Philippe BOUYER

Quantum sensors for navigation and mobile gravimetry

Quantum Delta the Netherlands
UvA
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY
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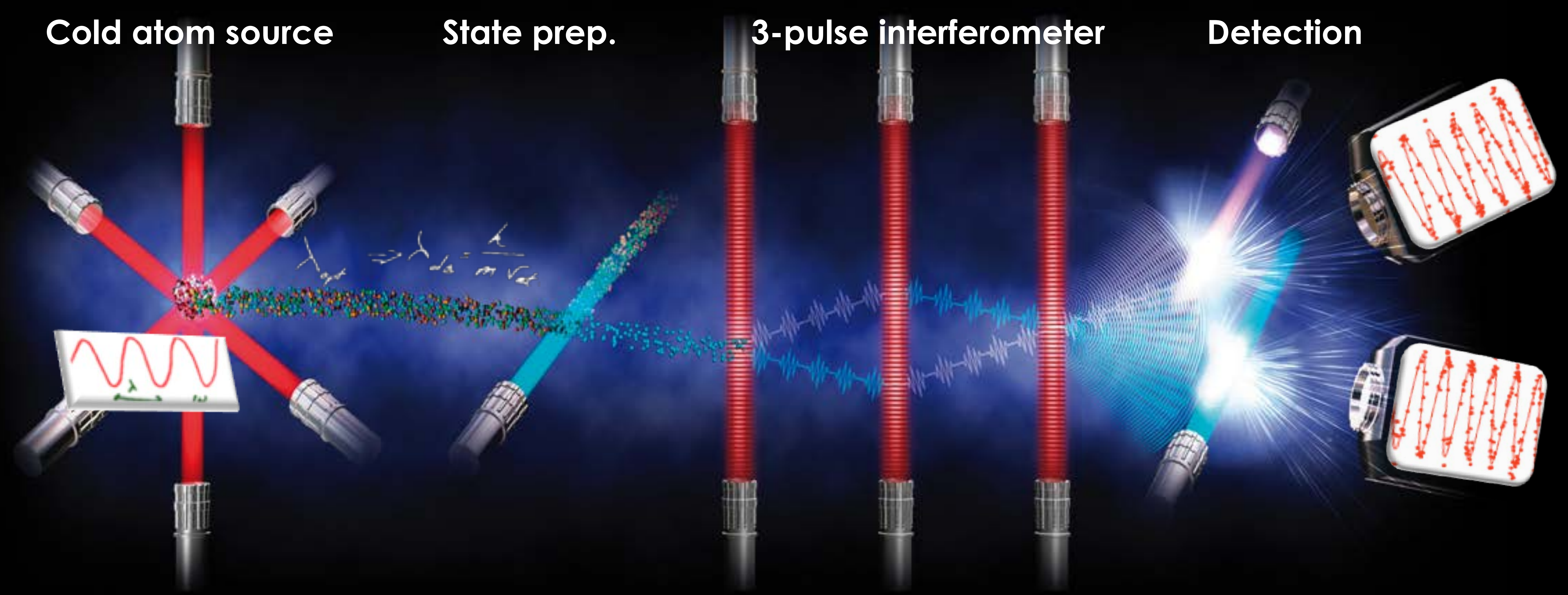
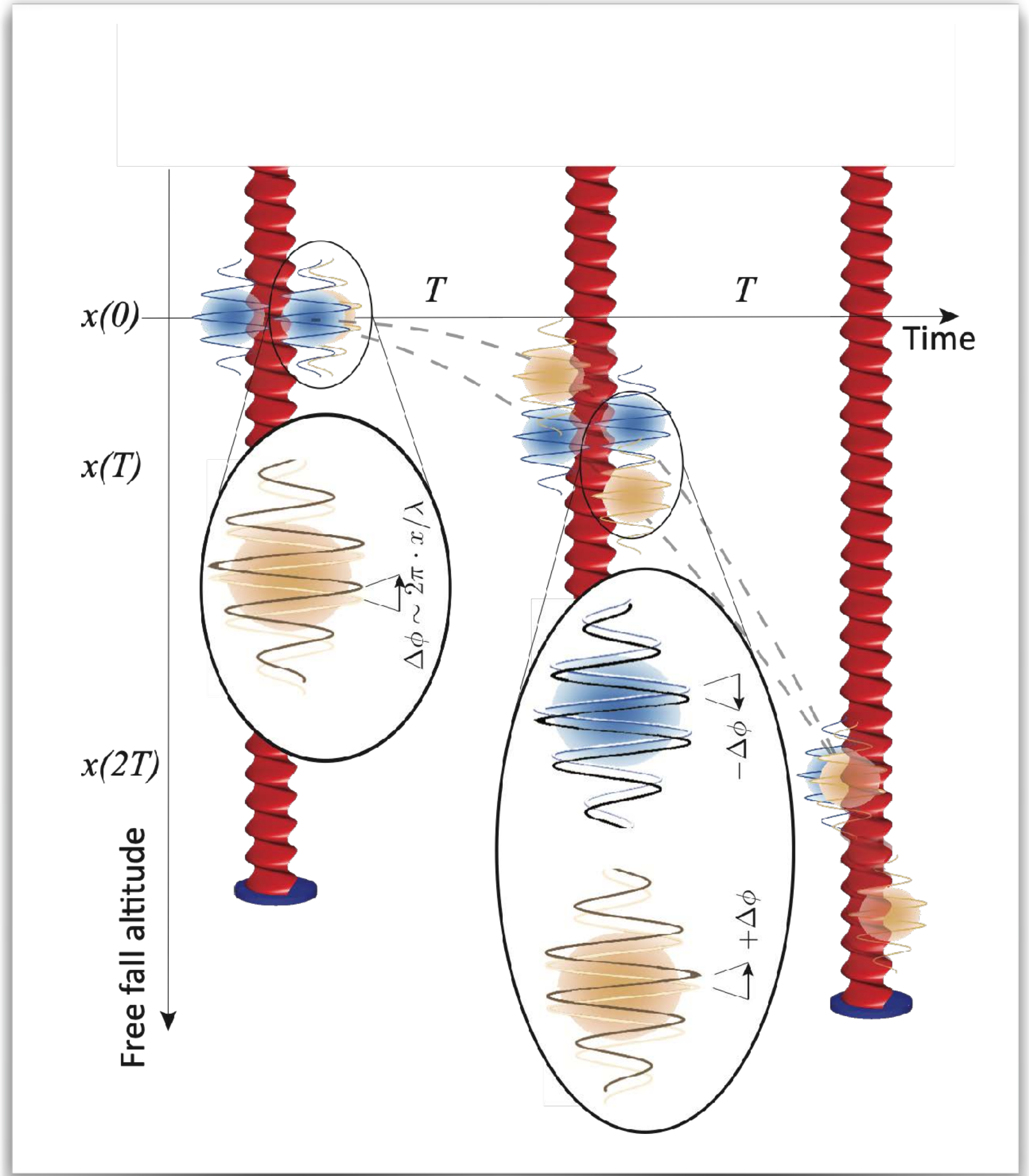
INSTITUT d'OPTIQUE GRADUATE SCHOOL
cnrs
université de BORDEAUX

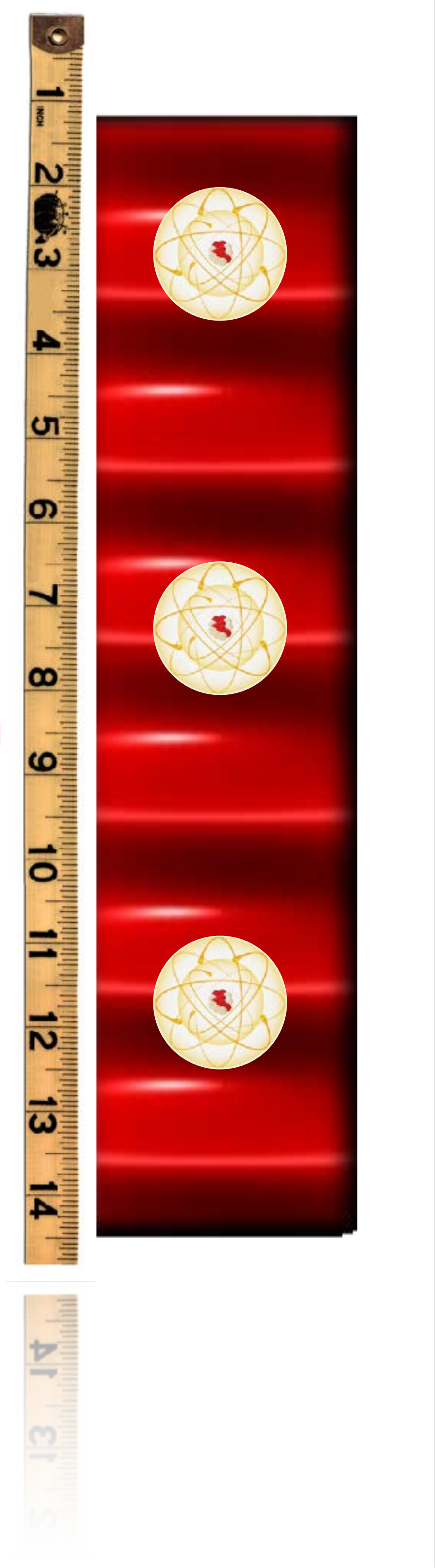
LIGHT PULSE COLD ATOMS INERTIAL SENSOR

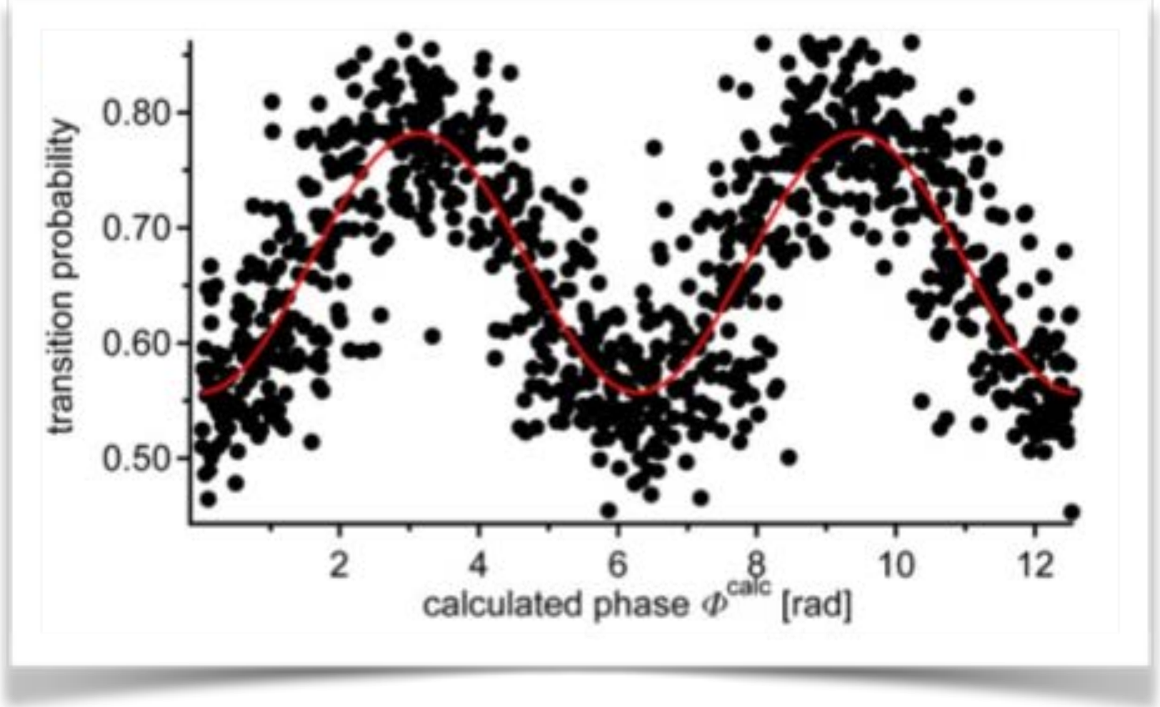


Matter-wave inertial sensor



$\cos(kx+\phi_0)$



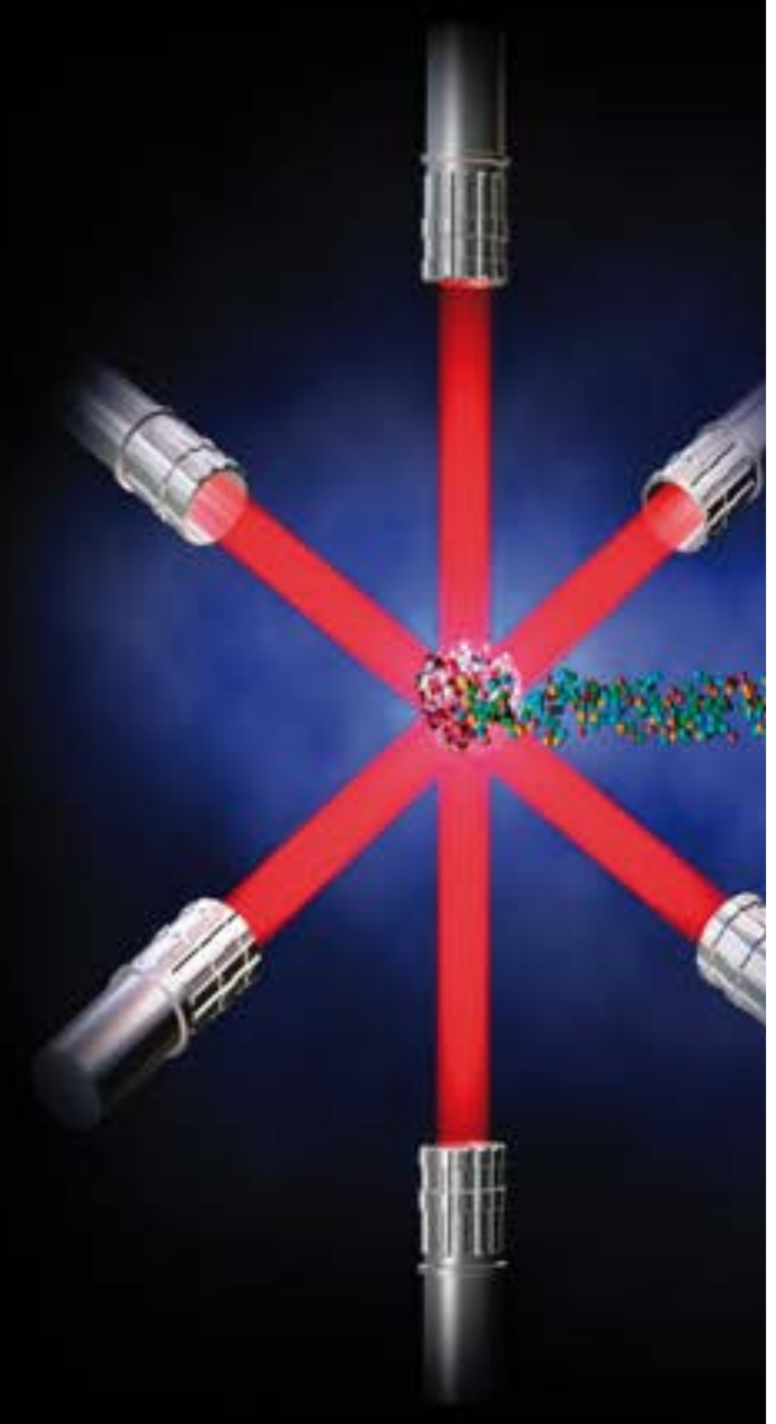


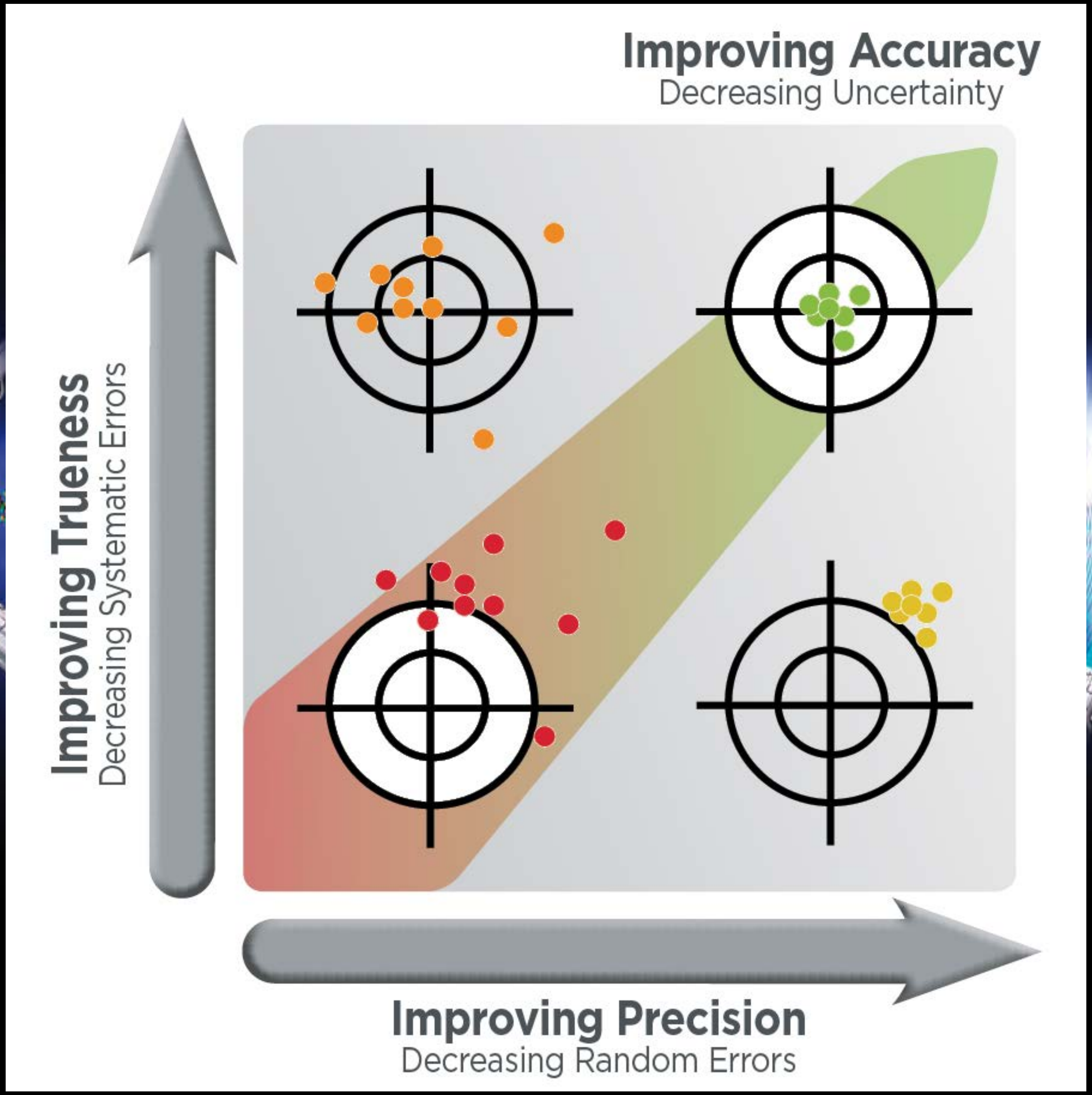
$$\Delta\phi \sim \frac{2\pi}{\lambda_{laser}} g T^2$$

- If we have a S/N ration of 1000, the sensitivity of the accelerometer is (T = 1s) :

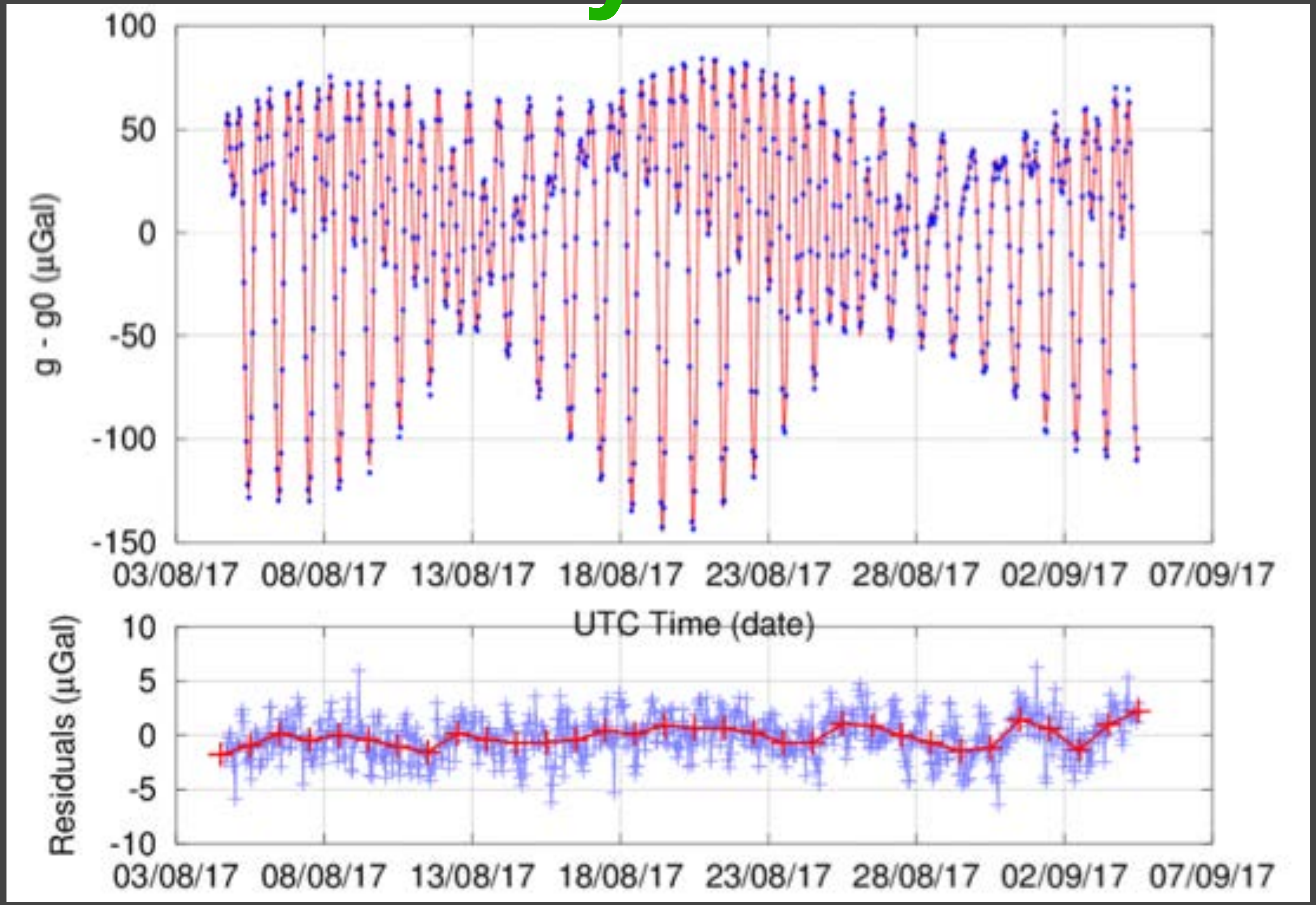
$$\Delta g_{min} \sim \frac{\lambda_{laser}}{6000}\frac{1}{T^2} \sim \frac{6\,10^{-7}}{6\,10^{3}} \sim 10^{-10}\,m.s^{-2}$$

Precision, Trueness or Accuracy and stability



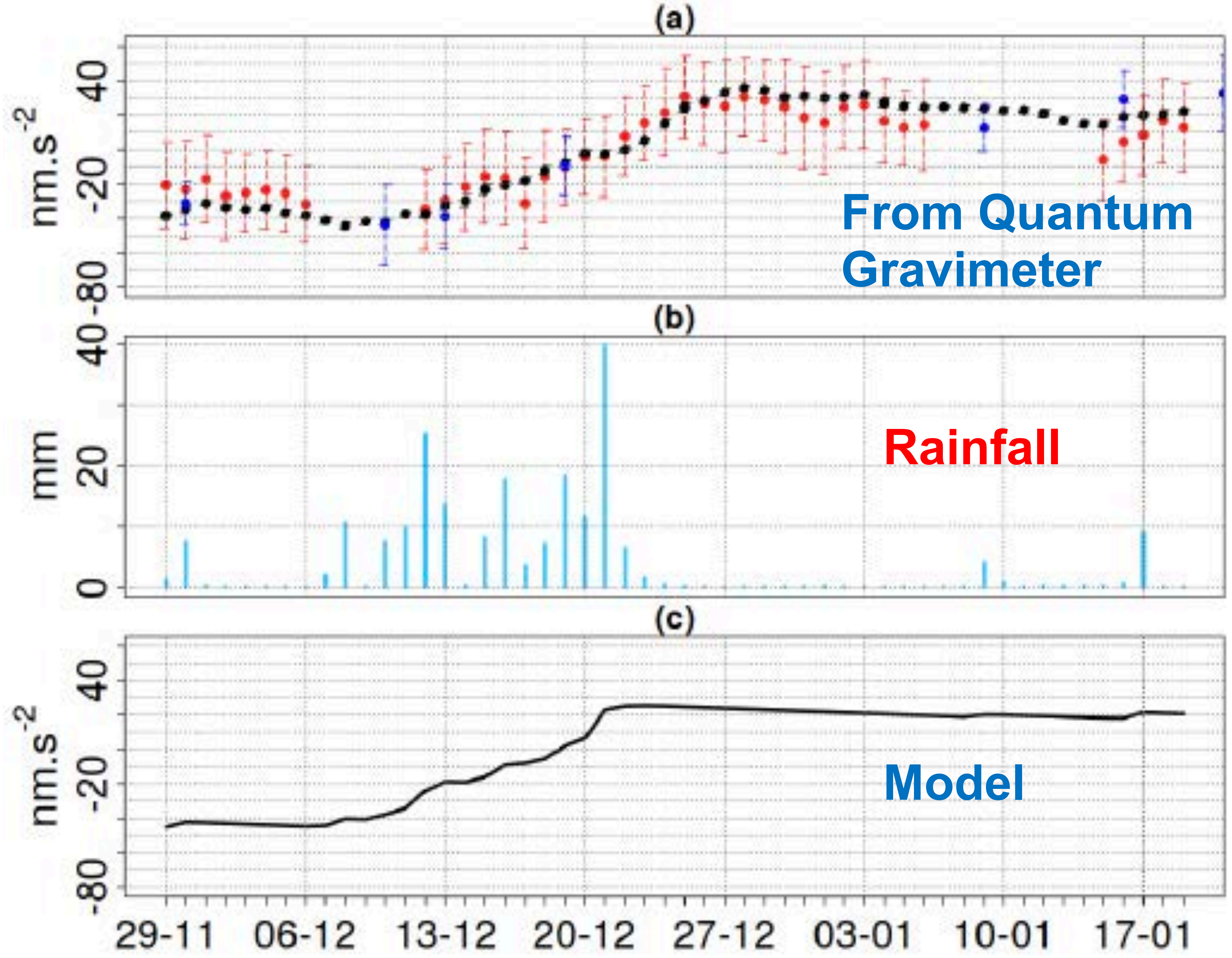


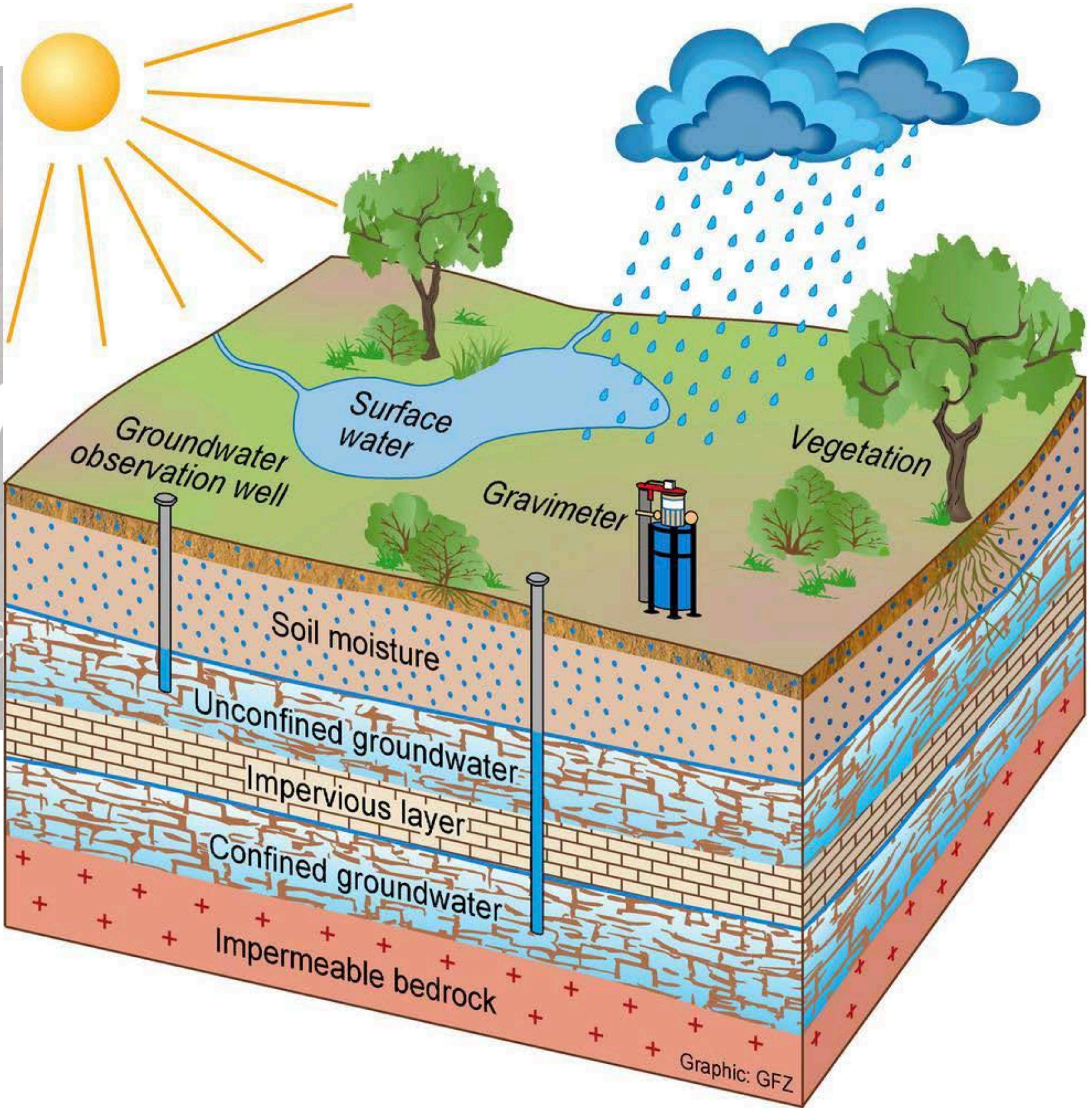
Commercially available



Menoret et al. Scientific Reports ***8****, Article number: 12300 (2018)*

Monitoring water storage



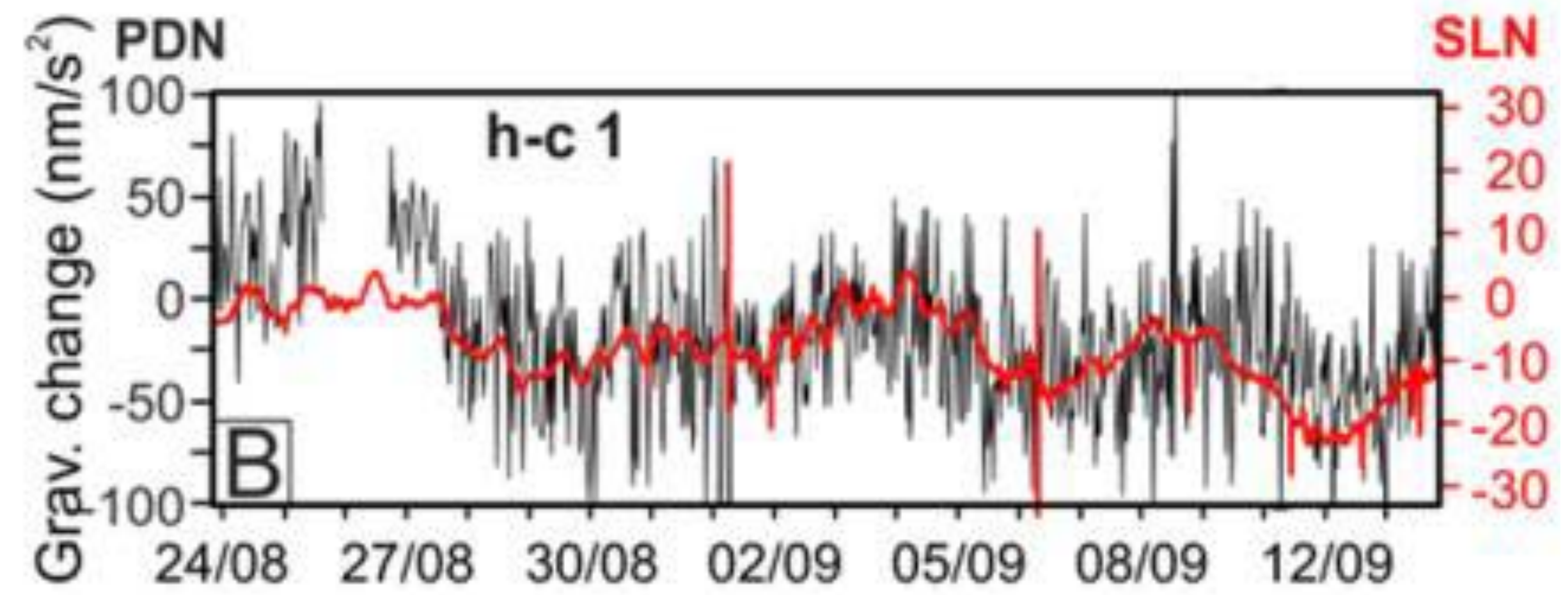


Monitoring volcano (ETNA) activity

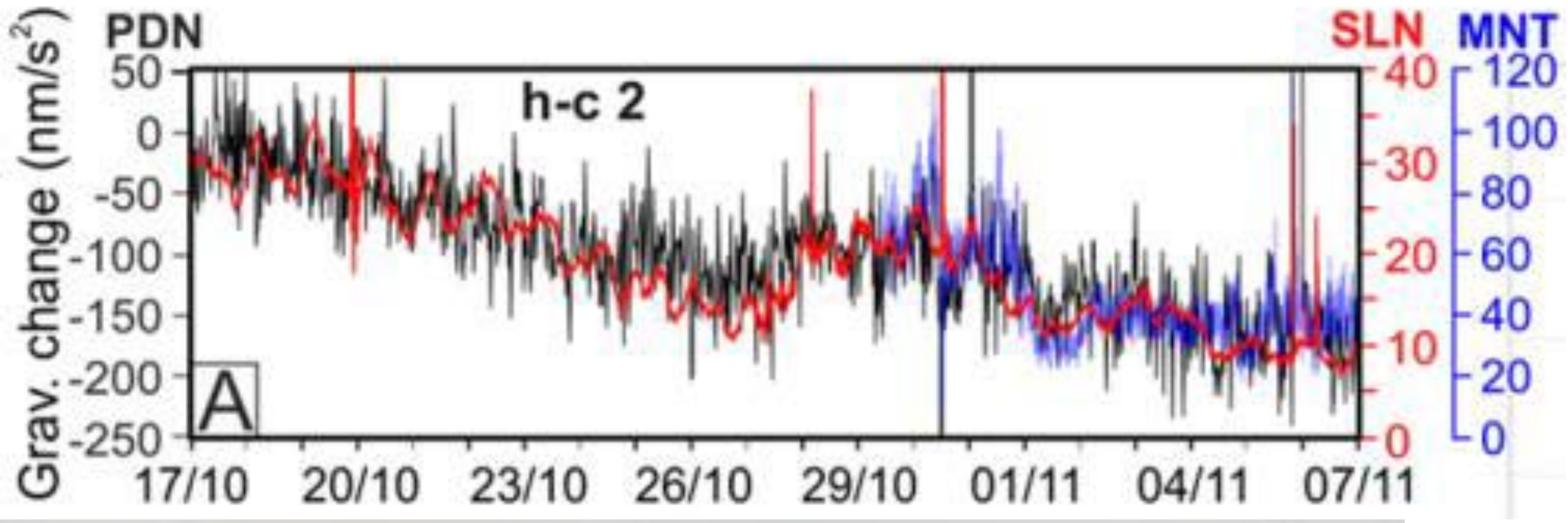
- 2800 m elevation
- 2.7 km from summit craters

Hard conditions

- Volcanic tremor
- Temperature changes
- Difficult access in summer
- No access in winter (snow)
- Dedicated off-grid power supply



Magma mass (10^{10} kg) variations 4 km below surface



Geophysical Research Letters

RESEARCH LETTER

10.1029/2022GL097814

Detecting Volcano-Related Underground Mass Changes With a Quantum Gravimeter

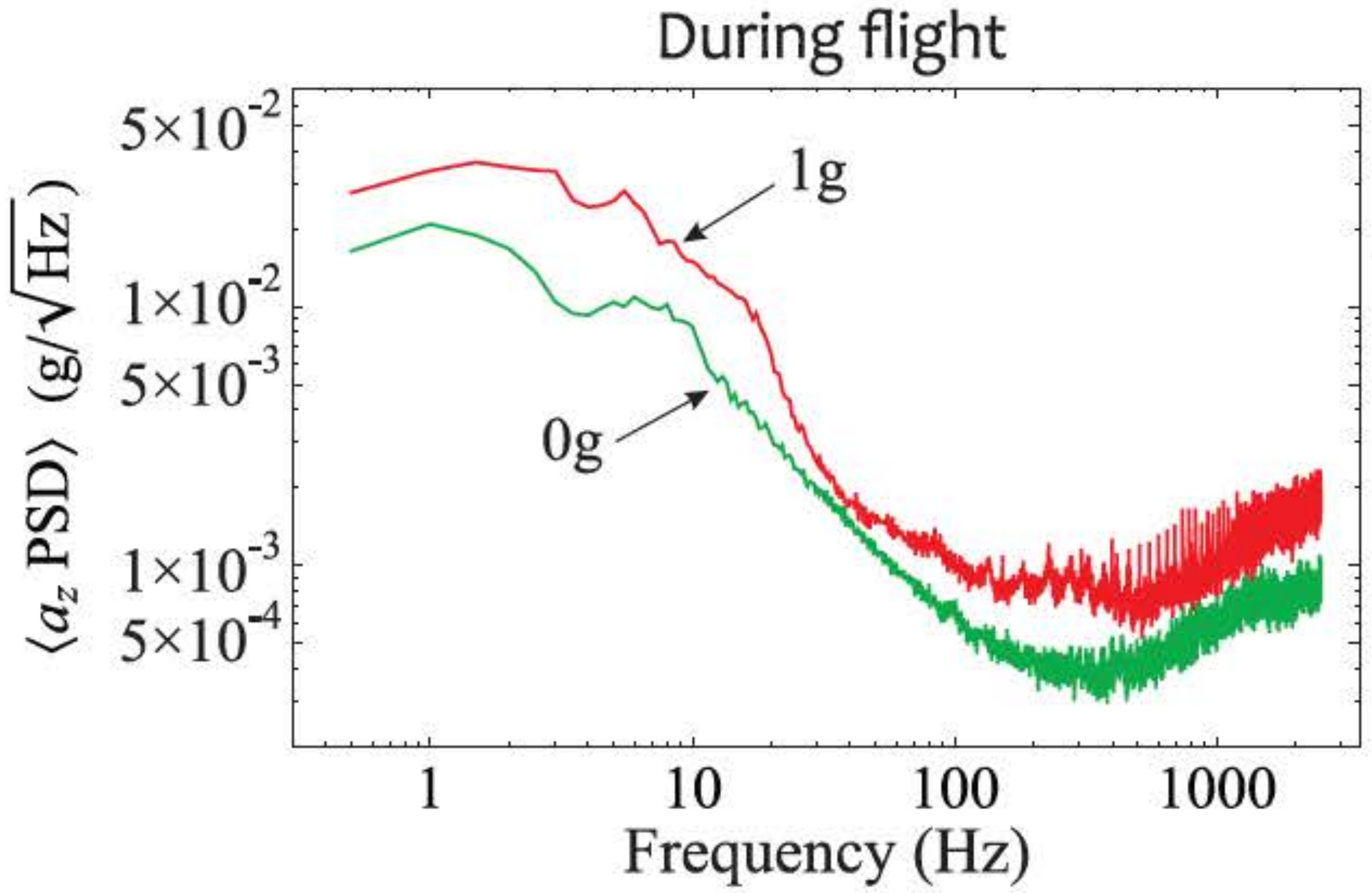
Laura Antoni-Micollier[1], Daniele Carbone[2], Vincent Ménoret[1], Jean Lautier-Gaud[1], Thomas King[2], Filippo Greco[2], Alfio Messina[2], Danilo Contrafatto[2], and Bruno Desruelle[1]

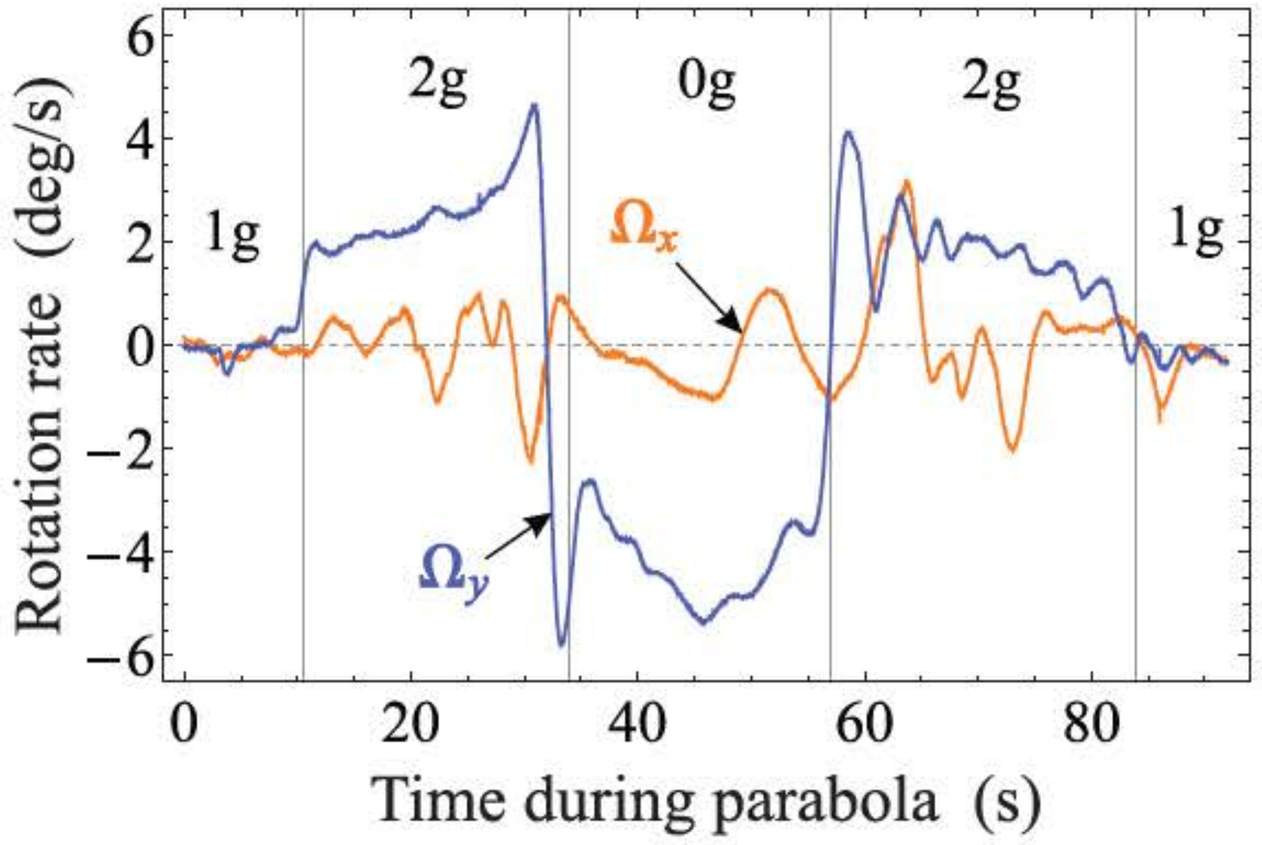
[1]iXblue, Institut d'Optique d'Aquitaine, Talence, France, [2]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania - Osservatorio Etneo, Catania, Italy

Key Points:

- We present the world's first time series acquired with an absolute quantum gravimeter in the summit crater zone of an active volcano
- Despite the unfavorable ambient

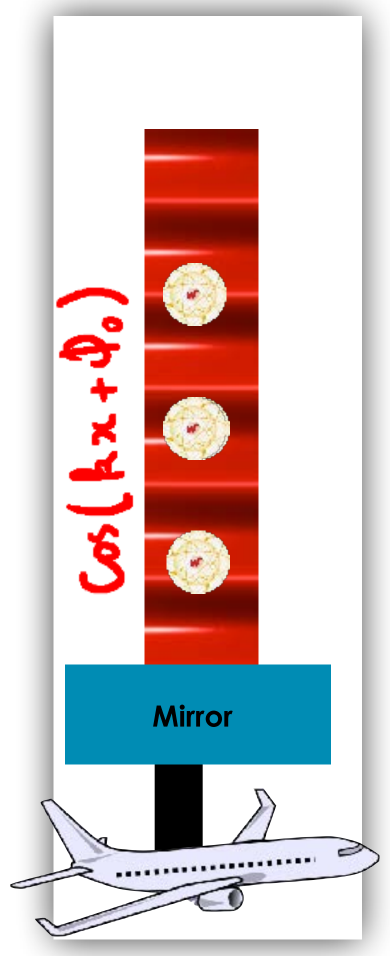
Can it work in any environment

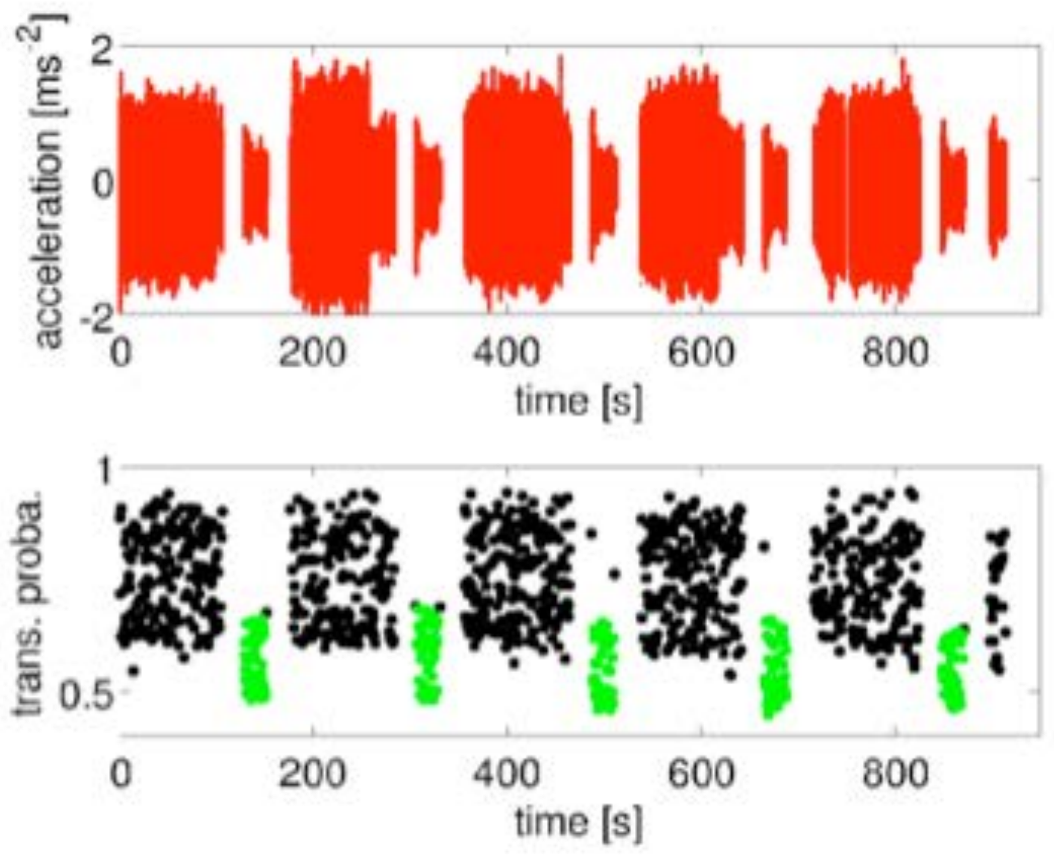


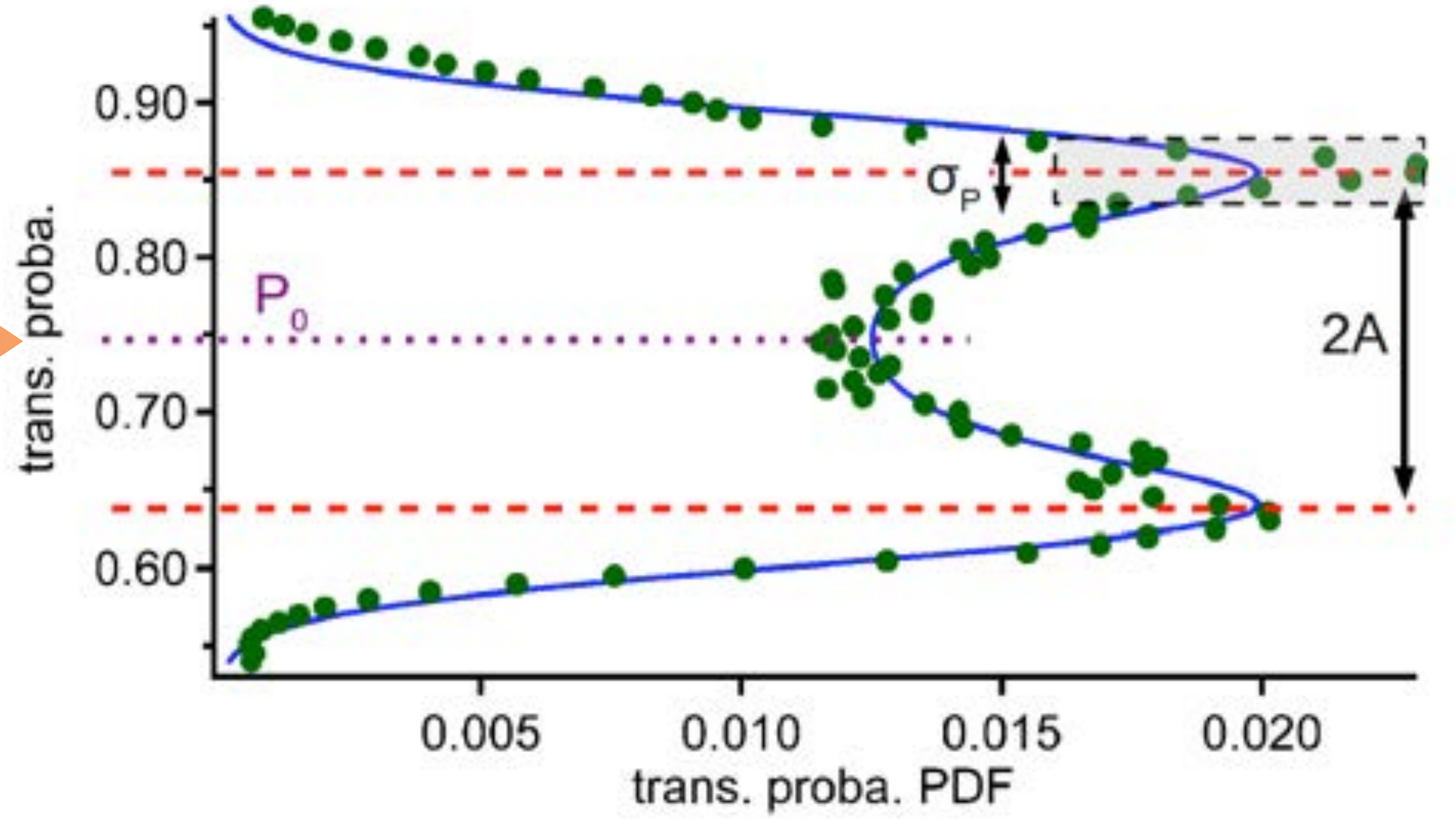


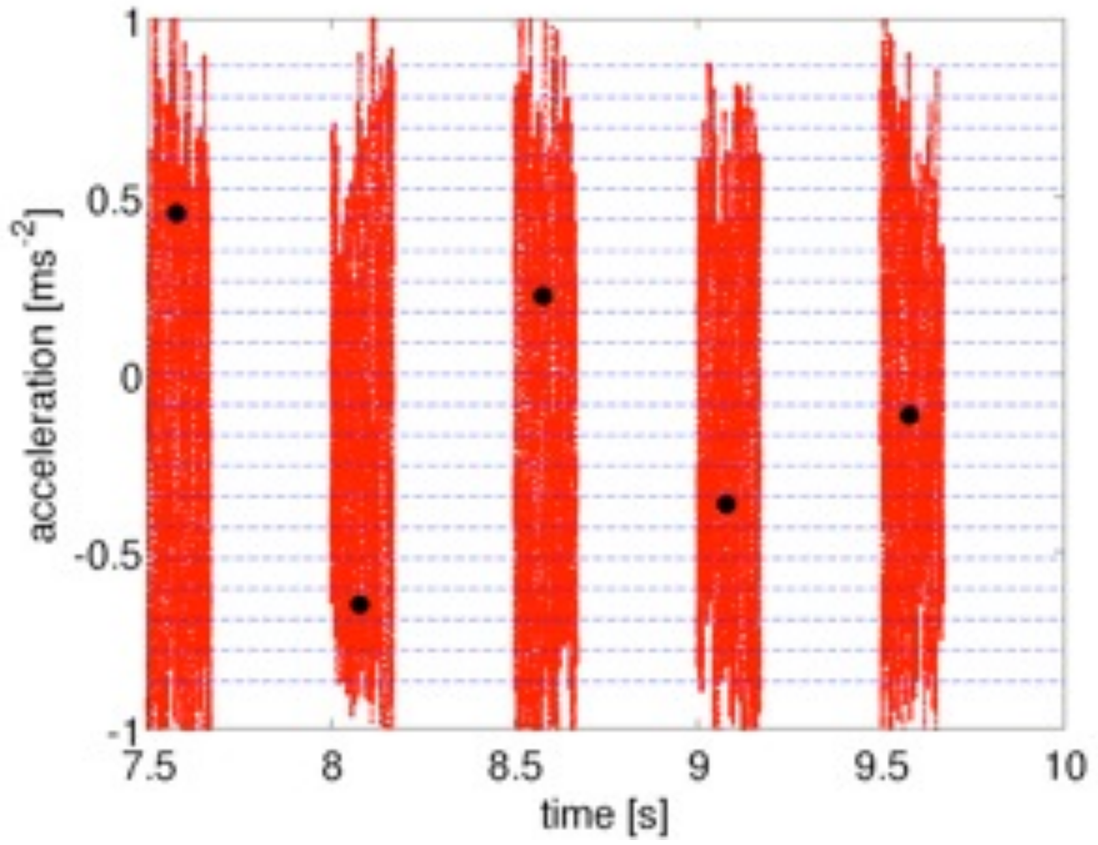
- ➩ **High rotation rate**
- ➩ **Strong vibrations**

How to cope with acceleration noise



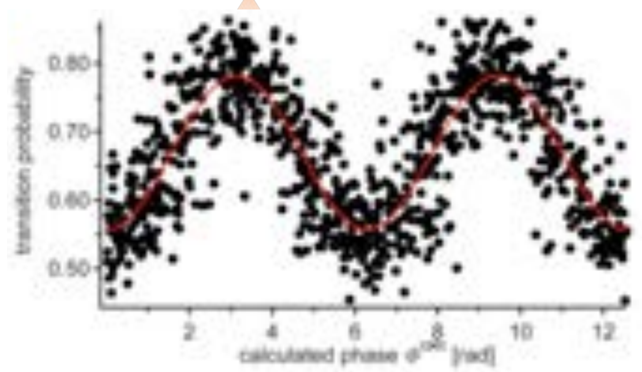






$$\Phi = a_m \times kT^2$$

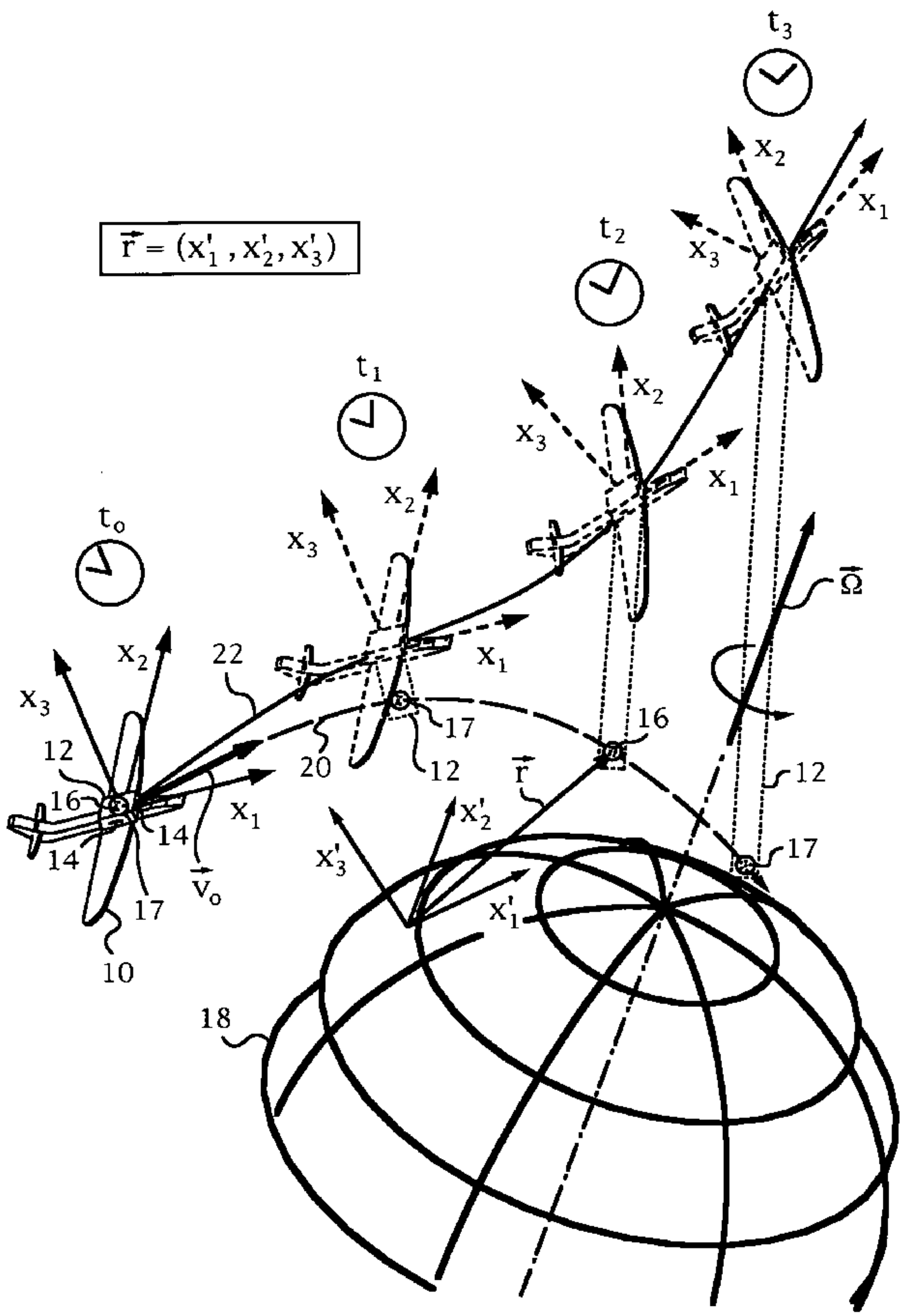
$$P^{AI}(\Phi) = P_0 - A\cos\Phi$$



$$\mathrm{SNR} = A/\sigma_P$$

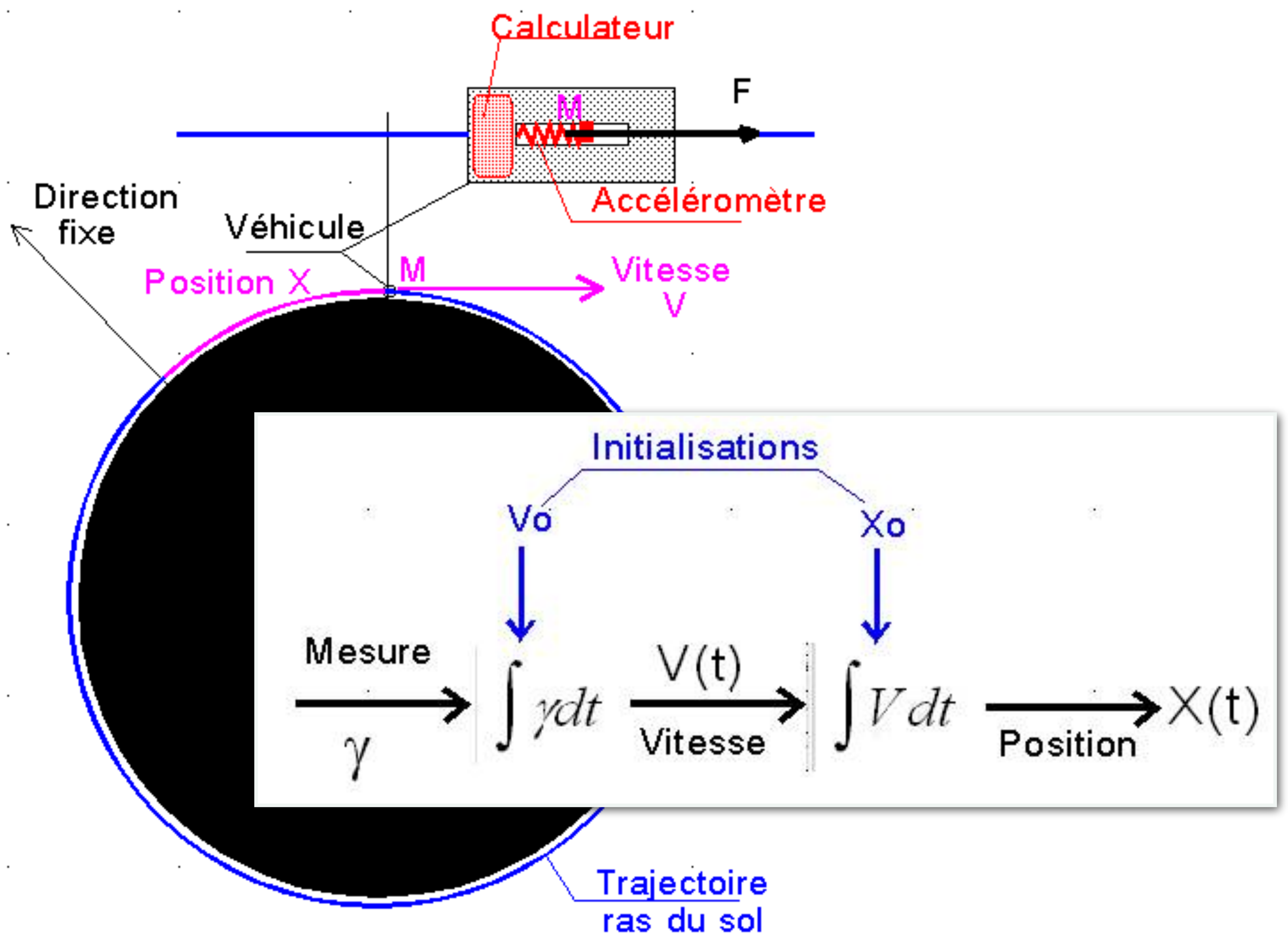
$$P_0 = 0.747,\ 2A = 0.261 \text{ and SNR} = 4.7$$

Geiger et al., Nature Comm. DOI: 10.1038/ncomms1479
Barrett, et al., New J. Phys. 17 085010 doi:10.1088/1367-2630/17/8/085010, Patent FR306314



Navigation system

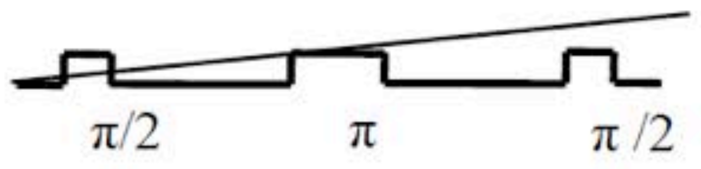
- Inertial
- Integrate acceleration and angle measurement
- Black box




ABSOLUTE QUANTUM GRAVIMETER
ABSOLUTE QUANTUM GRAVIMETER

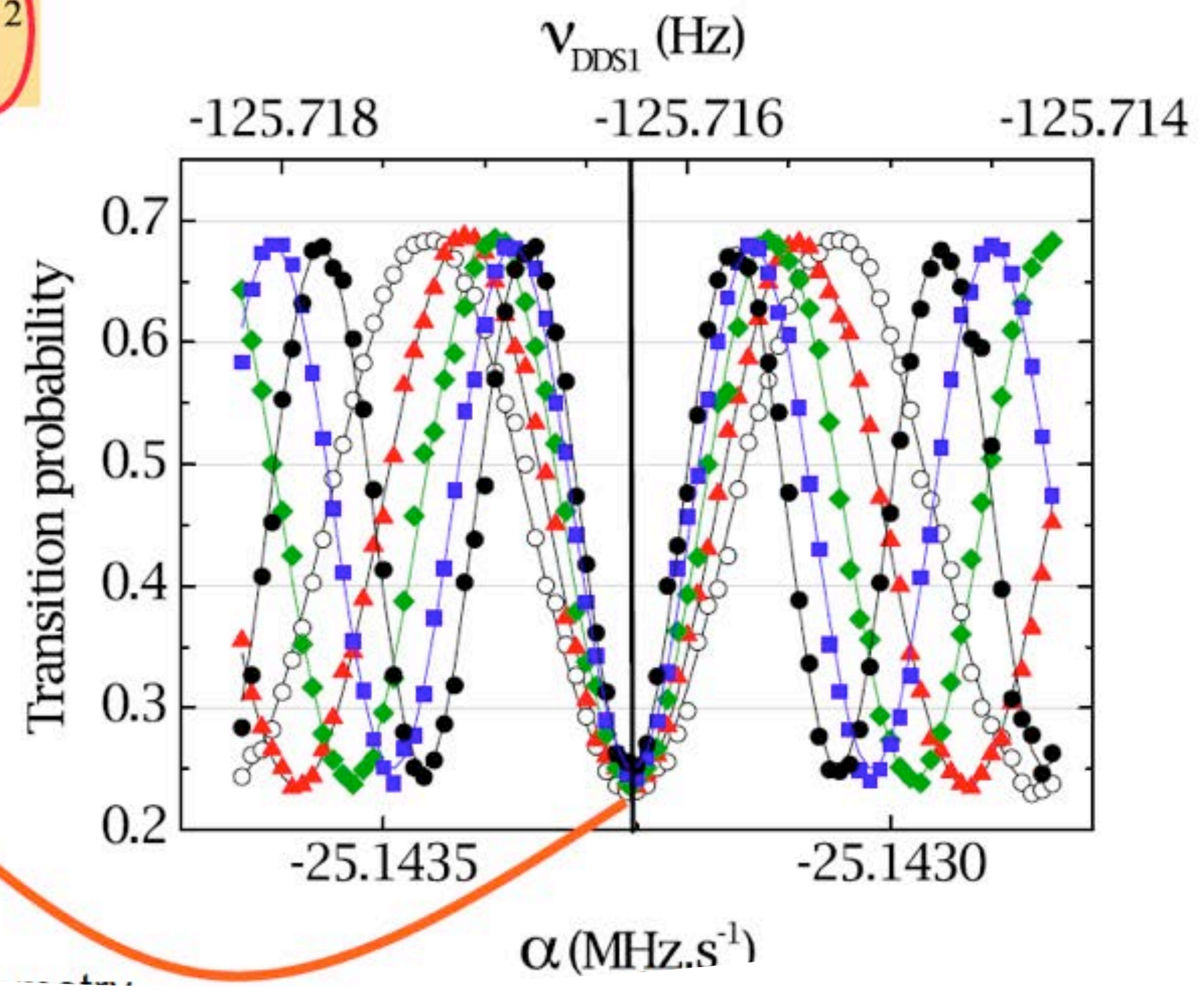

g(t)
a_vib(t)
ABSOLUTE QUANTUM GRAVIMETER

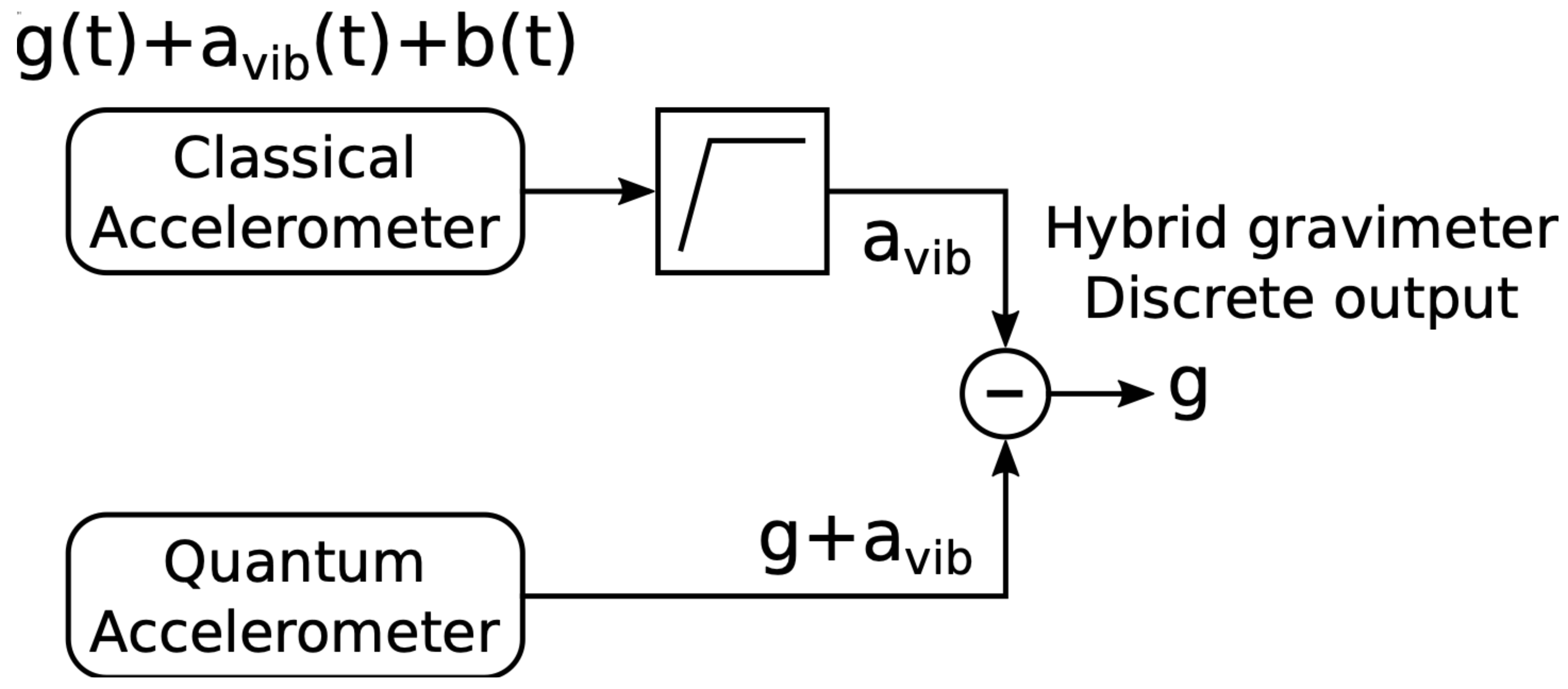
$$\Delta\Phi = \overrightarrow{k_{eff}}\,\vec{g}\,T^2 - \alpha\, T^2$$



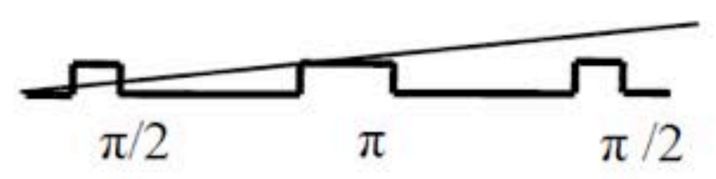
• Dark fringe : independent of T

$$g = \frac{\alpha_0}{k_{eff}}$$



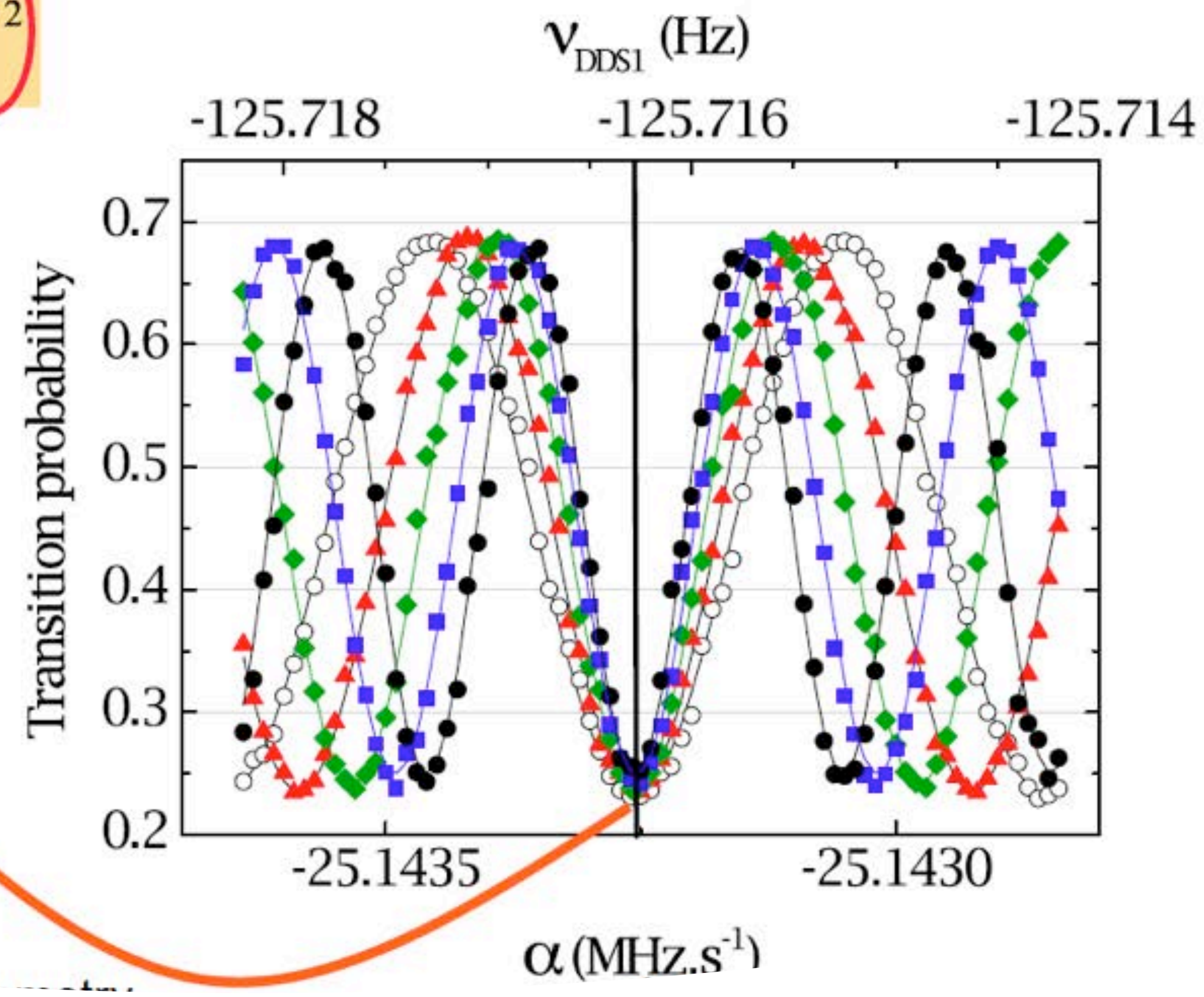


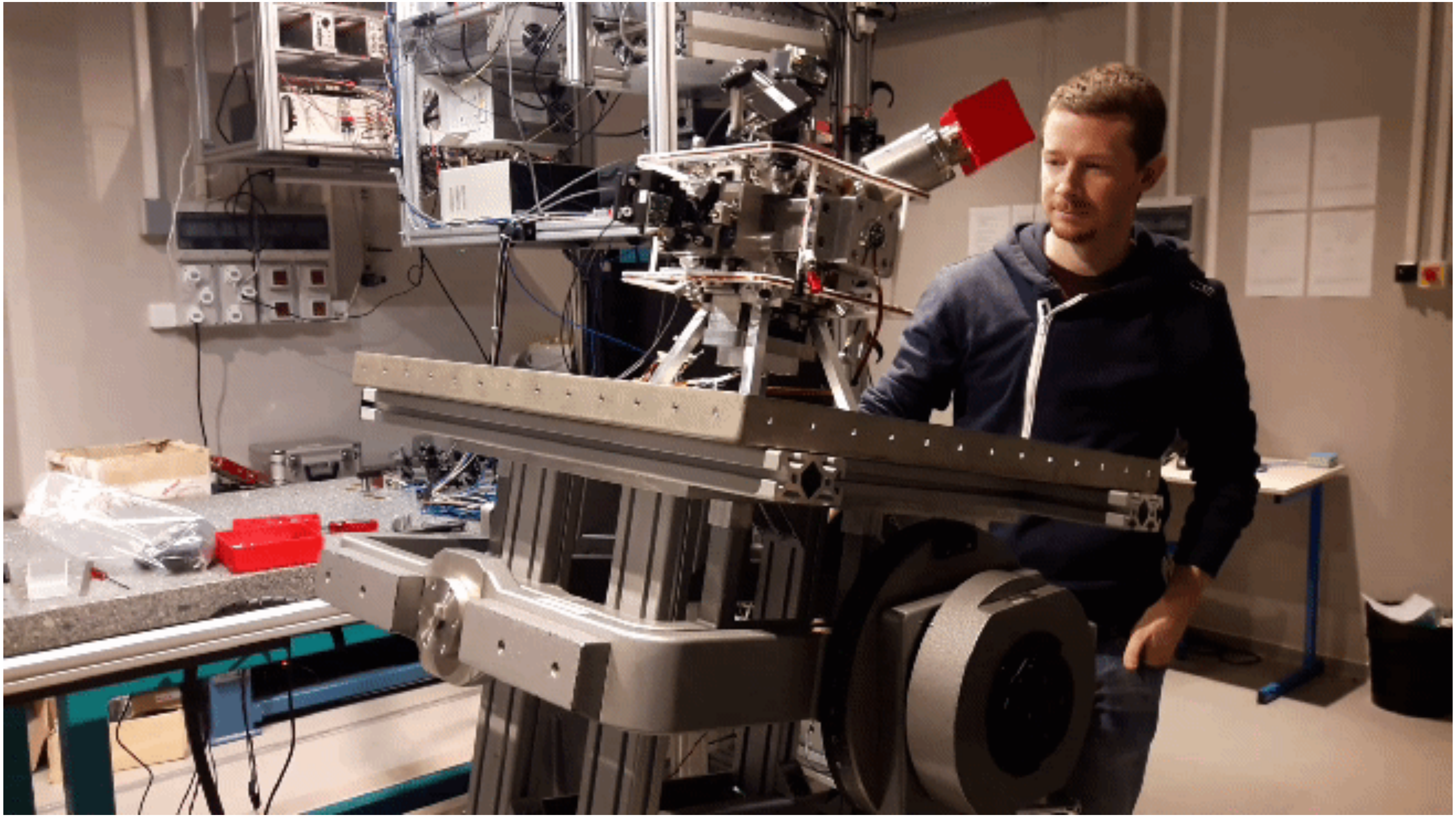
$$\Delta\Phi = \vec{k}_{eff}\,\vec{g}T^2 - \alpha T^2$$



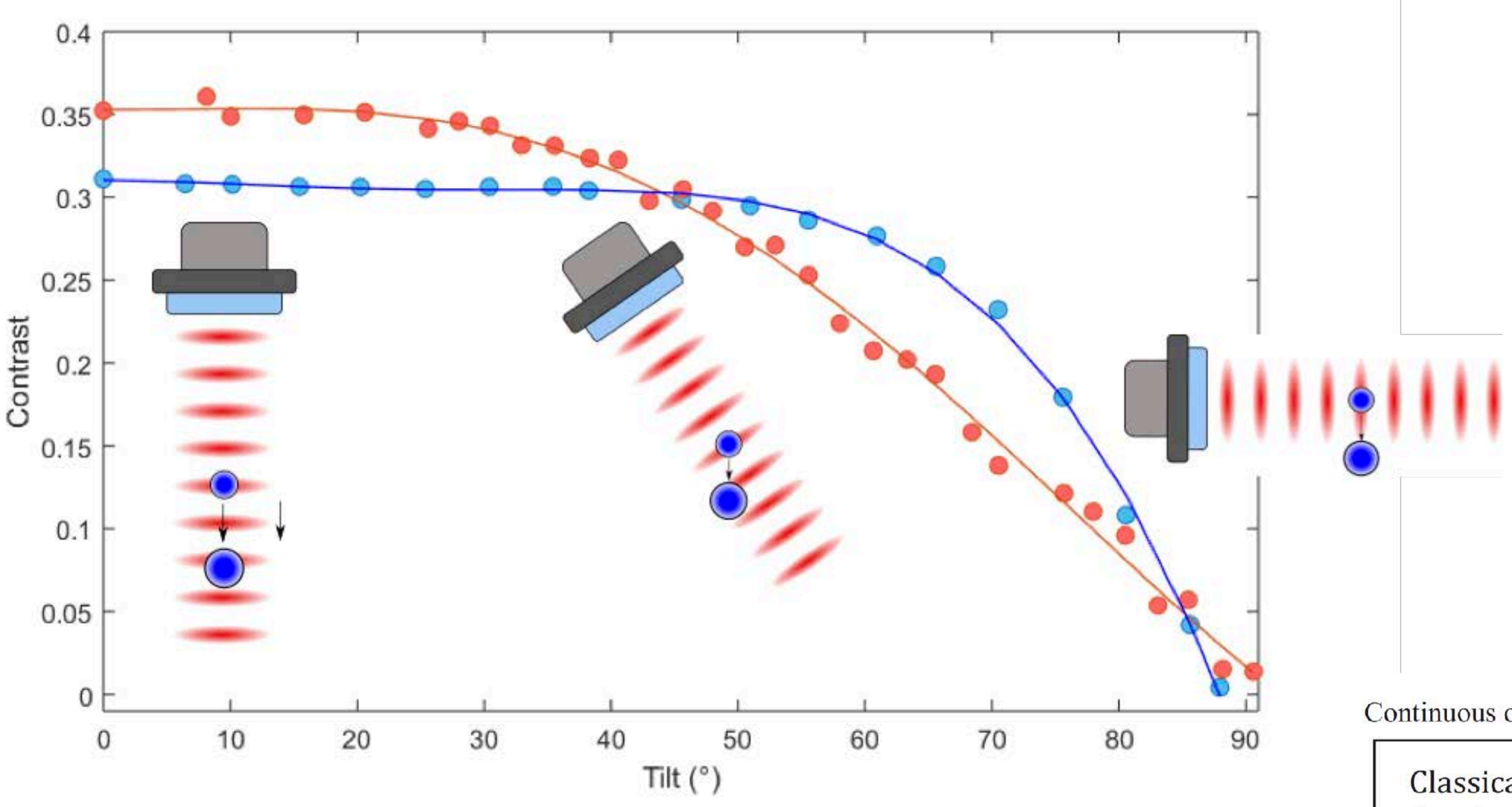
- Dark fringe : independent of T

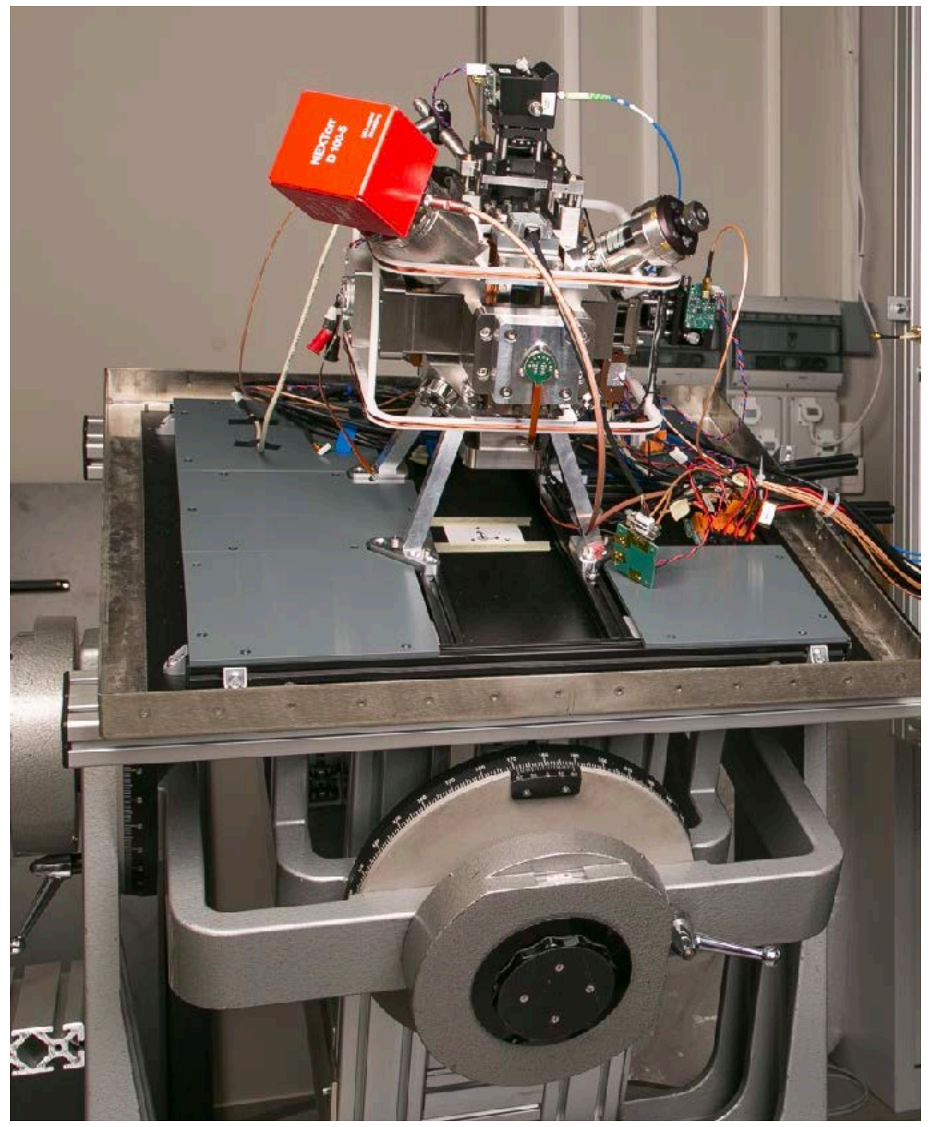
$$g = \frac{\alpha_0}{k_{eff}}$$

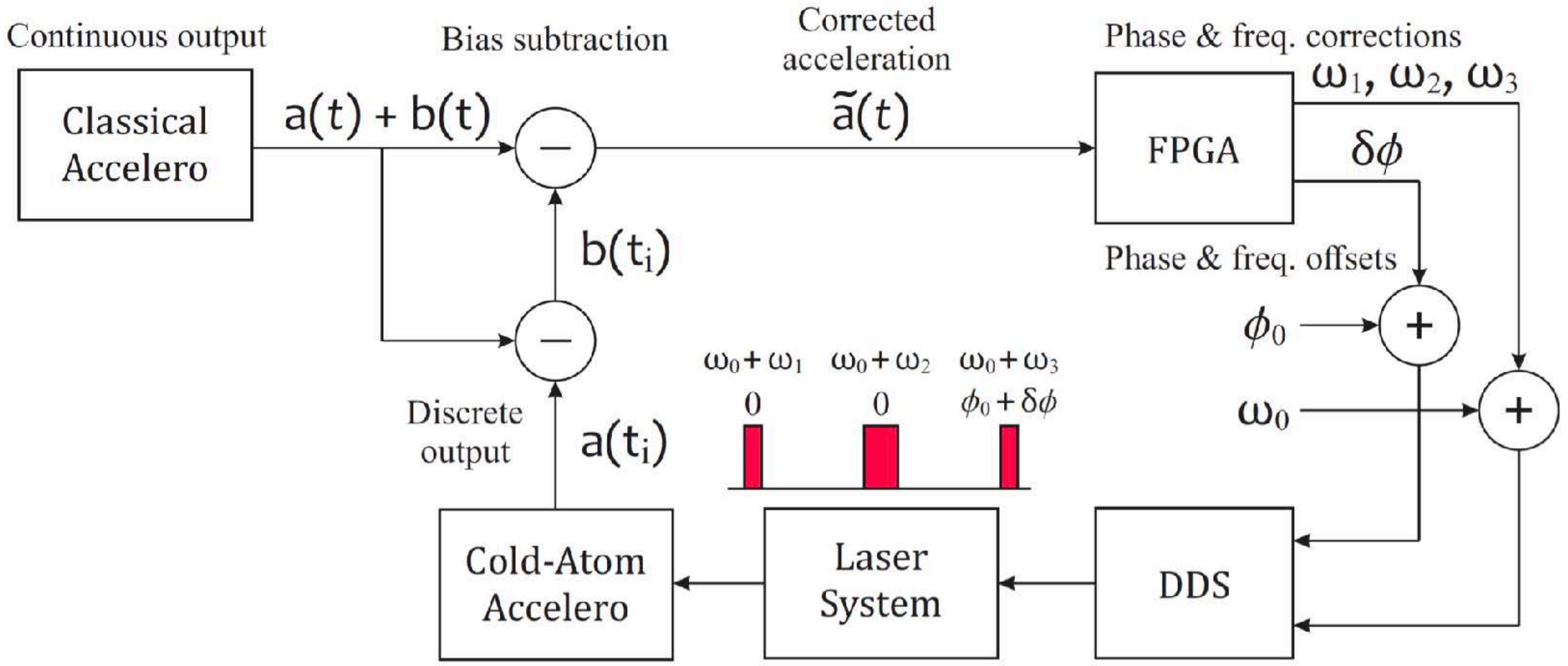




Real time compensation of tilt

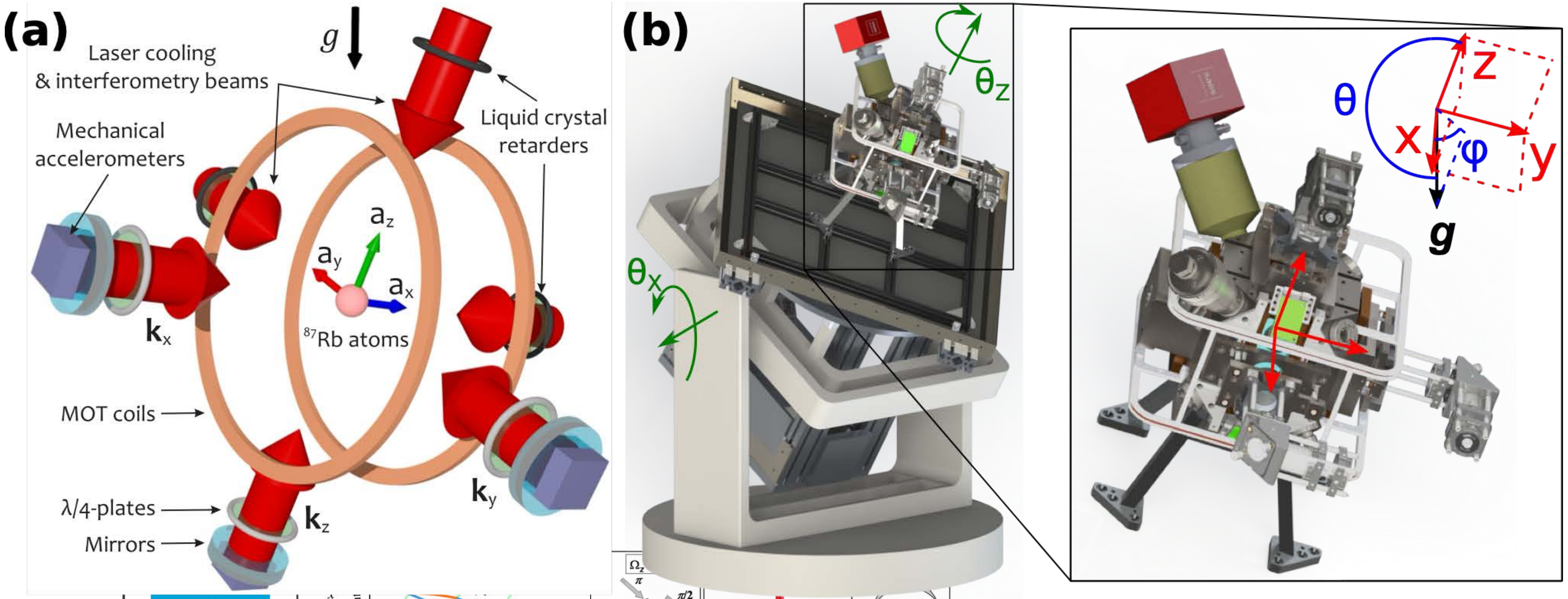


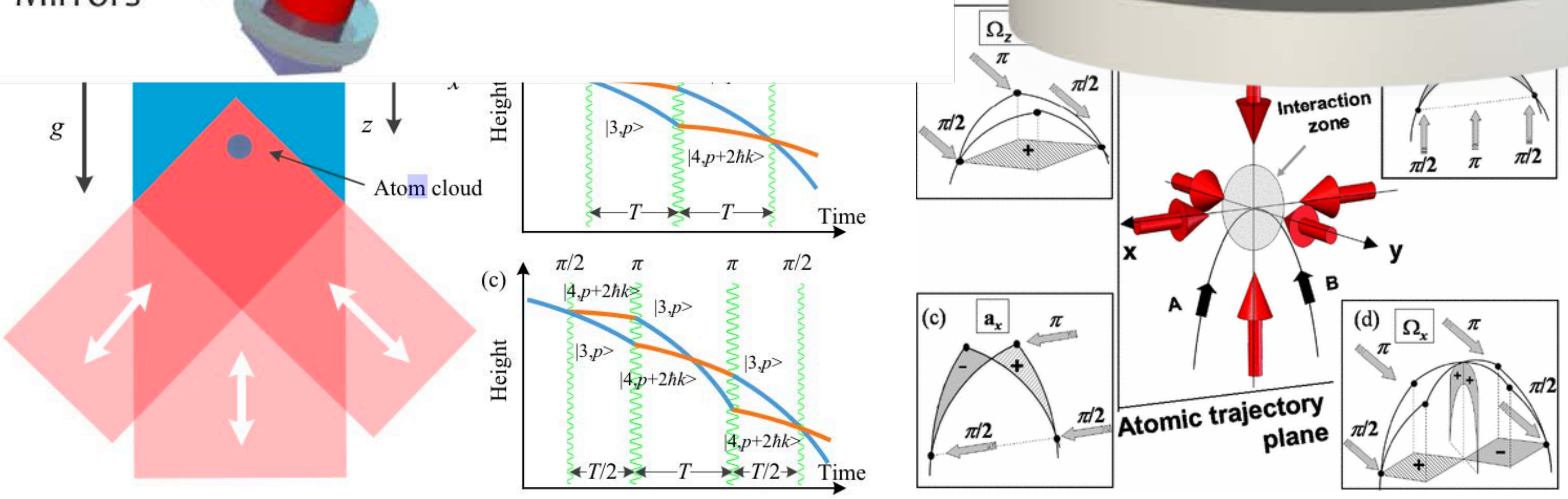




- **Contrast is maintained over a large range.**
- **Close to the horizontal, the contrast is lost due to the finite size of the beam and mixing with parasitic interferometers.**

Hybrid Quantum Accelerometer Triad

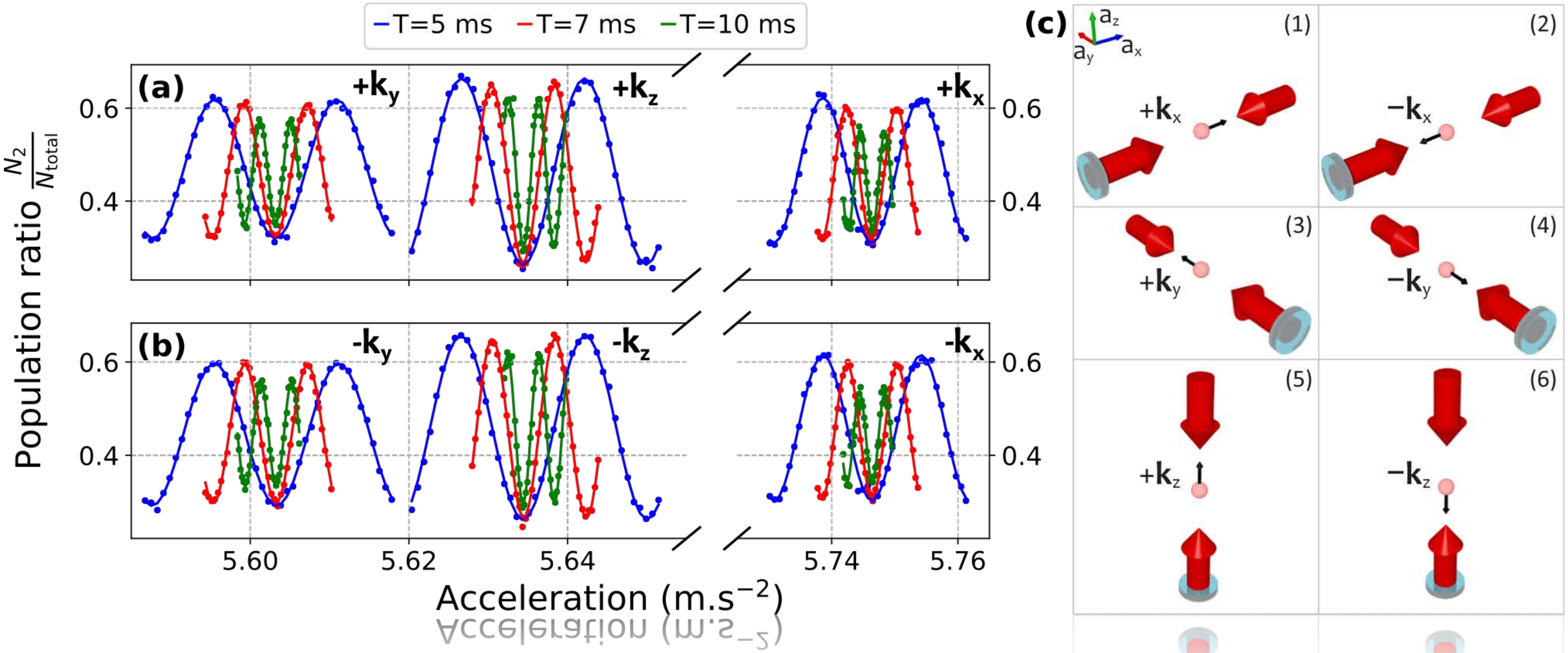


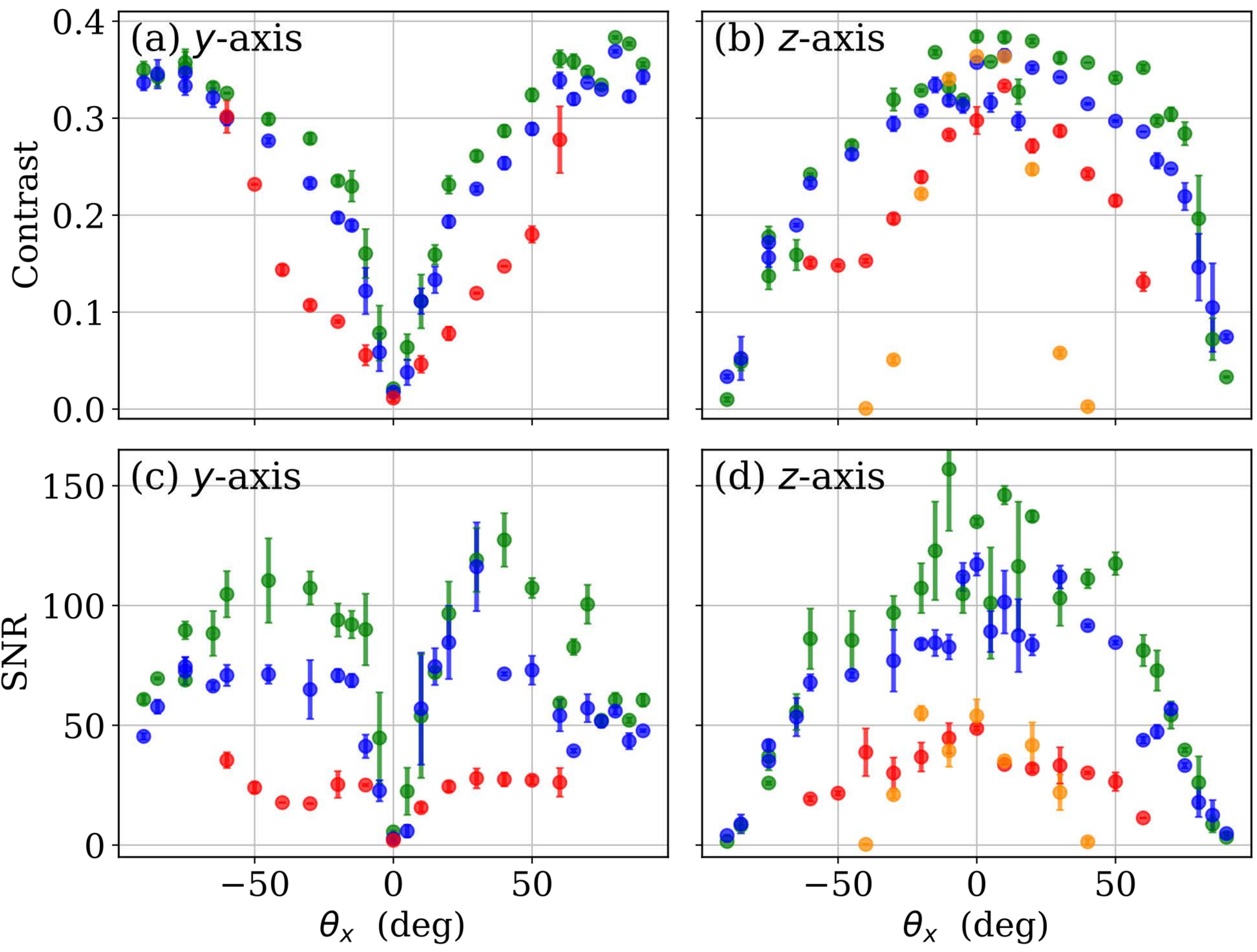


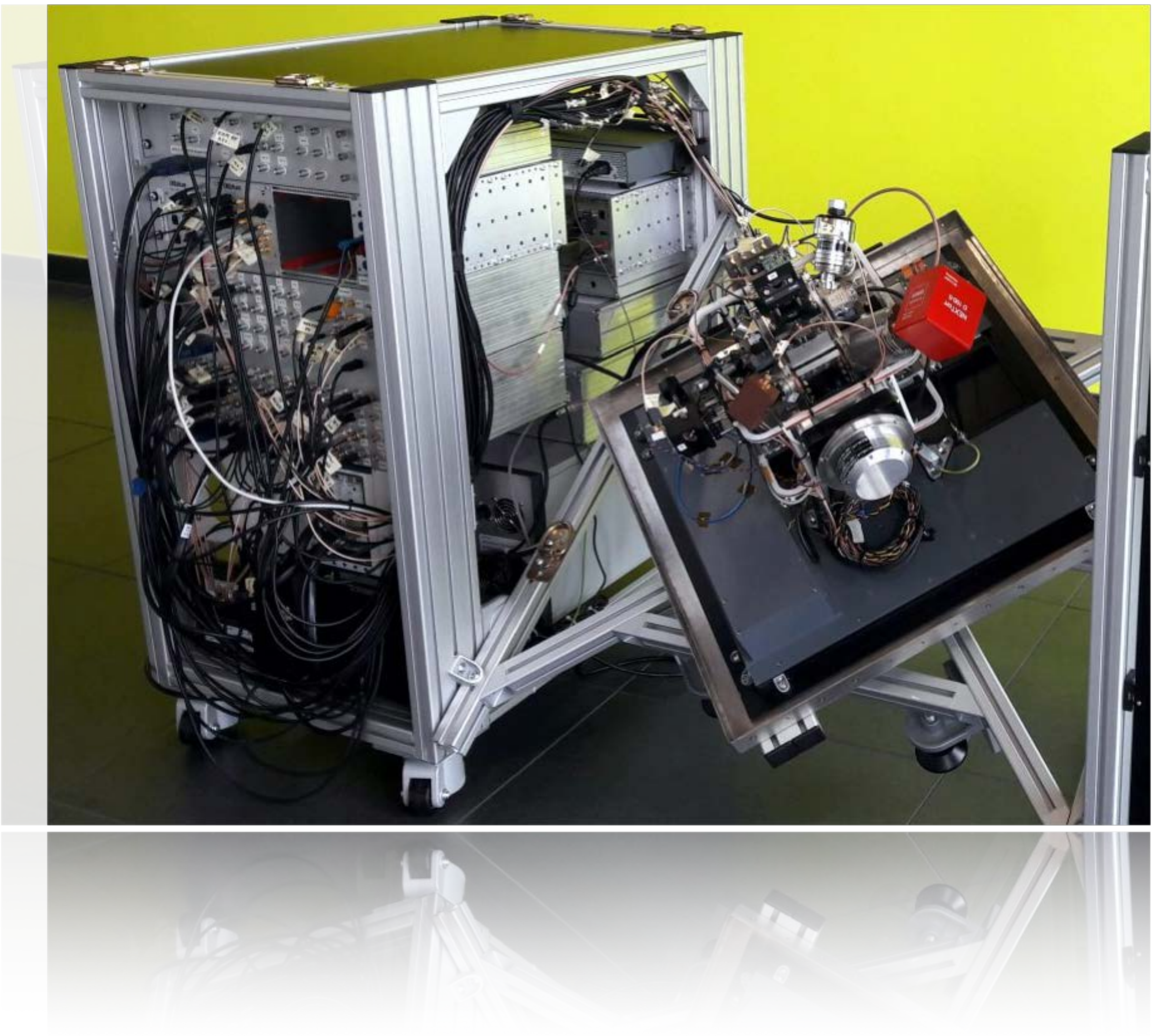
B. Canuel et al, Phys. Rev. Lett. 97, 010402 (2006)

X. Wu et al, Phys. Optica 4, 12, (2017)

Sequential interrogation sequence




(a) y-axis
(b) z-axis
(c) y-axis
(d) z-axis
Contrast
SNR
0.0
0.1
0.2
0.3
0.4
0
50
100
150
−50
0
50
θx (deg)



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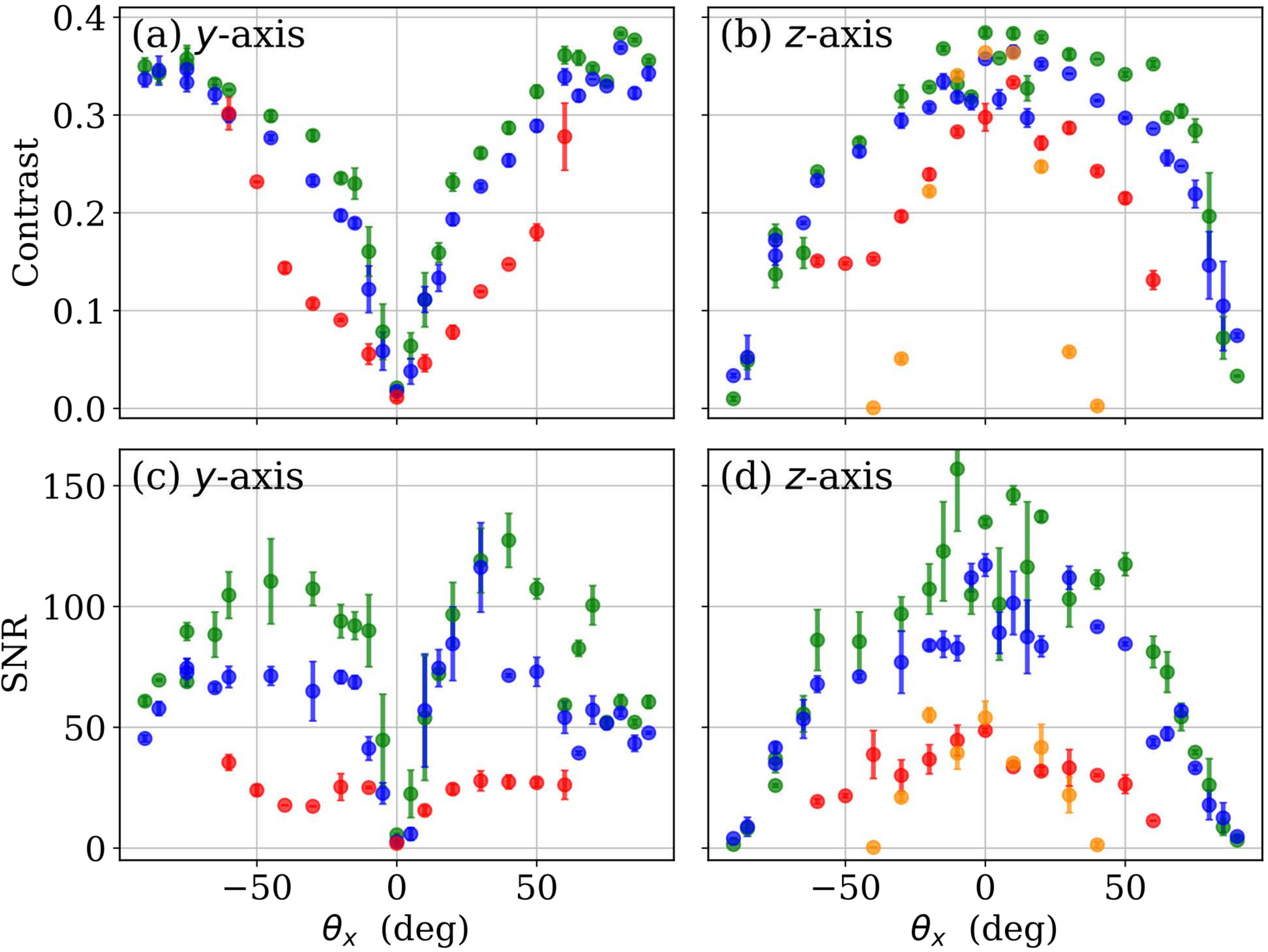
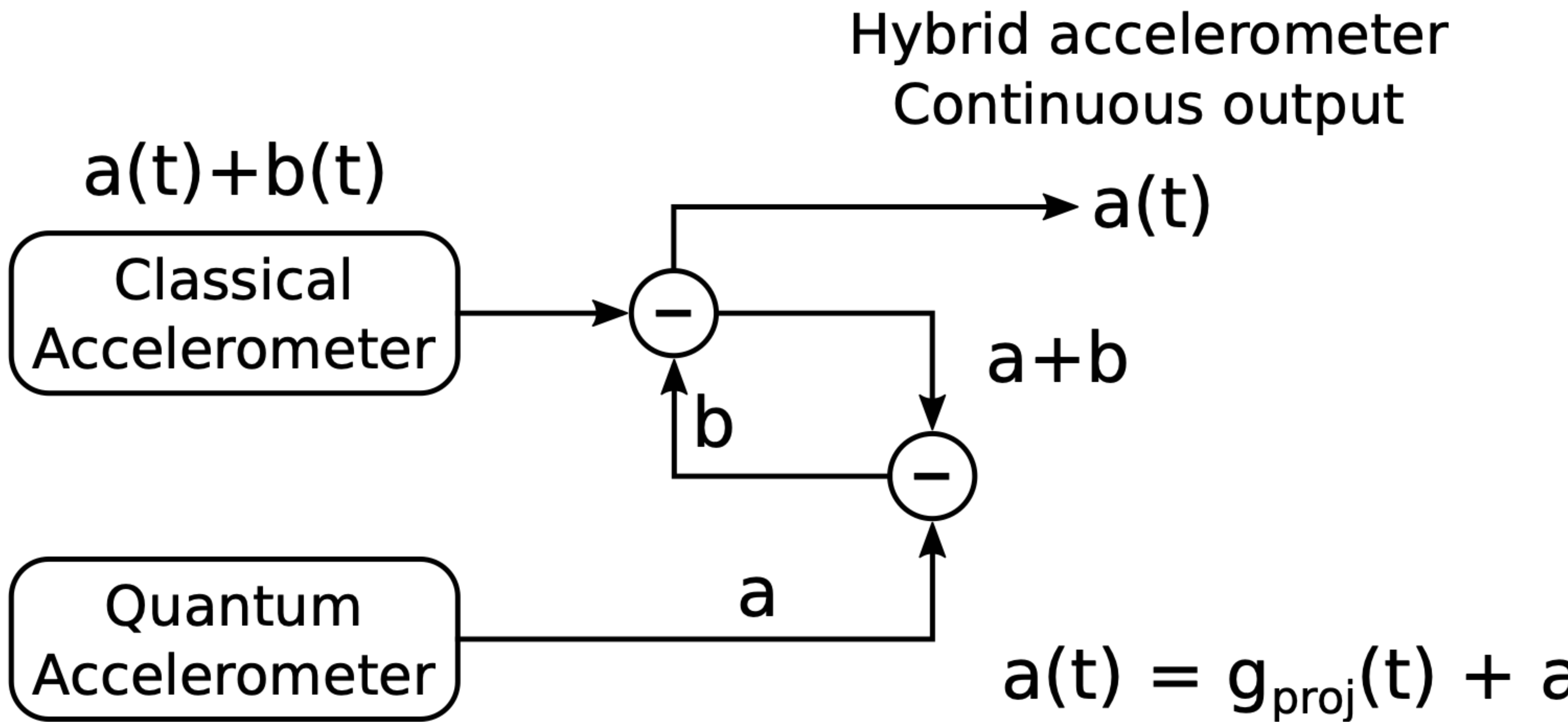
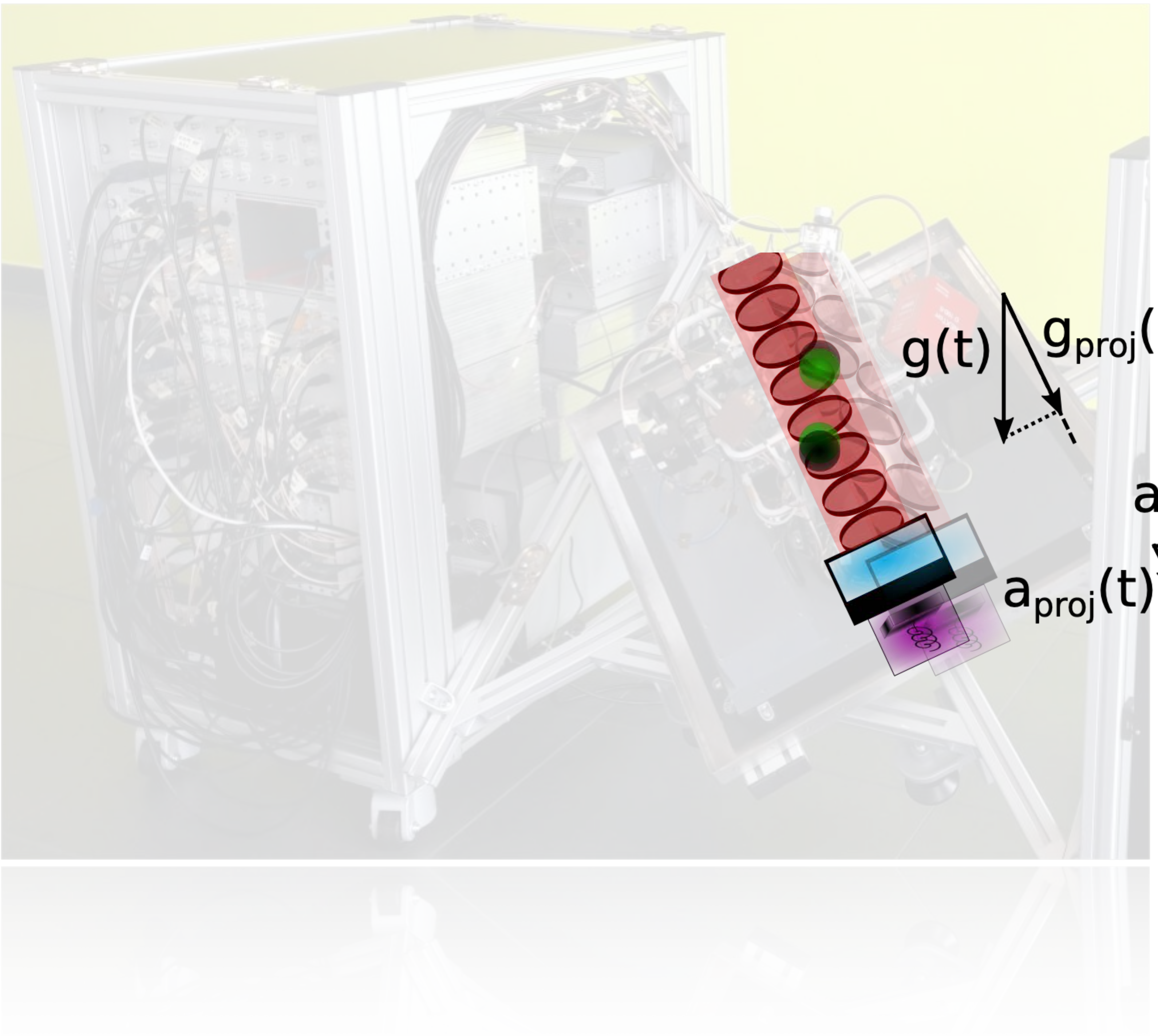
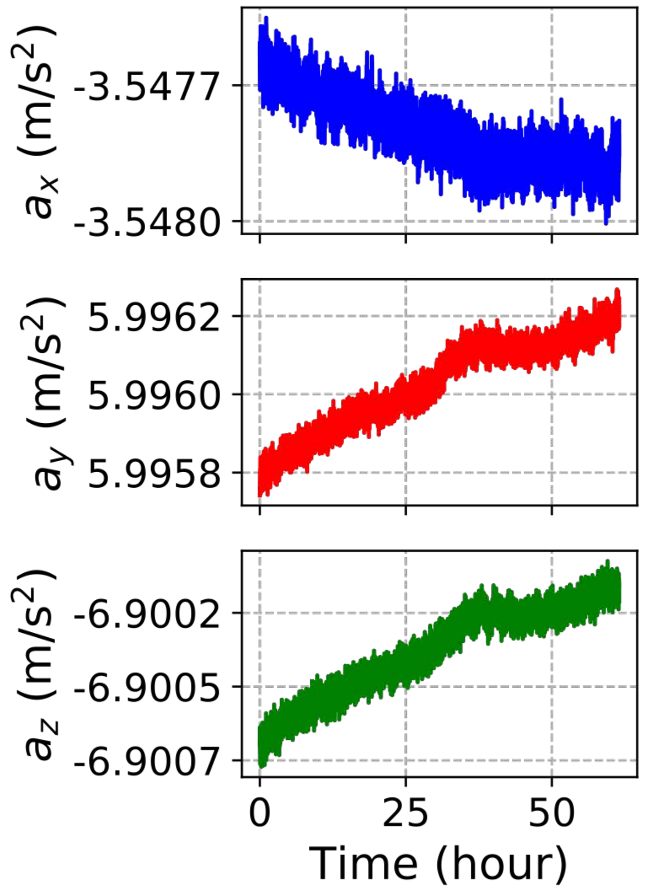
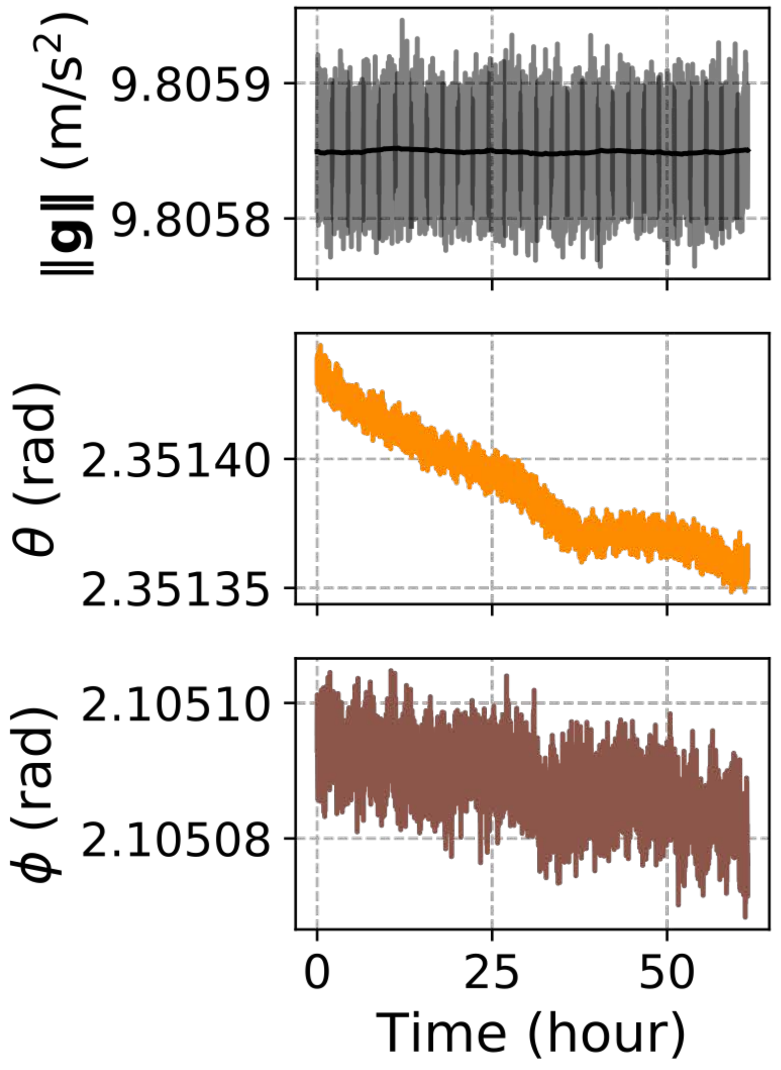
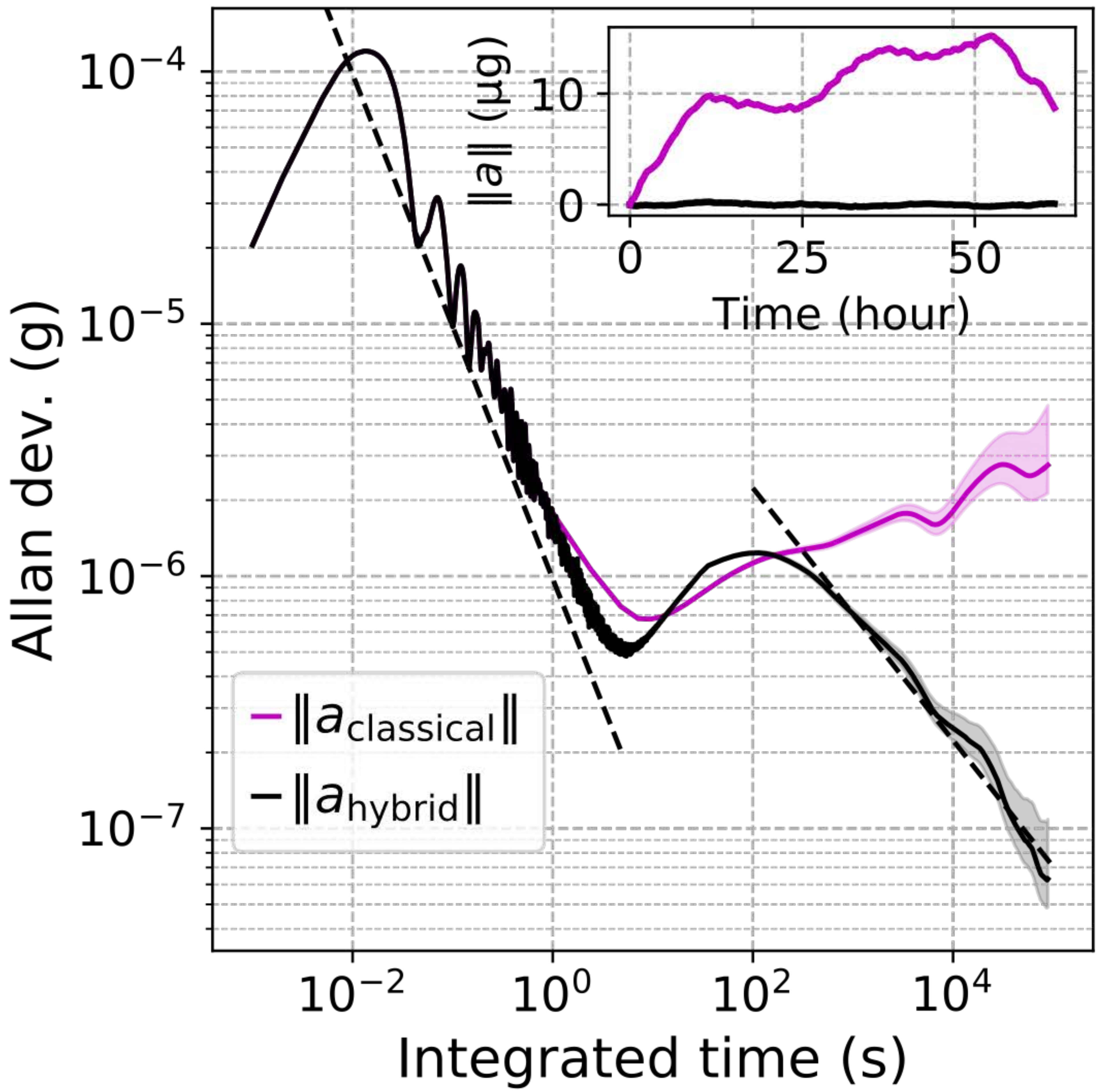






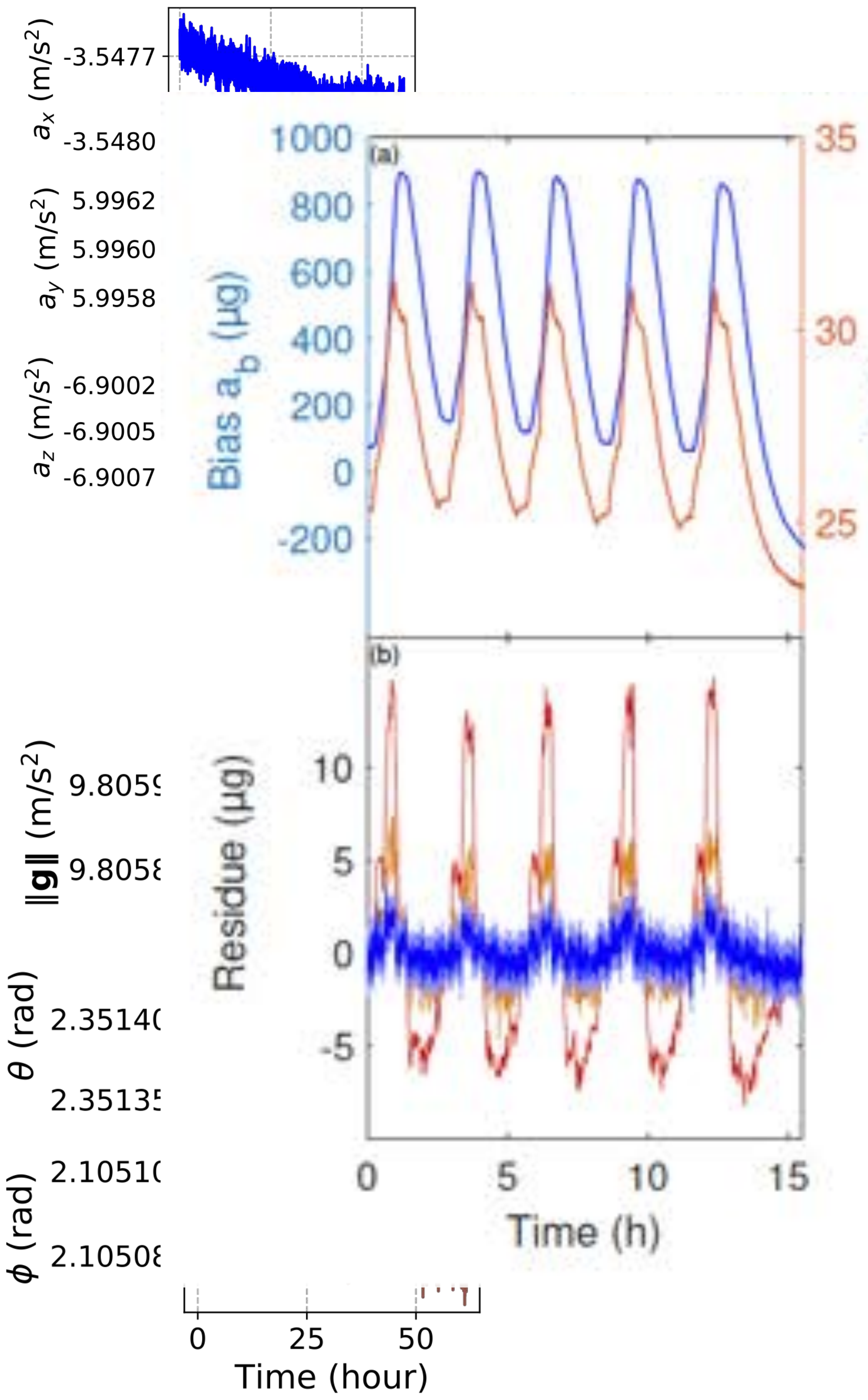


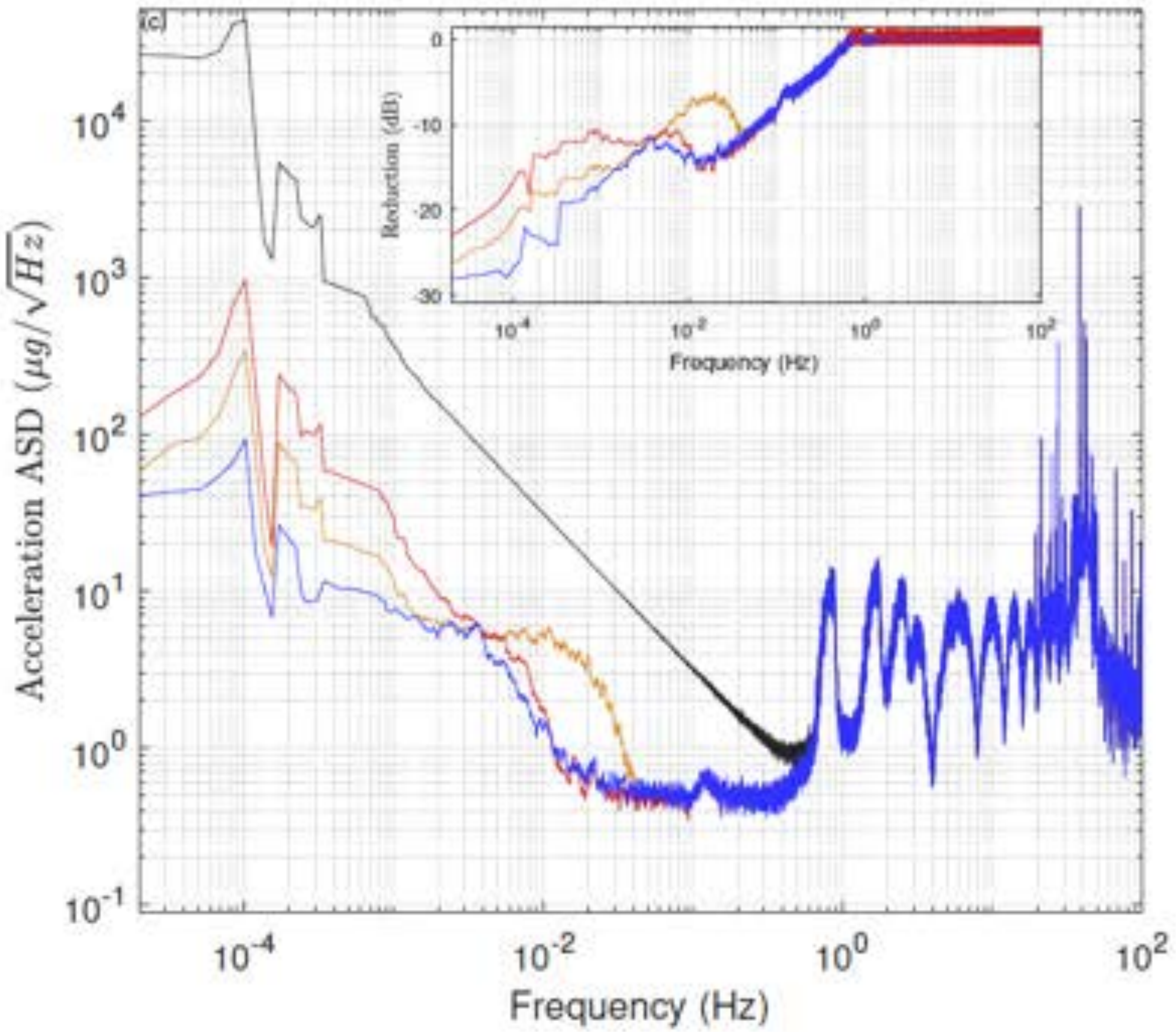




P. Cheinet et al, Phys. Rev. App. 10, 3 (2018)

Science Adv.



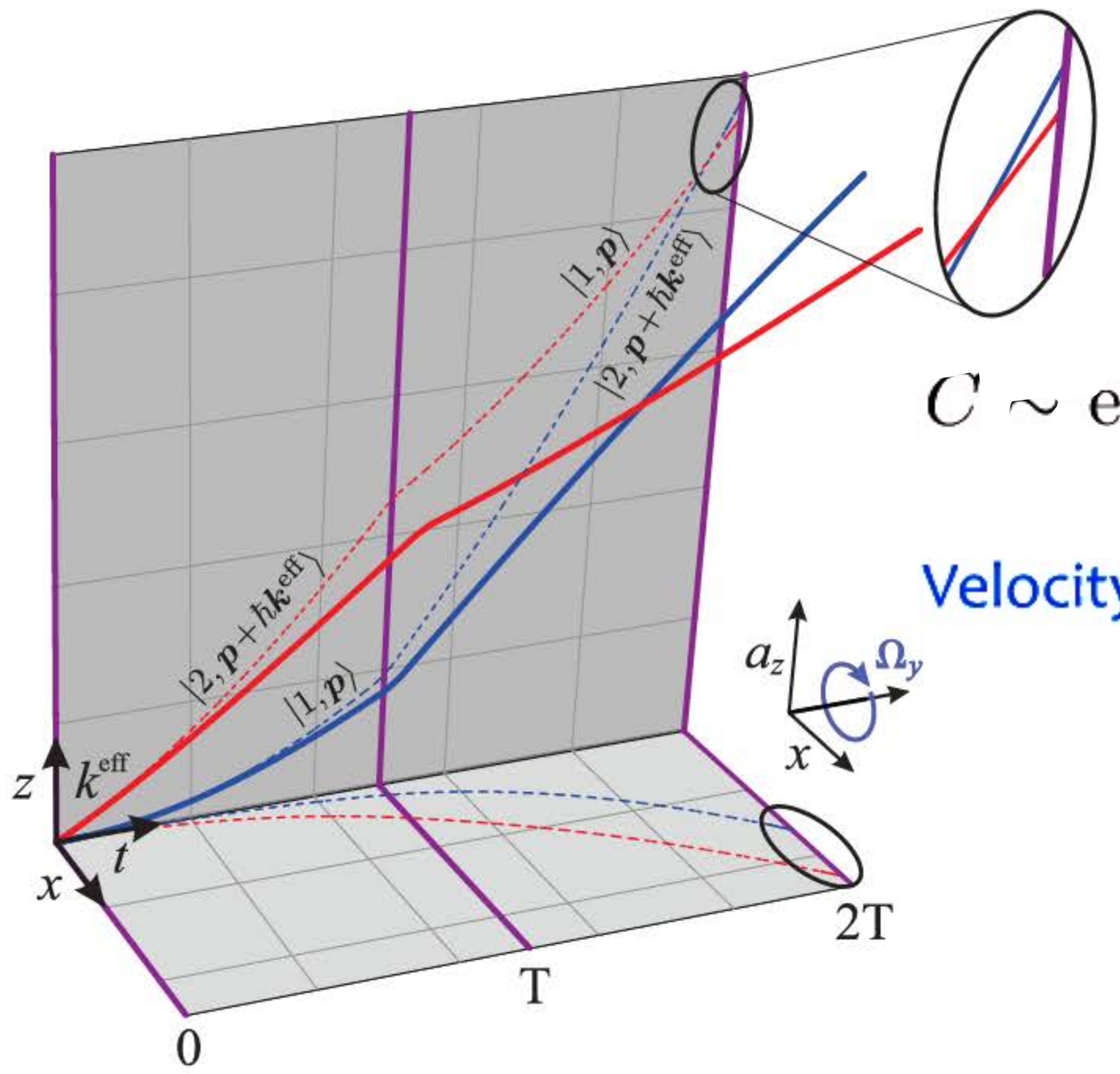


Integrated time (s)

P. Cheinet et al, Phys. Rev. App. 10, 3 (2018)

Science Adv.

How to cope with rotations

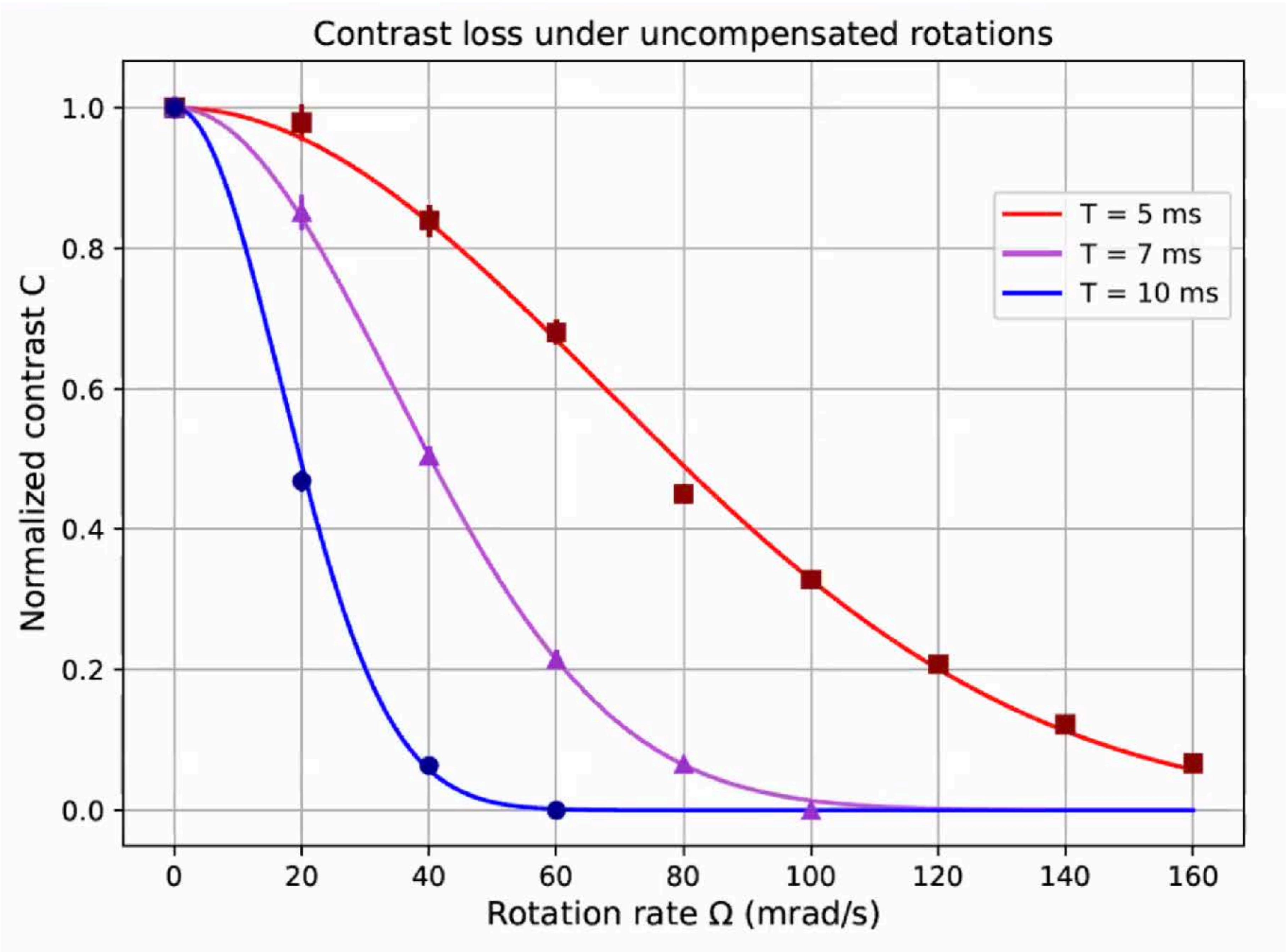


$$C \sim \exp\left[(k_{\text{eff}}\sigma_v T)^2 (|\Omega_T| T)^2 \right]$$

Velocity spread

Interrogation time

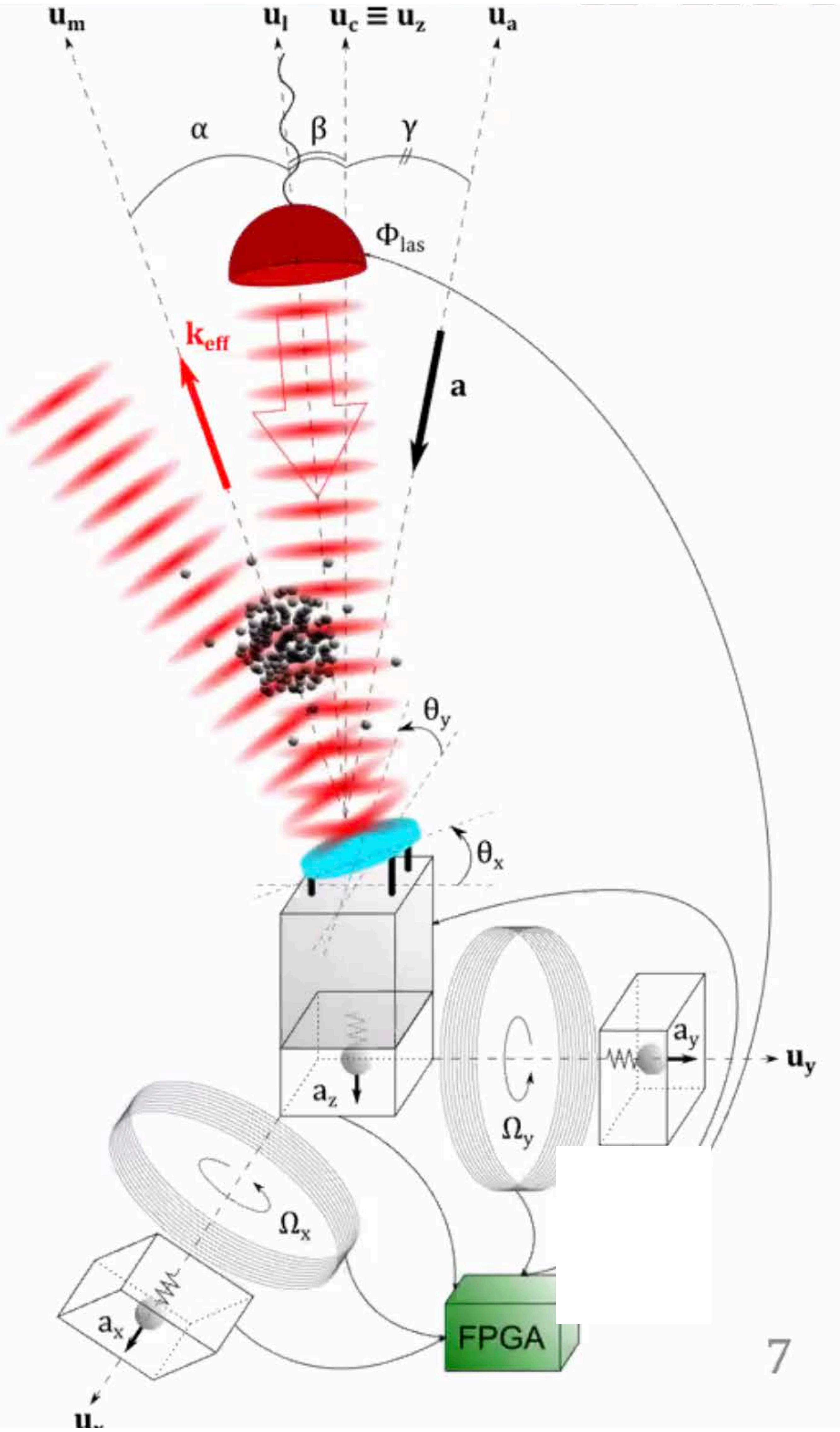
Rotation rate transverse to $\mathbf{k}_{\text{eff}}$



Rotation in the plane Ωy ≈ 5 deg/s

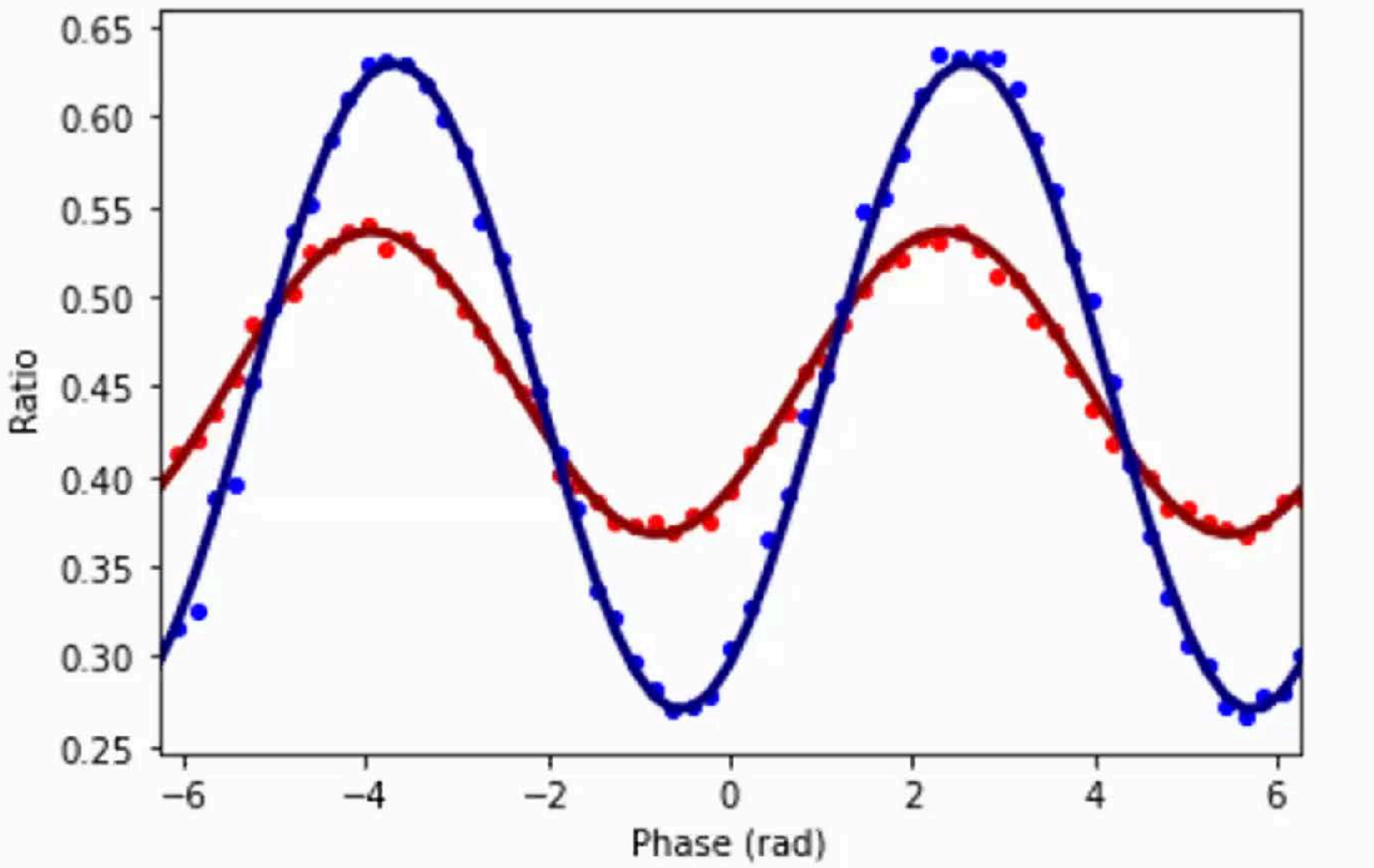
- **100 % contrast loss in ≈ 10 ms**
  - **Limiting for navigation systems**
  - **Limiting for space mission in LEO**
- **For 5 second interrogation time, rotation needs to be ≈ 6 10^{-5} deg/s (50 times than earth rotation)**
  - **Rotation compensation of retroretlecting mirror**

- ✓ High accuracy, low noise FOGs used for both navigation purposes and interferometer contrast loss compensation
- ✓ Tip-tilt stage used for fast and accurate mirror's orientation correction
- ✓ Real-time FOGs data acquisition and processing, tip-tilt driving through custom FPGA board and software



IXATOM
Quantum technologies for high end Inertial Sensors

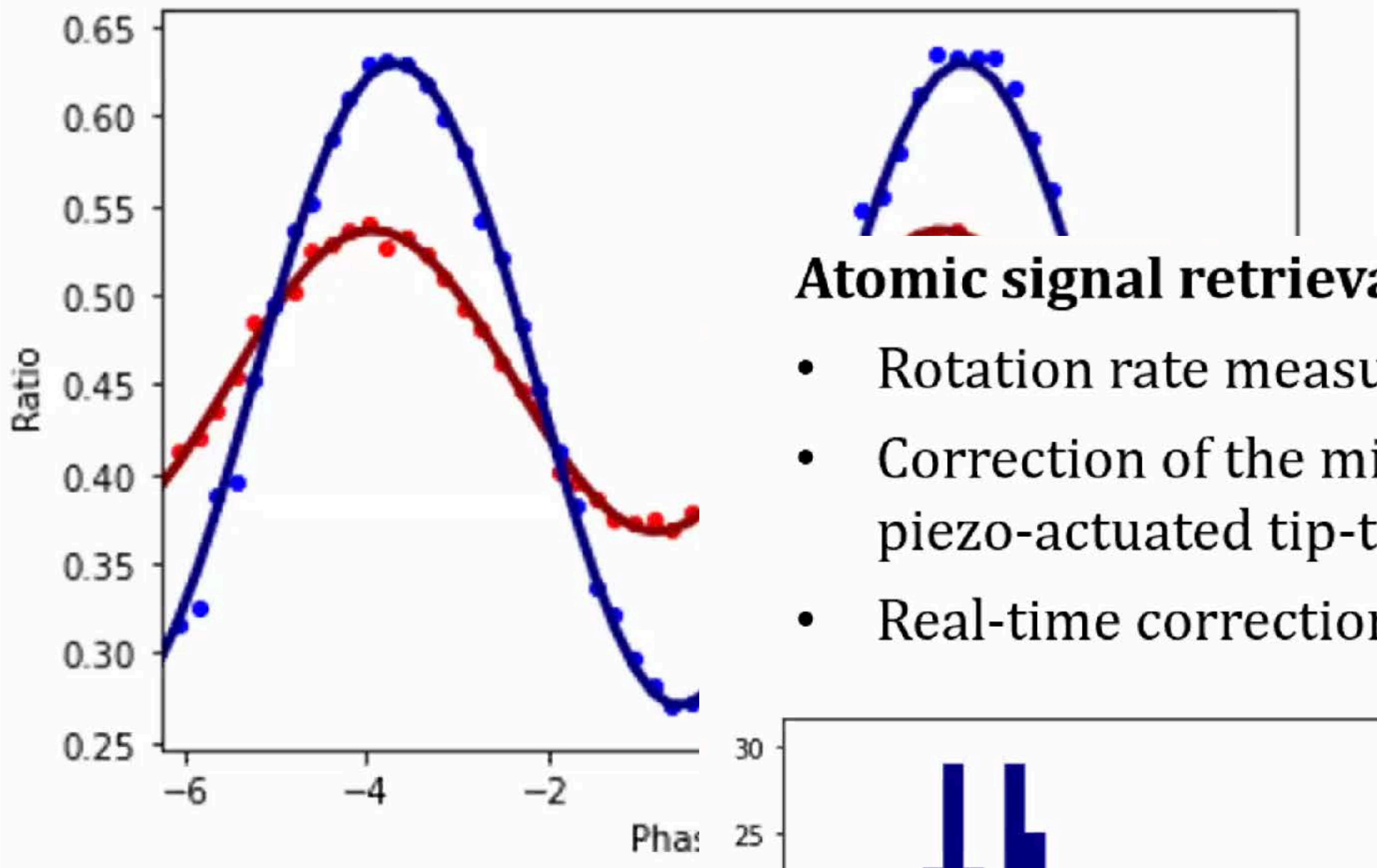
Dynamic compensation of rotation



Fringes without correction at T = 10 ms under:

- Ω = 0 mrad/s
- Ω = 20 mrad/s ≈ 1.1 °/s

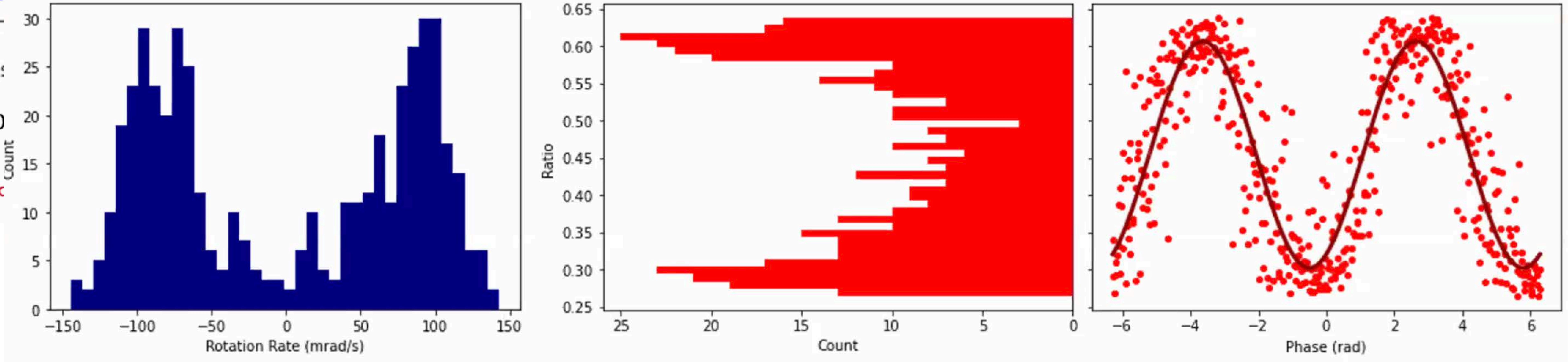
Dynamic compensation of rotation

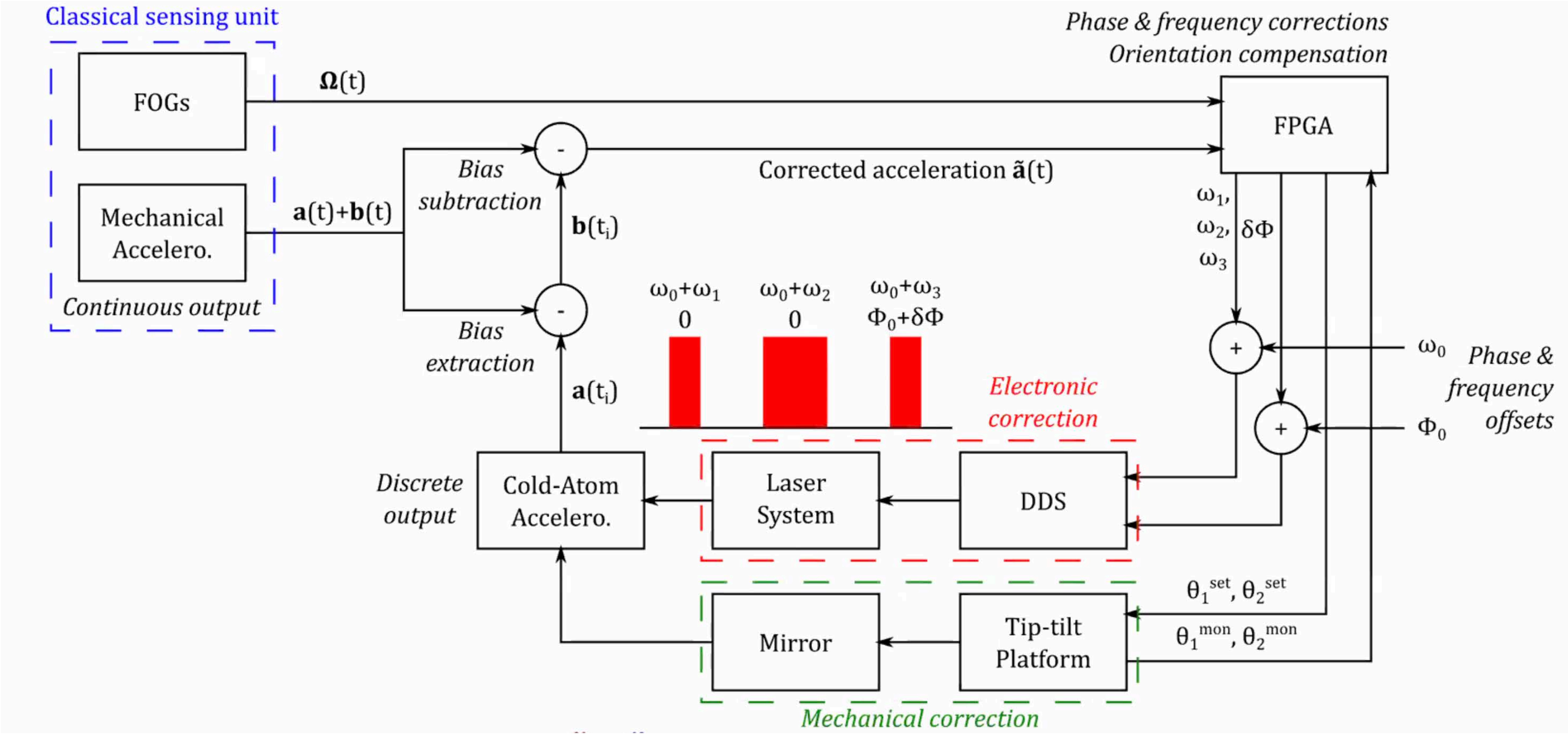


Fringes without correctio
- $\Omega = 0$ mrad/s
- $\Omega = 20$ mrad/s ≈ 1.1 °

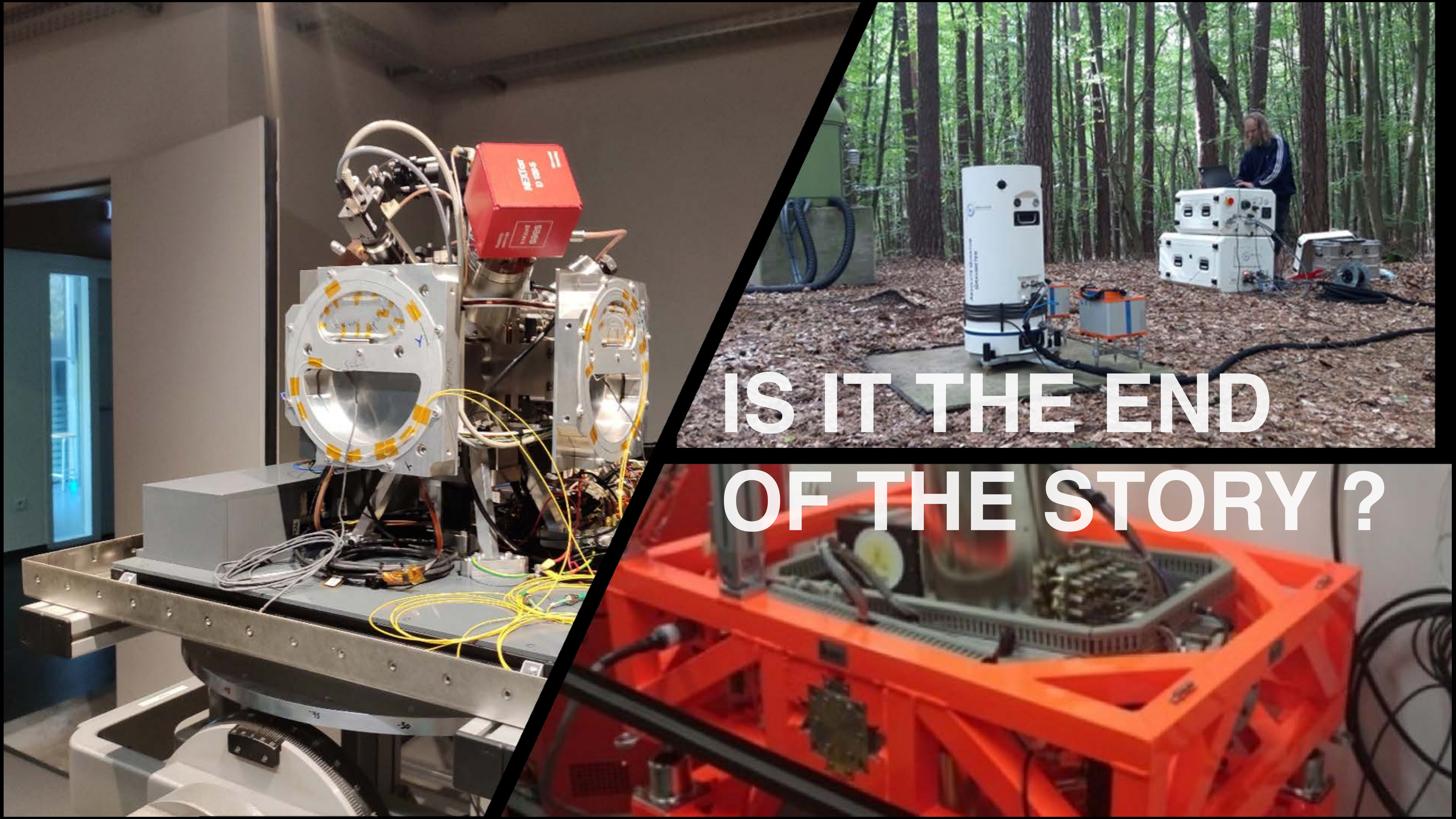
Atomic signal retrieval process
- Rotation rate measurement with FOGs
- Correction of the mirror orientation with a piezo-actuated tip-tilt platform
- Real-time correction of the laser phase

Performances of the correction system
- Full contrast retrieval
- Visible fringes with partial phase correction
  - ✓ Interrogation times up to 10 ms
  - ✓ Rotation rates up to 150 mrad/s ≈ 8.6 °/s





Classical sensing unit
FOGs
Mechanical Accelero.
Continuous output
Ω(t)
a(t)+b(t)
Bias subtraction
Bias extraction
b(t_i)
a(t_i)
Corrected acceleration ã(t)
Phase & frequency corrections
Orientation compensation
FPGA
ω_1, ω_2, ω_3
δΦ
ω_0+ω_1
0
ω_0+ω_2
0
ω_0+ω_3
Φ_0+δΦ
ω_0
Φ_0
Phase & frequency offsets
Electronic correction
Discrete output
Cold-Atom Accelero.
Laser System
DDS
Mirror
Tip-tilt Platform
θ_1^set, θ_2^set
θ_1^mon, θ_2^mon
Mechanical correction



IS IT THE END OF THE STORY ?

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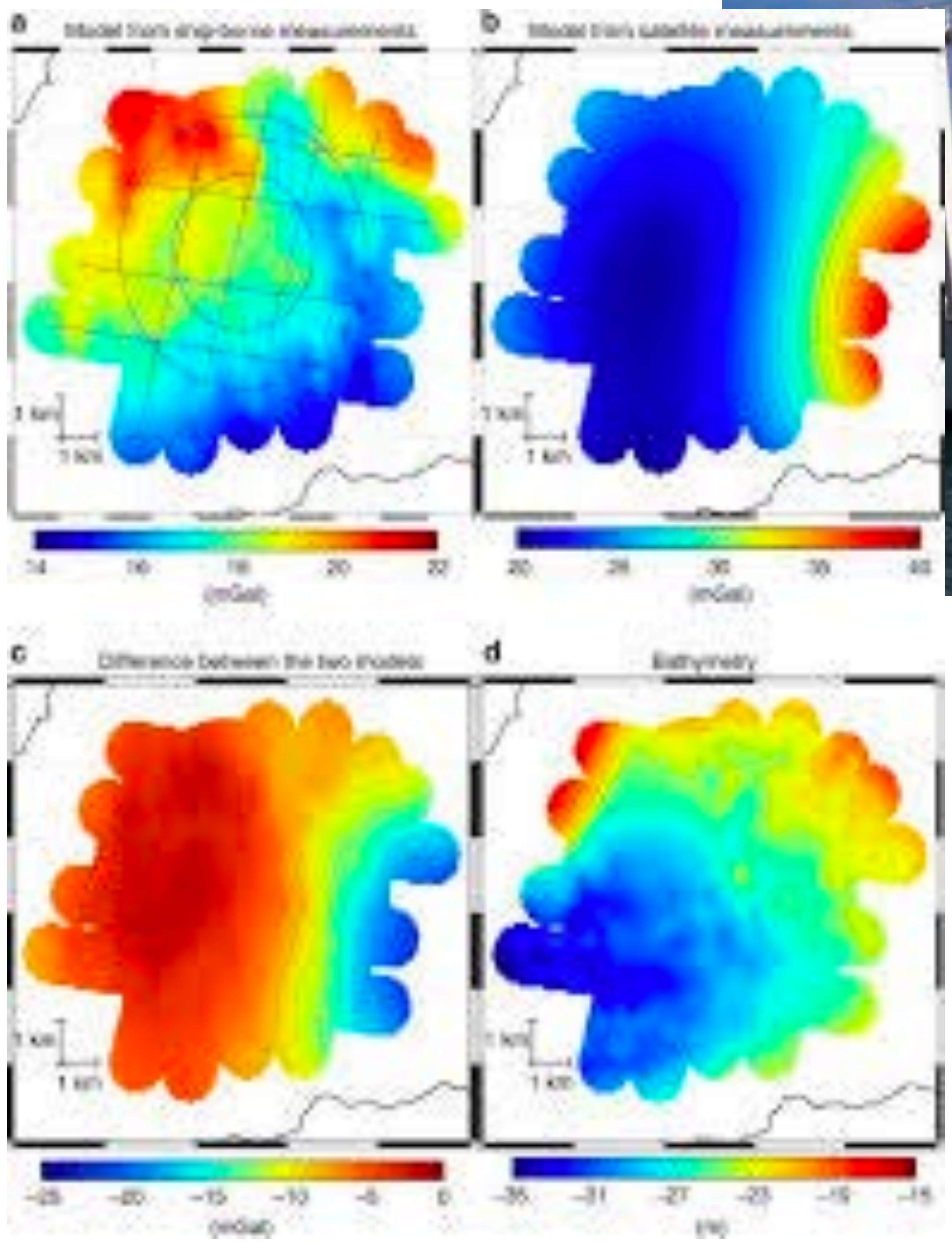
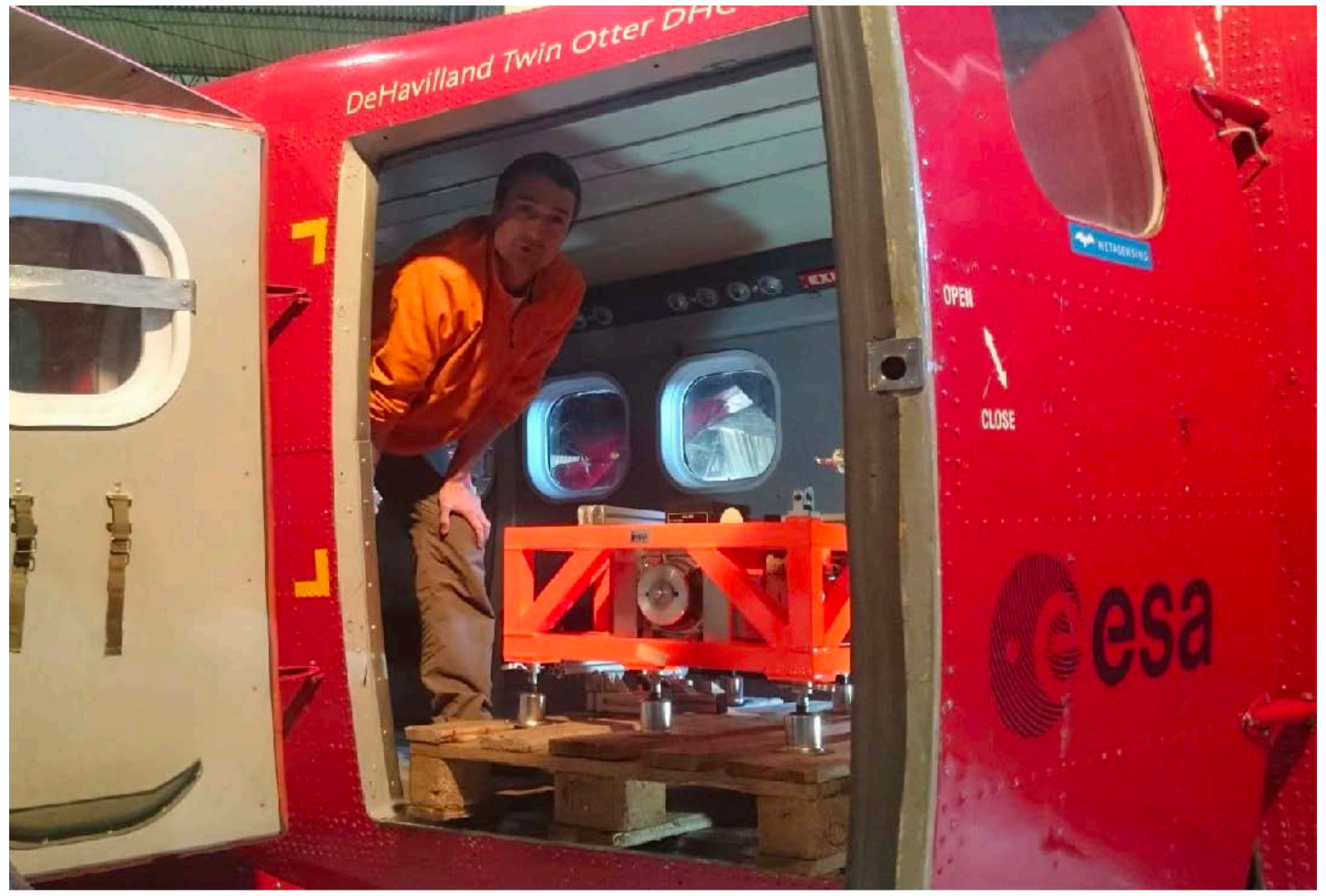
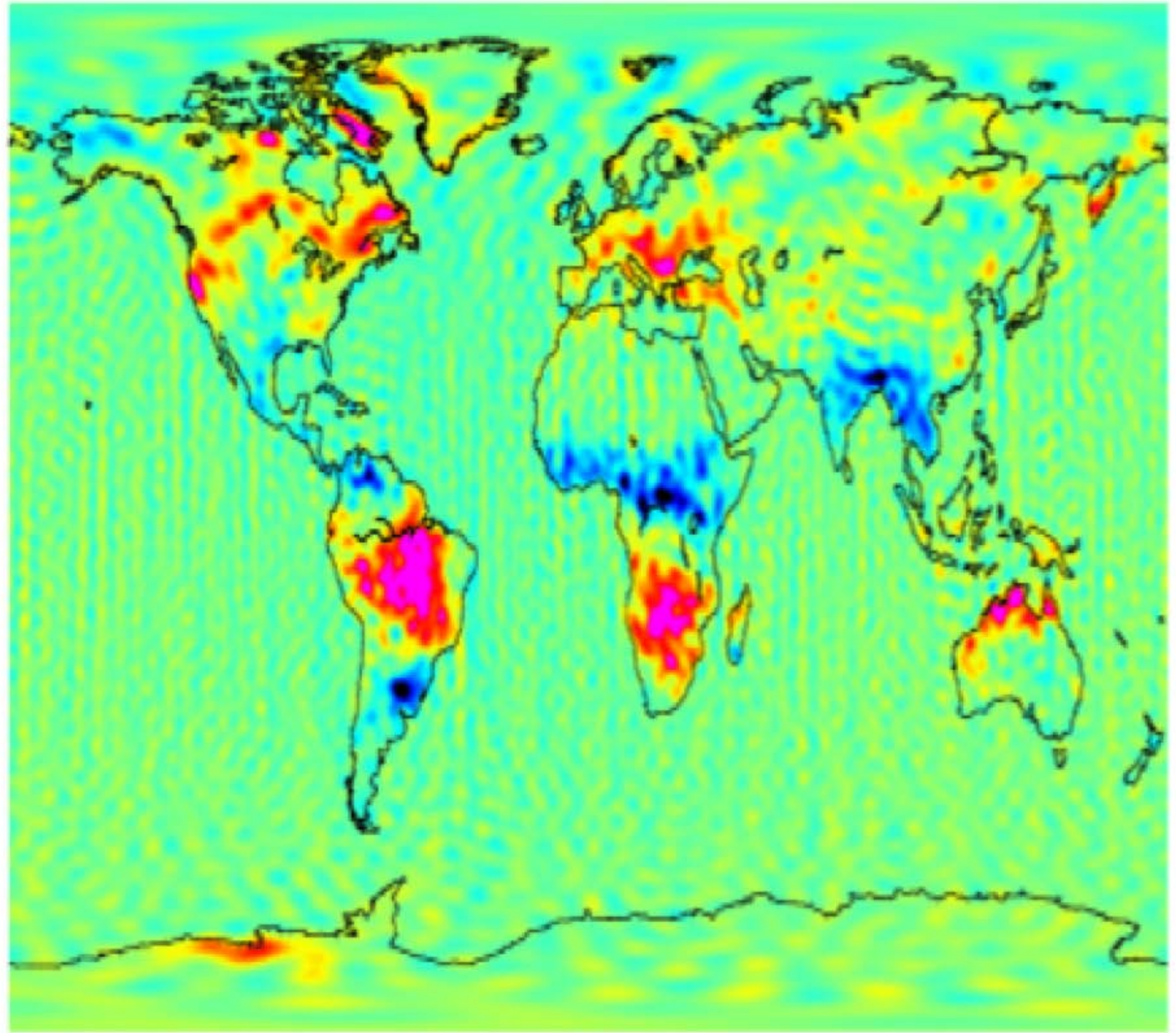
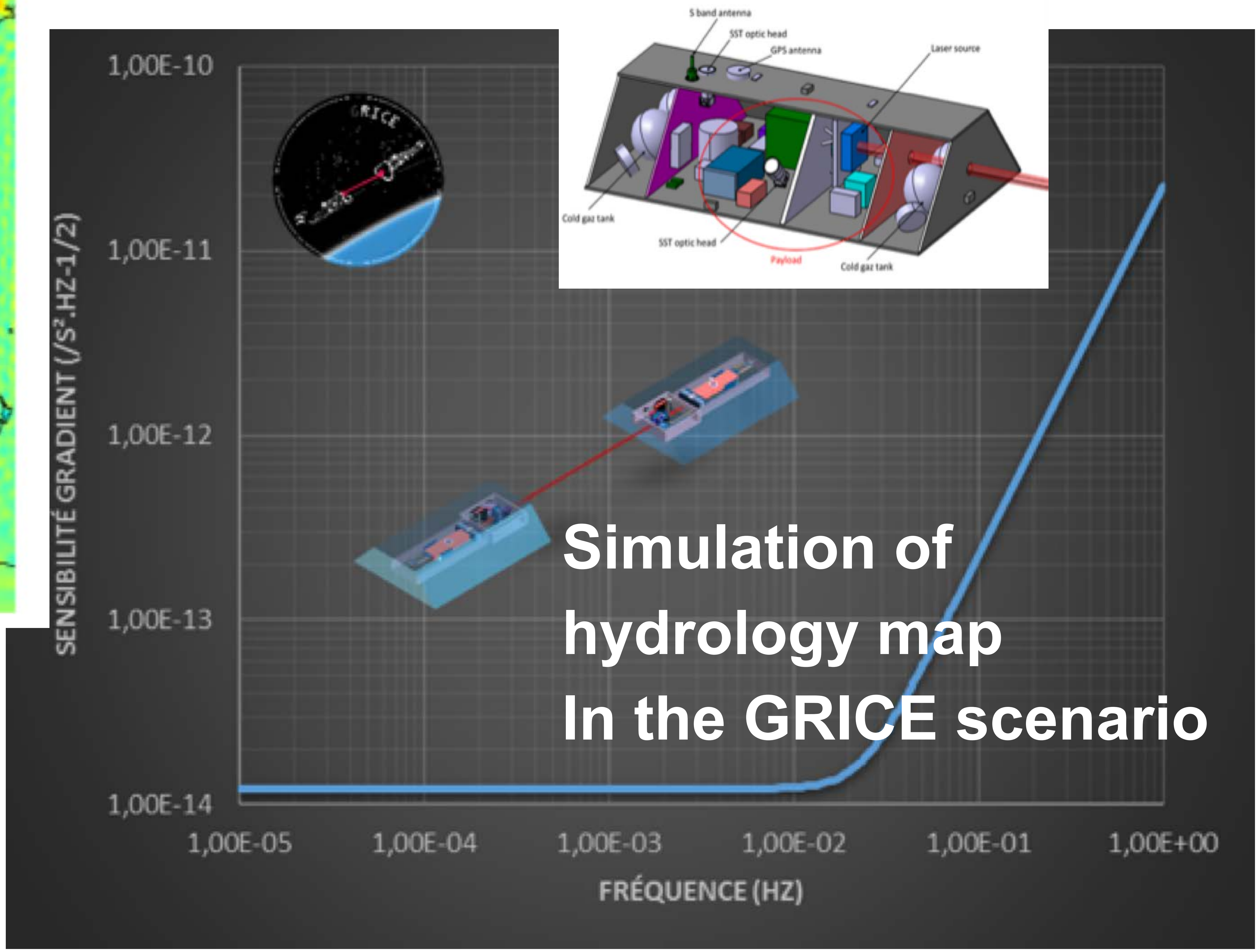
Underwater gravity mapping





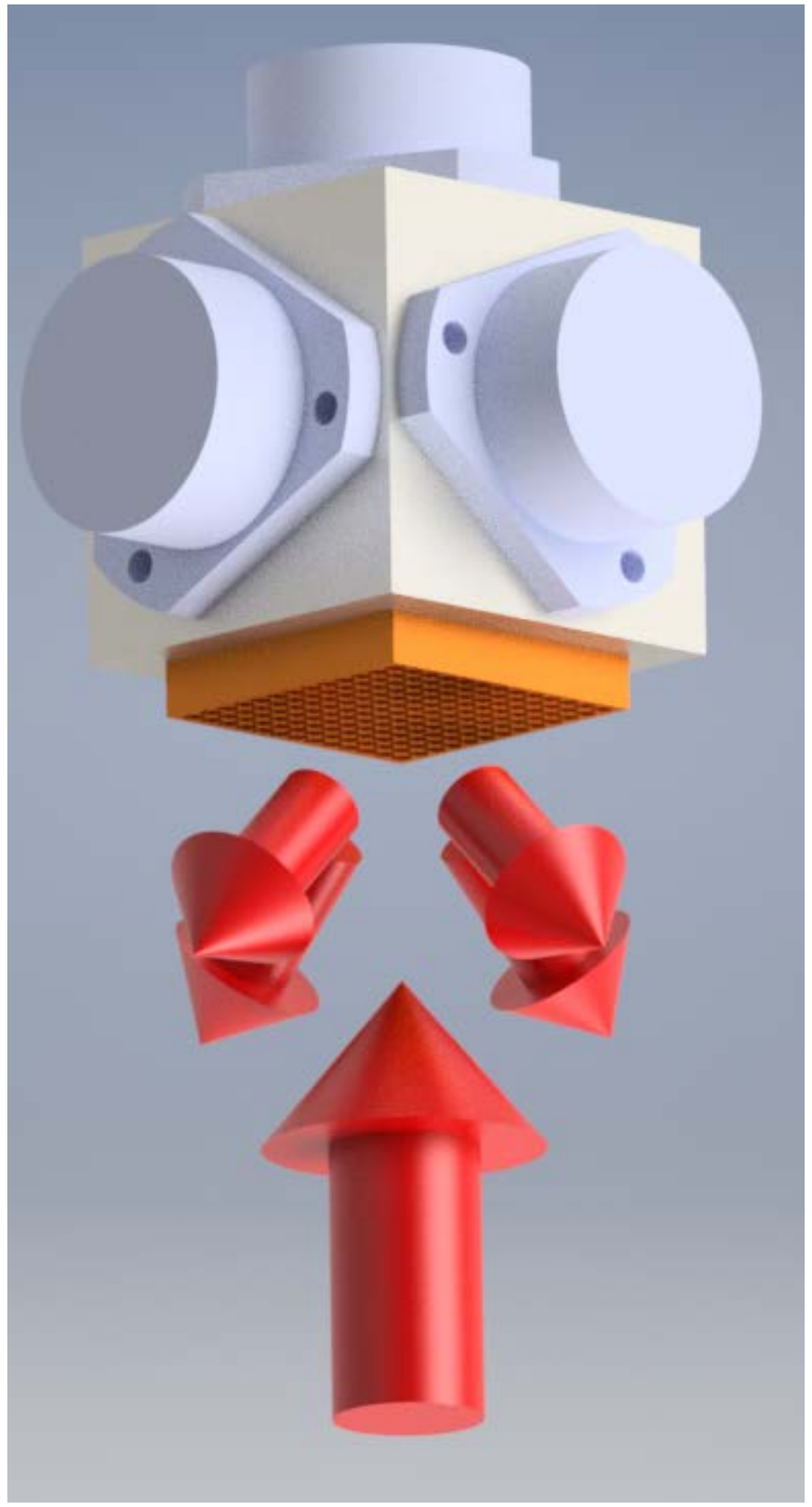
Space geodesy

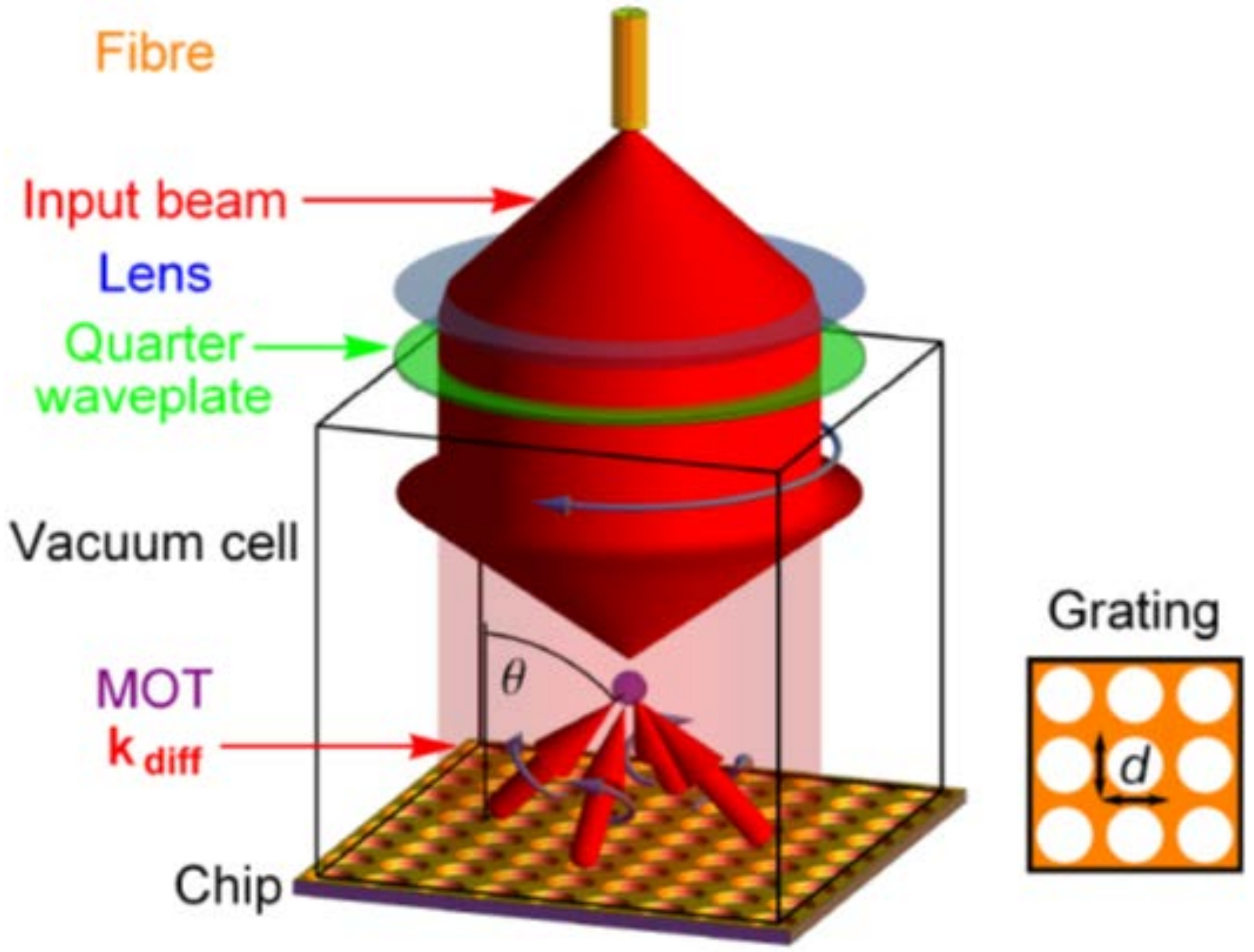




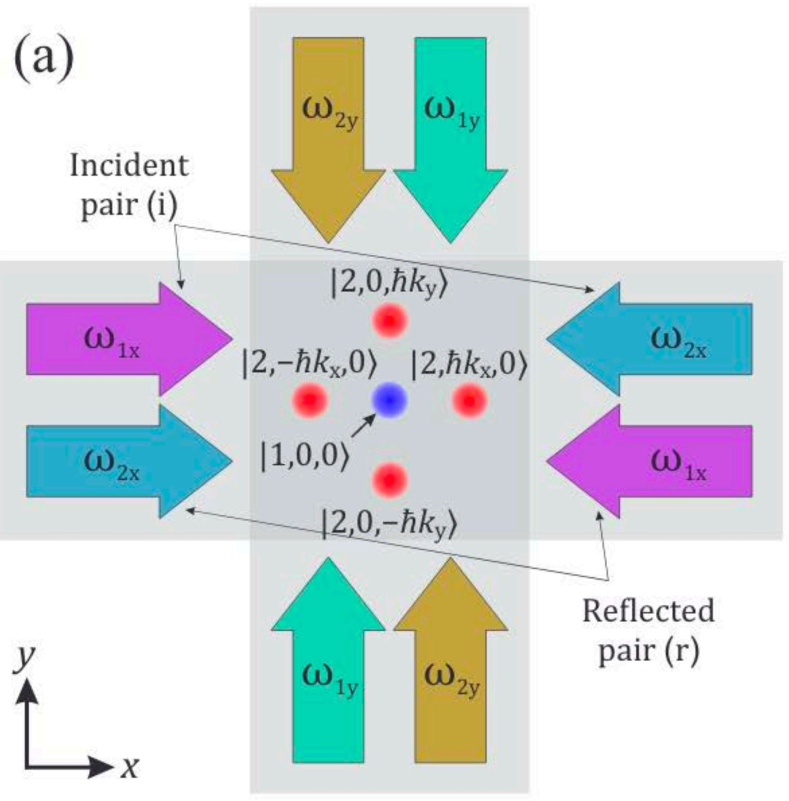
CNES GRICE phase 0 study

Future compact sensors

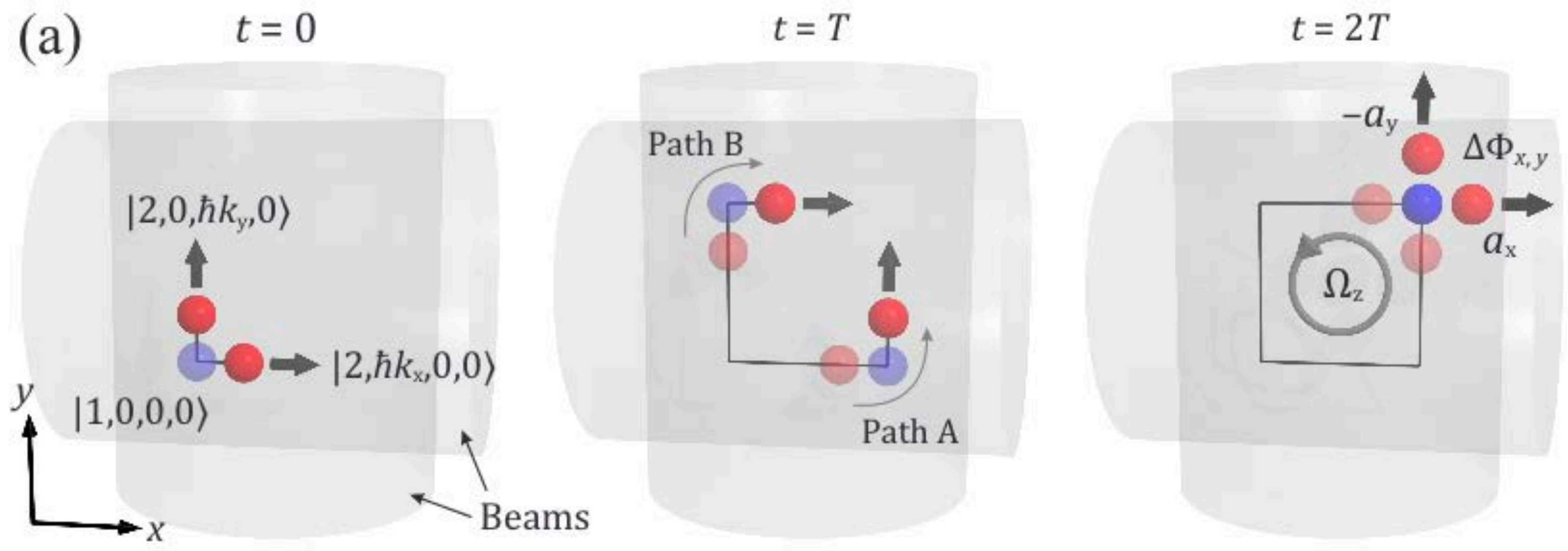


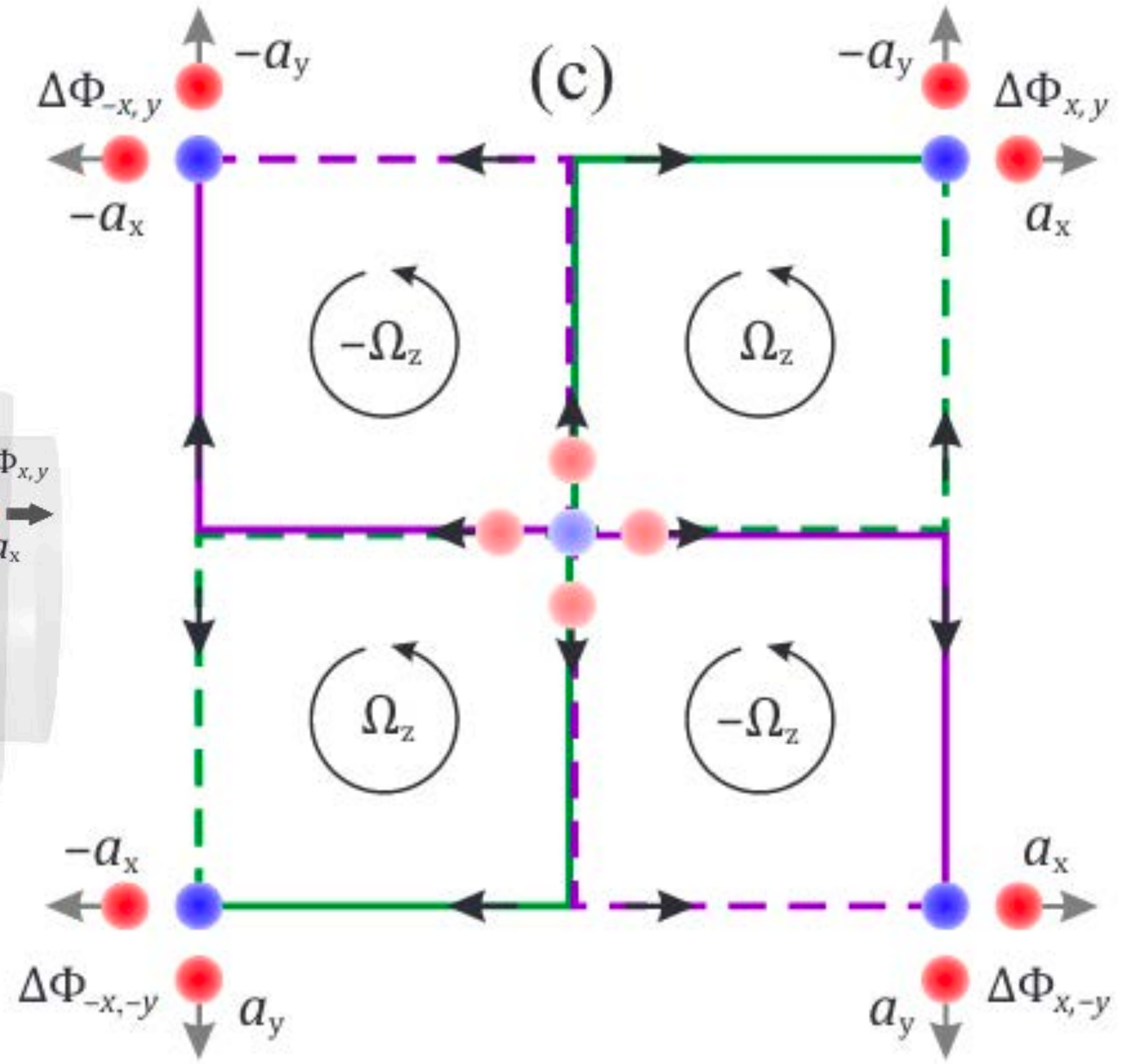


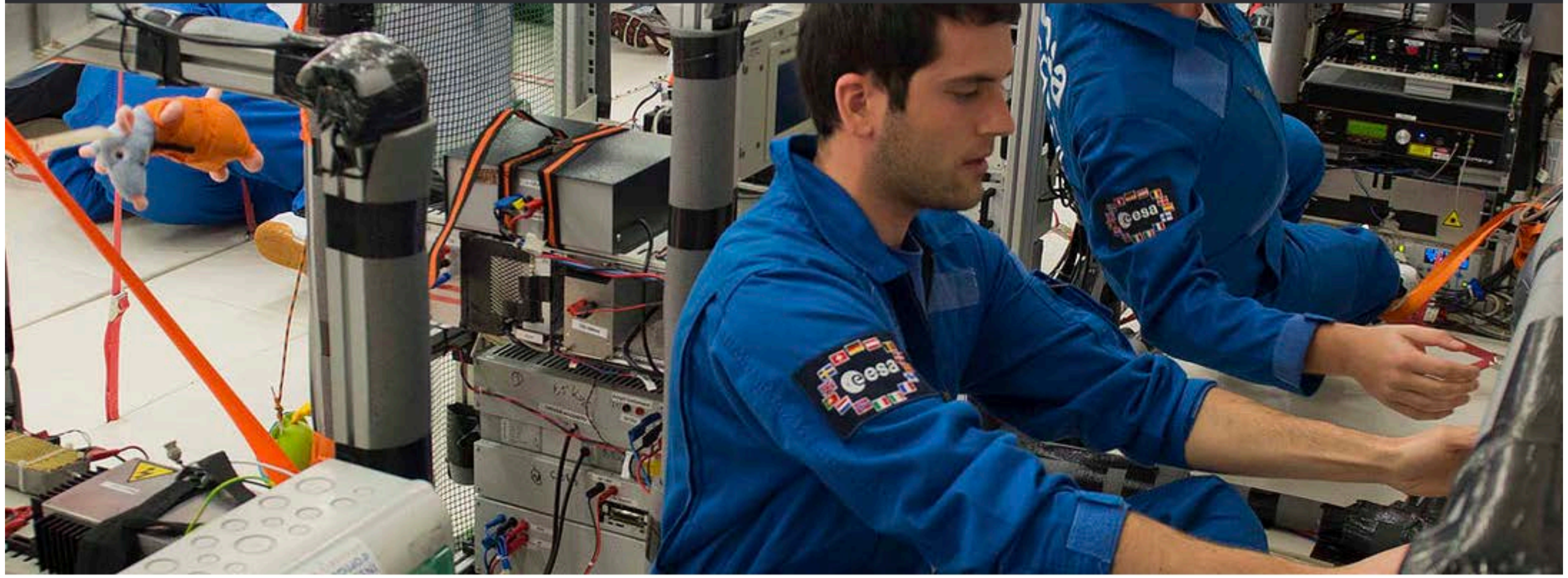
Cheinet et al., Patent n° FR2003648



Barret et al., Patent FR3087883







The team

The research group "Cold Atoms in Bordeaux" (CAB) is devoted to the use of atomic waves, either to exploit the unrivaled sensitivity of matter-wave interferometers or to develop quantum simulators where the atoms are used to study the properties of transport and propagation in exotic potentials.

More

This research team is part of the LP2N laboratory of the "Institut d'Optique d'Aquitaine" (IOA) in Bordeaux, France.

Projects

Click a project to access it

ICE
AUFRONS
iXAtom BIARO MICA
ALCALINF

Ultracold atoms and matter-waves

We are exploring the physics of ultracold atoms and matter-waves through 6 research projects.

- ALCALINF studies the interplay between quantum mechanics and gravity with Strontium atom interferometry.
- AUFRONS brings ultracold atoms close to nanostructures to create new quantum simulators for condensed matter.
- BIARO uses ultracold atoms in a resonant cavity to explore quantum physics and squeezing.
- ICE brings atom interferometry in microgravity for studying the frontiers of General Relativity.
- iXAtom joins academic research with industrial R&D to design the next generation of navigation systems.
- MICA is a large infrastructure to study Gravitation Wave physics.

Open positions

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