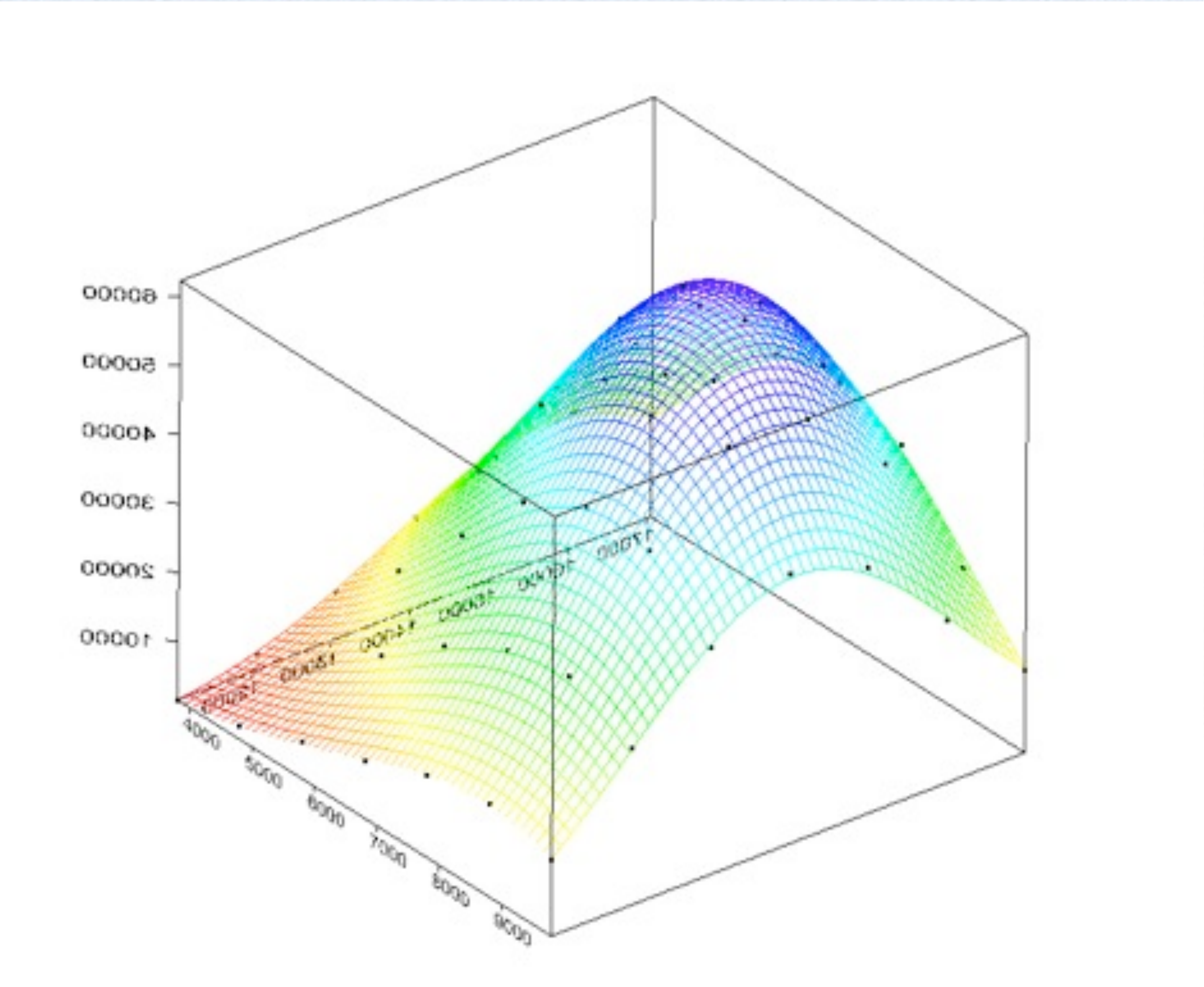


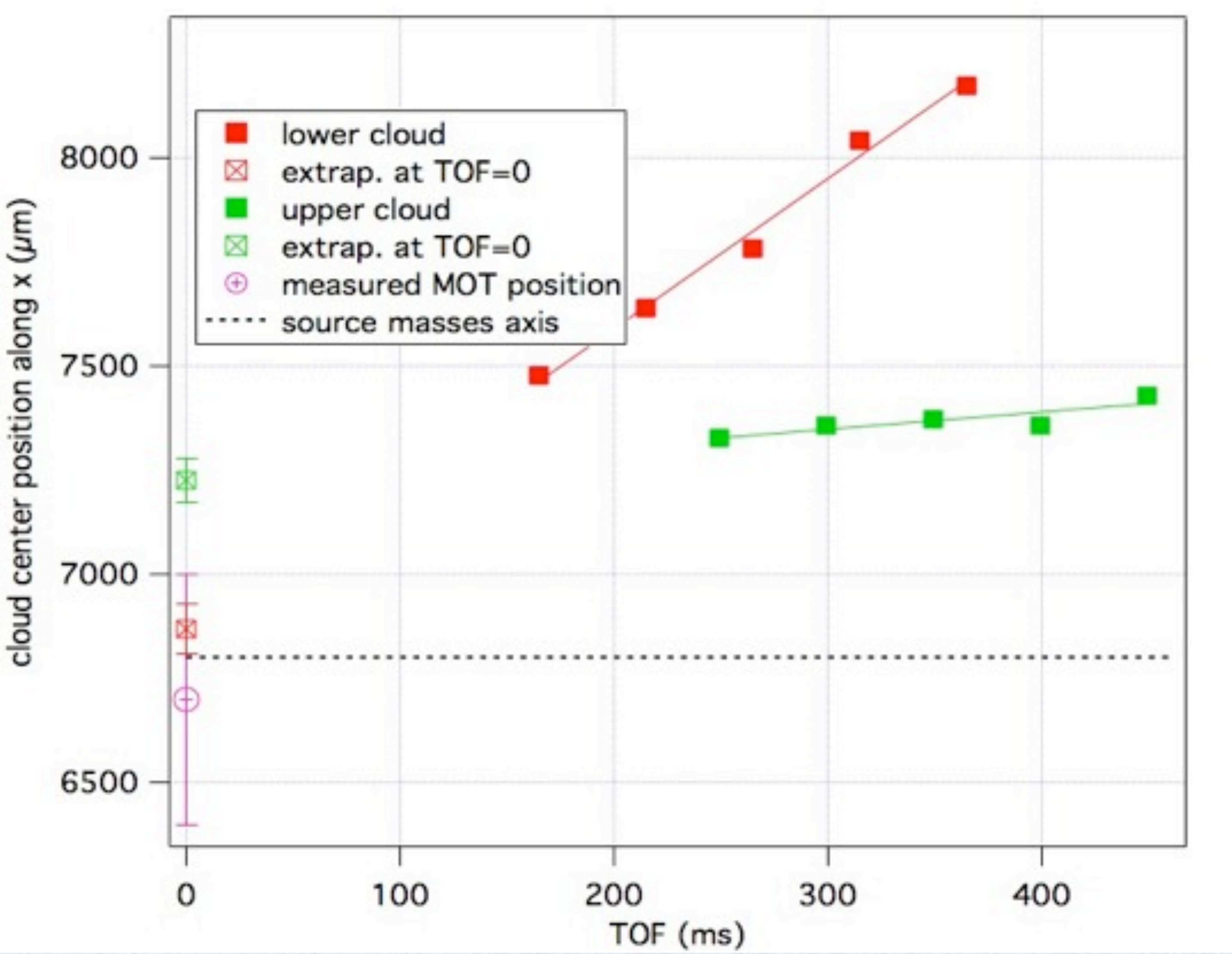
Bias on *G* from Coriolis acceleration

- Transverse velocities are found in the range of a few mm/s
- These are due to small tilt (~1 mrad) of the atomic fountain

$$\phi_{Coriol} = -2\Omega k_{eff} T^2 \cos\theta_l (v_u - v_l) \sin\theta_{tilt} \simeq -34\theta_{tilt}$$

- Corresponding AI phase shift due to Coriolis acceleration ~40 mrad, i. e. 10^{-9} g
- For a Coriolis shift below 10^{-4} on *G*, launching direction should change **less than 2 μrad** on average when moving the sources masses





Coriolis compensation

- We reduce the frame rotation by at least a factor 10 with a tip-tilt Raman retro-reflecting mirror [M. Hogan et al., Proc. intern. school of physics Enrico Fermi CLXVIII, 411 (2007)]
- Still we would need to control the C/F launching direction changes to better than 20 μrad
- Double stage compensation: ellipse phase shift vs. rotation rate is proportional to the transverse atomic velocity difference
- When comparing for the two configurations of source masses, we determine C/F transverse velocity changes to be lower than 20 μm/s
- Under the conservative assumption of Earth rotation compensation at 10%, **corresponding uncertainty on *G* is 36 ppm**

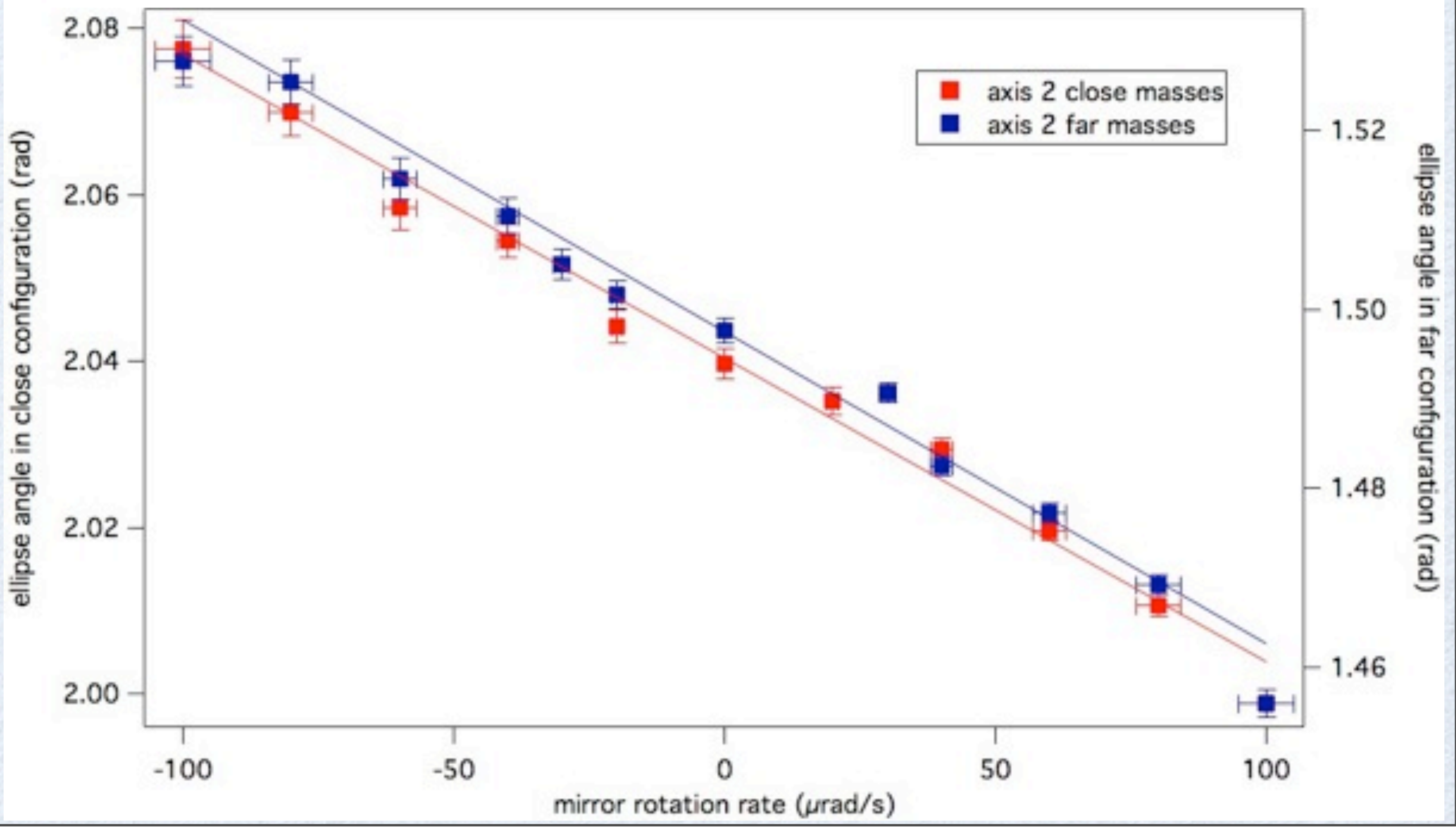
$$\phi_{Coriol} = -2k_{eff}T^2(\Omega_{m1}\Delta v_\perp \cos\beta + \Omega_E \cos\gamma \Delta v_\perp \cos(\alpha+\beta))$$

$\Delta\Phi$ = (542.81+/- 0.2) mrad (comp.)

$\Delta\Phi$ = (542.63 +/- 0.2) mrad (non comp)

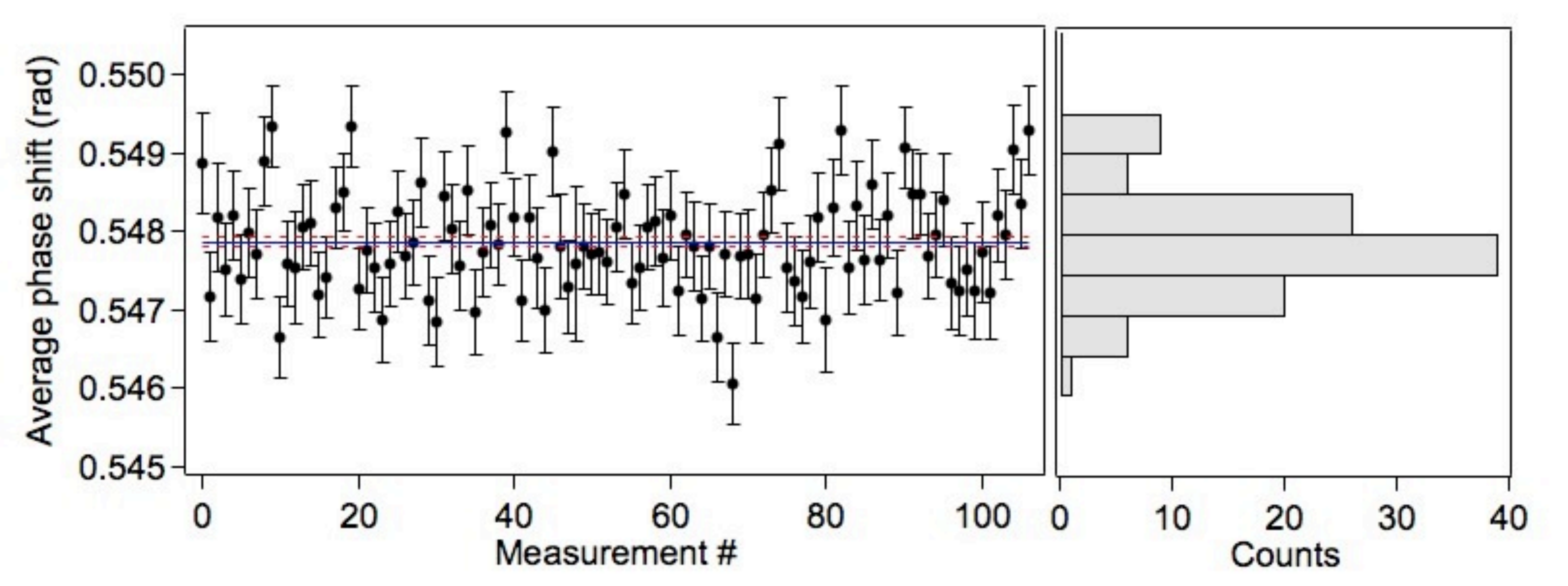
difference < 0.28 mrad

=> $\Delta v_{E\text{-}O} <$ 20 μm/s



F. Sorrentino

G measurement



From our data we deduce G=6.67191(77)(65)$m^3kg^{-1}s^{-2}$

Statistical error 116 ppm

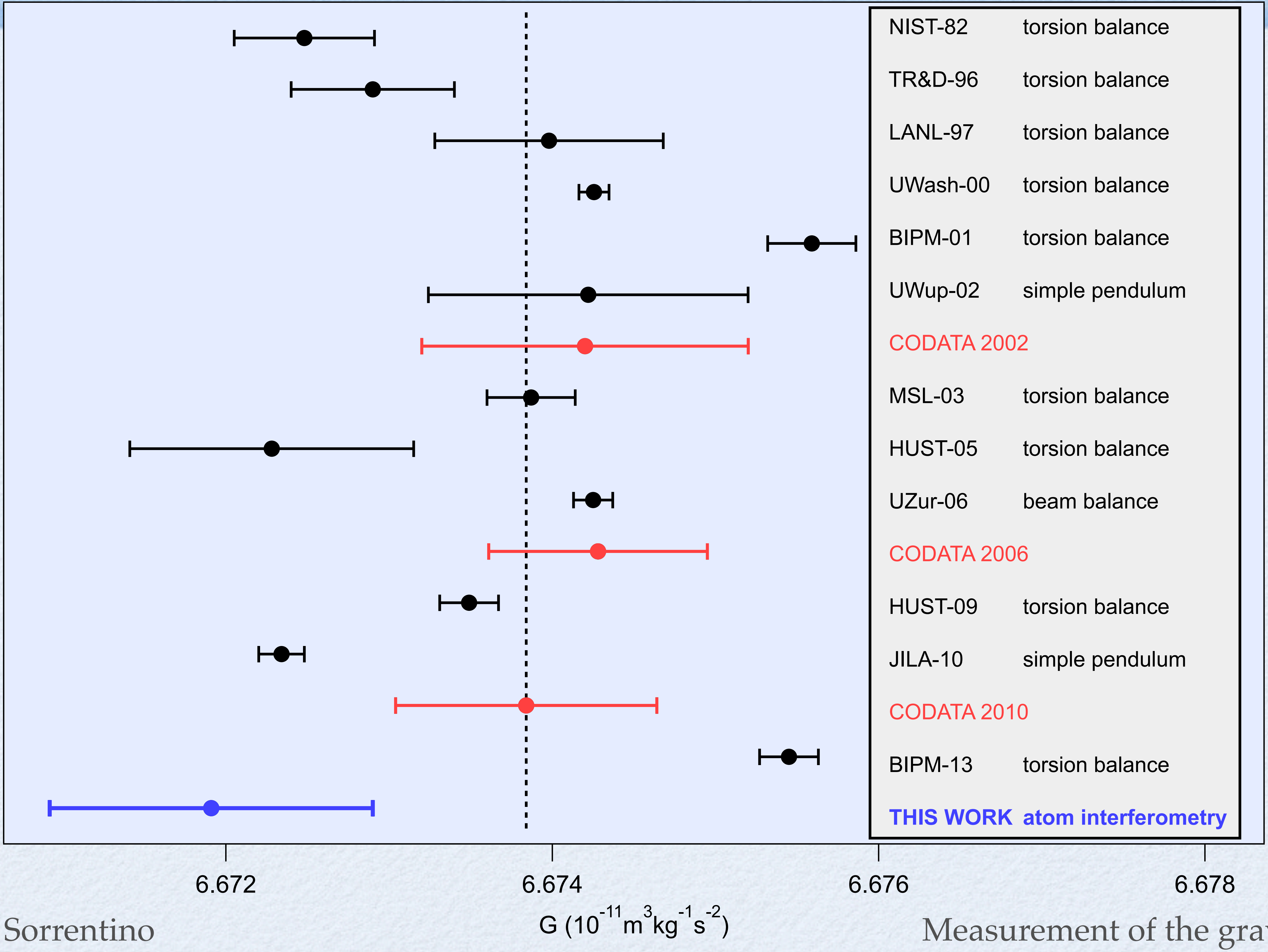
Systematic error 92 ppm

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli and G. M. Tino, *Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms*, Nature **510**, 518 (2014)

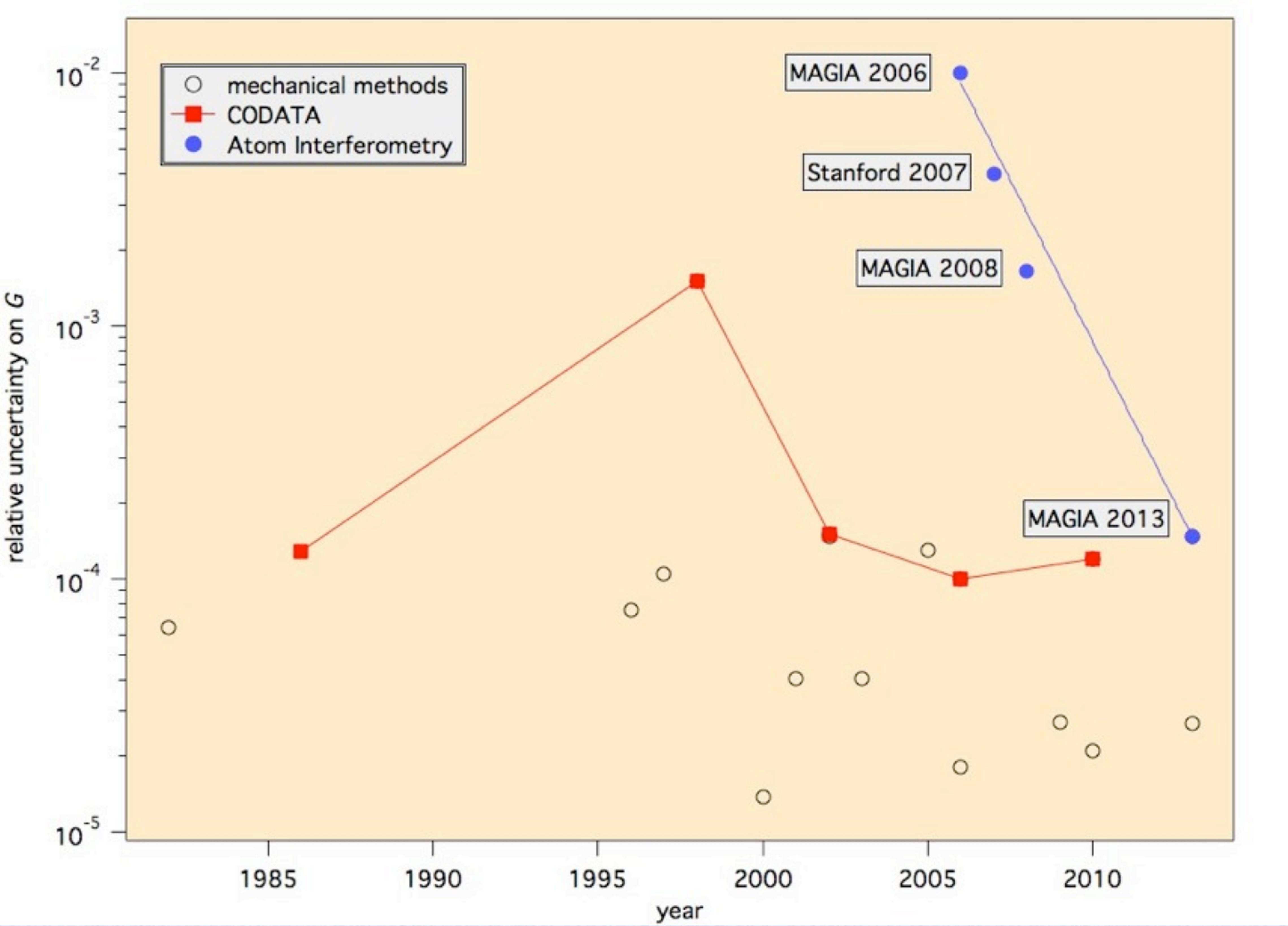
MAGIA error budget

	Uncertainty on parameter	Relative correction on G (ppm)	Relative uncertainty on G (ppm)
Air density	10 %	60	6
Apogee time	30 μs		6
Atomic clouds horizontal size	0.5 mm		24
Atomic clouds vertical size	0.1 mm		56
Atomic clouds horizontal position	1 mm		37
Atomic clouds vertical position	0.1 mm		5
Atoms launch direction change C/F	8 μrad		36
Cylinders density homogeneity	10^{-4}	91	18
Cylinders radial position	10 μm		38
Ellipse fit		-13	4
Size of detection region	1 mm		13
Support platforms' mass	10 g		5
Translation stages position	0.5 mm		6
Other effects		<2	1
Systematic uncertainty			92
Statistical uncertainty			116
Total		137	148

G measurements: current status



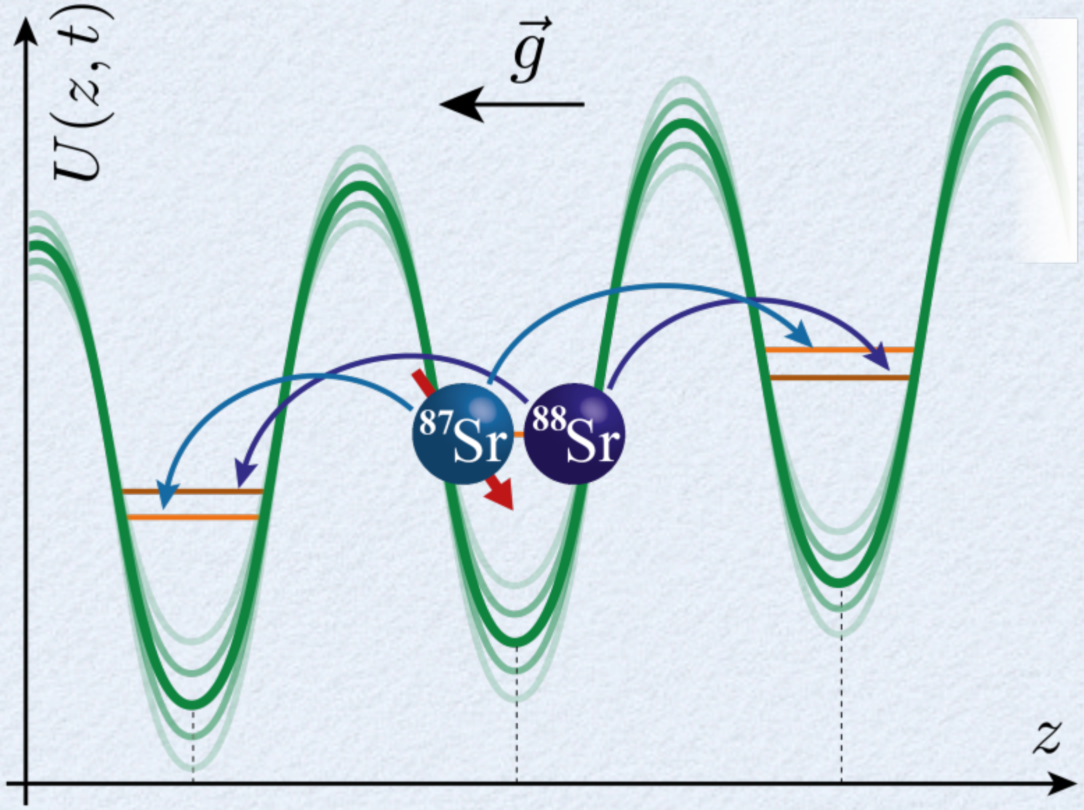
From proof of principle to G measure

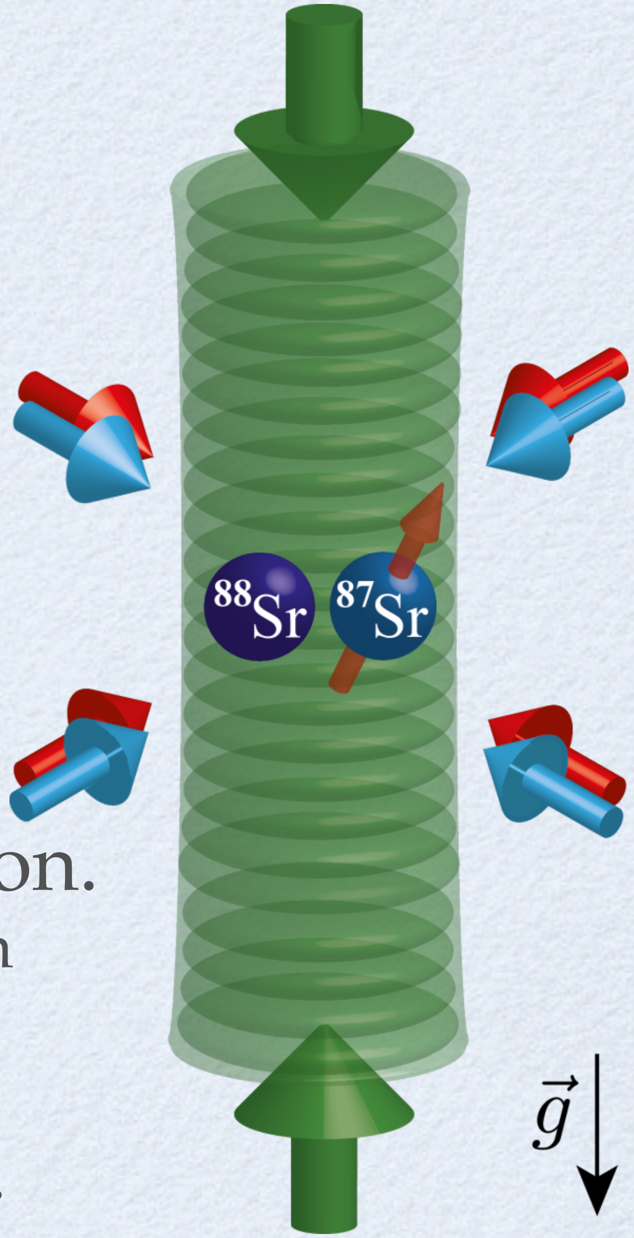


Atom interferometry WEP test with Sr

M. G. Tarallo, T. Mazzoni, N. Poli, D. V. Sutyrin, X. Zhang, and G. M. Tino, *Test of Einstein equivalence principle for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects*, Phys. Rev. Lett. Accepted 23 June 2014

- ^{88}Sr
  - Boson
  - Zero total spin
- ^{87}Sr
  - Fermion
  - Total spin I=9/2





- First test to compare a single Boson and a single Fermion.
  - Measured **Eötvös parameter** for violation due to difference between gravitational and inertial mass: η=(0.2±1.6)×10^{-7}
- First test to directly measure limits on EP violation for different orientations of the nuclear spin of cold atoms.
  - Measured **spin-gravity coupling** parameter: k=(0.5±1.1)×10^{-7}

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