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COLD ATOM SENSORS FOR FIELD APPLICATIONS

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STATIC ABSOLUTE GRAVITY MEASUREMENTS

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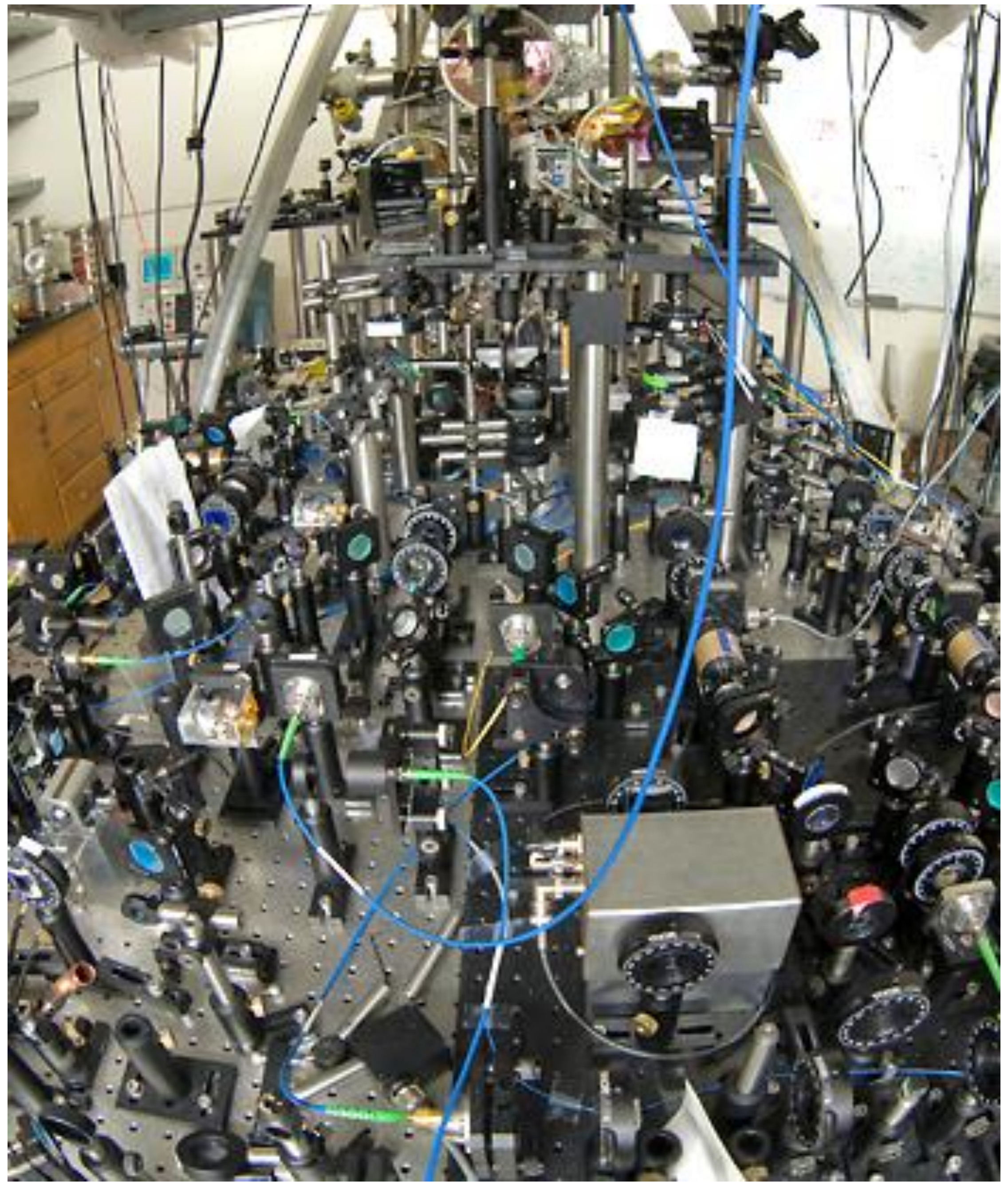
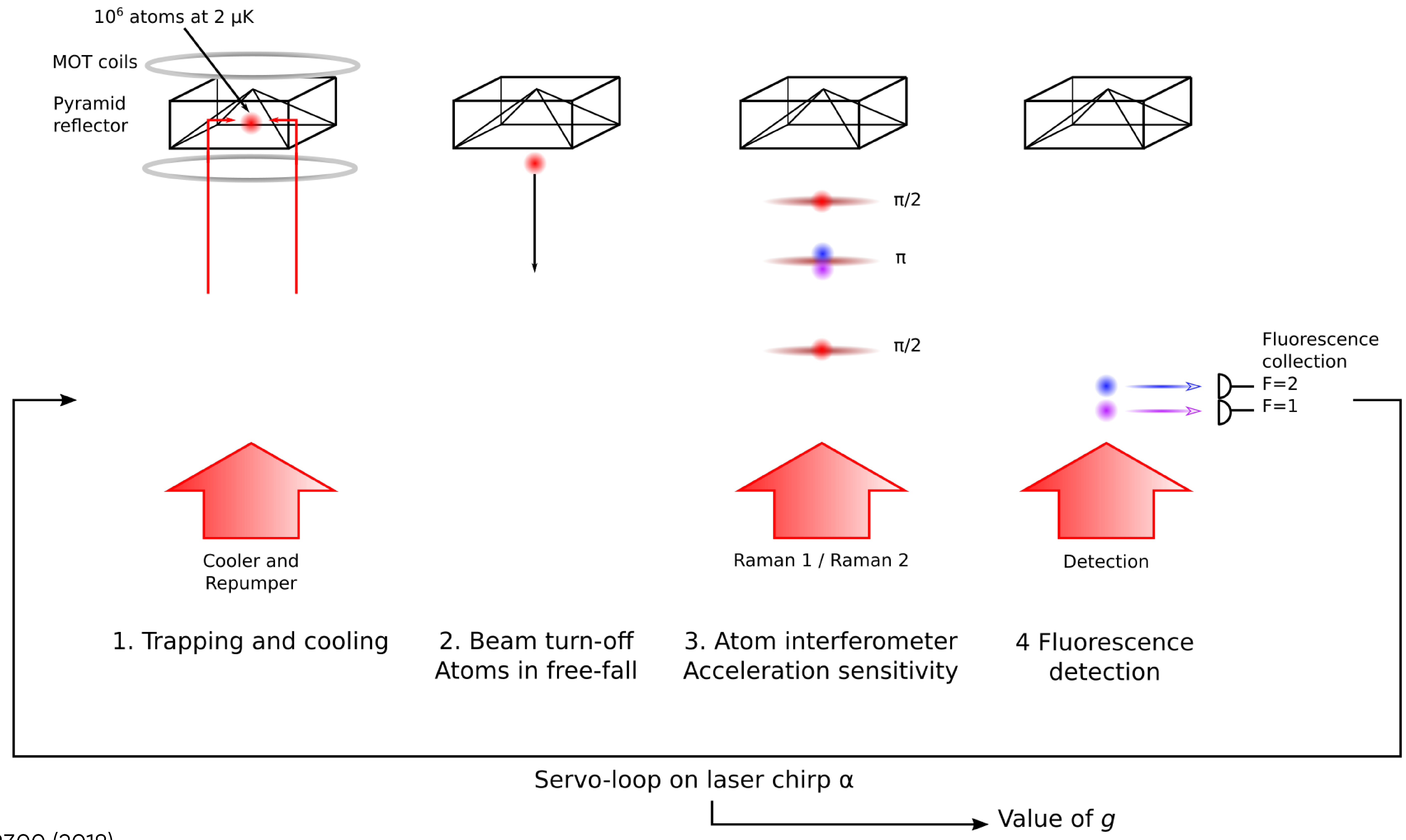
A bit of a challenge...



Berkeley, 2010

Muquans / Exail, 2020

Absolute Quantum Gravimeter (AQG)



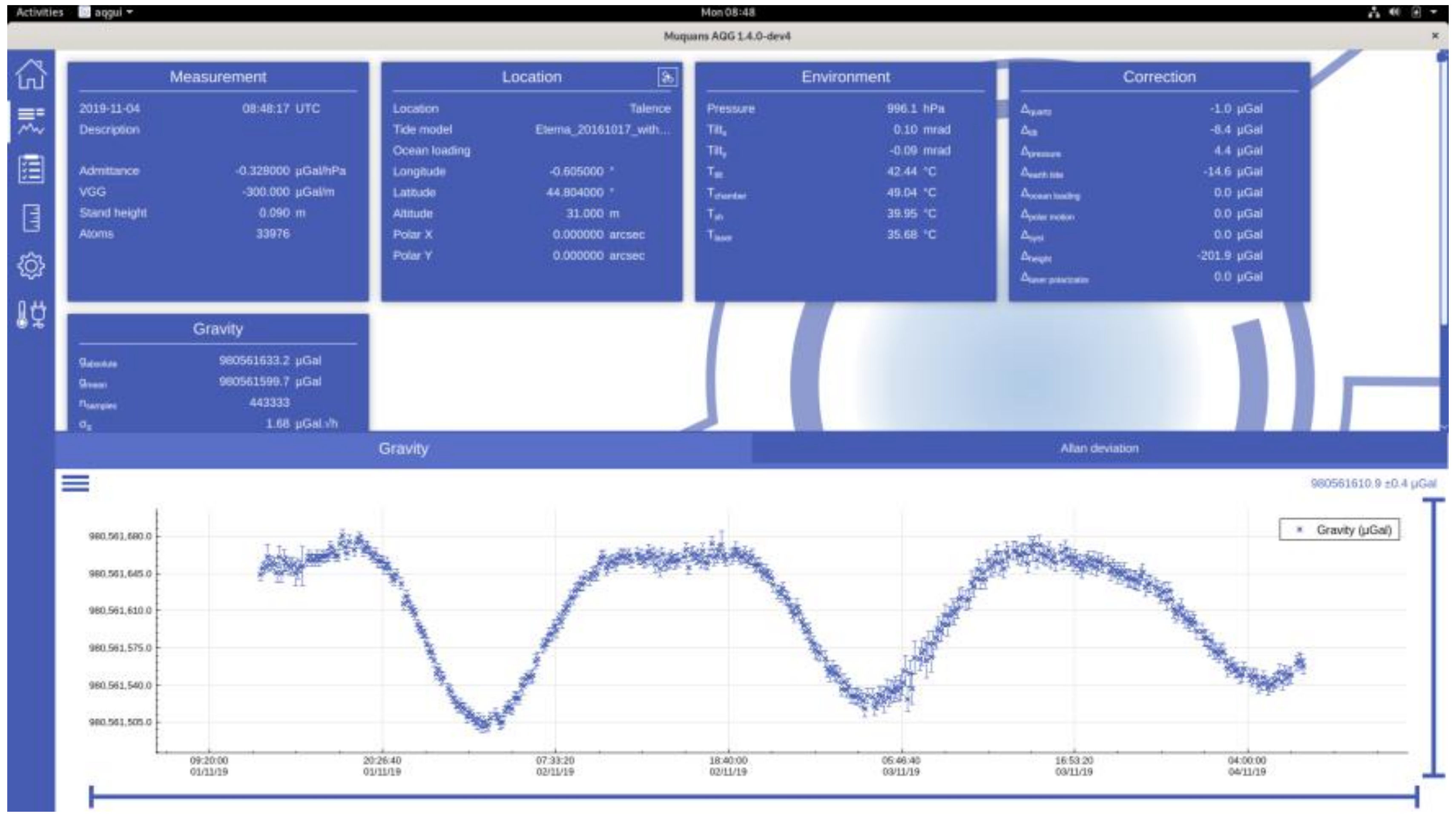
Ménoret et al., Sci Rep 8, 12300 (2018)

Absolute Quantum Gravimeter (AQG)

Fully integrated
- Home-made electronics, software, vacuum…
- Integrated supervision and monitoring
- Robust and compact design

User friendly
- Easy to install and operate
- Intuitive software
- Remote operation

High-performance
- Continuous absolute gravity measurements
- Resolution 1 µGal = 10 nm.s^{-2} ~ 10^{-9} *g*
  - Tides ~ 100 µGal/day
  - Earth gradient (vertical) ~ 300 µGal/m



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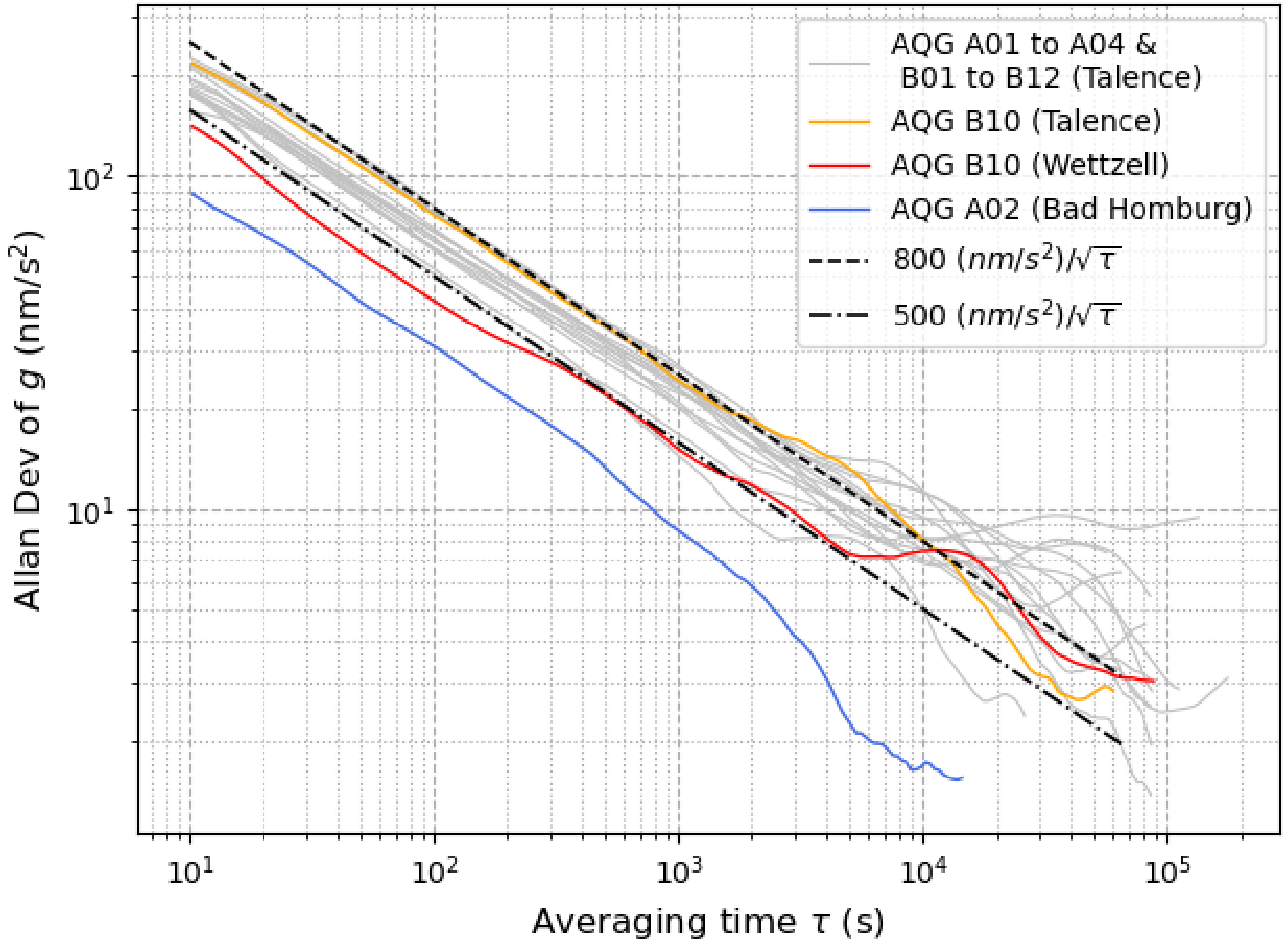
Performance evaluation

› Reproducible short-term sensitivity across 15+ instruments



L. Antoni-Micollier et al, IEEE I&M, 2024

› Evaluation of accuracy and repeatability

- Systematic effects
- Instrument comparisons

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Volcano monitoring: the NEWTON-g project

D. Carbone et al., Front. Earth Sci. 8:573396 (2020)

- **AQG installed on Mt Etna in July 2020**
  - 2800 m elevation
  - 2.7 km from summit craters

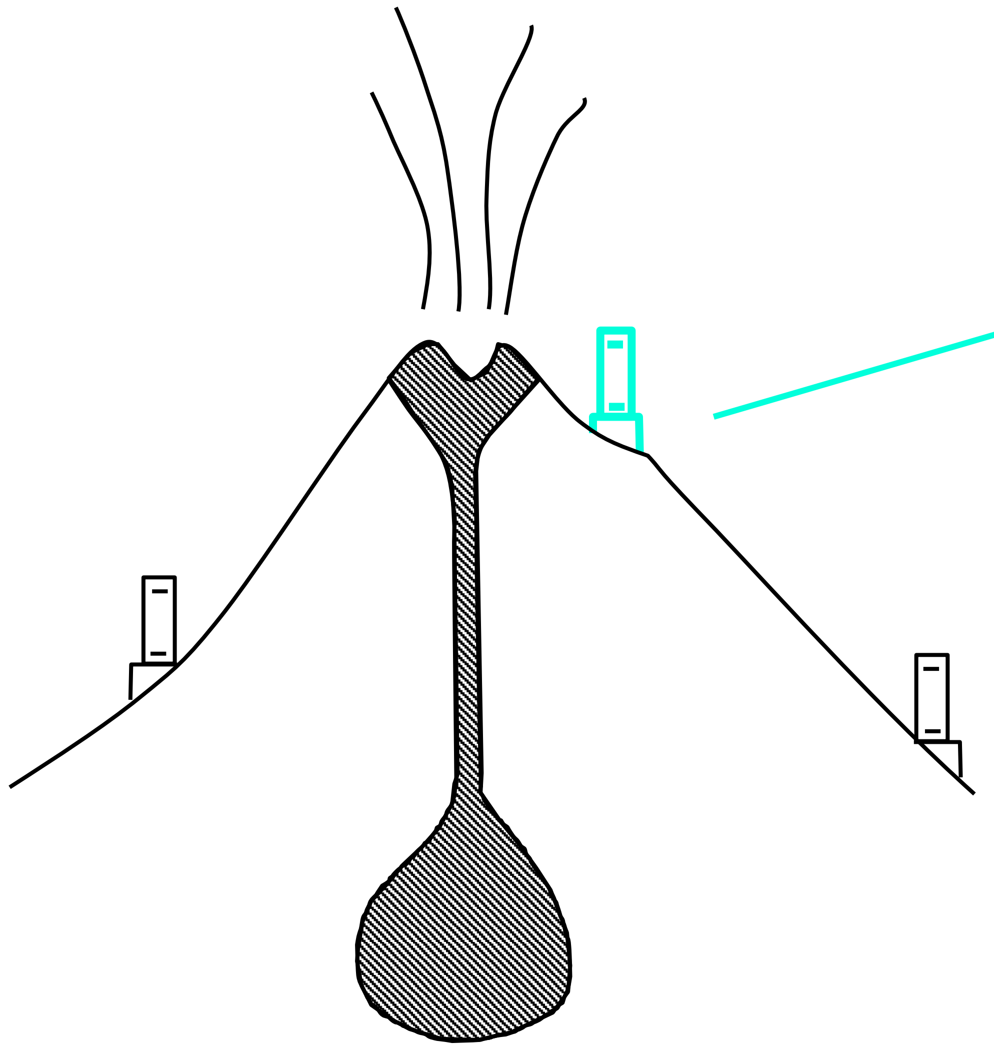
- **Hard conditions**
  - Volcanic tremor / eruptions
  - Temperature changes
  - Corrosive and dusty atmosphere
  - Difficult access (impossible in winter)
  - Unstable off-grid power supply

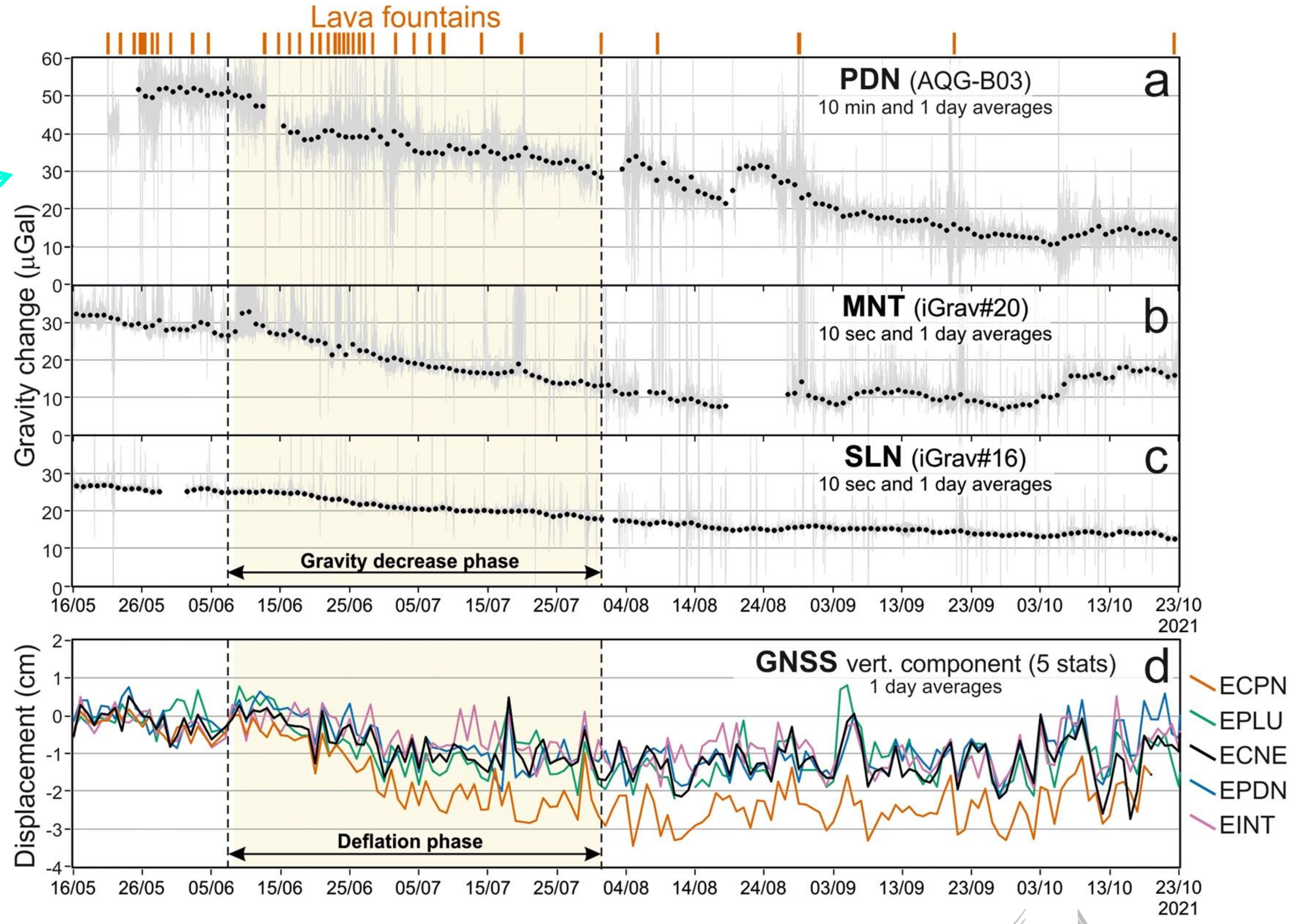
Volcano monitoring

- Joint inversion with other instruments + GNSS
- Helps to understand volcano dynamics
- AQG now part of Mt Etna's monitoring infrastructure

L. Antoni-Micollier et al., Detecting volcano-related underground mass changes with a quantum gravimeter, Geophys. Rev. Lett. e2022GL097814 (2022)

D. Carbone et al., Gas buffering of magma chamber contraction during persistent explosive activity at Mt Etna volcano, Commun. Earth & Environment, 4, 471 (2023)





NEWTON-g

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AQGs in operation

- **15 units operating around the world**
- **Several use cases**
  - Hydrology
  - Geodesy
  - Volcanology
- **Various conditions**
  - From nice observatories to field missions in Antarctica
- **A lot of experience**
  - A new way way of doing physics with cold atom sensors

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DIFFERENTIAL GRAVITY MEASUREMENTS

APPLICATION TO GRAVITY MAPPING

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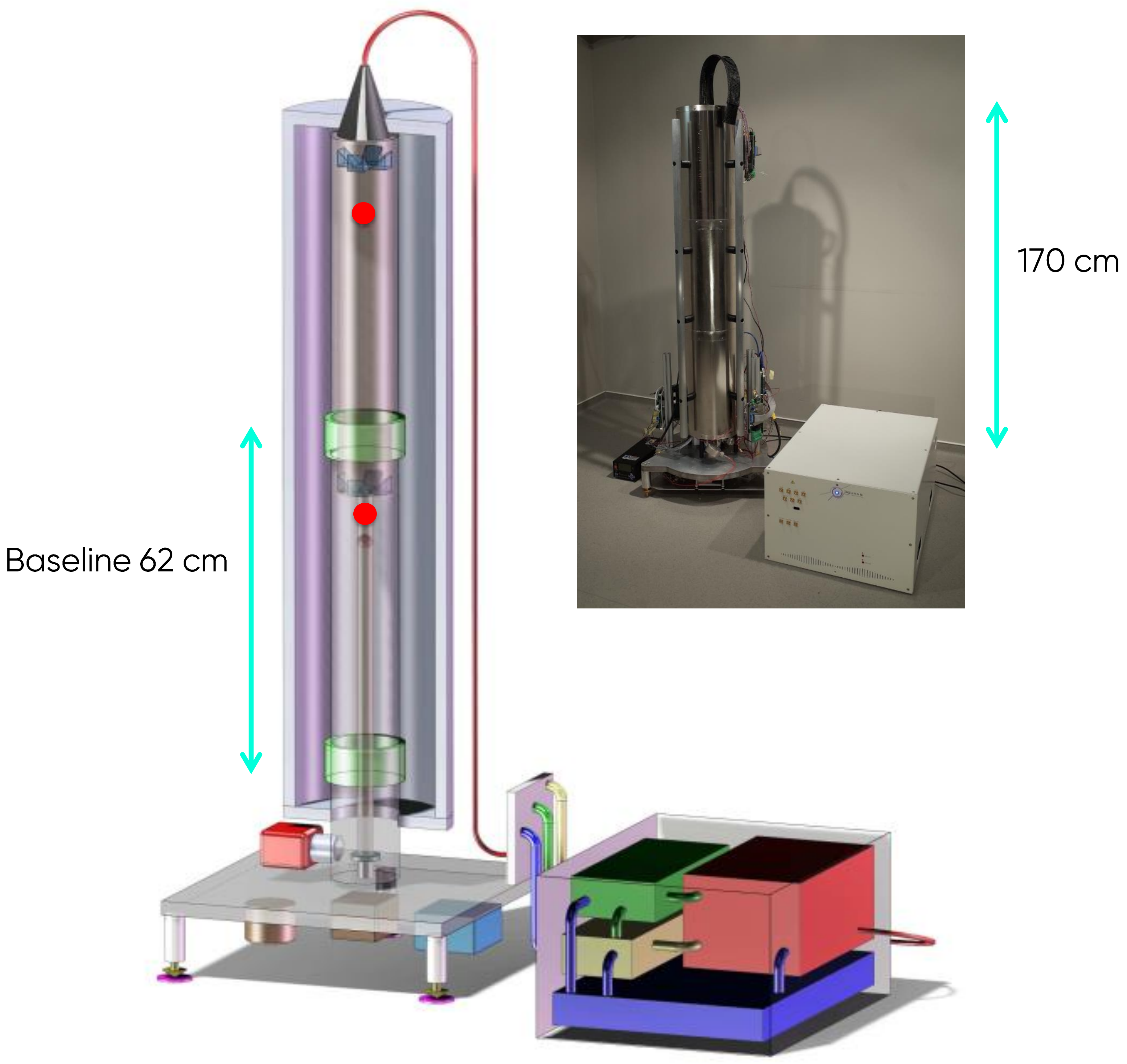
Differential Quantum Gravimeter

Gravimeter

$$\bar{g} = \frac{g_1 + g_2}{2}$$

Gradiometer

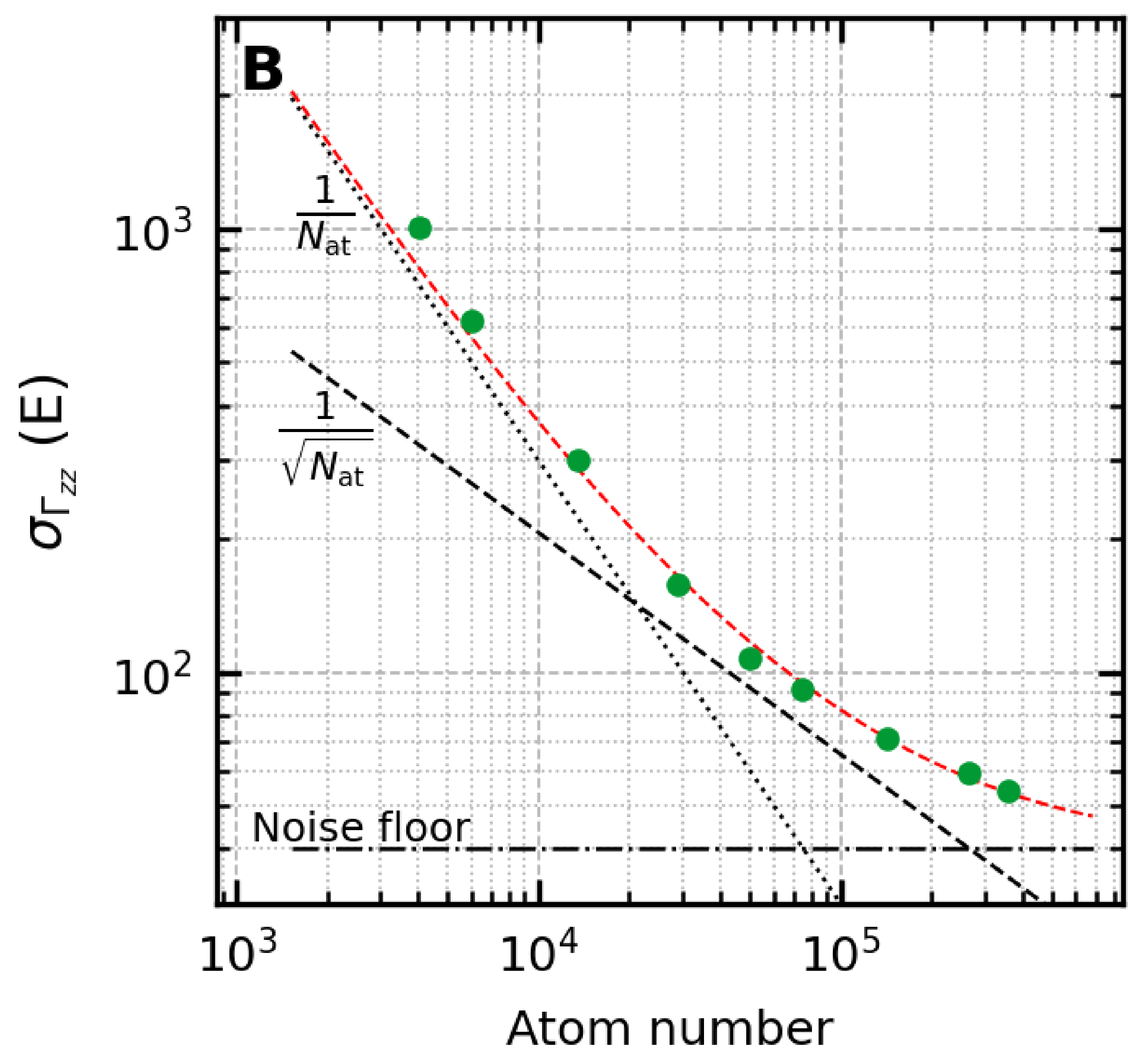
$$\Gamma_{zz} = \frac{g_1 - g_2}{L}$$



Janvier et al., PRA 105, 0222801 (2022)

Quantum projection noise

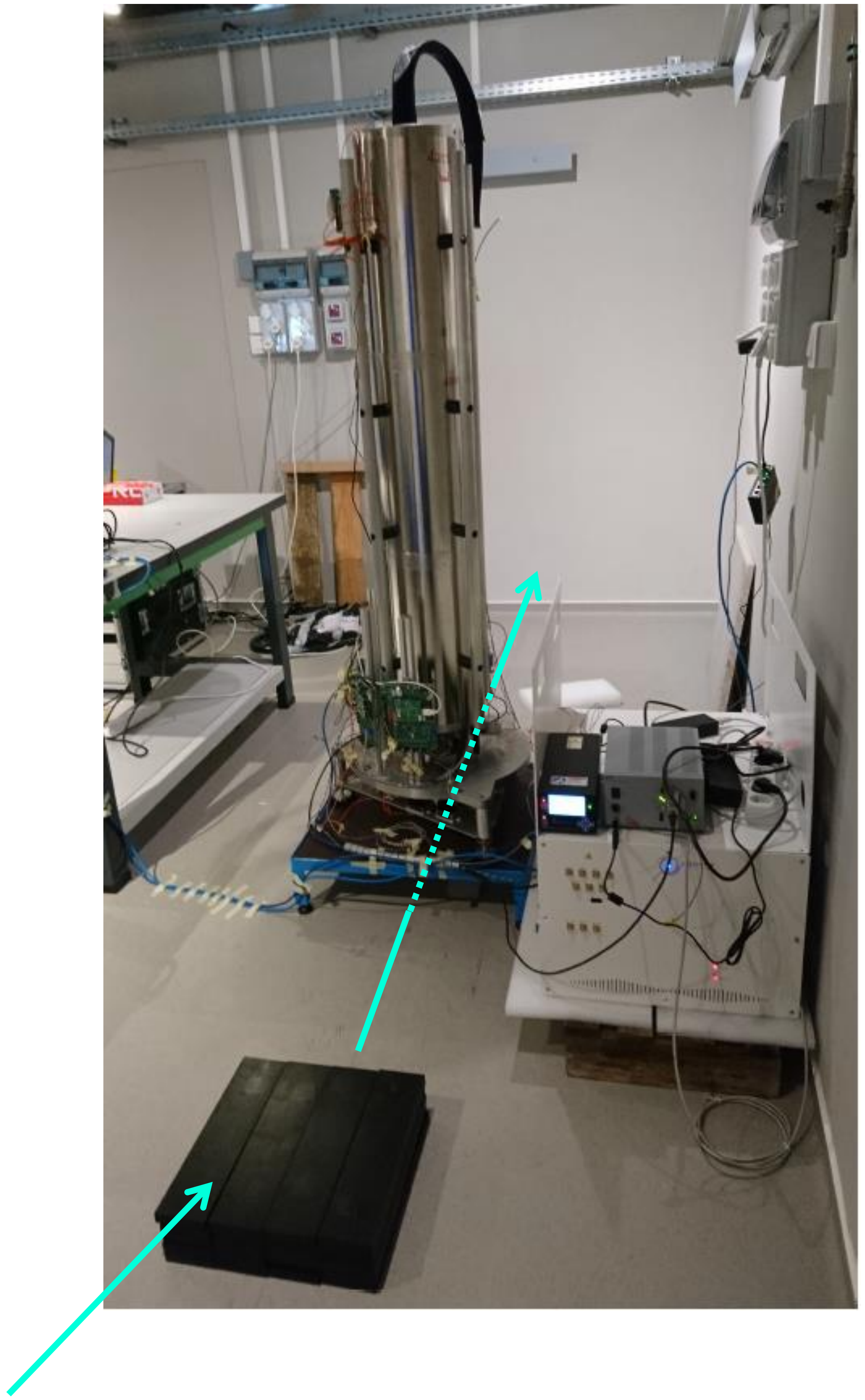
- **Simultaneous operation of the two atom interferometers**
  - in phase
  - at mid-fringe
- **Differential measurement limited by QPN between 2.5x104 and 2.5x105 atoms**
- **Noise floor ~ 40 E**
  - Compatible with frequency noise on Raman lasers



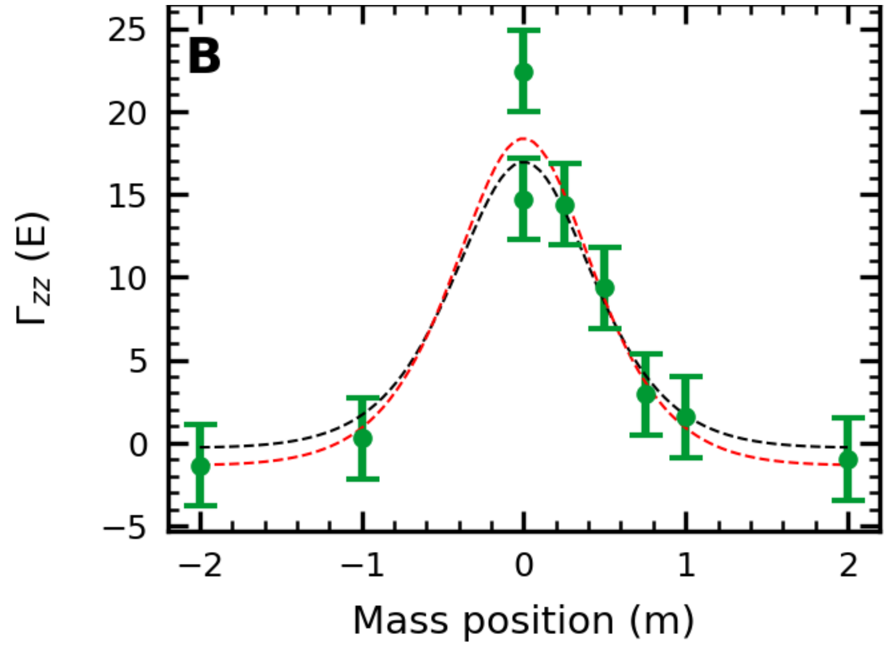
Janvier et al., PRA 105, 0222801 (2022)

Mass detection

- **Realistic conditions**
  - Small mass (147 kg)
  - 1 hour integration per position
- **Mass estimation: 168 ± 17 kg**
  - Within 2-sigma uncertainty
- **Even more sensitive when mass is located halfway between the two clouds**
  - Detection of a person in a few minutes



Lead bricks



Janvier et al., PRA 105, 0222801 (2022)

SYRTE l'Observatoire de Paris | PSL
SYstèmes de Référence Temps-Espace
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TOWARDS ONBOARD APPLICATIONS

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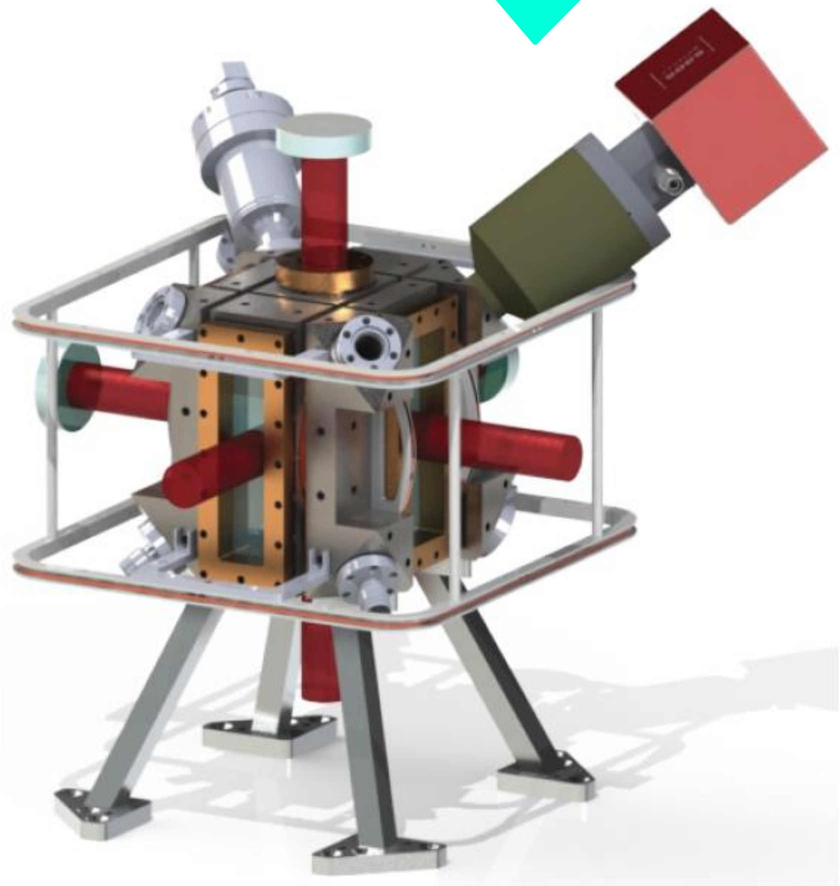
Double hybridization

Increase dynamic range and bandwidth

Atom interferometer
- High sensitivity
- High stability
- Accurate
- Dead times
- Low data rate
- Low dynamic range



Classical accelerometer / gyroscope
- Large bandwidth
- No dead time
- Linear
- Bias
- Drifts

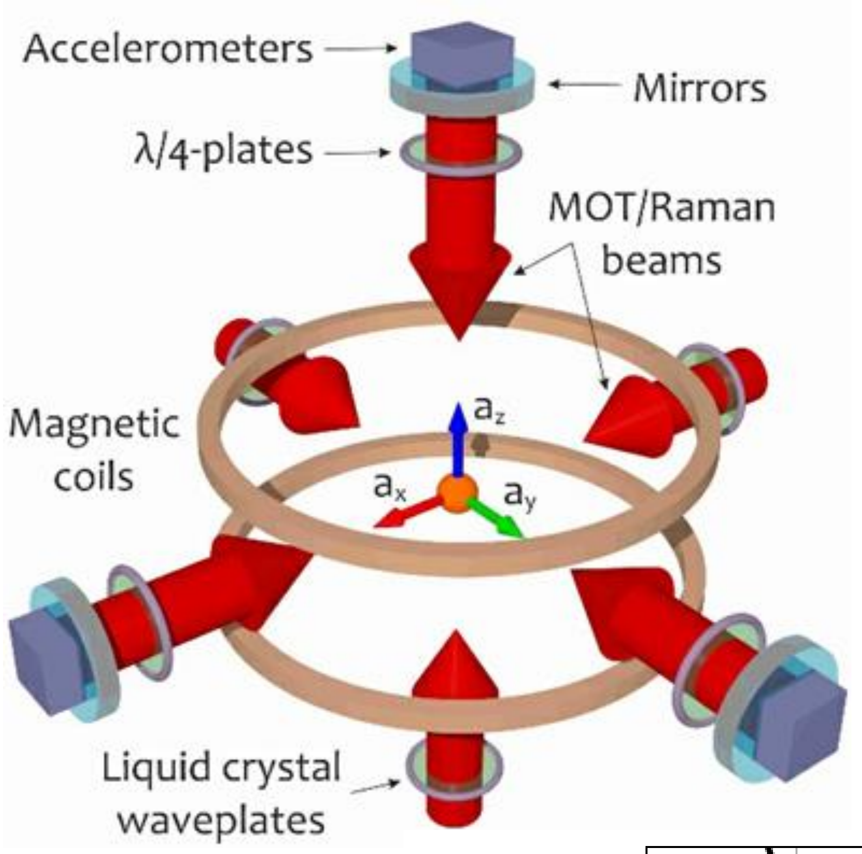
Correct slow drifts

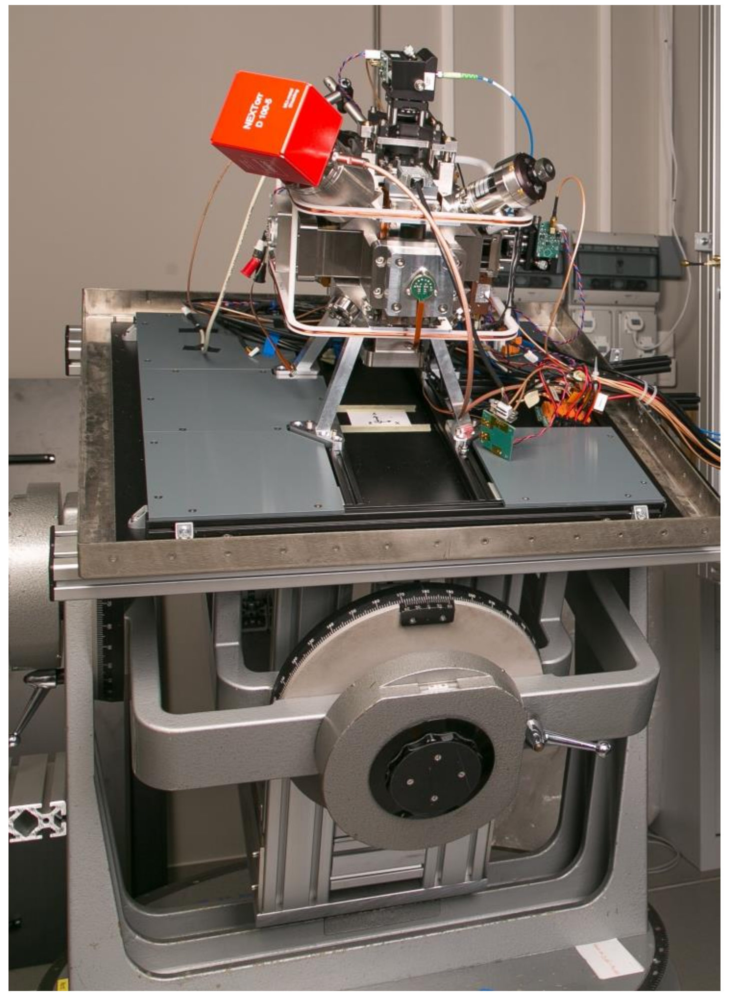
S. Templier et al., Science Advances 8, 45 (2022)

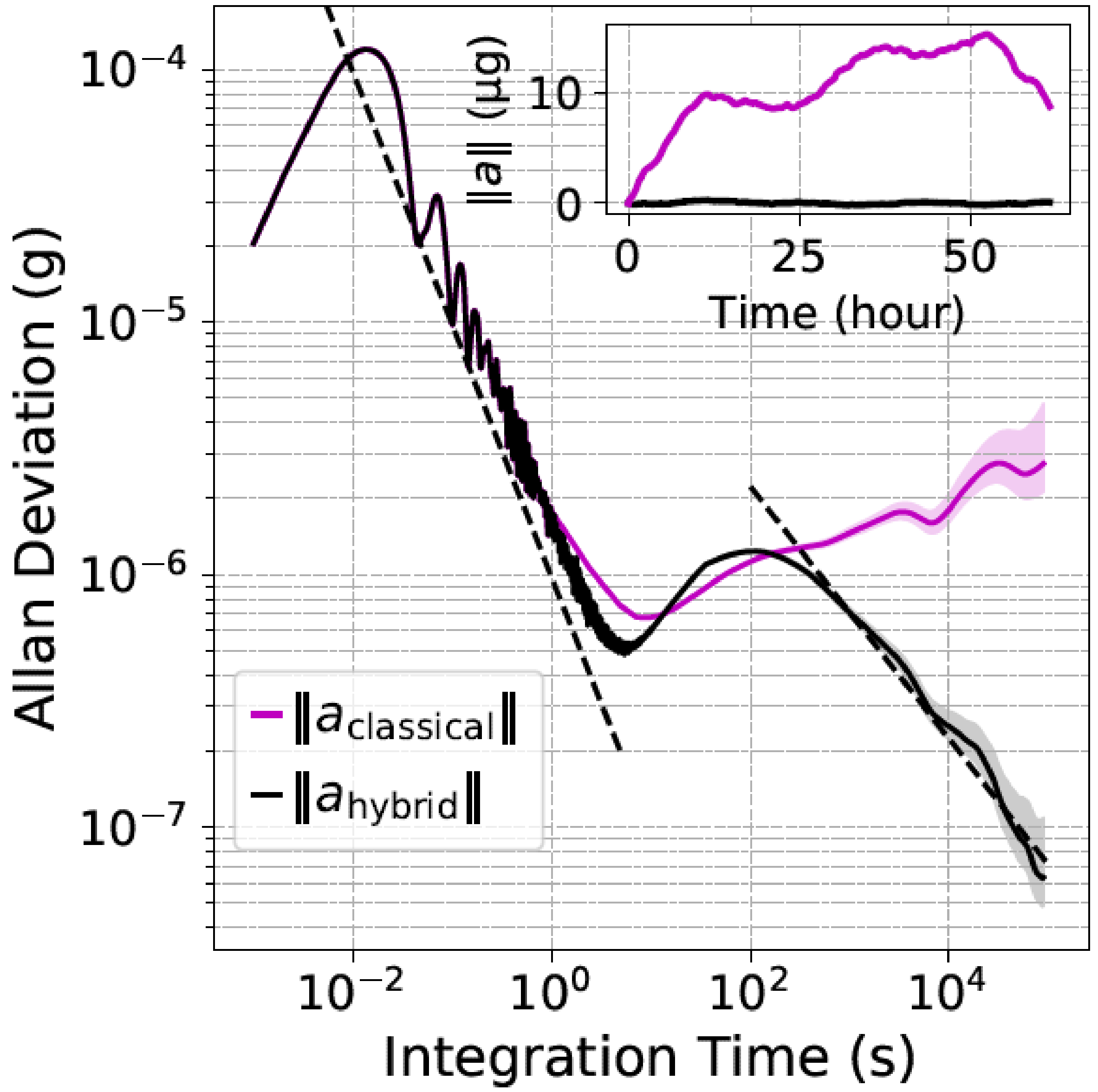
ixatom JOINT LAB

Multi-axis measurements

- 3D ‘strapdown’ accelerometer
- Alternative measurements on 3 axes
- Reconstruction of the acceleration vector
- 50-fold improvement in stability w.r.t. classical accelerometers





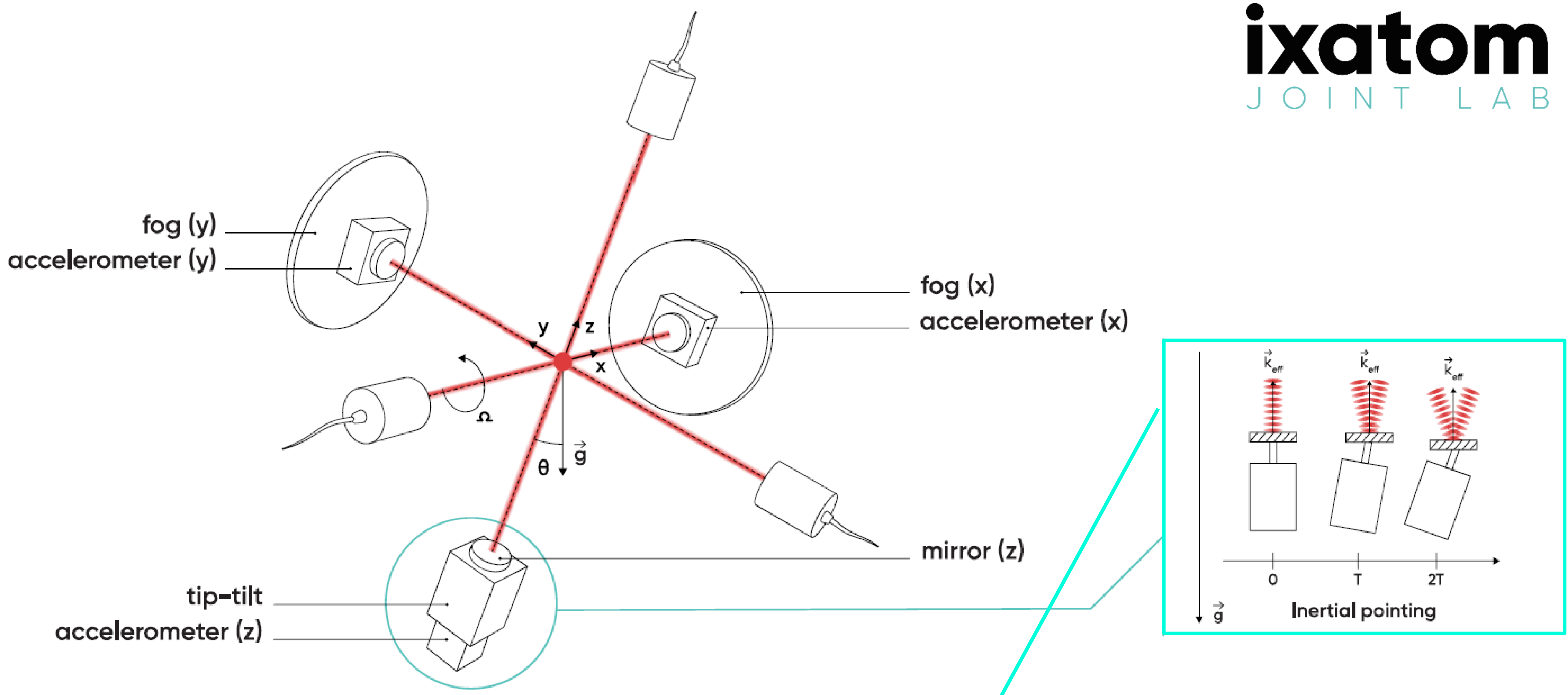


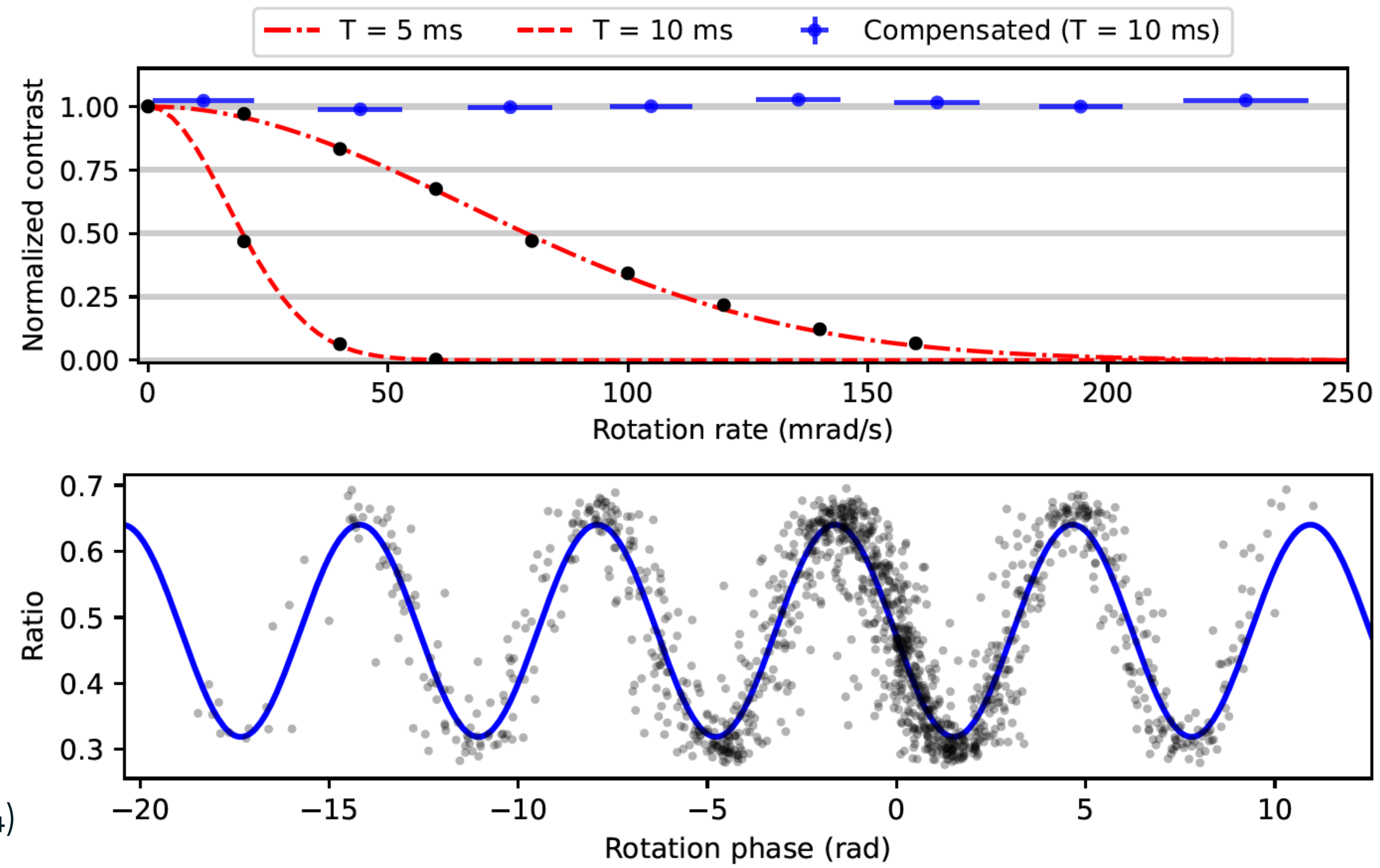
S. Templier et al., Science Advances 8, 45 (2022)

Dealing with rotations

- **Rotations**
  - Loss of contrast
  - Phase shifts

  →Must be taken into account in dynamic environments
- **Hybridization with Fiber Optics Gyroscopes (FOGs)**





Q. D'Armagnac et al., Nature Communications (2024)

CONCLUSION

Conclusion

Absolute Quantum Gravimeter
- Ground instruments are mature and operational
- 15 units in operation around the world

Differential Quantum Gravimeter
- Gravity + gradient measurement
- High resolution at shallow depth

Onboard measurements
- Ongoing research
- Rotations, multi-axis measurements

Perspectives
- New use cases for gravimetry
- Inertial Navigation
- Space-qualified systems