The MAGIA experiment
current status and future prospects

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with support from

LENS

esa

SEVENTH FRAMEWORK PROGRAMME

asi agenzia spaziale italiana

ENTE CASSA DI RISPARMIO DI FIRENZE

Atom interferometry sensors (I)

- Virtual sensitivity improvement of several orders of magnitude over optical interferometers.
- However, such advantage is currently reduced by
  - small particle flux (10^{10} for alkali, 10^{18} for H)
  - small separation of matter-wave paths (few photon recoils).
- Nevertheless, AI sensors already compete with optical counterparts.
- Already achieved: inertial sensing (acceleration, gravity gradient, rotations) measurement of fundamental constants (G, α).
- In progress/proposed: tests of GR (EP, Lense-Thirring, limits on PPN parameters); test of Newton's $1/r^2$ law at short length scale; atom neutrality; GW detection.
- Large progress are foreseen in the next future (LMT beam splitters, high flux atomic sources, sub-shot noise detection schemes, etc.)

Atom interferometry sensors (II)

- AI inertial sensors feature very good long term stability and control over systematic effects
  - Differential configurations allow for very large CMRR of vibrations
  - Based on quantum atom-light interaction, which can be precisely modeled
  - The possible choice of different internal/external quantum states, as well as of different isotopic species, provides “knobs” to isolate, model and minimize several possible noise sources

MAGIA

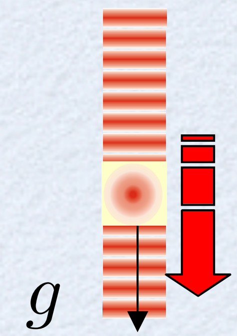
Misura Accurata di G mediante Interferometria Atomica

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

MAGIA

Misura Accurata di G mediante Interferometria Atomica

- Measure g by atom interferometry

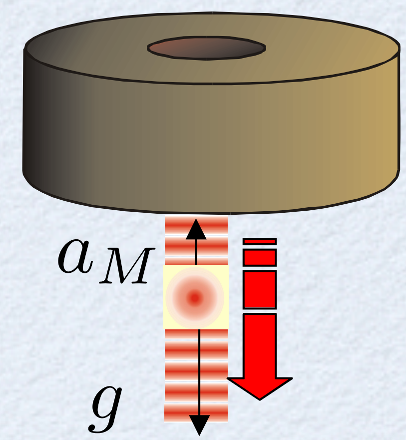


http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA

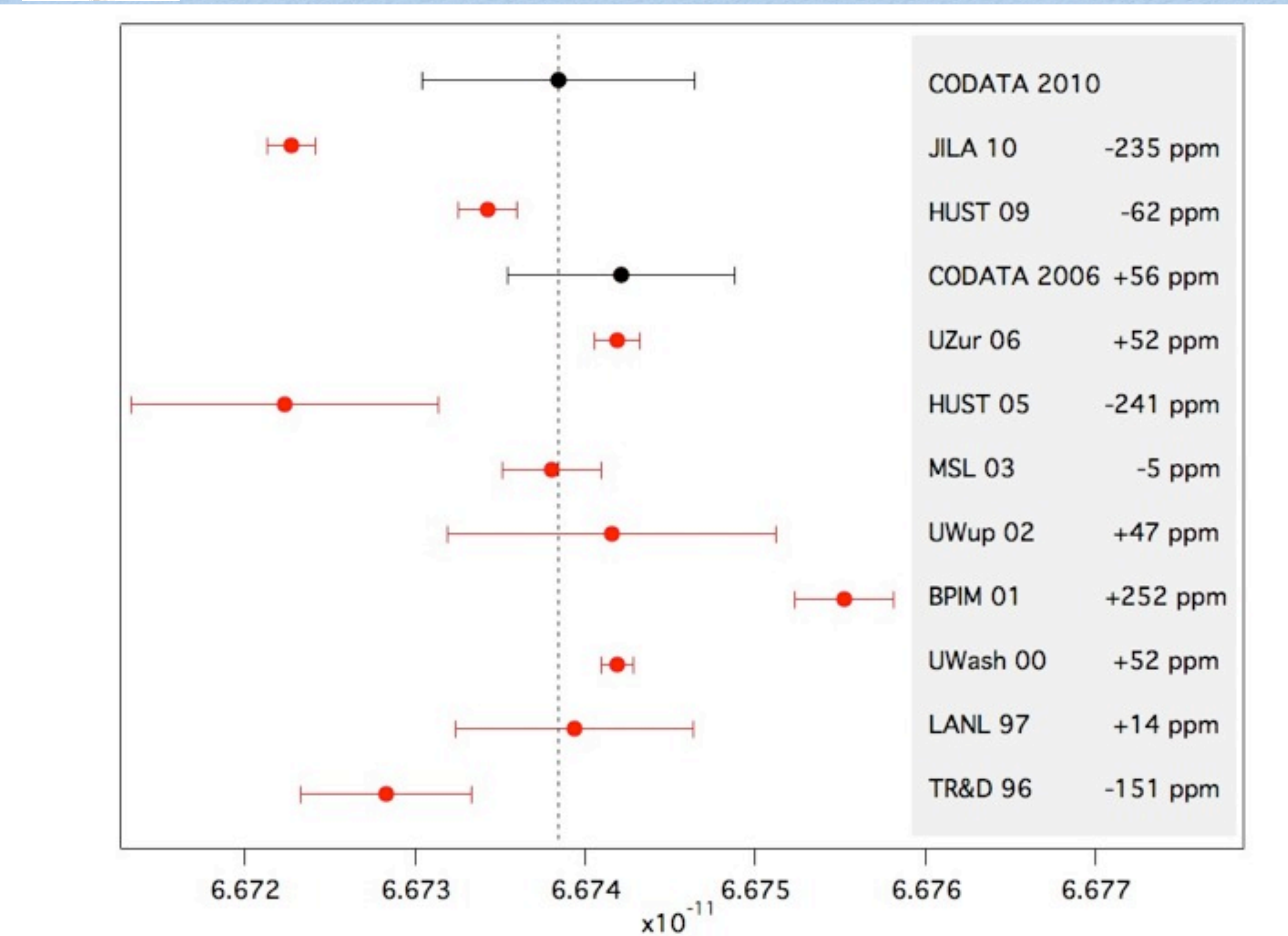
Misura Accurata di G mediante Interferometria Atomica

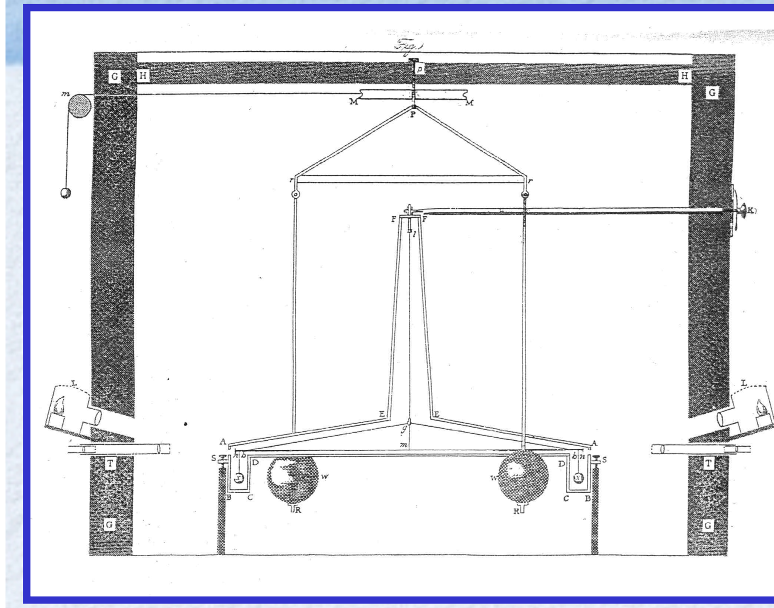
- Measure g by atom interferometry
- Add source masses
- Measure change of g



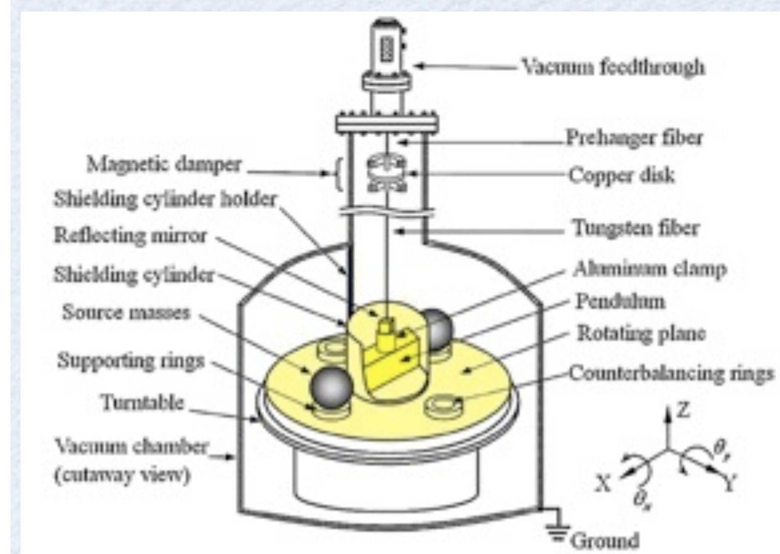
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Motivation





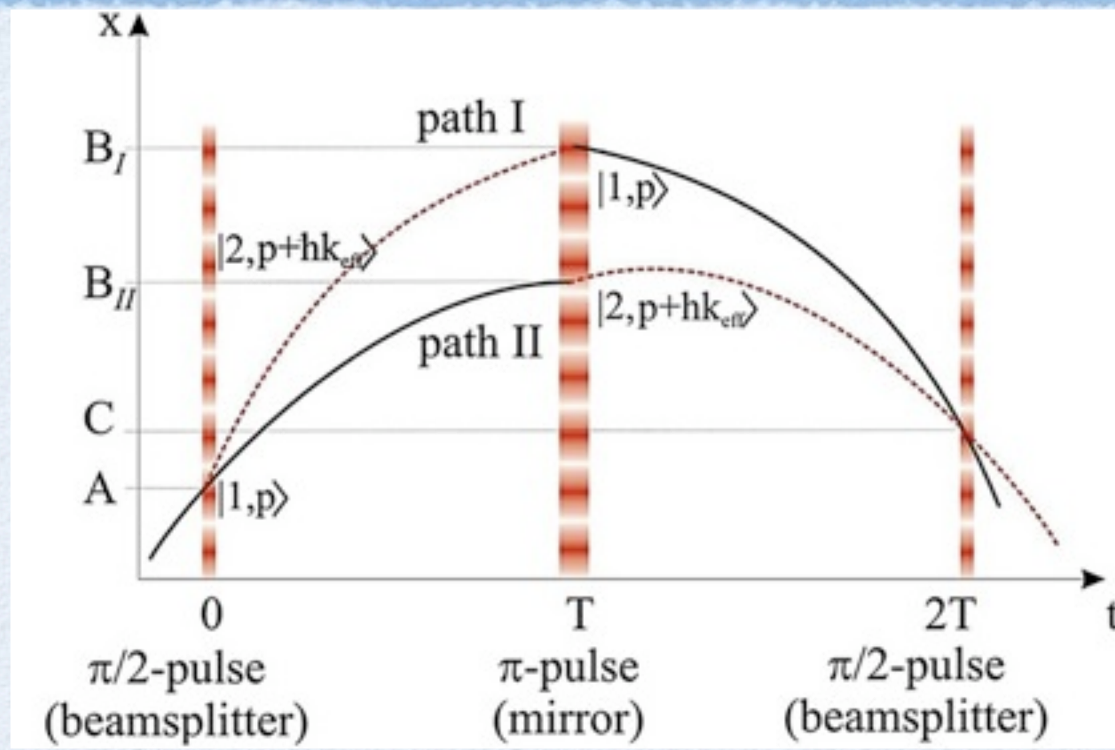
Cavendish 1798



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

Zang 2009

Raman interferometry in a ^{87}Rb atomic fountain



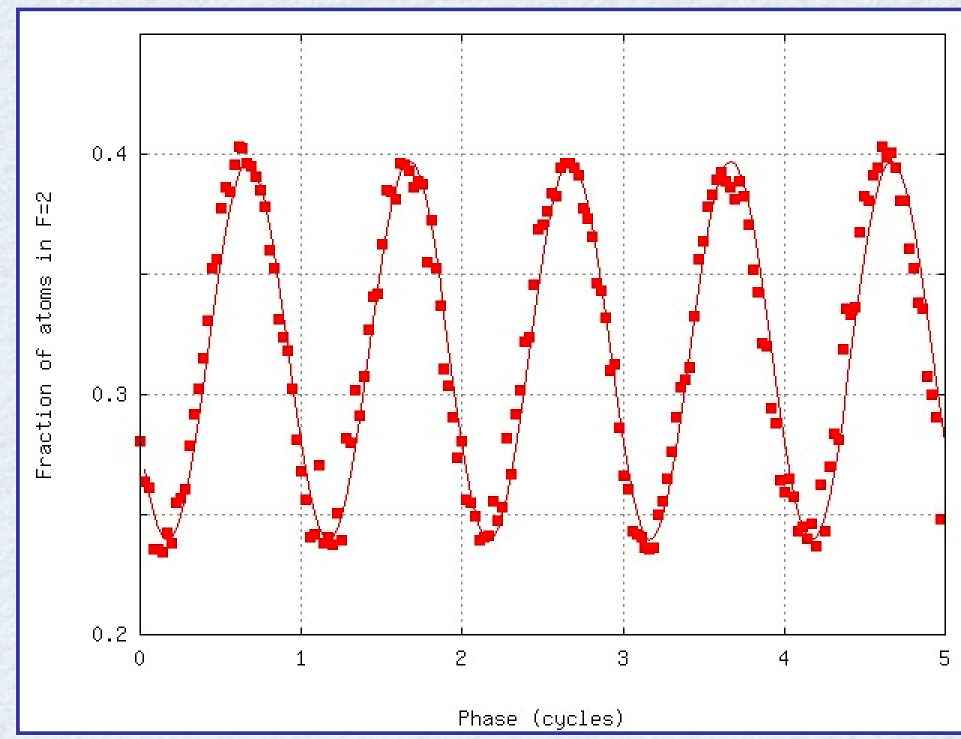
Phase difference between the paths:

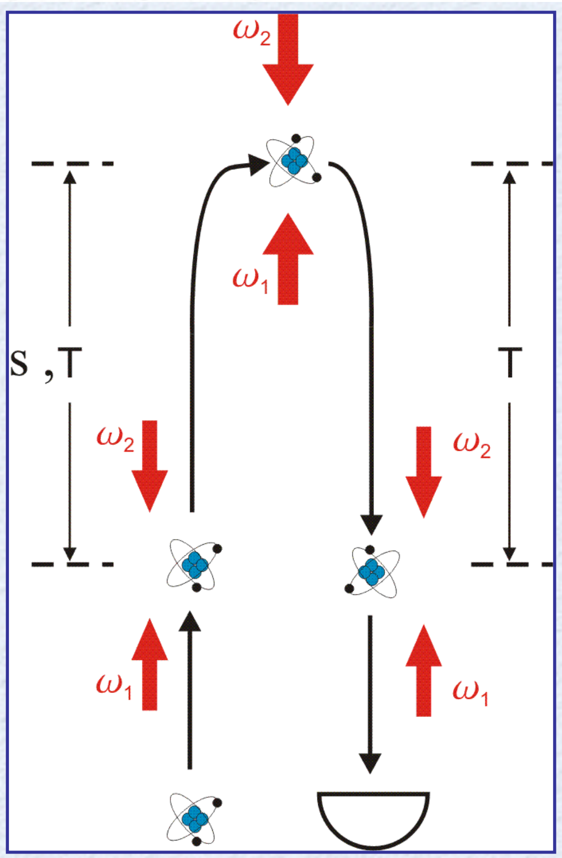
$$\Delta\Phi = k_c[z(0)]2z(T)] + \Phi_e$$

$$k_e = k_1 - k_2$$

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

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





Final population:

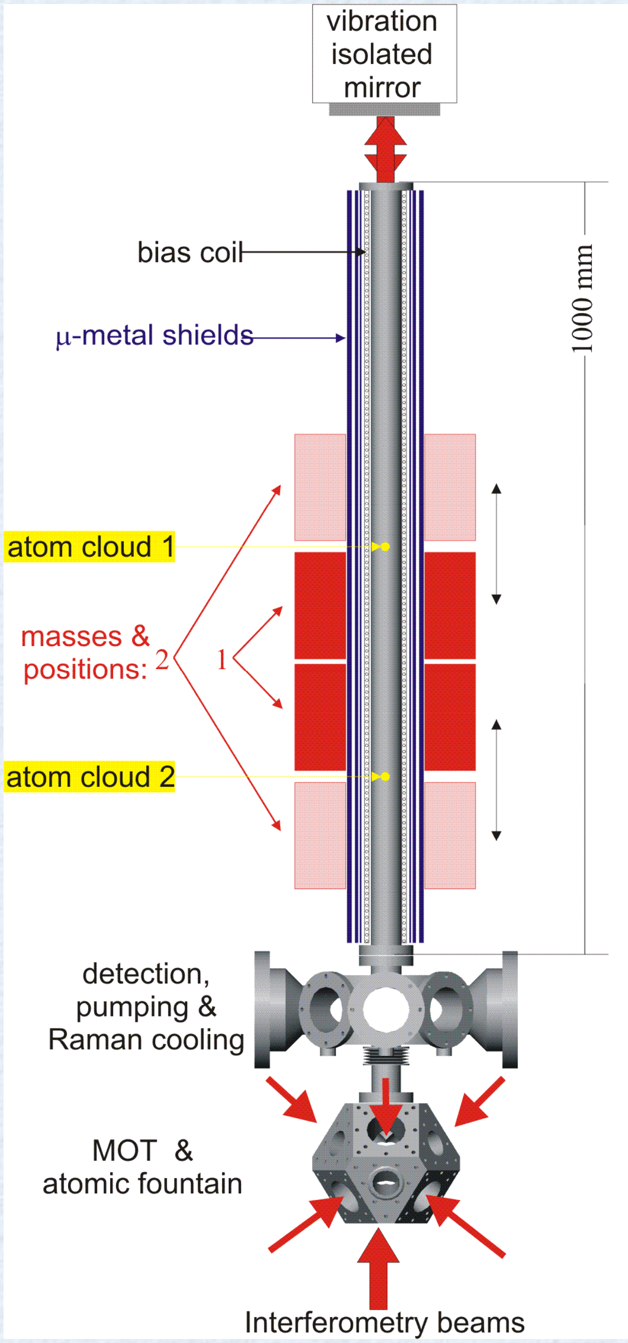
$$N_a = N/2(1 + cos[\Delta\Phi])$$

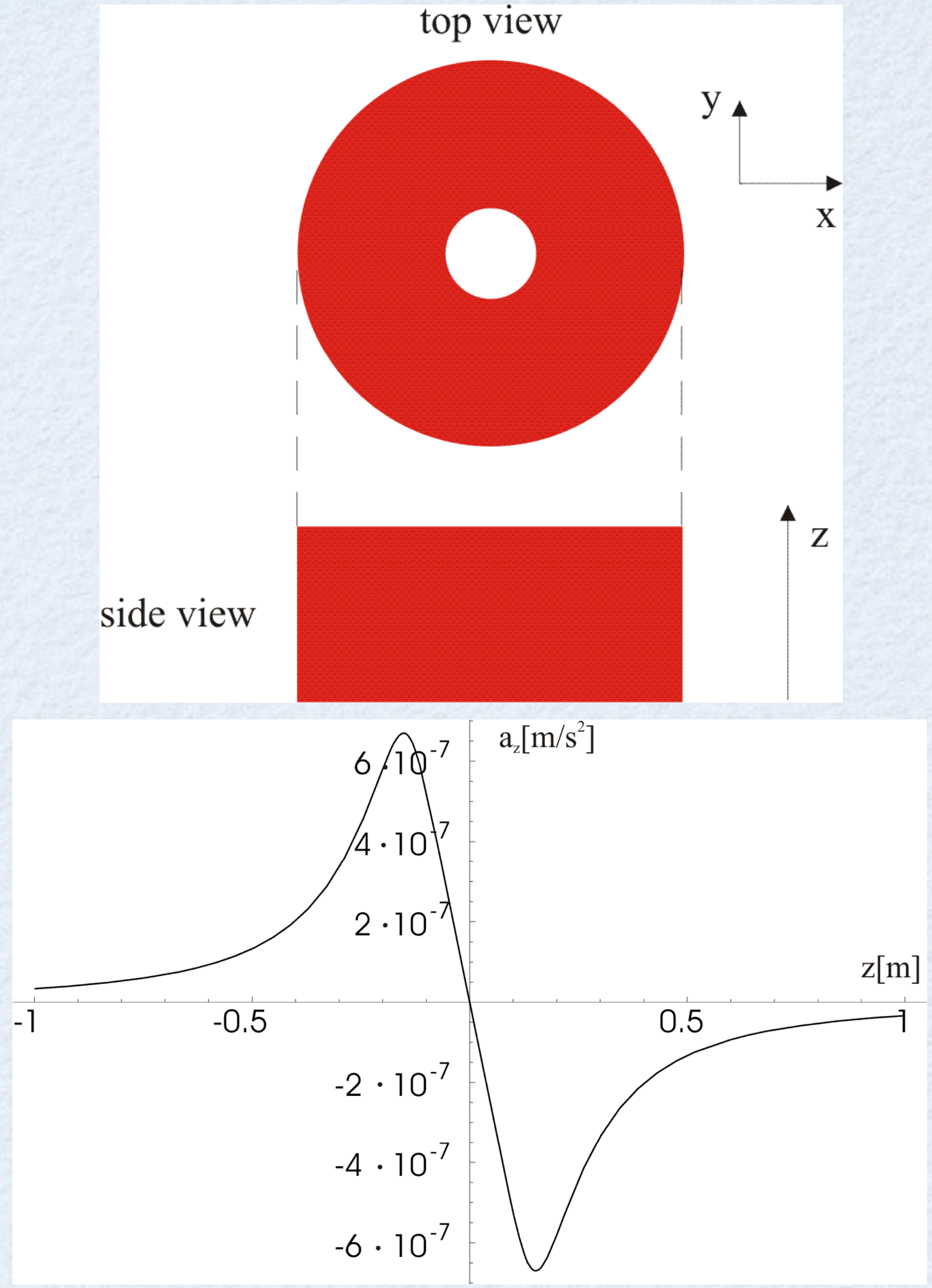
$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

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

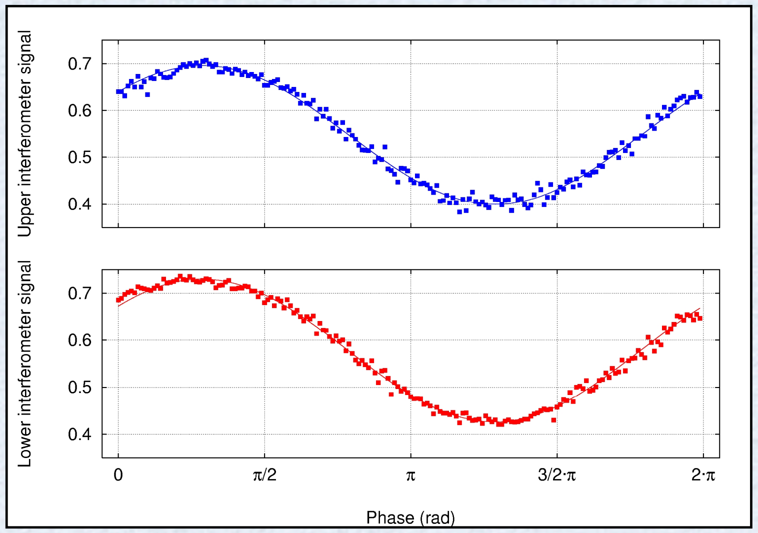
one shot $\rightarrow \Delta G/G \sim 10^{-2}$

500 Kg tungsten mass

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

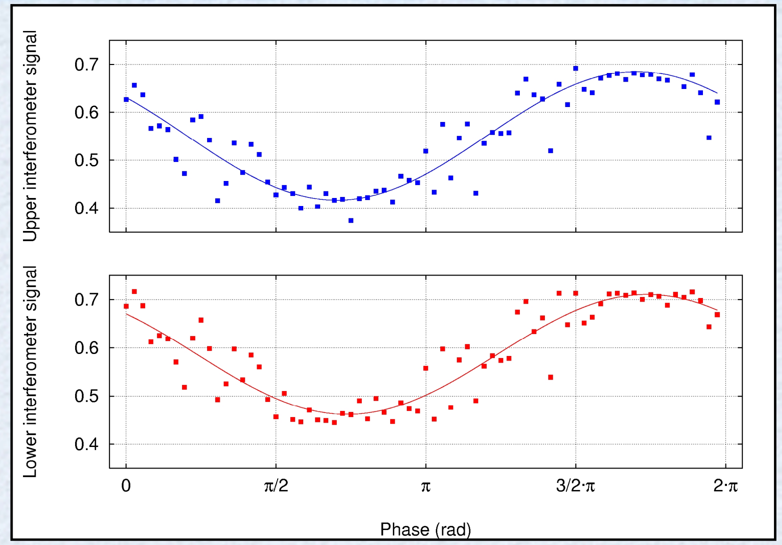
10000 shots $\rightarrow \Delta G/G \sim 10^{-4}$

Raman gravity gradiometer



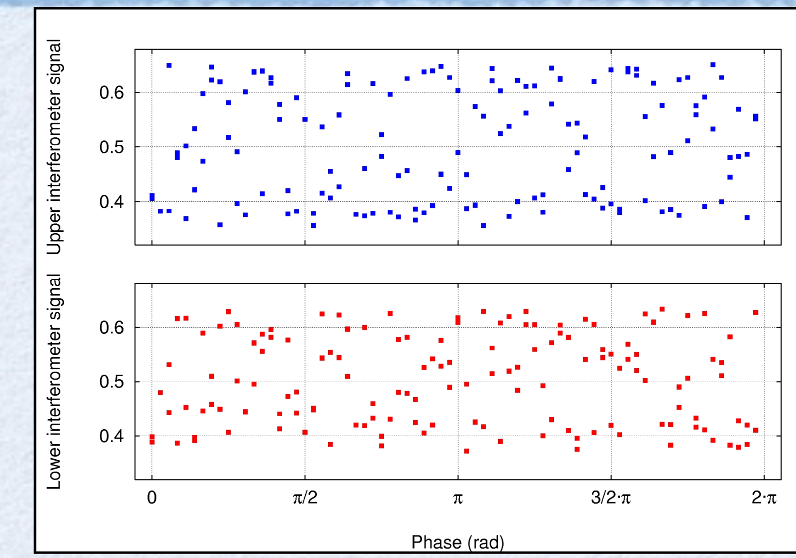
$T=5$ ms

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



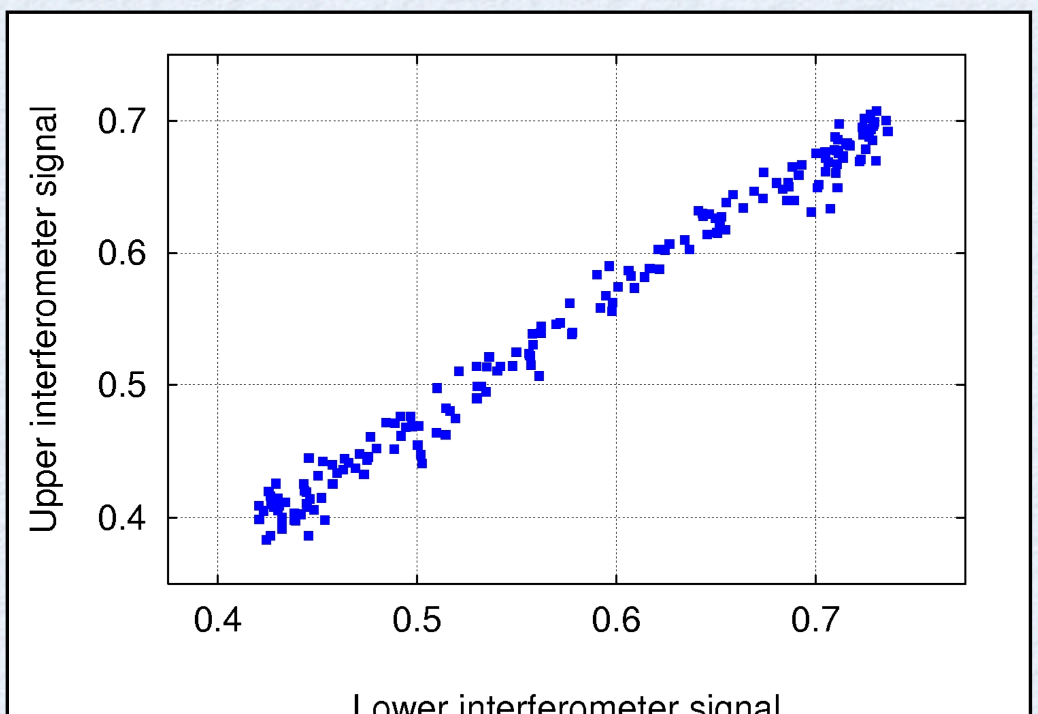
$T=50$ ms

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



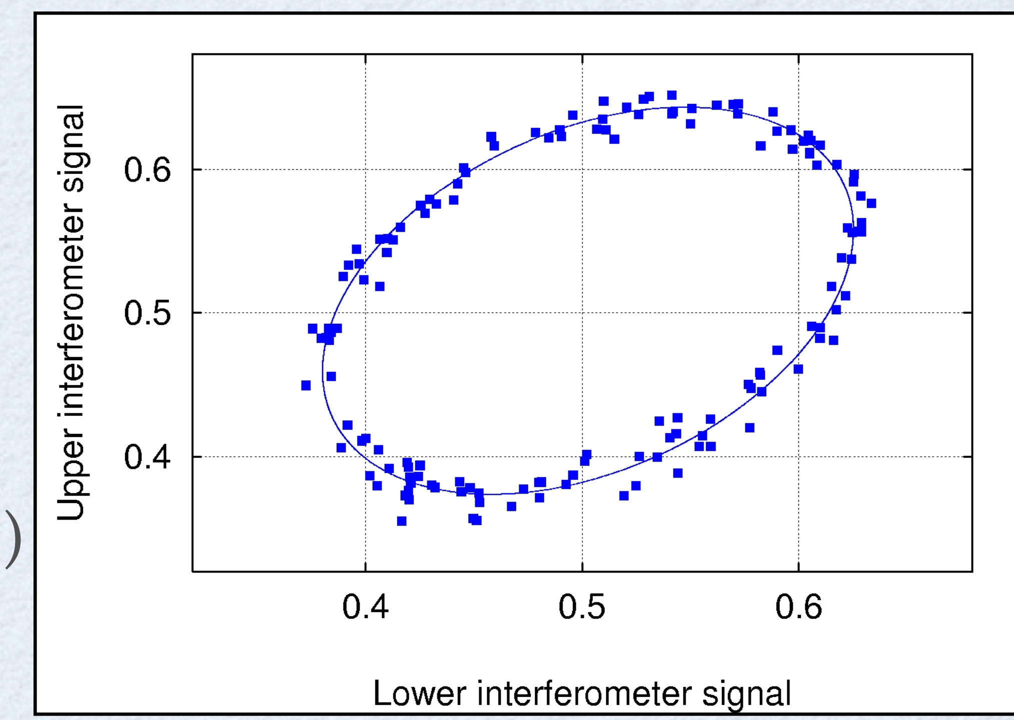
$T=150$ ms

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



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

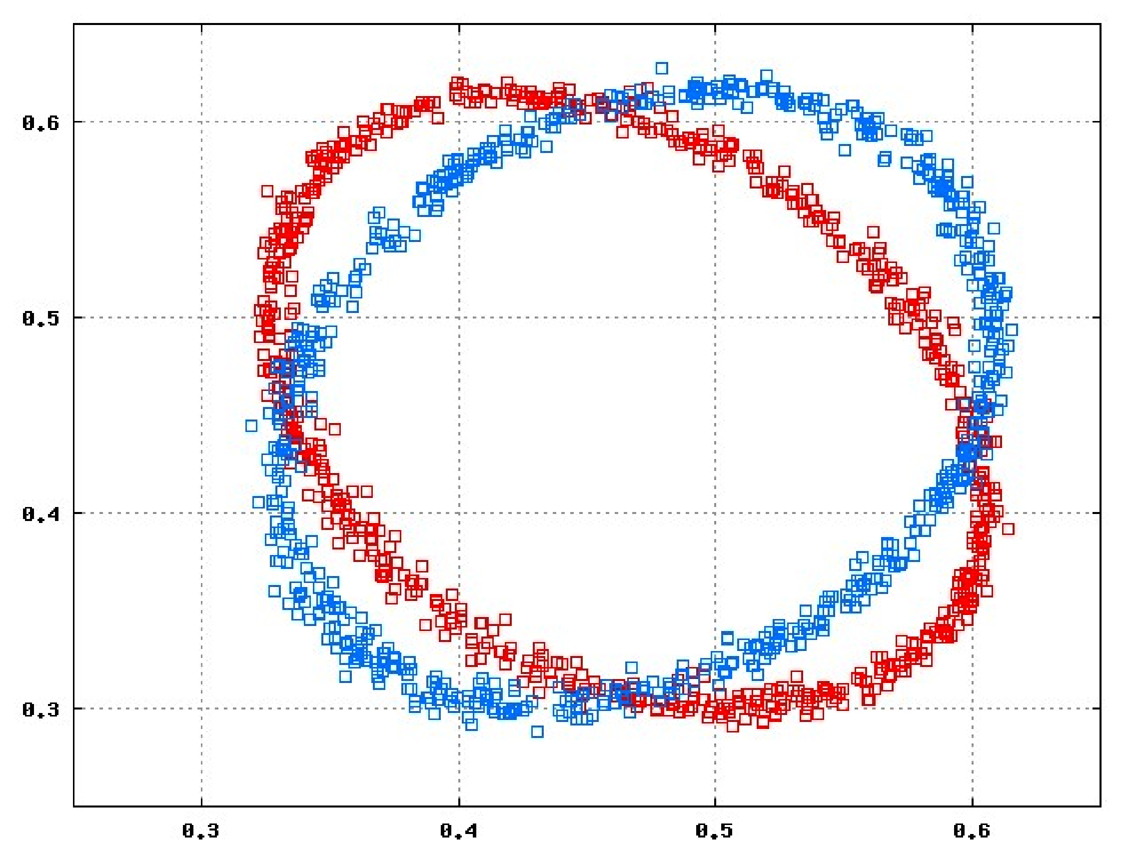
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

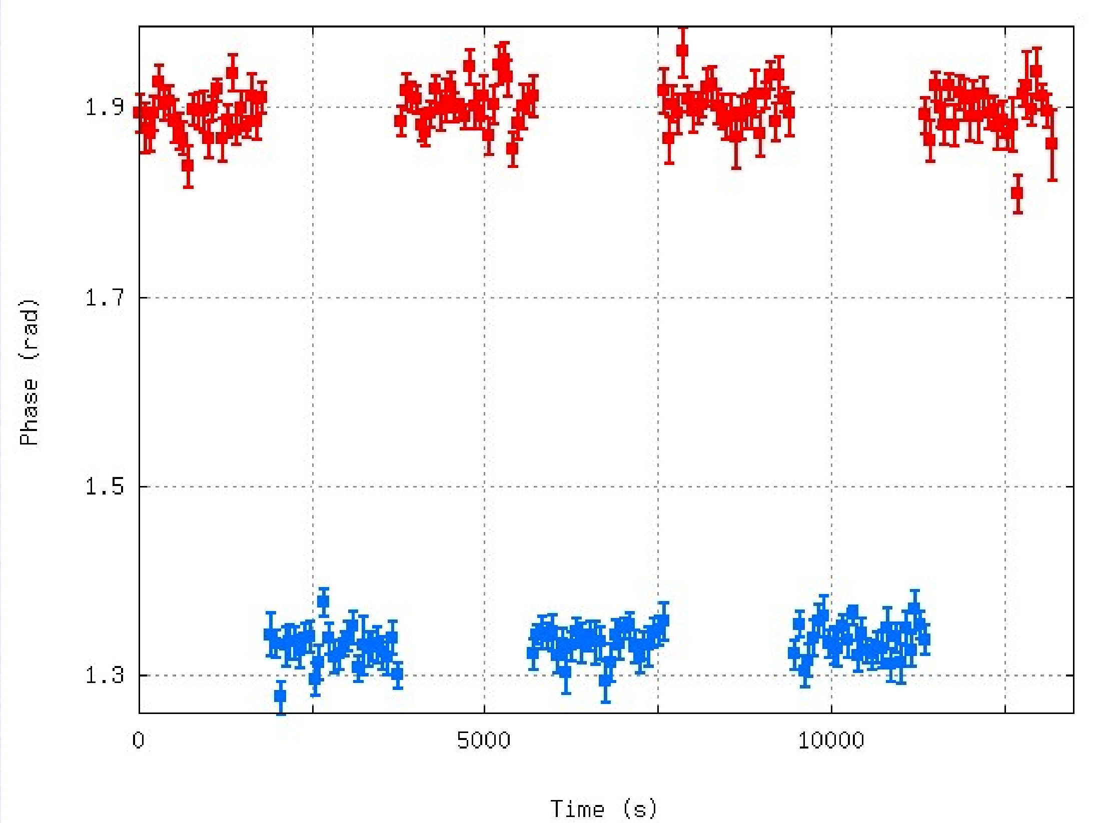


CMRR > 140 dB

J. M. McGuirk et al., Phys. Rev. A **65**, 033608 (2002)

MAGIA: first results

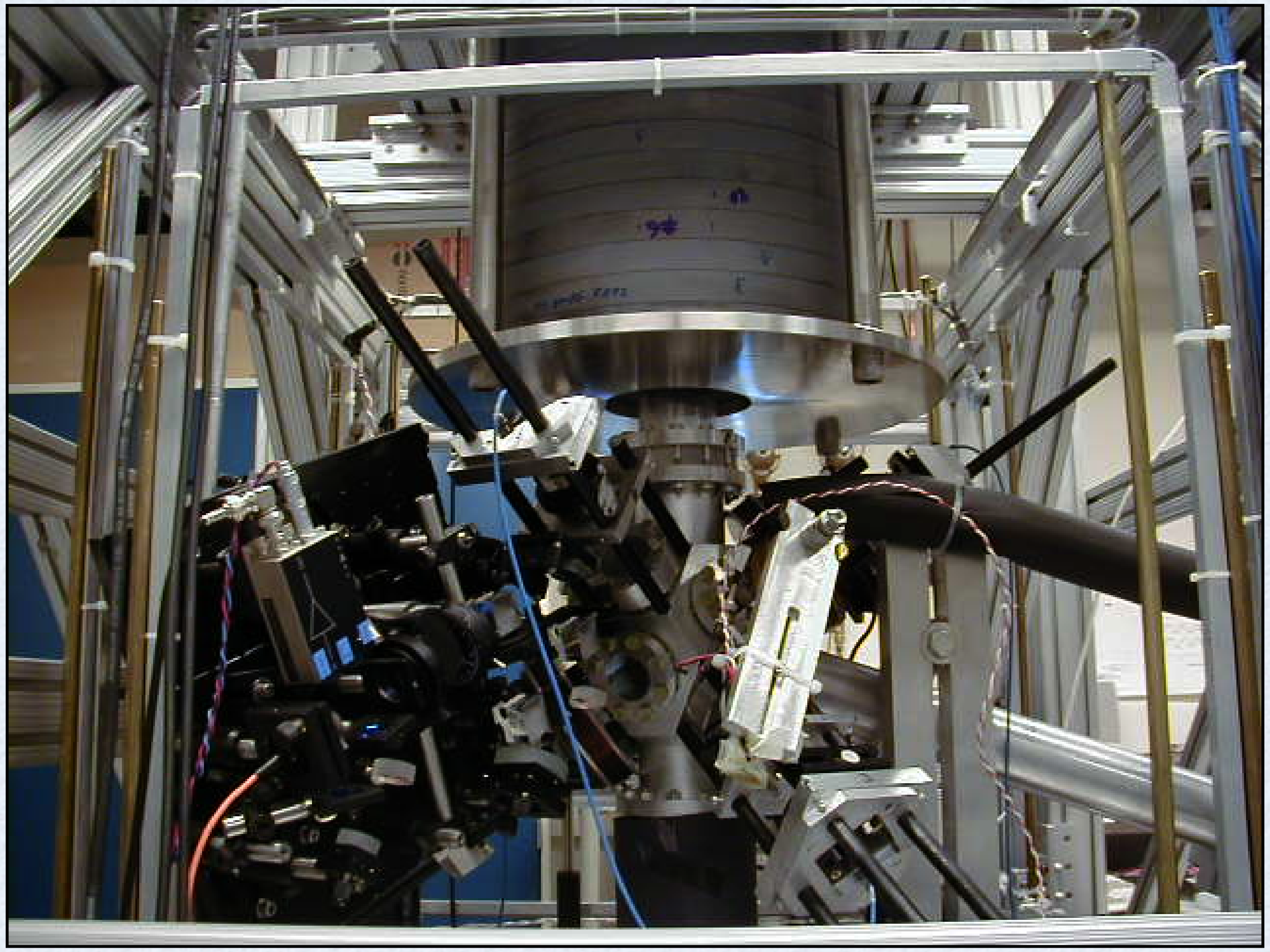


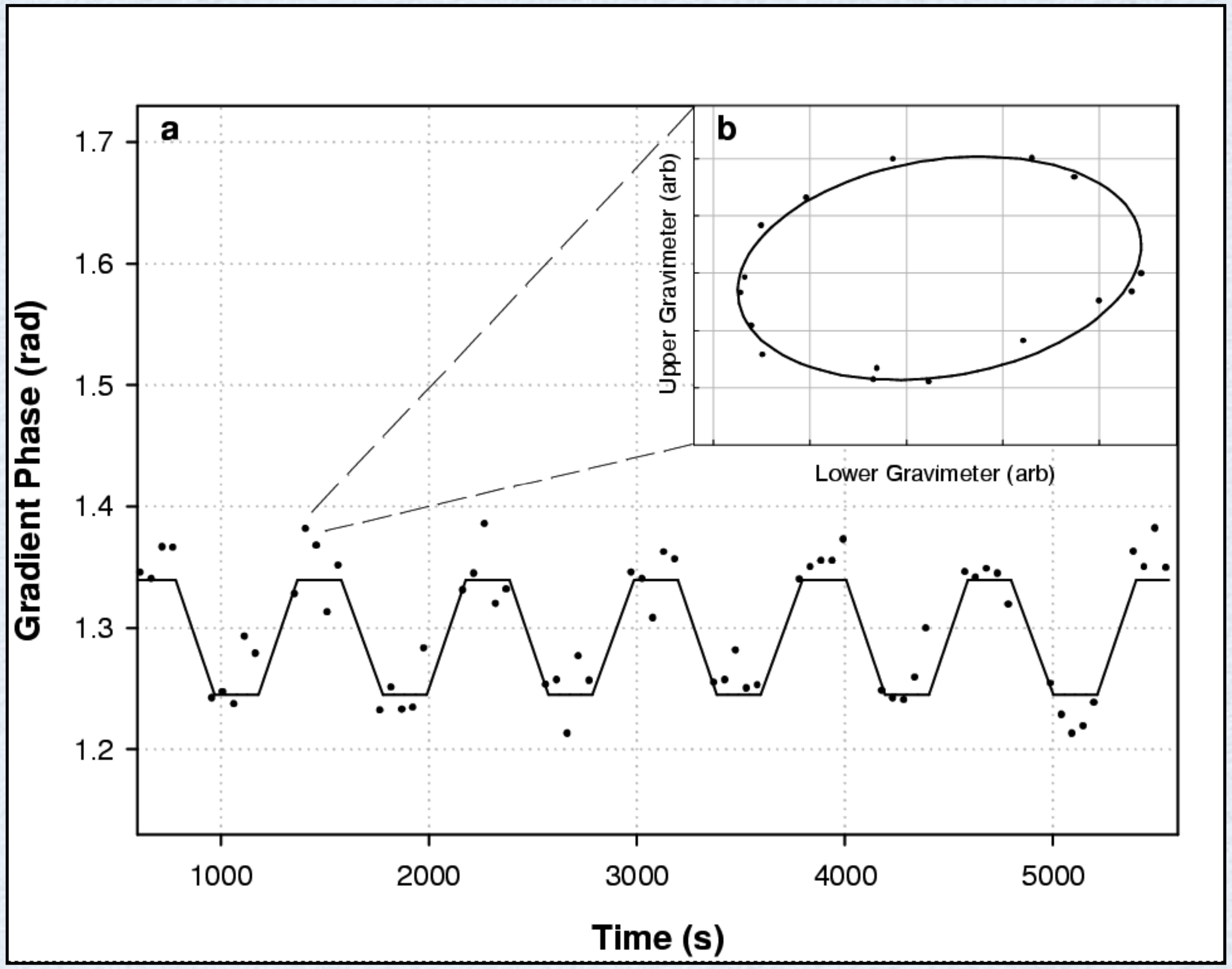


$$G = 6.667\ (11)\ (3)\ m^3\ kg^{-1}\ s^{-2}$$

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

G measurement at Stanford

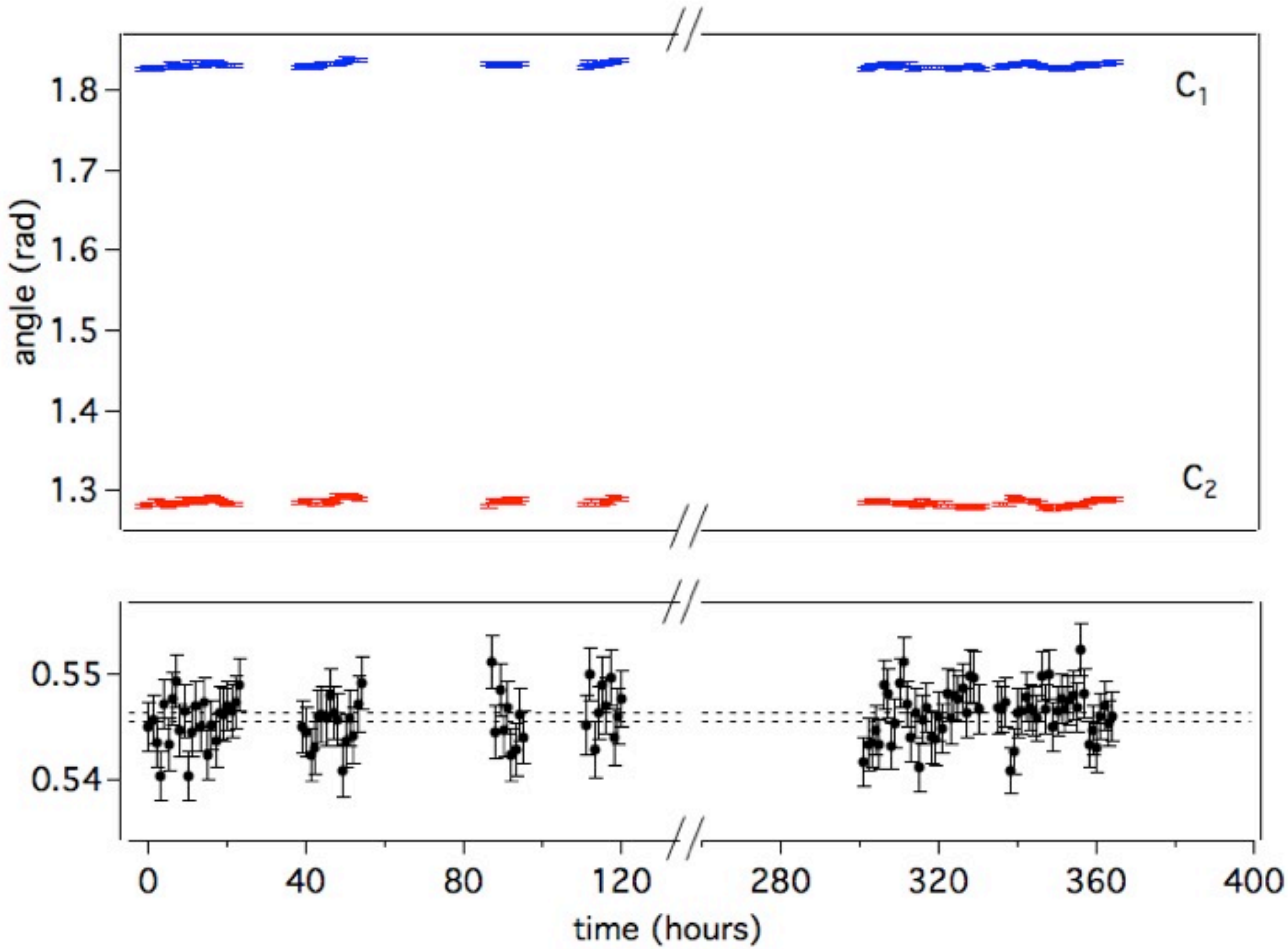




$G = 6.693\ (27)\ (21) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

J. B. Fixler, G. T. Foster, J. M. McGuirk and M. A. Kasevich, *Atom Interferometer Measurement of the Newtonian Constant of Gravity*, Science **315**, 74 (2007)

Interim progress

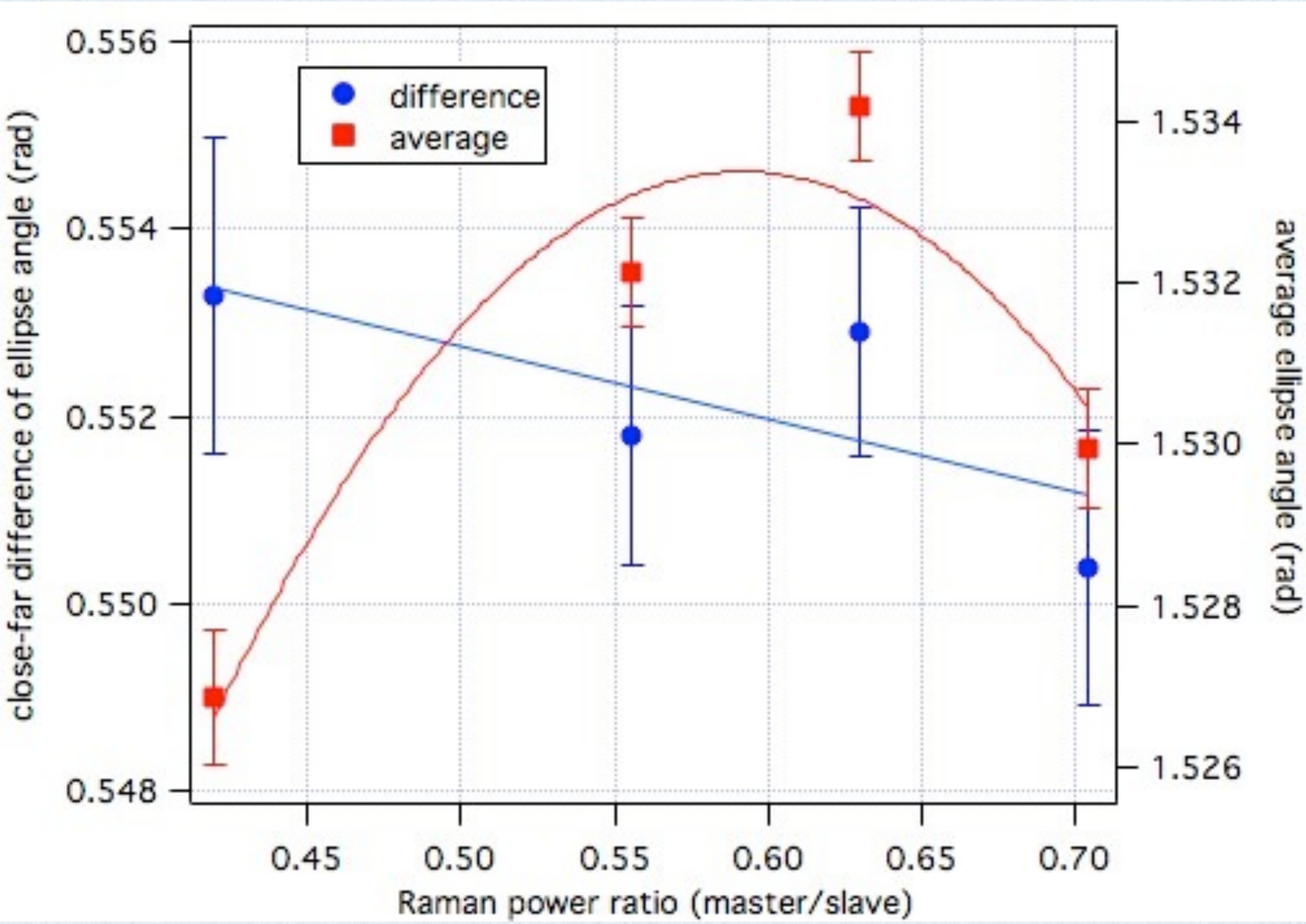


$$\Phi = 0.54597 \pm 0.00022 \text{ rad}$$

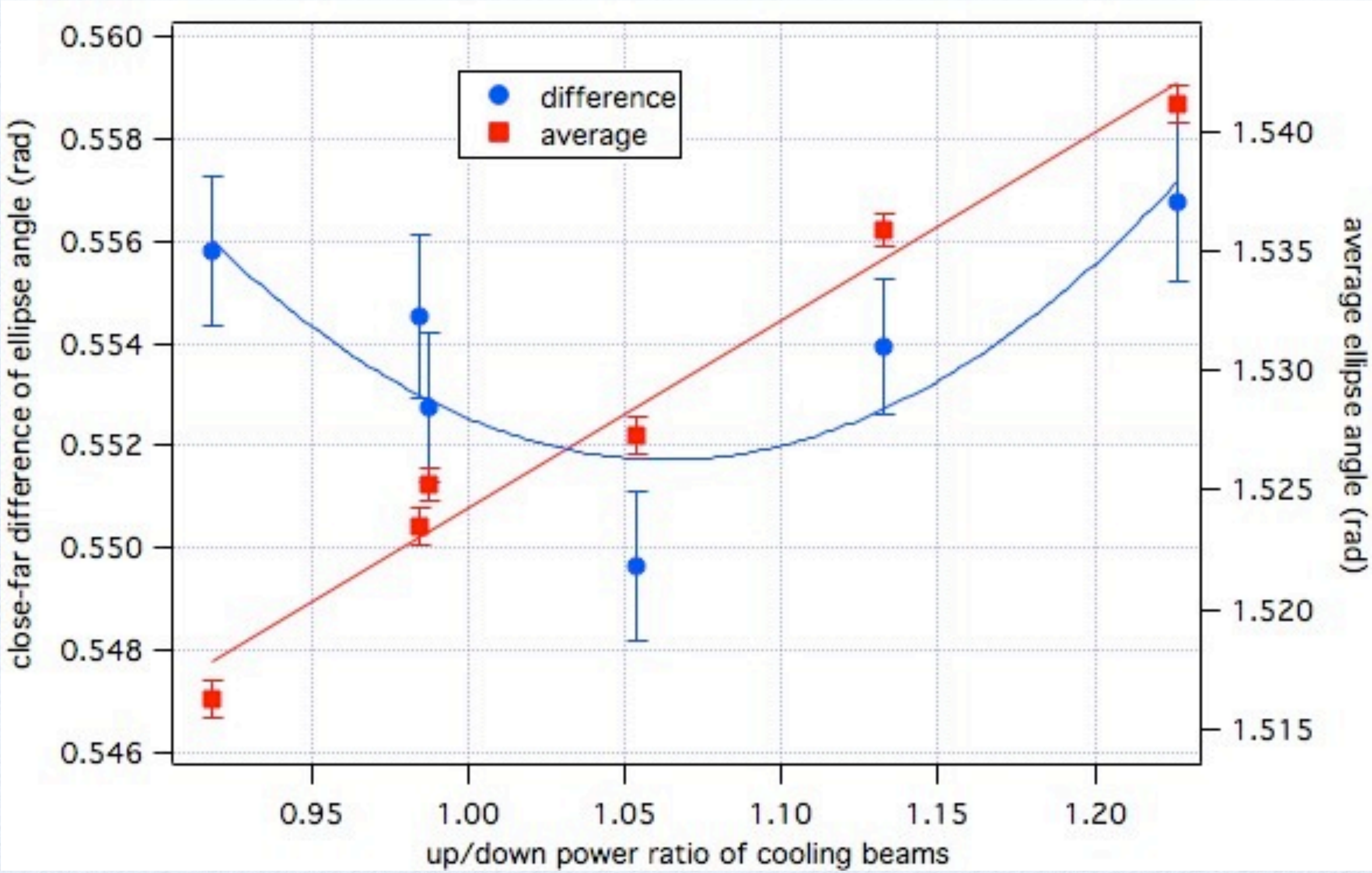
Corresponding to a statistical uncertainty of 400 ppm on G

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

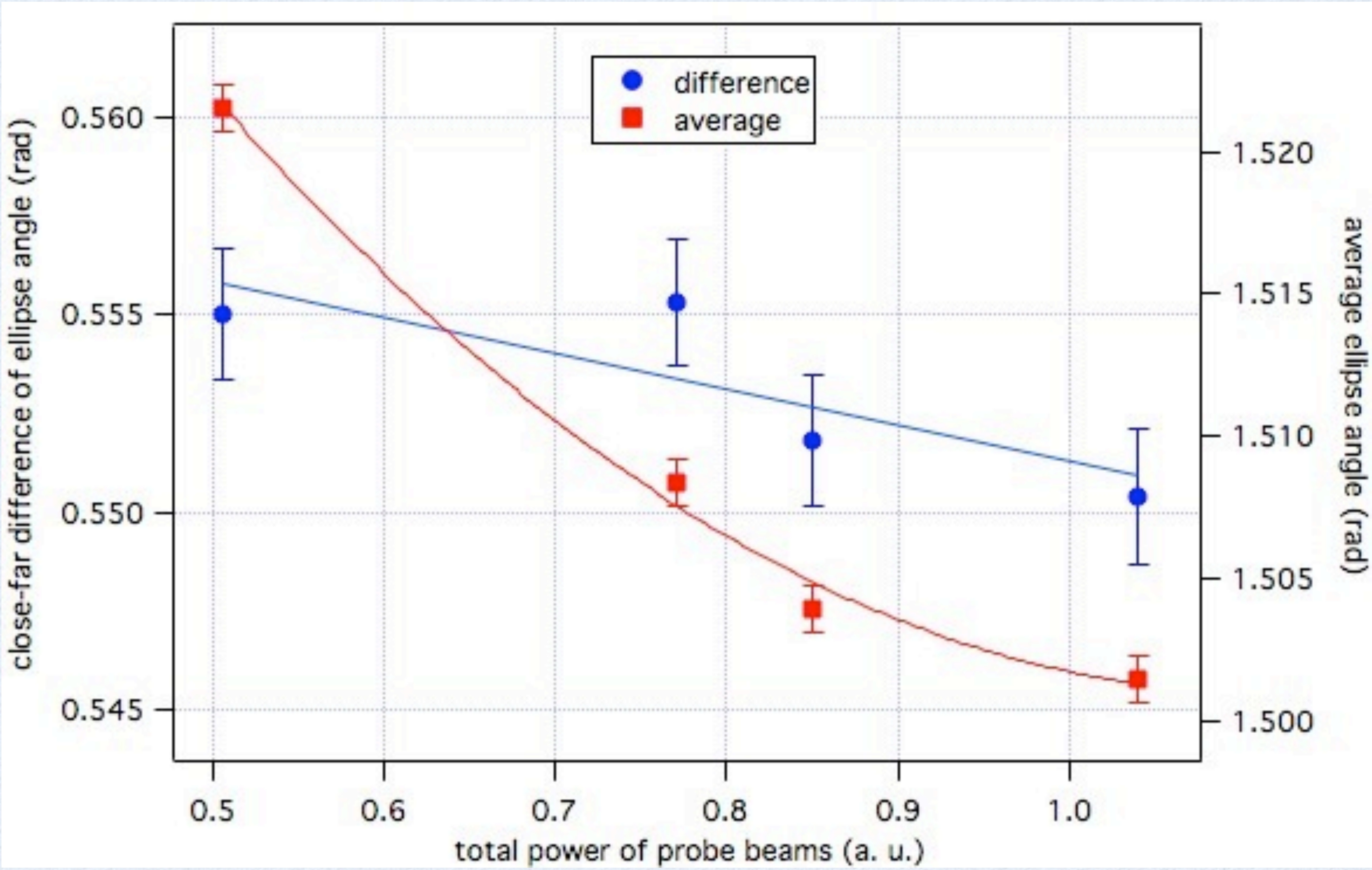
Sensitivity to experimental parameters



Sensitivity to experimental parameters

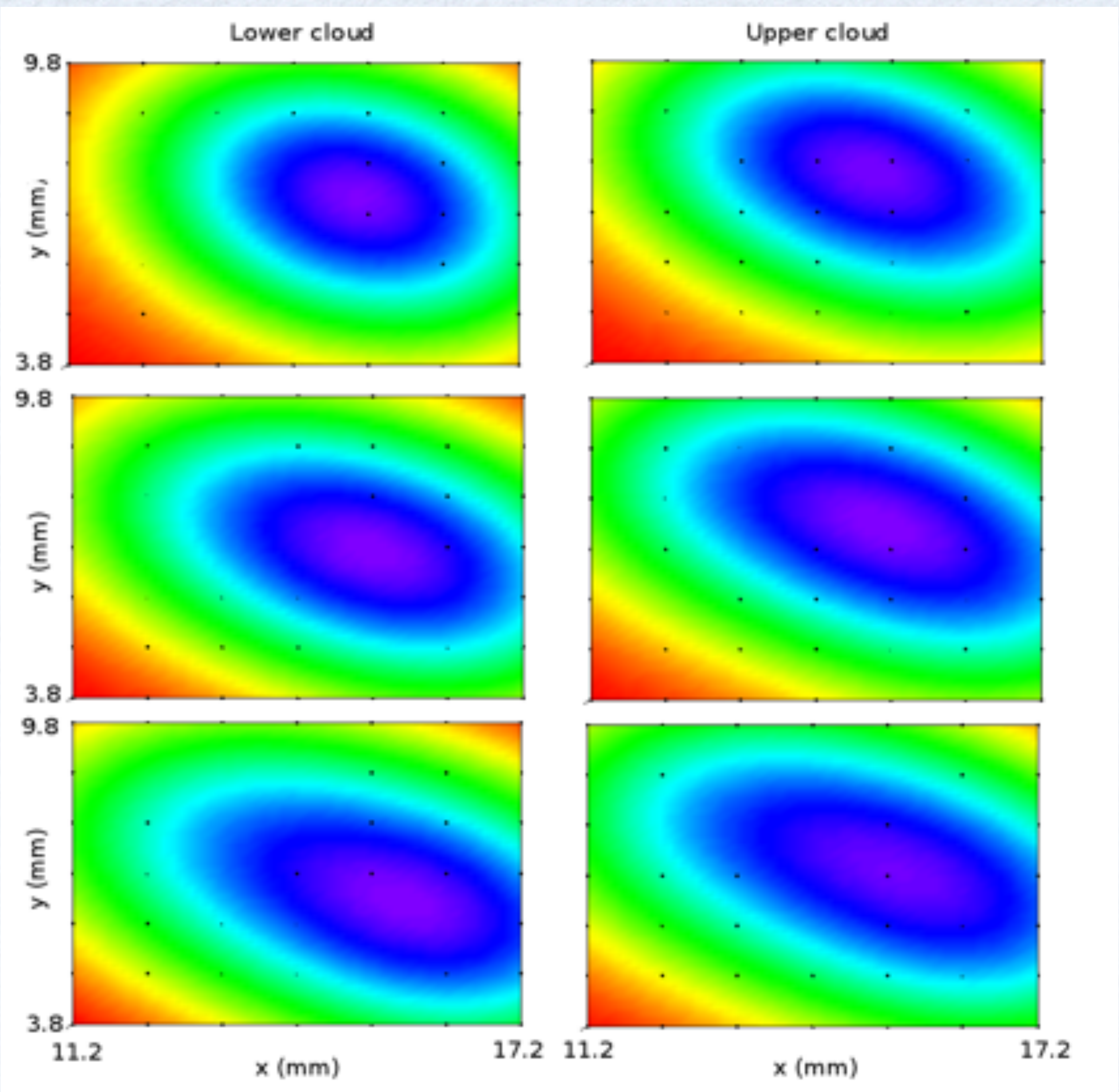


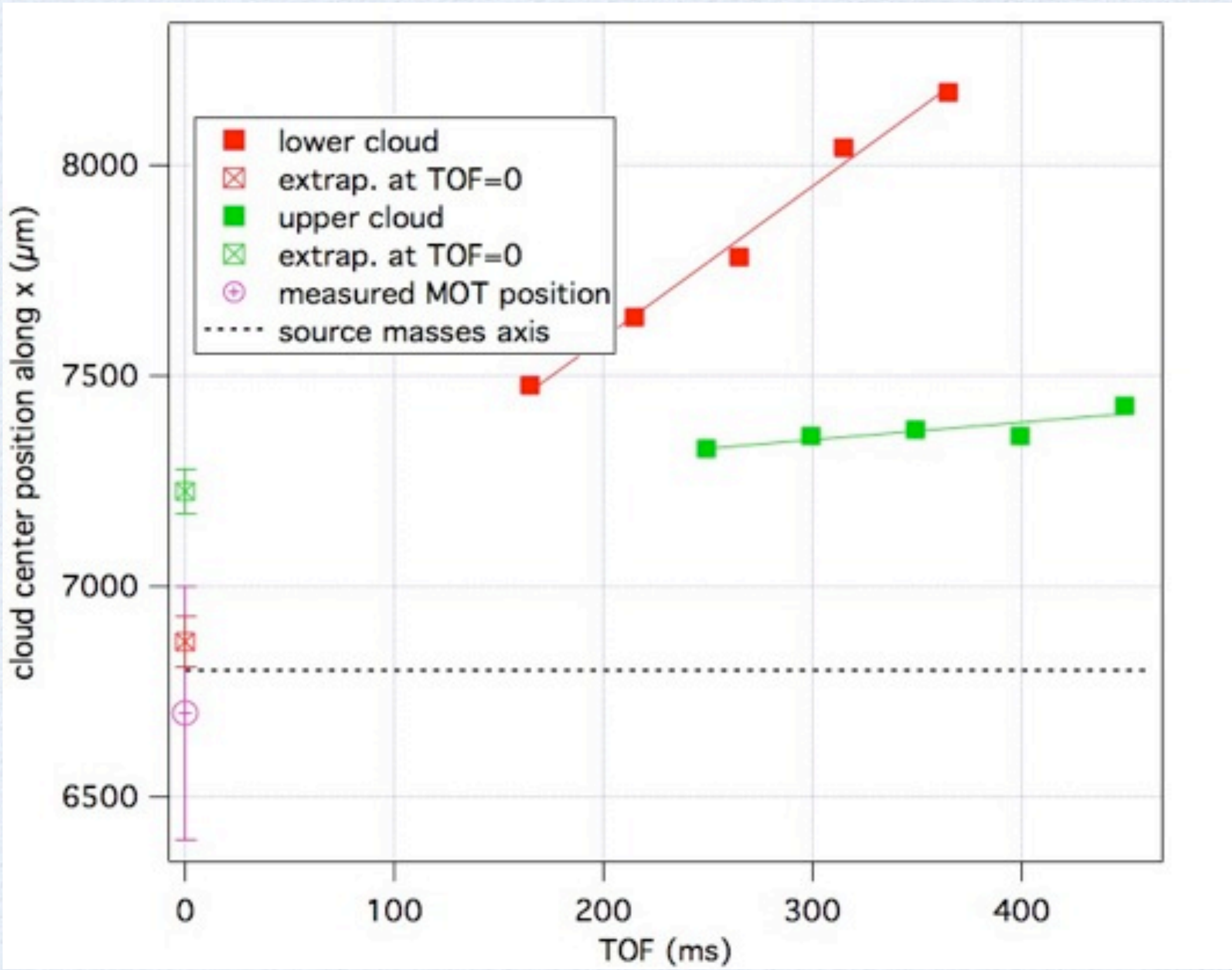
Sensitivity to experimental parameters



Atomic trajectories

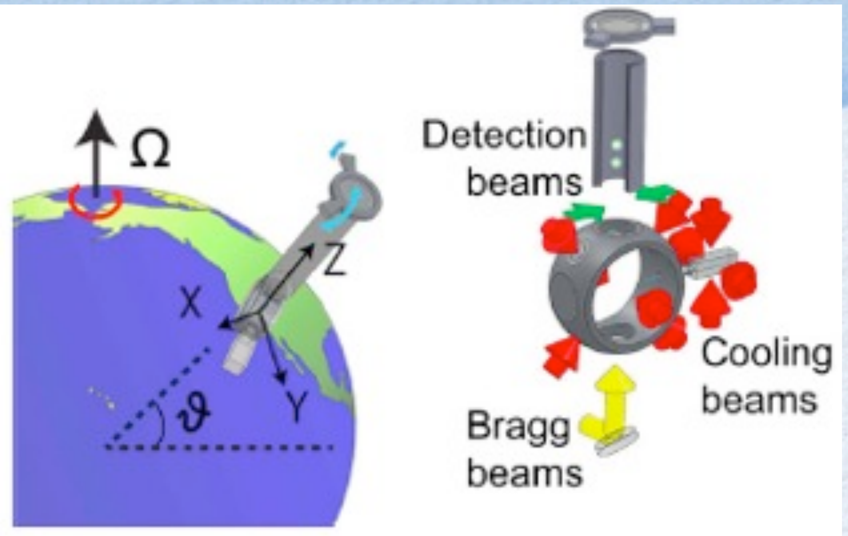
- Density distribution of clouds know within 0.1 mm from TOF
- Transverse velocities are found in the range of a few mm/s
- These are due to small tilt (~1 mrad) of the atomic fountain
- Corresponding AI phase shift due to Coriolis acceleration ~40 mrad, i. e. 10^{-9} g
- For a Coriolis shift below 10^{-4} on *G*, launching direction should change less than 2 μrad on average when moving the sources masses



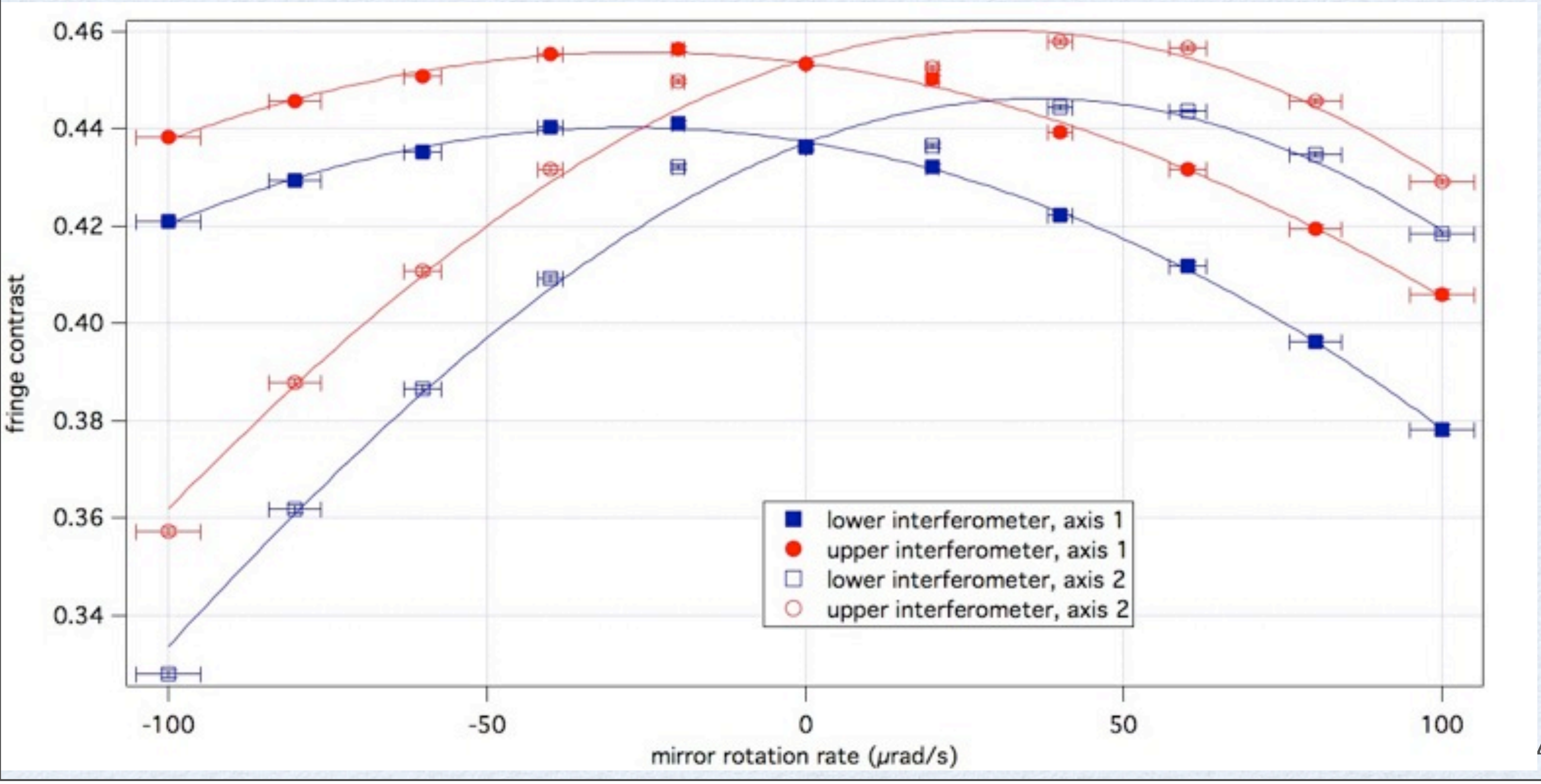


Coriolis compensation (I)

- Tip-tilt mirror steering the retro-reflected Raman beam to compensate for the Earth rotation
- Already shown to improve contrast in AI with LMT beam splitters
- In MAGIA, contrast drop due to Coriolis is minimal, but still detectable thanks to the large SNR



J. M. Hogan et al., Proc. intern. school of physics Enrico Fermi **CLXVIII**, 411 (2007)
S.-Y. Lan et al., PRL **108**, 090402 (2012)



AGIA experiment...

Coriolis compensation (II)

- If we reduce the frame rotation by a factor 10 with a tip-tilt Raman retro-reflecting mirror, we still 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
- In MAGIA we measure transverse velocity components with a precision of a few μm/s
- When comparing for the two configurations of source masses, we determine C/F transverse velocity changes to be lower than 6 μm/s
- Sensitivity to transverse velocity differences scales with T^2: in Q-WEP or STE-QUEST it can easily get down to ~10nm/s

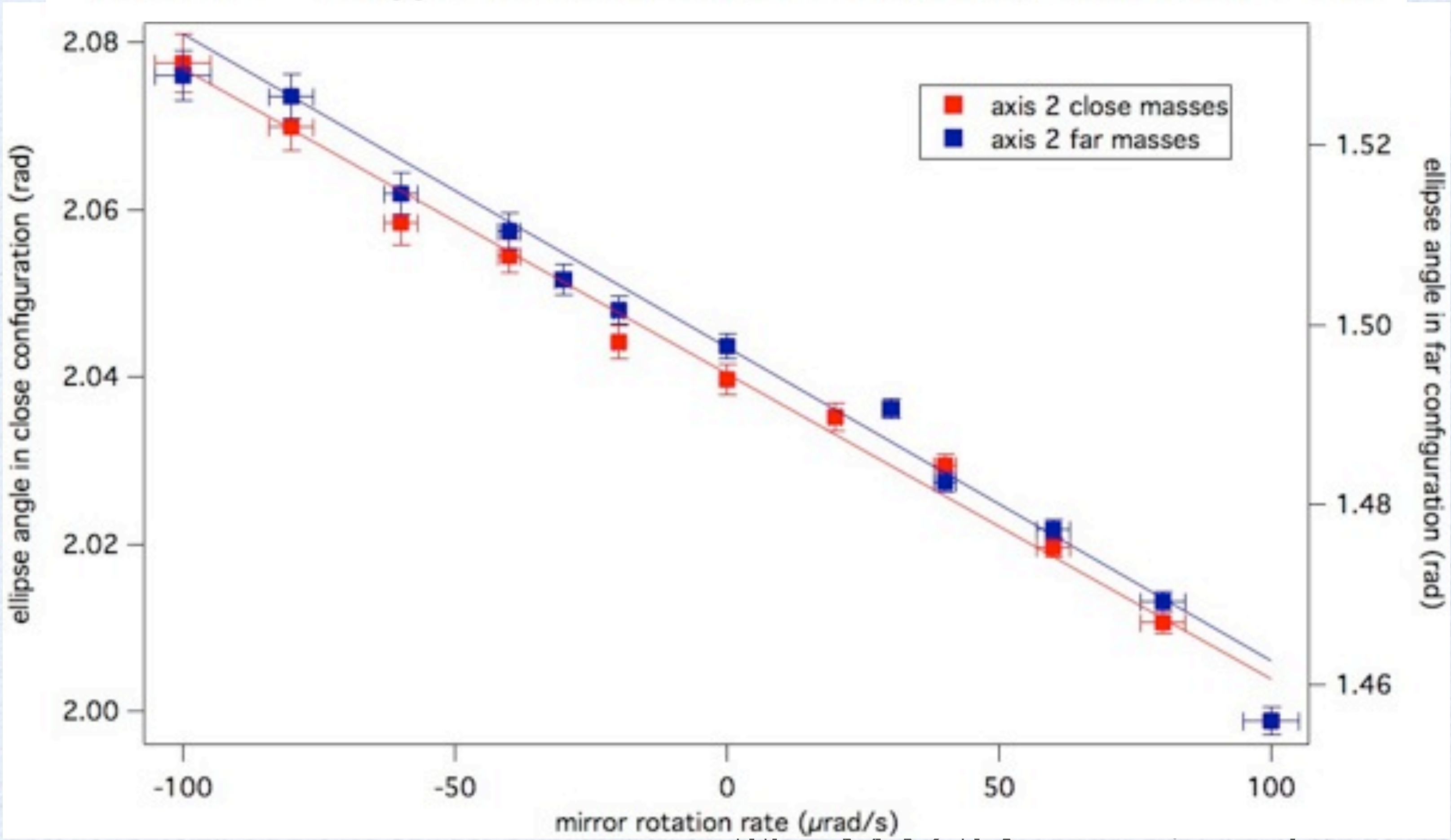
$$\phi_{Coriol} = -2k_{eff}T^2(\Omega_{m1}\Delta v_\perp \cos\beta + \Omega_E \cos\gamma \Delta v_\perp \cos(\alpha+\beta))$$

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

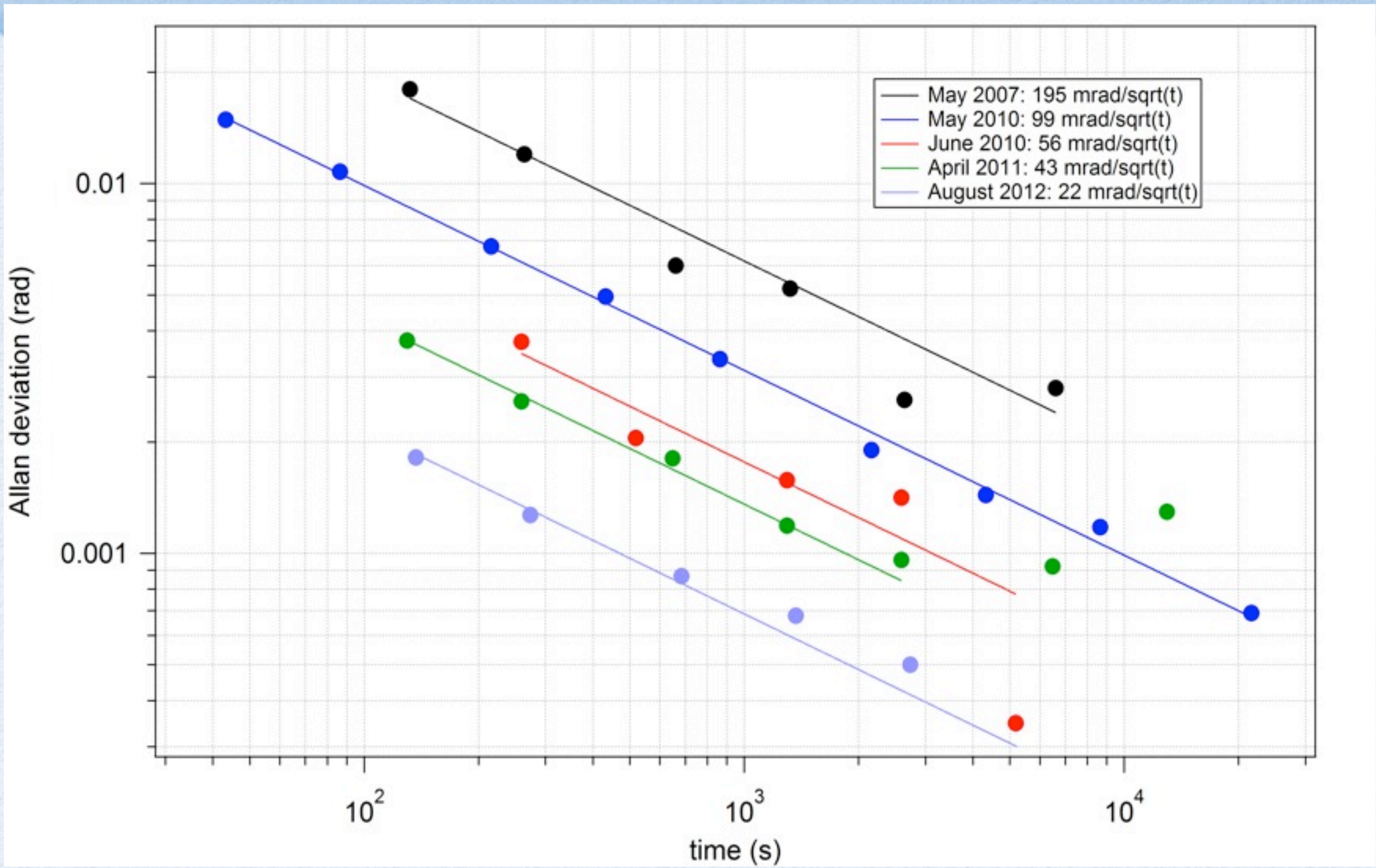
$\Delta\Phi$ = (542.63 +/- 0.2) mrad (non comp)

difference < 0.28 mrad

=> Δv_{E-O} < 6 µm/s



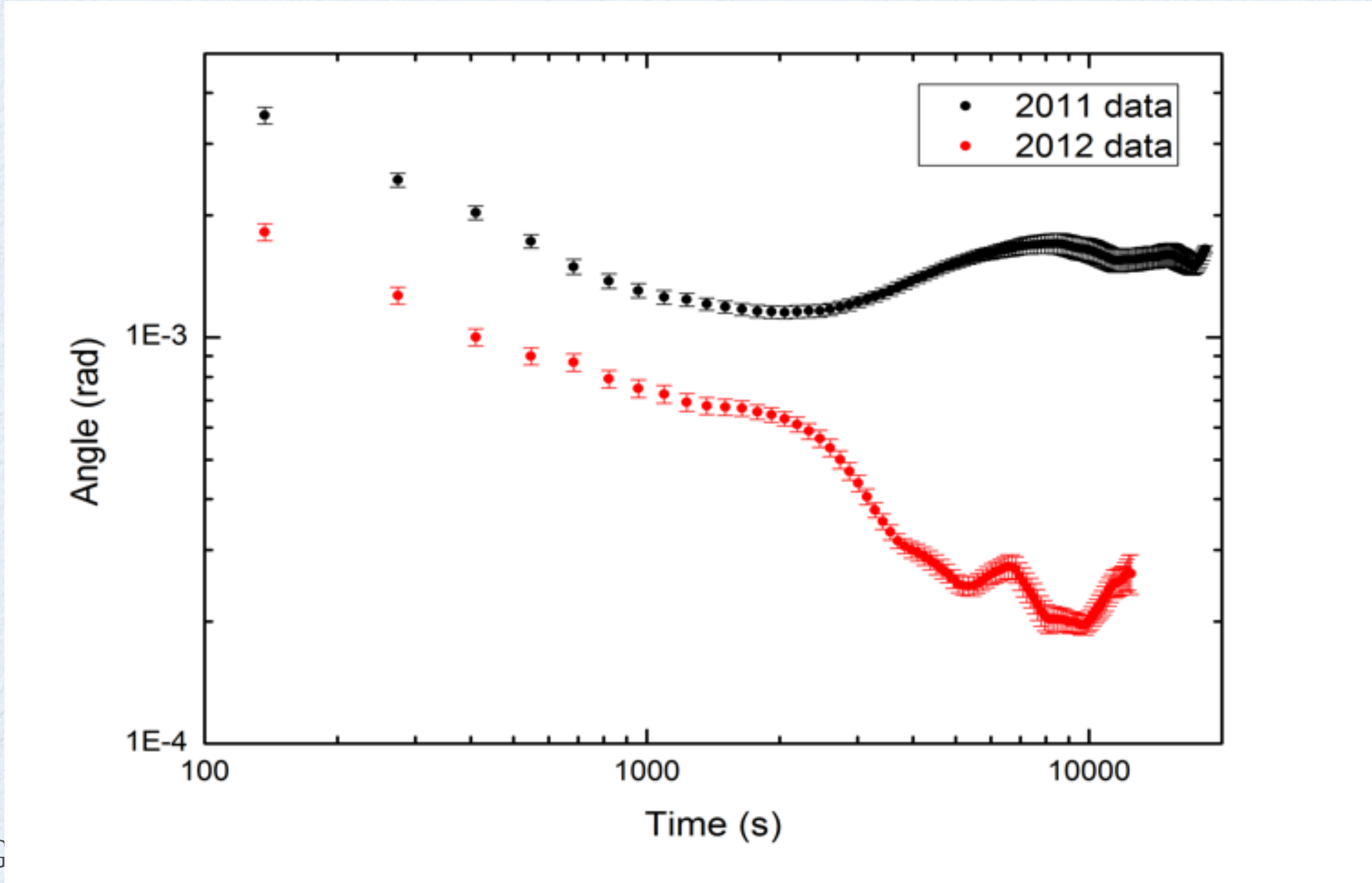
Short-term sensitivity



Current sensitivity to differential acceleration: $5x10^{-9}$ g @ 1s
corresponding to the QPN limit for $2x10^5$ atoms

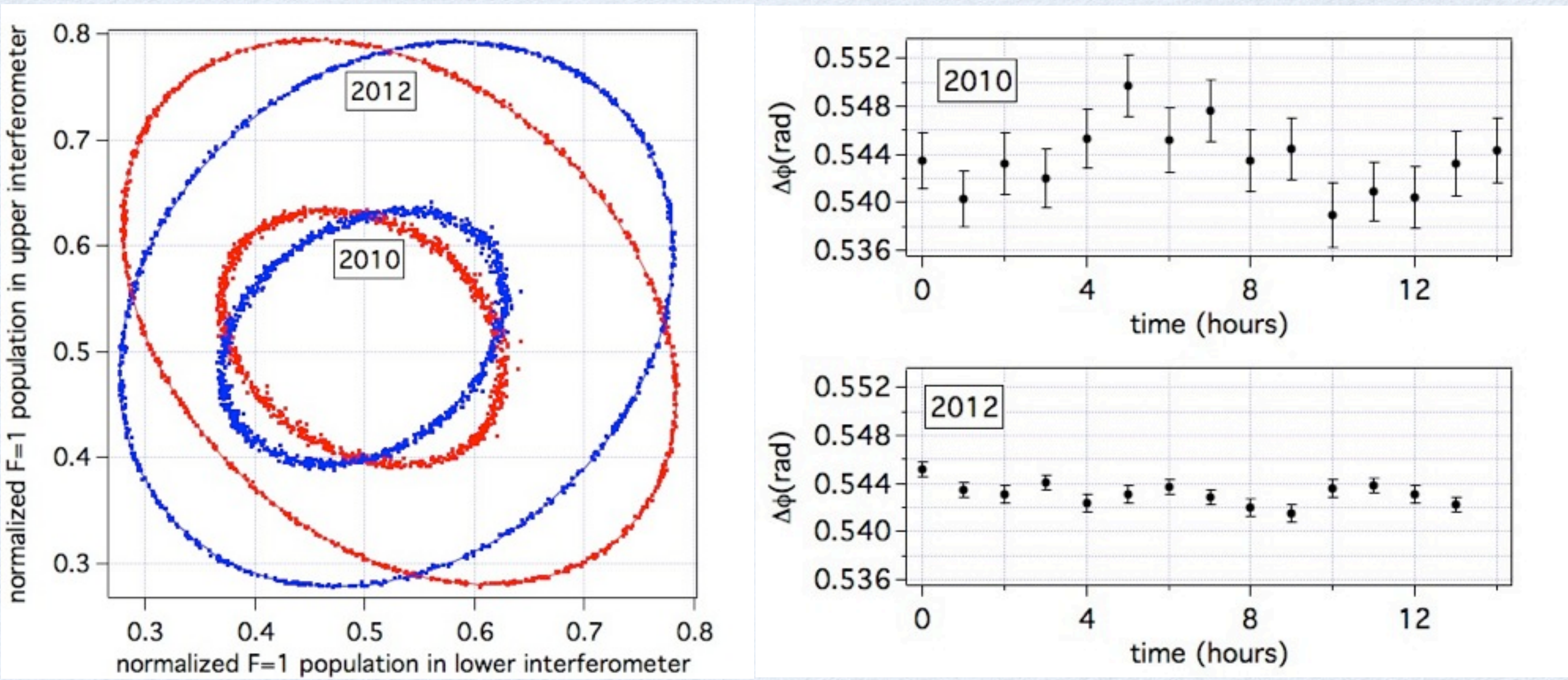
Long term sensitivity

- Active intensity control of cooling and probe laser beams; tilt stabilization of Raman retro-reflecting mirror
- Coriolis compensation with tip-tilt mirror
- Allan variance on gravity gradient measurement ~0.2 mrad @ 10000 s, corresponding to 5×10^{-11} g (5x improvement from 2011)

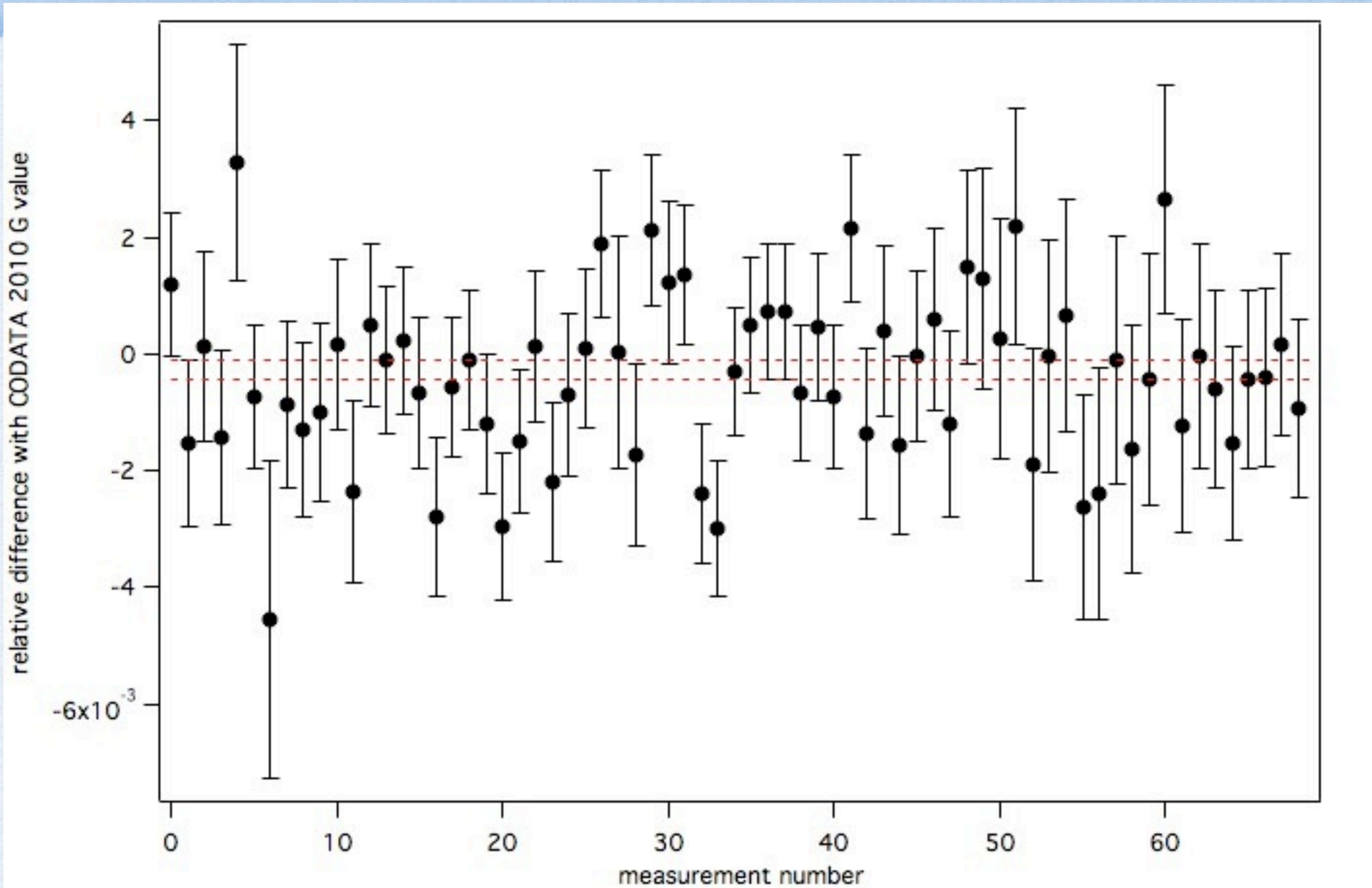


MAGIA: recent progresses

- 2010
  - differential acceleration sensitivity: **$2*10^{-8}$ g /√Hz**
  - sensitivity in G measurement: **400 ppm in 120 hrs**
- 2012
  - differential acceleration sensitivity: **$5*10^{-9}$ g /√Hz**
  - sensitivity in G measurement: **300 ppm in 12 hrs**

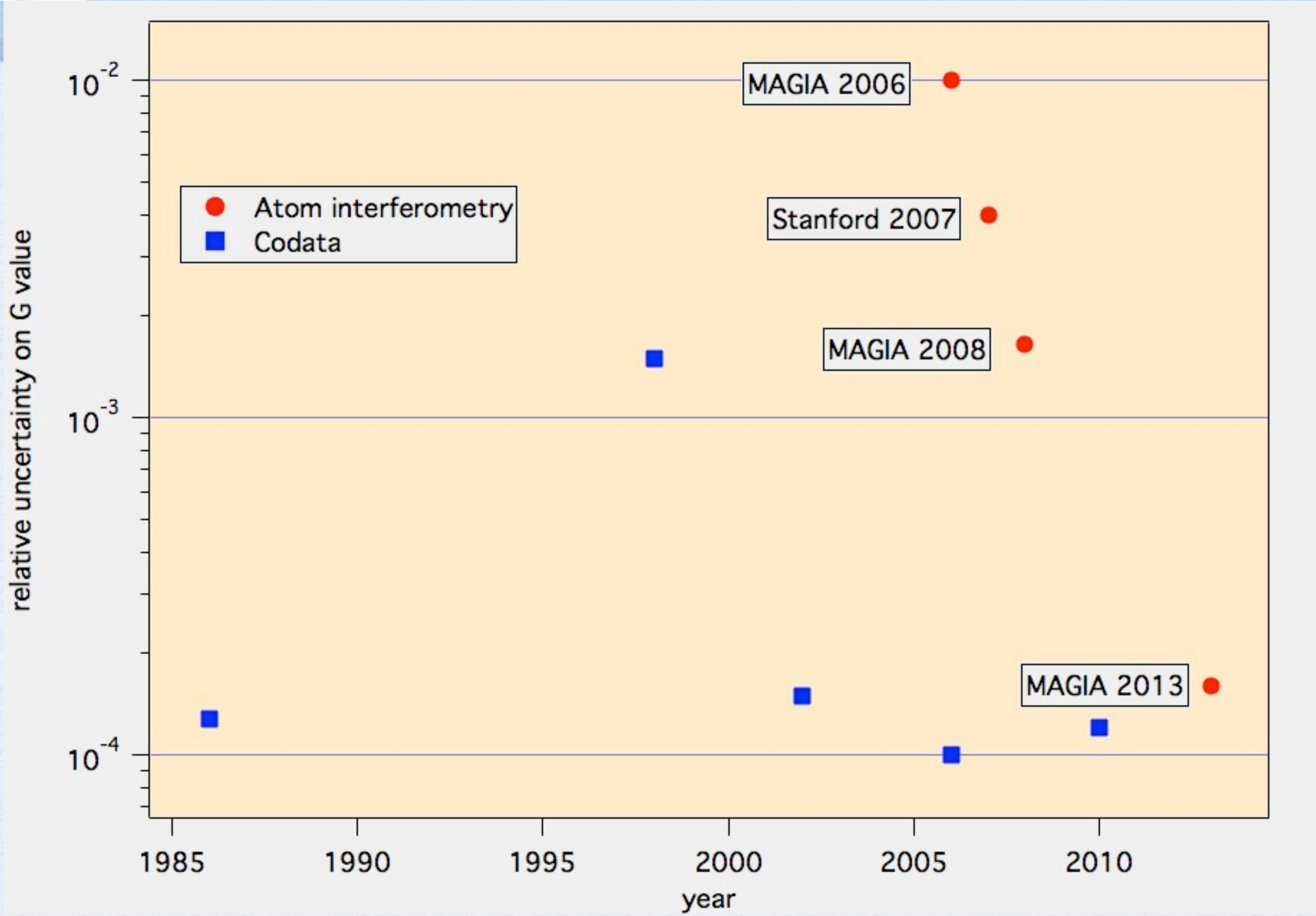


G measurement (preliminary)

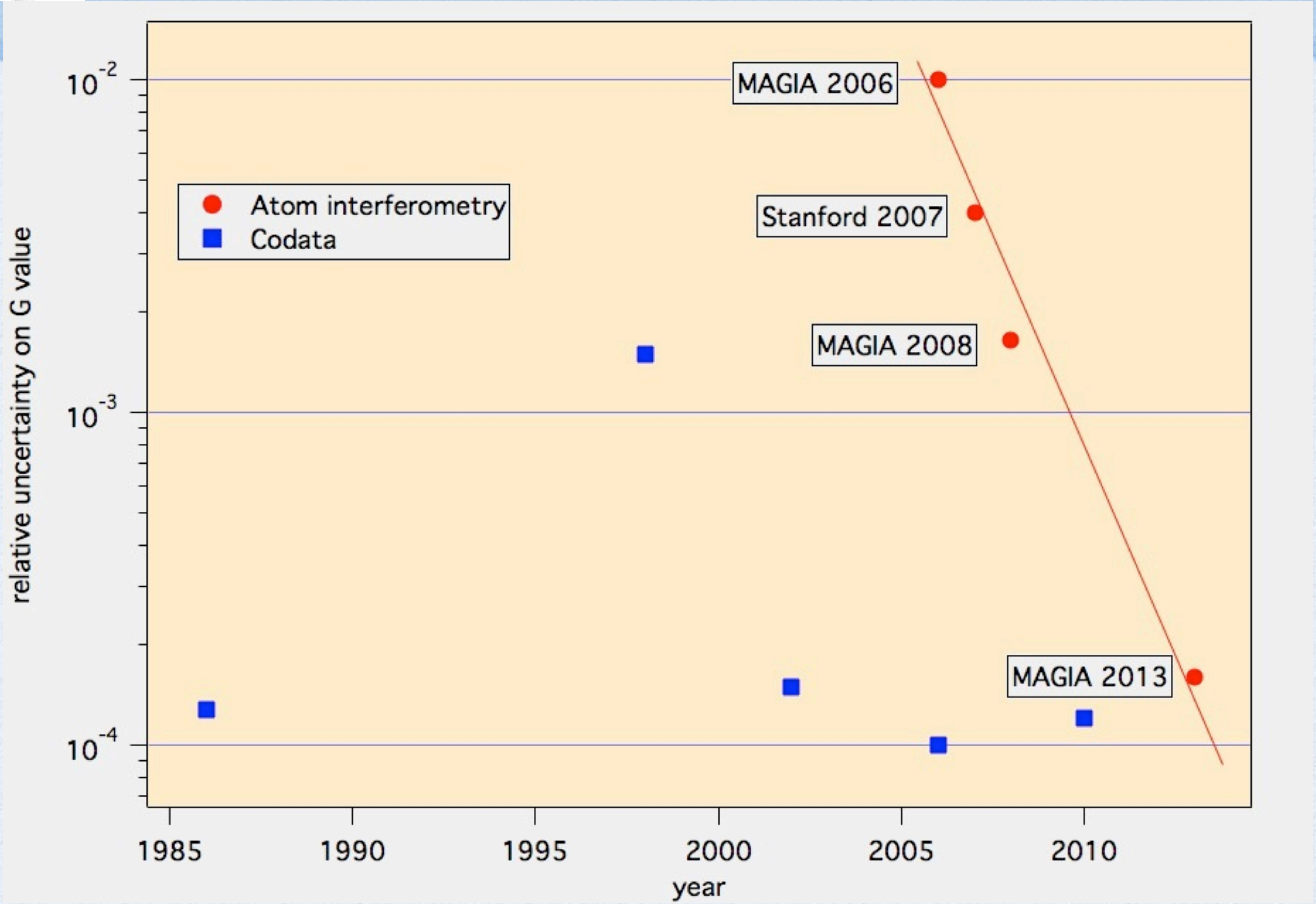


Statistical error 1.6 x10^{-4}

G measurement with atomic sensors

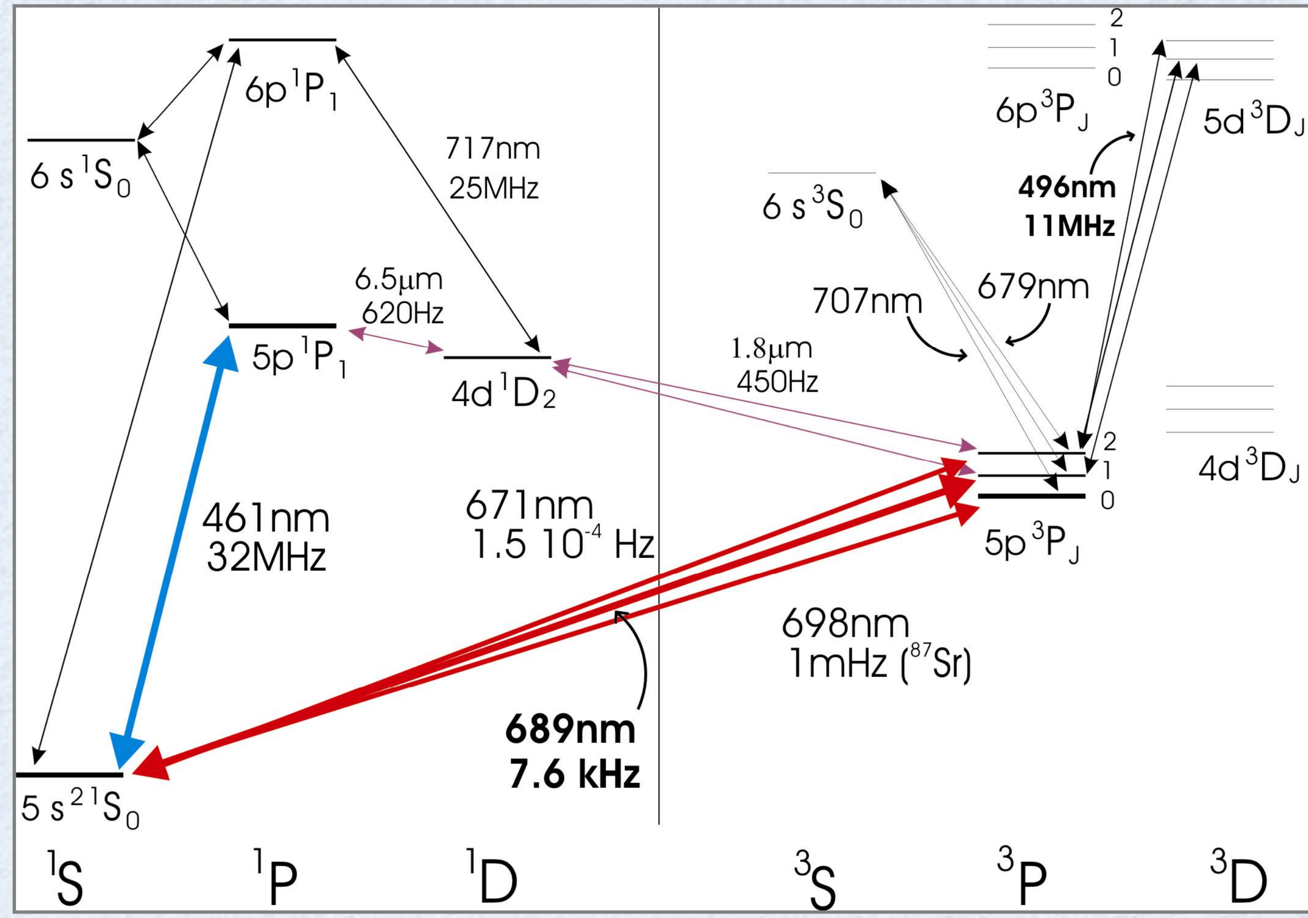


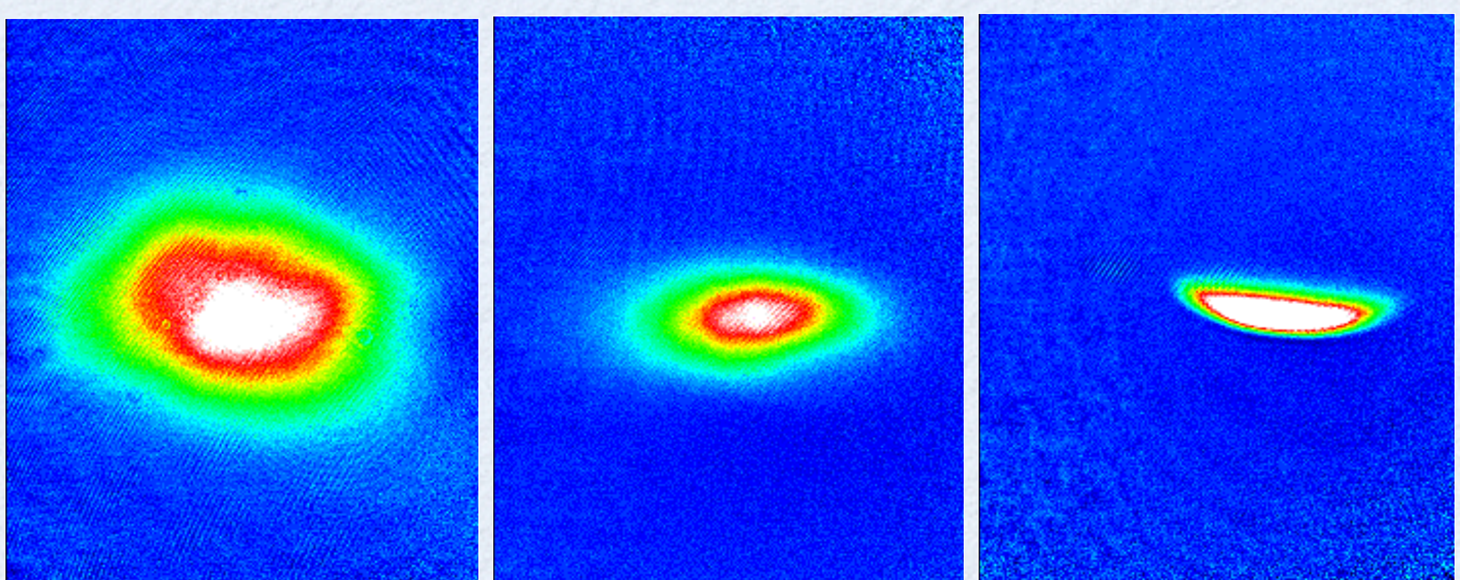
G measurement with atomic sensors

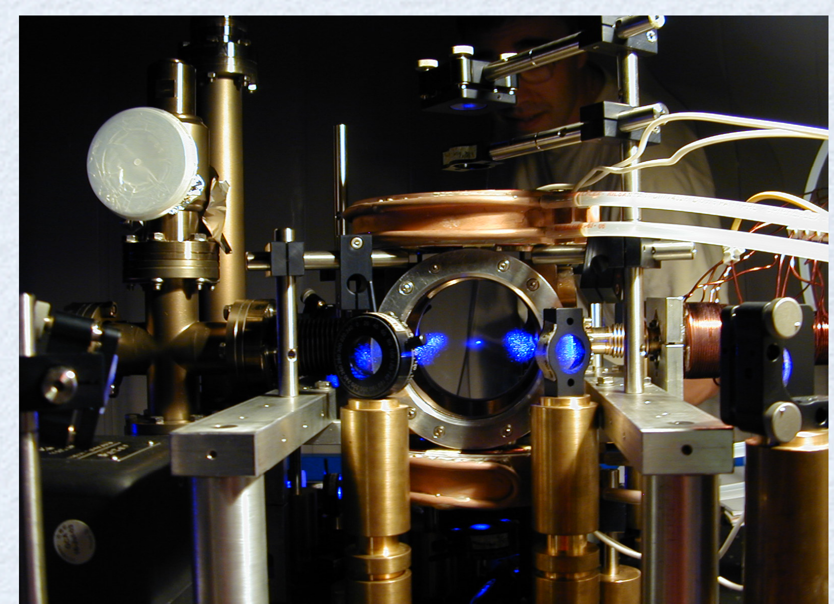


Using ultracold strontium

- Extremely fast multi-stage cooling
- Sub-recoil temperatures with narrow line cooling
- Very small size of ultracold atomic sample (few μm)
- Insensitive to stray fields
- Fermionic and bosonic isotopes
- Unique collisional properties
- Among best candidates for optical atomic clocks



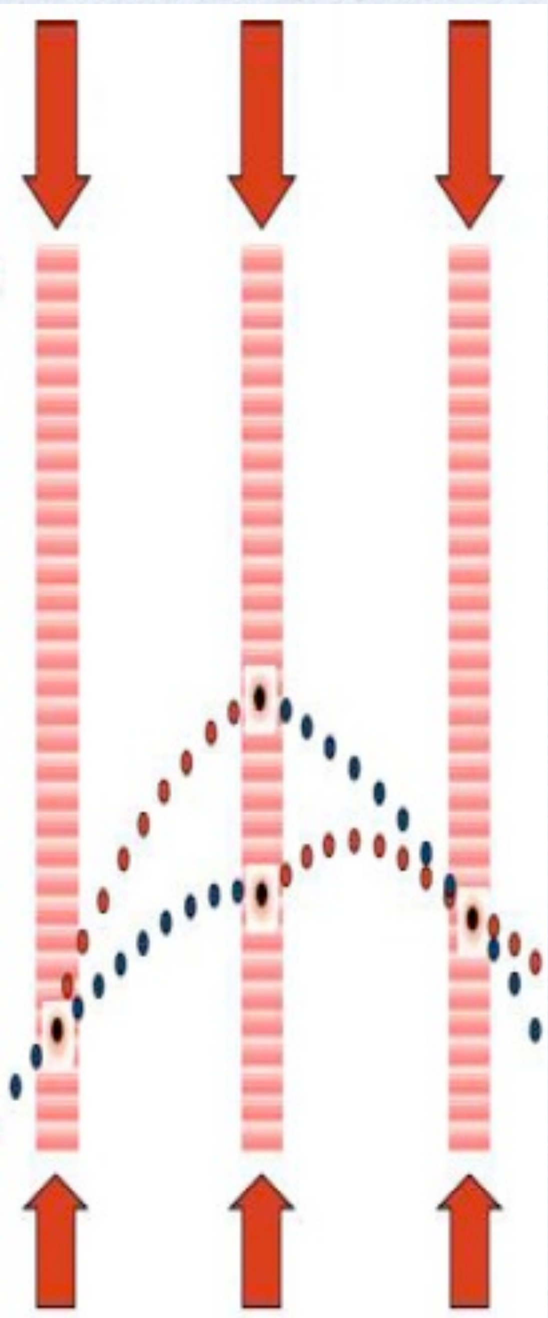




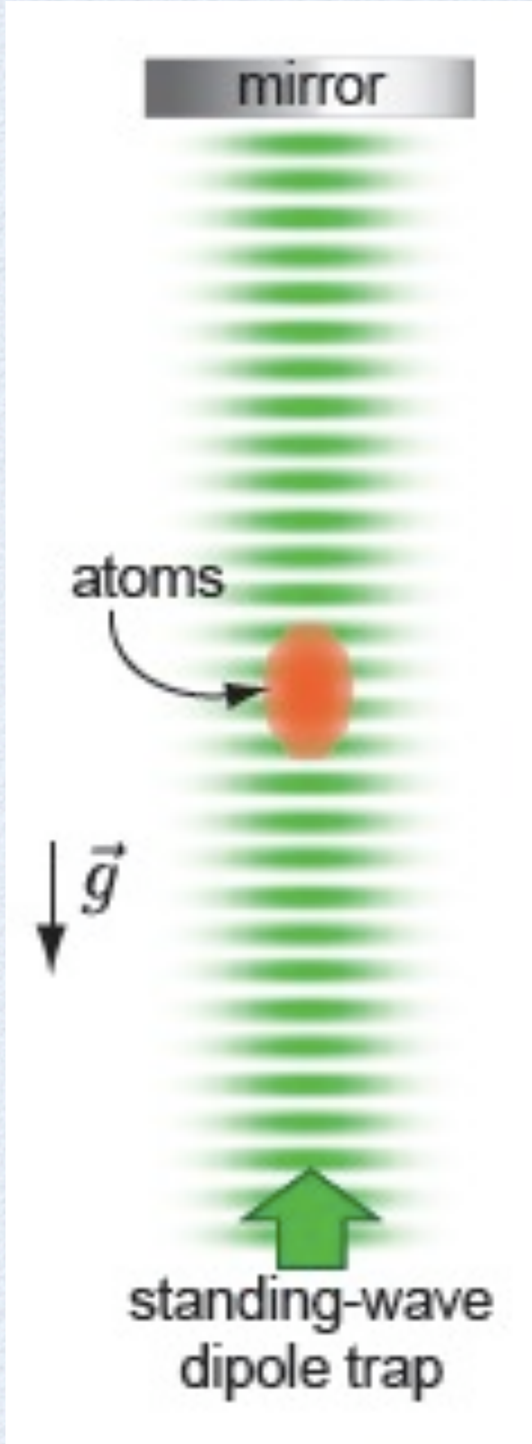
F. Sorrentino, GWADW2013

The MAGIA experiment...

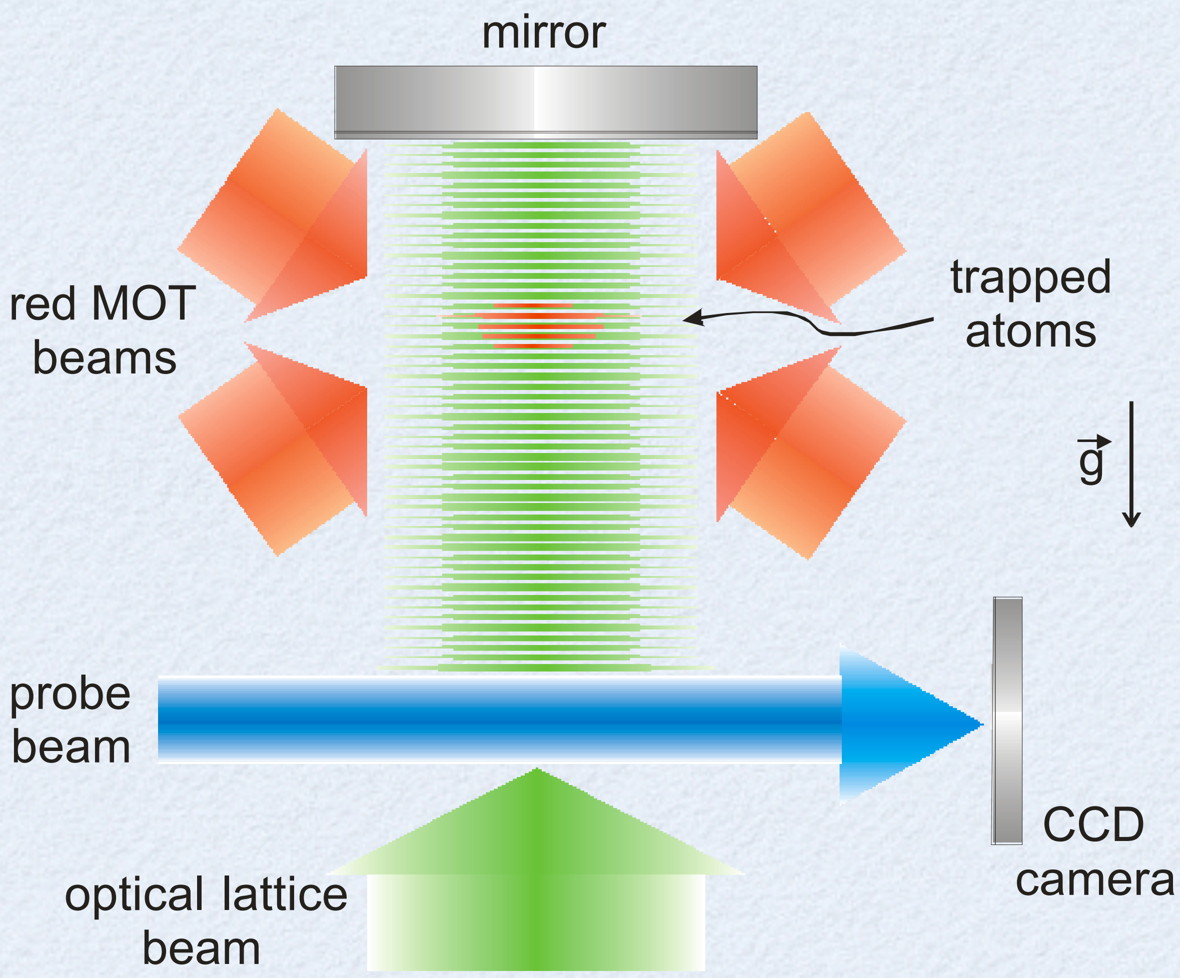
Free falling vs trapped atoms

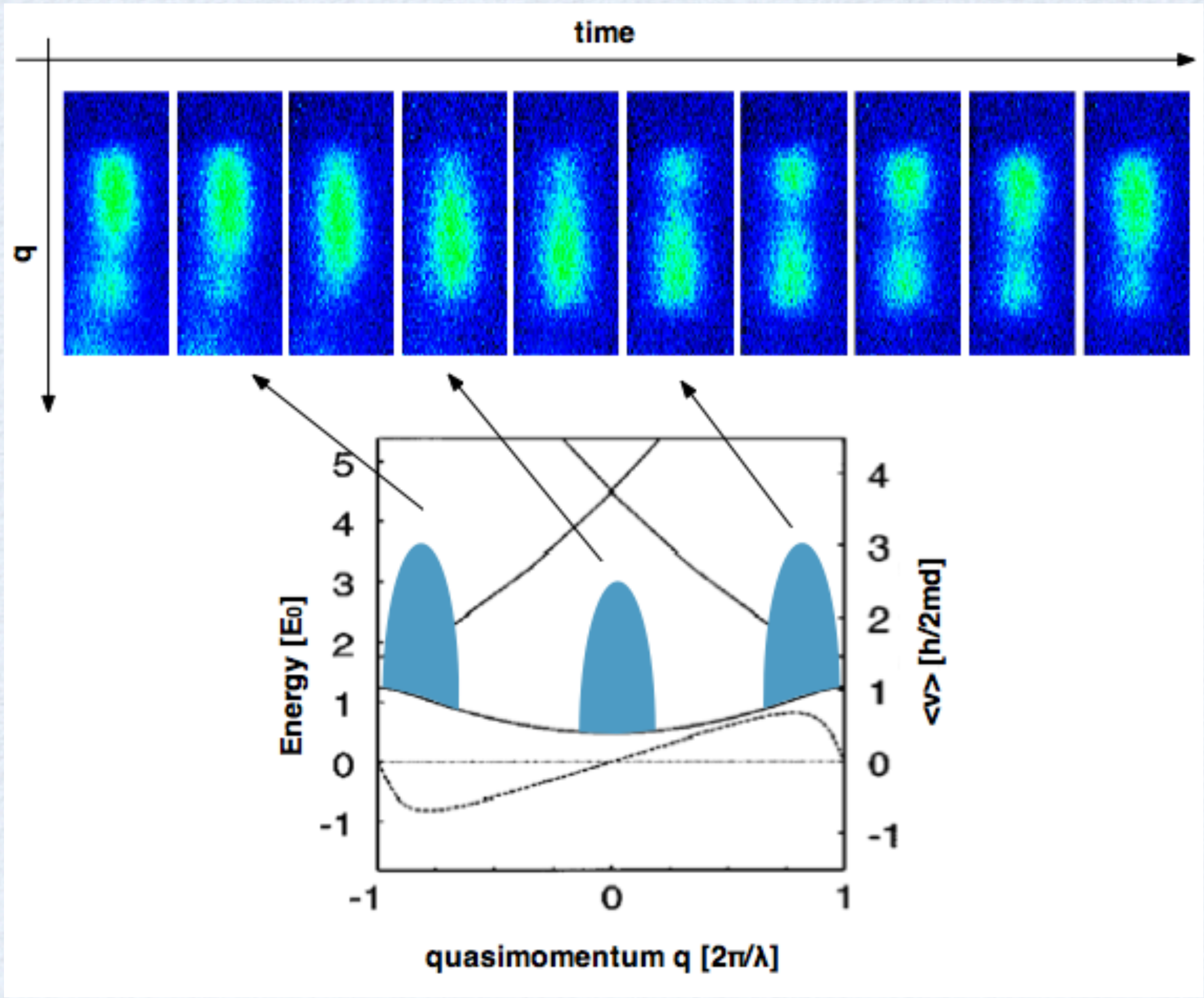


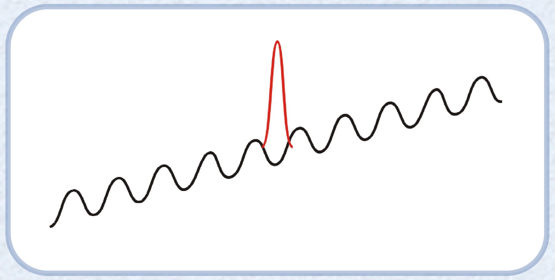
- Light-pulse (Raman or Bragg) atom interferometry
  - highest precision and highest accuracy so far demonstrated
  - atomic wave-function evolves in the absence of external fields
- AI in optical lattices
  - No free fall or free expansion
  - Small intrinsic size of the sensor
  - but... perturbation by laser field and by interatomic collisions



Bloch oscillations in optical lattice

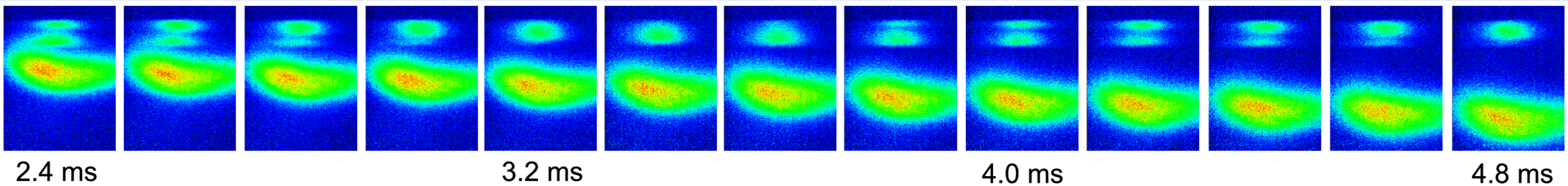


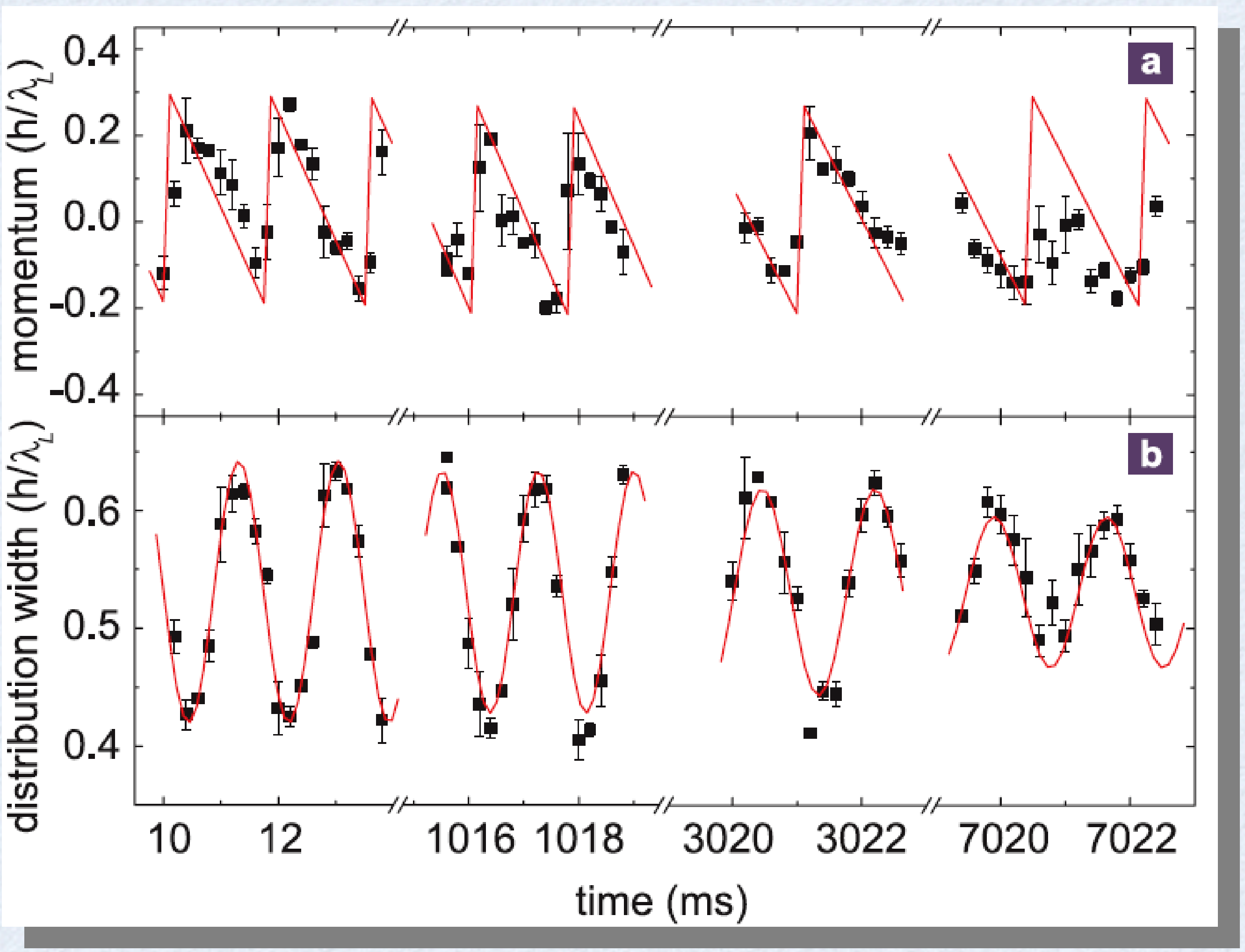




$$q(t) = q_0 + Ft/\hbar \quad \Rightarrow \quad \nu_B = \frac{F\lambda}{2h} = \frac{mg\lambda}{2h}$$

Bloch oscillations of ^{88}Sr





Bloch frequency 574.568(3) Hz

8000 photon recoils in 7 s

g_{meas}=9.80012(5) m/s^2

*G. Ferrari et al., PRL **97**, 060402 (2006)*

Decoherence time > 500 s

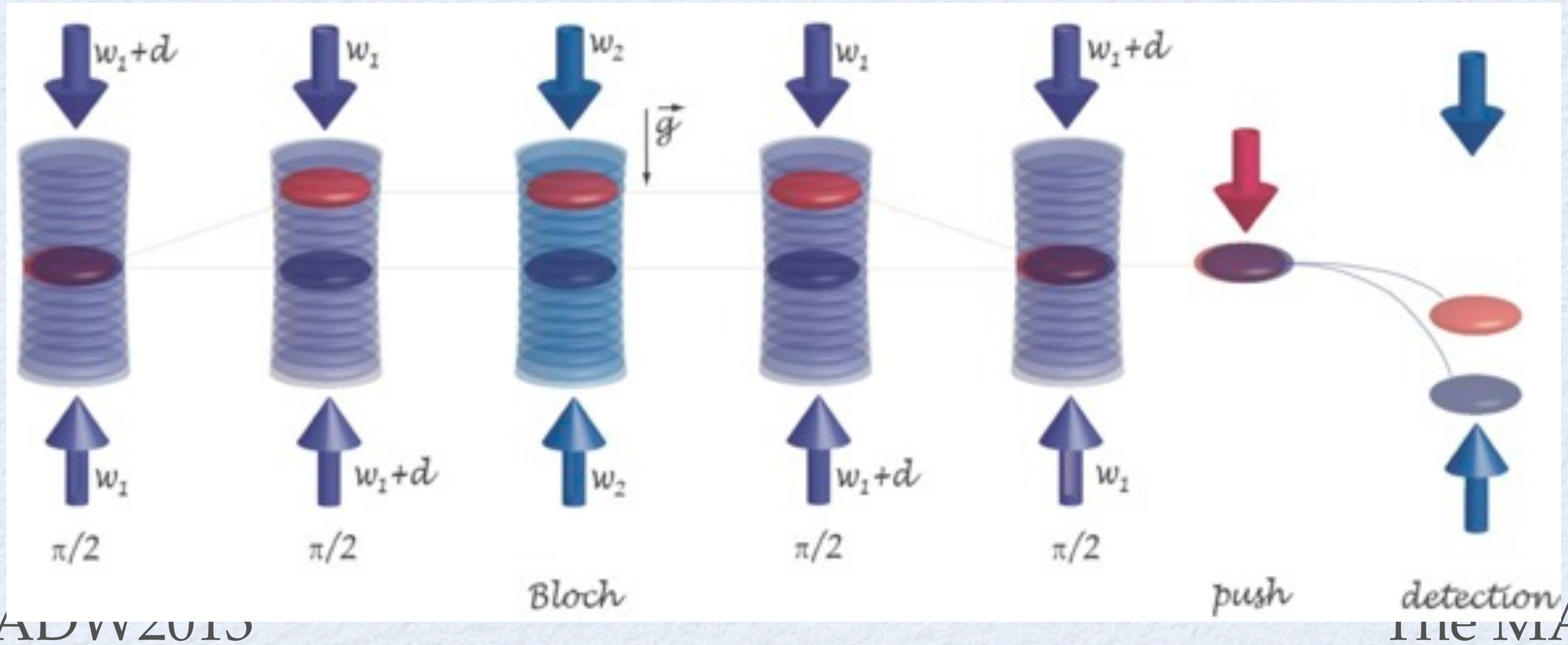
*M. Tarallo et al., PRA **86**, 033615 (2012)*

- Direct acceleration sensitivity limited by the small splitting (~1 μm)
- However, acceleration via BO already employed for LMT splitters in free-fall interferometers

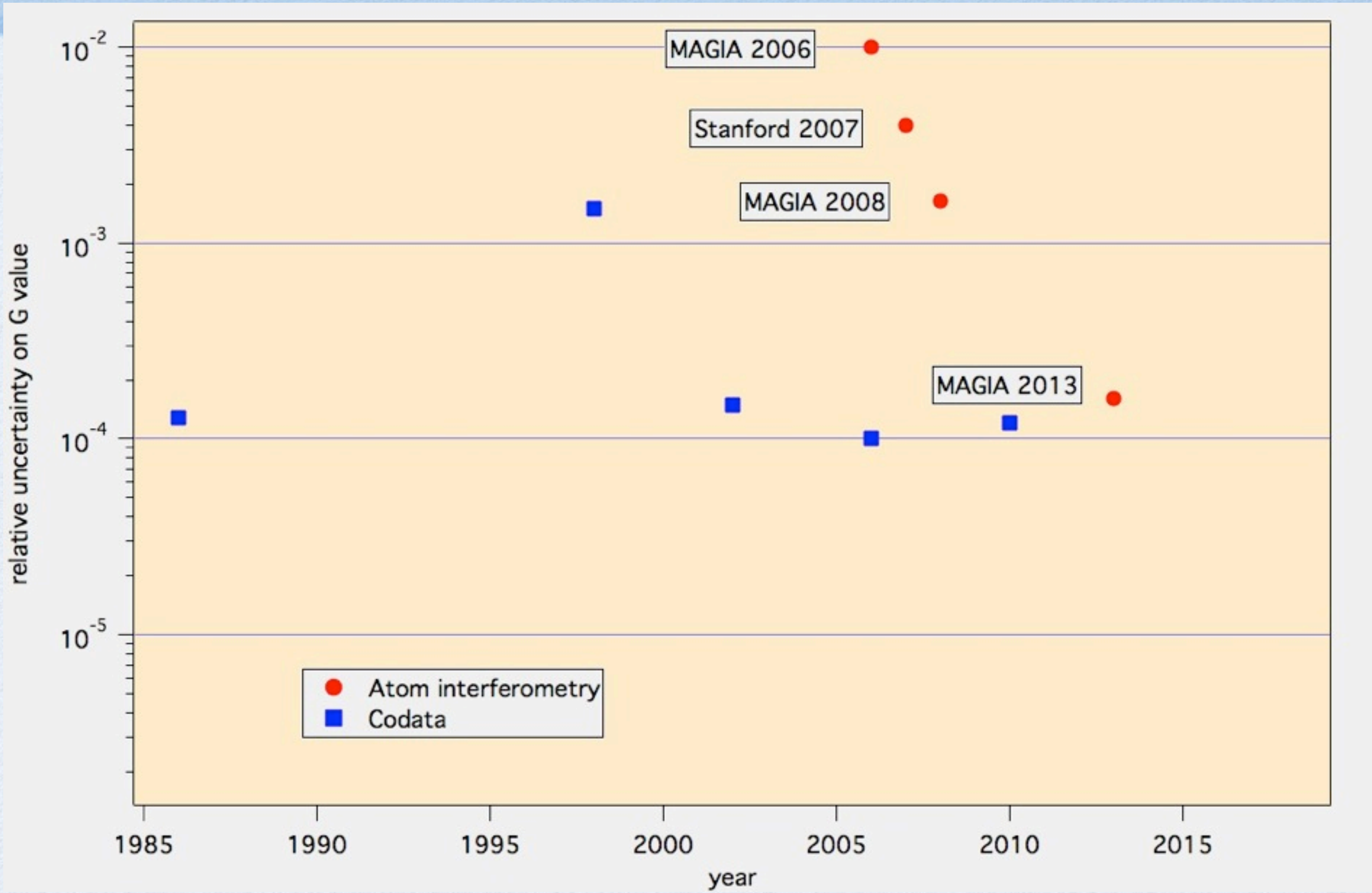
*H. Mueller et al., PRL **102**, 240403 (2009)*

Proposal for MAGIA Advanced

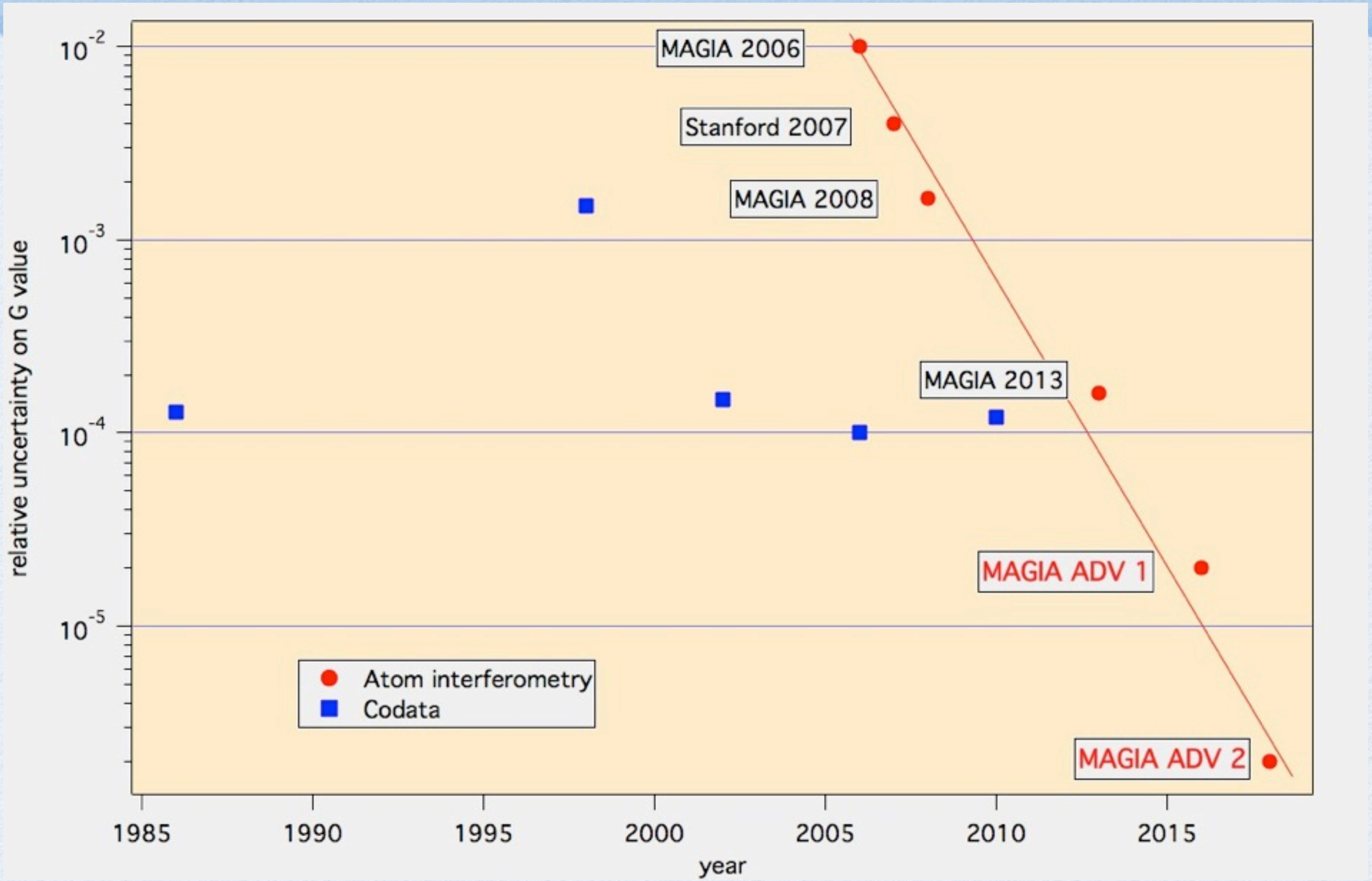
- Combining the advantages of the two methods
  - free fall: large splitting -> large sensitivity
  - BO in optical lattice: small spatial scale & long coherent evolution
- Experimental sequence with
  - LMT splitter with *N* photon recoils and free fall for a time *t*
  - trapping in optical lattice and BO for time T
  - free fall for time *t* and recombination pulse with *N* photon recoils
  - already shown with Rb: R. Charrière et al., PRA **85**, 013639 (2012).
- Two configurations with increasing sensitivity
  - **MAGIA ADV 1**: t=0.2 s, T=0, N=20, sens. ~3×10^{-10} g/shot
  - **MAGIA ADV 2**: t=10 ms, T=10 s, N=20, sens. ~10^{-11} g/shot



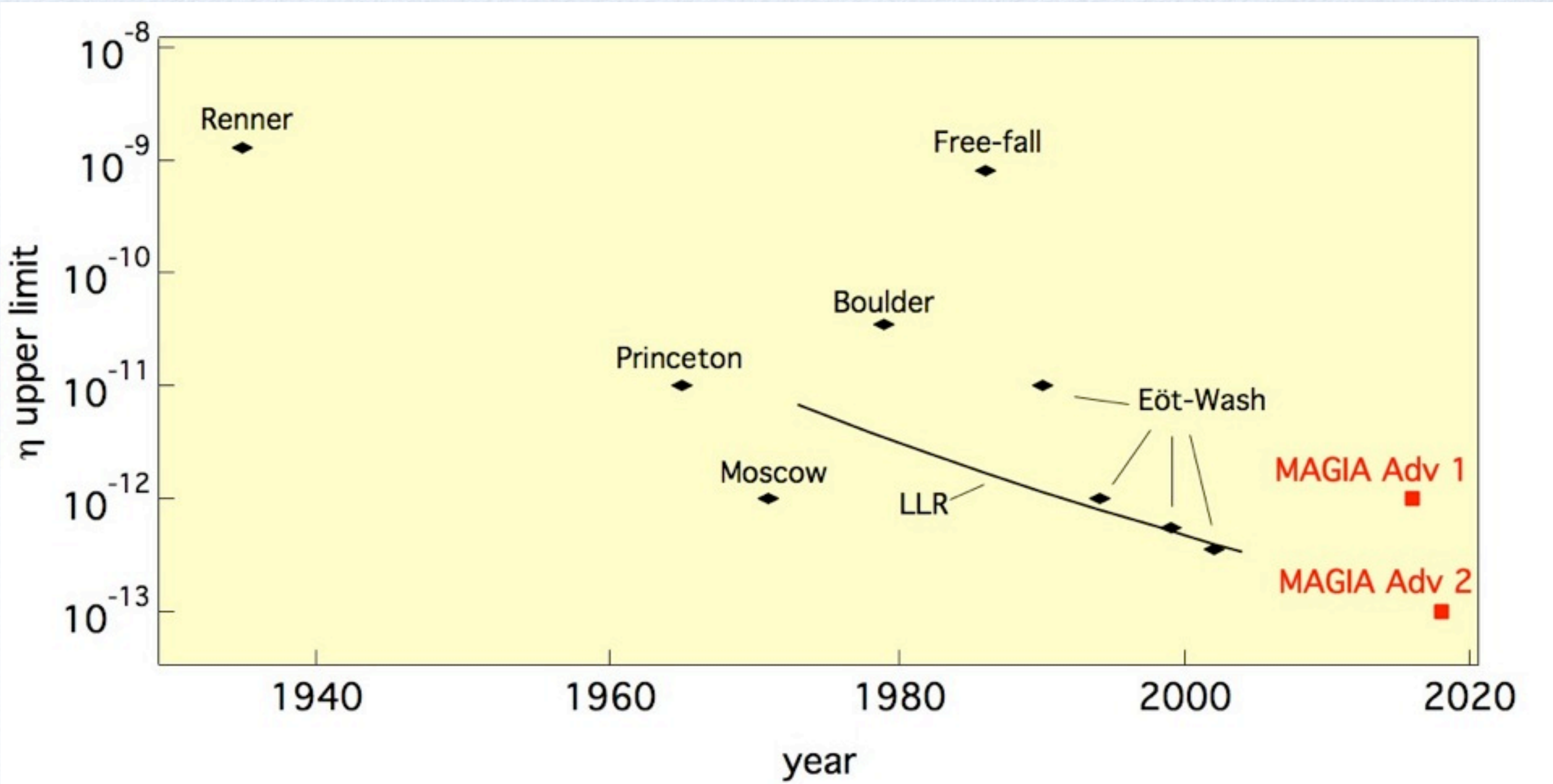
MAGIA Adv. - application to G



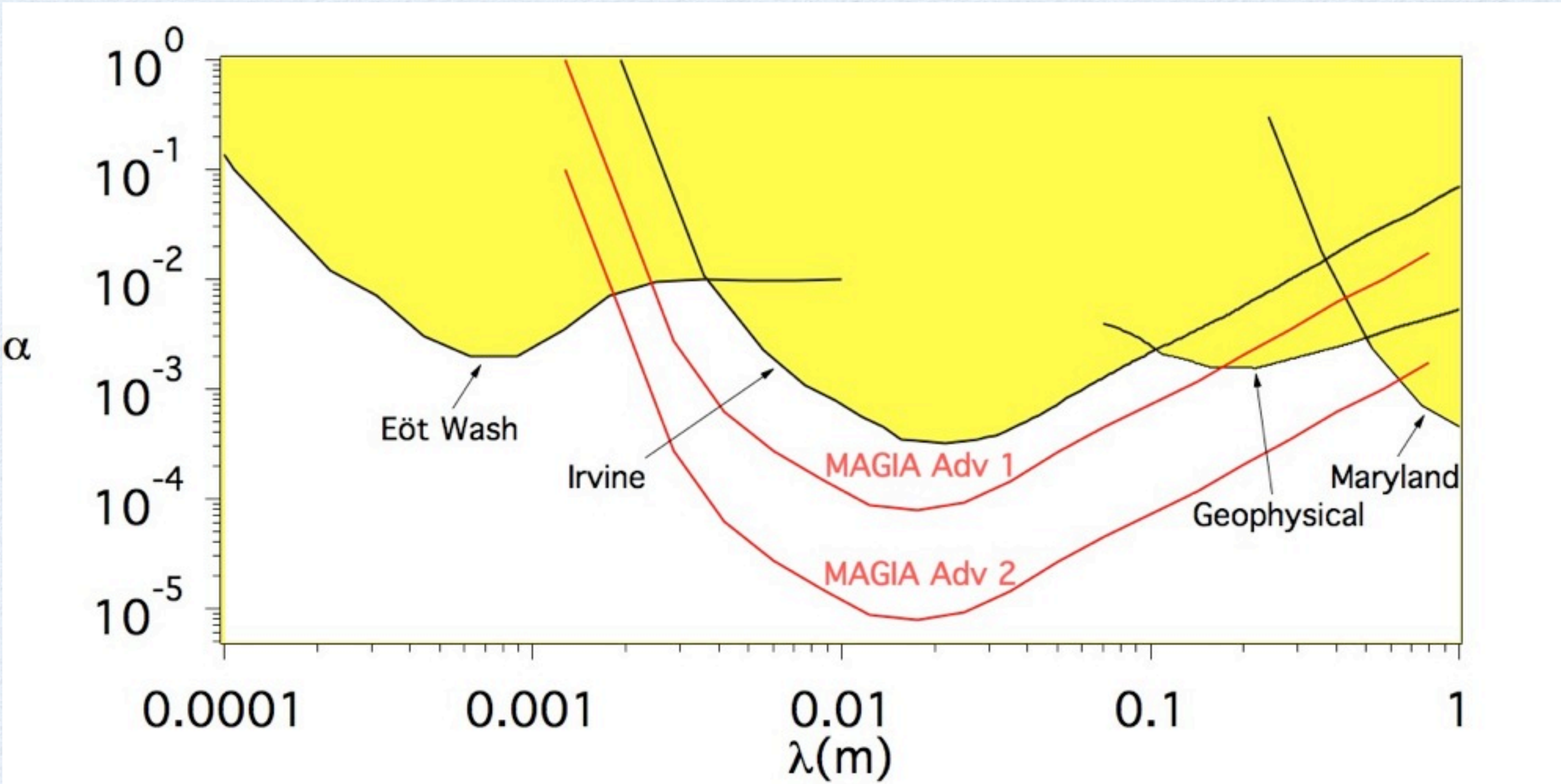
MAGIA Adv. - application to G



MAGIA Adv. - WEP test

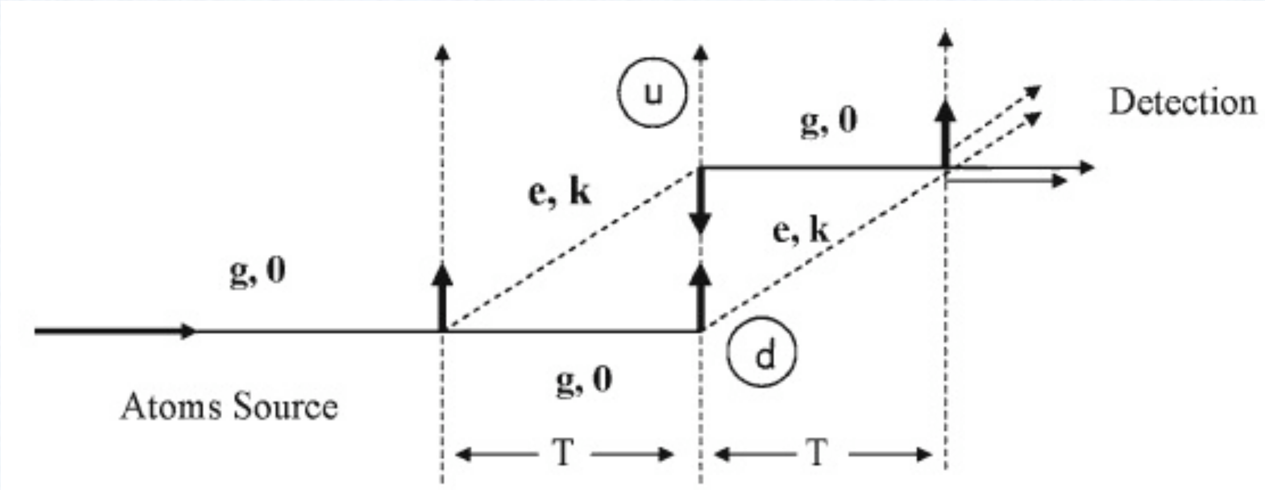


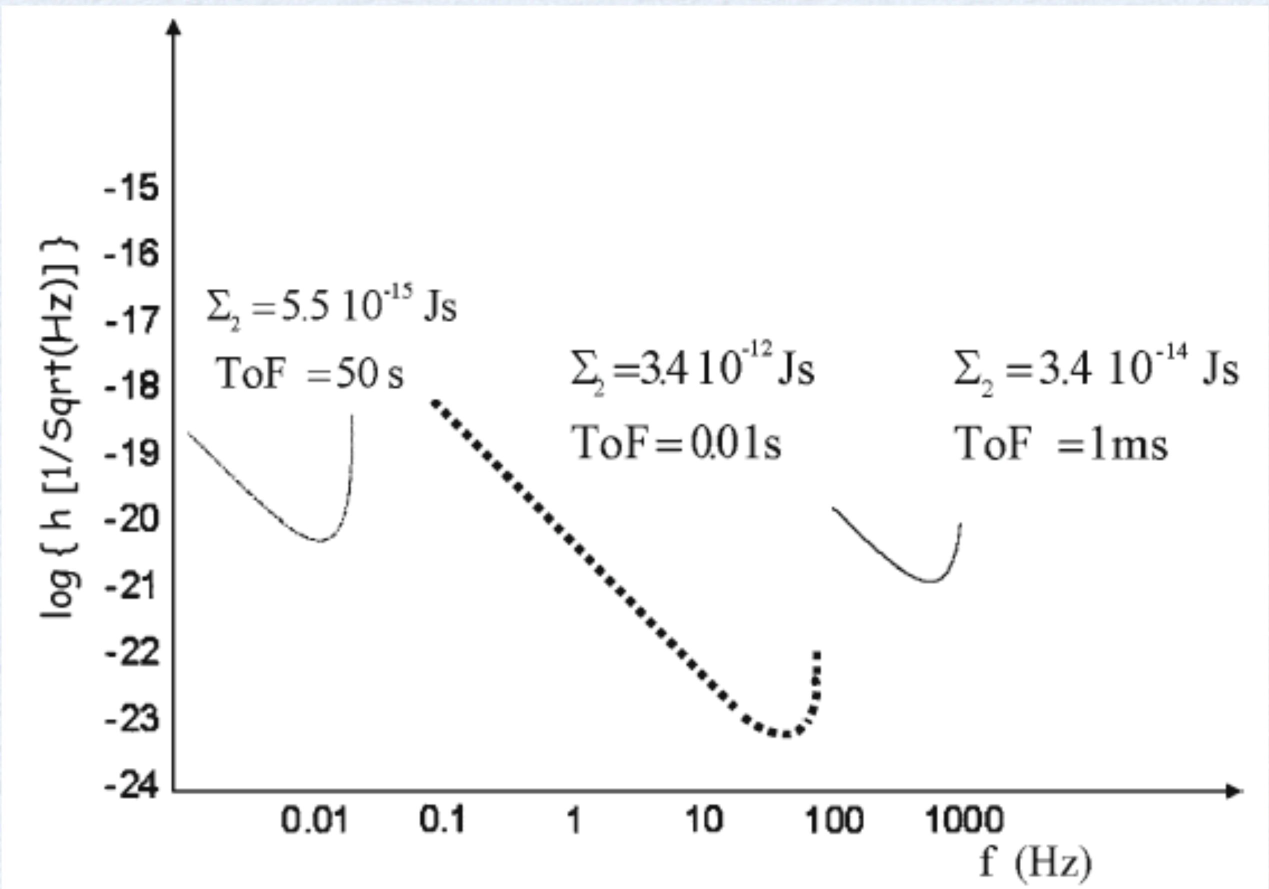
MAGIA Adv. - test of Newton's law

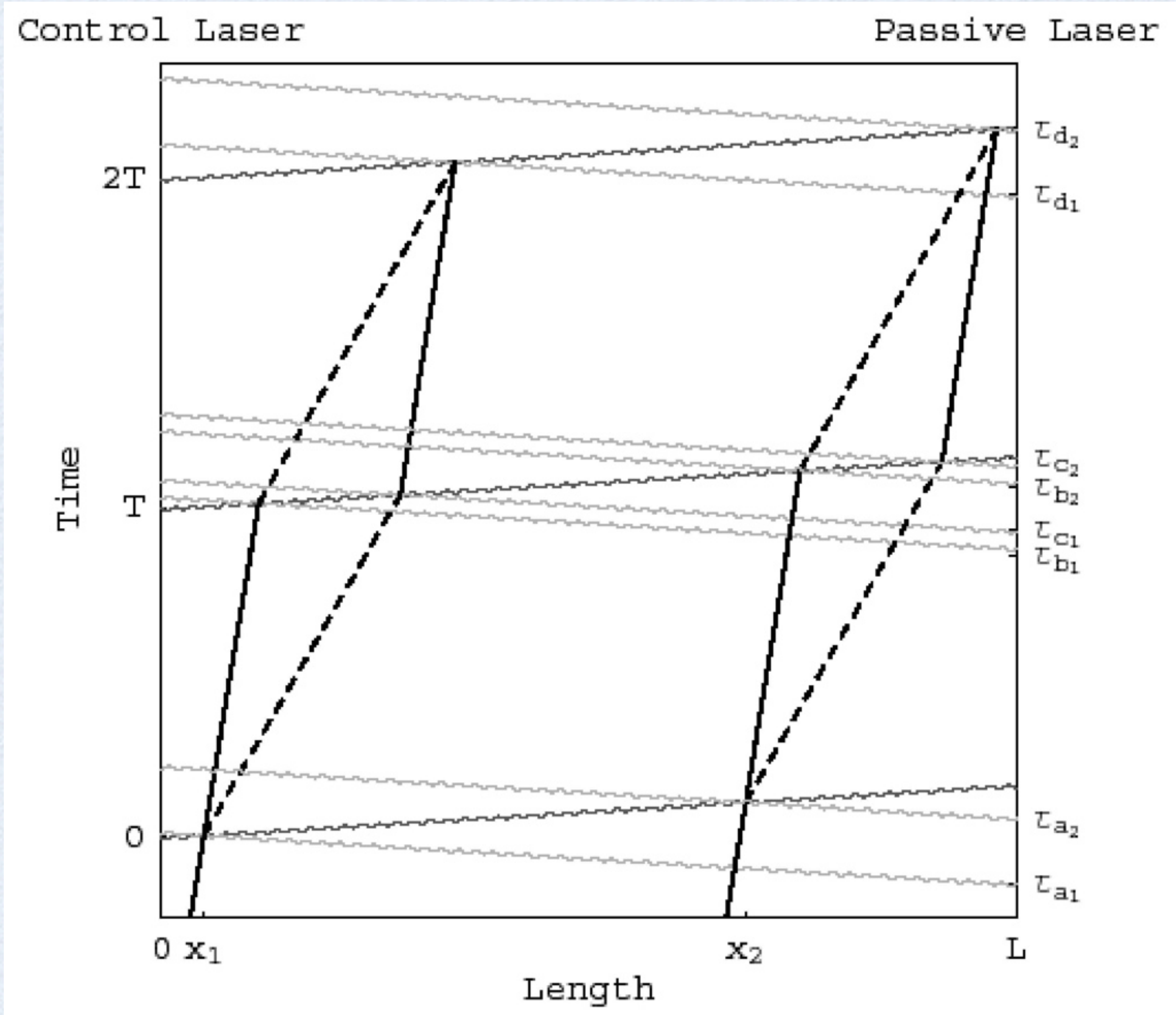


$$V(r) = -G\frac{m_1 m_2}{r}[1 - \alpha e^{-(r/\lambda)}]$$

AI and GW detection







G. M. Tino and F. Vetrano, Class. Quant. Grav. **24** (2007)
G. M. Tino and F. Vetrano, Gen. Relativ. Gravit. **43**, 2037 (2011)

S. Dimopoulos, et al., Phys. Rev. D **78**, 122002 (2008)
S. Dimopoulos, et al., Phys. Lett B **678**, 37 (2009)

Recent and forthcoming literature

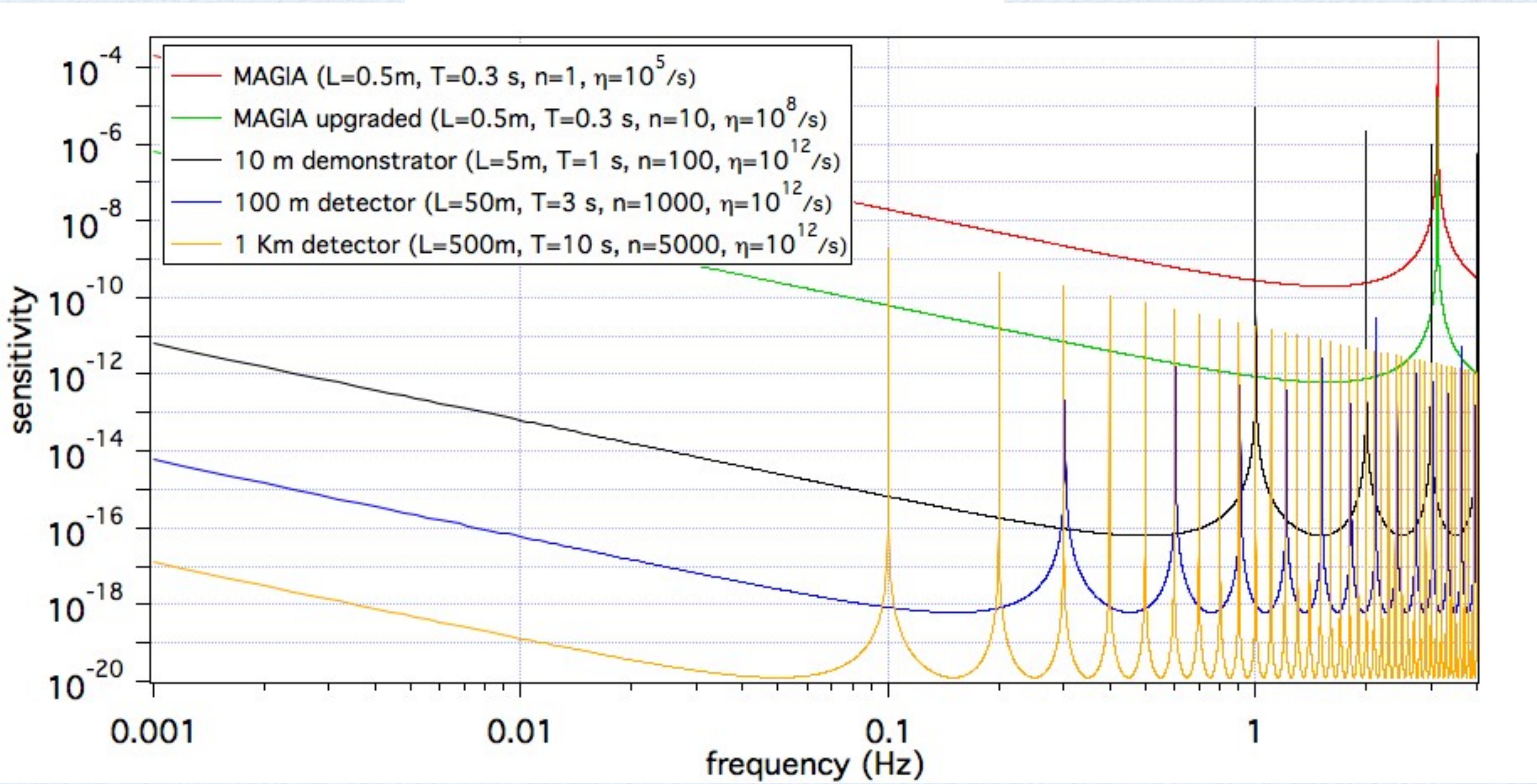
- G. M. Tino, F. Vetrano and C. Lämmerzahl Eds., Special Issue on *Gravitational waves detection with atom interferometry*, Gen. Relativ. Gravit. **43**, 1901 (2011)
- G. M. Tino and M. Kasevich Eds., *Atom Interferometry*, Proc. intern. school of physics Enrico Fermi CLXXXVIII (2013) (School to be held 14÷20 July 2013, proceedings to be published in 2013)

AI towards GW detection

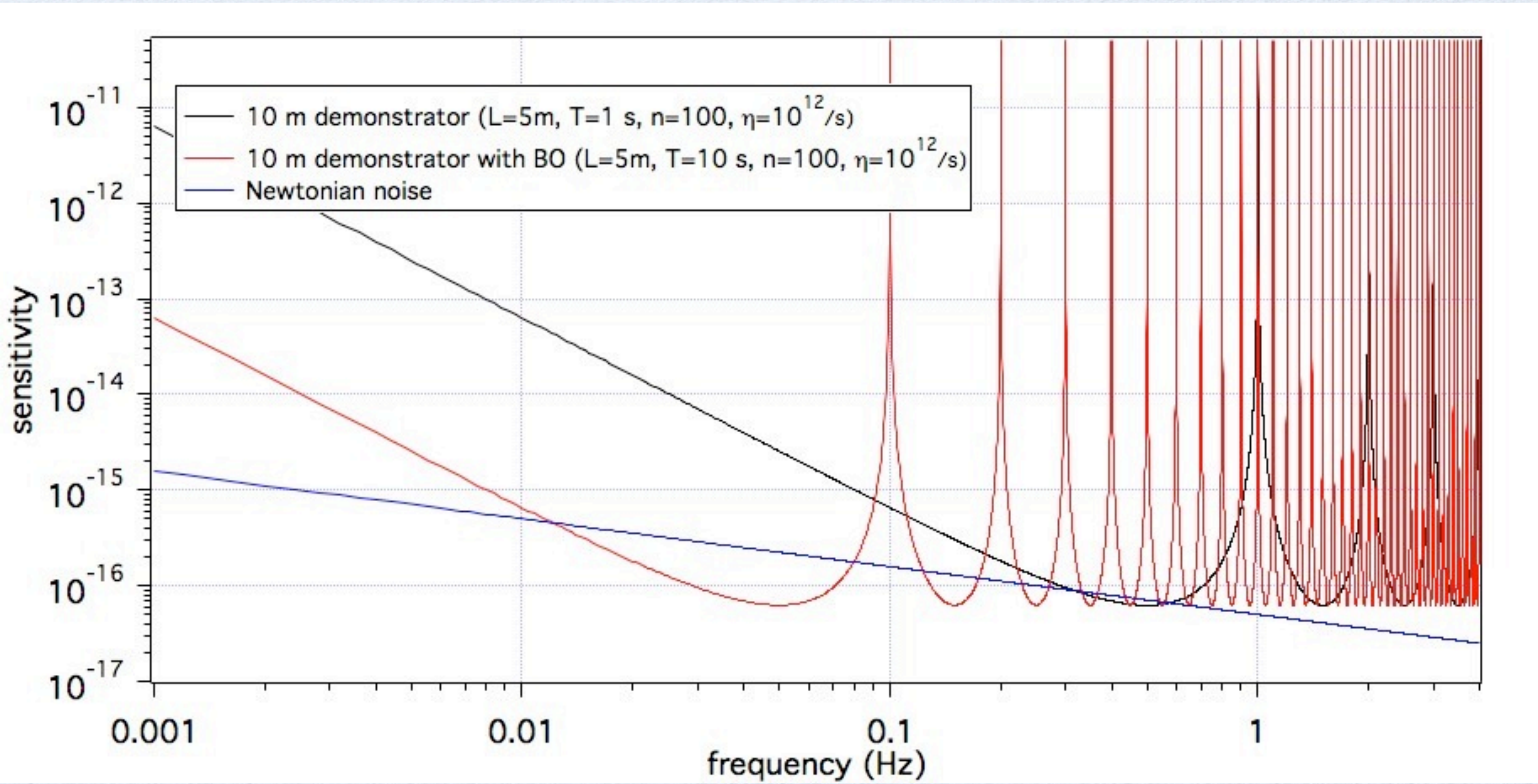
- Increasing the wave-packet separation with LMT splitters
  - interferometers with ~100 photon recoils already demonstrated
- Improving the QPN limit with large flux atomic sources
  - current achievements: ~10^8 at/s below 1 μK with alkali
- Increasing the size and separation between simultaneous interferometers
- Beating the QPN limit
  - QND measurement of atomic populations
  - use of entangled and/or coherent states
- Sensor modeling
  - understanding noise sources other than QPN (laser wavefront, Newtonian noise, atomic motion etc.)
  - design of optimal configurations
- Possible advantages:
  - excellent CMRR for vibration noise in differential configurations
  - no thermal noise
  - several "knobs" to tune sensitivity function and isolate noise sources
  - room for improvements (experimental configurations, technical limits)

MAGIA Adv. & GW detection

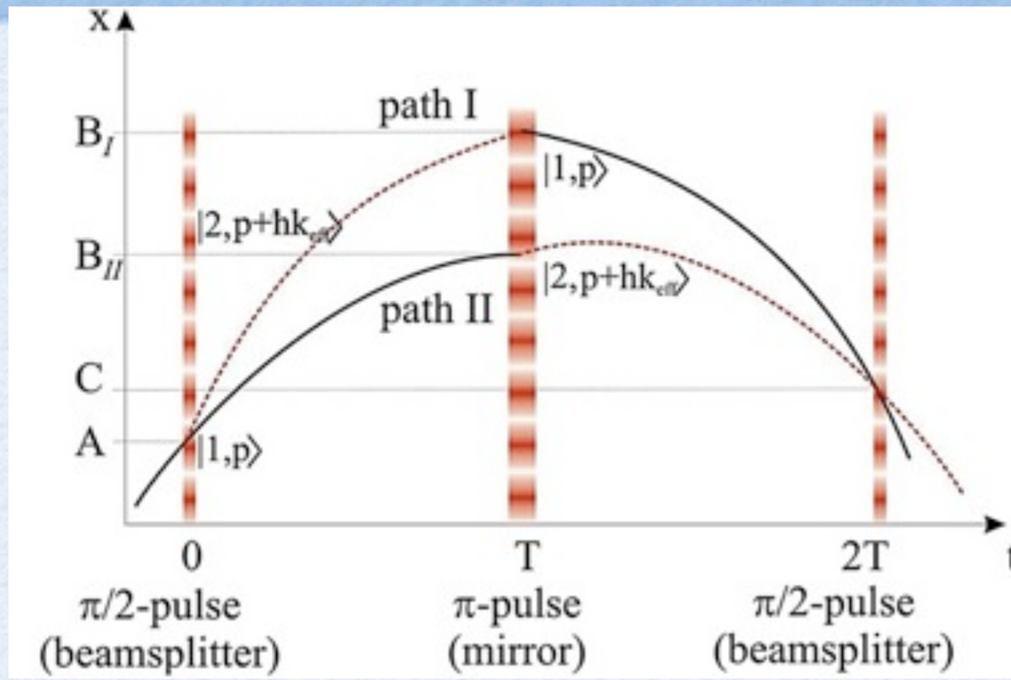
$$h_{rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}}$$



Using trapped atoms



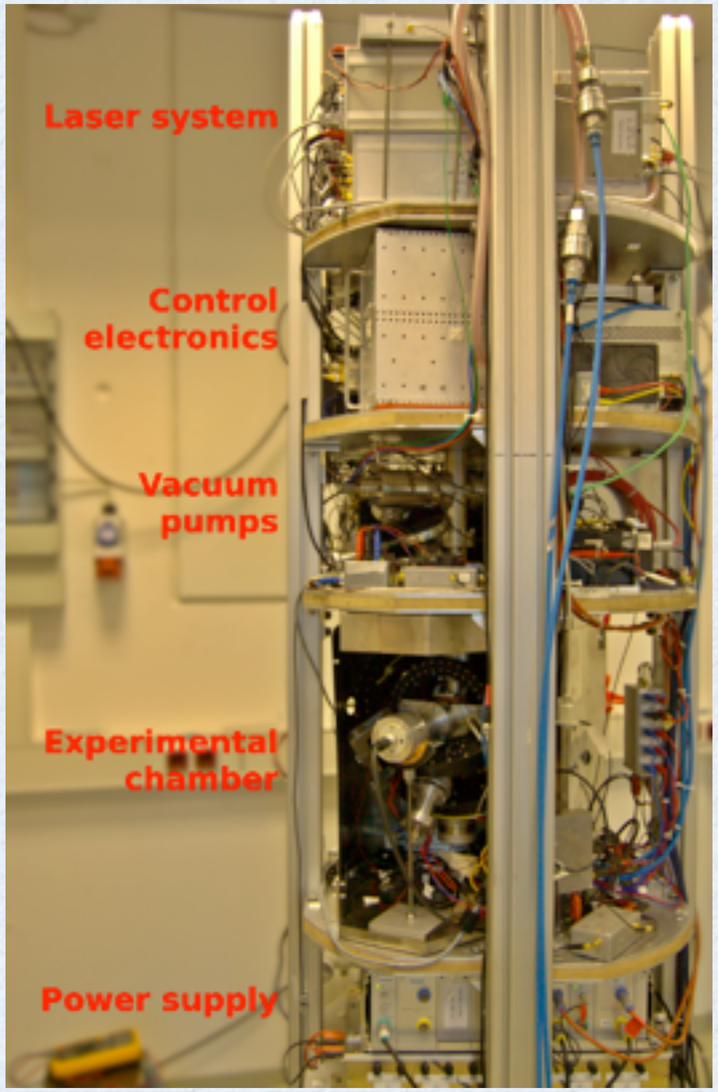
AI measurements in space

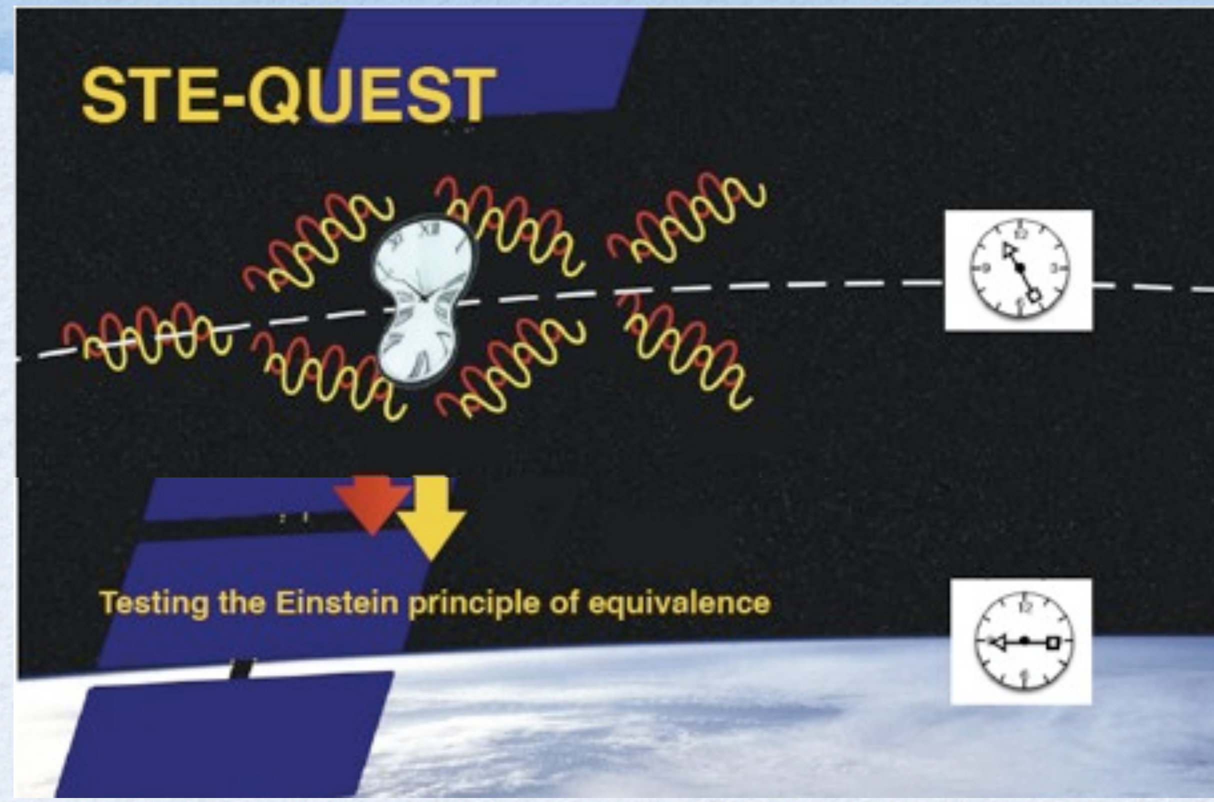


$$\Delta\phi = kgT^2$$

- Terrestrial AIs achieve differential gravity accuracy approaching $\sim 10^{-11}$ g with T~0.1 s
- In space $\sim 10^{-15}$ g or better is foreseen with T>>1s with same splitting
- Main issues to address for AI experiments in space:
  - TRL (lot of work in progress)
  - Motivation for space (on ground, large T requires long free-fall distance)
  - Understanding noise and error sources (test bench experiments on ground)

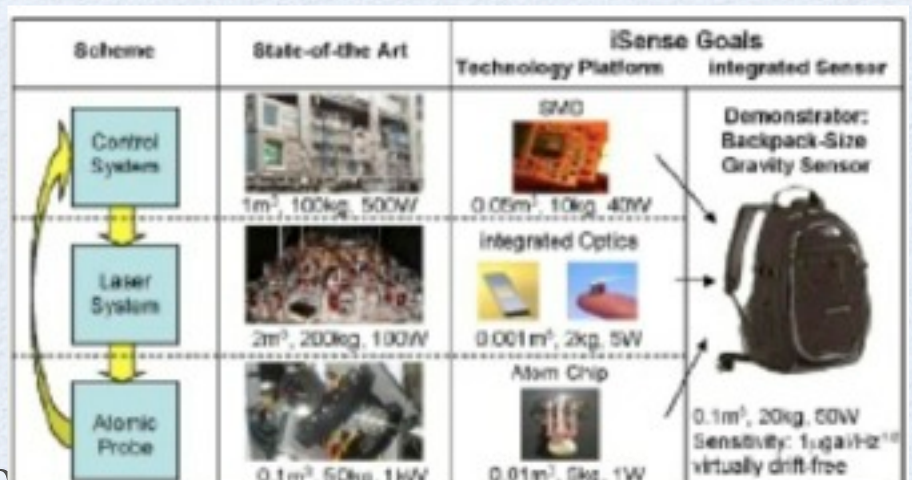
TRL of AI





iSENSE

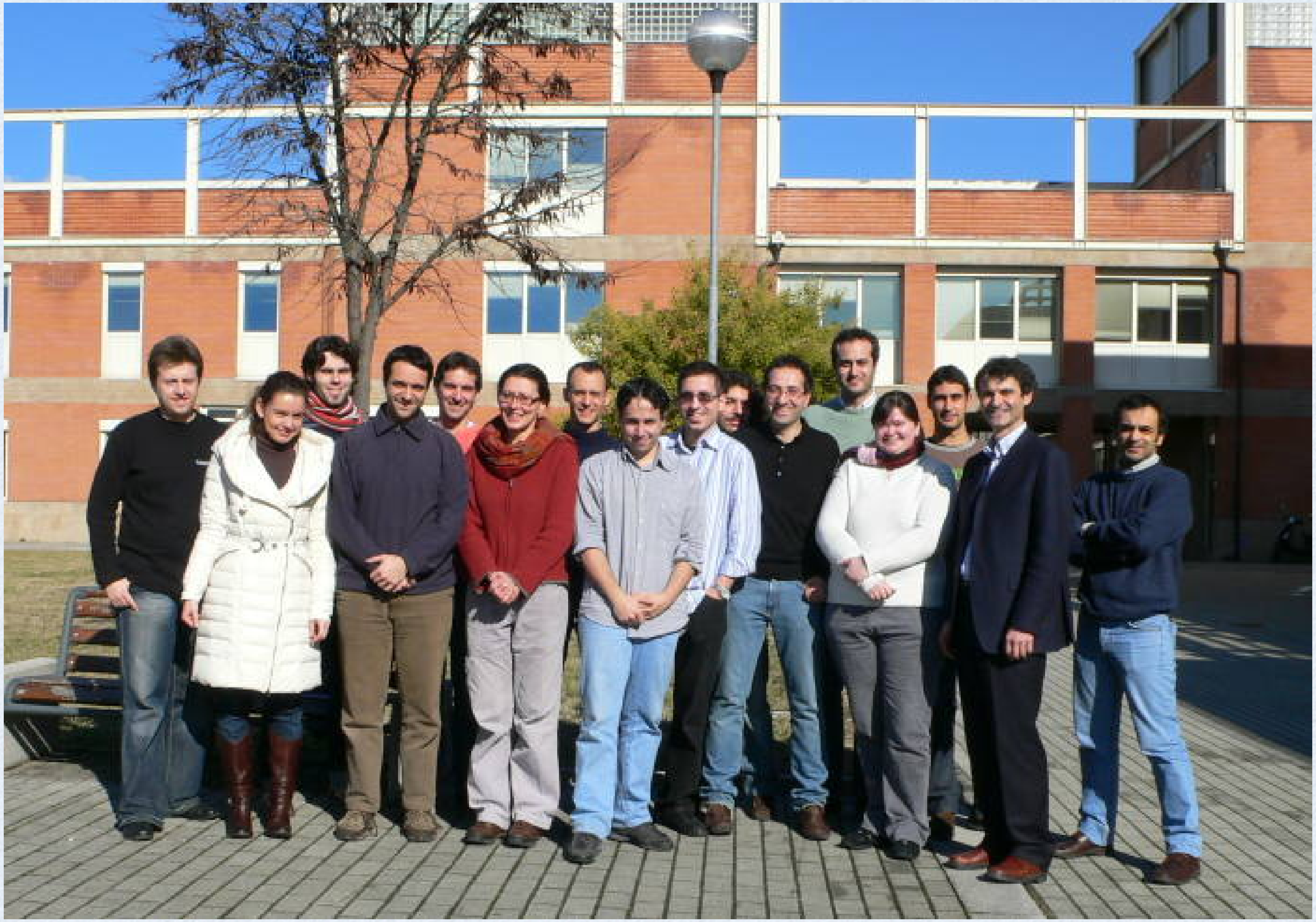
QUANTUS



Conclusions

- MAGIA current status: statistical & systematic errors at the 100 ppm level
  - control of main experimental parameters
  - atomic motion: double-stage reduction of Coriolis induced systematics
  - QPN limited gravity gradient measurement down to several hours
- Atom interferometry with ultracold ^{88}Sr
  - Fast and efficient cooling down to nK temperature
  - Long coherence time up to 500 s
  - Optical atomic clock and gravity sensor in the same device
- Future prospects: towards an advanced atom interferometer for gravitational physics
  - gravity sensor with free fall + BO in optical lattice
  - large interaction time within small size
  - LMT splitters + high flux atomic source
  - foreseen G measurements down to the ppm level and WEP test @ 10^{-13}
  - demonstrator for GW detection

Our team



Guglielmo M. Tino's group web page: http://coldatoms.lens.unifi.it

Post-doc positions available!