universität wien

VCQ Vienna Center for Quantum Science and Technology

IQOQI Vienna

ÖAW AUSTRIAN ACADEMY OF SCIENCES

How to avoid the appearance of a classical world in gravity experiments?

Steps towards a quantum Cavendish Experiment

Prelude – Chapel Hill

- 1957: The Role of Gravitation in Physics

  The absence of any paradox or discrepancy in gravitation theory at the human and astronomical levels creates an obligation to apply Einstein's ideas down to smaller and smaller distances. One must check as one goes, until one has either a successful extension to the very smallest distances, or a definite contradiction or paradox that will demand revision. ... The challenge cannot be evaded. Exactly how to proceed is a matter of wisdom, skill, judgement, and a good idea. Nobody guarantees to have a good idea, but the DeWitts, fortunately, have a very sound plan of what to do while searching for a good idea.

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Do gravitational waves exist?

Do we need a quantum description of gravity?

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Approaches to Quantum Gravity

I. **Assume the existence of a quantum theory of gravity**

- probe its low-energy consequences

  e.g. Lämmerzahl Appl. Phys. B 84, 563 (2006);

  or specifically for mechanical quantum systems:
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Future: Design of a quantum and gravity experiment

e.g. Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)

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”One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference”

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Quantum entanglement via gravity

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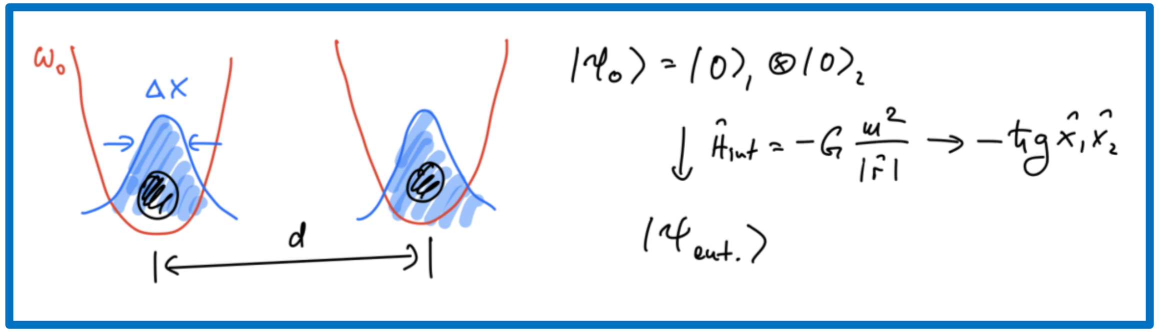
Large Quantum States



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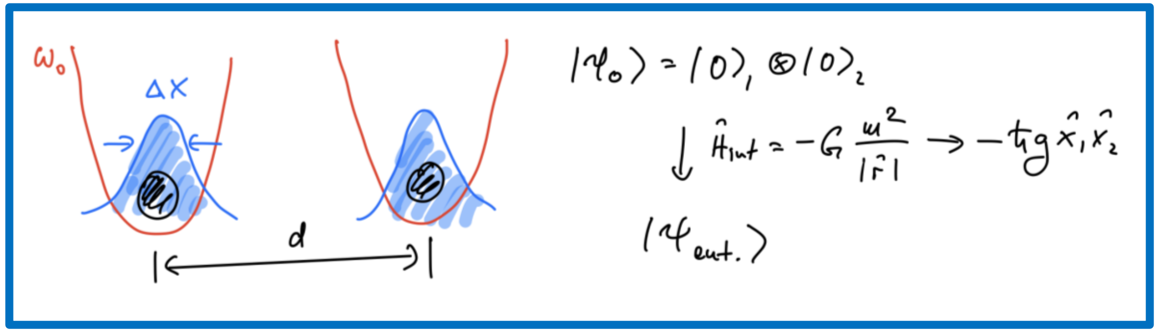

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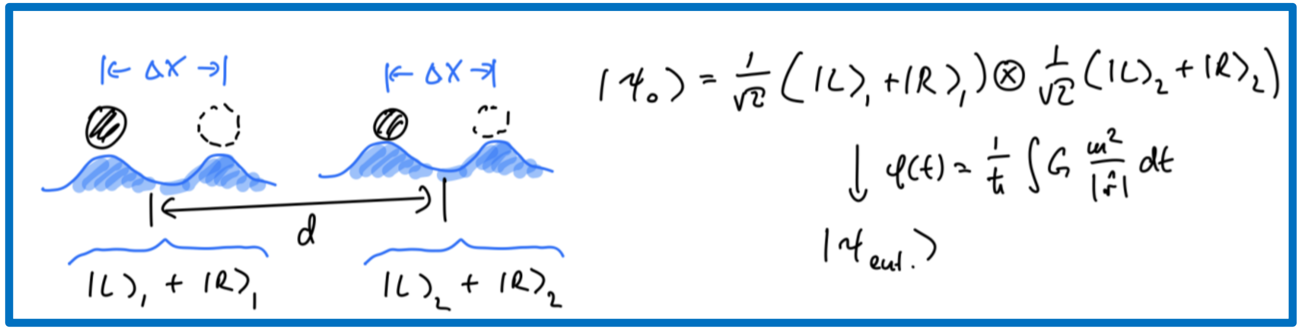

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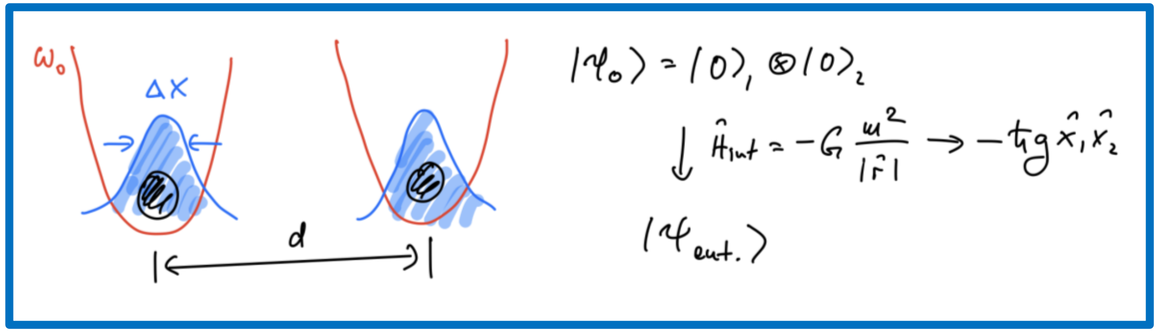

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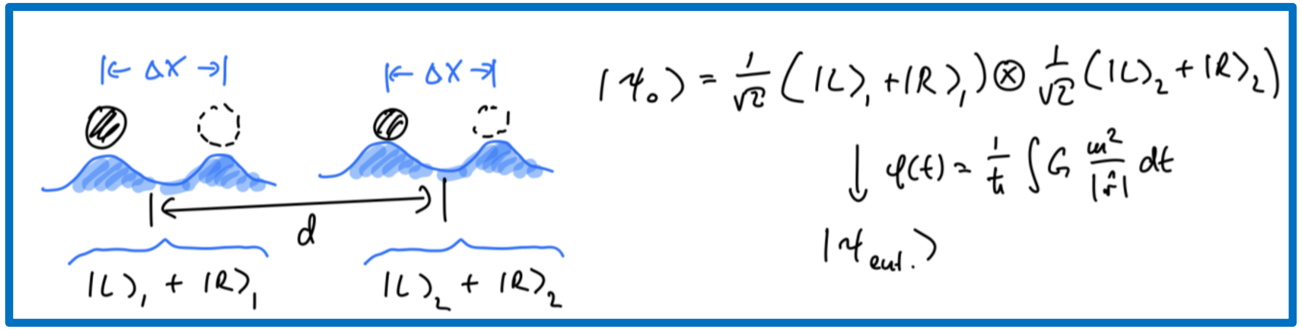

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ENTANGLEMENT RATE $g = \frac{G}{\hbar}\frac{m^2}{d}\left(\frac{\Delta x}{d}\right)^2 \overset{!}{>} \Gamma_{decoherence}$

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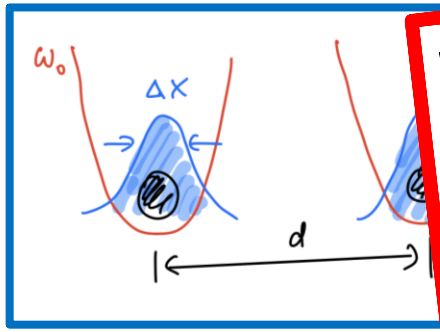

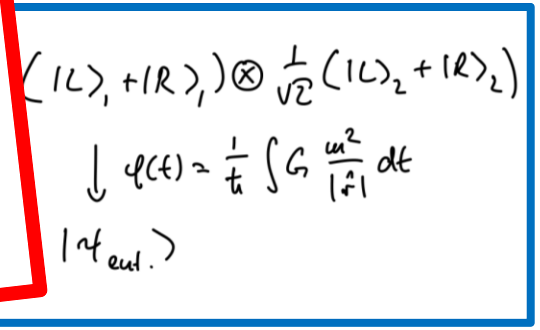

NOTE! Generation of **entanglement via gravity**
from a **quantum perspective**: *obvious*
from a **GR perspective**: *inconsistent with a fixed space-time metric,*
e.g. Christodoulou and Rovelli, arxiv 1808.05842

$$G_{\mu\nu} \overset{?}{=} 8\pi \langle T_{\mu\nu} \rangle$$

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Motivation

$$m^2 \Delta x^2 \tau_{coherence} \, d^{-3} \overset{!}{>} \hbar / G$$

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Quantum Experiments

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$$m^2 \, \Delta x^2 \, \tau_{coherence} \, d^{-3} \overset{!}{>} \hbar / G$$

Quantum Experiments ($m^2 \, \Delta x^2 \, \tau_{coherence}$)

Gravity Experiments (d^{-3})

Motivation

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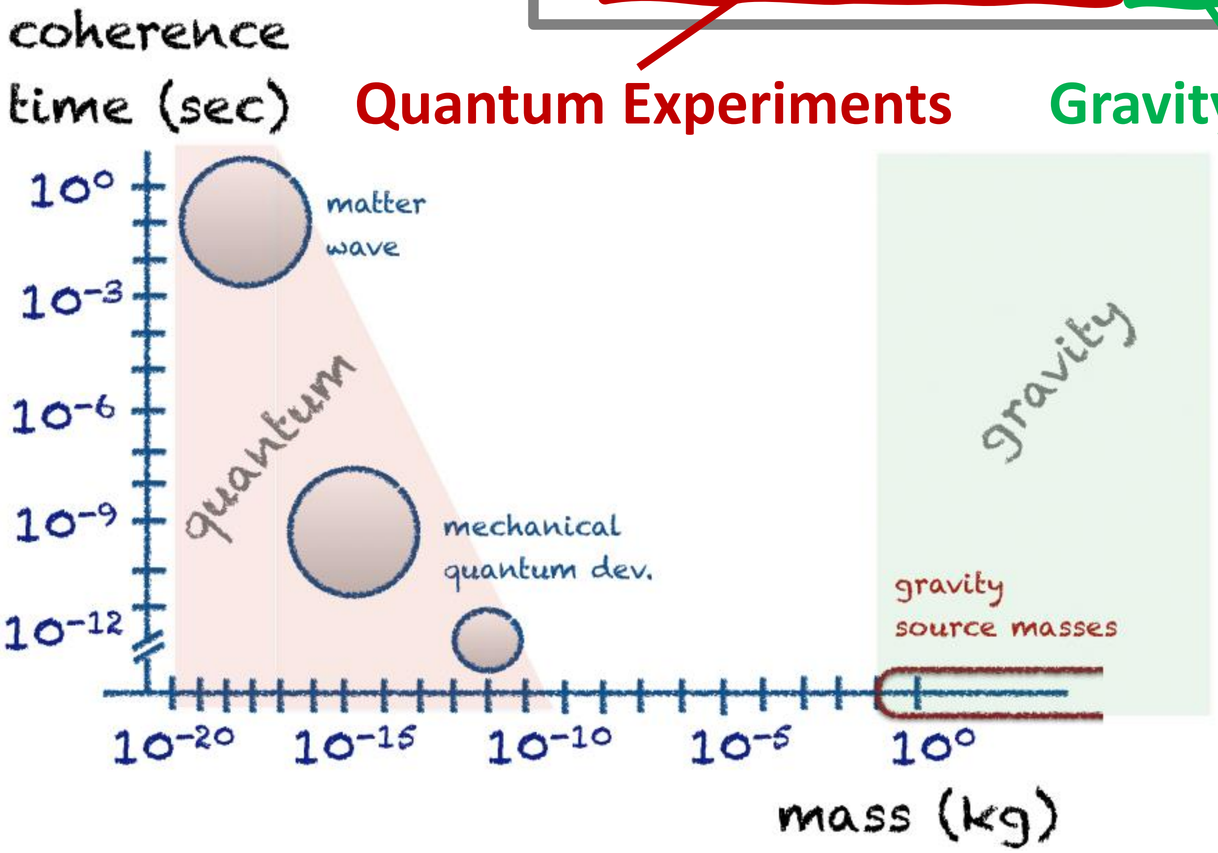
Quantum Experiments **Gravity Experiments**



How **big** can we get?

How **small** can we get?

Smallest source mass to date: **0.7 g**

Mitrofanov et al., Zh. Eksp. Teor. Fiz. 94,16-22 (1988)
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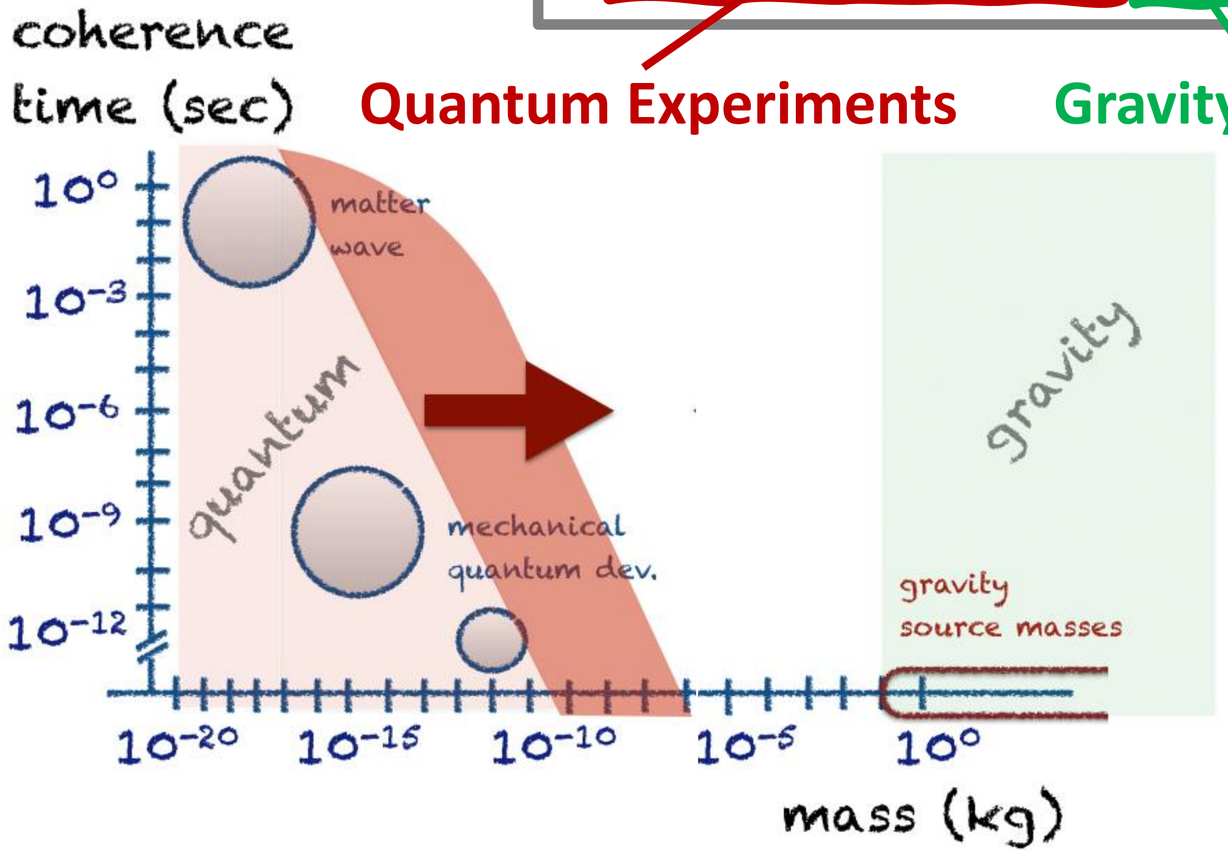

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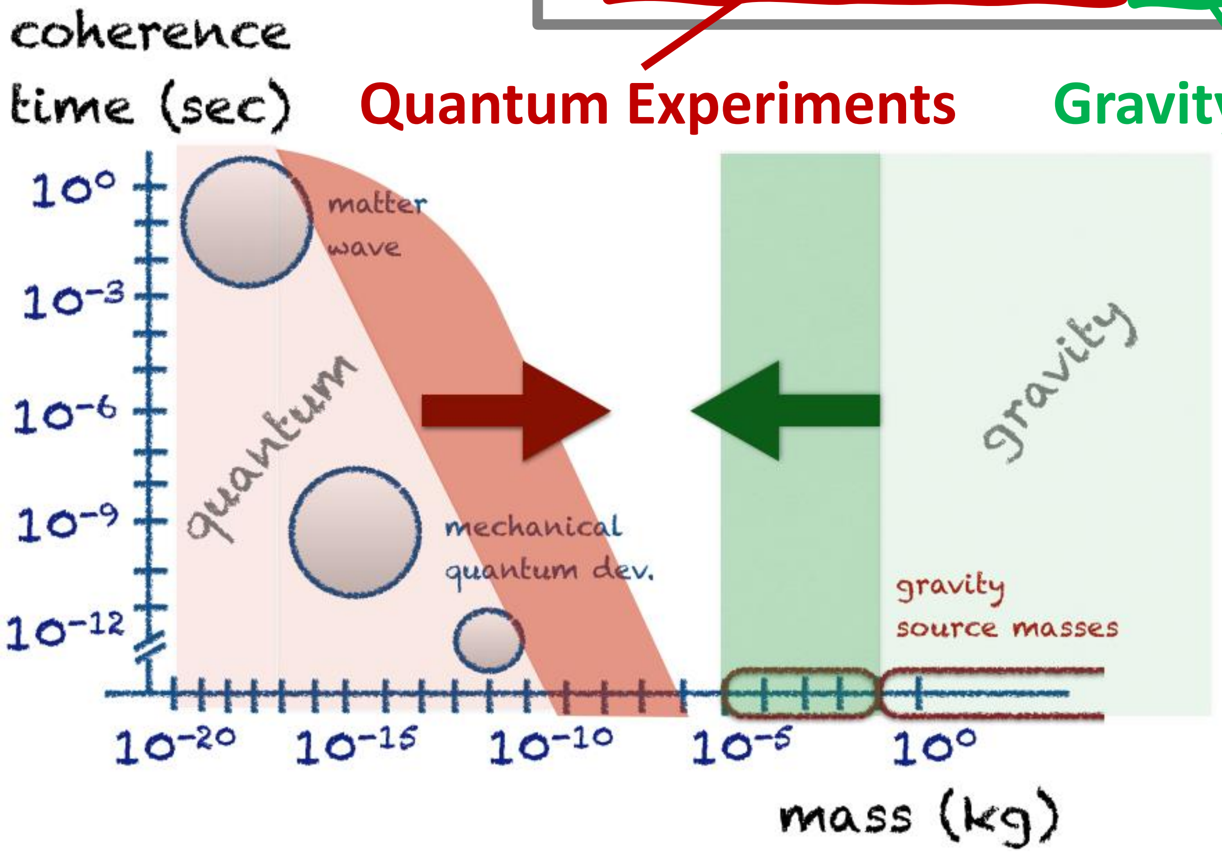

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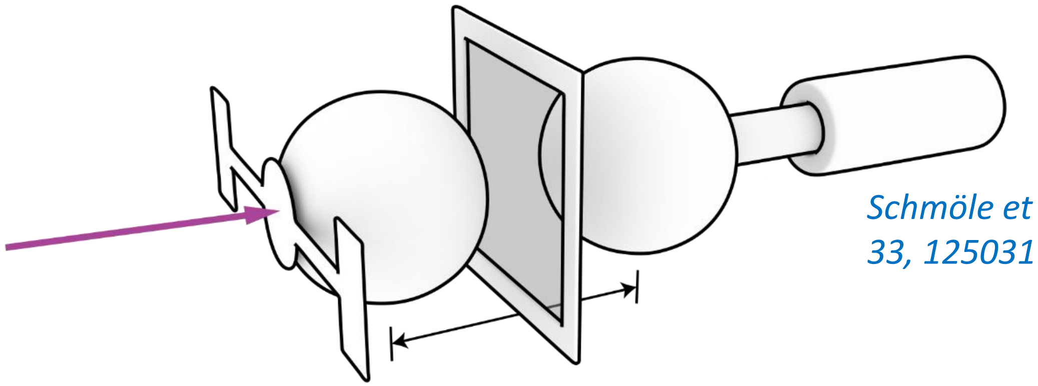
How small can we go?

- Periodic modulation of source mass @ f_{mod}
- Test mass acceleration @ n x f_{mod}
- Fundamental limit: thermal noise of test mass oscillator



Schmöle et al., Class. Quant. Grav. 33, 125031 (2016)

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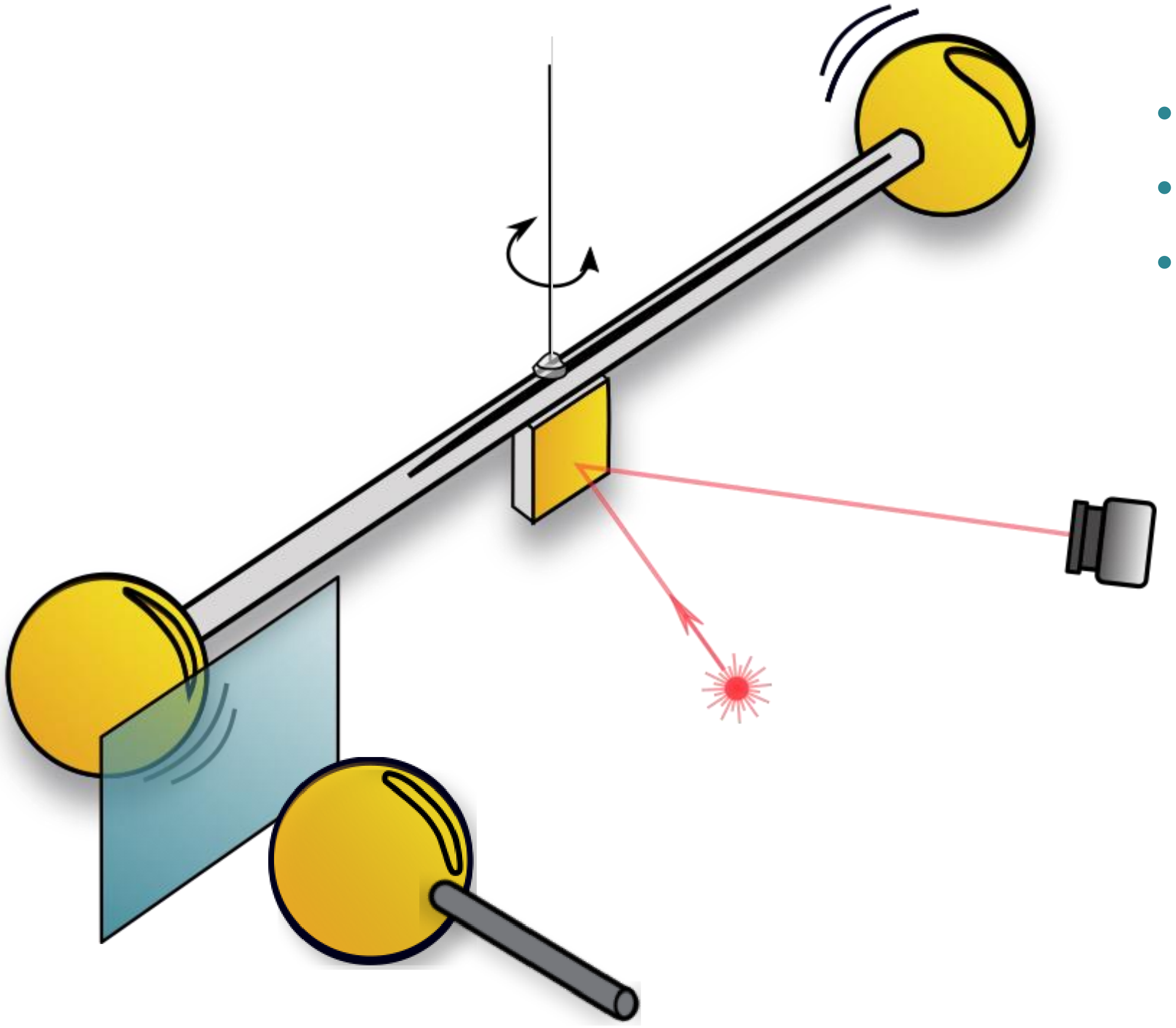

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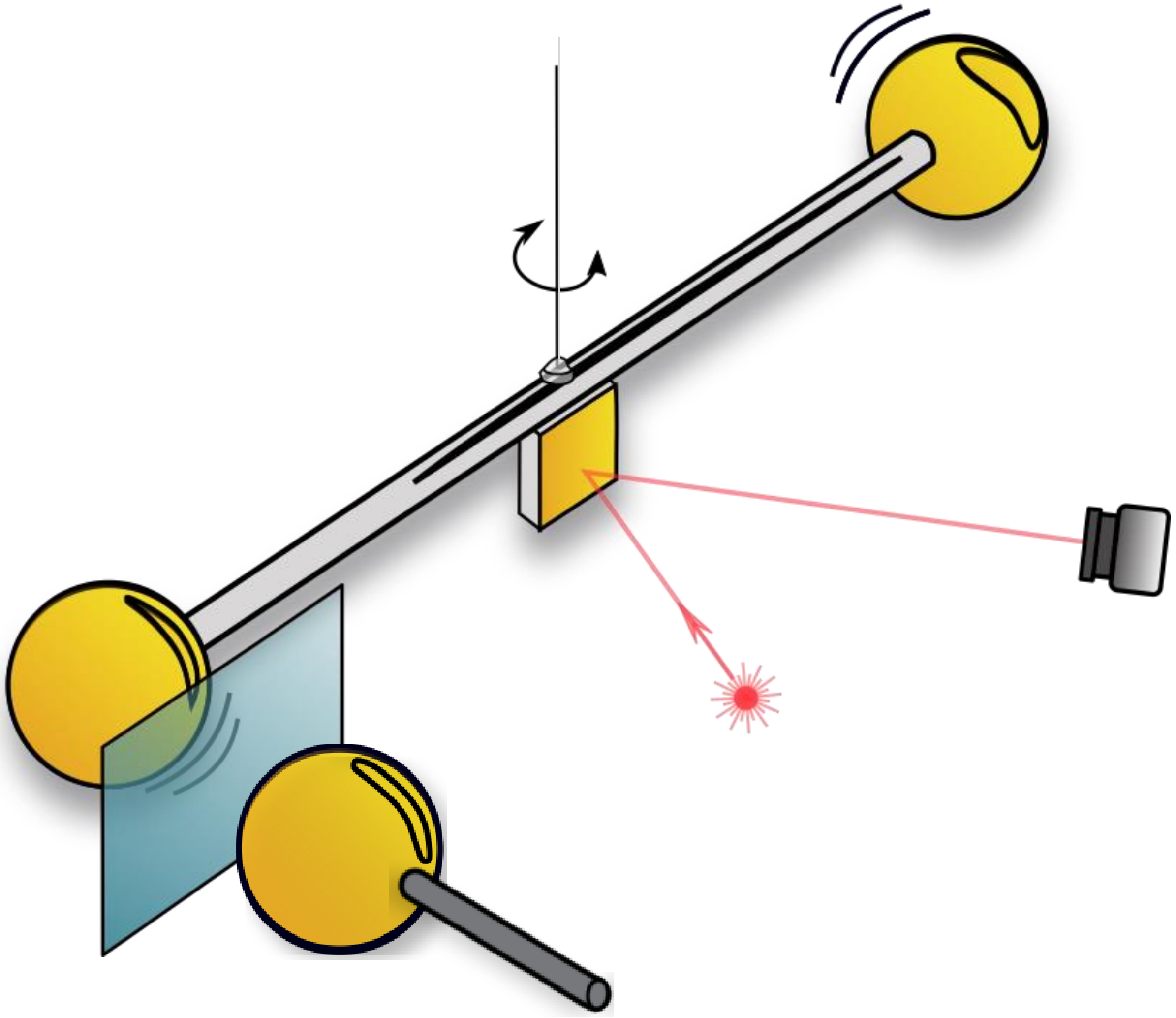
Experimental Concept



- Test mass: torsion pendulum
  - 2mm gold spheres (90mg each)
  - $f_0 \approx 3.6$mHz, $Q \approx 4$
- Source mass: 2mm/90mg gold
  - few mm position, grounded
- $5 \cdot 10^{-7}$ mbar vacuum
- room temperature

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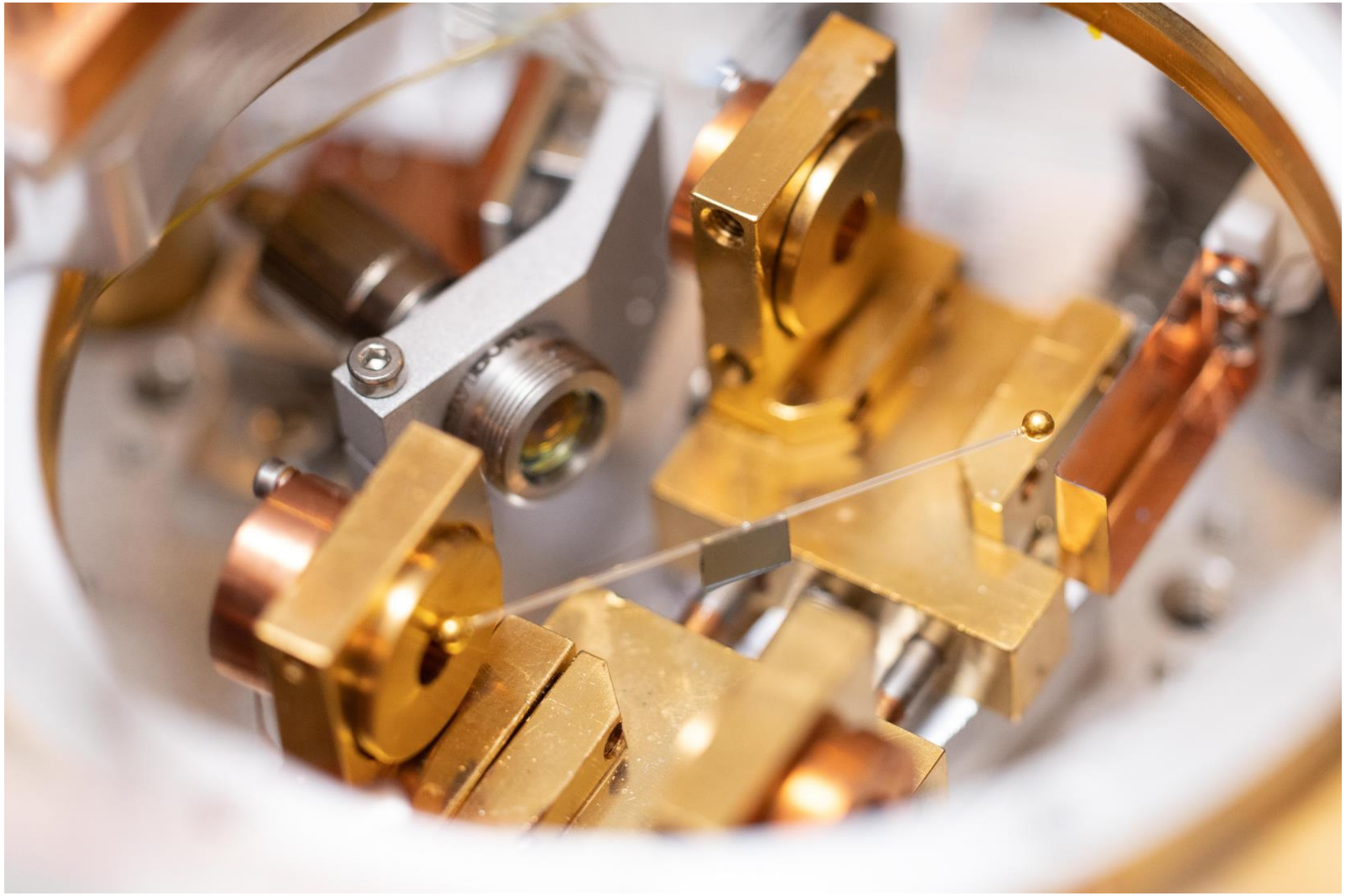

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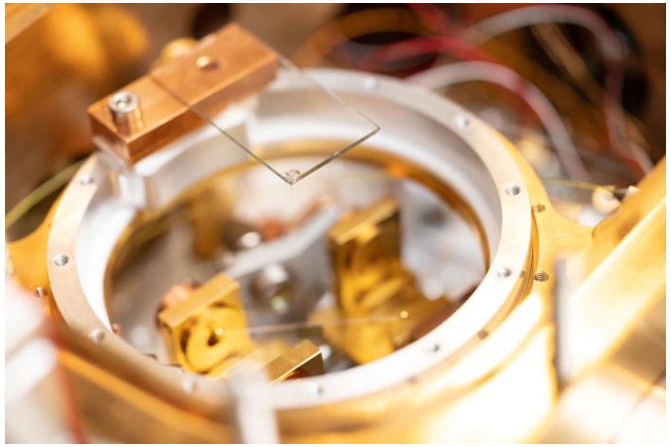
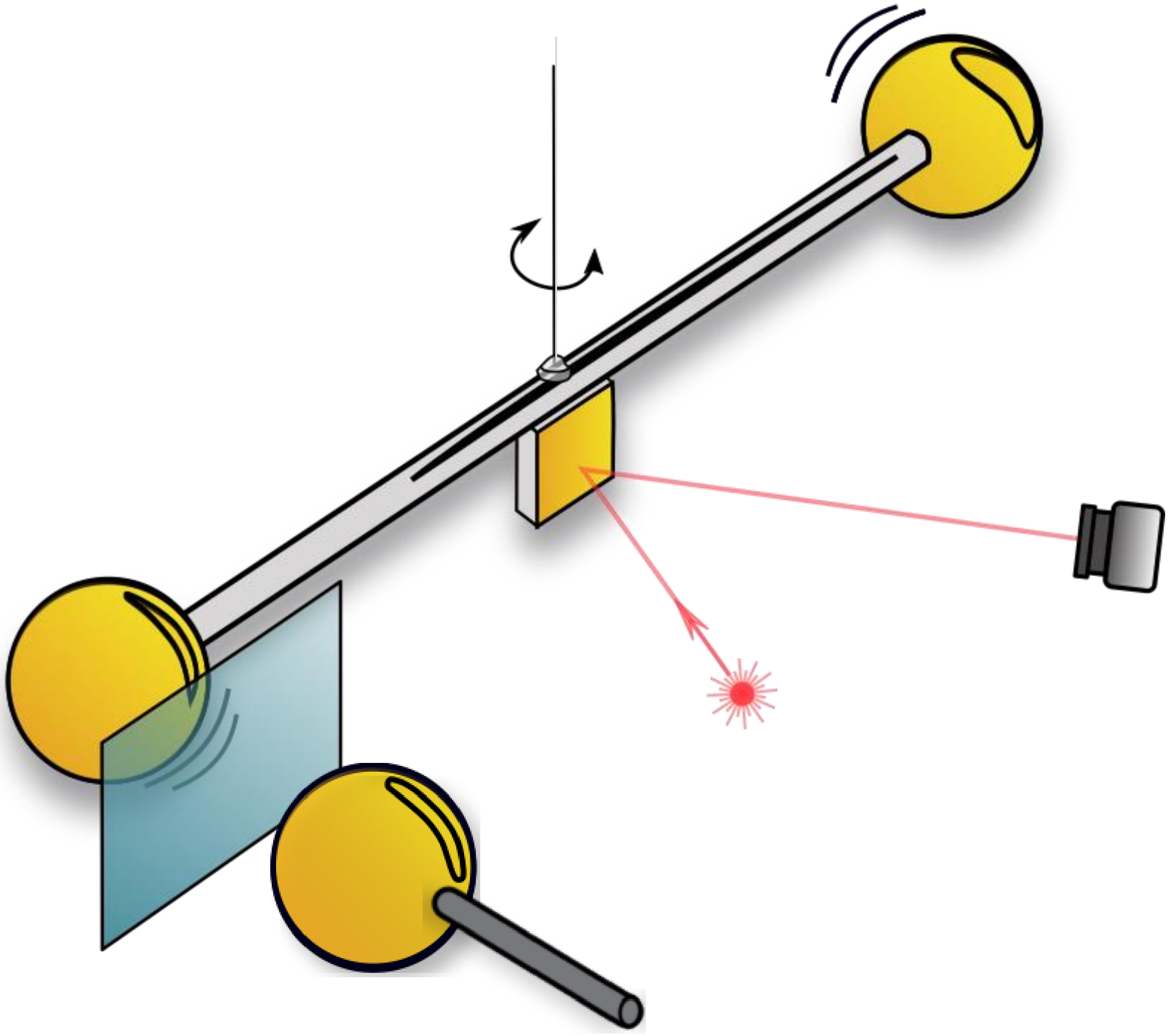


Noise Contributions



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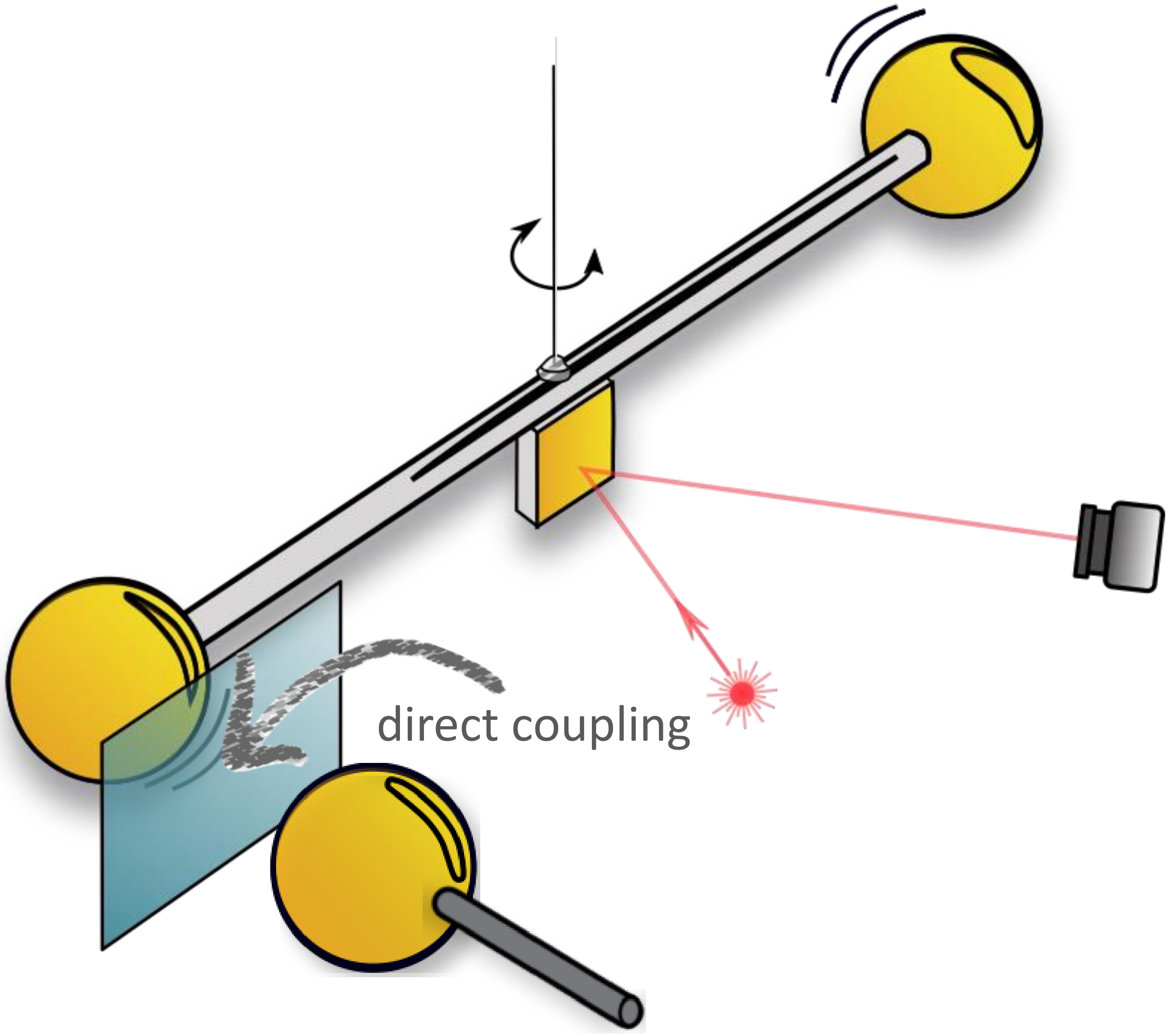
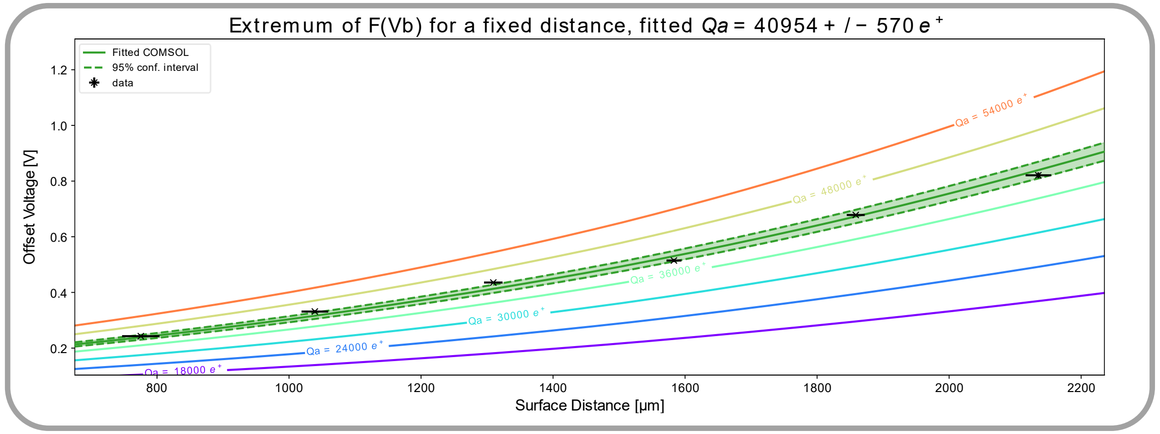


Electrostatic Coupling



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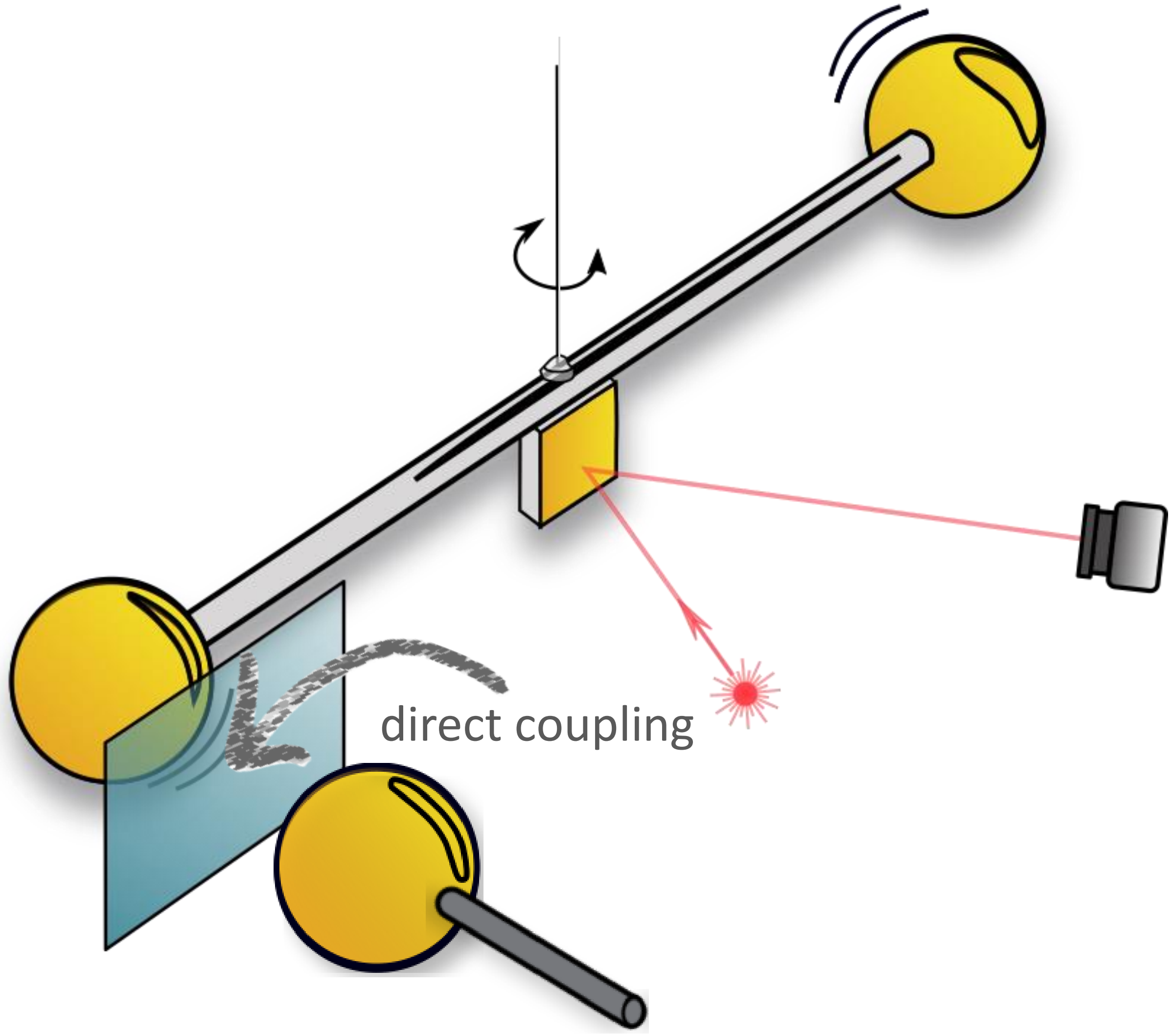
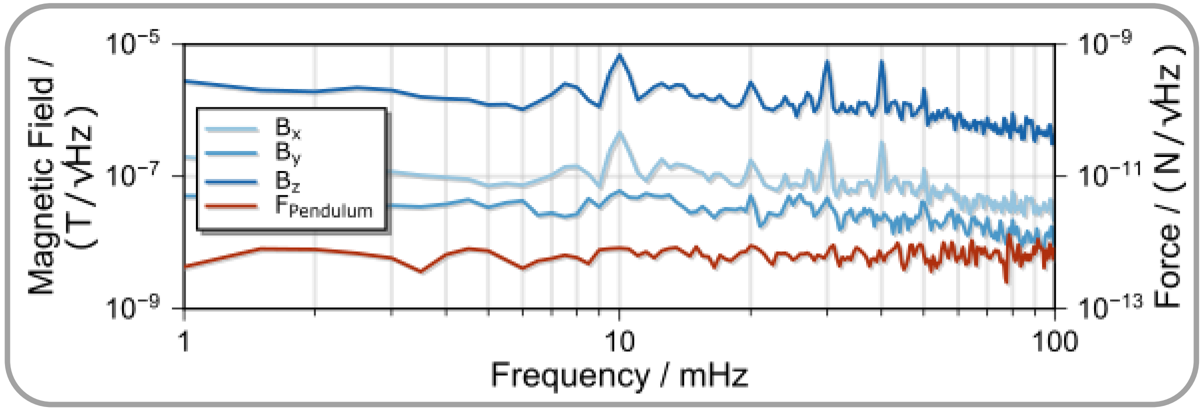


Magnetic Coupling



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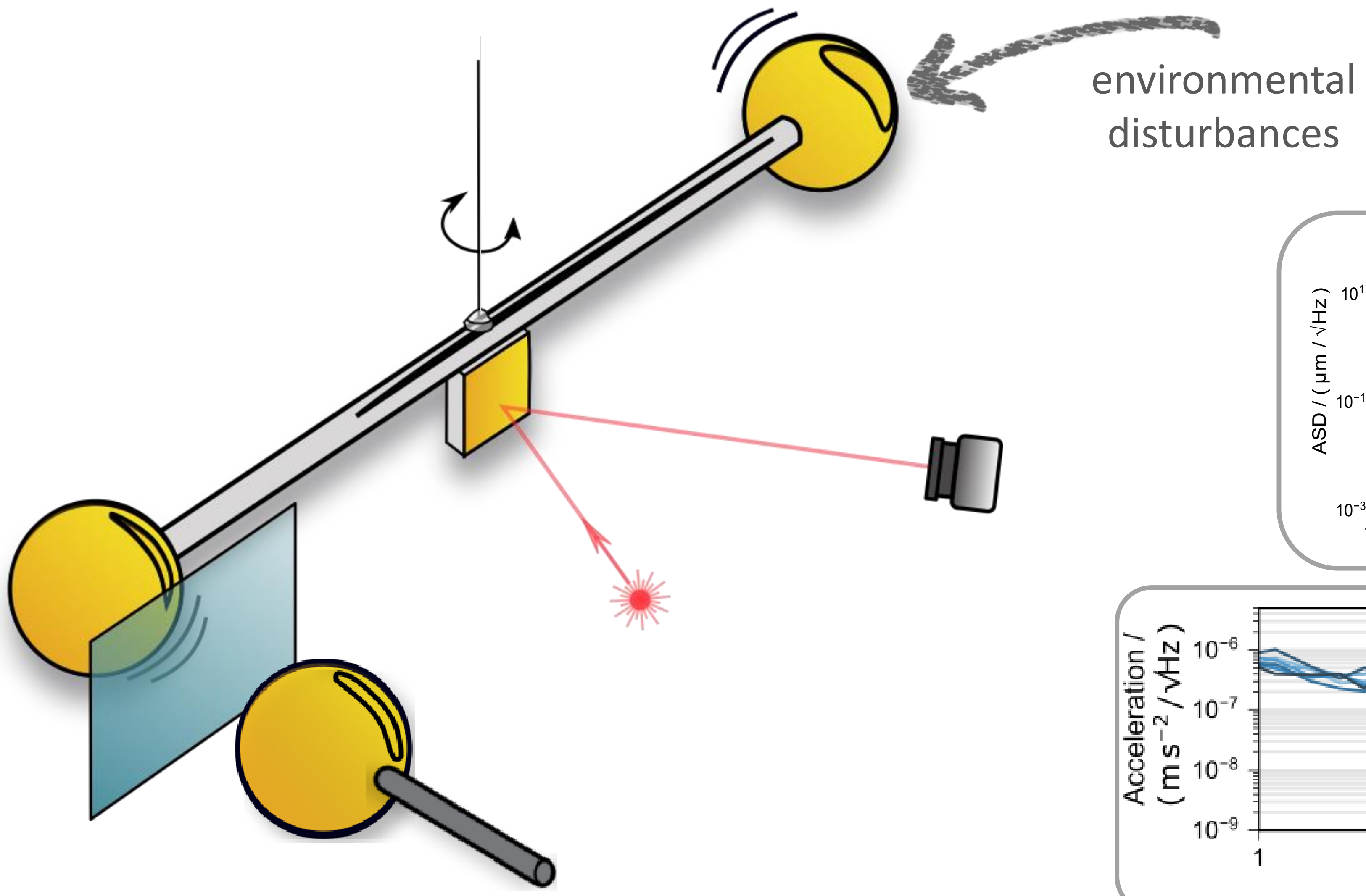
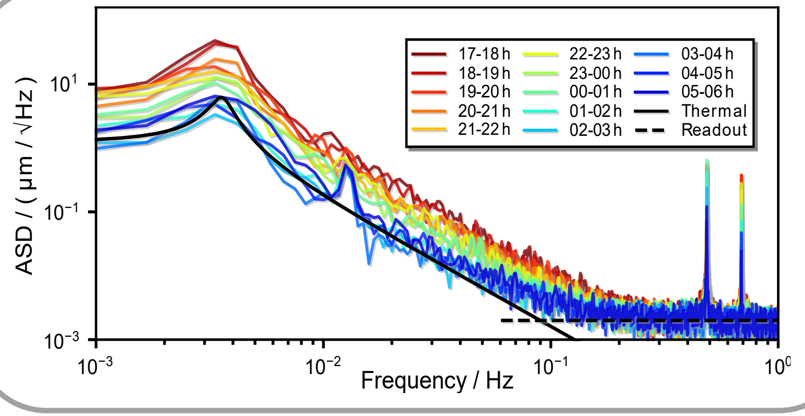
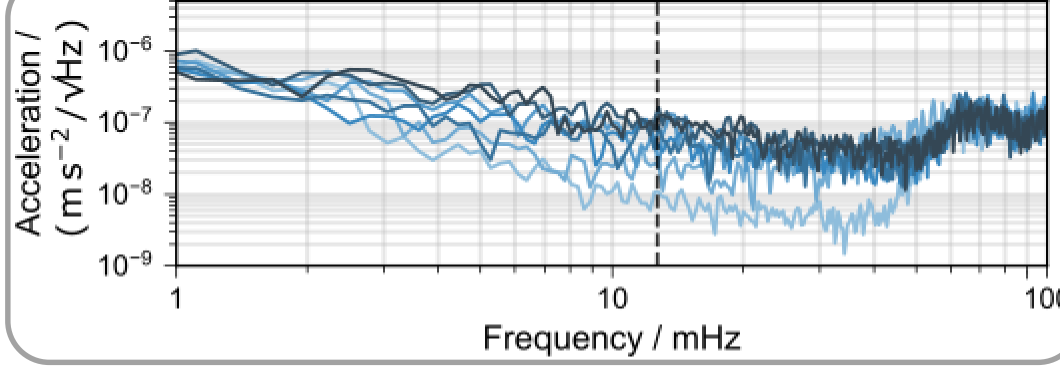


Seismic Coupling





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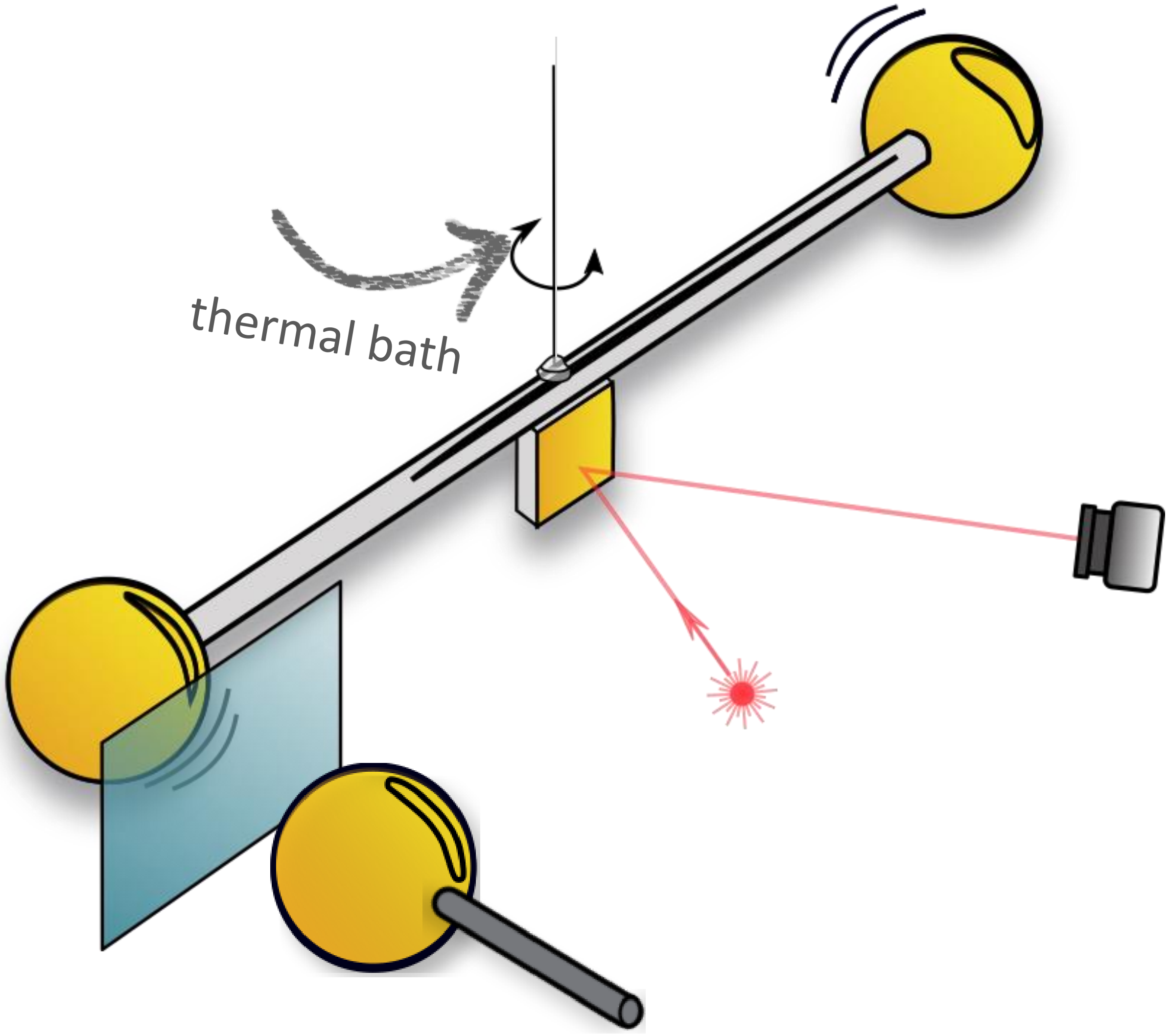
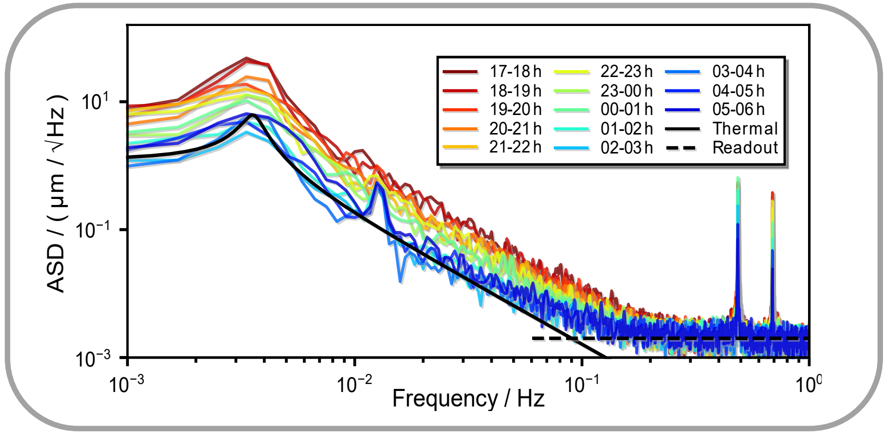


Thermal Noise Limited



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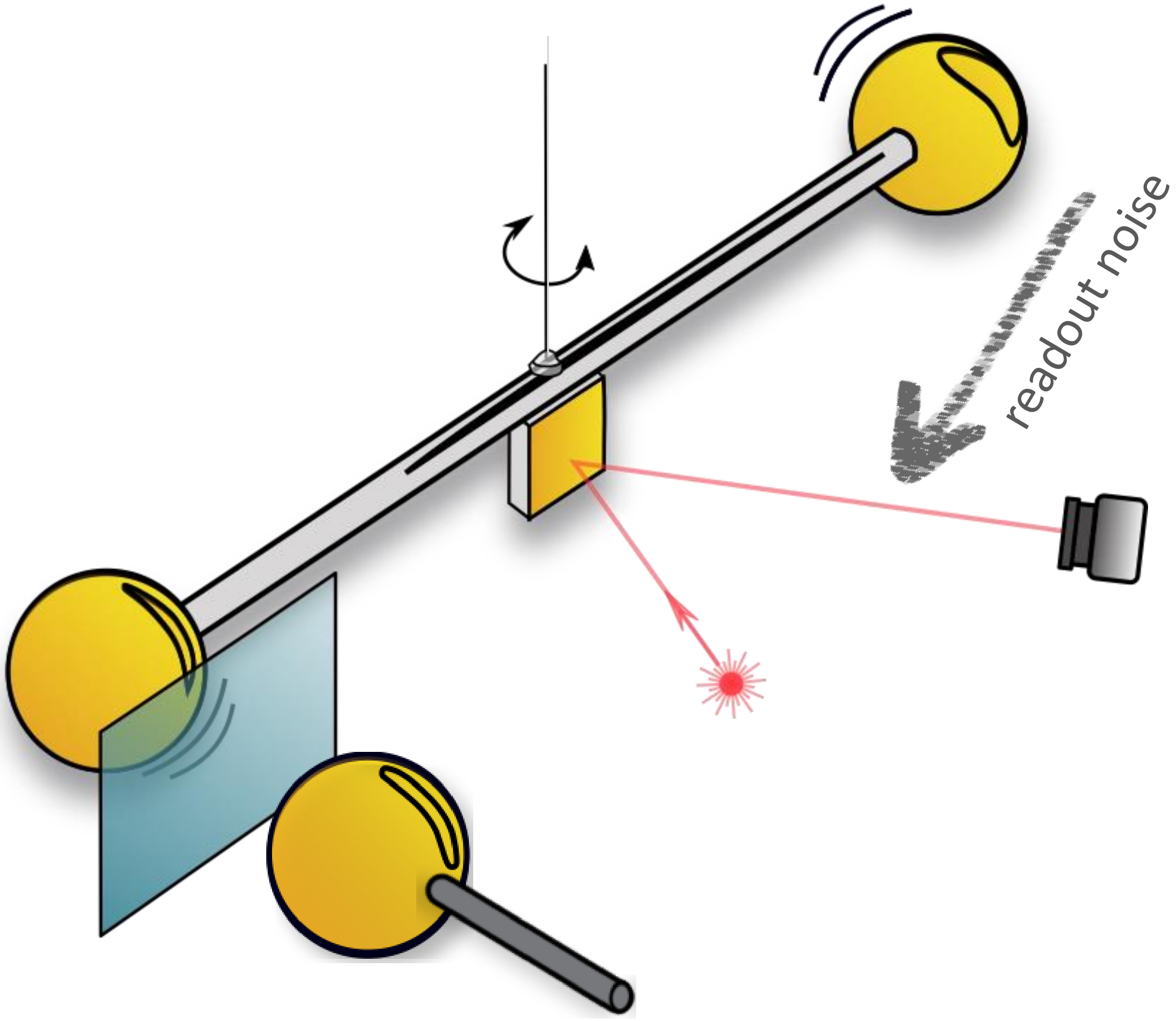
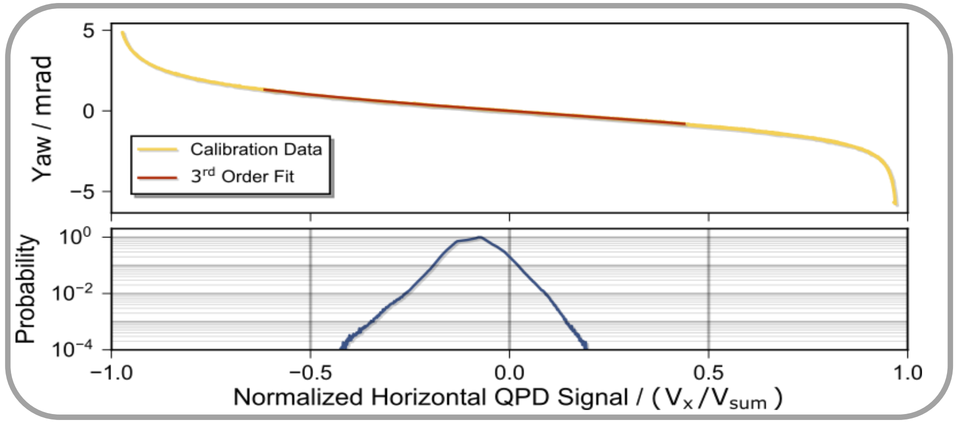
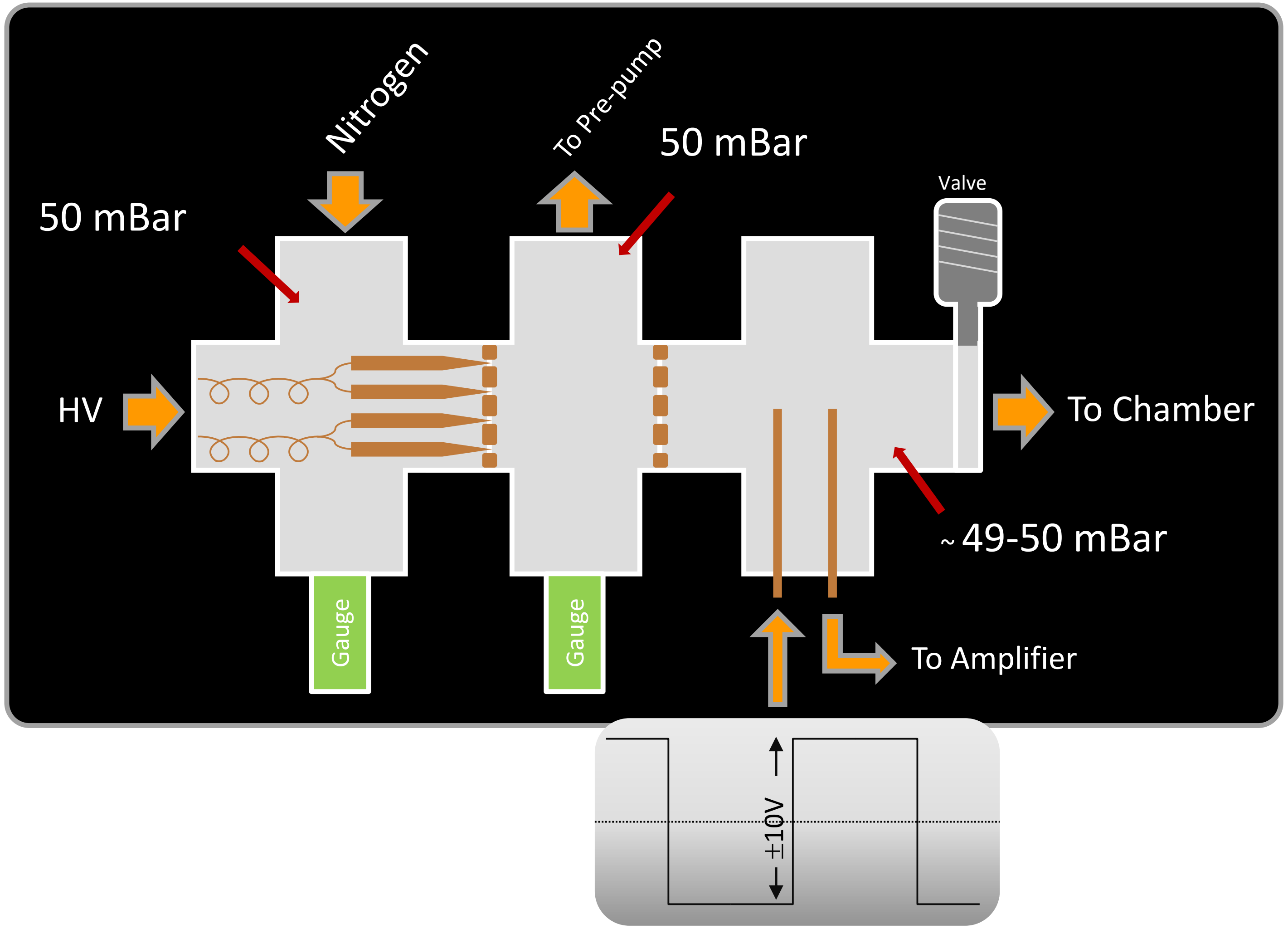


QPD Calibration



Charge Control



Method developed for LIGO test masses

D. Ugolini et al. (2014), DOI: 10.1063/1.4867248
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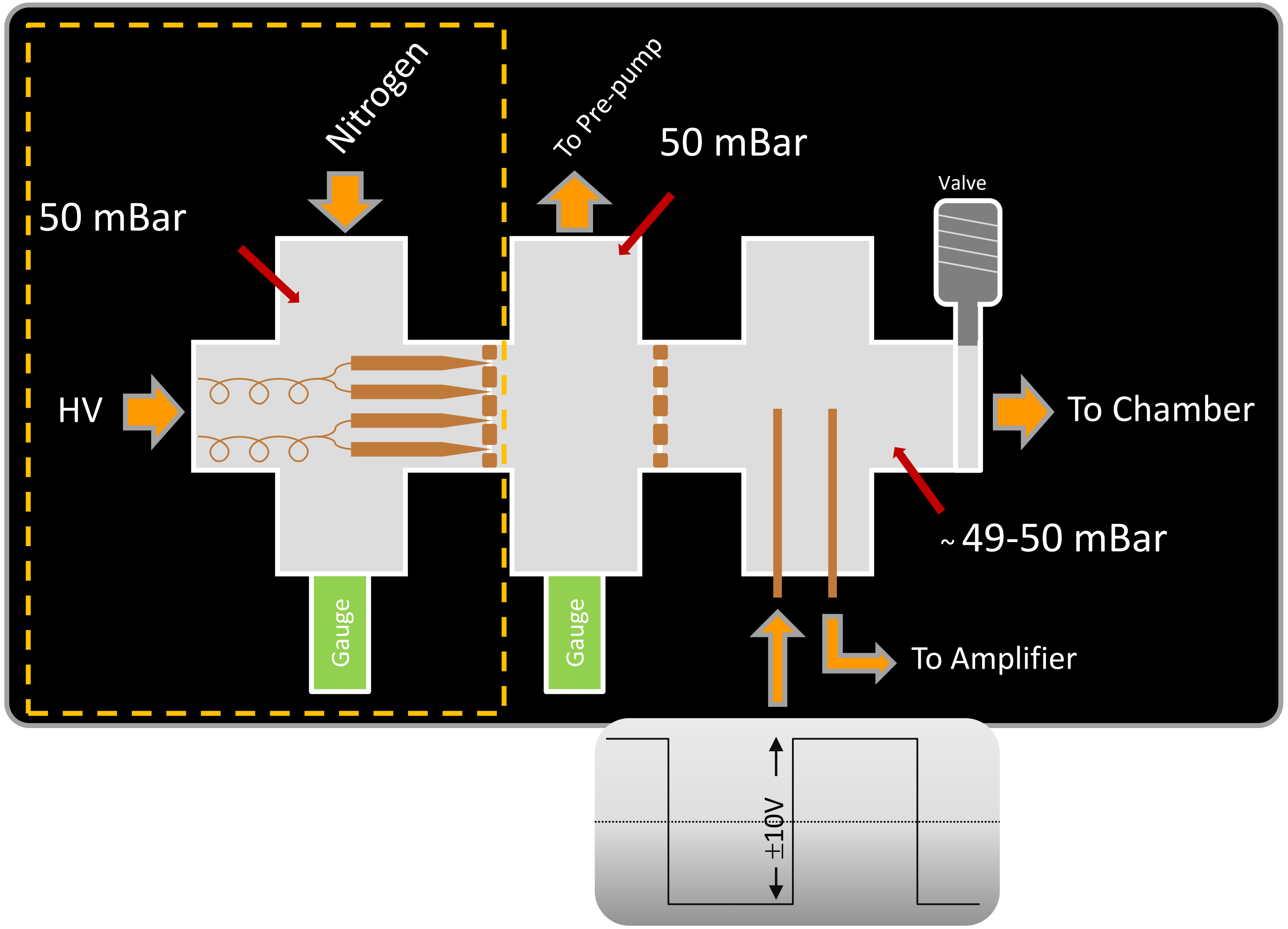

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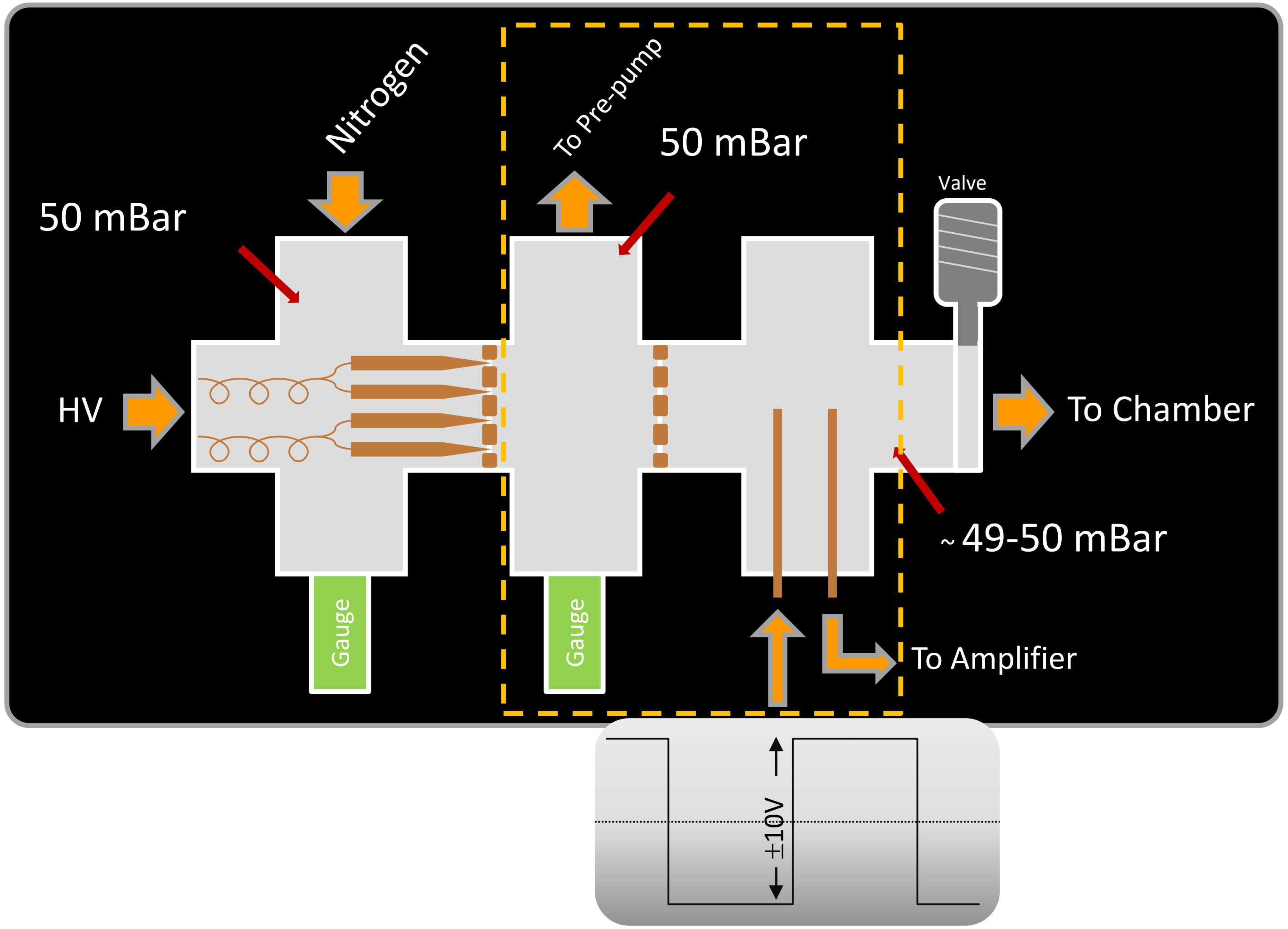

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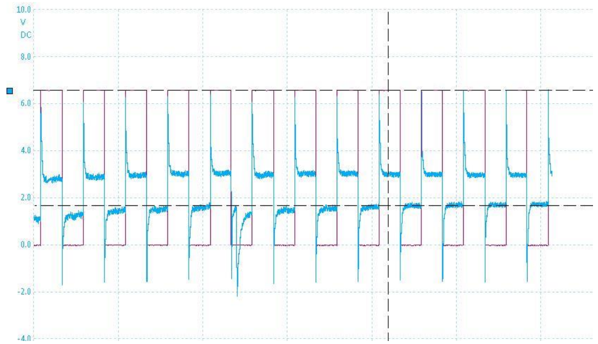
- measure ion flow



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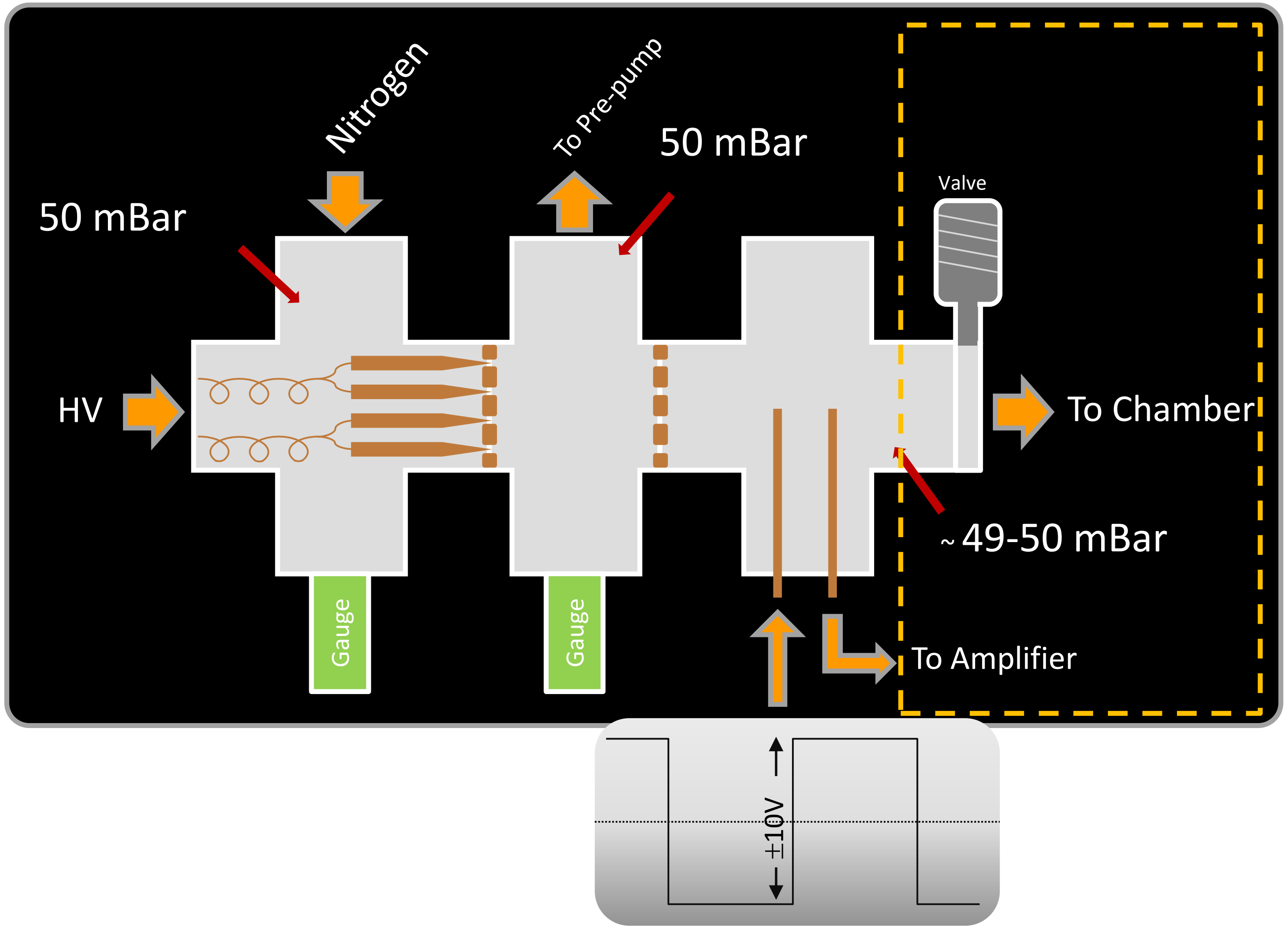

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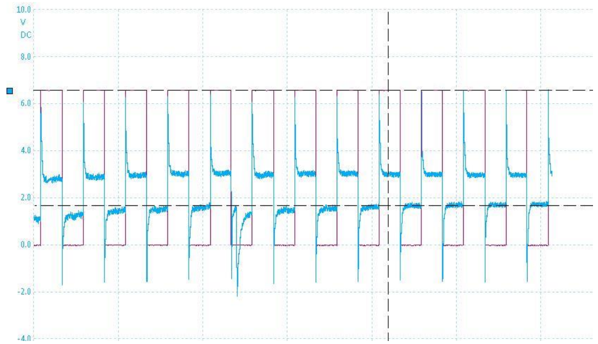
- produce ionized N_2
- measure ion flow
- diffusion process in the vacuum chamber neutralizes surface potentials



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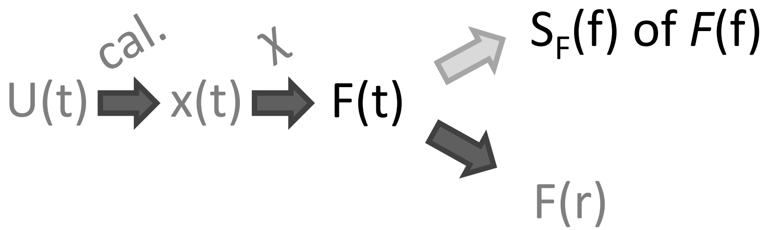
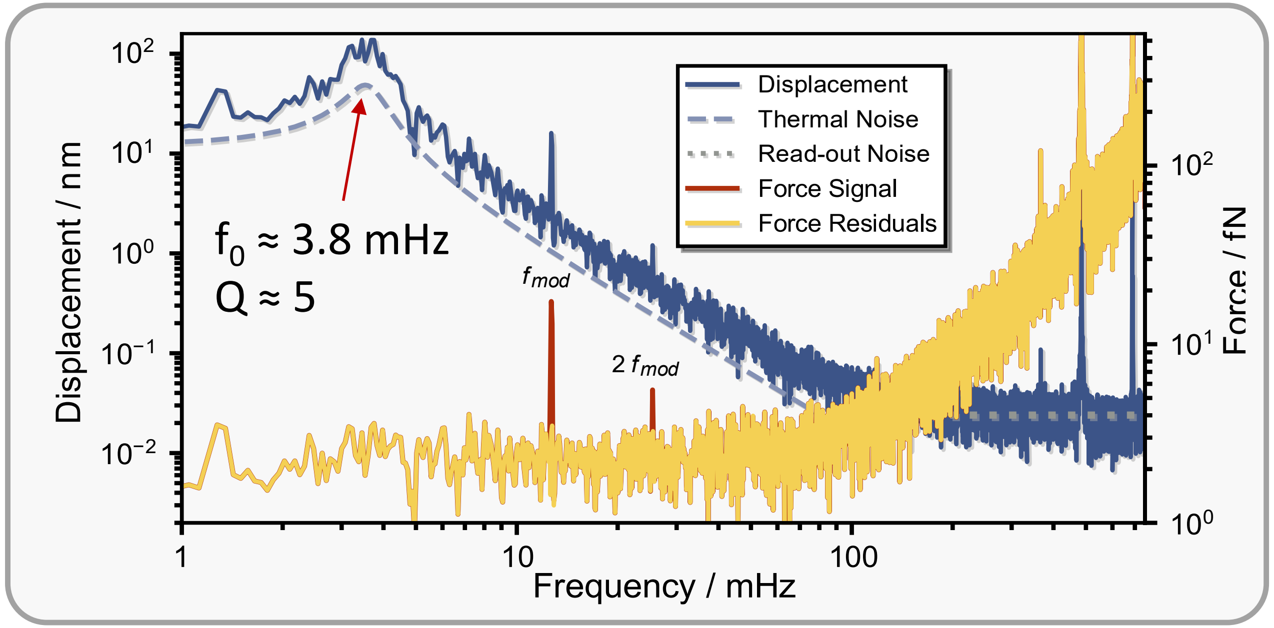
Analysis - Spectrum





- Spectral analysis shows harmonics of modulation frequency

Analysis - Spectrum

U(t) ⇨(cal.) x(t) ⇨(χ) F(t) ⇨ $S_F(f)$ of $F(f)$

F(t) ⇨ F(r)

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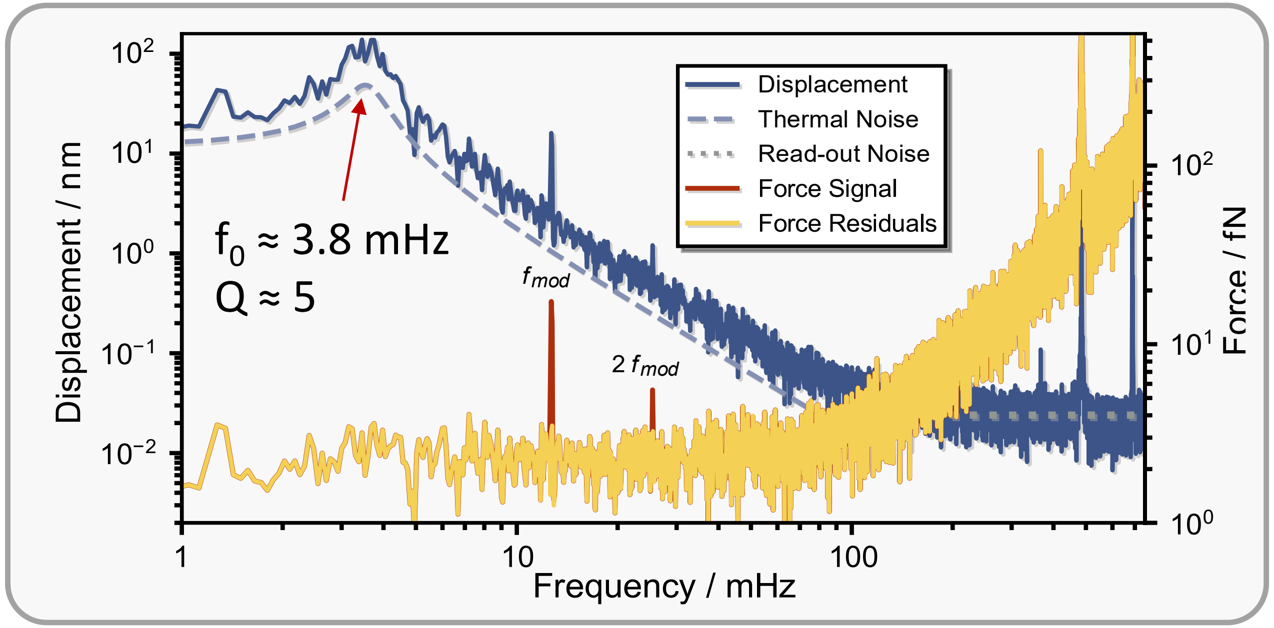
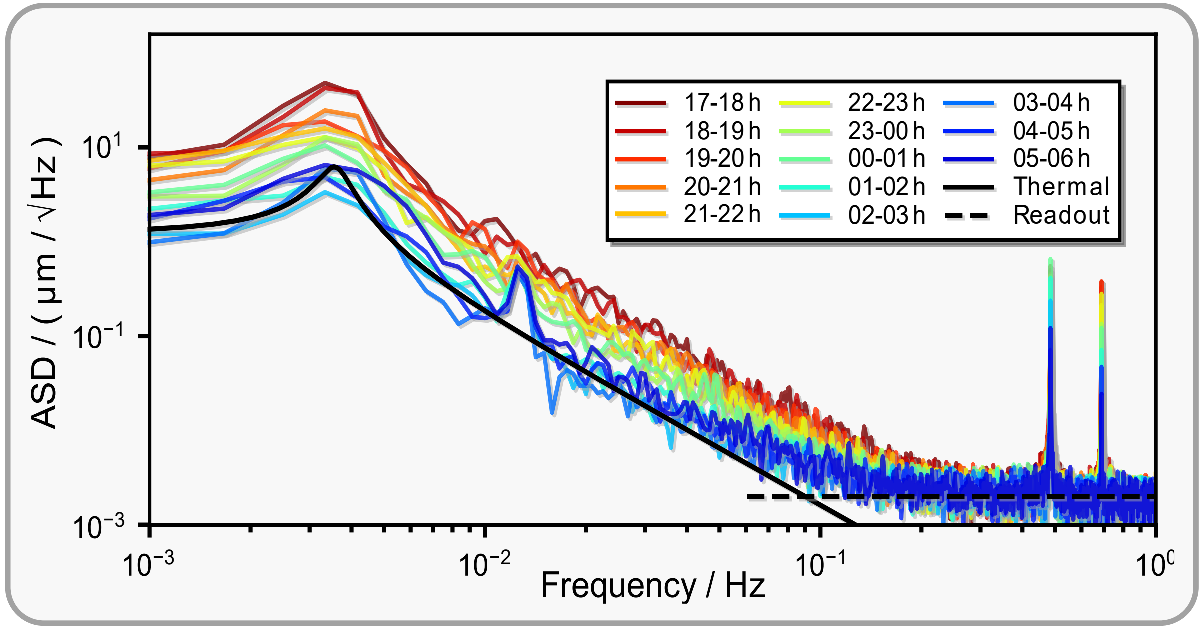
BUT:

- No stable environmental conditions
  - Violates underlying assumptions of a steady state…





Noise level varies up to 10x

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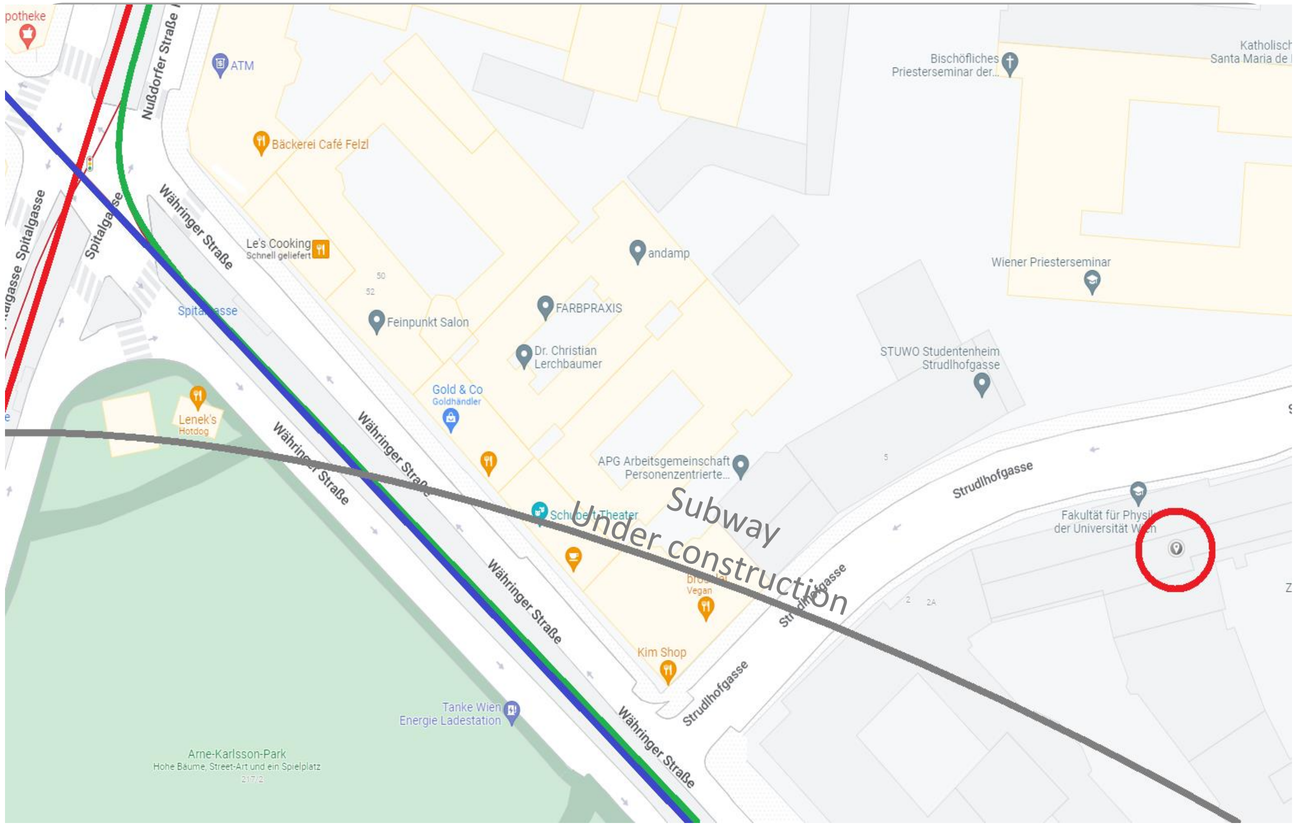

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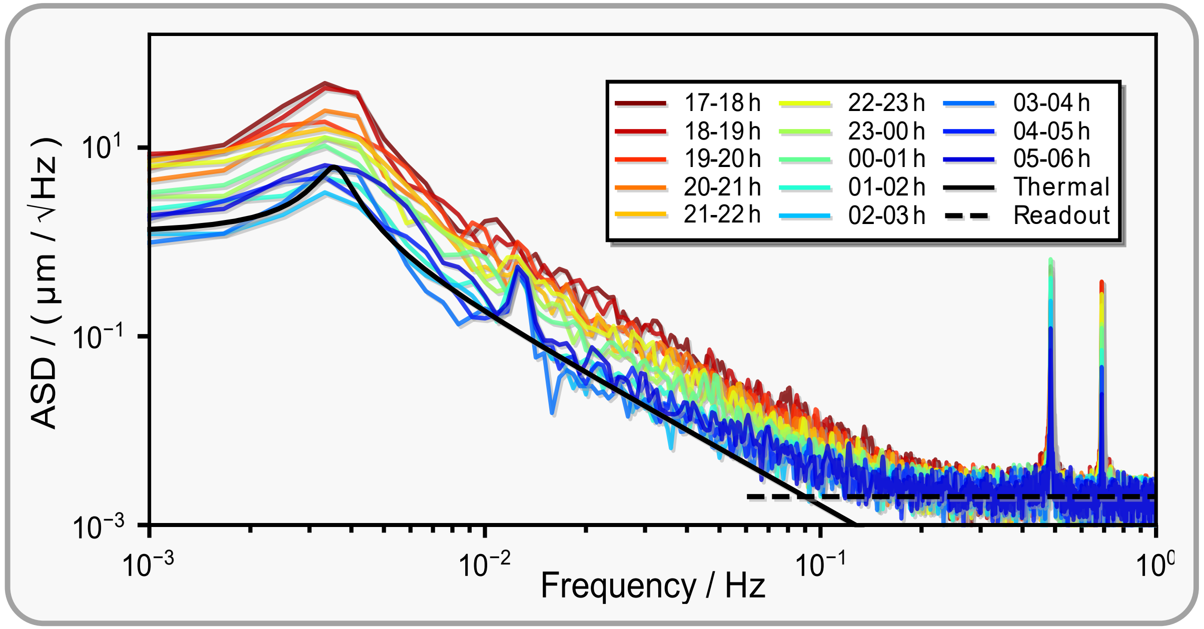
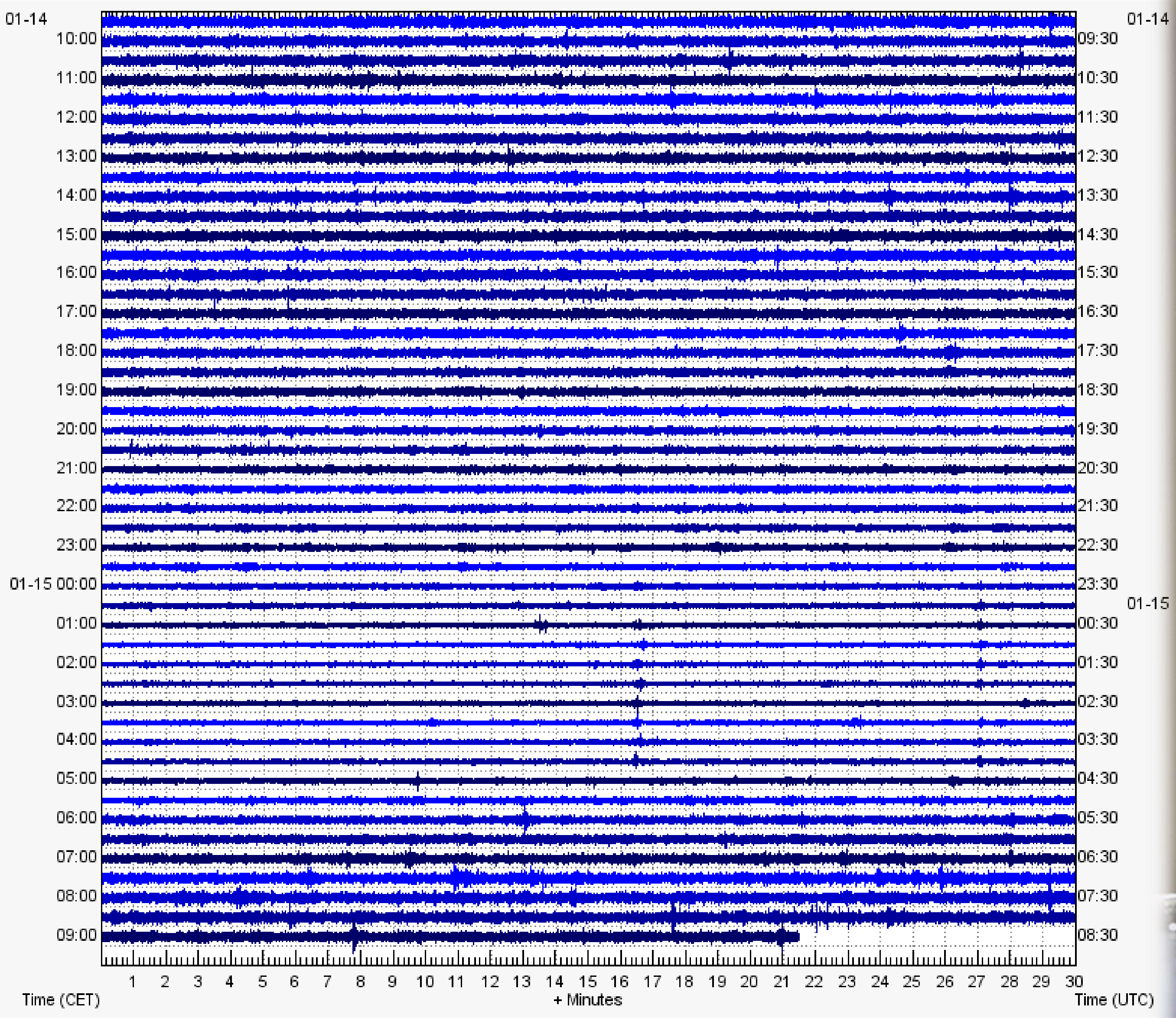
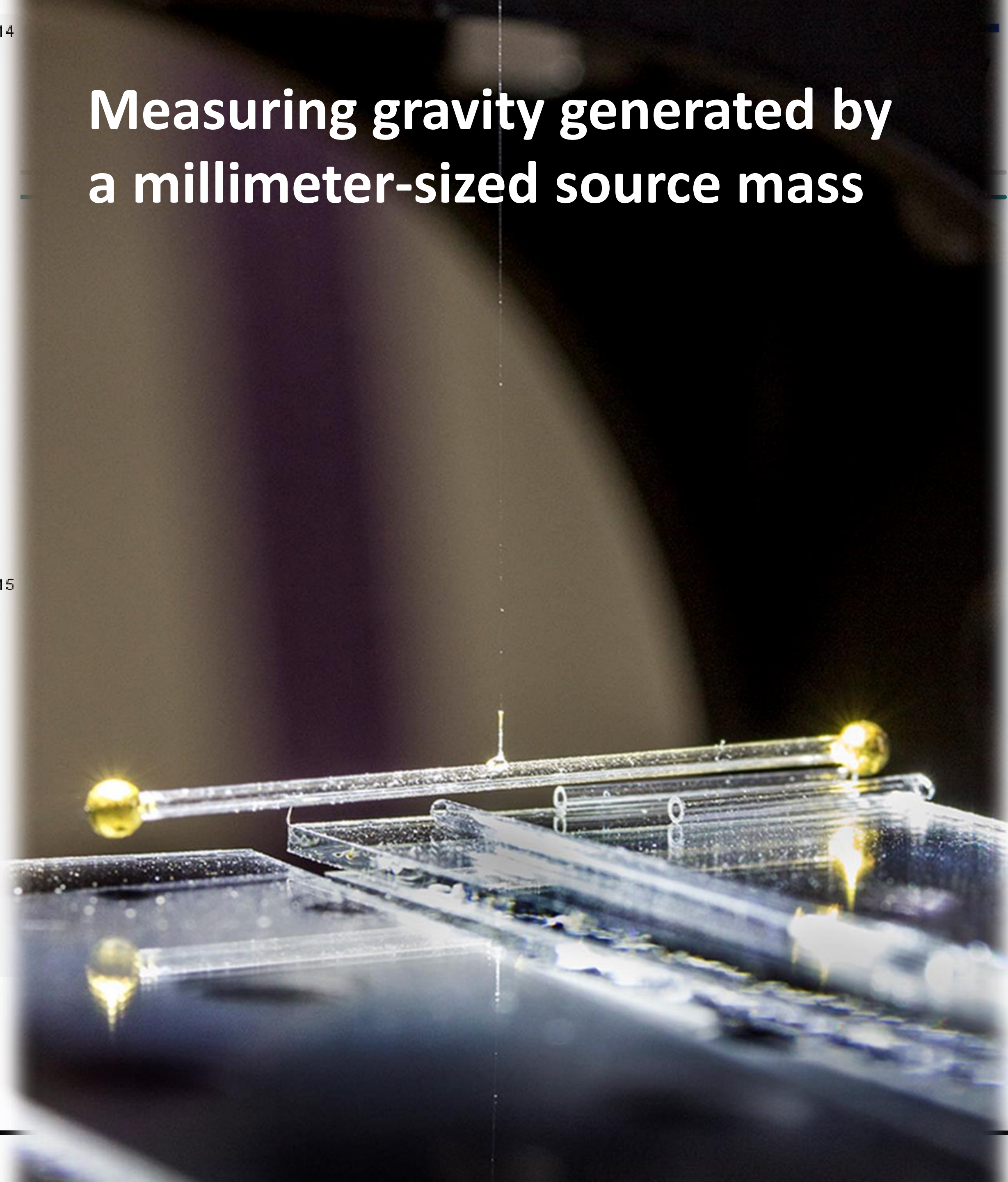


Measuring gravity generated by a millimeter-sized source mass





- Seismogram of a typical day

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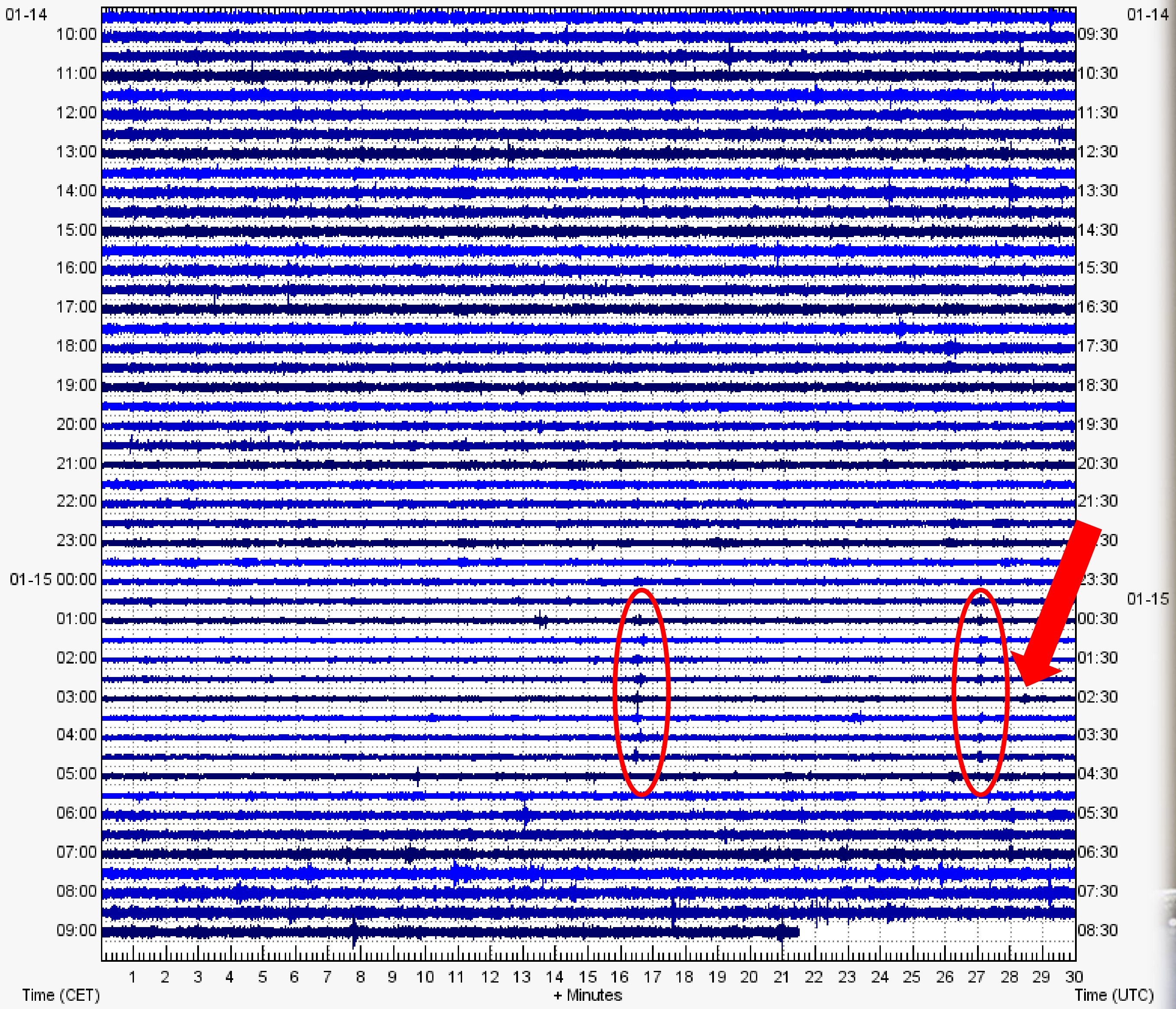

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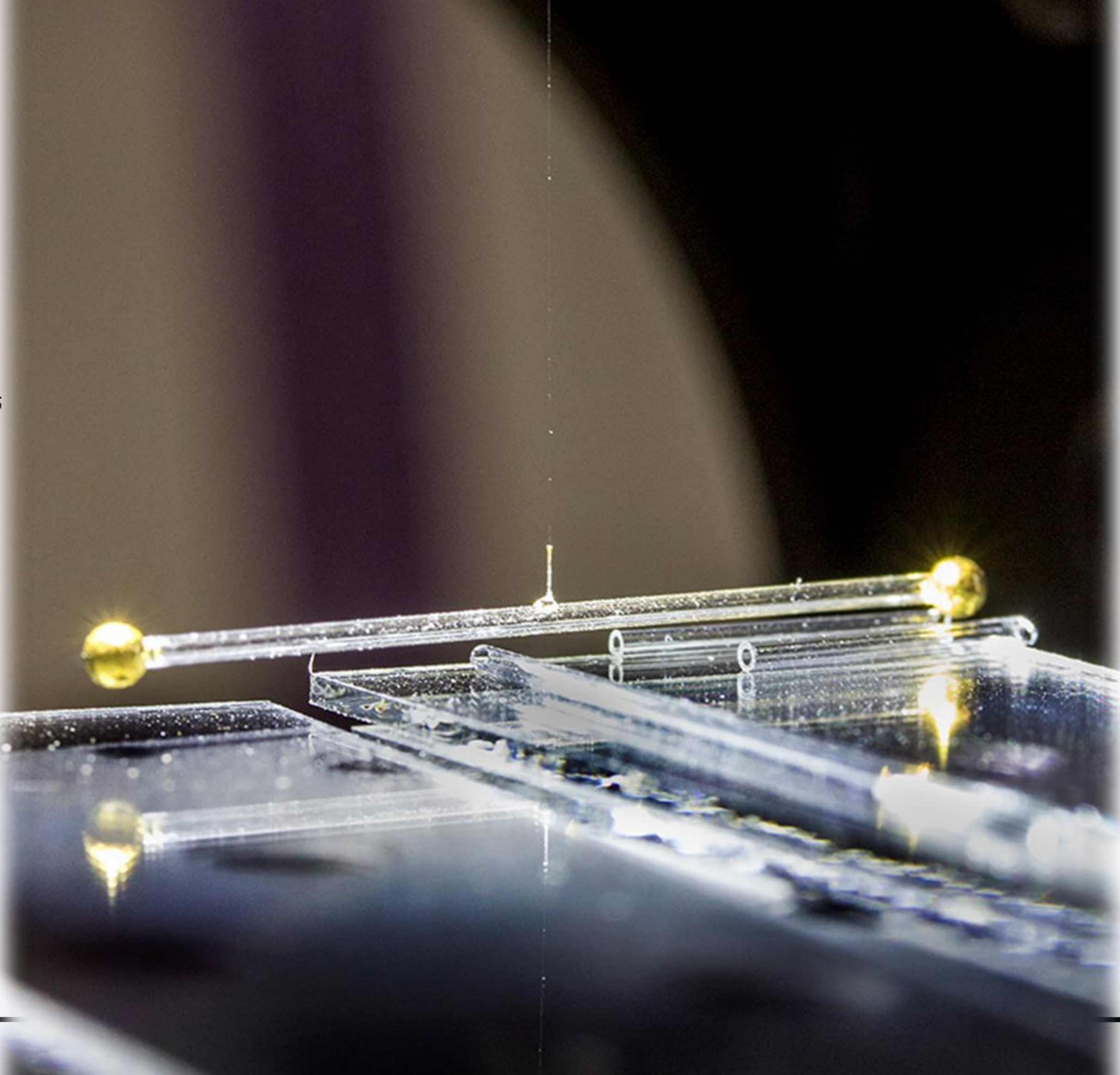
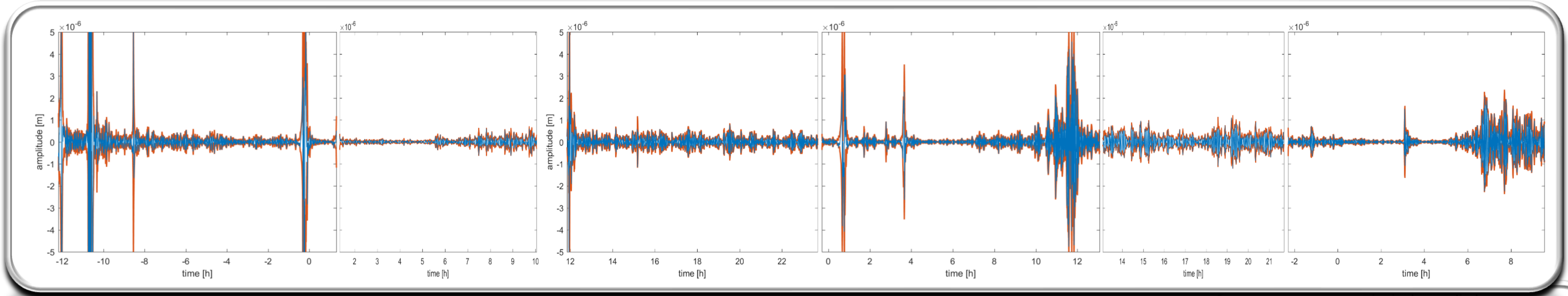
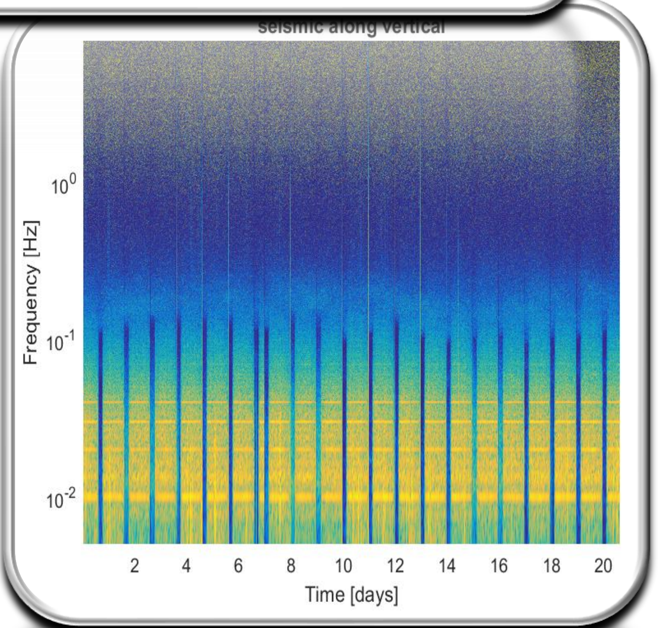
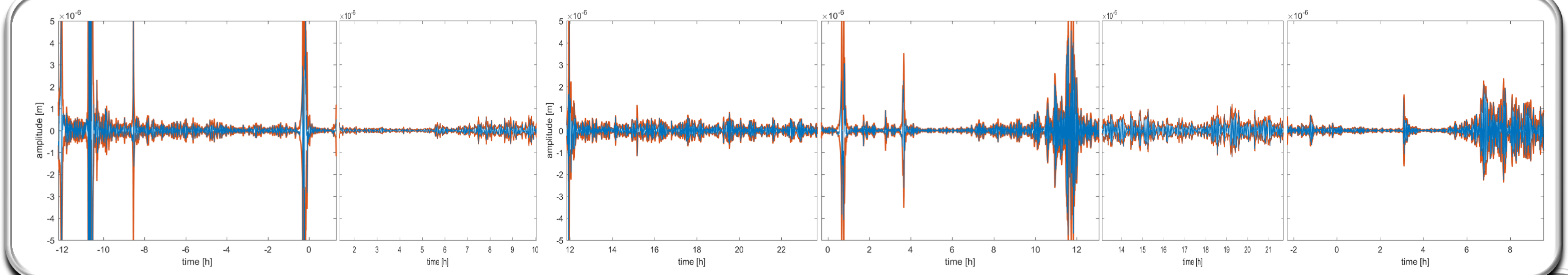


A Weekend in the life of Milli-G





A Weekend in the life of Milli-G



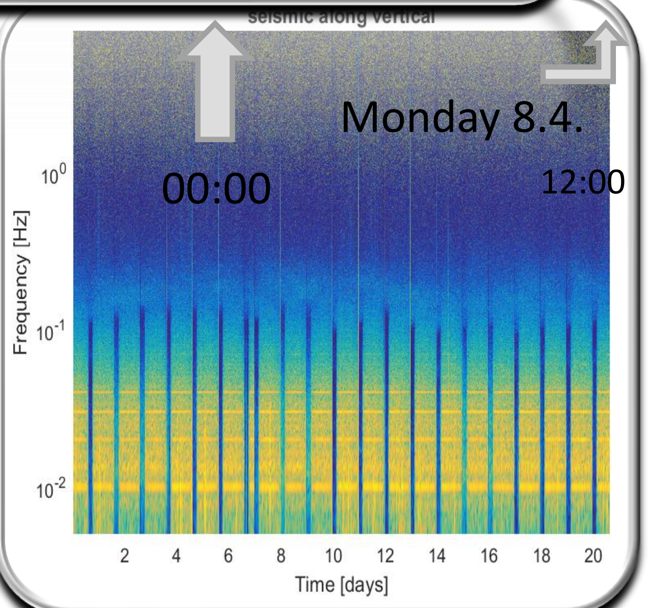
Friday 5.4.
12:00

00:00

Saturday 6.4.
12:00

00:00

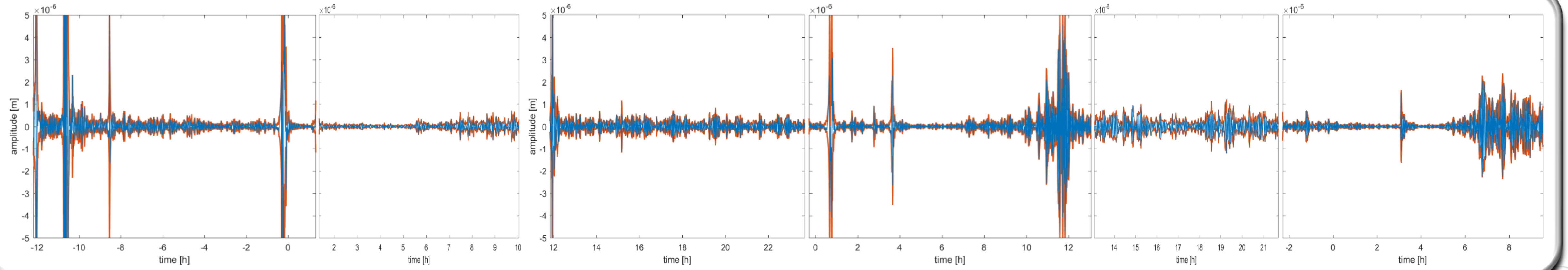
Sunday 7.4.
12:00



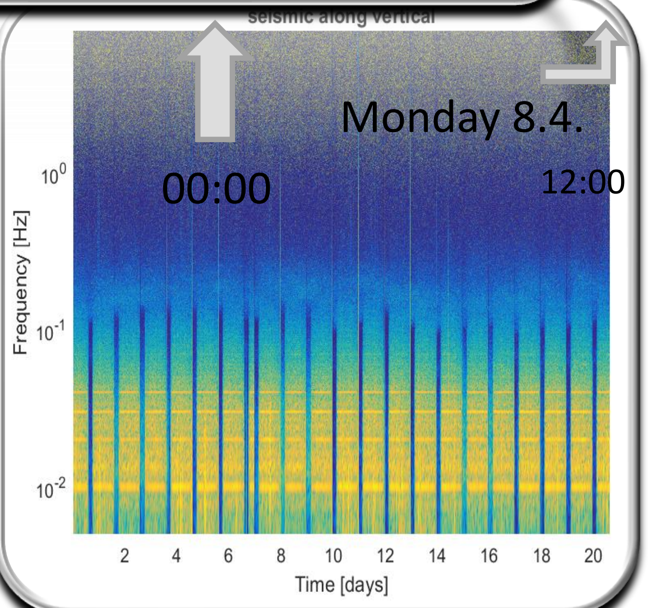
00:00

Monday 8.4.
12:00

A Weekend in the life of Milli-G

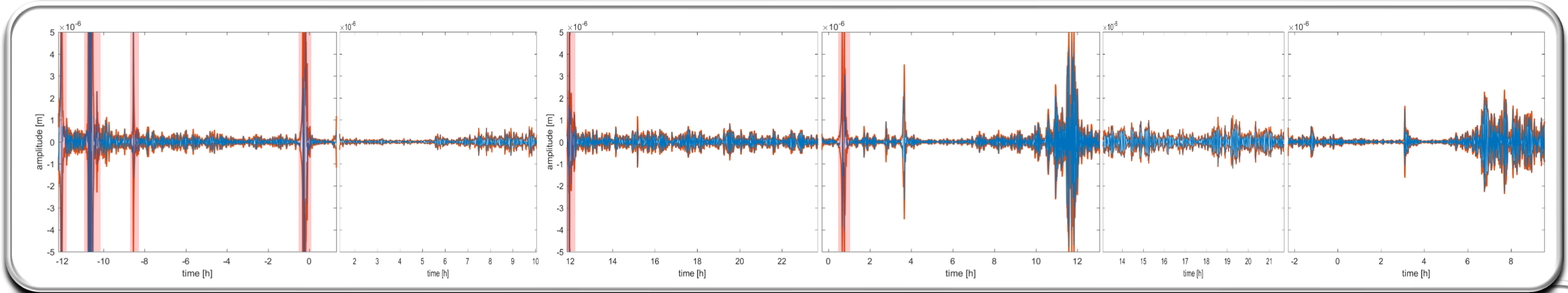


Friday 5.4. 12:00 — 00:00 — Saturday 6.4. 12:00 — 00:00 — Sunday 7.4. 12:00 — 00:00 — Monday 8.4. 12:00



- 1 weekend time-series of milli-G
- 3mHz-100mHz band

A Weekend in the life of Milli-G



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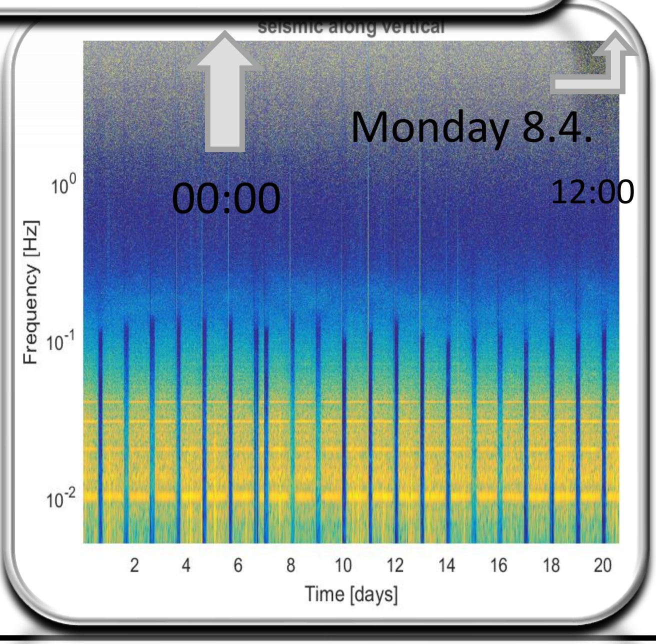


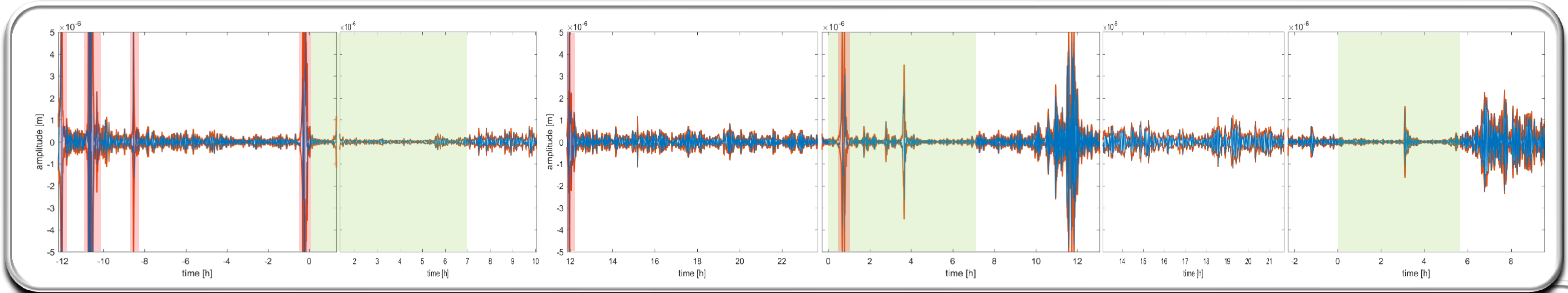
00:00

Monday 8.4.
12:00

- 1 weekend time-series of milli-G
- 3mHz-100mHz band

Table or pendulum work

A Weekend in the life of Milli-G



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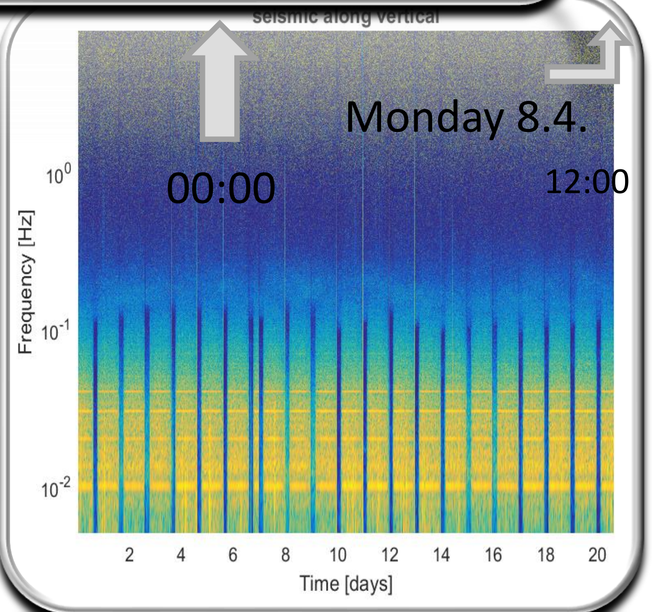
- 1 weekend time-series of milli-G
- 3mHz-100mHz band

Table or pendulum work

Nighttime (0:00-7:00/0:30-5:30)



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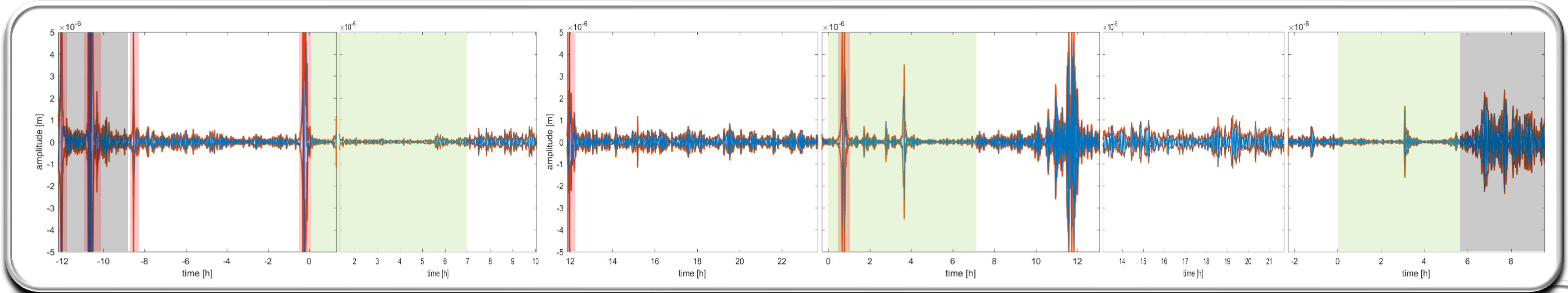

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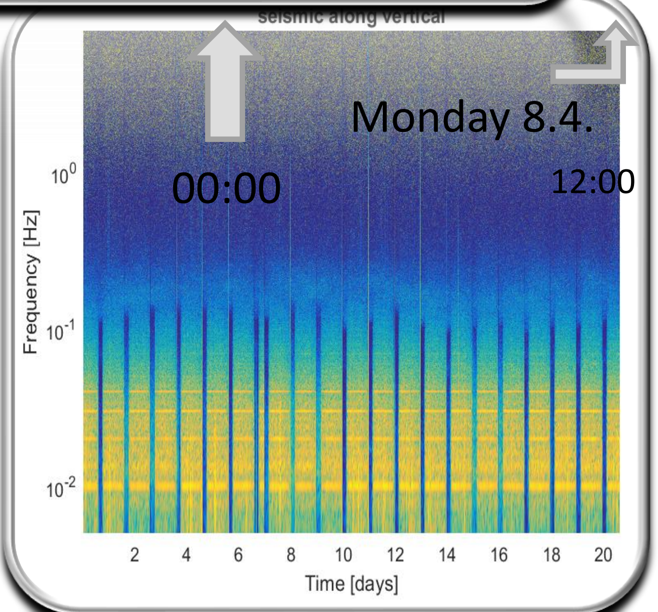
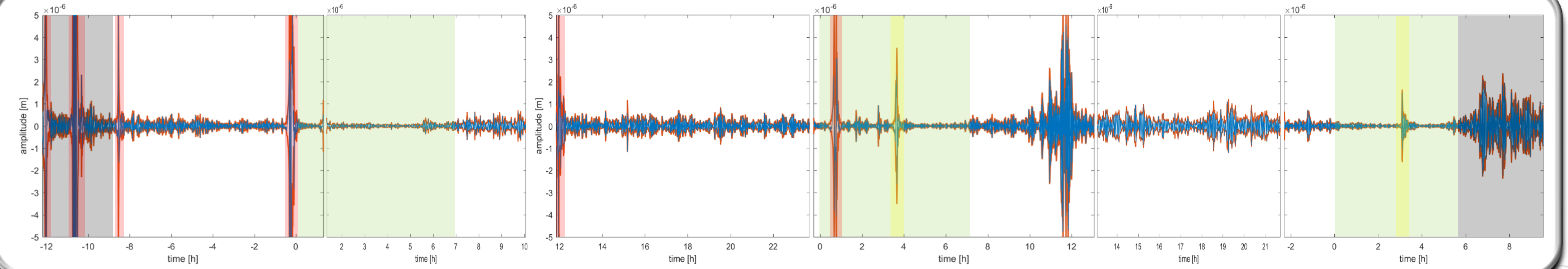
Table or pendulum work

Nighttime (0:00-7:00/0:30-5:30)

Normal weekday



A Weekend in the life of Milli-G



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- 1 weekend time-series of milli-G
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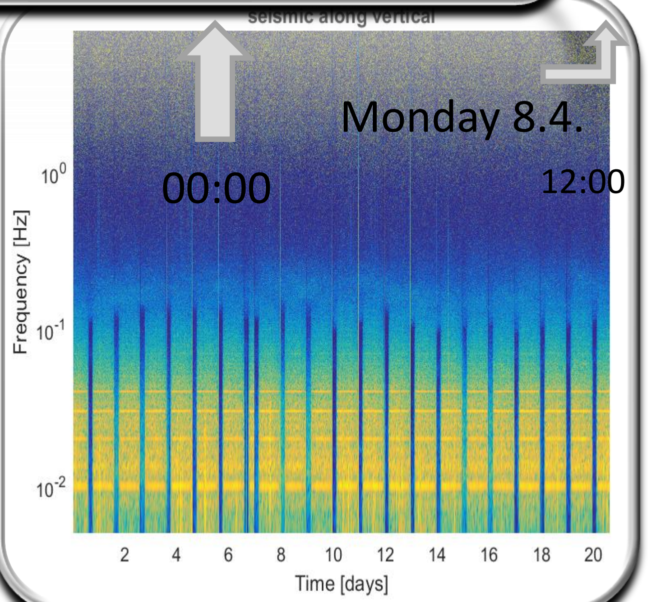
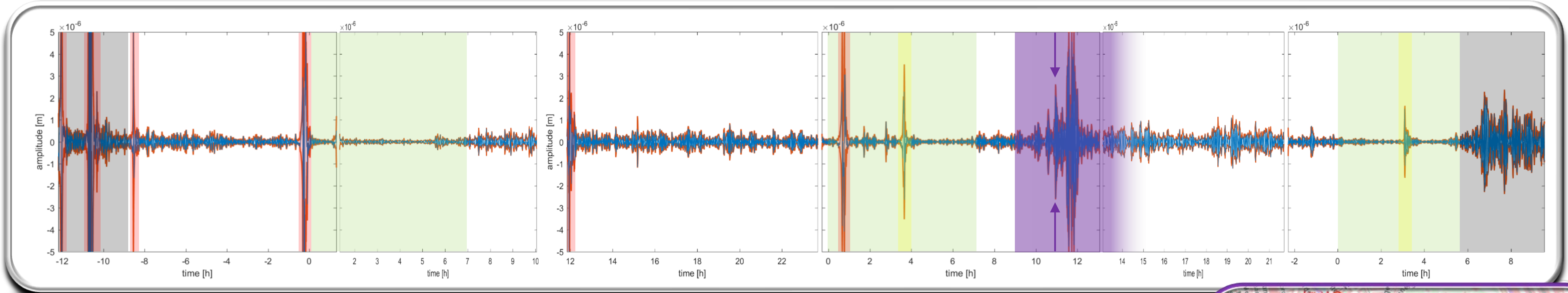
(red)	Table or pendulum work
(green)	Nighttime (0:00-7:00/0:30-5:30)
(dark grey)	Normal weekday
(yellow)	Something new



A Weekend in the life of Milli-G



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- 1 weekend time-series of milli-G
- 3mHz-100mHz band

Table or pendulum work

Nighttime (0:00-7:00/0:30-5:30)

Normal weekday

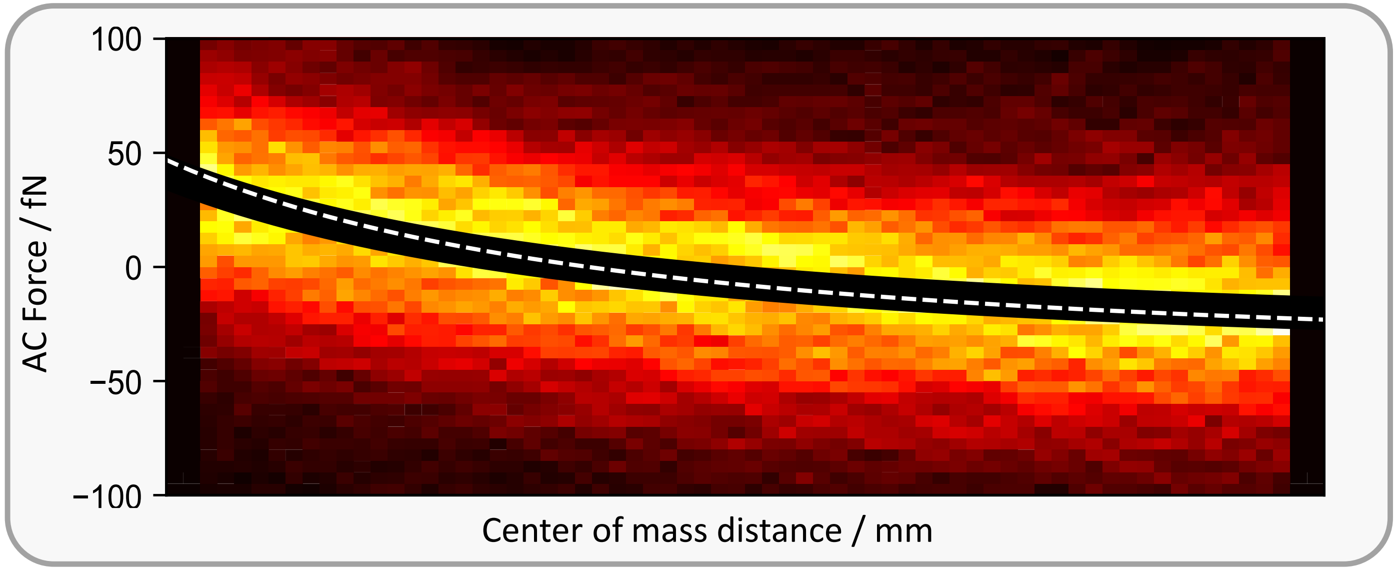
Something new

Marathon (1st finisher)

Analysis – Time Domain

U(t) → x(t) → F(t) → S_F(f) of *F*(f)

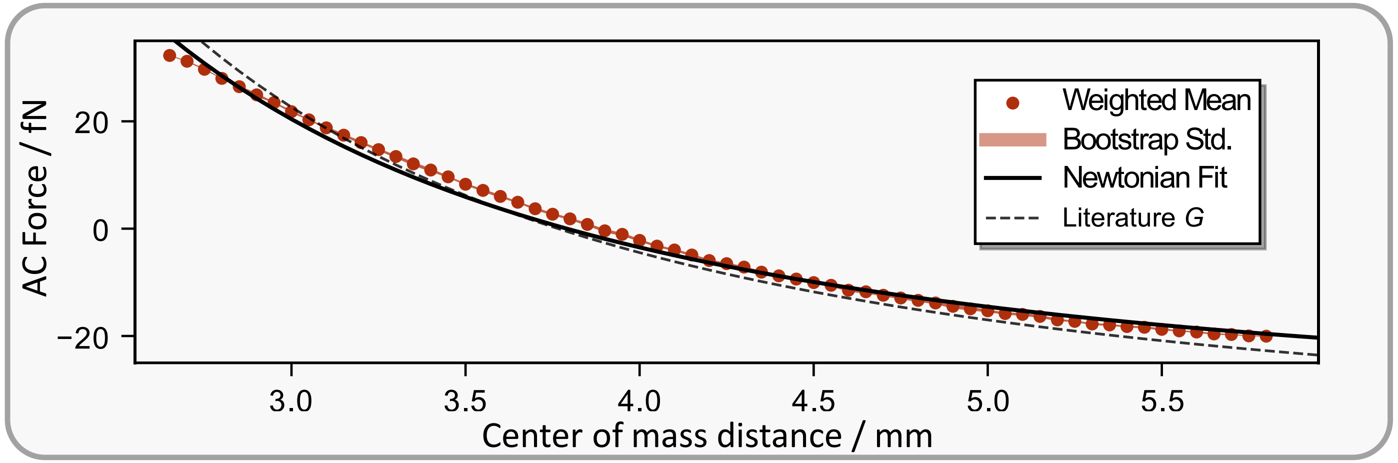
F(t) → F(r)



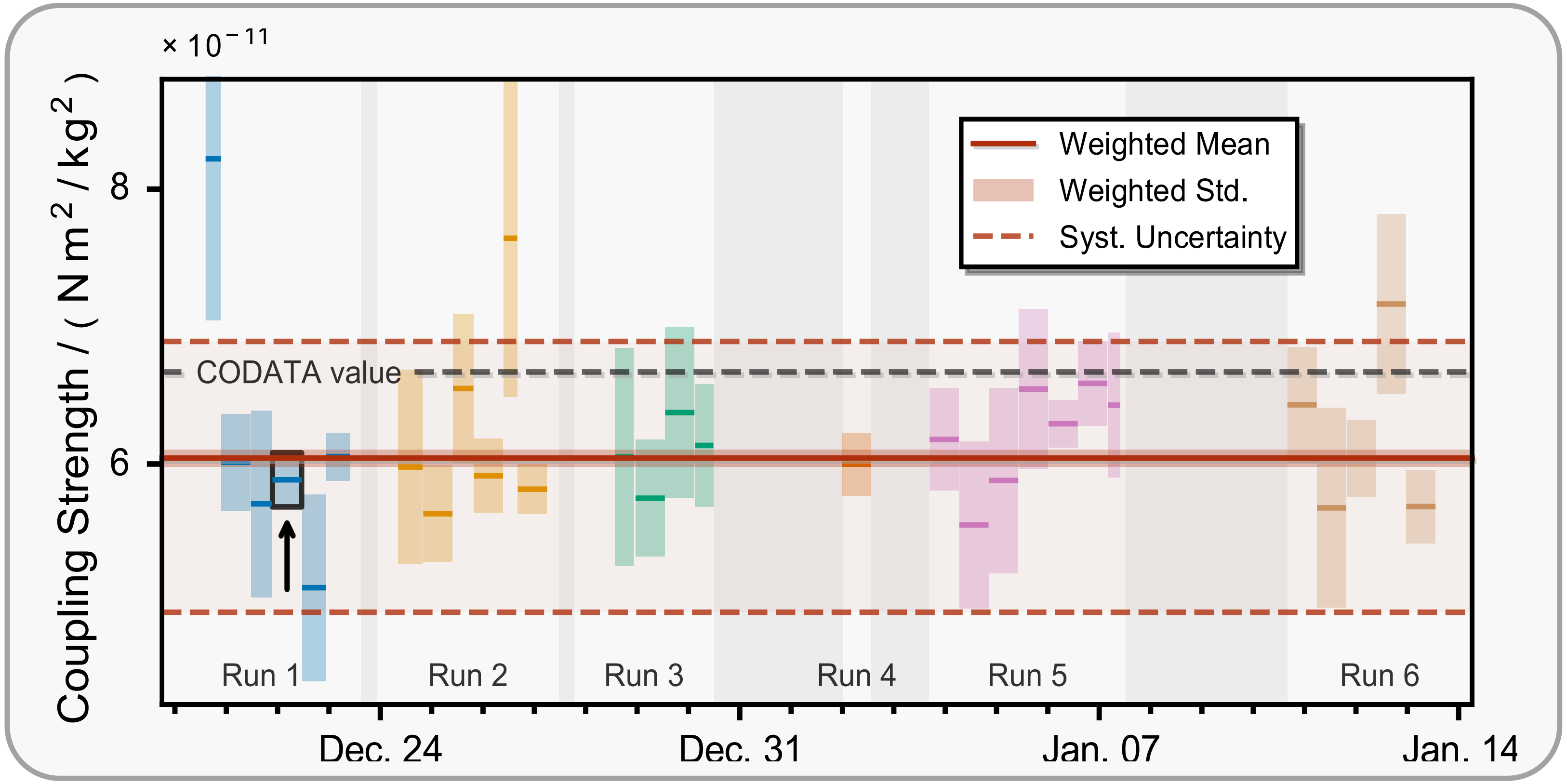
Position dependent force measurement

- Mapping of the gravitational potential
- Online noise estimate

- Single model parameter:
  - coupling strength



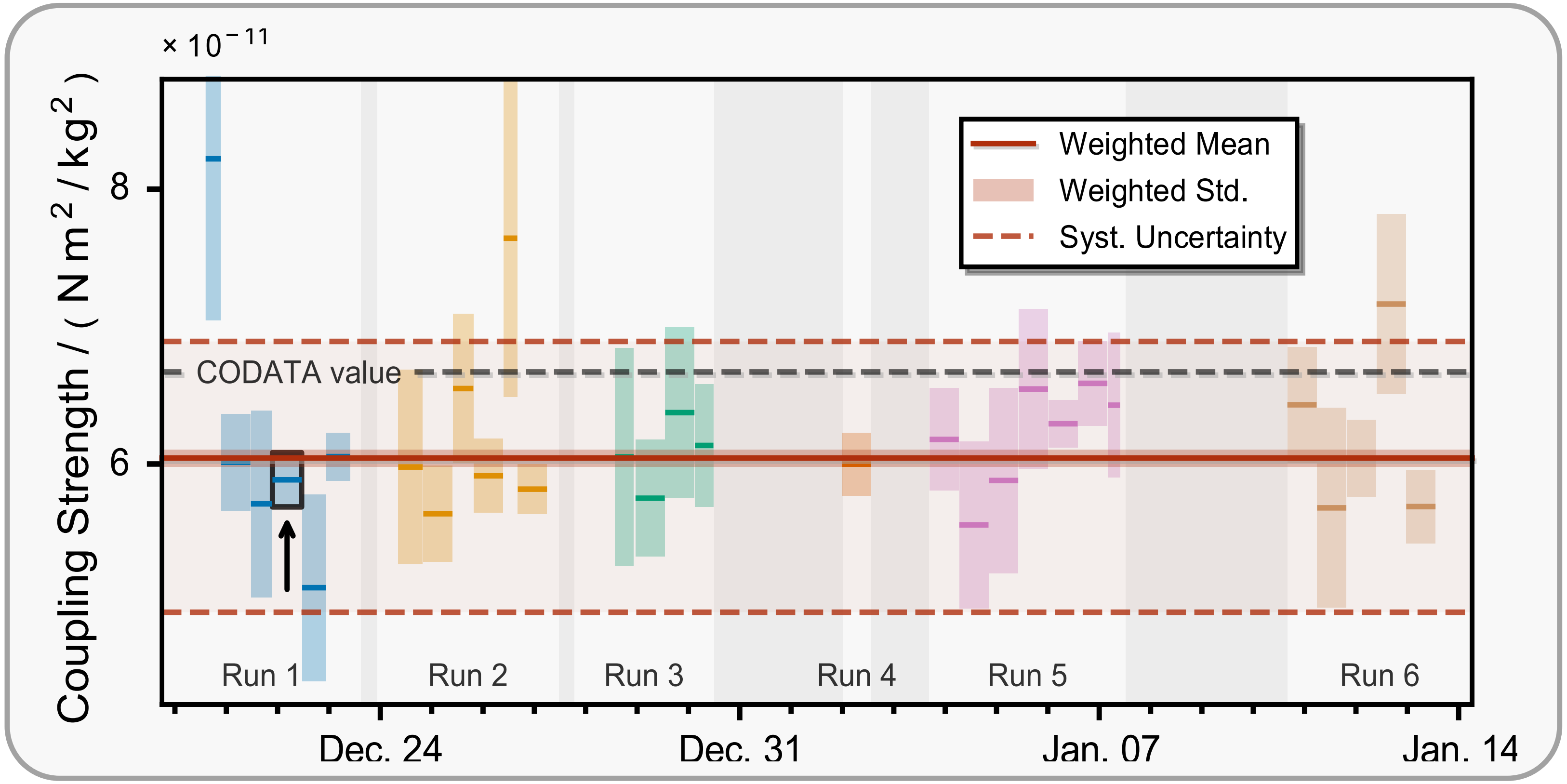
Coupling Strength Measurements



Combined coupling strength

$$G = (6.04 \pm 0.06) \times 10^{-11} \frac{m^3}{kg\, s^2}$$

Coupling Strength Measurements



Deviation of 9% from CODATA (covered by systematics)

- Interaction is >90% gravitational

Combined coupling strength

$$G = (6.04 \pm 0.06) \times 10^{-11} \frac{m^3}{kg\, s^2}$$

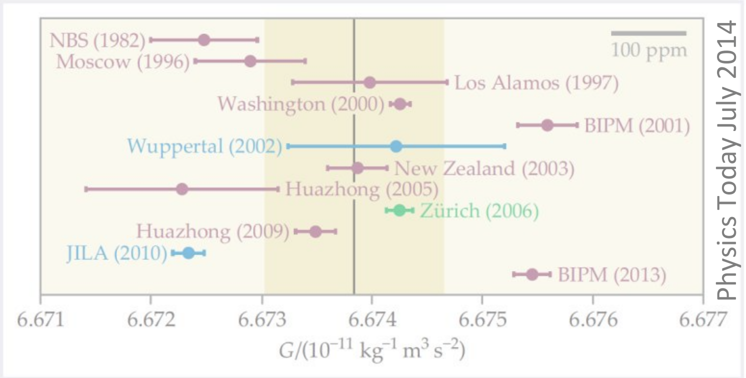
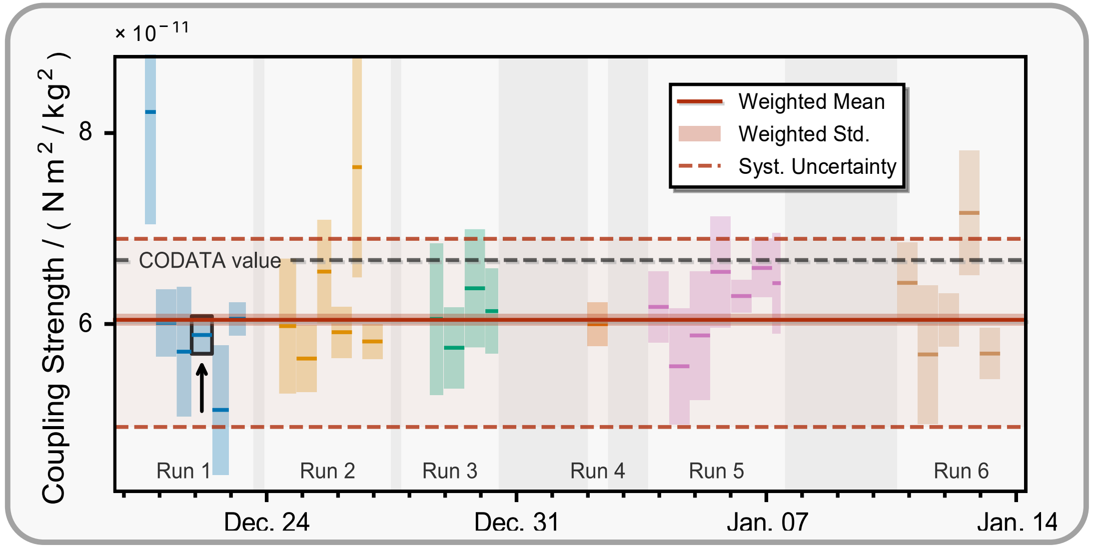


Figure 1. Measurements of Newton's gravitational constant *G* have yielded conflicting results. Here, the results of torsion-balance (maroon), pendulum (blue), and beam-balance (green) experiments discussed in the text are shown, along with the location and year in which they were measured. Error bars correspond to one standard deviation; the shaded region indicates the assigned uncertainty of the value recommended by the Committee on Data for Science and Technology in 2010. (Adapted from T. J. Quinn et al., *Phys. Rev. Lett.* **111**, 101102, 2013.)

Identified Systematics

- Data Evaluation: 1.7×10^{-2}
  - bandpass: 1.6e-2
  - downsampling: 1e-3
  - response shaping: 1e-5
  - AA filter: 2e-6
- Mass uncertainties: 2.4×10^{-2}
  - Source mass: 1.1e-3
  - Test mass: 1.1e-3
  - Sphere – suspension connection: 8.6e-3
  - Suspension: 6.1e-3
  - Capillary: 4.5e-3
  - Glue: 3e-3
  - Counterbalance mass: 1.1e-4
- External forces: 3.0×10^{-2}
  - Electrostatic (# charges): 3e-2
  - Magnetic: 1e-4
  - Seismic: ?
- Pendulum properties: 4.7×10^{-2}
  - Drive calibration: 1.6e-2
  - Height offset: 1.5e-2
  - Readout calibration: 6e-3
  - Quality factor: 5e-3
  - Source mass roundness: 3.2e-3
  - Test mass roundness: 1e-3
  - Mass separation: 1e-3



Identified systematics have NOT been corrected!

Identified Systematics

- Data Evaluation: 1.7 x 10^{-2}
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  - Quality factor: 5e-3
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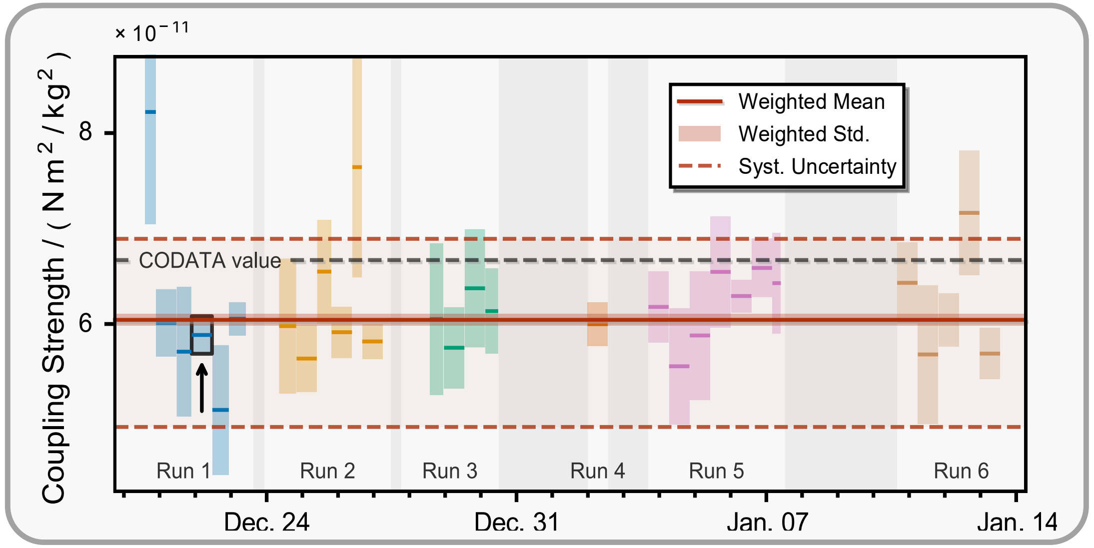
  - Test mass roundness: 1e-3
  - Mass separation: 1e-3

Upper Limit: + 15.9E-2
Lower Limit: - 11.8E-2



Identified systematics have NOT been corrected!

Summary and Future Prospects

Gravitational field of 2mm gold sphere is detectable

- with a tabletop experiment at room temperature
- in a noisy urban environment

Decrease the distance

- Probe corrections for Newton

Decrease the mass

- Measure gravitational field of a Planck mass sized object

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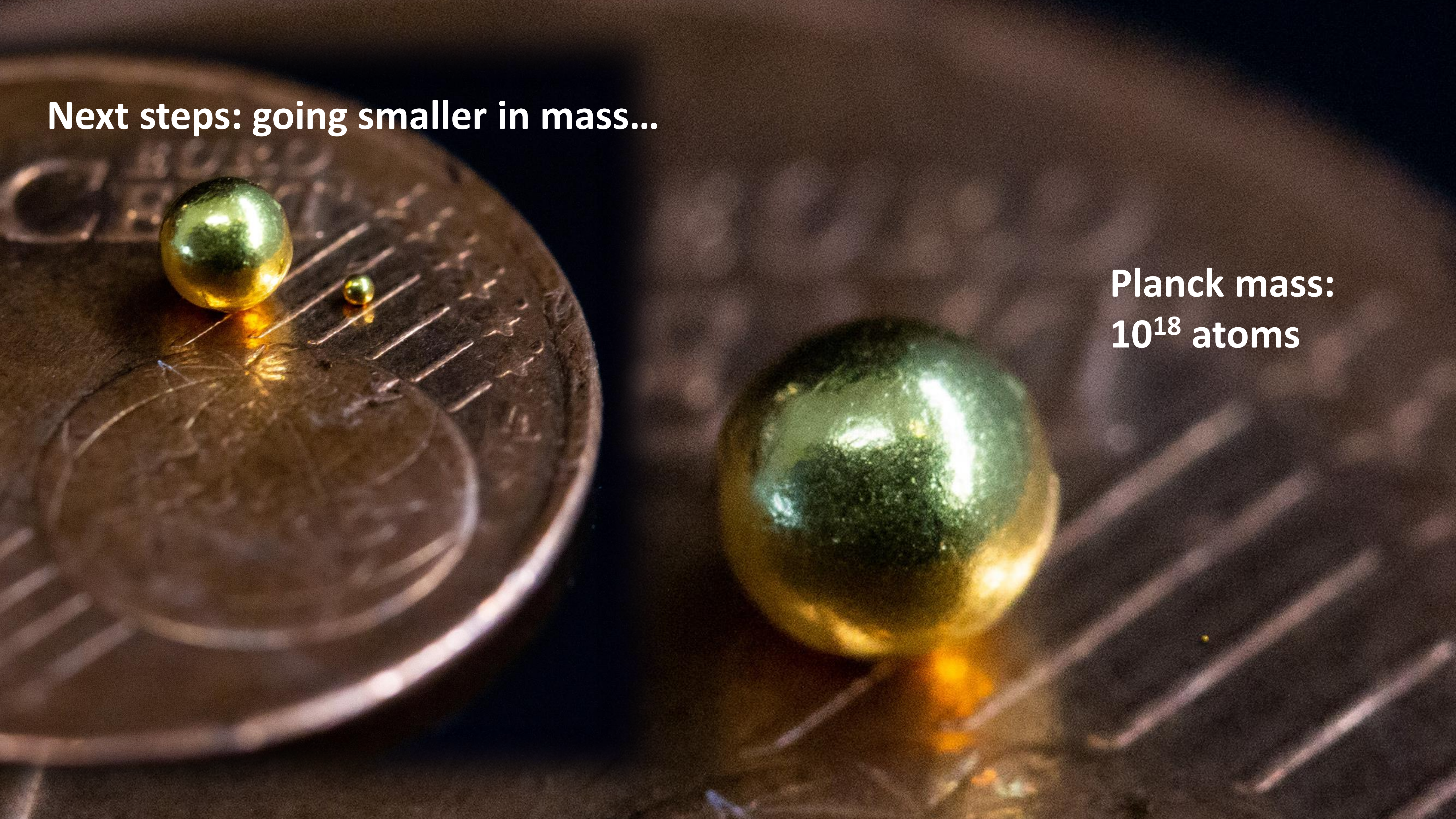
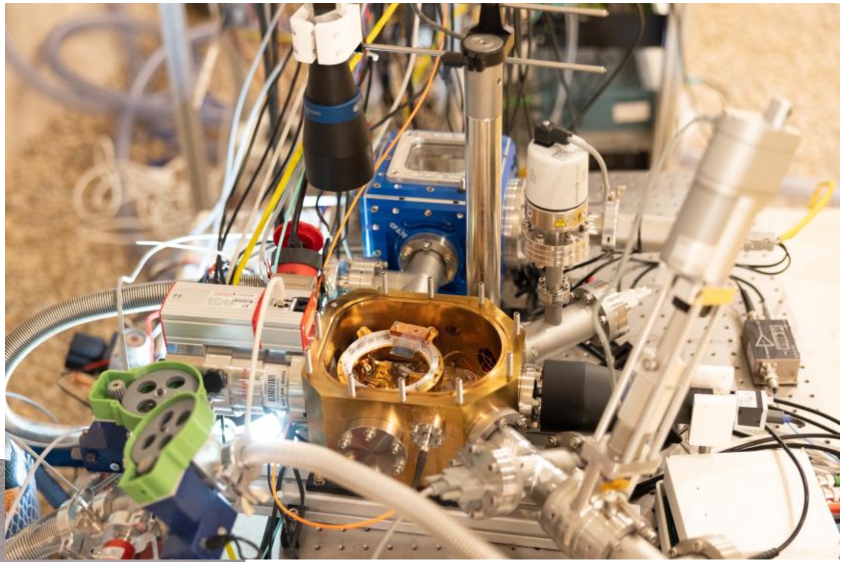
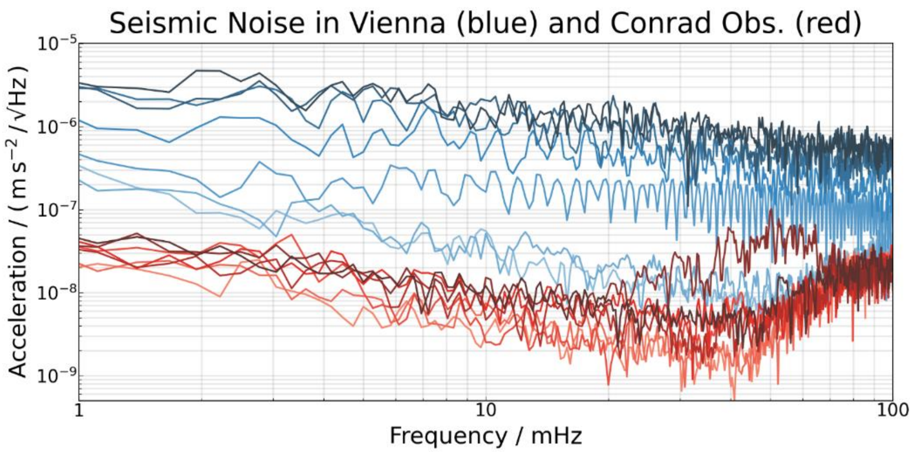
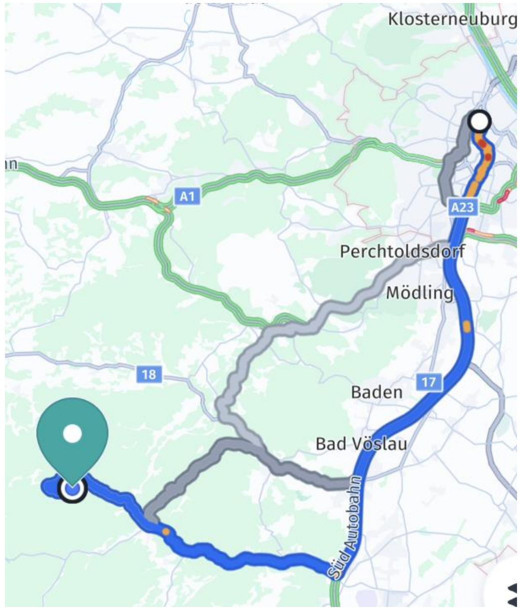

Next steps: going smaller in mass…
Planck mass:
10^{18} atoms

Lab Relocation

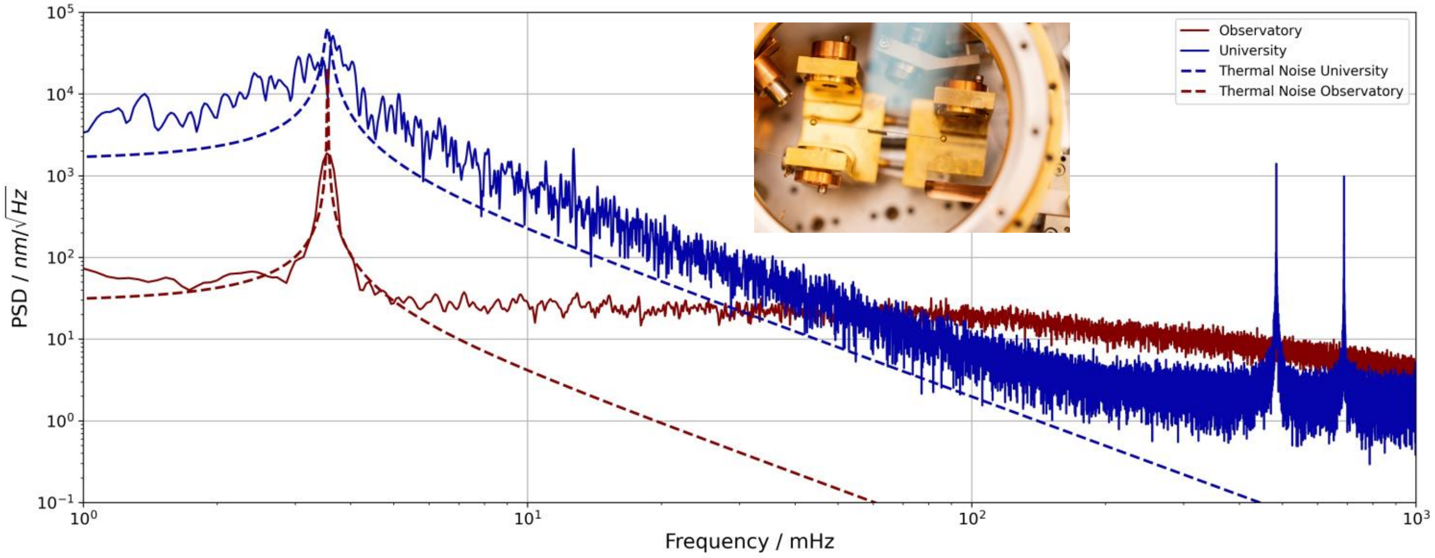


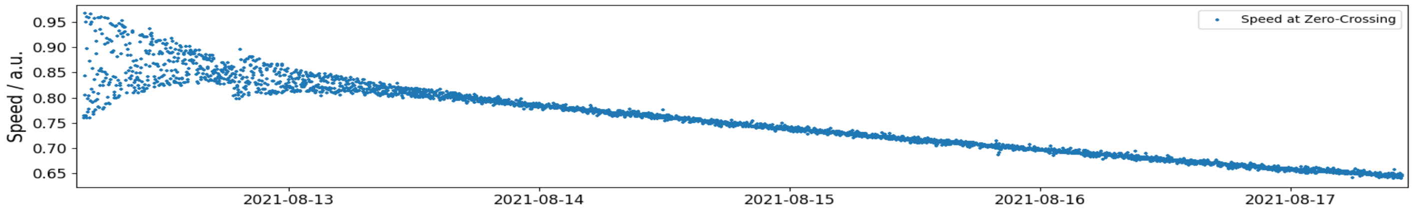
- COBS 80km south of Vienna
- One of the best sites for magnetic and seismic observations world wide
- Ideal lab conditions

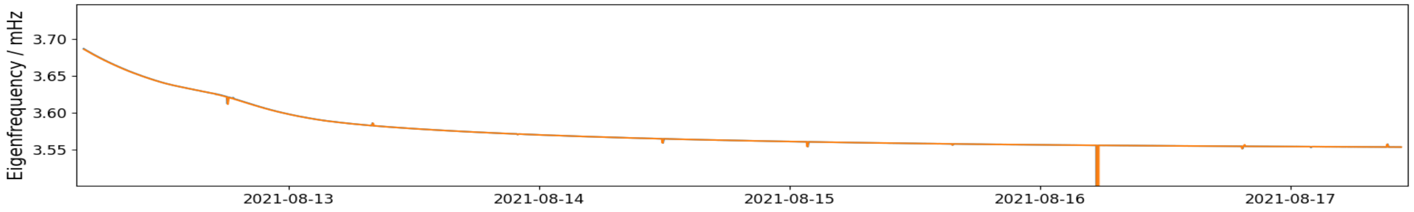




Possible Planck Mass Measurements



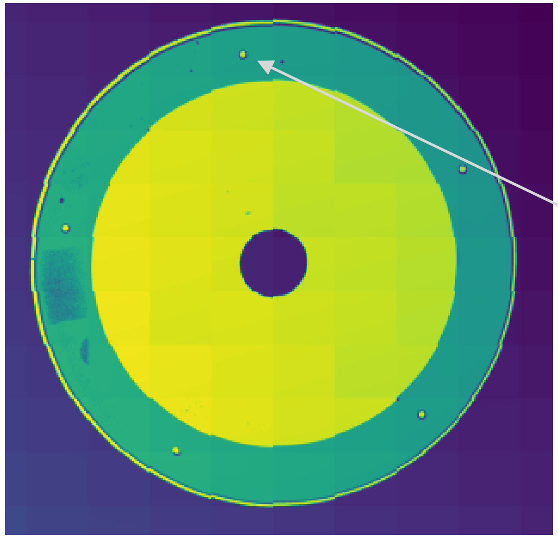




Advantages @ COBS

- Stable environment
- Abundance of available sensors
- Q ≈ 4 -> Q ≈ 18k

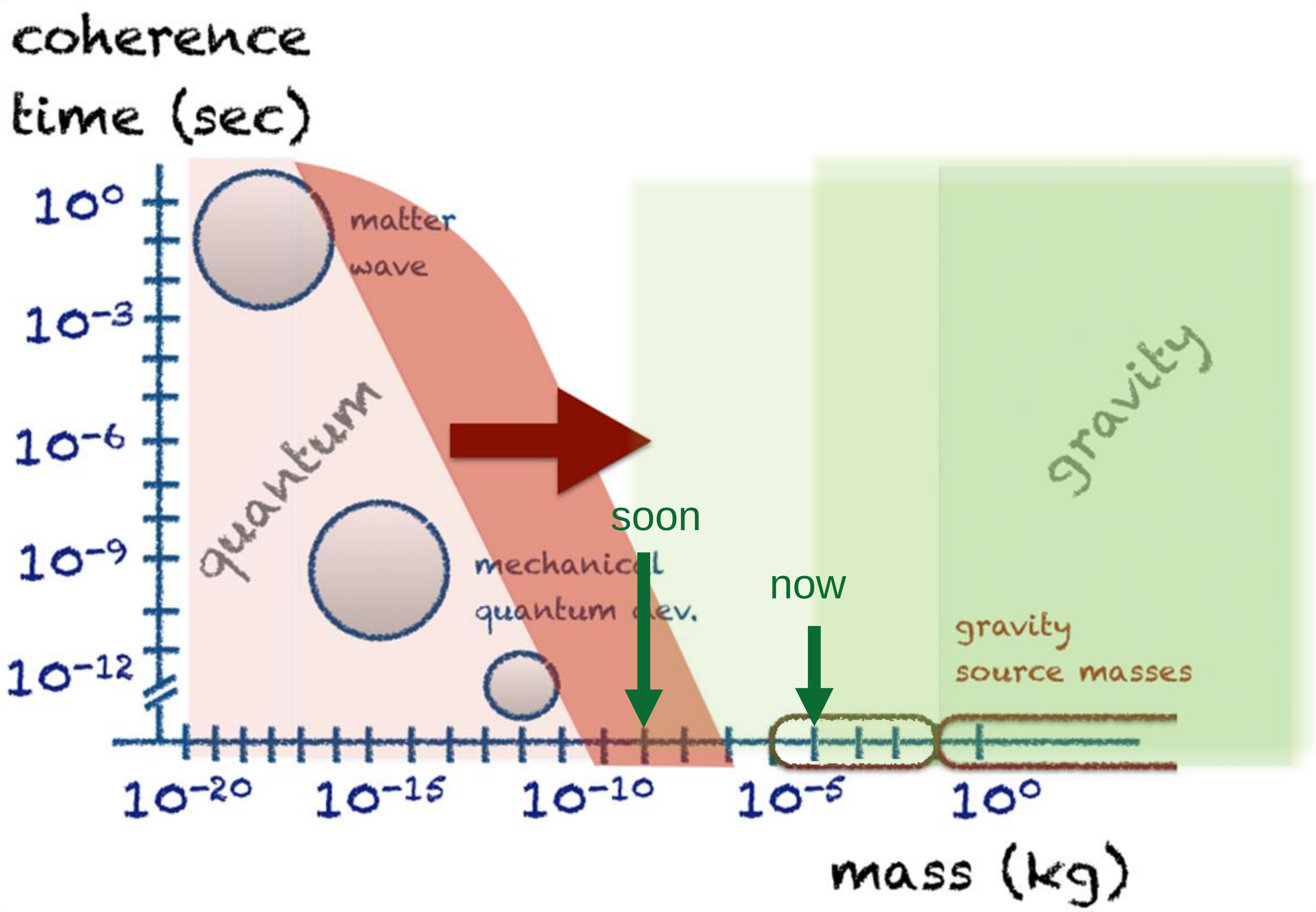
Rotary Source Mass



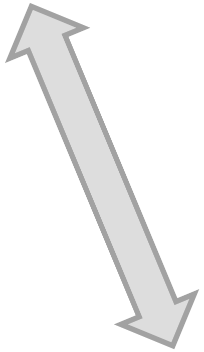
3-5 source masses

$m_s \approx m_p$

Quantum Systems as Gravitational Source masses



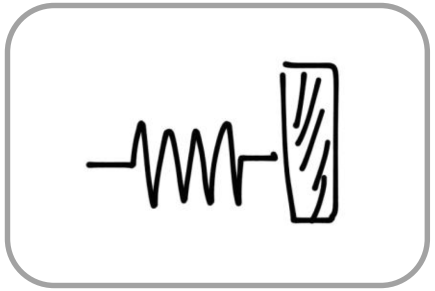
How **big** can we get?



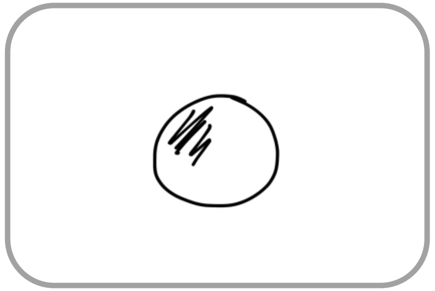
How **small** can we get?

Smallest source mass to date: **0.09 g**

Main Ingredients or Experimental Challenges



+



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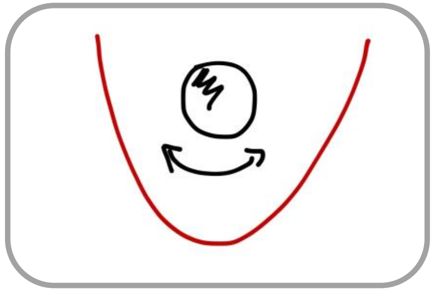
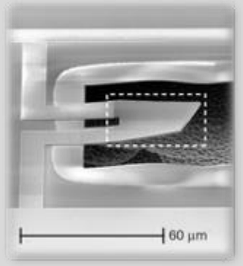


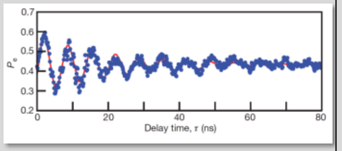
Solid-State Mechanical Quantum Devices (clamped)

$10^{10} – 10^{16}$ atoms

Coherence Time

$10^{-12} – 10^{-8}$ seconds





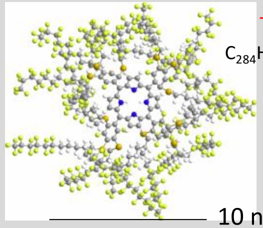
Nature 464, 697 (2010)

Matter-Wave Interferometry (free-fall)

$10^{0} – 10^{4}$ atoms

Coherence Time

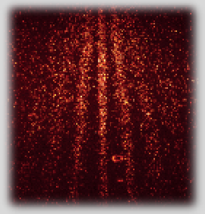
$10^{-3} – 10^{0}$ seconds



TPPF320

$C_{284}H_{190}F_{320}N_4S_{12}$

10 nm



Nature Nanotech. 7, 297 (2012)

Levitated (Opto-) Mechanics

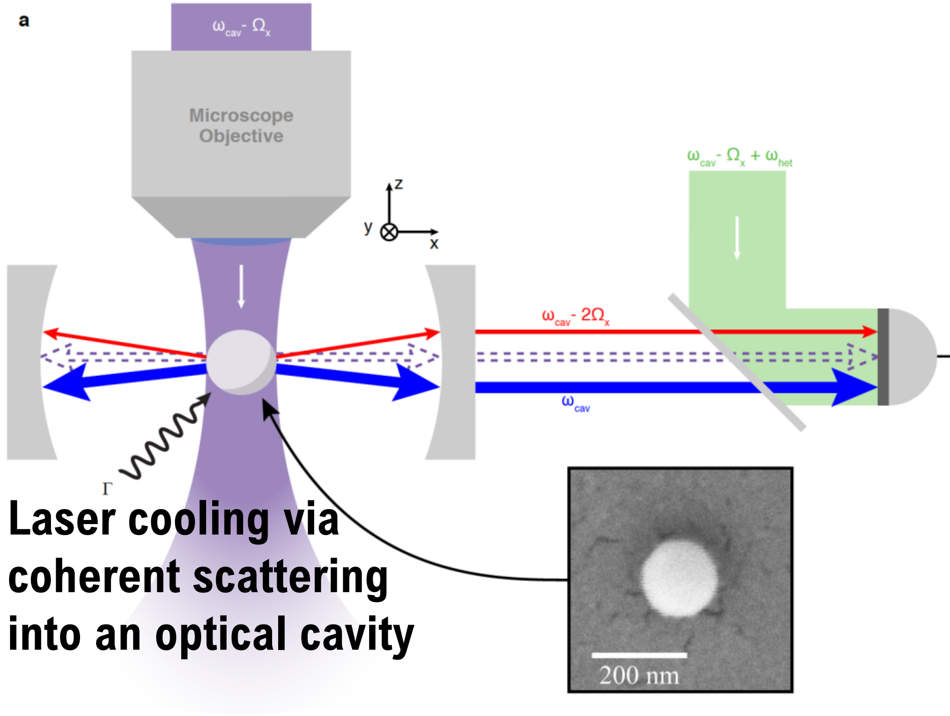
- Quantum control of trapped solid state object **>> 10^{10} atoms**
- Long coherence time up to **seconds**
- Arbitrary potential landscape
- Exceptional force sensitivity

recent review:
Gonzalez-Ballestero et al., Science **374**, 168 (2021)

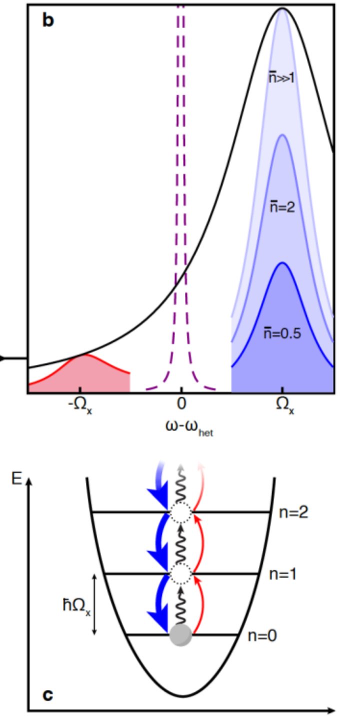
universität wien

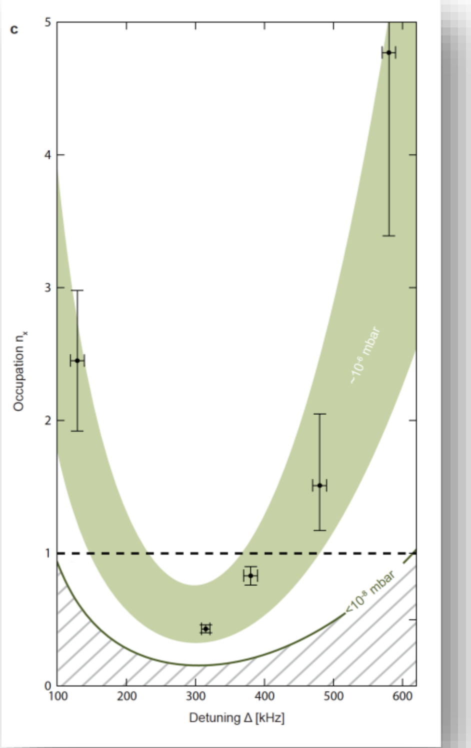
Motional Quantum Ground State of a Levitated Nanoparticle

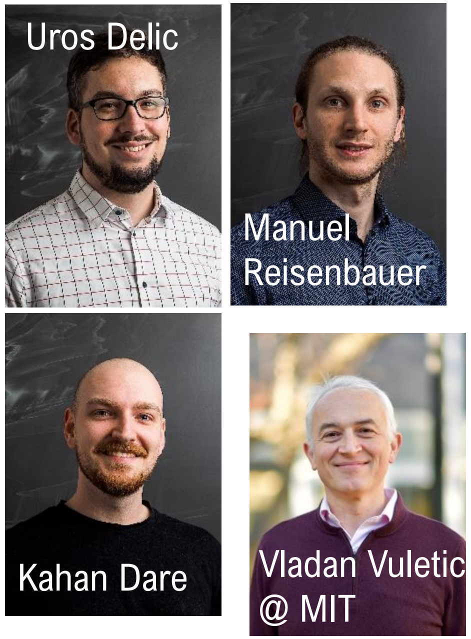
ÖAW



Laser cooling via coherent scattering into an optical cavity







Delic et al., PRL 122, 123602 (2019)
Windey et al., PRL 122, 123601 (2019)

$\omega_x \approx 2\pi \times 305$ kHz

$\omega_z \approx 2\pi \times 80$ kHz

$\omega_y \approx 2\pi \times 275$ kHz

p = 1e-6 mbar, T = 300K

Delić et al., Science **367**, 892 (2020)

n_x **< 0.5** (ground state probability **> 2/3**)

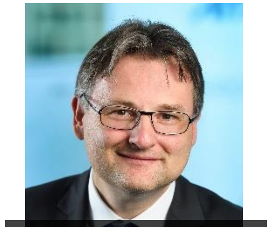
Center-of-mass Tc = 12uK; environment Te > 300K

$g_x = 2\pi$ x 71 kHz, Cooperativity C = 5

Quantum Kalman Control: Ground-State Cooling

Magrini et al., Nature 595, 373 (2021)

- **Confocal backplane imaging** allows **quantum limited position measurement @ 1.7 x Heisenberg limit** (10^{-14} m/sqrt{Hz})
- **Kalman filtering** allows **real-time tracking of the quantum trajectory @ 1.3 x zero-point motion**
- **Optimal feedback (LQR)** allows to stabilize particle motion in its **quantum ground state (<n> = 0.5) in a room temperature environment**



Andreas Kugi
@ TU Wien

related:
Wieczorek et al., PRL 114, 223601 (2015)
Rossi et al., PRL 123, 163601 (2019)

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Magrini et al., Nature 595, 373 (2021)

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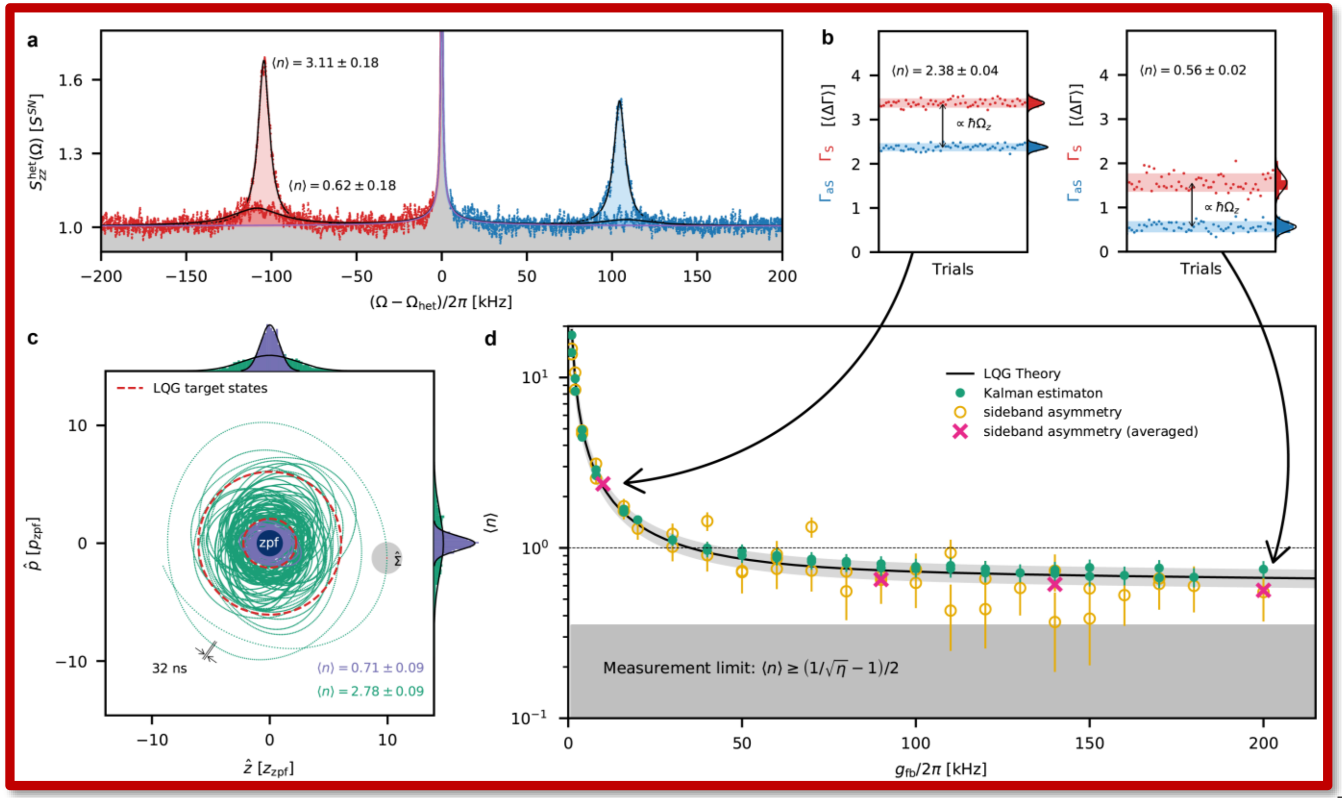
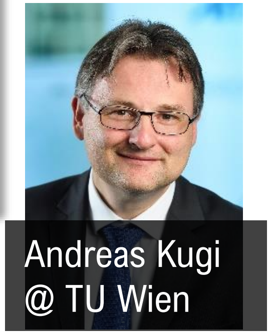
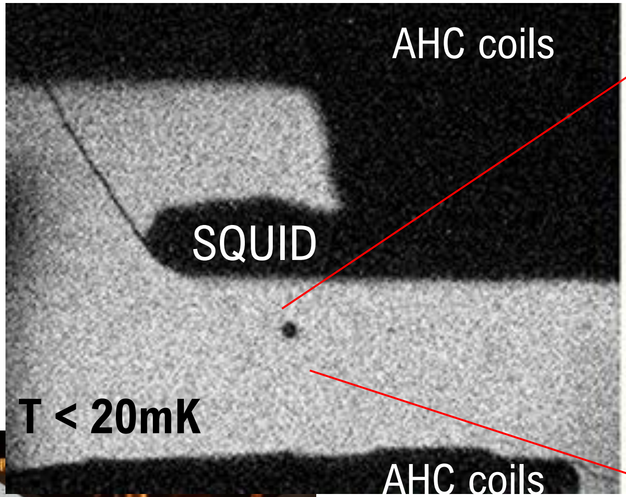
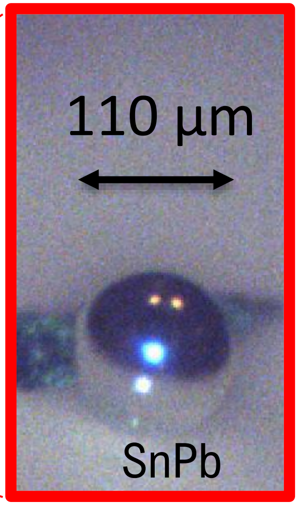




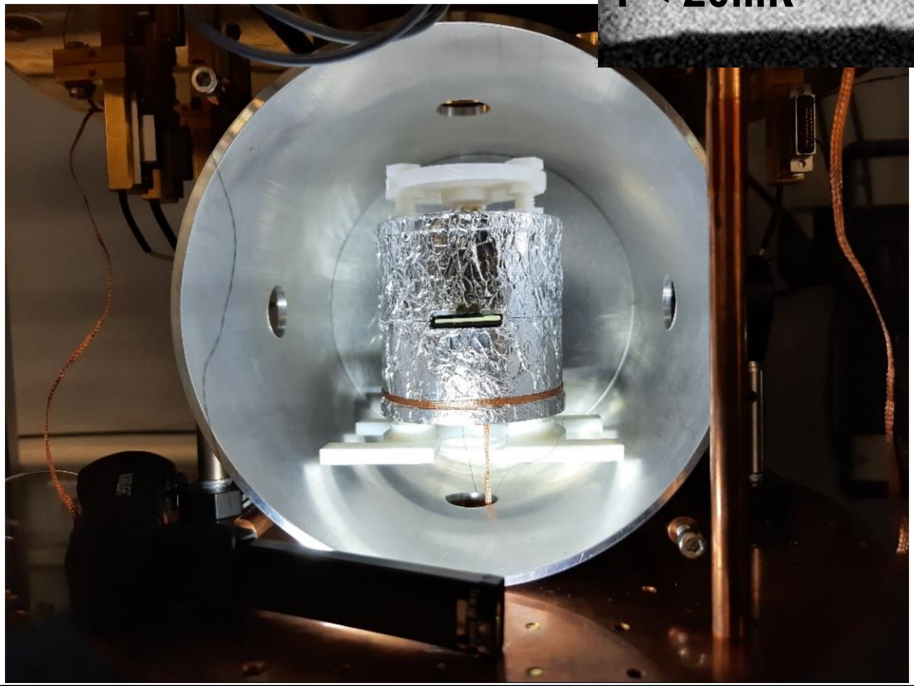
related:
Wieczorek et al., PRL 114, 223601 (2015)
Rossi et al., PRL 123, 163601 (2019)

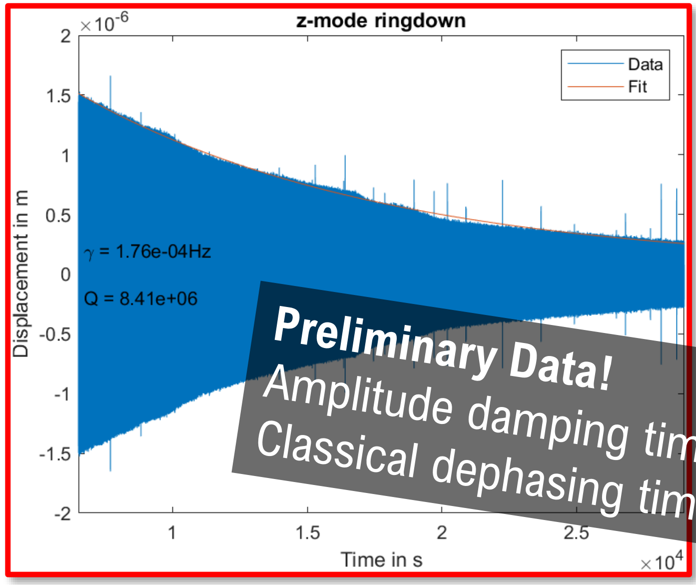
Towards larger masses: Superconducting Levitation



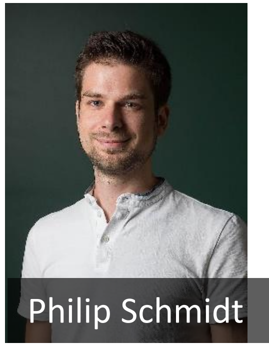


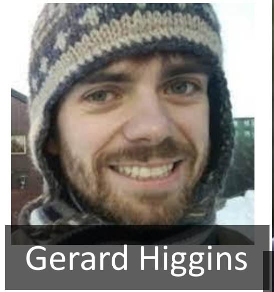
ca. Planck mass

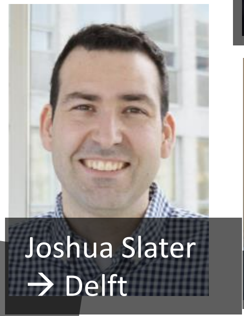




Preliminary Data!
Amplitude damping time > 40,000 sec
Classical dephasing time > 80 sec



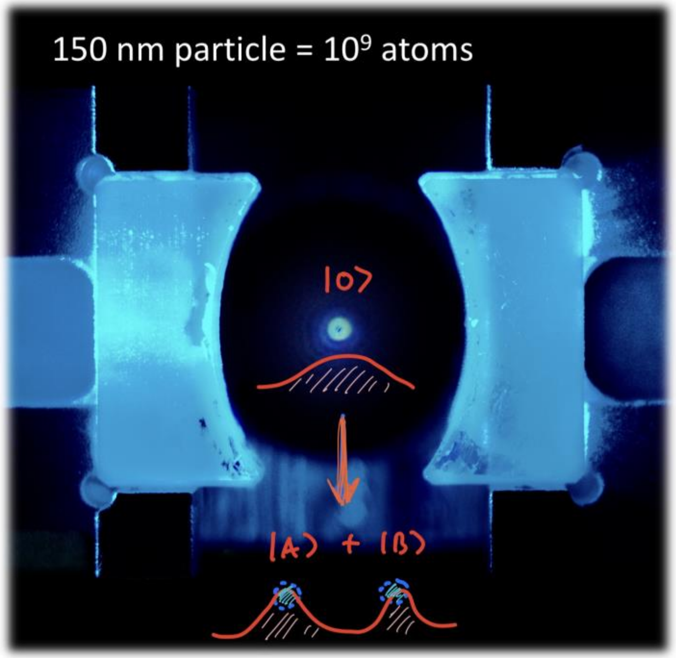




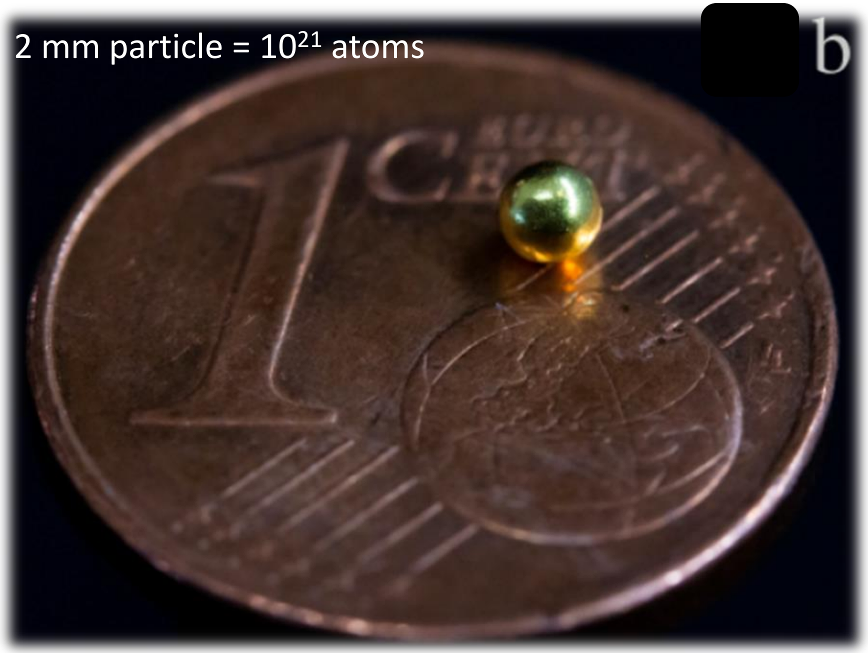
Summary

Levitated quantum control in the regime of large mass and long coherence times

- Bottom-Up: Quantum regime of nanoparticles
- Top-Down: Gravitational coupling of mm-sized particles



Largest quantum mass in our lab:
Quantum motion of a silica nanosphere at room temperature
Delic et al., Science 367, 892 (2020)
Magrini et al., Nature 595, 373 (2021)



Smallest gravitational source mass to date
(2mm gold sphere = 4,000 times the Planck mass)

Westphal et al., Nature 591, 225 (2021)

Quantum-"Mechanics" in Vienna: The Levitation Team 2022

+ our collaboration partners:
The ERC Synergy team: Lukas Novotny, Romain Quidant (ETH) / Oriol Romero-Isart (Innsbruck)
Eric Adelberger (UWash) / Caslav Brukner (Vienna) / Rudolf Gross (WMI) / Andreas Kugi (TU Wien) / Nikolai Kiesel (Vienna) /
Monika Ritsch-Marte (Innsbruck) / Vladan Vuletic (MIT) / Robert Wald (Uchicago) / Witlef Wieczorek (Chalmers)

ÖAW
erc European Research Council
Alexander von Humboldt Stiftung/Foundation
FWF Der Wissenschaftsfonds.
cQOM
OMT OPTOMECHANICAL TECHNOLOGIES
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Former Members:


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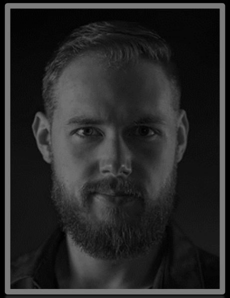
Jonas Schmoele

universität wien
SEVENTH FRAMEWORK PROGRAMME
CoQuS ComplexQuantumSystems
VCQ Vienna Center for Quantum Science and Technology
erc
FWF Der Wissenschaftsfonds.
cQOM
ÖAW
IQOQI

Jonas Schmöle PhD thesis (2017)
Jonas Schmöle *et al.*, Class. Quant. Grav. **33** (2016)
T. Westphal, *et al.*, Nature, 225-228 (2021)