Mobile quantum gravity sensor with unprecedented stability

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Gravimetric atom interferometer GAIN

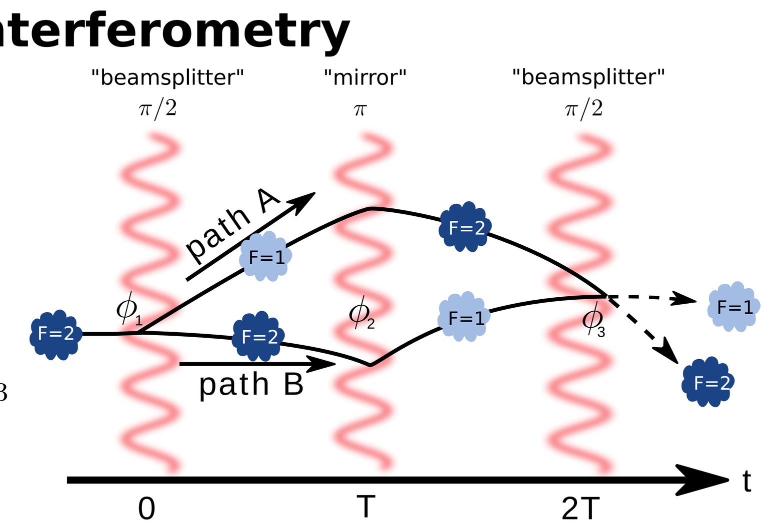
The **gravimetric atom interferometer GAIN** is a mobile sensor that uses atom interferometry based on stimulated Raman transitions to measure Earth's gravity. It's performance has been tested against other state-of-the-art gravimeters in two comparison campaigns. To our knowledge, GAIN's long-term stability of 0.5 nm/s^2 is the best value of an absolute gravimeter published in literature.

Atom interferometry

Mach-Zehnder sequence of Raman pulses (T = 260 ms)

Local laser phase ϕ_i imprinted onto atoms connects interferometer phase with gravity:

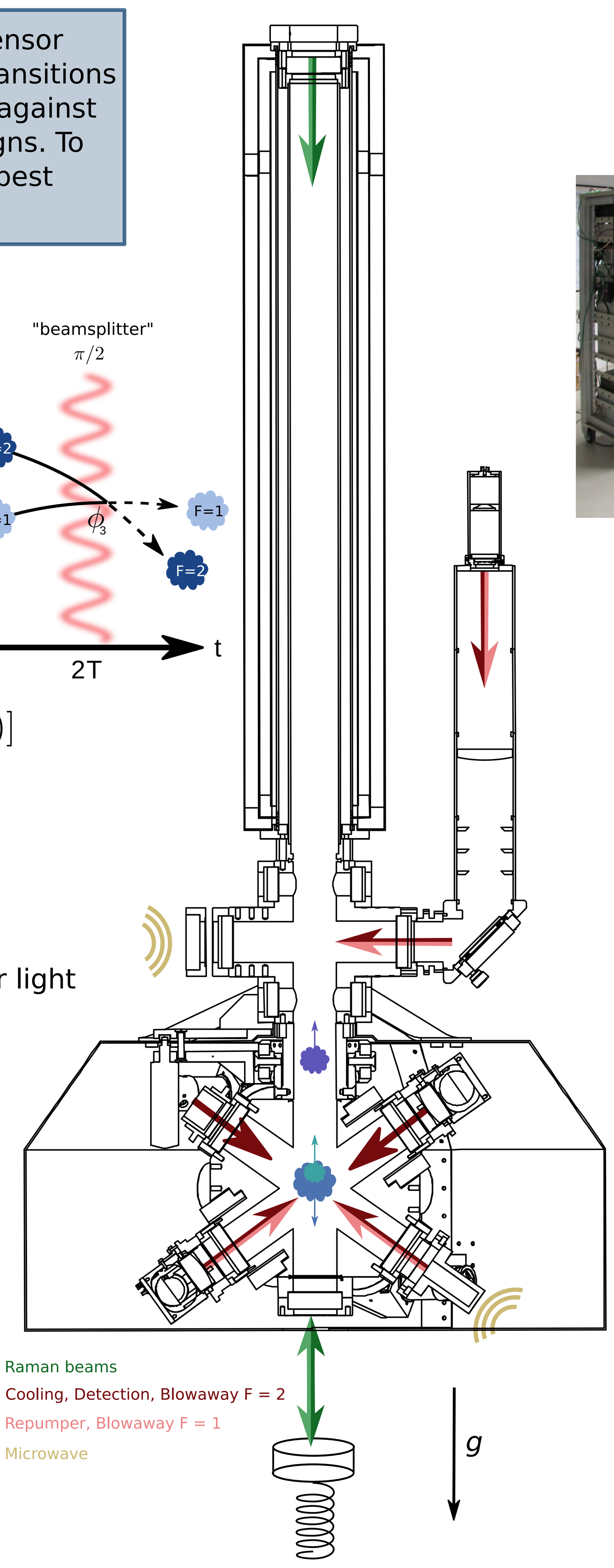
$$\Delta\Phi = -\boldsymbol{k}_{\text{eff}} \cdot \boldsymbol{g} \cdot T^2 = \phi_1 - 2 \cdot \phi_2 + \phi_3$$



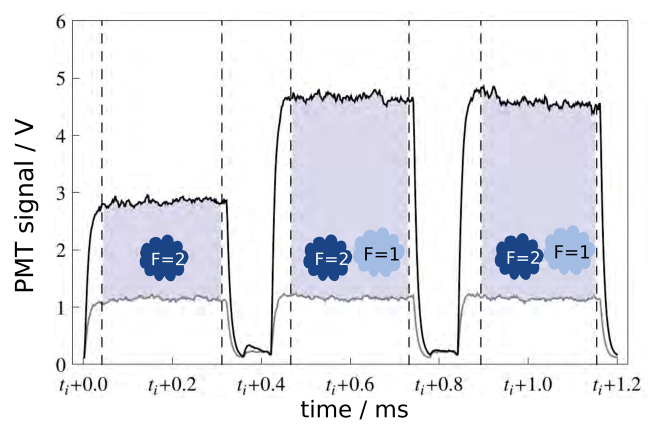
Interferometer phase is encoded in population of states:

$$P_{|F=2\rangle} = \frac{1}{2}\left[1 + C \cdot \cos\left(\Delta\Phi + \Delta\phi_{\text{chirp}} + \Delta\phi_{\text{offset}}\right)\right]$$

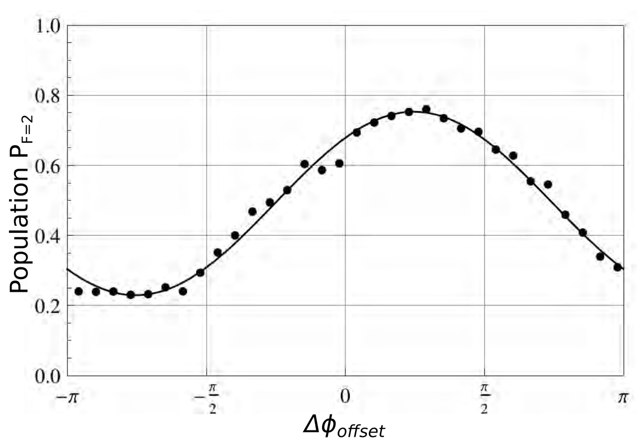
(C: contrast, $\Delta\phi_{\text{chirp}}$: Doppler shift compensation, $\Delta\phi_{\text{offset}}$: fringe scanning)



Fluorescence detection



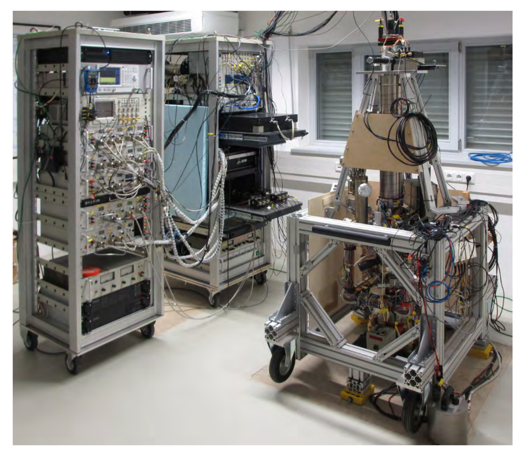
- Detection pulses with intermediate repumper light
- Fluorescence light collected on photo-multiplier tube.



- Variable phase offset $\Delta\phi_{\text{offset}}$ of last interferometer pulse for fringe scanning

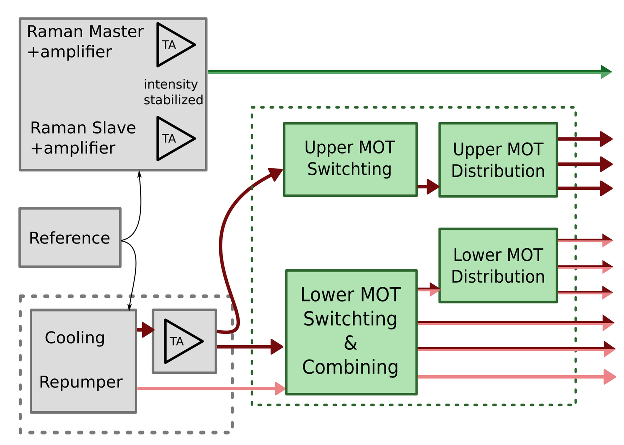
Mobile setup

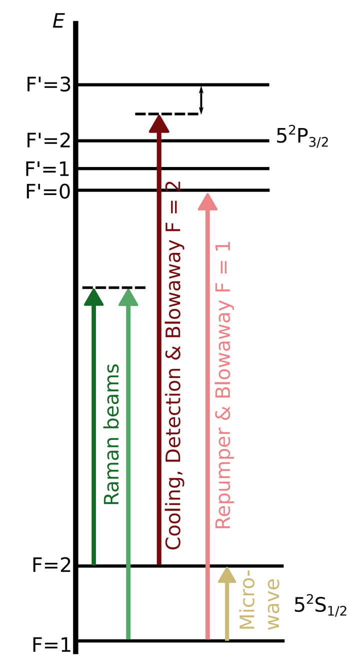
- physics package
- electronics rack
- laser rack



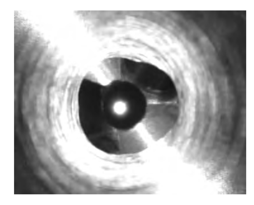
Laser system

- 780 nm ECDL and DFB lasers
- modular design
- transport-stable setup



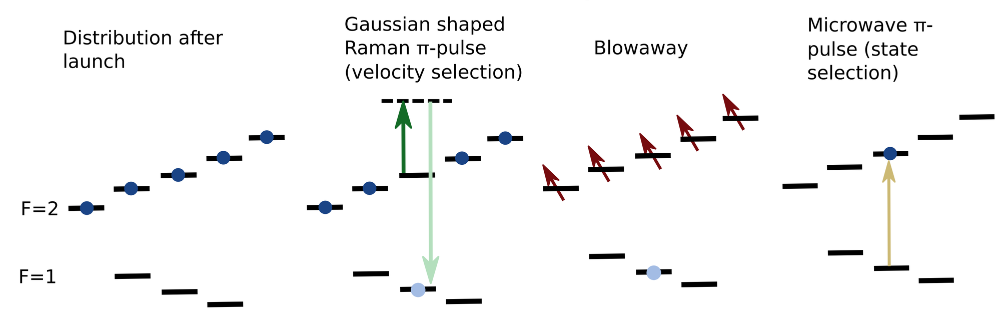


Cooling and preparation of atoms

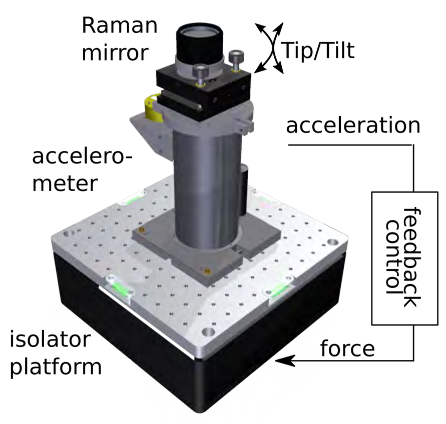


Load some 10^8 ^{87}Rb atoms in 0.6 s in magneto-optical trap, cool to 2 − 3 μK and launch with moving molasses technique

Select small vertical velocity spread (~150 nK) with Raman transition, discard other atoms, prepare in F=2, m_F=0 with microwave:

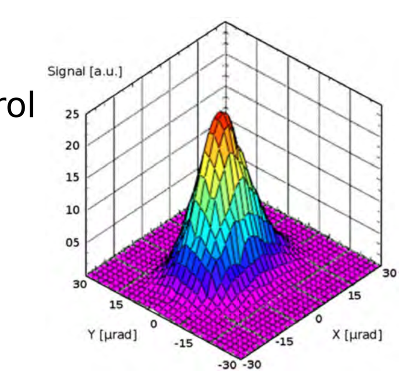


Active vibration isolation and Tip/Tilt stage



Modified minusK vibration isolation platform with active feedback control

Piezo Tip/Tilt stage:
- counteracting Coriolis effect
- active tilt stabilization by back-coupling into fiber (right)

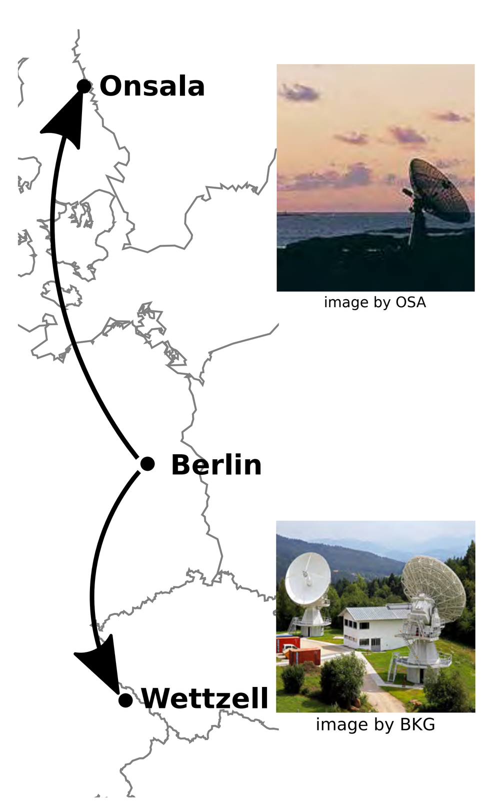


Campaigns & Performance

Campaigns

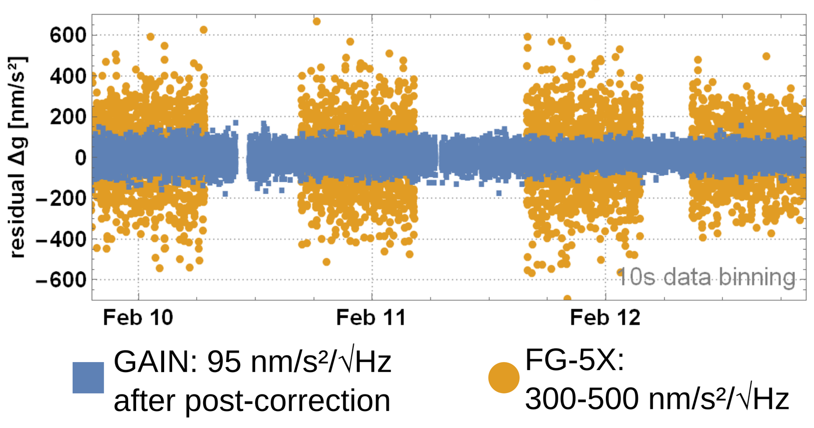
Two comparison campaigns with relative superconducting (SG) and absolute falling corner-cube (FG-5(X)) gravimeters [1]:

- Onsala Space Observatory (2015)

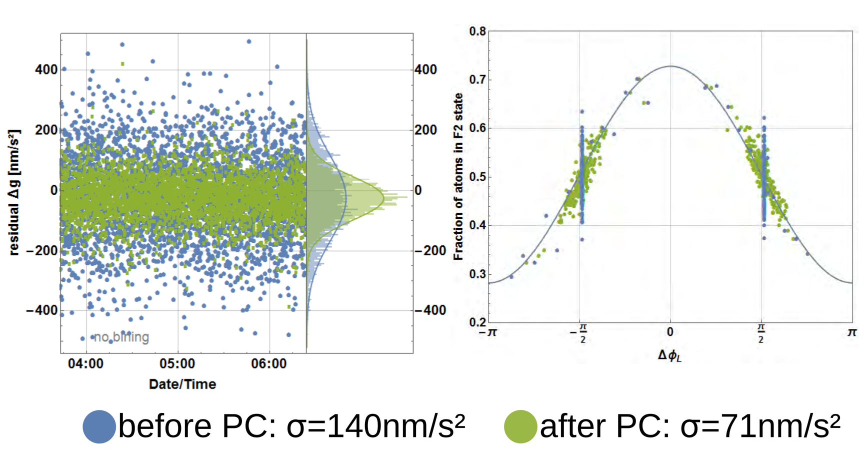


- Geodetic Observatory Wettzell (2013)

Sensitivity

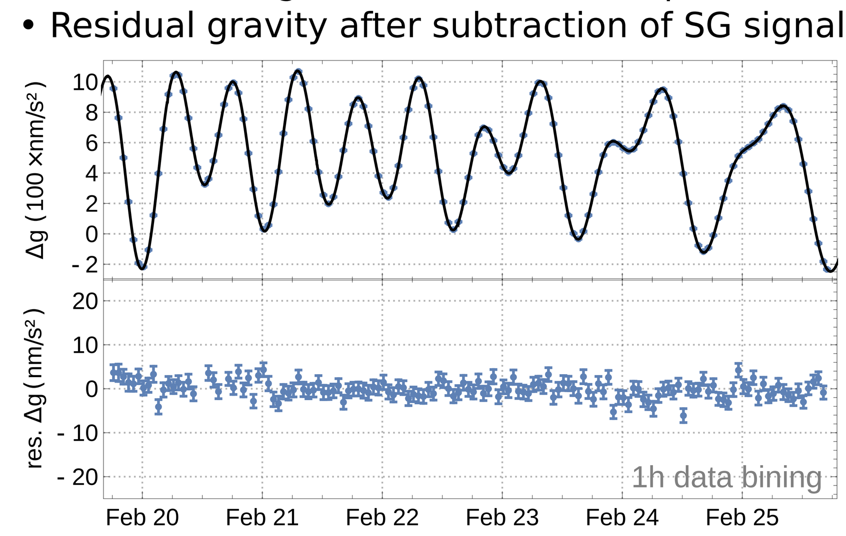


- Repetition time 1.5 s (FG-5: 10 s)
- GAIN phase noise dominated by vibrations of Raman mirror
- Post-correction [3] (PC) with data from accelerometer on vibration isolator

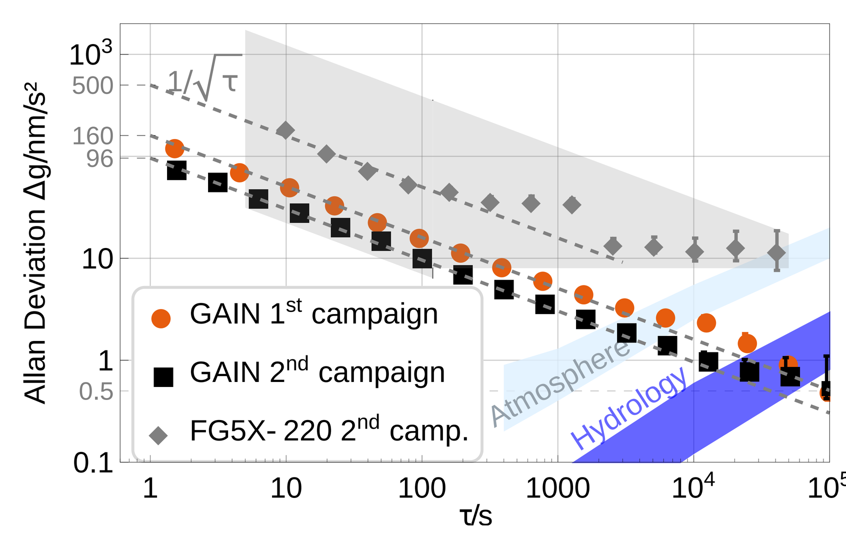


Stability

- Variations of g due to tidal & atmospheric effects
- Residual gravity after subtraction of SG signal



- Allan deviation of residuals indicate white noise
- Stability of 96 nm/s^2 / √ Hz and long-term stability of 5×10^{-11} g



Accuracy

- GAIN's gravity value slightly higher than reference/FG-5. Bias during both campaigns:

  Wettzell, 2013: (62 ± 64) nm/s^2
  Onsala, 2015: (32 ± 39) nm/s^2

- Developed method to calculate effect of Raman wavefront distortions [2], still limiting contribution
- Systematic error budget as of 2016-02:

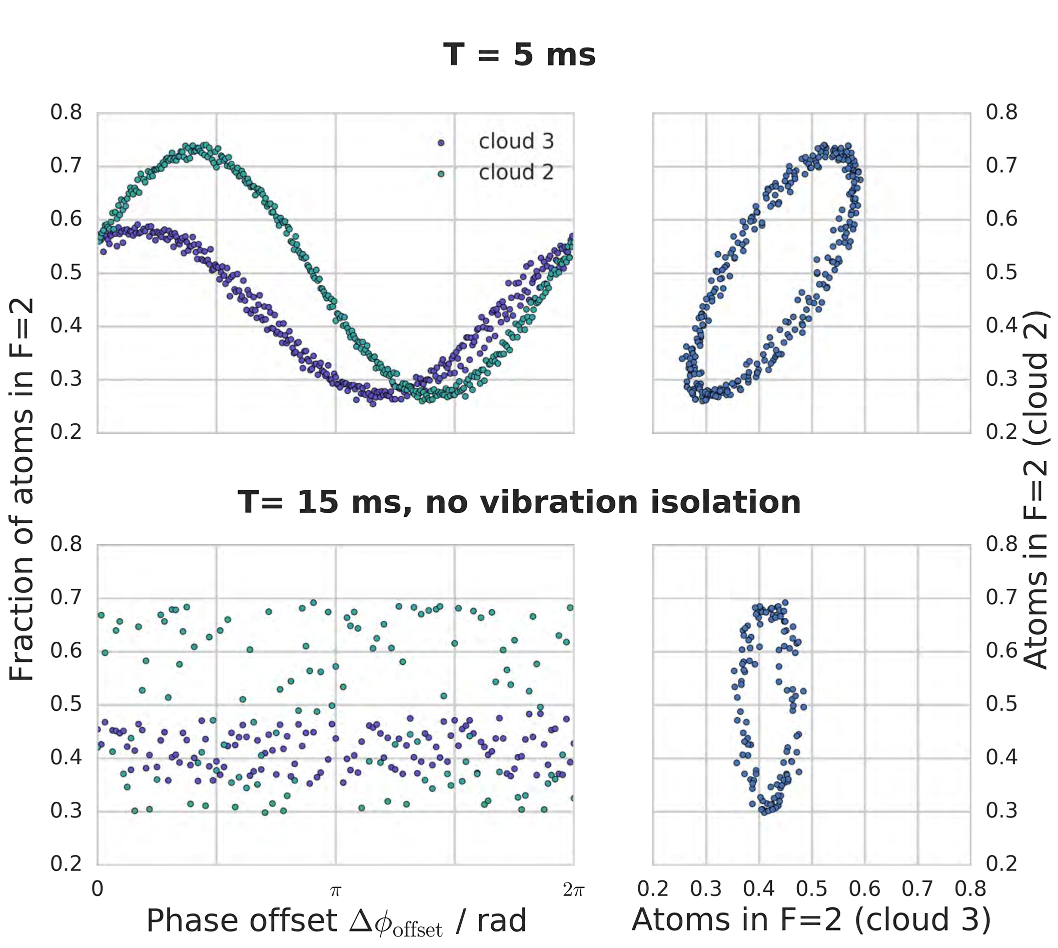
Systematic effect	Bias (nm / s²)	Error (nm / s²)
Raman wavefronts	– 28	± 22
Coriolis effect	0	± 15
Magnetic field effects	0	± 10
rf group delay	0	± 10
Self gravitation	+ 19	± 5
Reference laser frequncy	– 12 / (– 10)	± 5
Synchronous vibrations	0 / (+ 90)	± 5 / (± 50)
AC Stark shift (1pls)	0	± 5
Rb background vapour	+ 5	± 3
AC Stark shift (2pls)	0	± 2
Vertical alignment	0 / (– 1)	± 1
Total	**– 16** / (+ 77)	**± 32** / (± 61)

Towards a gradiometer

Juggling atom fountain for differential measurements

Goal:
- Interferometry with two clouds in different vertical positions for gravity gradiometry [4]
- Applications of gradiometers include underground and resource exploration, navigation and determination of the Newton's constant G [5].

Progress at HUB:
- Increased loading rate by juggling technique [6]
- Simultaneous interference fringes of both clouds
- Suppression of common-mode noise in the differential signal
- Differential phase can be extracted from ellipse fit even when a fringe fit fails



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