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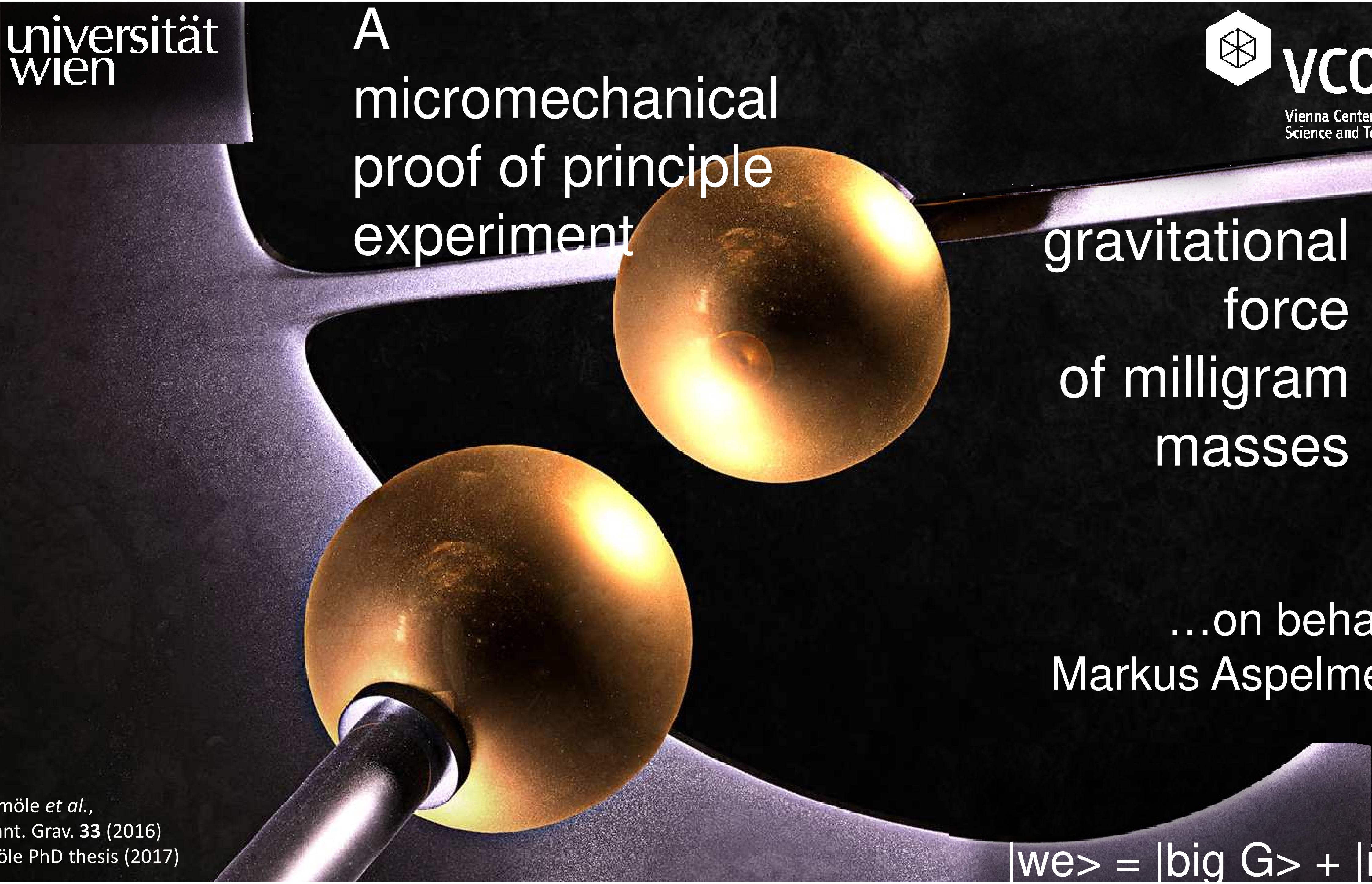


A micromechanical proof of principle experiment

VC
Vienna Center
Science and T

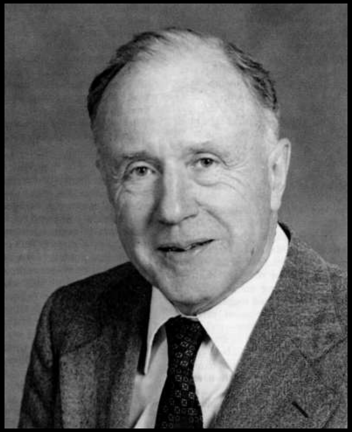
gravitational force of milligram masses

…on beha
Markus Aspelme

möle *et al.*,
nt. Grav. **33** (2016)
öle PhD thesis (2017)

|we> = |big G> + |i

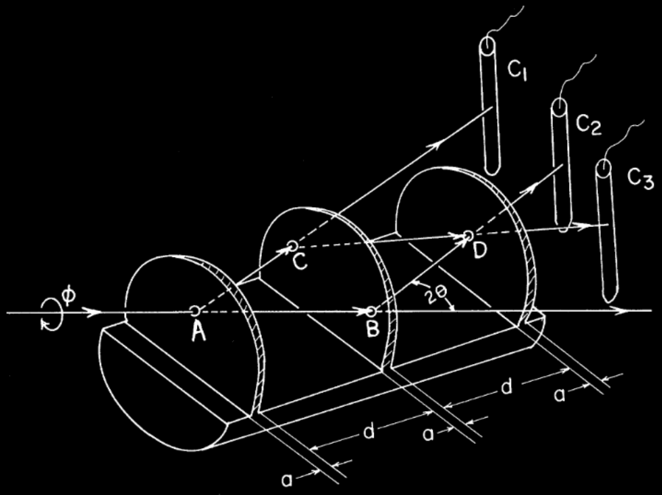
How do quanta gravitate

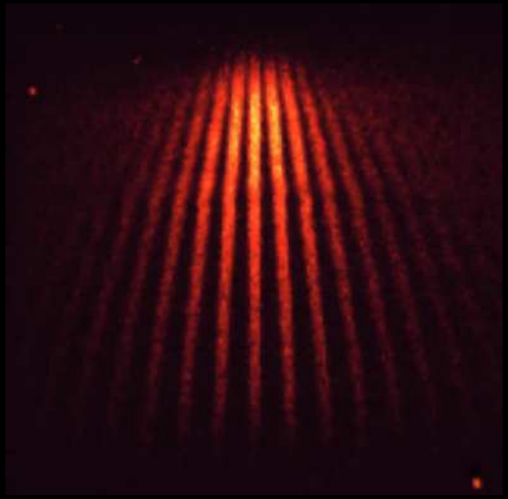


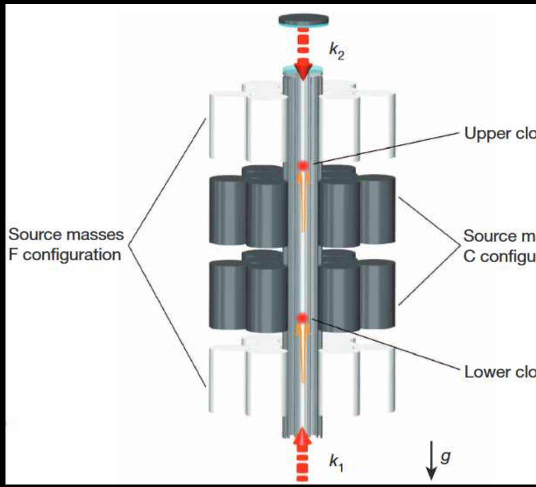
John Archibald Wheeler:

- Spacetime tells matter how to move → COW experiment
- Matter tells spacetime how to curve → Matter wave interferometry

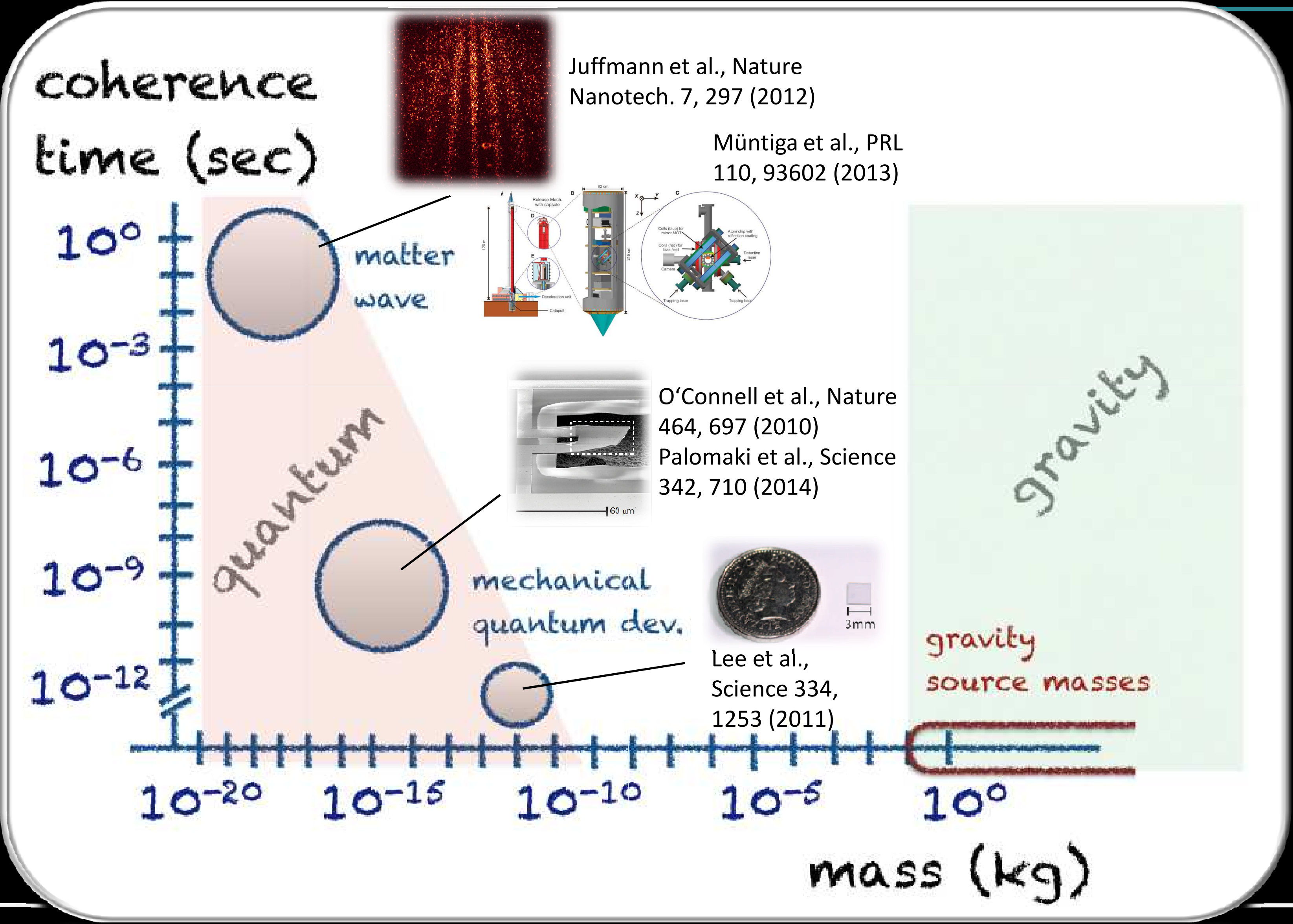
→ Atom fountains







A quantum source mass?



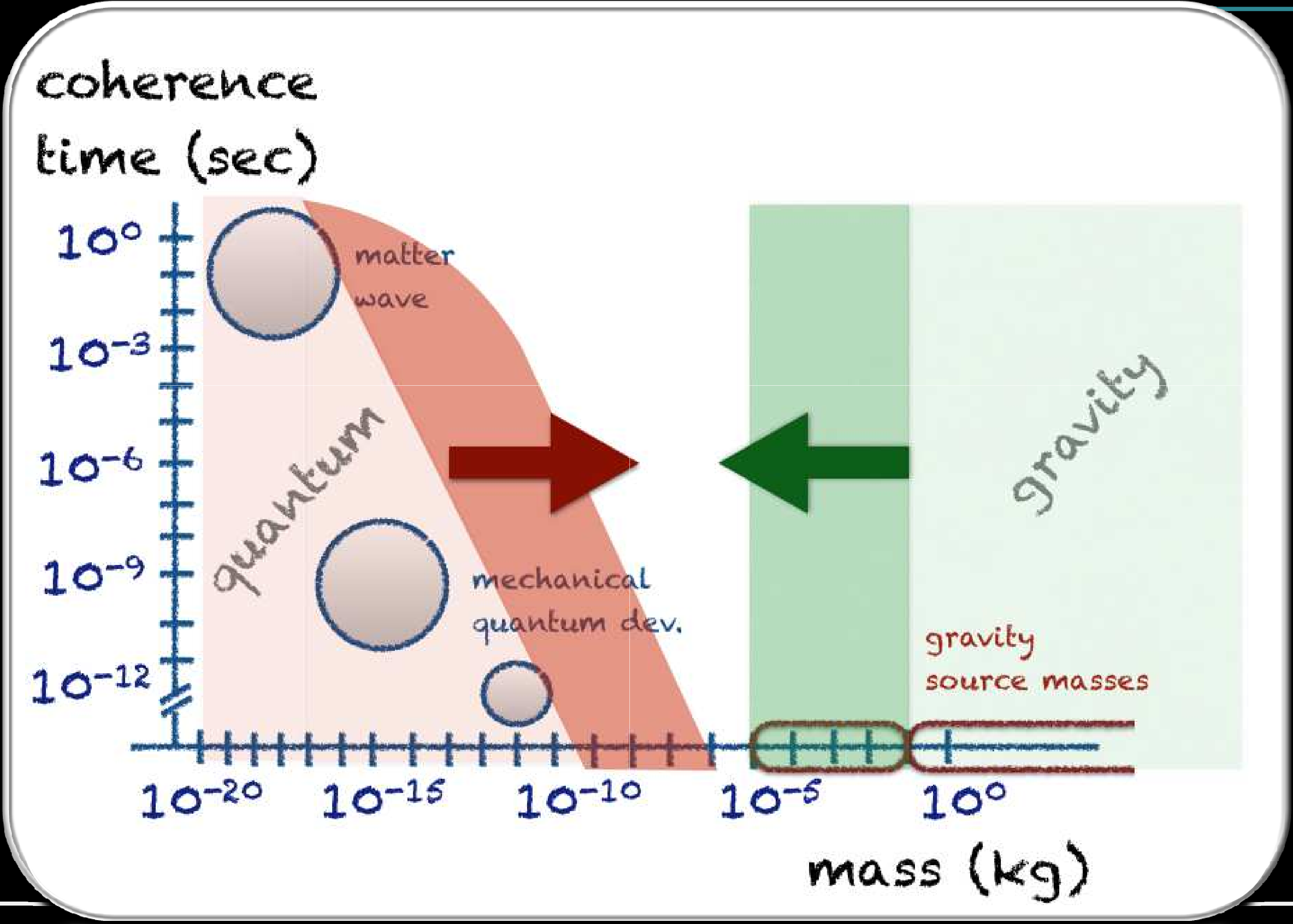
Juffmann et al., Nature Nanotech. 7, 297 (2012)

Müntiga et al., PRL 110, 93602 (2013)

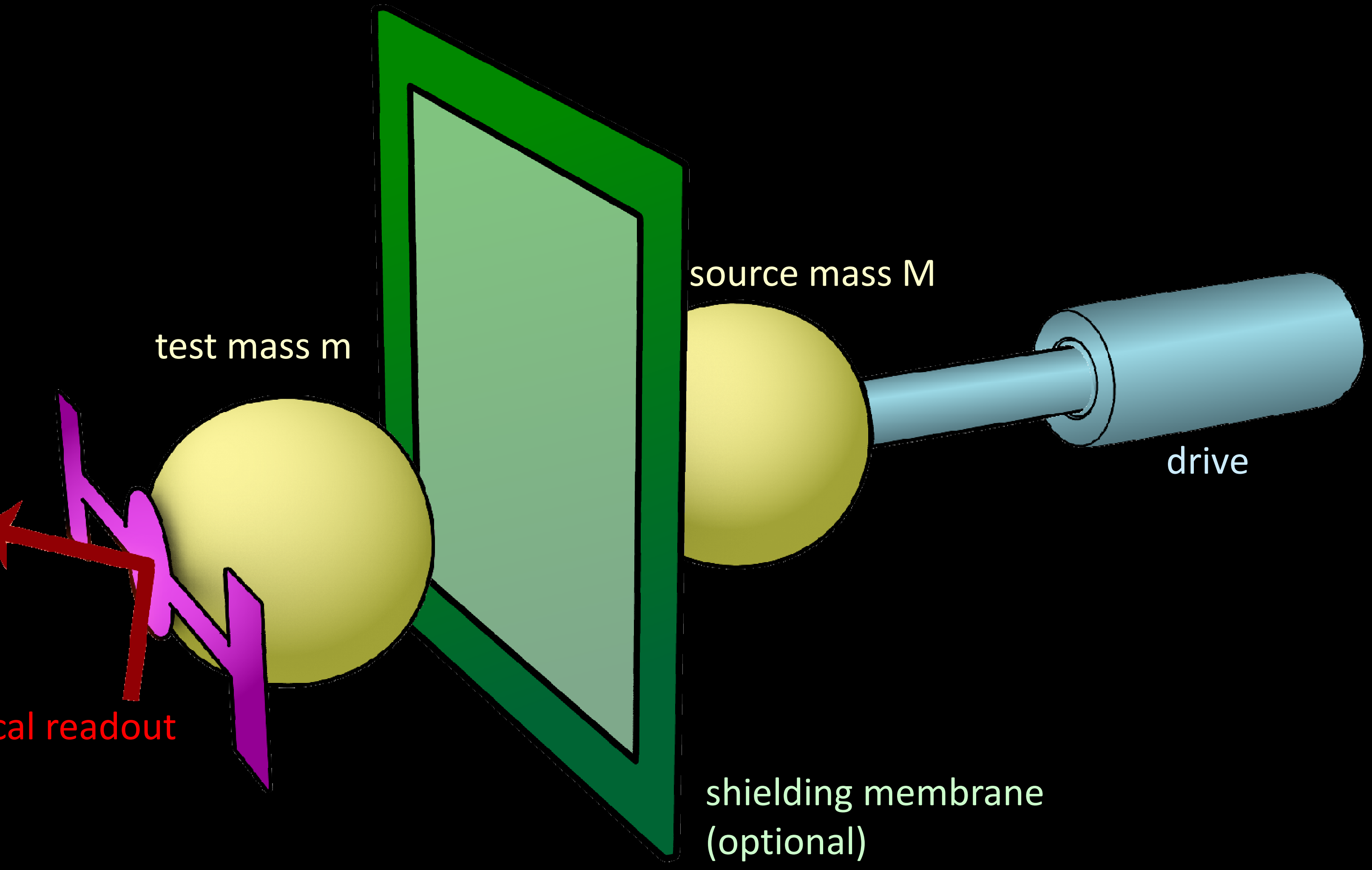
O'Connell et al., Nature 464, 697 (2010)
Palomaki et al., Science 342, 710 (2014)

Lee et al., Science 334, 1253 (2011)

How massive/small can we go?

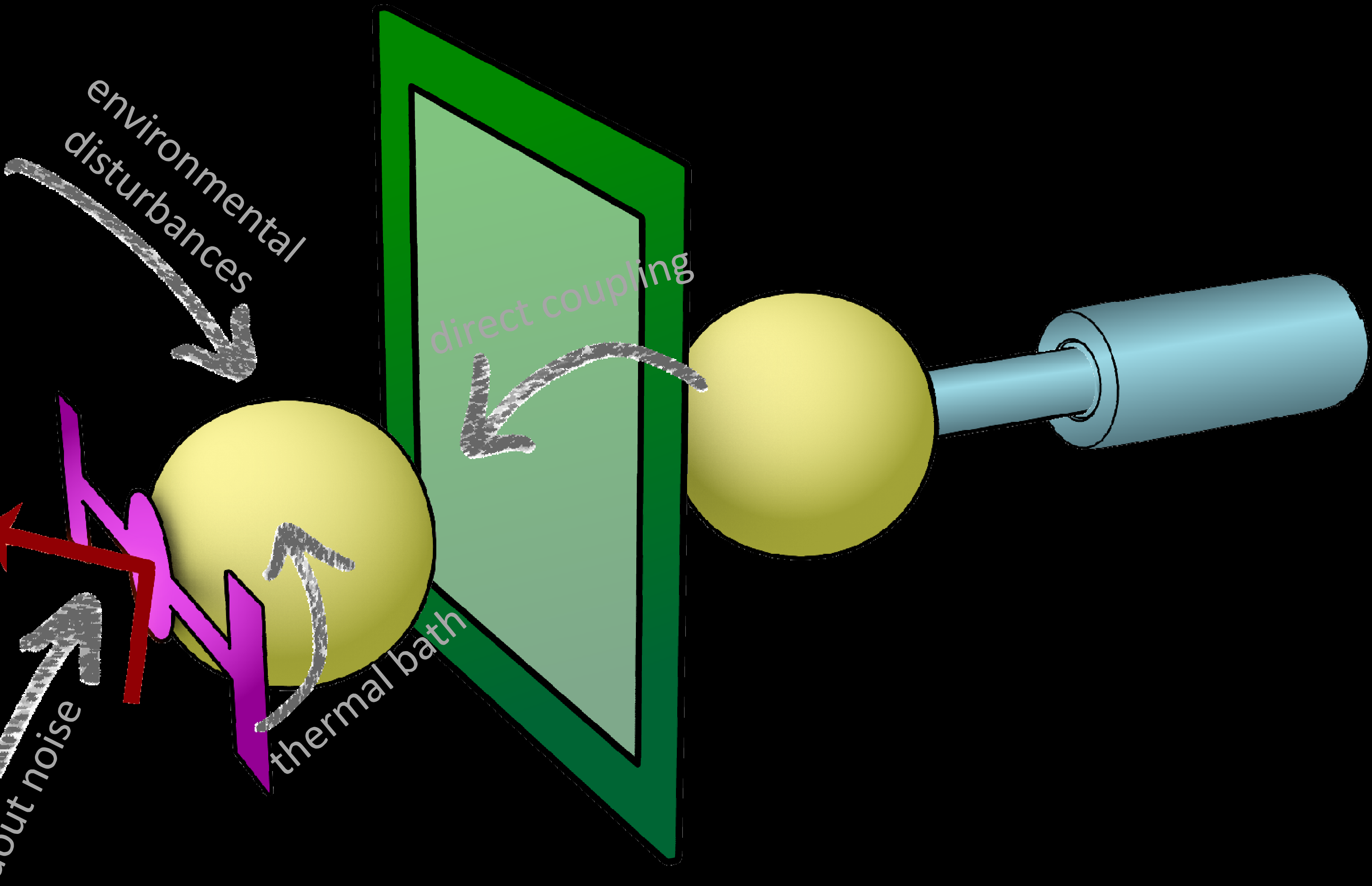


Experimental setup



- 100 mg masses
- Modulate gravity
- Sense micromechanic
- Read out optically
- Demodulate digitally

Noise couplings



- Direct coupling
  - Recoil
  - Gas momentum
  - Electrostatic
- Environmental disturbances:
  - Seismic
  - Acoustic
  - Thermal drifts
- Readout noise
  - Shotnoise
  - Interferometer
  - Detector
- Thermal bath
  - Due to support

Force contributions ≈ sensitivity curve

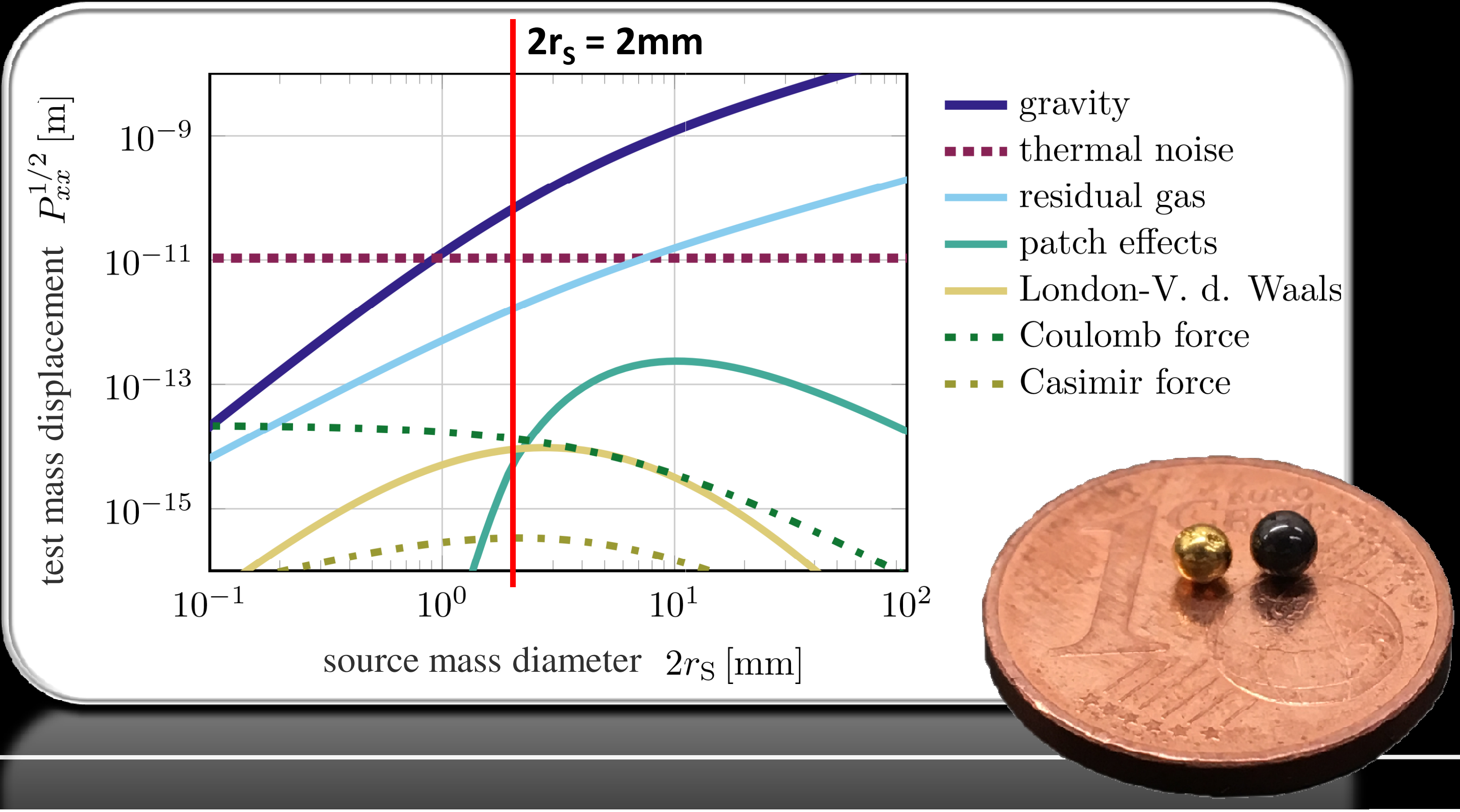
- Effect vs source mass size
- Fixed test mass assembly
- w/o shielding membrane!

→

2 mm sphere, gold

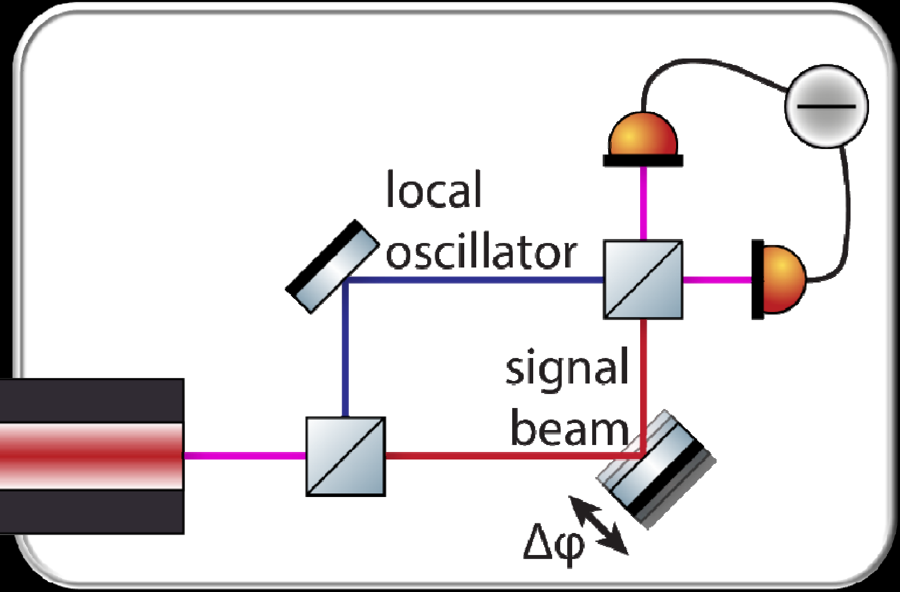
50 Hz mode, **Q = 20,000**

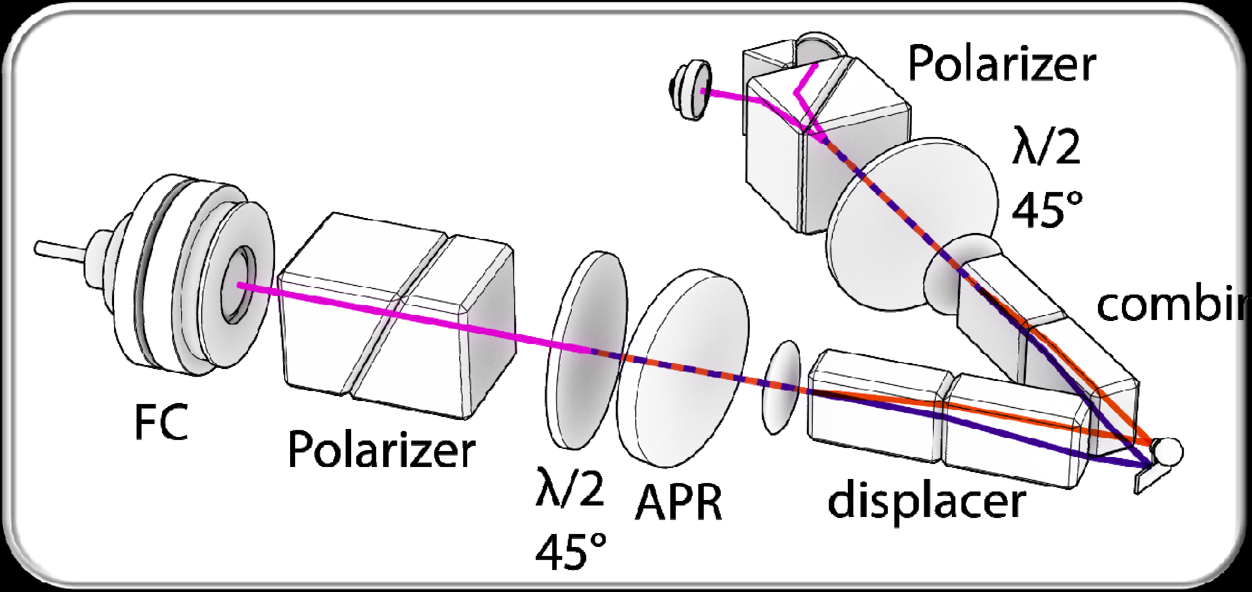
Integration time: **60 min**



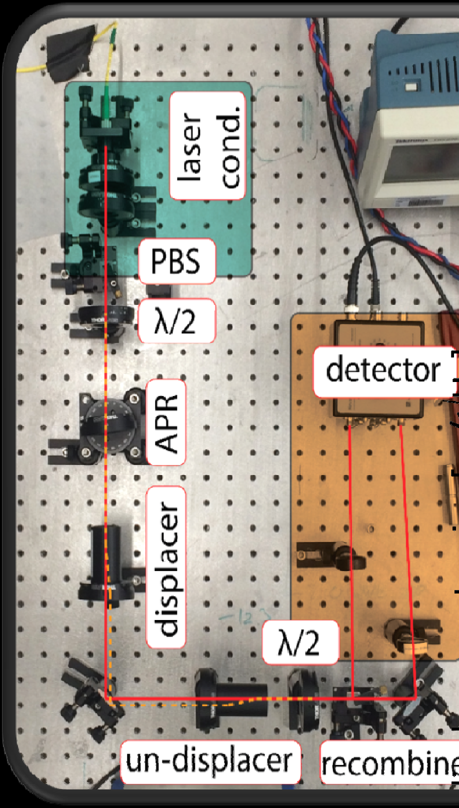
Position readout: interferometer layout

- Polarization based Mach Zehnder
  - small and short beam separation (common path ifo)
  - high common mode rejection (test mass support as reference)
  - equally long arms
- Balanced homodyne detection
  - in-vacuum & suspended
- Short coherence length laser?
  - minimize scattering effects



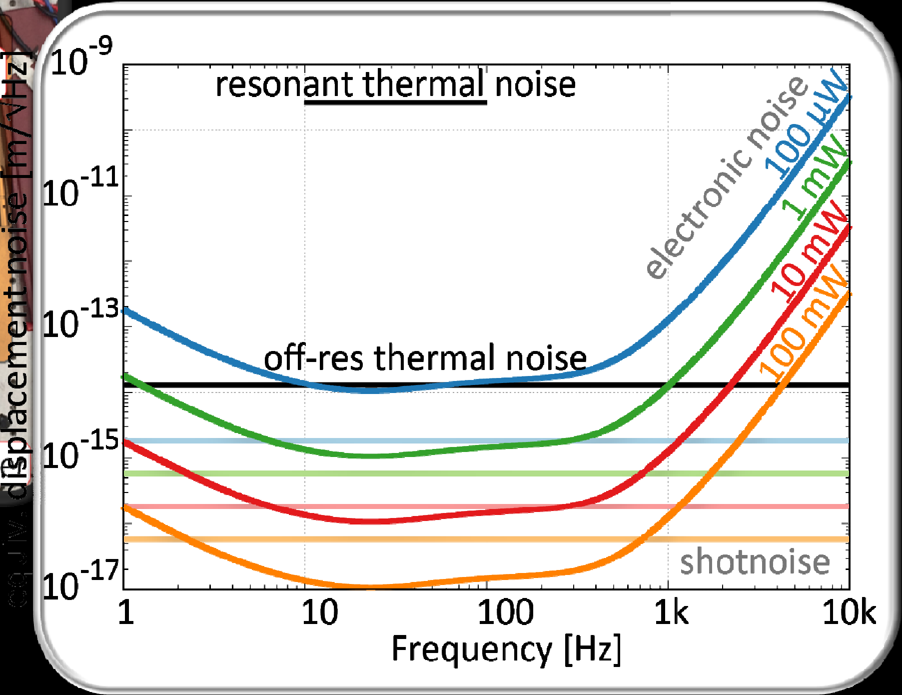


Interferometer: first results



Fringe scan

- Rotate birefringent element
- Geometric effect
- Choose set point of the ifo

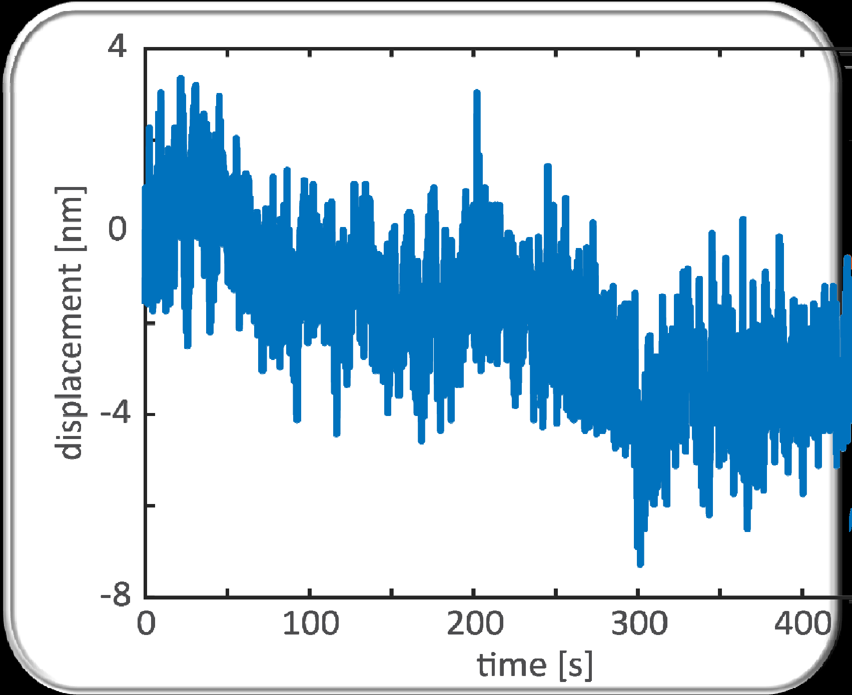


Ifo drift

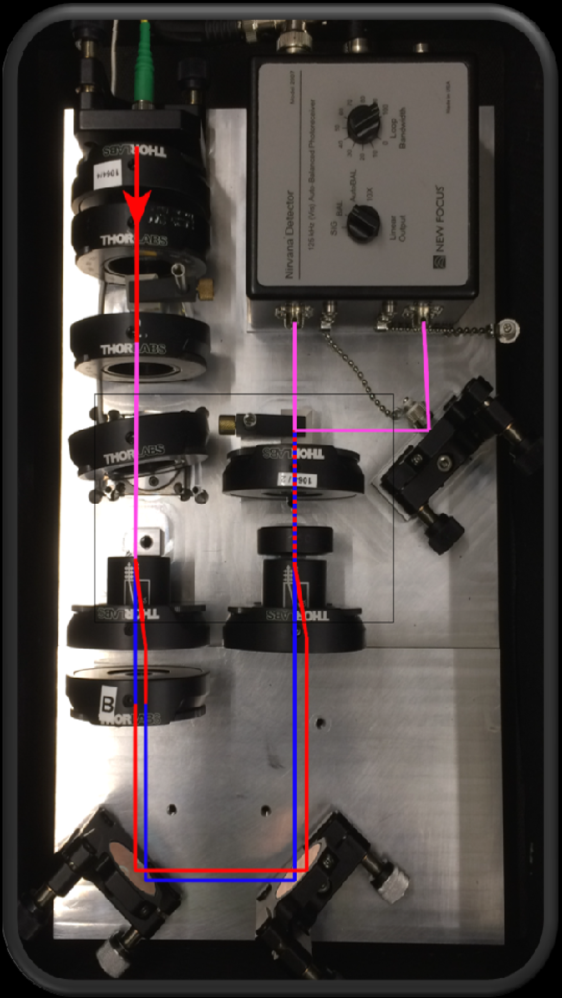
- On air, tabletop (ground!), no isol

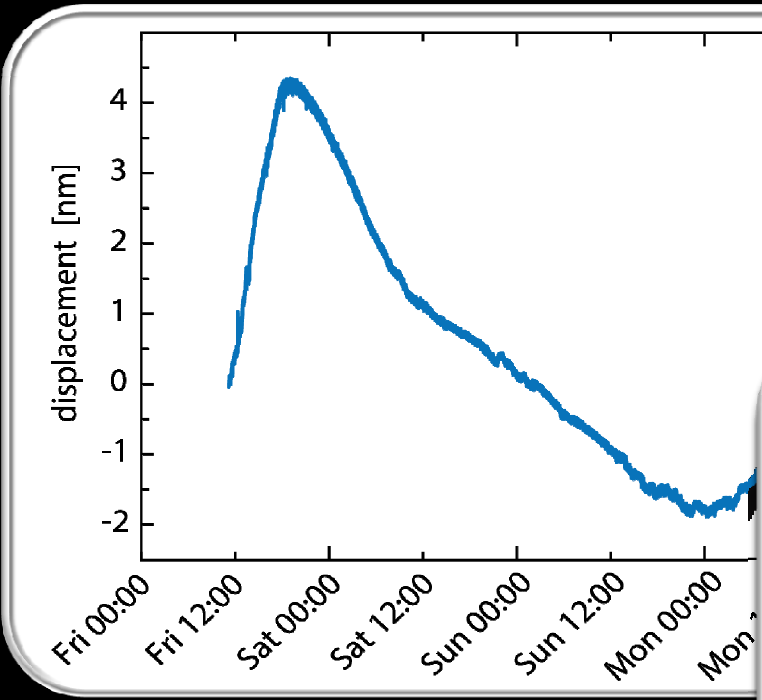
Spectrum

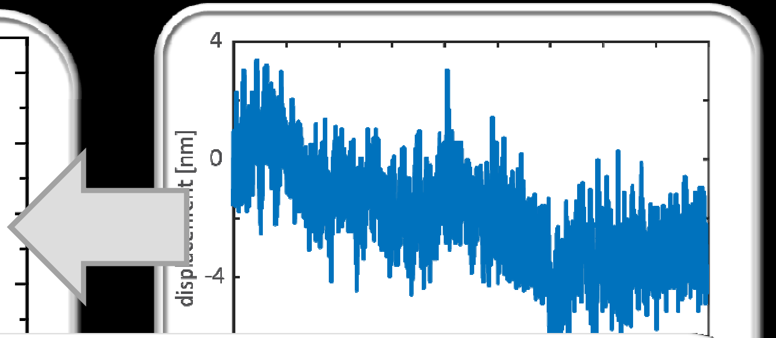
- 10-100 above off-res. thermal no

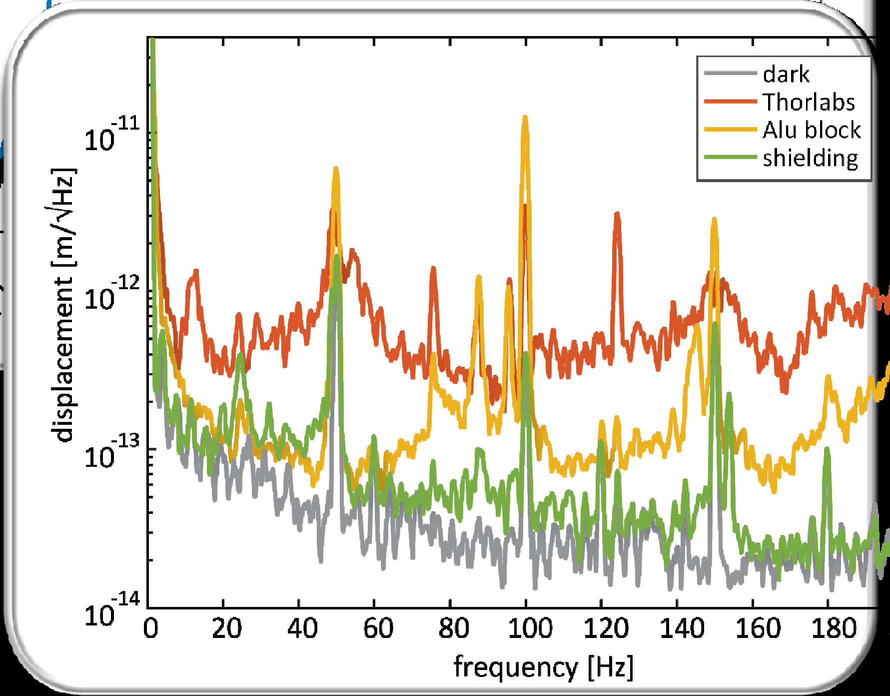


Interferometer: current status









Limit:

- Almost @ detector dark noise
- Power & other lines
- Improved detector under way

Detector development

Original: didn’t work

- Don’t know why

Next one (2): didn’t work

- Lets say, design flaws…

Then (3): didn’t work

- Too integrated (complicated)

After (4): didn’t work

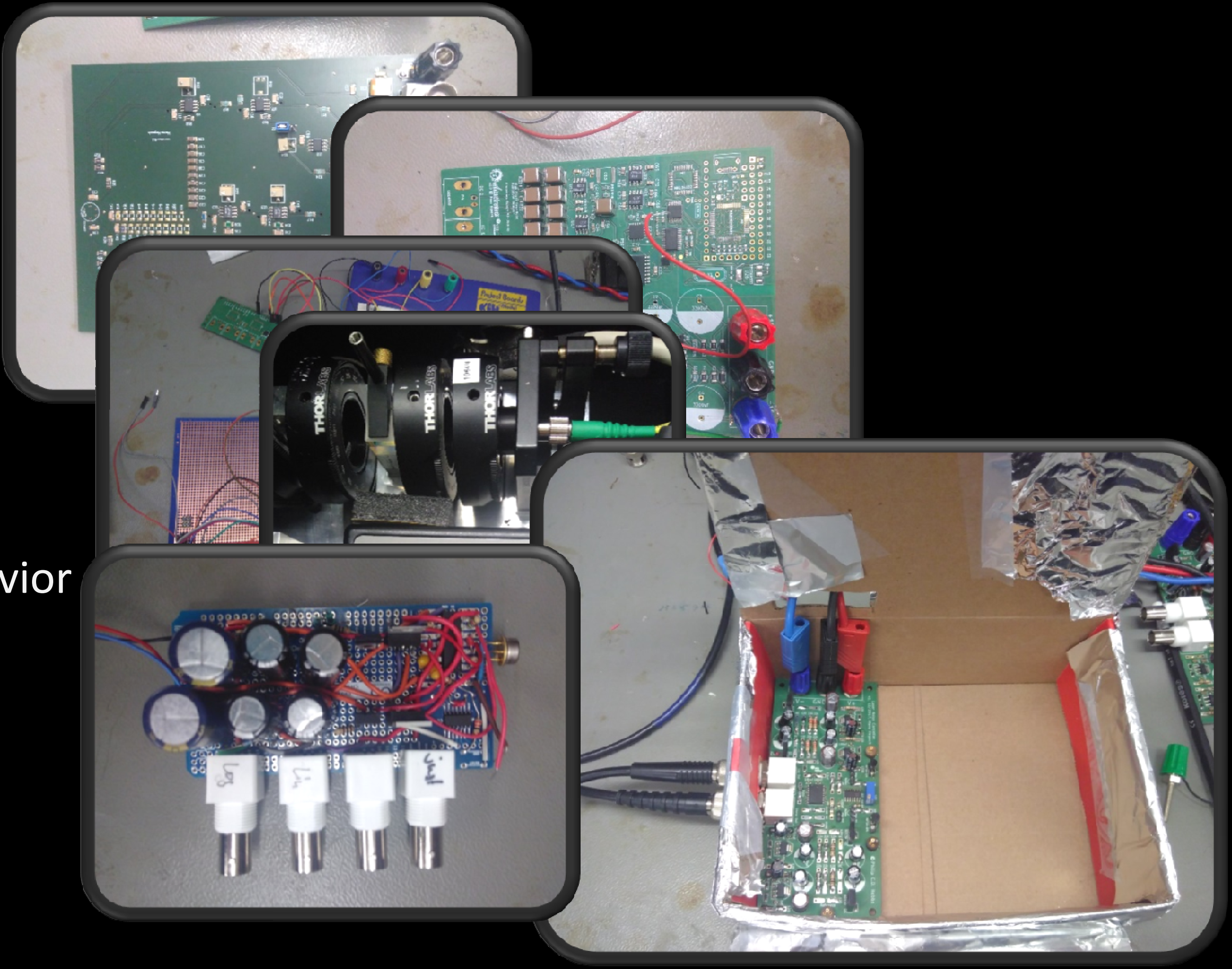
- Less integrated, more odd behavior

Workaround:

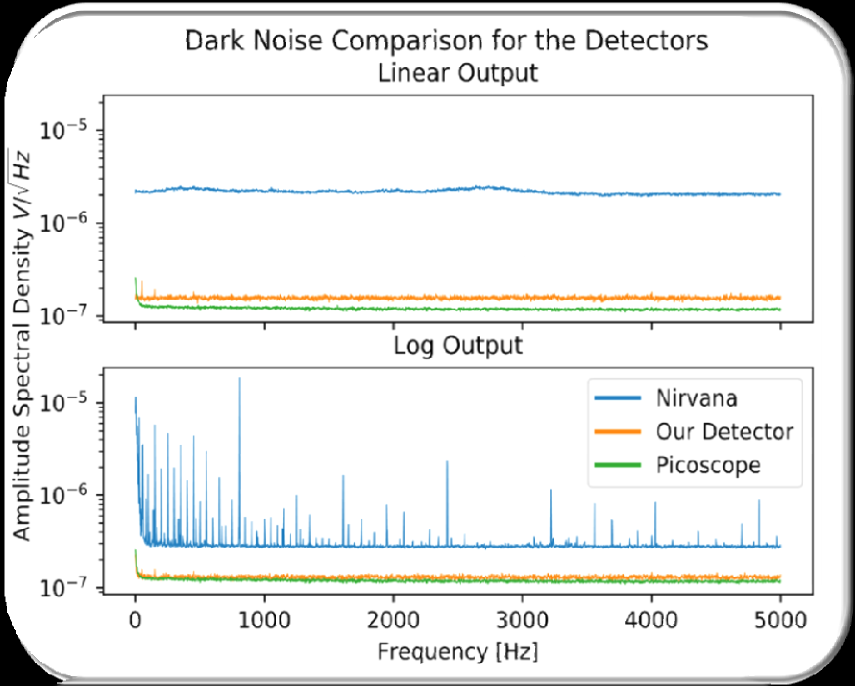
- Bad noise but works :o)

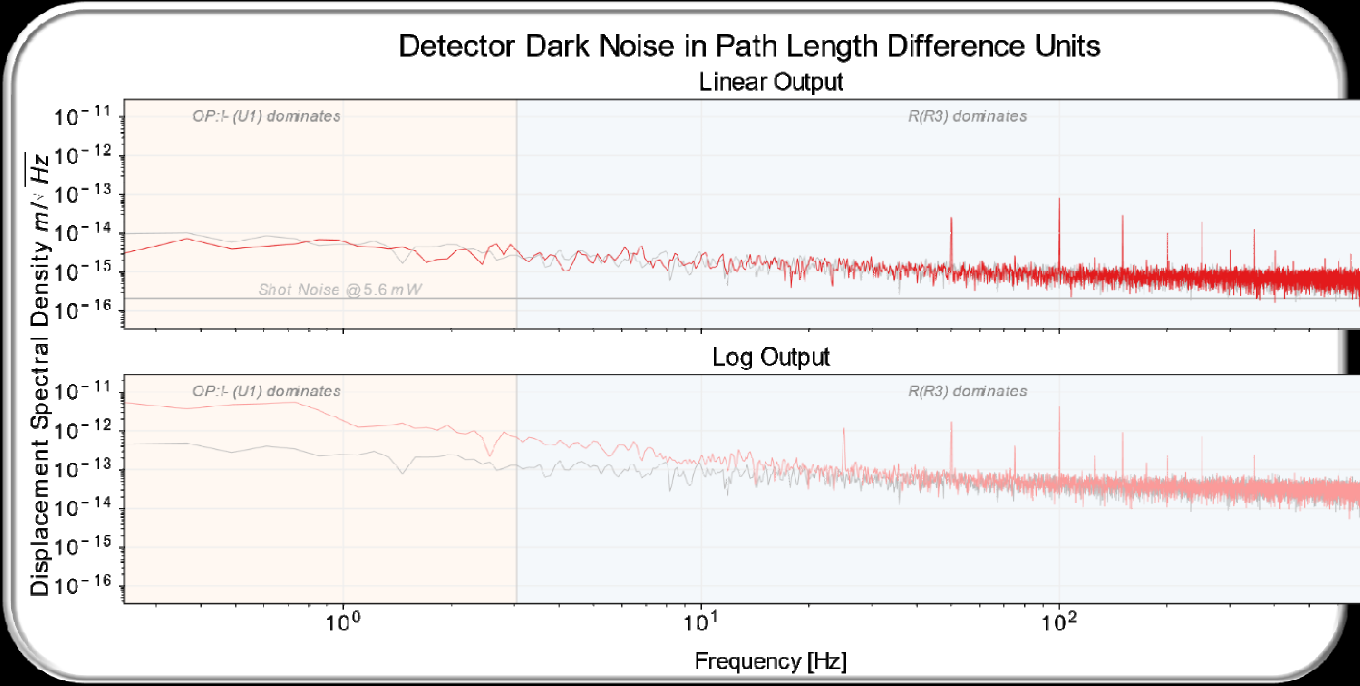
Now (5): work in progress

- Stolen design, blame others!



Detector improvements (dark century)





tered power supply

- Minimizes DC noise
- Reduces power lines

Integrated design

- quad layer board
  → (Almost) uninterrupted ground layer
- Onboard 24bit ADC

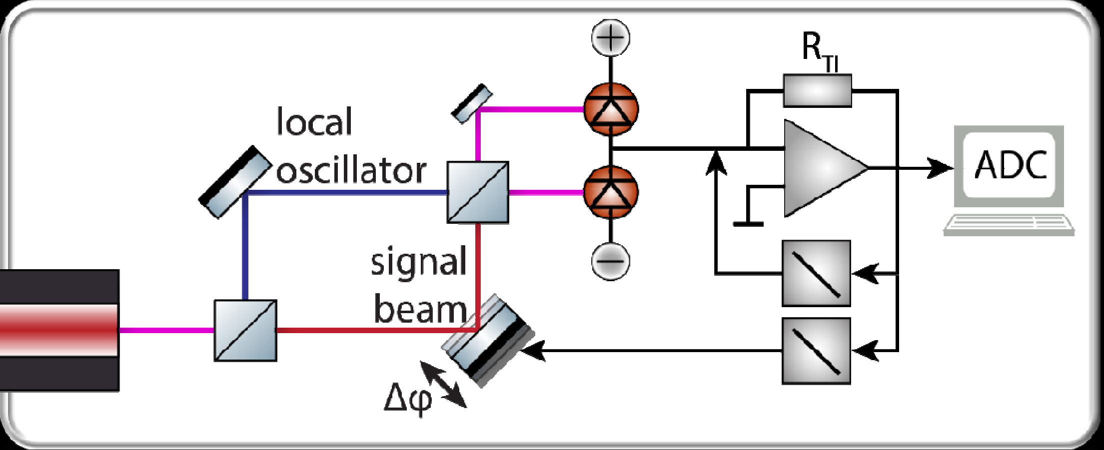
Detector balancing

alibration

- Typically DC fringe scan

easurement

- AC (tens of Hz), shot noise limited

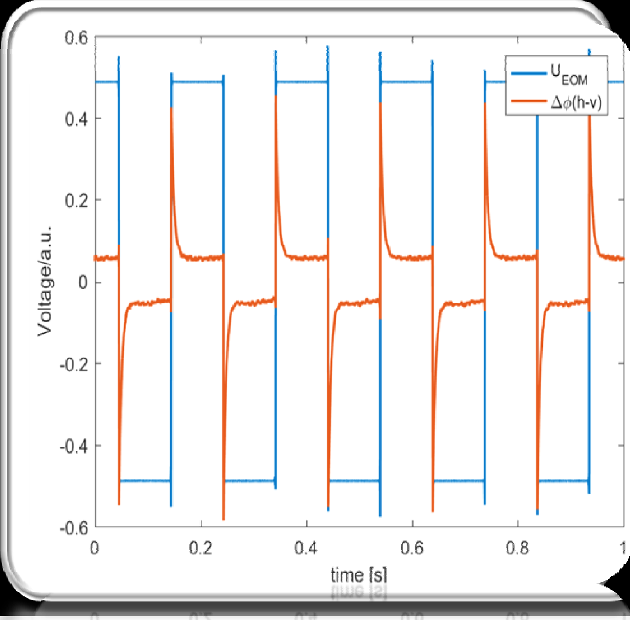


Challenge:

- Big dynamic range required
- Know your frequency response!

Feedback:

- Electronic: many unknowns
- Optical: more native
  - Temperature
  - EOM



Test mass oscillator evolution

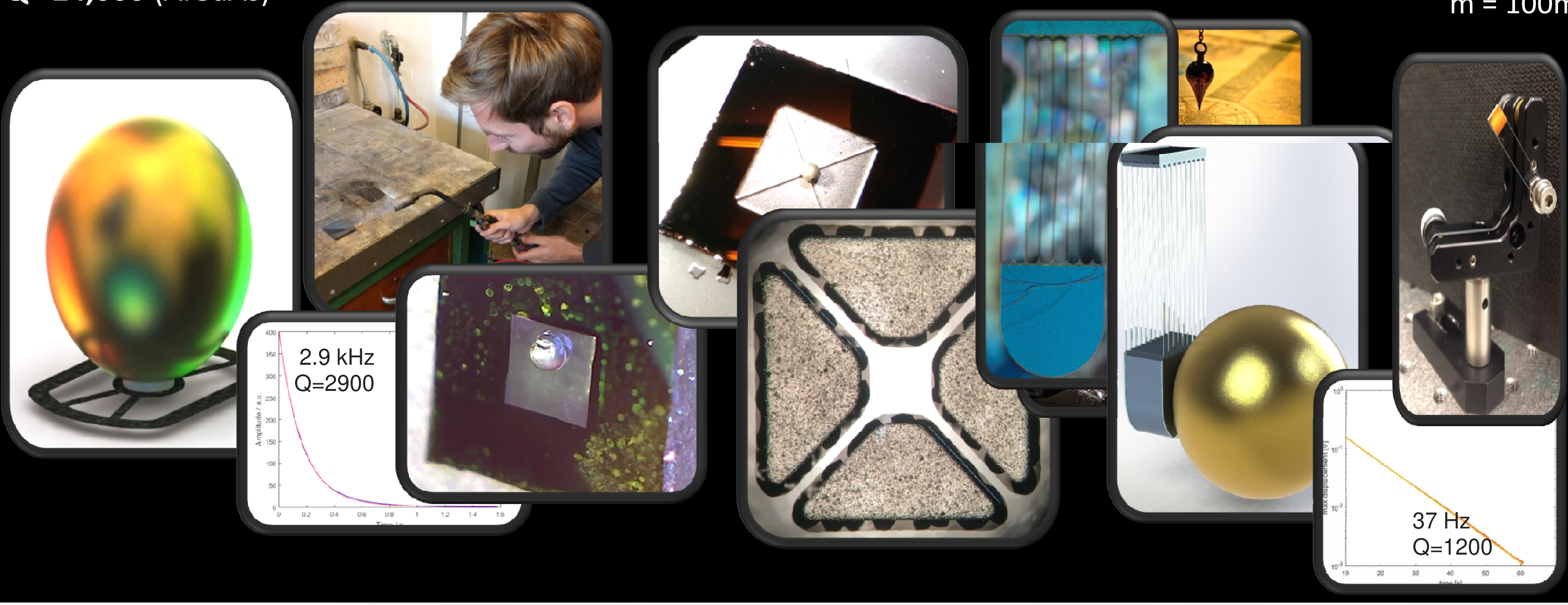
M simulation
- **2 mm** diameter (gold)
- **f_{res} = 50 Hz**
- **Q = 24,000** (AlGaAs)

- 1st DIY steps:
  - **bruteforce**
  - 1 mm sphere (lead) on SiN membrane

- 'Advanced':
  - **clean microfab**
  - 0.8 mm sphere (lead) on SiC/SiO² trampoline

- Going crazy:
  - **a micro-pendulum**
  - 300nm x 20um SiN tethers

- Workaround
  - **Optical re**
  - Steel wire
  - f_0 = 37Hz m = 100m



Recipe for low-f micro-mech. oscillators

Waver coated with high-Q material
- SiN, SiC, SiO^2 on Si; AlGaAs on GaAs

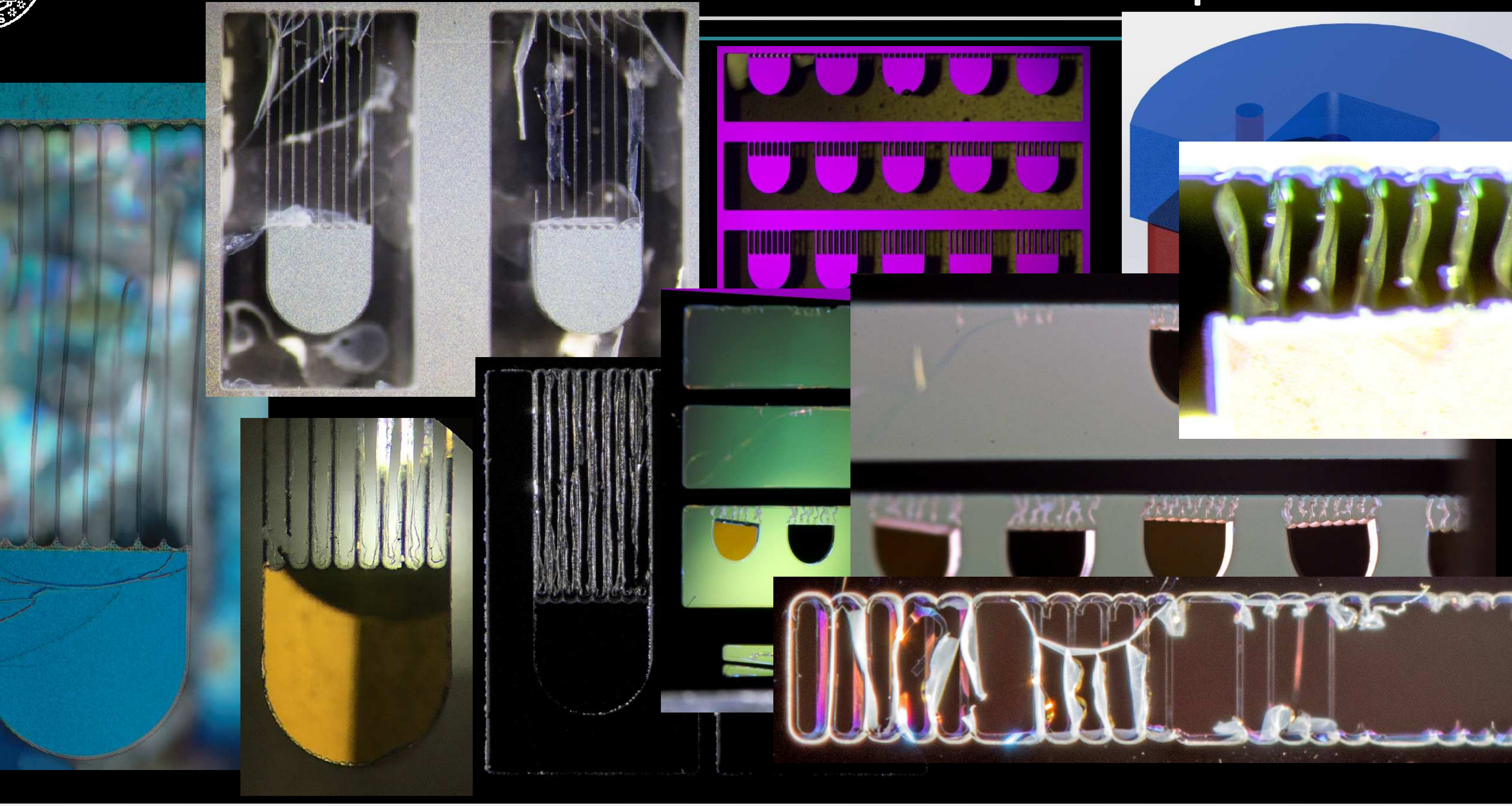
Write 2D-structure in mask
- e-beam

1D-etch
- deep reactive ion etch (DRIE)

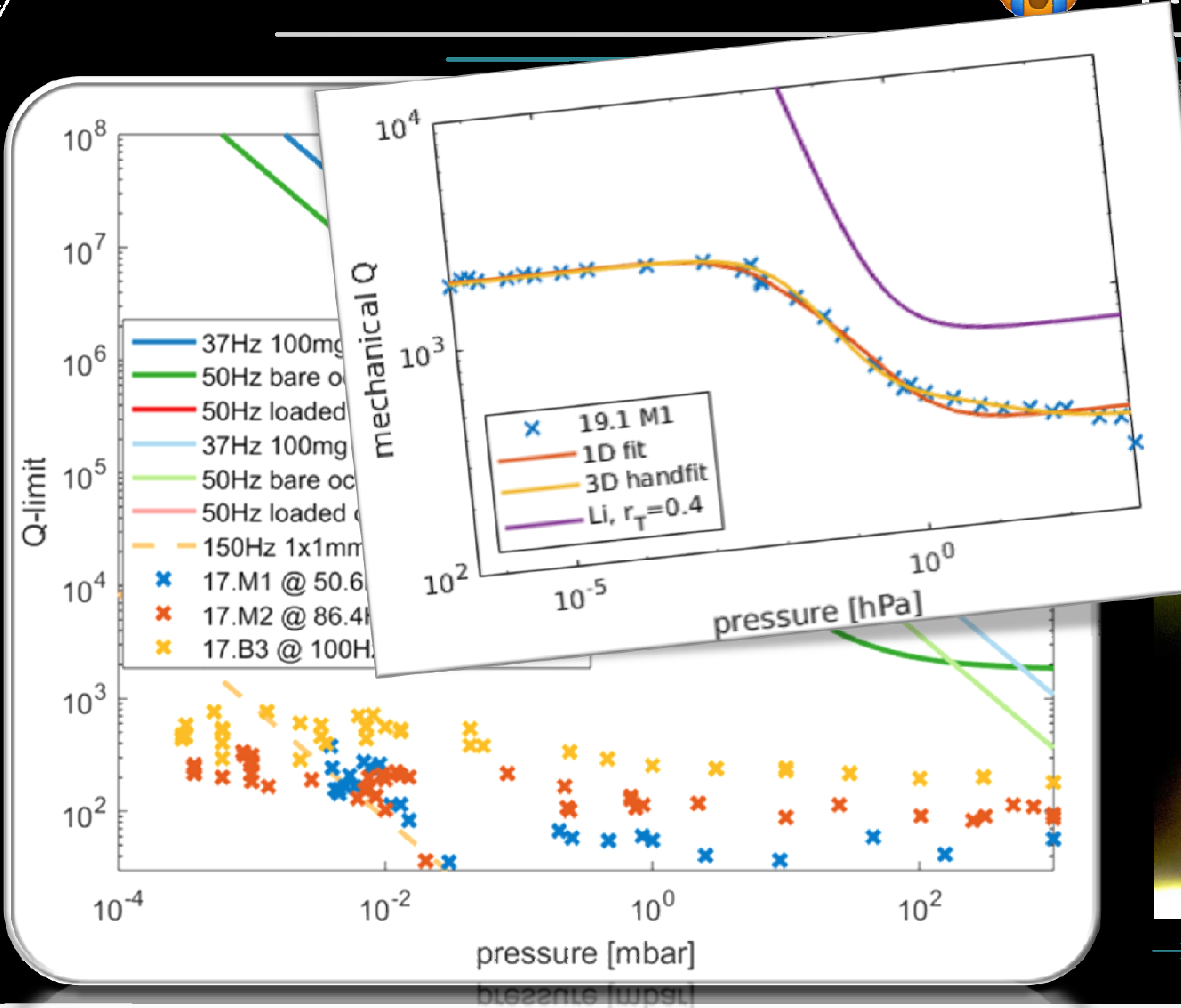
Mass-loading

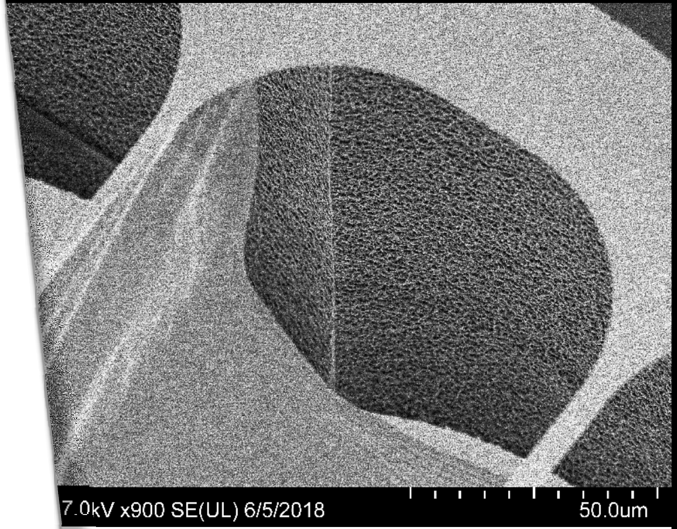
3D-etch waver selectively - release
- XeF^2 dry etch

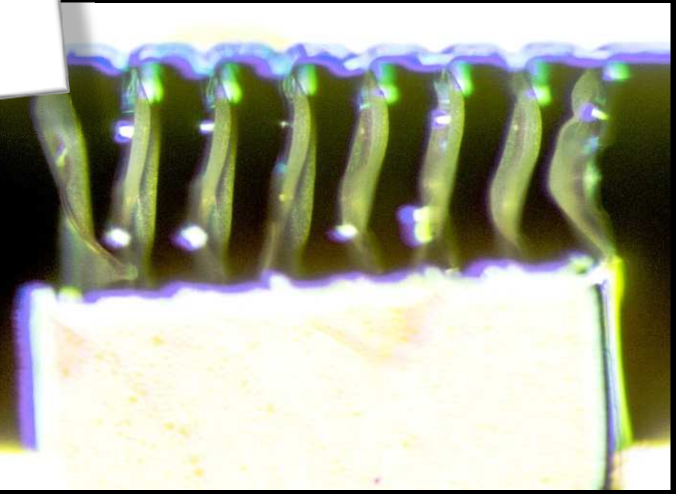
Test mass oscillator pictures



😭 Recent Q-values

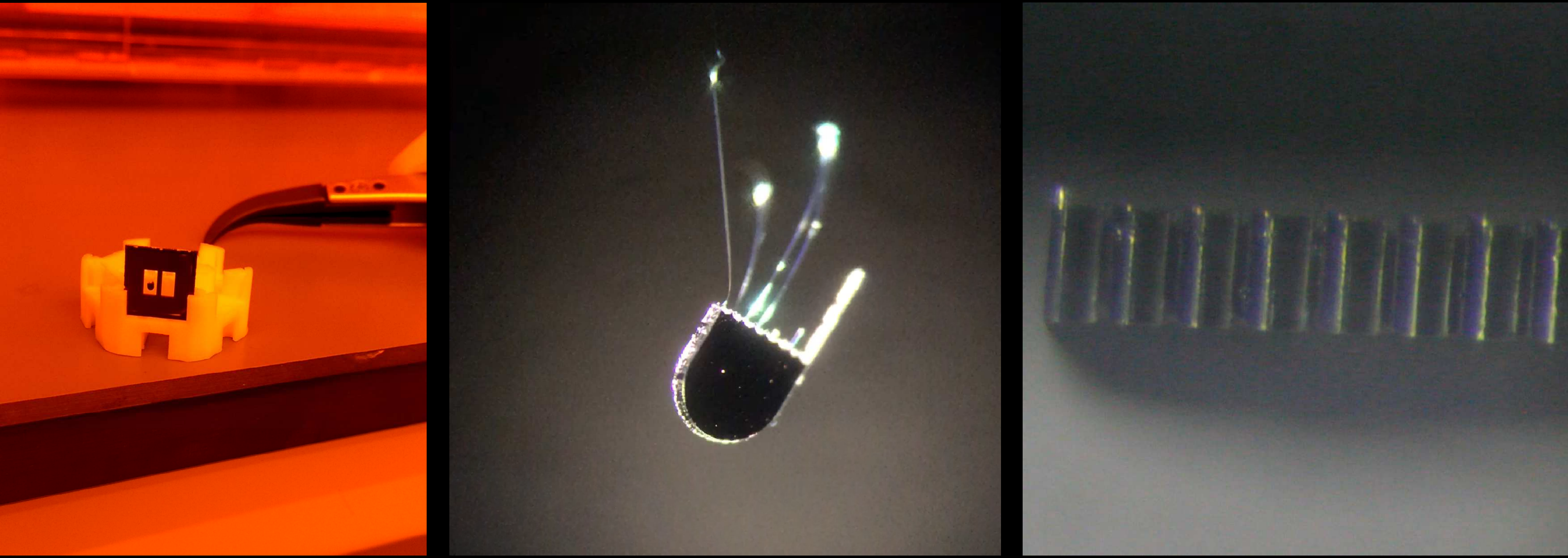






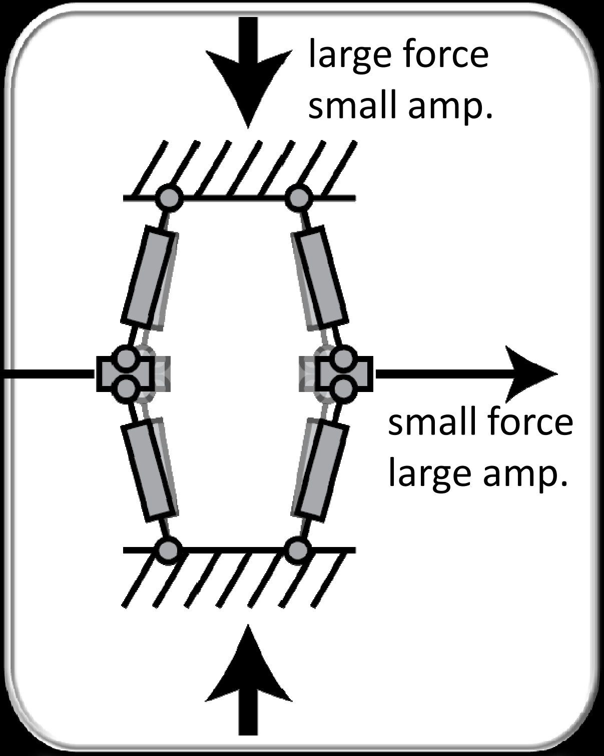
→ waste (SiO²) between tethers

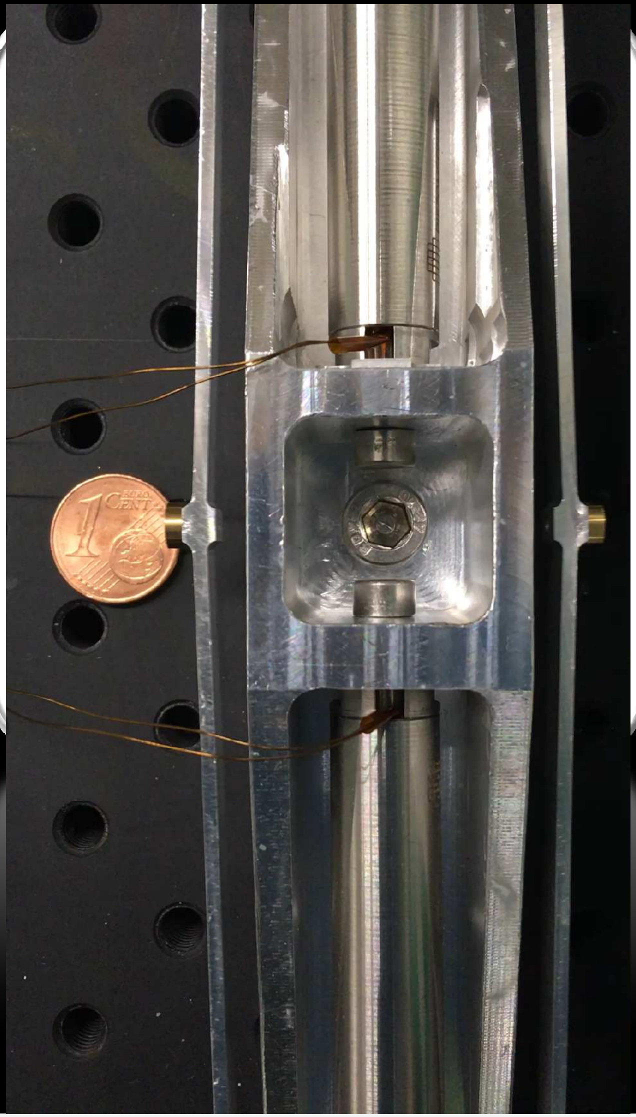
Test mass oscillator videos



Source mass motor

- Ideal drive amplitude
  - 1.25mm at 50Hz (acceleration =25g)
- Minimize COM motion (recoil)
- Plunger reduces motor coupling





Design

- Long range piezo (100um)
- Mechanical amplifier (x10)
- Multiple frequencies
  - → an-harmonic Disp.
  - → harmonic Force

Tests

- DC range: passed
- Fatigue test: passed
- Thermal test: passed
- Frequency response: promi
- 2^{nd} generation (UHV): TBD

Mechanical AWG

- 0-100/200Hz

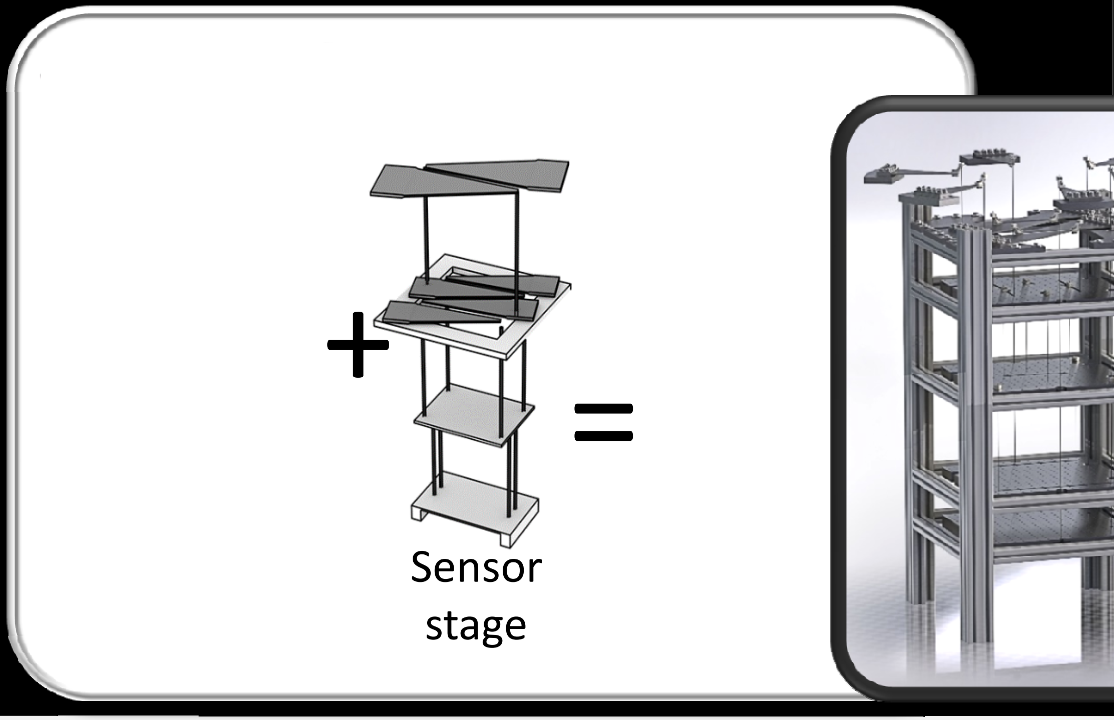
Vibration isolation

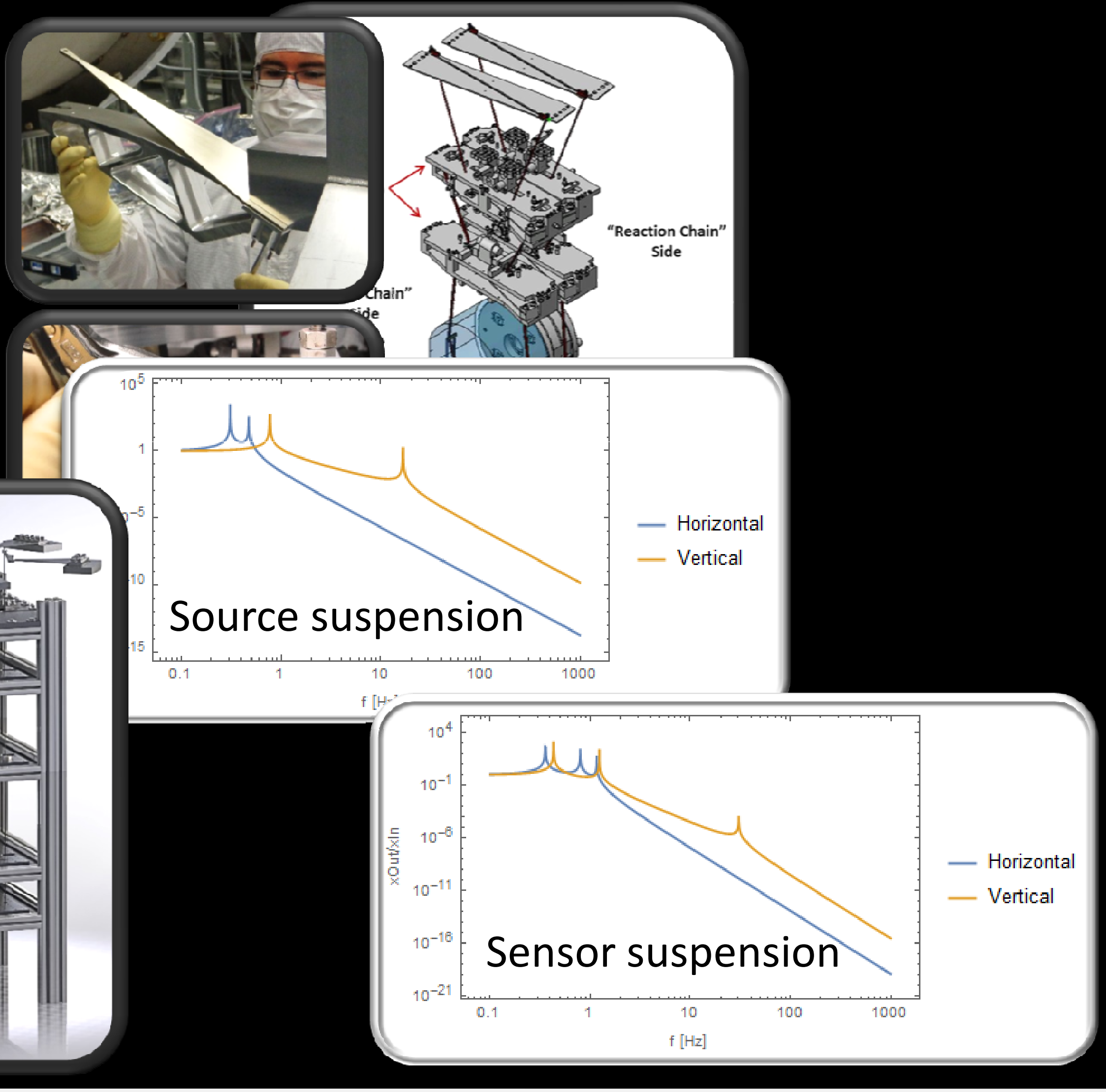
- Minimal environmental isolation

$$T_{\mathrm{E}}(\omega) < \left(\frac{2k_BT}{Qm\omega_0^3}\right)^{1/2} S_{x_{\mathrm{E}}x_{\mathrm{E}}}^{-1/2} \approx 10^{-7},$$

- Minimal isolation from source

$$T_{\mathrm{S}}(\omega_{\mathrm{S}}) < 2\left(\frac{k_BT\Gamma}{\pi Qm\omega_0^3}\right)^{1/2} d_{\mathrm{S}}^{-1} \approx 10^{-13}.$$





New lab → milli-G 2.0

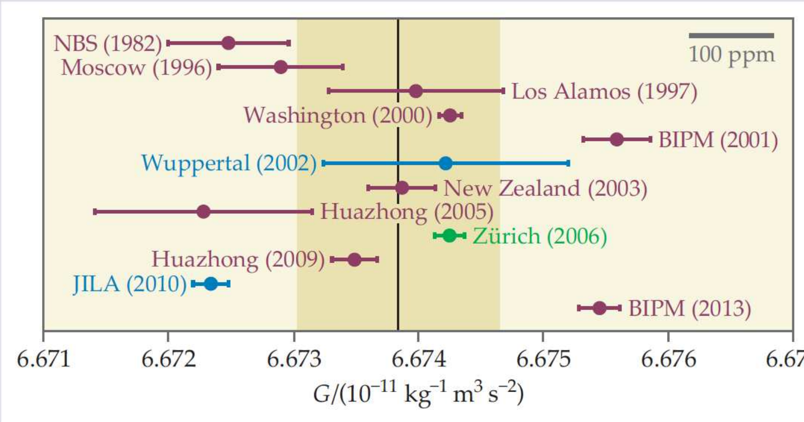
Vacuum system

- 0.7x1.5m, Viton, diff. pumping
- 1E-8mbar
- No baking → test UV-desorption
- Testing at manufacturer

Summary & outlook

- Gravitational field of 2 mm gold sphere is detectable
  - With current technology
  - At room temperature
  - Beating current source mass record by 10^3

- Two paths for the future:
  - Increase mass
  - → perform actual precision measurements of gravity
    - G
    - non-Newtonian forces
  - Decrease mass and/or go cryogenic
    - Investigate gravitational interaction of ***massive quantum things*** (long term)
    - Levitated nanospheres?

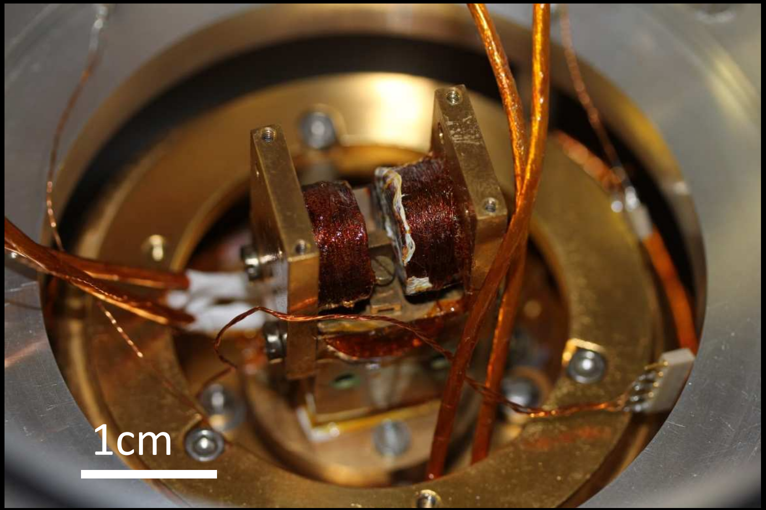


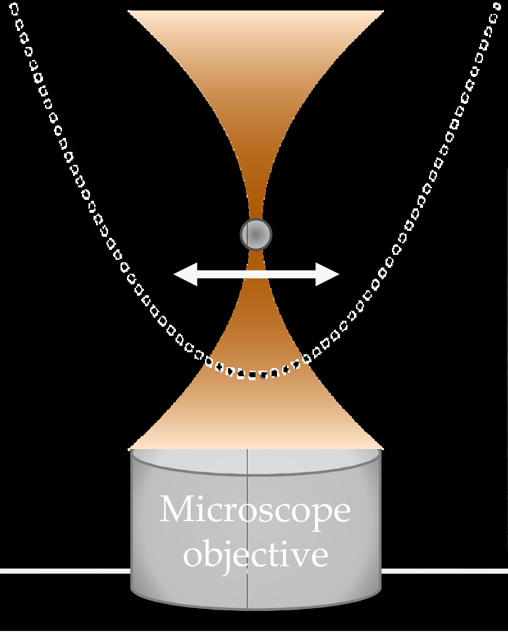
Physics Today July 2014

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.)

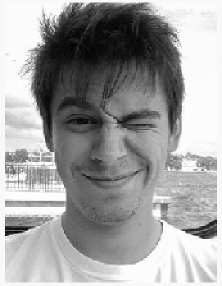
Levitated stuff @ Aspelmeyer labs

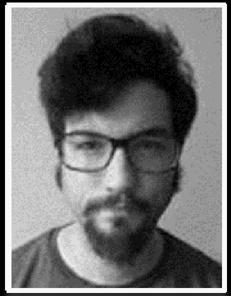
- Source mass and or test mass
- Eliminate dissipation arising from soft support
- Magnetically
  - \+ High density
  - \+ High mass
  - – Induced fields
- Optically
  - \+ High Q
  - – Low density
  - – Low mass





Team, support & funding


Mathias Dragosits


Jeremias Pfaff


Hans Hepach


Tobias Westphal


Markus Aspelmeyer


Jonas Schmoele


Claus Gärtner


Richard Norte


Simon Gröblacher

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SEVENTH FRAMEWO
PROGRAMME

CoQuS
ComplexQuantumSystems

VCQ
Vienna Center for Quantum Science and Technology

FWF
Der Wissenschaftsfonds.

Leibniz Universität Hannover

TUDelft

University of Virginia

Schmöle PhD thesis (2017)

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

componentlibrary version three
by alexander franzen 2k+6

Interferometer isolation

Thermal isolation

- Styrodur
- Huge improvement in drift

Acoustic isolation

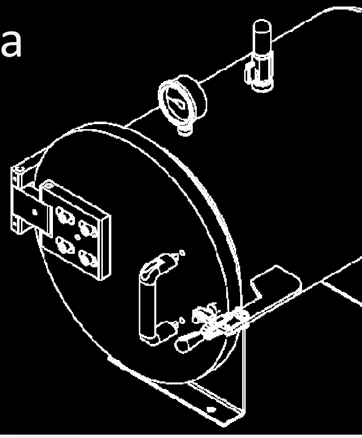
- Computer silencing
- No obvious spectral improvement
- But you can talk now :-)

Seismic isolation

- Minus-k
- No significant improvement (ye

Vacuum

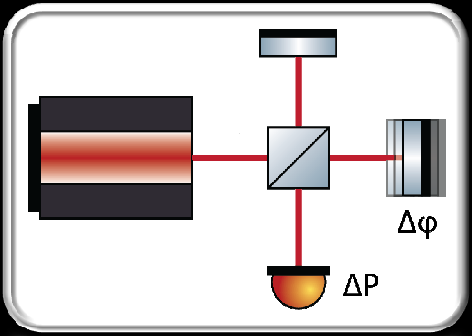
- Compatible with minus-k
- Approx. 10^{-4}hPa



Measuring ring-downs

ptical lever
- Easy/fast
- Low sensitivity
- High amplitudes → nonlinear damping?
- Relies on long. → pitch coupling
- Or have to use multiple optical levers

- Interferometrically
  - High sensitivity
  - Requires quiet conditions
  - Limited range



Ifo in/out relation: highly nonlinear!