Compensation of gravity gradients and rotations in precision atom interferometry

Albert Roura

partly based on *Phys. Rev. Lett.* **118**, 160401 (2017)

Bremen, 25 October 2017

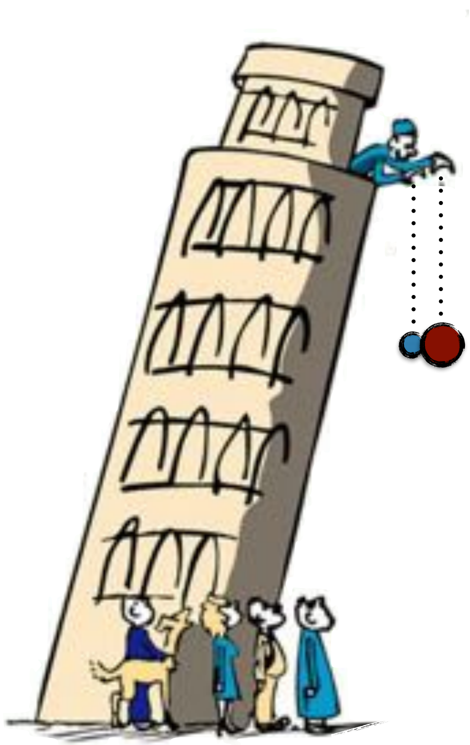
ulm university universität uulm

QUANTUS

DLR

Motivation

Tests of *universality of free fall* (UFF)

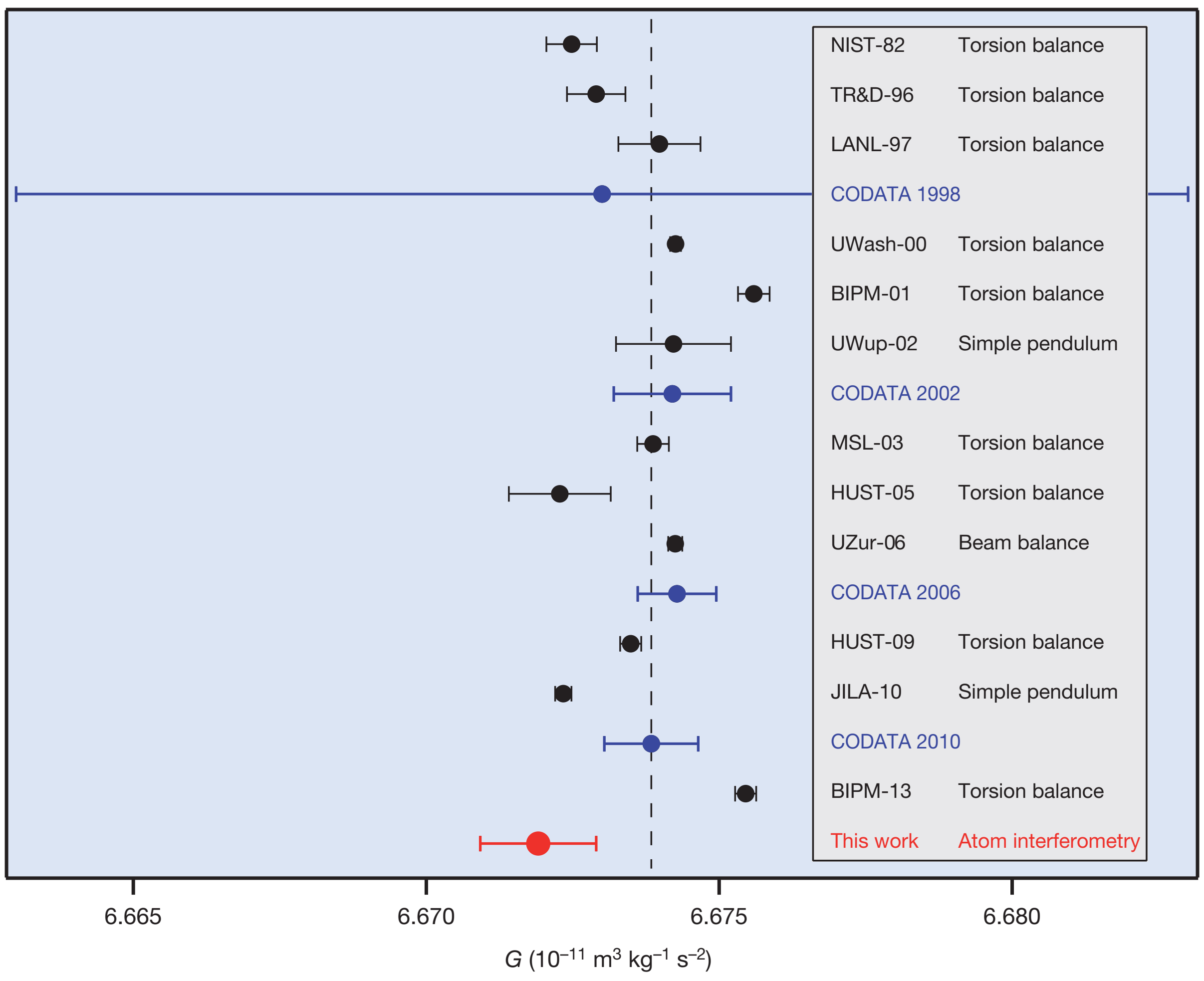


- Central to Einstein's equivalence principle.
- Tests of UFF with macroscopic masses:
  - free fall, *lunar laser ranging* (LLR)
  - *torsion balance* (Ëotvös)

$$\eta_{AB} = 2\,\frac{|g_A - g_B|}{g_A + g_B} \lesssim 10^{-13} \ldots\ 10^{-15}$$

Measurement of Newton's gravitational constant *G*

- By far the less accurately determined of all fundamental constants (using *macroscopic* masses).

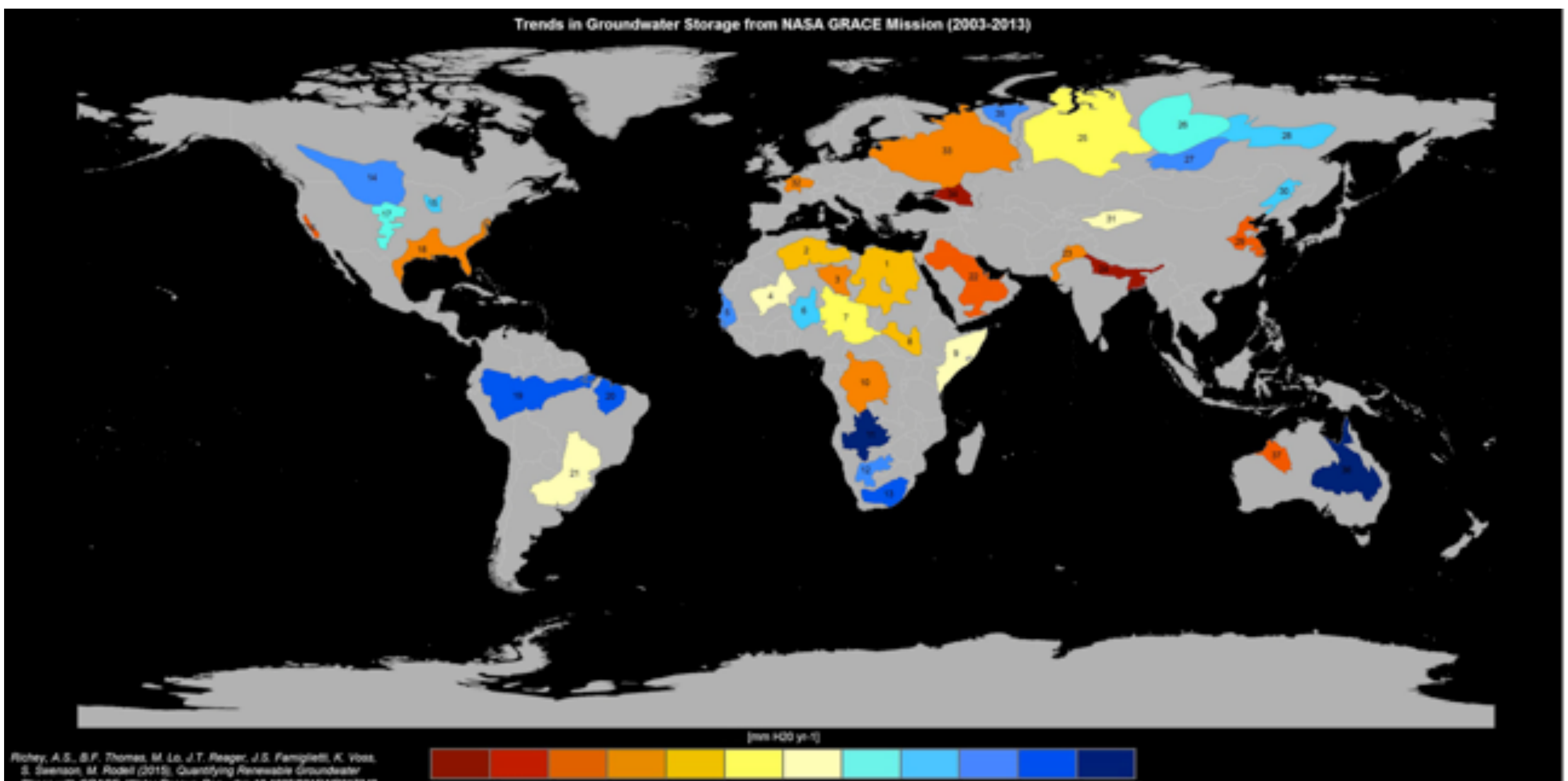


Rosi *et al.*, *Nature* **510**, 518 (2014)

Earth observations: mapping Earth's gravitational field

- Gravity gradiometry from space (*spatial resoultion* $\gtrsim 100\,\mathrm{km}$)
- Observing time evolution of mass distribution with applications to *geophysics*, *hydrology*, *oceanography* ...

  Example: *ground water* depletion and stressed aquifers



NASA GRACE Mission

Atom interferometry can make a *significant contribution* in all these cases

BUT

Gravity gradients (and *rotations*) pose a major challenge due to the dependence on the *initial position* and *velocity* of the atomic wave packets.

Outline

1. Motivation

2. Precise *gravitational* measurements with *atom interferometry*:
   - atom-interferometry-based gravimeters
   - long-time interferometry (& microgravity platforms)

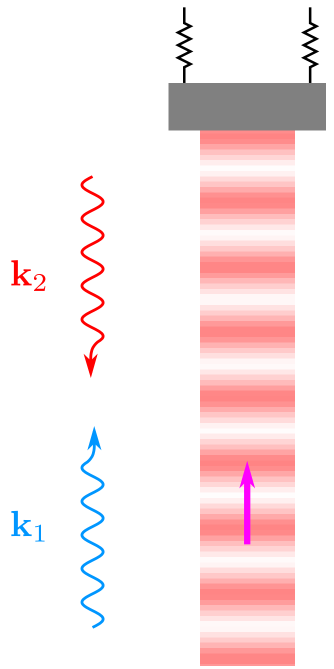
3. Challenges in UFF tests due to *gravity gradients*

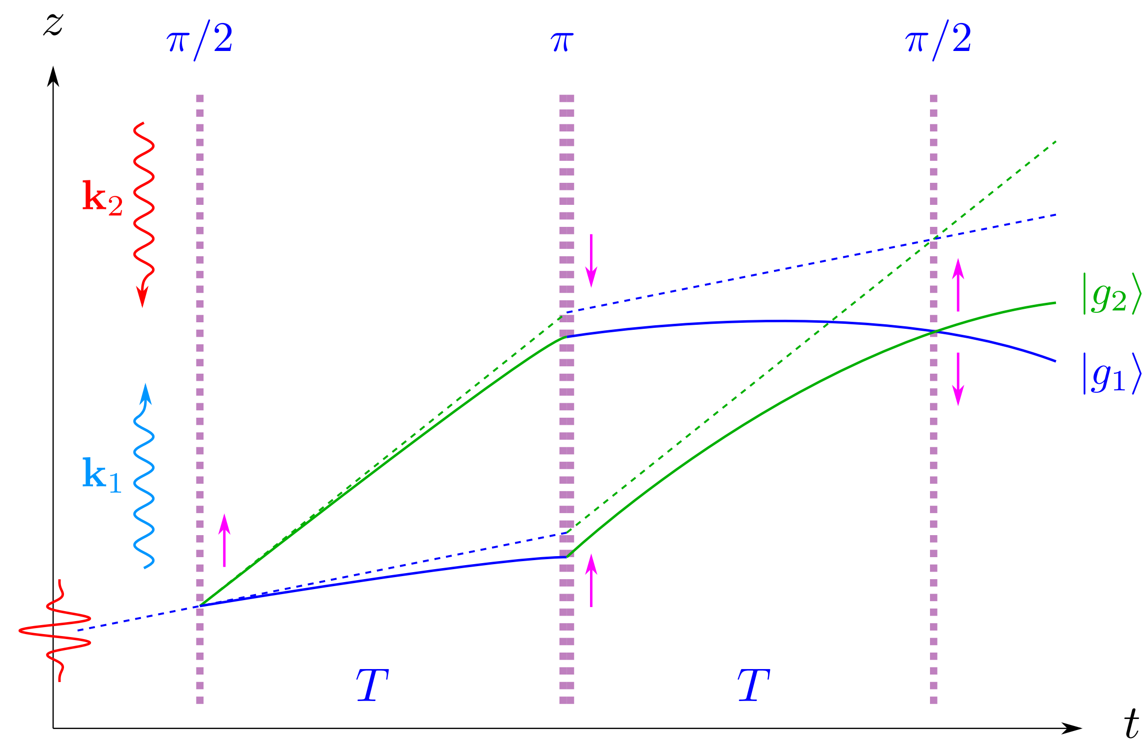
4. Overcoming loss of contrast and initial co-location problem

5. Compensation of large *rotation* rates

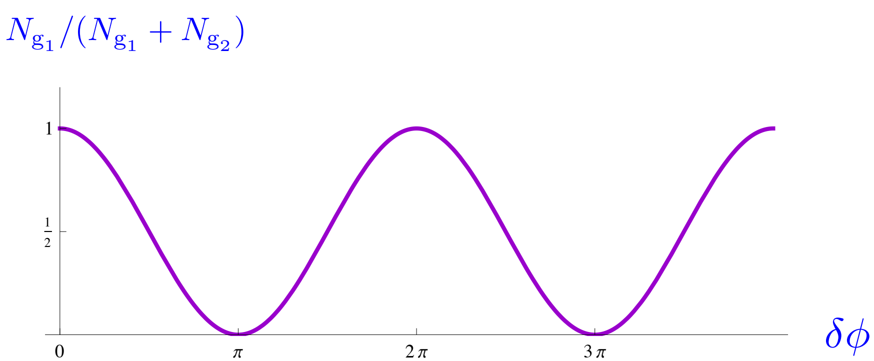
Precise gravitational measurements with atom interferometry (AI)

AI-based gravimeters





$\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$

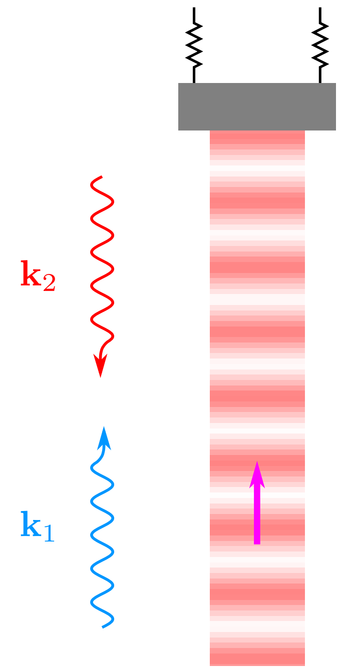


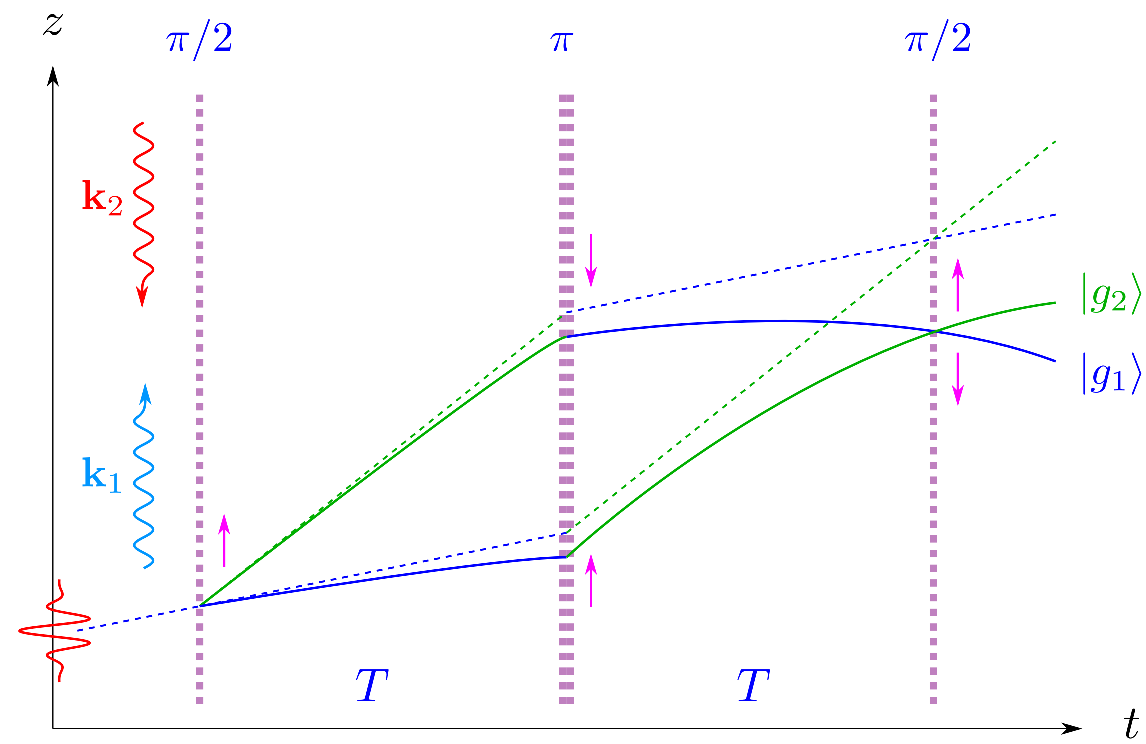
$$\delta\phi = -\,k_{\text{eff}}\; g\, T^2$$

The evolution of the wave packets can be decomposed into two independent aspects:

- expansion dynamics of a *centered* wave packet
- central position and momentum which follow *classical trajectories* including the kicks from the laser pulses

AI-based gravimeters





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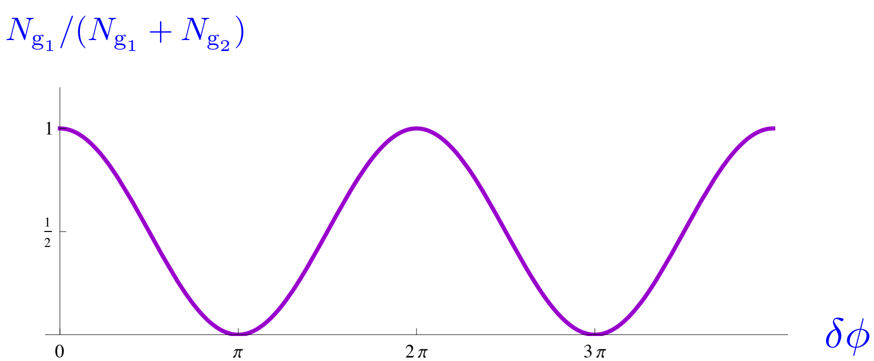

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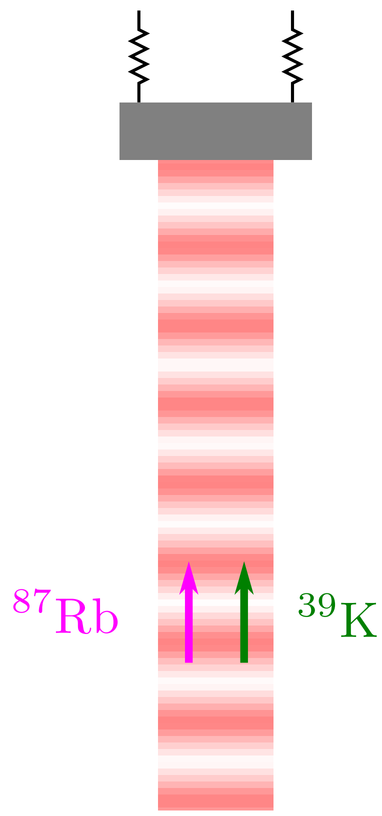
PRL **112,** 203002 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Quantum Test of the Universality of Free Fall

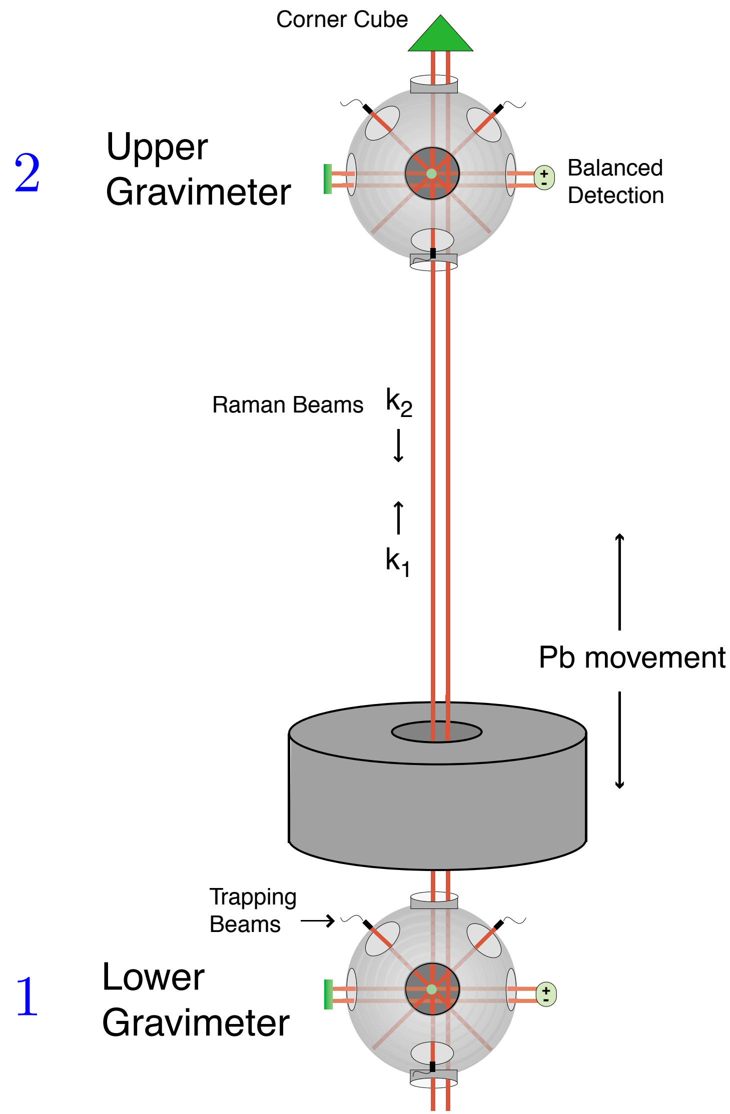
D. Schlippert,[1] J. Hartwig,[1] H. Albers,[1] L. L. Richardson,[1] C. Schubert,[1] A. Roura,[2] W. P. Schleich,[2,3] W. Ertmer,[1] and E. M. Rasel[1*]



- simultaneous differential measurement
- *common* mirror → effect of *vibration noise* highly suppressed
- Eötvös parameter: $\eta_{\mathrm{Rb,K}} < 5 \cdot 10^{-7}$
  improved bounds for *dilaton models* and *SME*
- Future plans for dedicated space mission:

$$\eta_{\mathrm{AB}} \lesssim 10^{-15}$$

Gradiometry and measurements of G



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

- differential measurement
- *common-mode* noise suppression
- determination of the gravity gradient

$$\Gamma_{zz} = -\frac{\partial^2 U}{\partial z \, \partial z} \approx -\frac{g_2 - g_1}{z_2 - z_1}$$

- *changing position* of well-characterized source mass → measurement of G

$$\Delta G/G \approx 1.5 \times 10^{-4}$$

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

Long-time interferometry

- Higher sensitivity → long-time interferometry

$$\delta\phi = k_{\rm eff}\, a\, T^2$$

- Natural compact set-ups in microgravity platforms (*freely falling frame*)

- Challenges:
  - *growing size of atom cloud* → *BECs, atomic lensing*
  - *rotations*
  - *gravity gradients* (effects grow cubically with time)

Microgravity platforms

$$\delta g \sim 10^{-5}g - 10^{-6}g$$

drop tower in Bremen
(> 500 drops)

QUANTUS (5-10 s)

sounding rocket
(23 Jan 2017)

MAIUS (6 min)

International Space Station
(late 2017-)

CAL / BECCAL
(several years)

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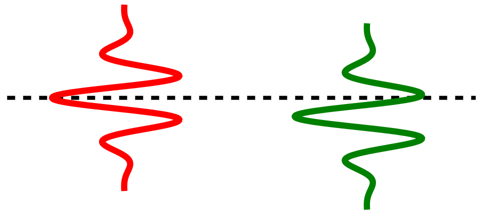
Challenges in UFF tests due to gravity gradients

Initial co-location

- *Systematics* associated with initial central position & momentum of the two species can a *mimic violation* of UFF:

$$\Delta g \sim \Gamma_{zz}\, \Delta z_0 + \Gamma_{zz}\, \Delta v_0\, T$$

$$\Gamma_{zz} \approx 3 \cdot 10^{-6}\, \mathrm{s}^2$$



$$\frac{\Delta g}{g} \lesssim 10^{-15} \;\rightarrow\; \begin{array}{l} \Delta z_0 \lesssim 1\, \mathrm{nm} \\ \Delta v_0 \lesssim 10^2\, \mathrm{pm/s} \end{array}$$

- No limitation in principle, but challenging in practice.

  Minimum time for verification set by *Heisenberg's uncertainty principle*.

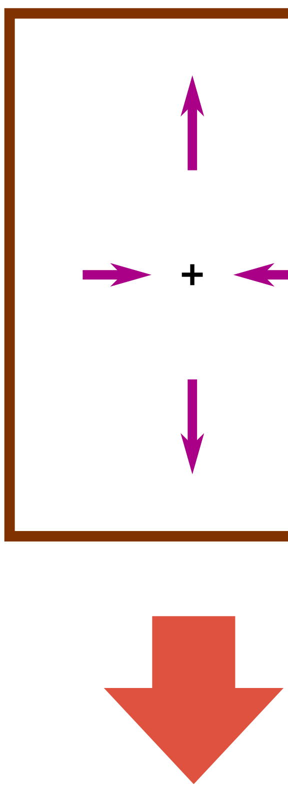
$$n\, N\, \sigma_p\, \sigma_z \;\geq\; \hbar/2$$

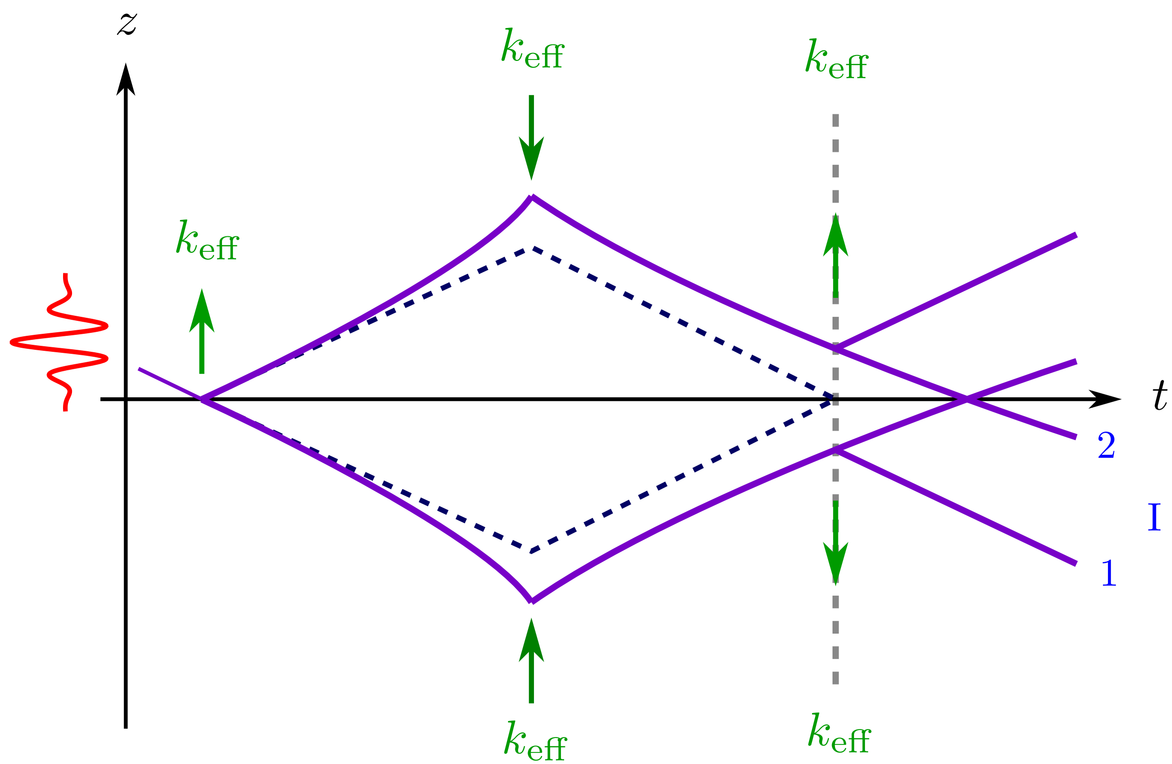
(time required may exceed entire mission lifetime)

Loss of contrast

- Gravity gradients (*tidal forces*) lead to open interferometers:

freely falling frame
(*Einstein elevator*)



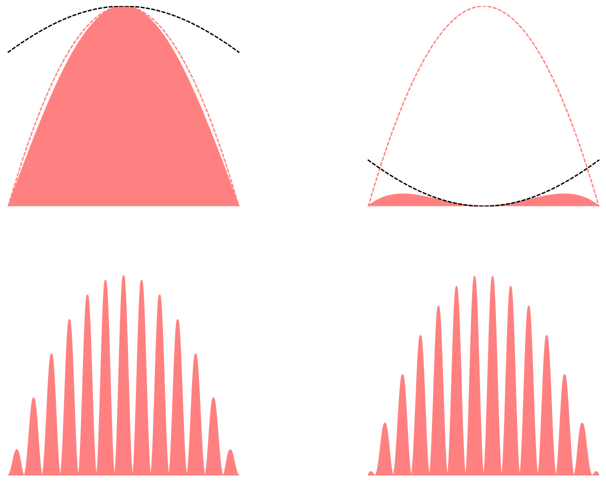


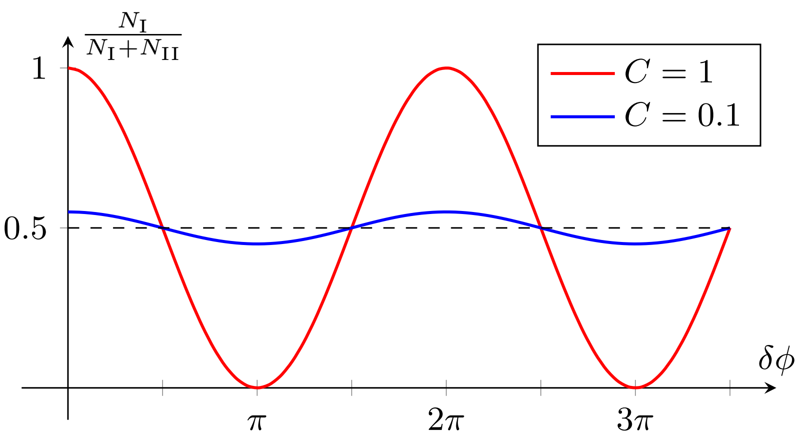
$$\delta z = \left(\Gamma_{zz}\, T^2\right) v_{\text{rec}}\, T$$

$$\delta p = \left(\Gamma_{zz}\, T^2\right) m\, v_{\text{rec}}$$

- *Relative displacement* between interfering wave packets at exit port
  → fringe pattern in density profile → loss of contrast

$$\delta z \neq 0\,,\ \ \delta p \neq 0$$



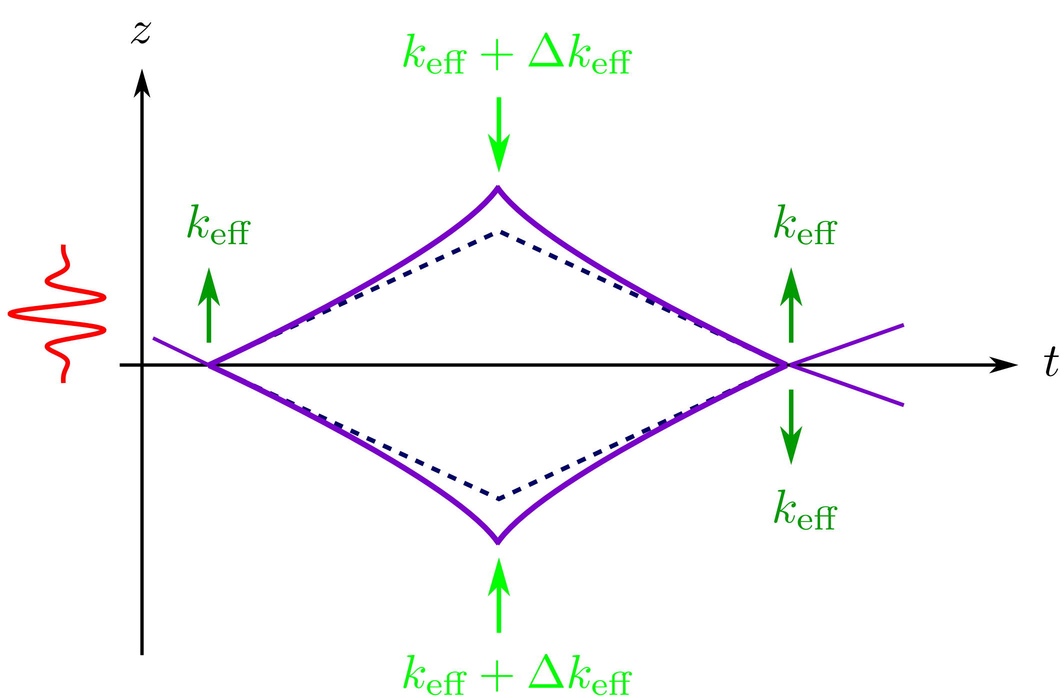


Overcoming loss of contrast and initial co-location problem

- Phase shift contribution connected with initial co-location directly related to $\delta z,\ \delta p$:

$$\delta\phi = \frac{1}{\hbar}\,\delta\mathbf{p}\cdot\big(\mathbf{x}_0 + 2\,\mathbf{v}_0 T\big) - \frac{1}{\hbar}\,\delta\mathbf{x}\cdot m\mathbf{v}_0 + \ldots$$

- Suitable adjustment of laser wavelength of *2nd pulse* ⟶ $\delta z = \delta p = 0$



$$\Delta k_{\text{eff}} = \big(\Gamma_{zz}\,T^2/2\big)\,k_{\text{eff}}$$

A. Roura, *Phys. Rev. Lett.* **118**, 160401 (2017)

Initial co-location as well as loss of contrast are simultaneously taken care of.

- Required *single-photon* frequency change:
  - for longer times in space

$$T = 5\,\mathrm{s} \longrightarrow \Delta\nu \sim 14\,\mathrm{GHz}$$

  - for moderate times (and higher $k_{\rm eff} = 2n\,k_{\rm ph}$) AOMs may be sufficient

$$2n = 50 \qquad T = 1\,\mathrm{s} \longrightarrow \Delta\nu \sim 0.6\,\mathrm{GHz}$$

- Dependence on the mirror position, but highly *suppressed* in the *differential* measurement.

PRL **118,** 160401 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Circumventing Heisenberg's Uncertainty Principle in Atom Interferometry Tests of the Equivalence Principle

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- Besides tests of UFF, application to gradiometry measurements: (*relaxing* coupling of static Γ to *initial-position/velocity jitter & bias*)
  - *mapping* of *Earth's gravitational field* from space
  - accurate *measurements* of G
  - *gravitational antennas*

- Several other groups have also expressed great interest:
  Stanford, *Florence*, *SYRTE* and *LKB/ENS* (*Paris*)

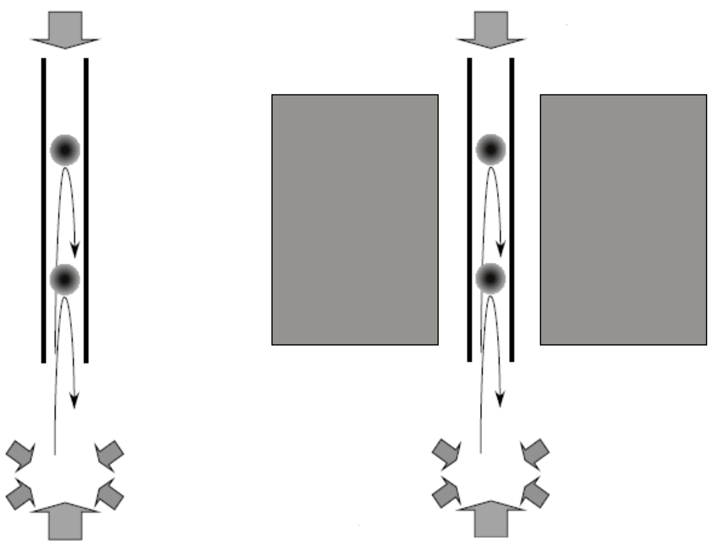
- Atomic fountain experiments in *Stanford's 10-meter tower*

- *gravity-gradient compensation* scheme successfully implemented
- very effective in overcoming the *initial-colocation* problem
- key ingredient in efforts to test UFF with *atom interferometry* at 10^{-14} level

Gradiometry & determination of G

- One can use the technique to cancel the effect of *static* gravity gradients in measurement of *time-dependent* ones.
- Also for measurements of *static gravity gradients* *insensitive* to *initial position & velocity*:

G. Rosi, *Metrologia* (2017)



vanishing *gradiometry phase* for

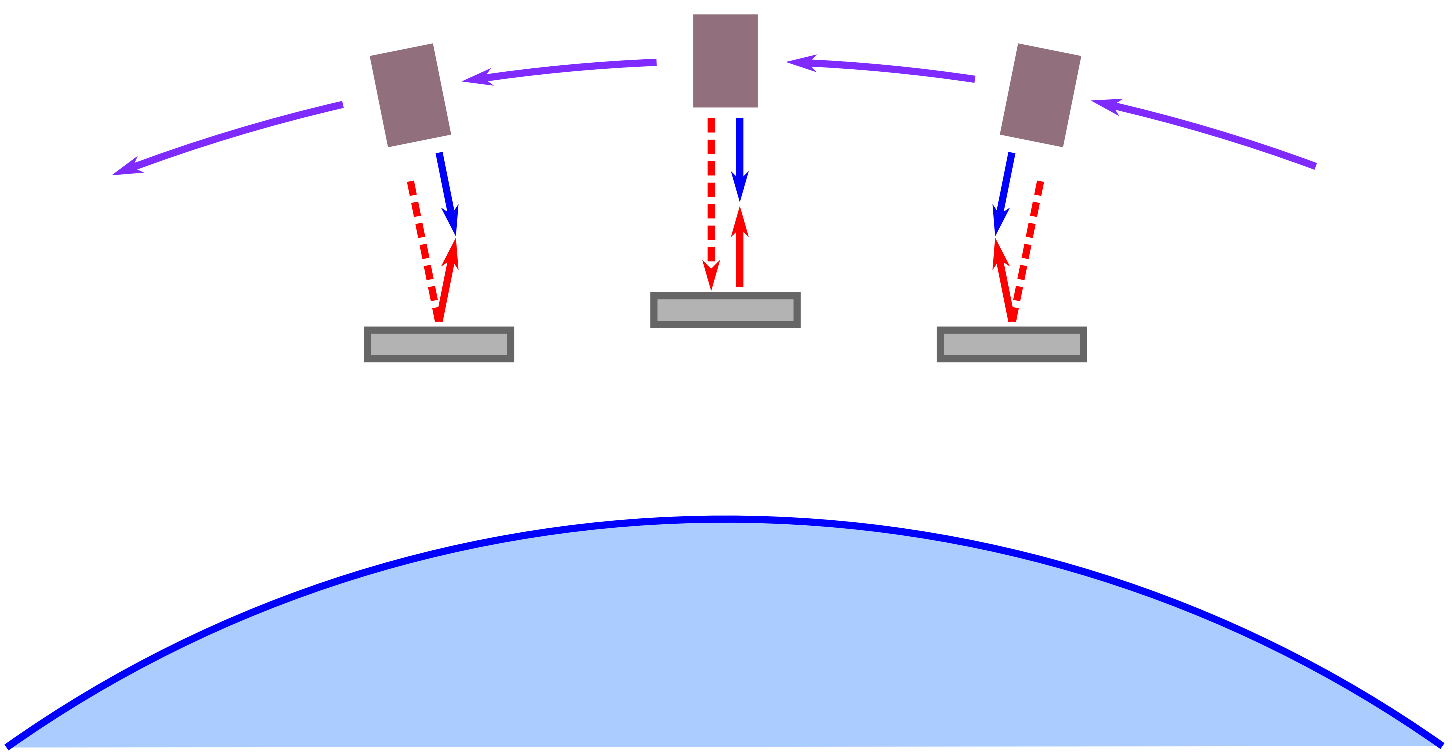
$$\Delta\nu = \frac{c}{4\pi}\left(\Gamma_{zz}\,T^2/2\right) k_{\text{eff}}$$

G. D'Amico *et al.* (submitted)

(application to determination of G)

Compensation of large rotation rates

- Compensation of rotations with a tip-tilt mirror as seen from a *non-rotating frame*:

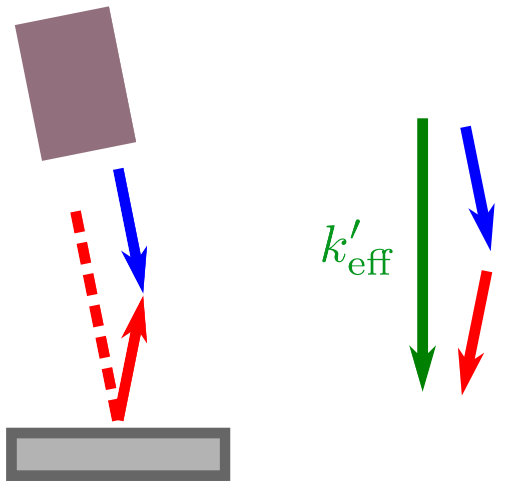


- Tip-tilt mirror leads to change in $k_{\rm eff}$ along the *longitudinal* direction:

$$k_{\rm eff} \;\rightarrow\; k'_{\rm eff} = \cos(\Omega T)\, k_{\rm eff}$$

- It can be compensated with following change for the second pulse:

$$\Delta k_{\rm eff} \;\approx\; -(1/2)(\Omega\, T)^2\, k_{\rm eff}$$



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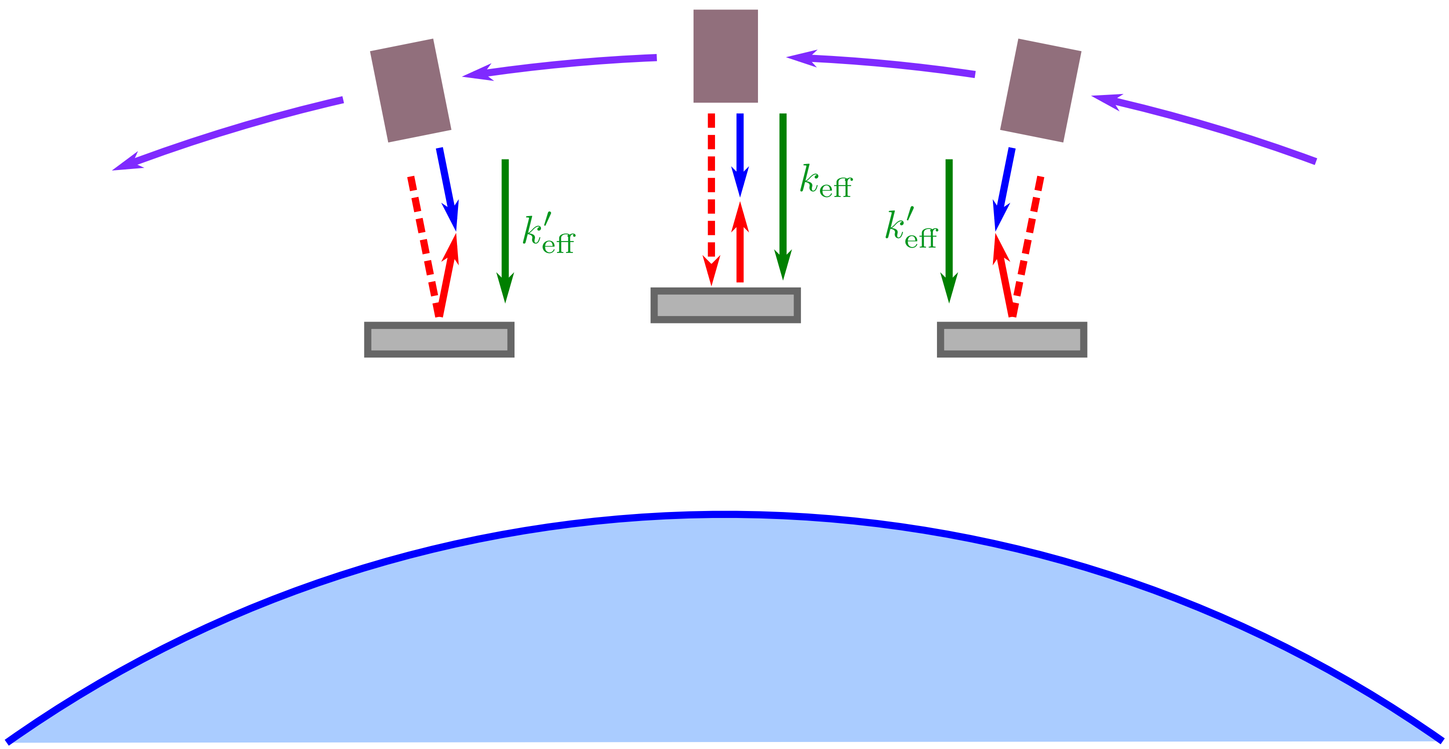

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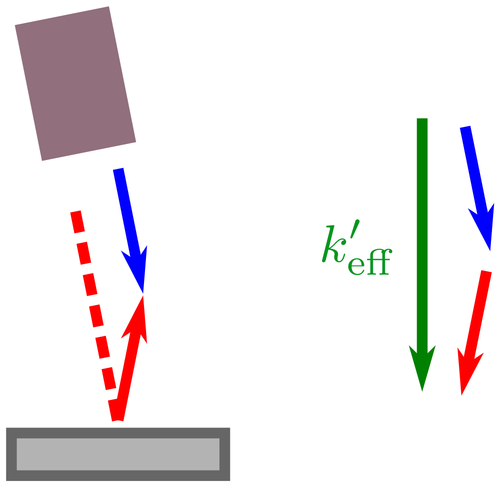
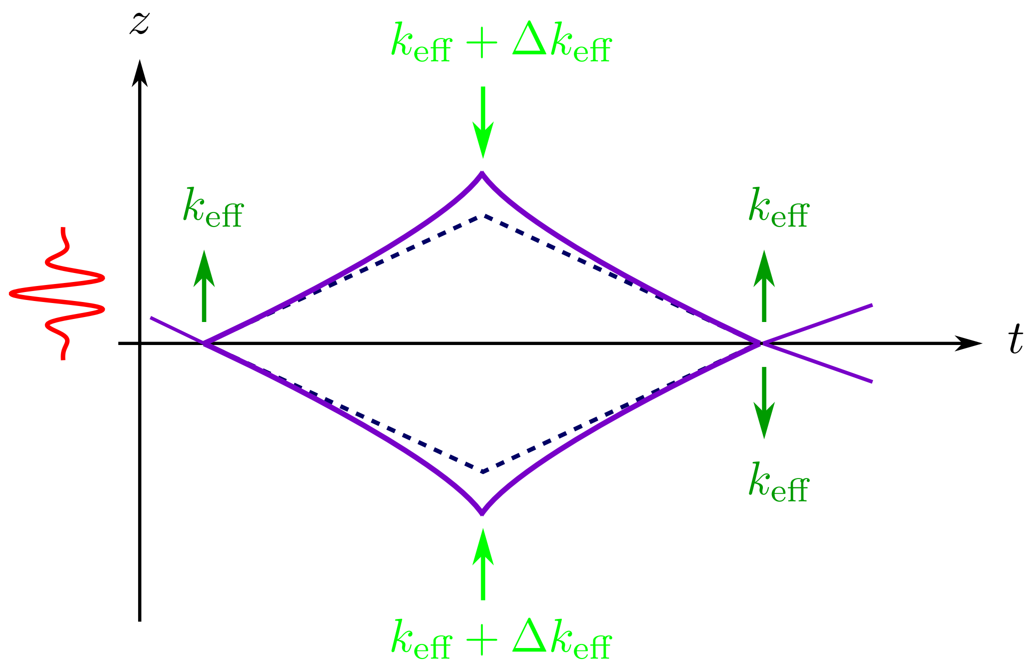


- Simultaneous compensation of gravity gradients and large rotation rates:



$$\Delta k_{\text{eff}} = \left(\Gamma_{zz} T^2/2\right) k_{\text{eff}} - (1/2)(\Omega T)^2 k_{\text{eff}}$$

- Quantitative example for BECCAL
  - ISS's *angular velocity* and *gravity gradient*:

$$\Omega_{\mathrm{ISS}} \approx 1.13\,\mathrm{mrad/s}$$

$$\Gamma \approx 2.5 \times 10^{-6}\ \mathrm{s}^{-2}$$

  - required frequency change for $T = 2.6\,\mathrm{s}$:

$$\Delta\nu \approx 1.5\,\mathrm{GHz}$$

(partial cancellation)

Conclusion

- Gradiometry and tests of UFF based on AI can provide a useful complement to those based on macroscopic masses.

- Gravity gradients pose a great challenge in practice as well as an ultimate limitation from *HUP* due to:
    - *initial co-location* of the two species
    - *loss of contrast*

- I have presented a novel scheme that can simultaneously overcome both difficulties.

- It can be combined with a *tip-tilt mirror* to compensate large rotation rates.

Thank you for your attention.

Gefördert durch:

Bundesministerium
für Wirtschaft
und Energie

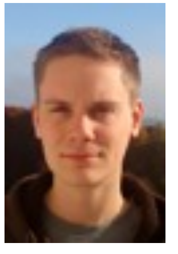
aufgrund eines Beschlusses
des Deutschen Bundestages

QUANTUS group @ Ulm University

Wolfgang Schleich

Albert Roura

Wolfgang Zeller



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Matthias Meister

Christian Ufrecht

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