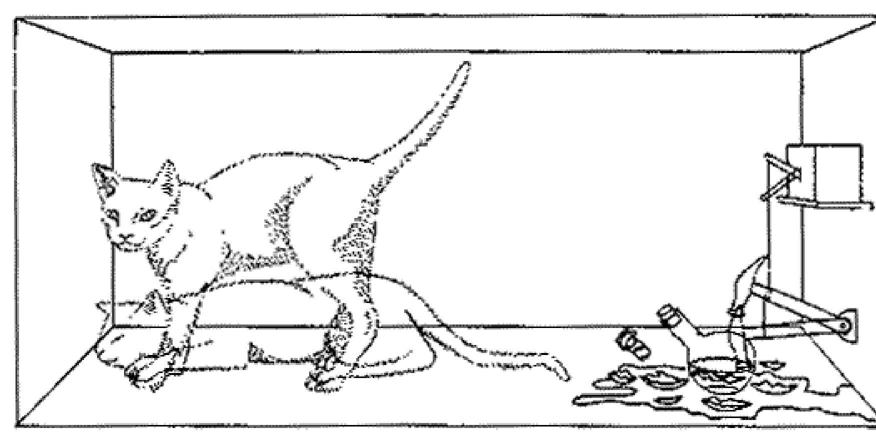
VCQ Vienna Center for Quantum Science and Technology

Emergent quantum technology for testing the foundations of physics in space

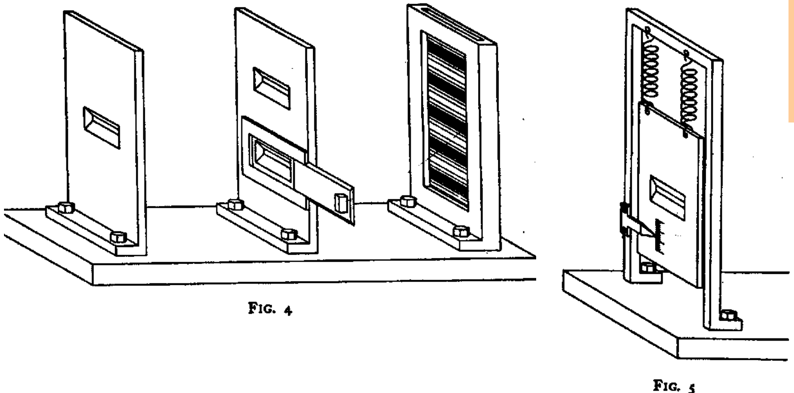
Rainer Kaltenbaek*

*Aspelmeyer group
Vienna Center for Quantum Science and Technology
Faculty of Physics, University of Vienna, Austria



Quantum superposition

Which slit does each particle "really" go through?



From J. D. Norton, Universtiy of Pittsburgh

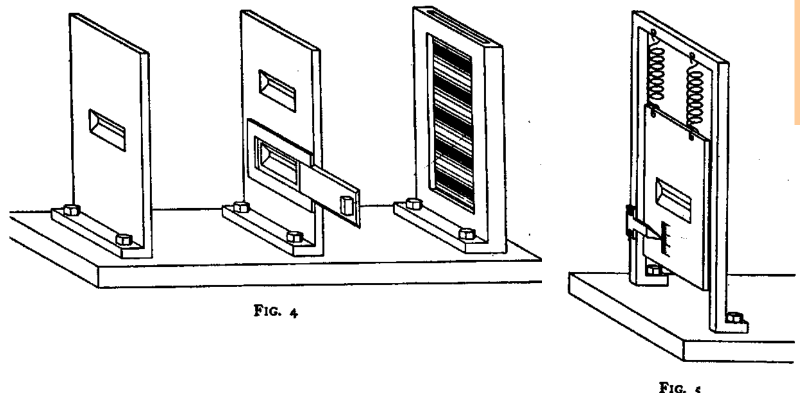
A particle **does not** pass either through one slit or the other

The path of a particle is **not real**.

Quantum superposition

Vienna Center for Quantum Science and Technology

Which slit does each particle “really” go through?

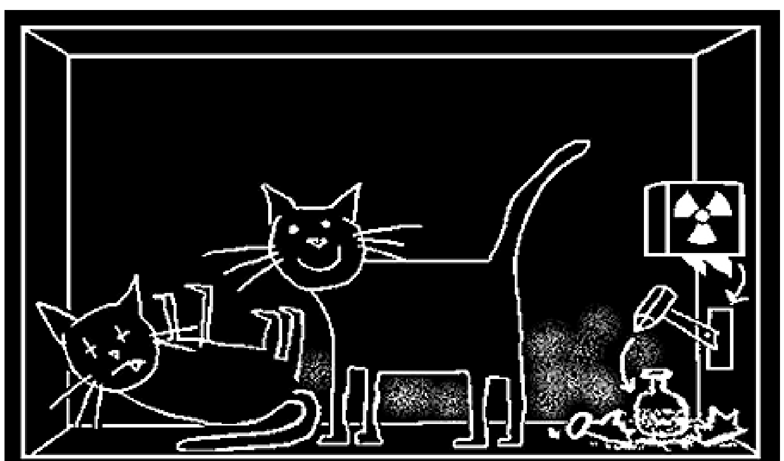


From J. D. Norton, Universtiy of Pittsburgh

A particle **does not** pass either through one slit or the other

The path of a particle is **not real**.

Does that hold true for massive objects?



Does Quantum Mechanics fail for large/massive systems?

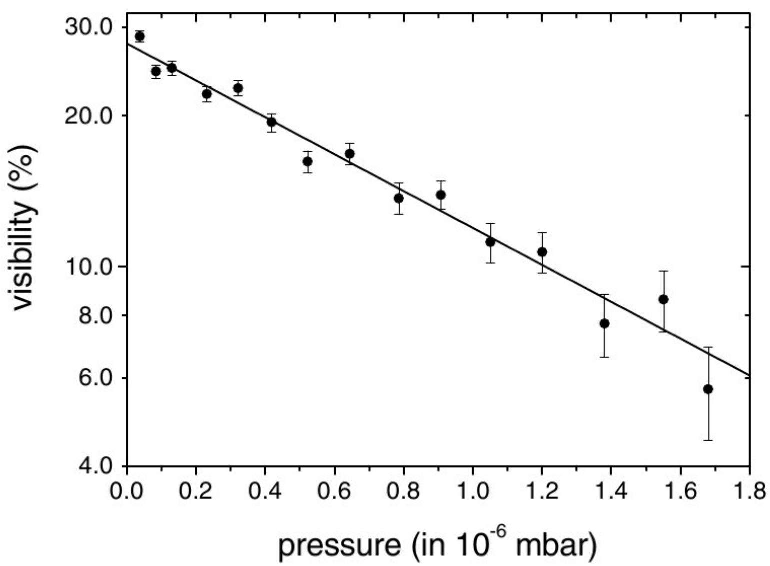
When do things Become “real”?

The quantum answer

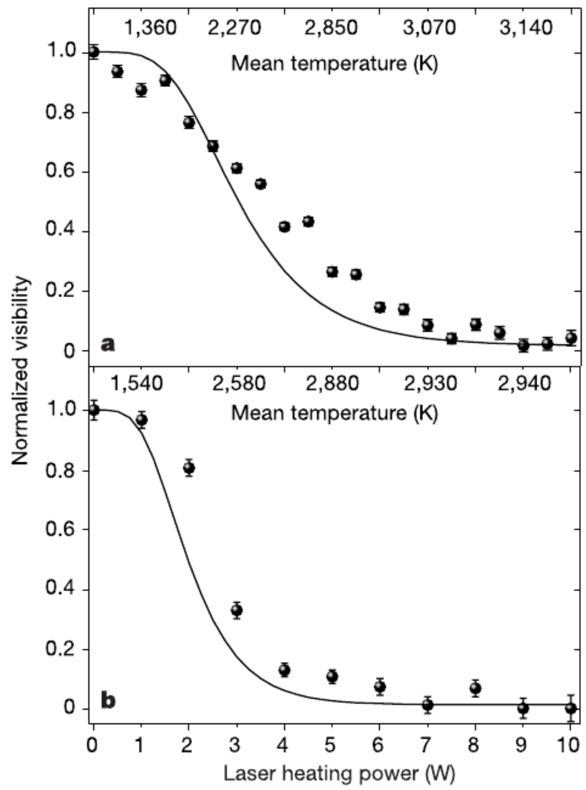
- Interference if there is no which-way information
- **BUT:** the larger the system the harder it is to isolate

Coupling to environment:

- Collisions with gas molecules
- Scattering of blackbody radiation
- Absorption/Emission of blackbody radiation
- …



L. Hackermüller et al., Appl. Phys. B **77**, 781 (2003)



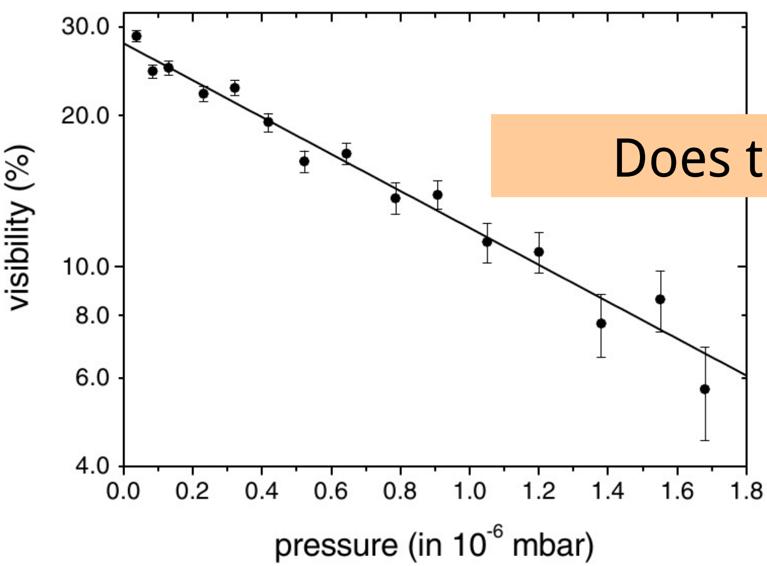
L. Hackermüller et al., Nature **427**, 711 (2004)

The quantum answer

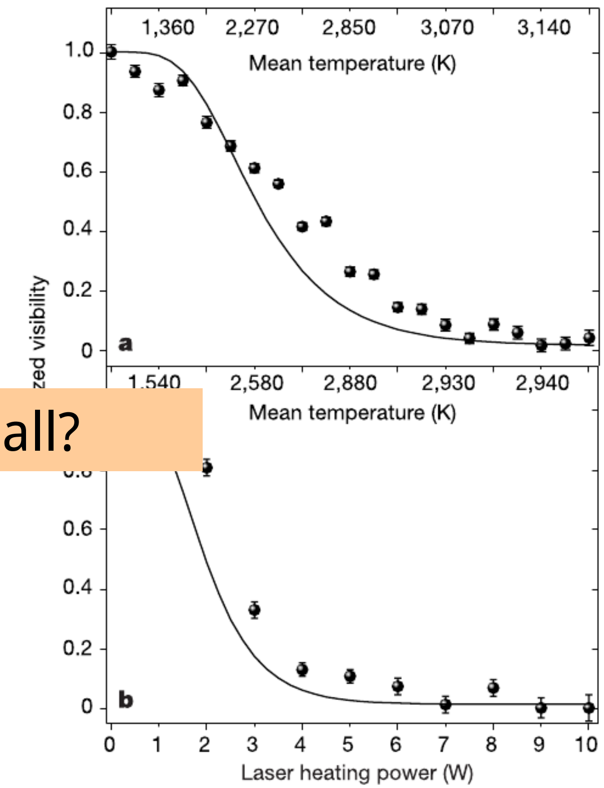
- Interference if there is no which-way information
- **BUT:** the larger the system the harder it is to isolate

Coupling to environment:

- Collisions with gas molecules
- Scattering of blackbody radiation
- Absorption/Emission of blackbody radiation
- …



L. Hackermüller et al., Appl. Phys. B **77**, 781 (2003)



Does that explain it all?

L. Hackermüller et al., Nature **427**, 711 (2004)

Macrorealism

- Inherent transition from quantum to classical
- NO Schrödinger Cats
- Modification of Schrödinger equation

  -> decoherence even for isolated systems

Physical reasons for the “collapse”:

- F. Károlyházy, Nuovo Cimento A 52, 390 (1966)
- L. Diósi, PRA 105, 199 (1984)
- R. Penrose, e.g., Gen. Rel. Grav. 28, 581 (1996)
- Ghirardi, Rimini & Weber, PRD 34, 470 (1986)
- Continuous spontaneous localization, Ghirardi, Pearle & Rimini, PRA 42, 78 (1990)
- Ellis, Mohanty, Nanopoulos, Phys. Lett. B 221, 113 (1989)
- …

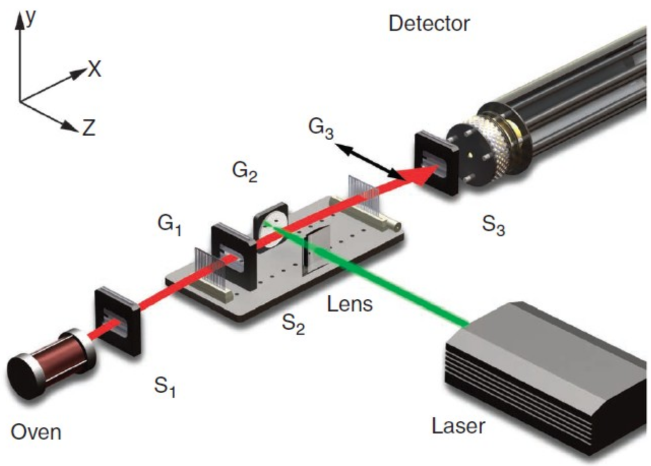
Wait a moment…

why is that interesting again?

the point is

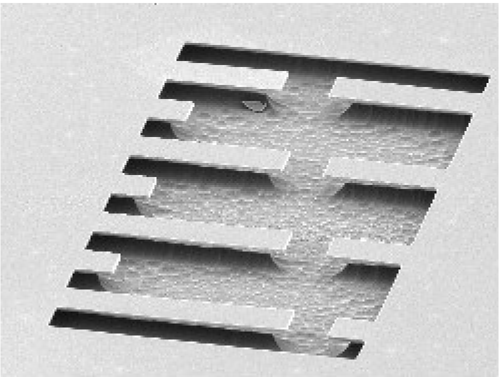
is there more than quantum physics? Gravity?

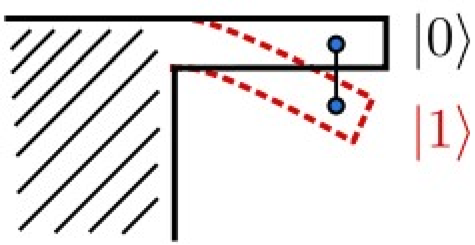
Matter-wave interferometry



S. Gerlich et al., Nature Comm. **2**, 263 (2011)

Quantum Optomechanics

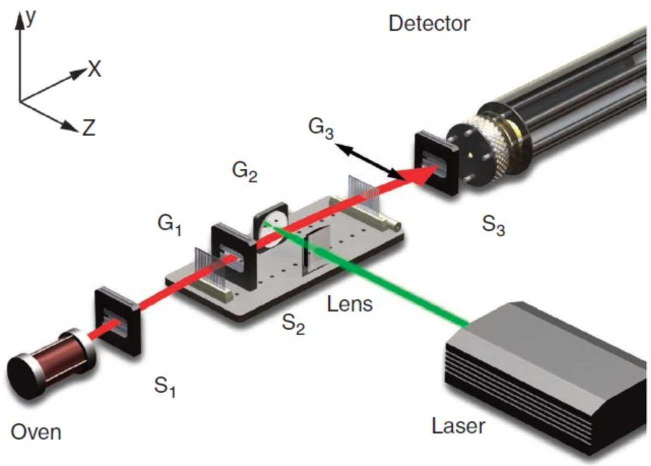




G. D. Cole et al., Appl. Phys. Lett. 92, 261108 (2008)

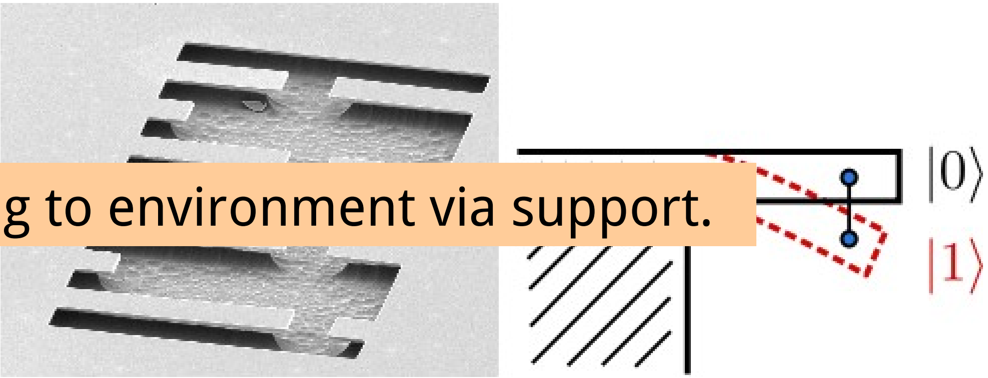
Can we test that experimentally?

Matter-wave interferometry



S. Gerlich et al., Nature Comm. **2**, 263 (2011)

Quantum Optomechanics



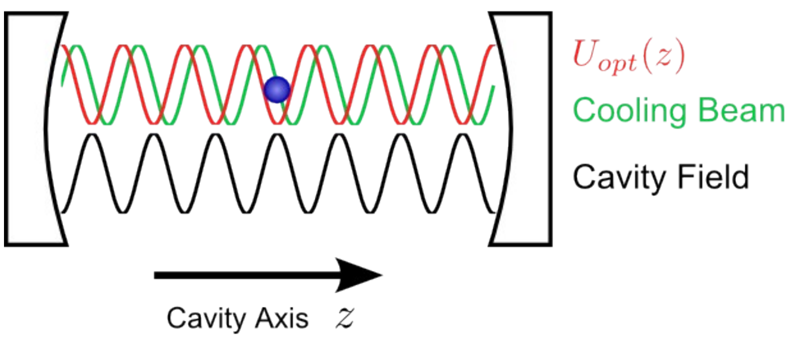
Disadvantage: coupling to environment via support.

G. D. Cole et al., Appl. Phys. Lett. 92, 261108 (2008)

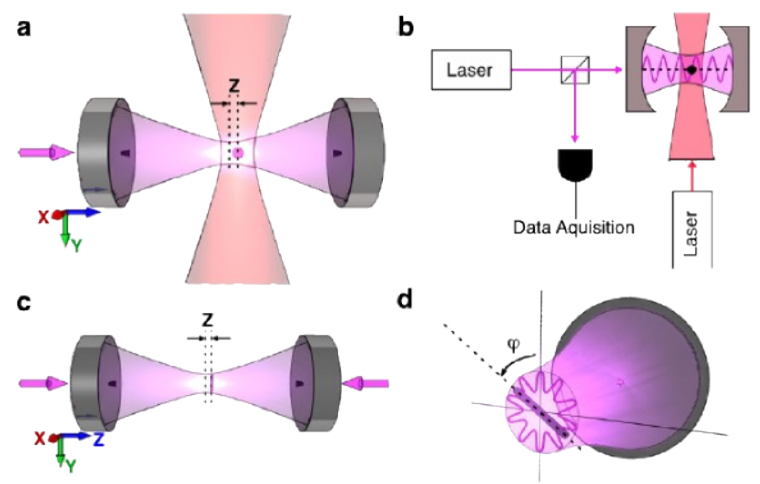
Optically trapped nanospheres

- optically trapped dielectric spheres
- combine optical-tweezer technology (A. Ashkin, PRL **24**, 147 (1970)) with optomechanics and atom-trapping toolbox

D. E. Chang et al., PNAS **107**, 1005 (2010)

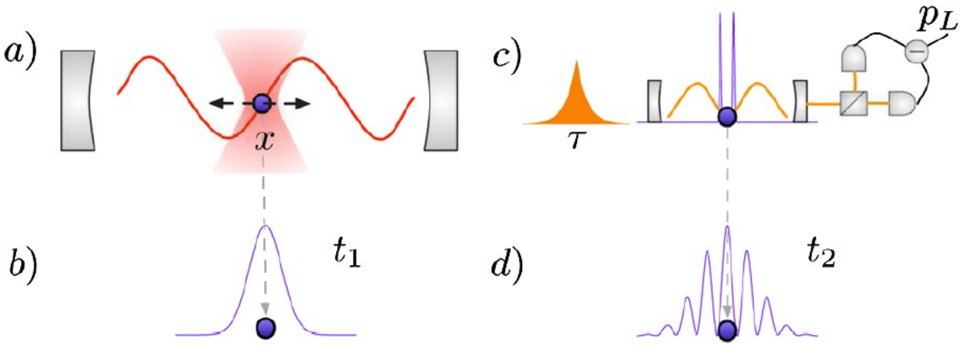


O. Romero-Isart et al., New J. Phys. **12**, 033015 (2010)
O. Romero-Isart et al., PRA **83**, 013803 (2011)

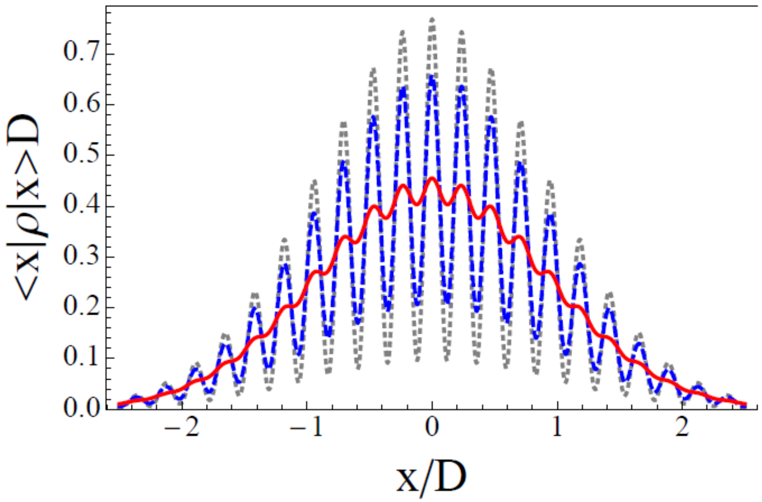


Double-slit with nanospheres

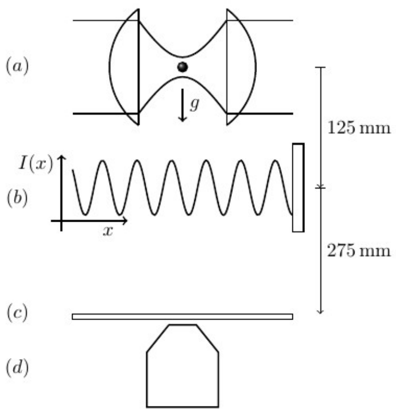
Ground-based experiments

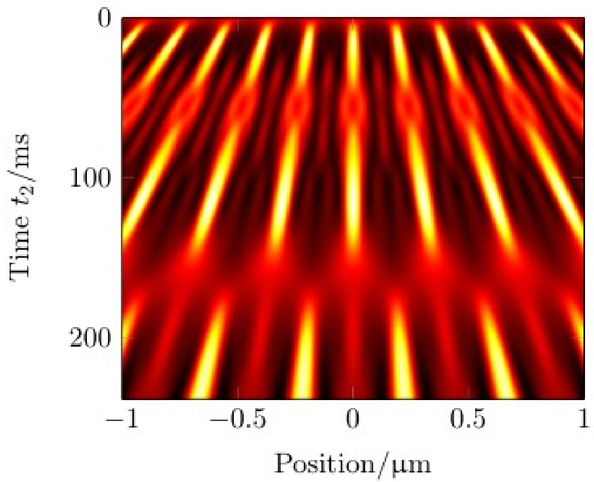


O. Romero-Isart , A. Pflanzer et al., PRL **107**, 020405 (2011)



O. Romero-Isart, PRA **84**, 052121 (2011)

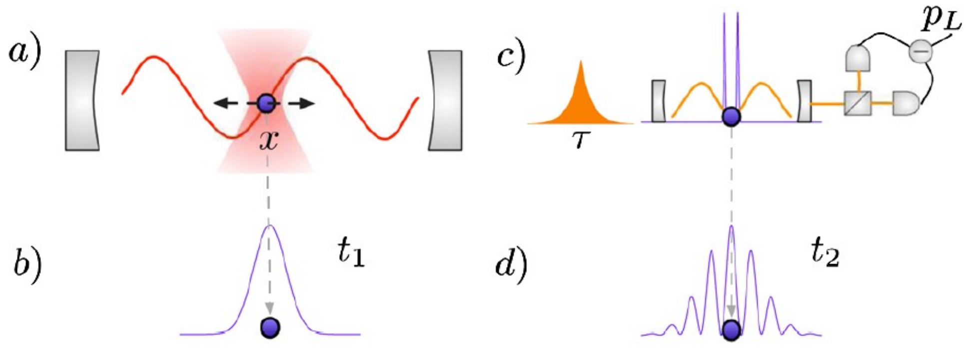




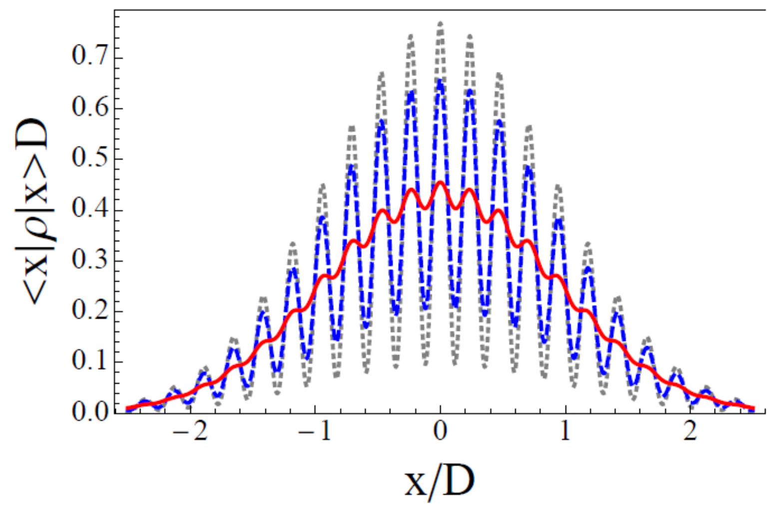
J. Bateman, S. Nimmrichter, K. Hornberger, H. Ulbricht
quant-ph/arXiv:1312.0500 (2013)

Double-slit with nanospheres

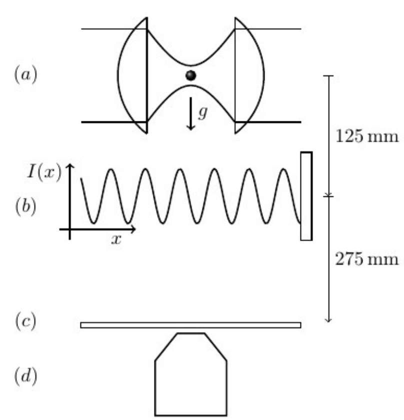
Ground-based experiments

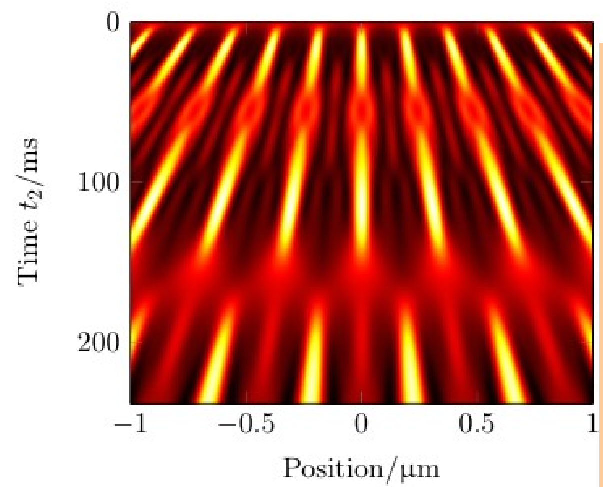


O. Romero-Isart , A. Pflanzer et al., PRL **107**, 020405 (2011)



O. Romero-Isart, PRA **84**, 052121 (2011)





J. Bateman, S. Nimmrichter, K. Hornberger, H. Ulbricht
quant-ph/arXiv:1312.0500 (2013)

Only good for testing Adler's CSL parameter

For other models:
→ need more massive particles
→ longer free-fall times
→ very good vacuum
→ cryogenic temperatures

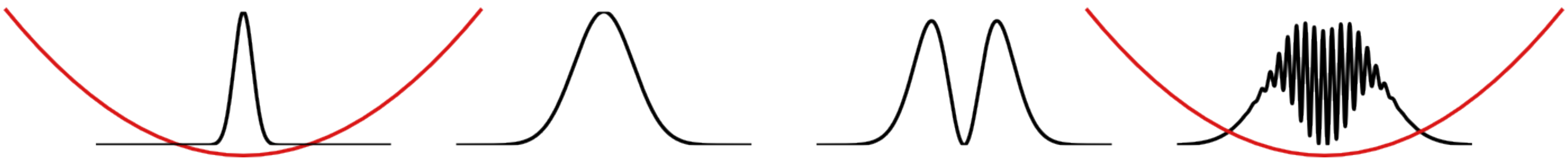
Vienna Center for Quantum Science and Technology

In other words…

do we need to go to space?

MAQRO – a double-slit experiment in space

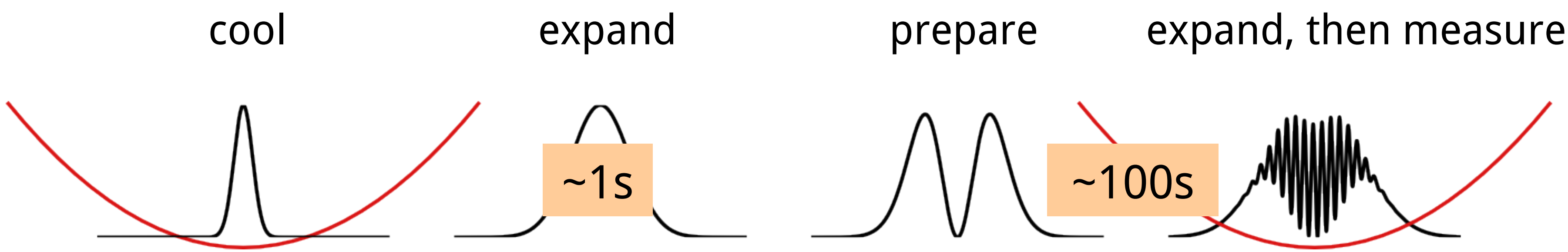
Perform double-slit experiment – **one particle at a time**



R. Kaltenbaek et al., Cosmic Vision proposal MAQRO (2010)
R. Kaltenbaek et al., Exp. Astronomy **34**, 123 (2012)

MAQRO – a double-slit experiment in space

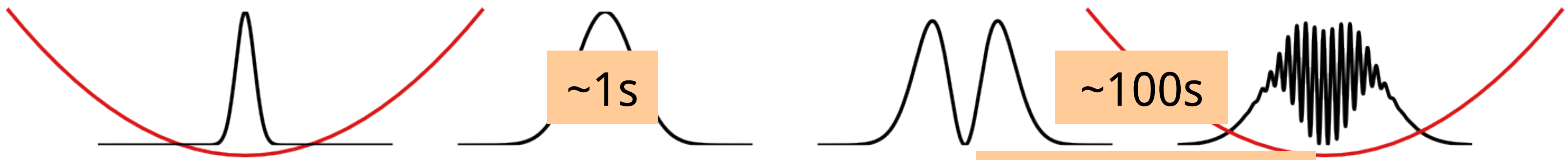
Perform double-slit experiment – **one particle at a time**



R. Kaltenbaek et al., Cosmic Vision proposal MAQRO (2010)
R. Kaltenbaek et al., Exp. Astronomy **34**, 123 (2012)

MAQRO – a double-slit experiment in space

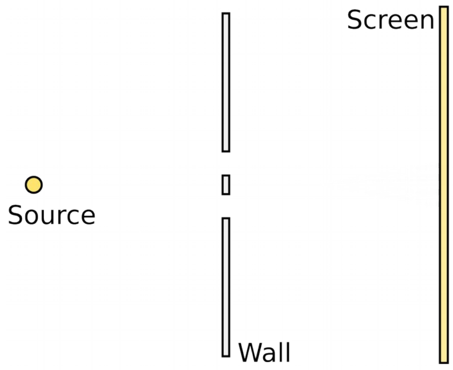
Perform double-slit experiment – **one particle at a time**



R. Kaltenbaek et al., Cosmic Vision proposal MAQRO (2010)
R. Kaltenbaek et al., Exp. Astronomy **34**, 123 (2012)

Very long coherence & free-fall times
→ need cryogenic & ultra-high-vacuum environment
→ need very good micro-gravity environment (no gradients, no vibrations, ...)

The double slit in MAQRO

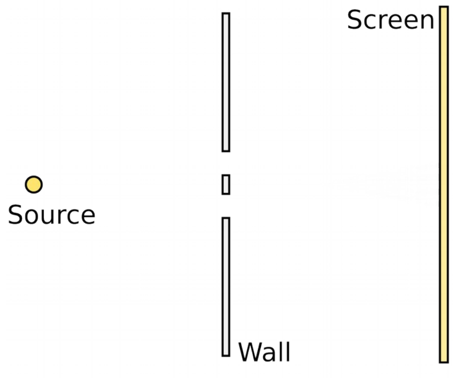


In space, our particle is always at the same spot

→ how do we prepare the quantum superposition?

→ local decoherence via a short, tightly focused UV pulse

The double slit in MAQRO



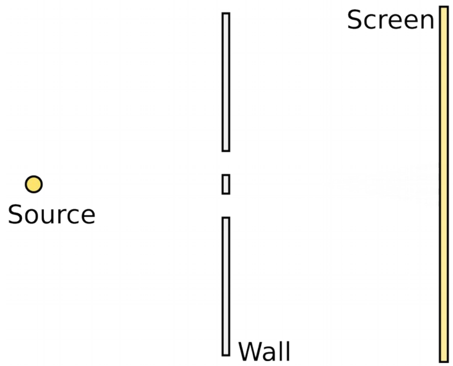
In space, our particle is always at the same spot

→ how do we prepare the quantum superposition?

→ local decoherence via a short, tightly focused UV pulse

1. Start well localized

The double slit in MAQRO

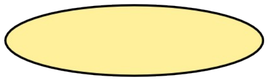


In space, our particle is always at the same spot

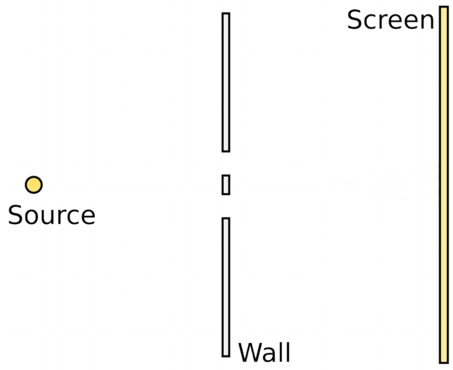
→ how do we prepare the quantum superposition?

→ local decoherence via a short, tightly focused UV pulse

1. Start well localized
2. Free expansion



The double slit in MAQRO

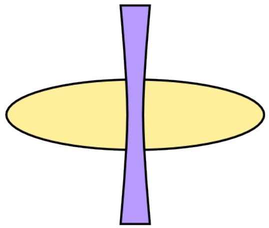


In space, our particle is always at the same spot

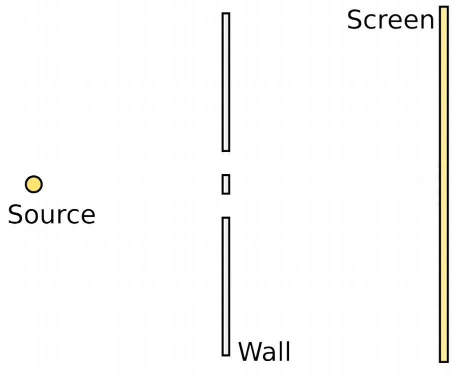
→ how do we prepare the quantum superposition?

→ local decoherence via a short, tightly focused UV pulse

1. Start well localized
2. Free expansion
3. Apply UV pulse



The double slit in MAQRO

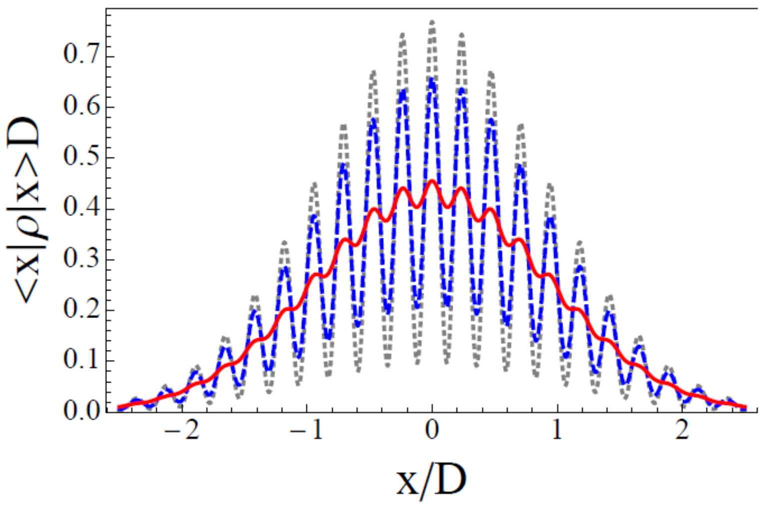


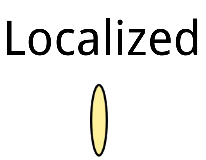
In space, our particle is always at the same spot

→ how do we prepare the quantum superposition?

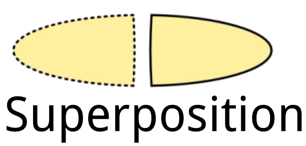
→ local decoherence via a short, tightly focused UV pulse

1. Start well localized
2. Free expansion
3. Apply UV pulse





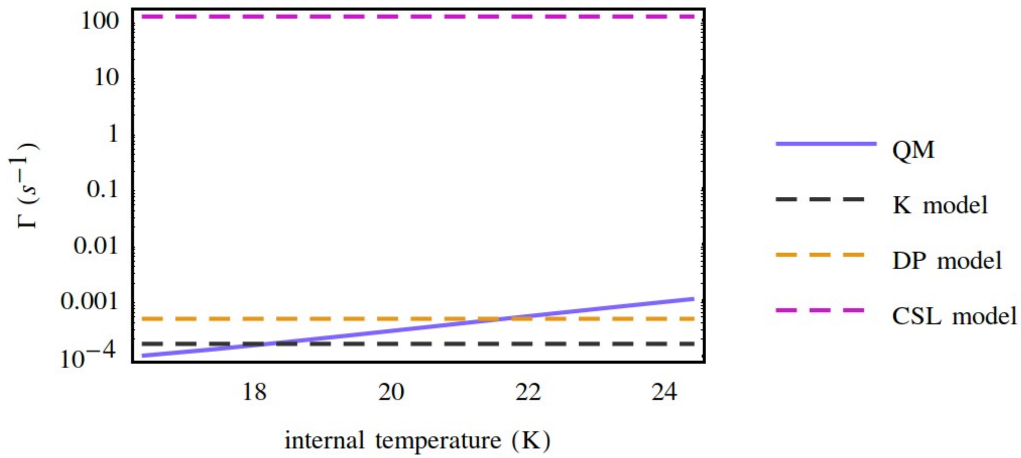
Incoherent mixture of two states



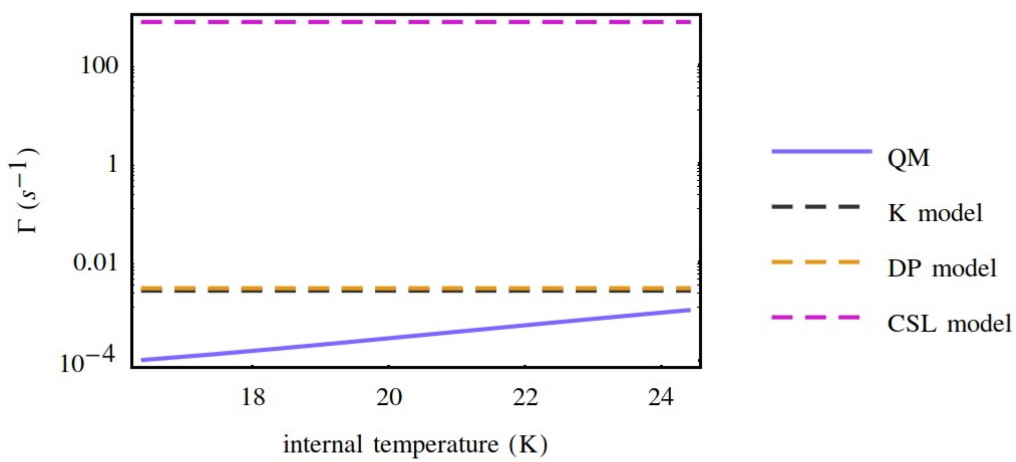
Theoretical estimates

- MAQRO requires low environment temperature $T \lesssim 16\,\mathrm{K}$
- **Very** good vacuum $p \lesssim 10^{-13}\,\mathrm{Pa}$
- Particle radius: $r \sim 100\,\mathrm{nm}$
- Requirements on internal temperature:

For fused silica spheres:



For heavier glass:

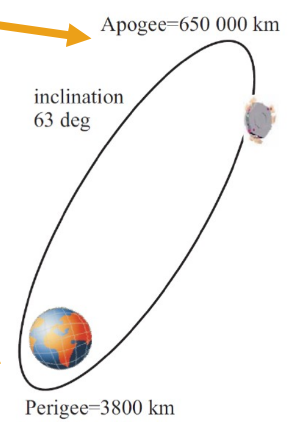


The MAQRO mission proposal

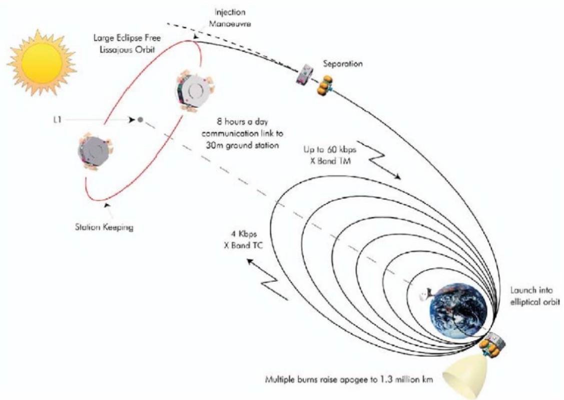
Considering possible orbits:

1. MAQRO
2. Other experiments

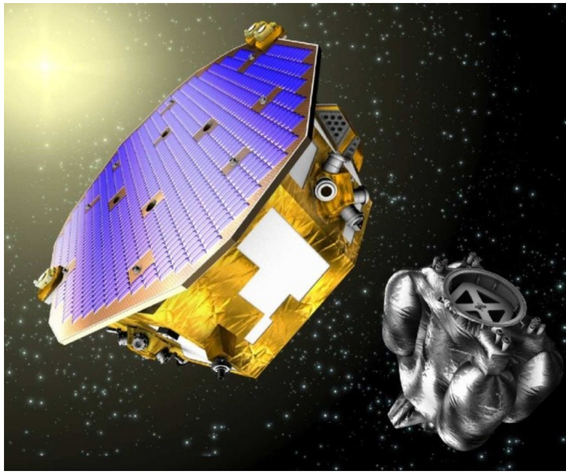
Highly eccentric orbit



L1- Lissajous orbit

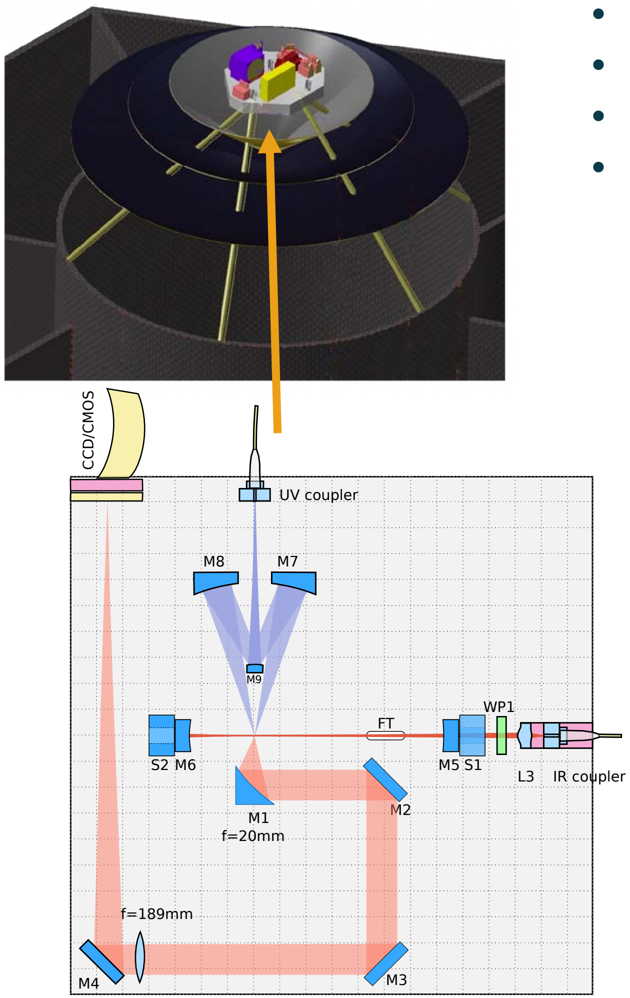


- Same spacecraft as in LISA Pathfinder
- Technological Heritage (LTP)
- L1 or L2 orbit ideal for MAQRO
- Alternative: solar orbit or highly-eccentric orbit



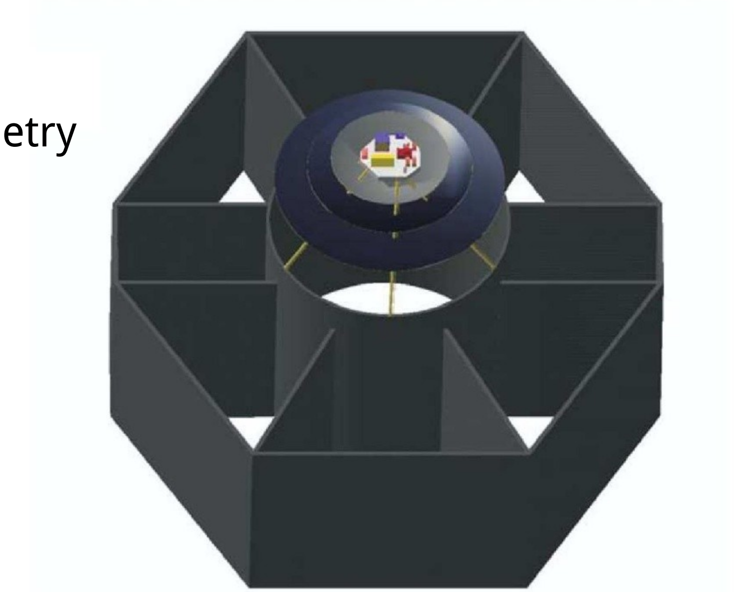
MAQRO, mission proposal 2010 - R. Kaltenbaek et al., Exp. Astron. **34**, 123 (2012)

MAQRO mission design

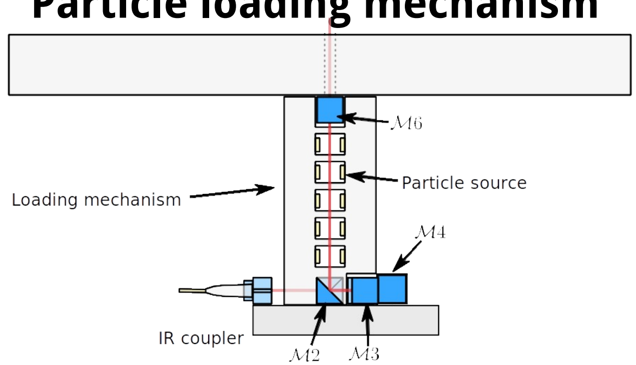


Matter-wave interferometry with massive particles (10^9 - 10^{11} amu)

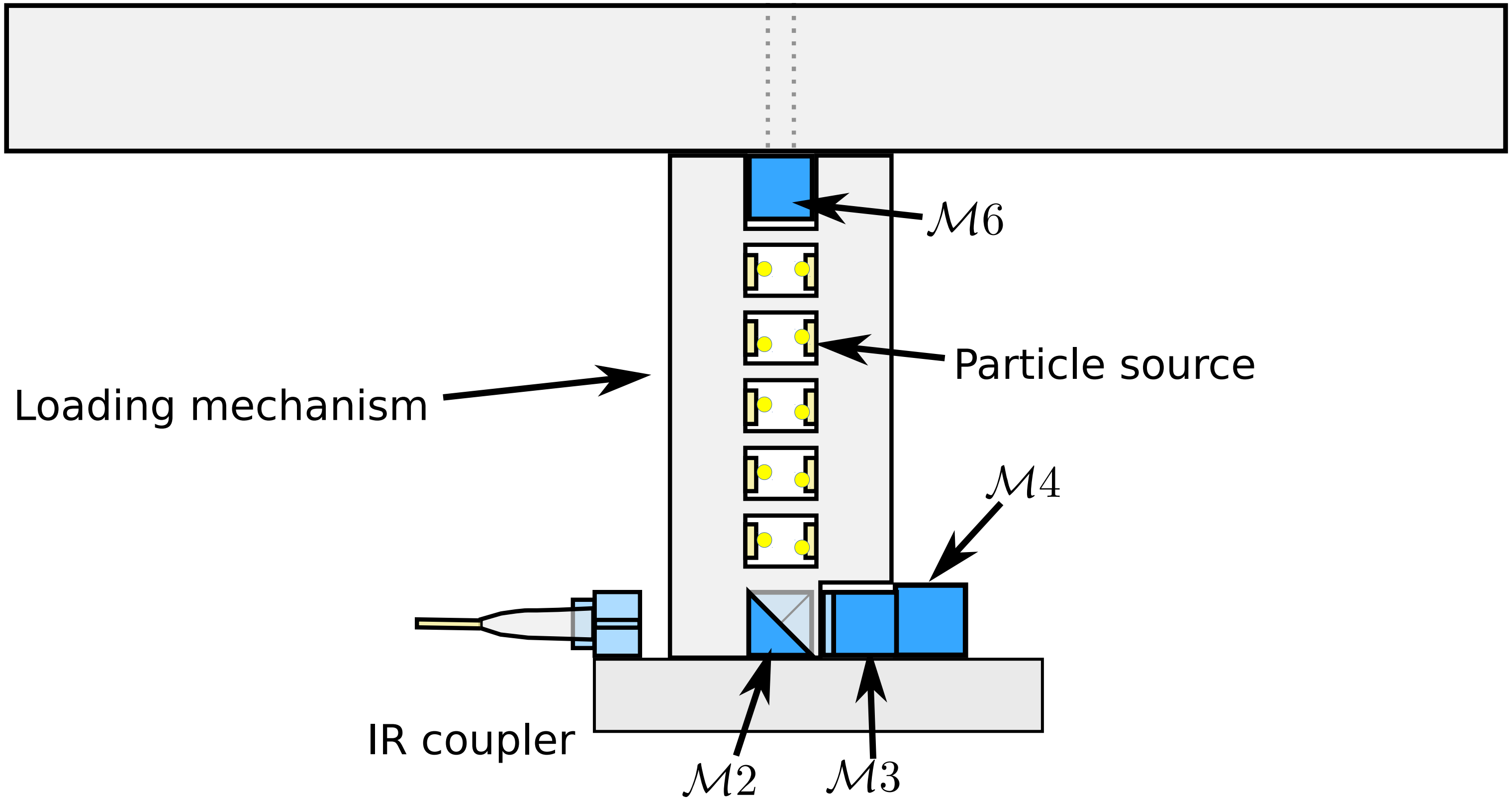
- Test quantum theory
- High-sensitivity interferometry
- Test macrorealism
- (quantum) gravity?



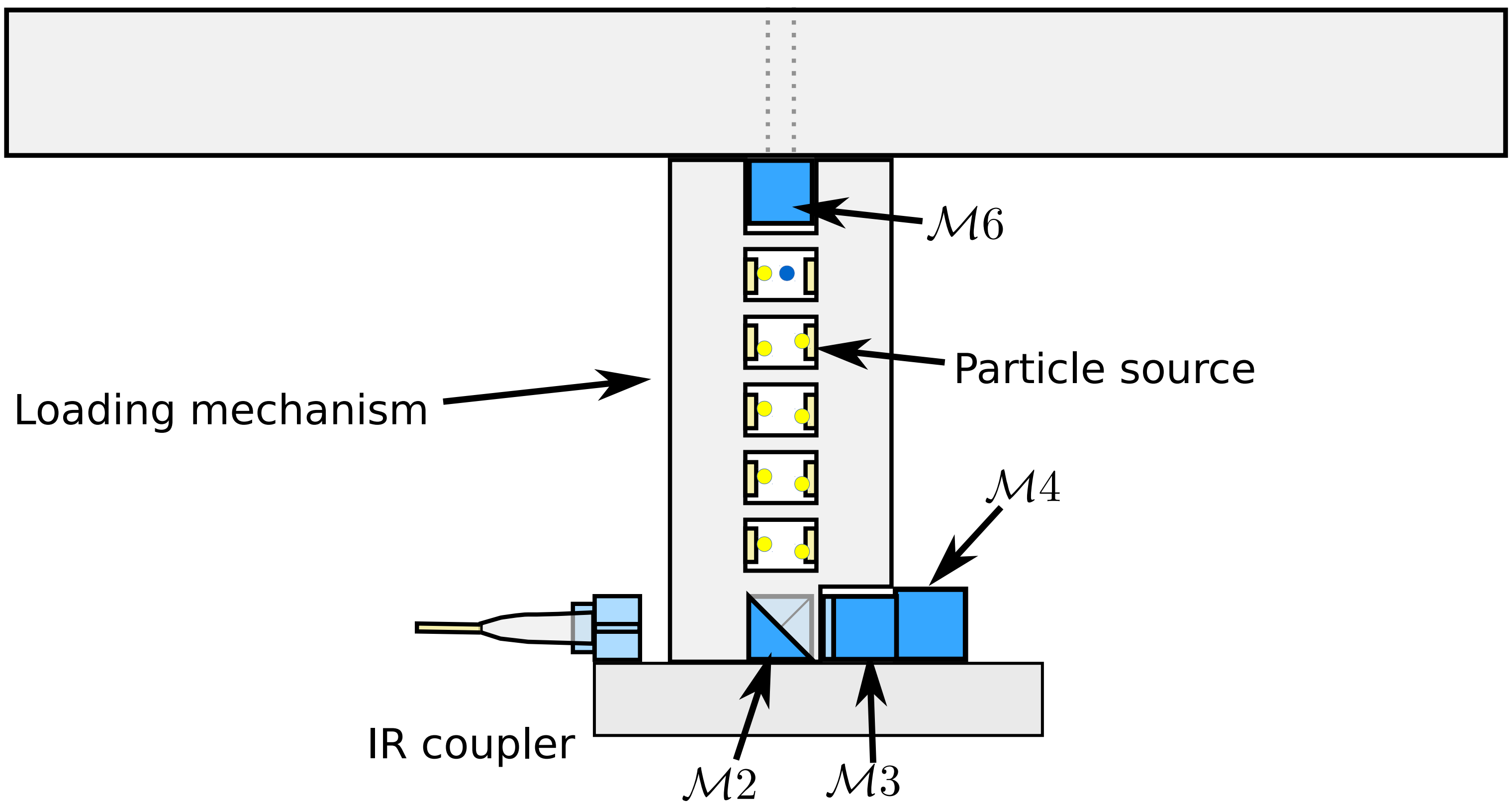
Particle loading mechanism



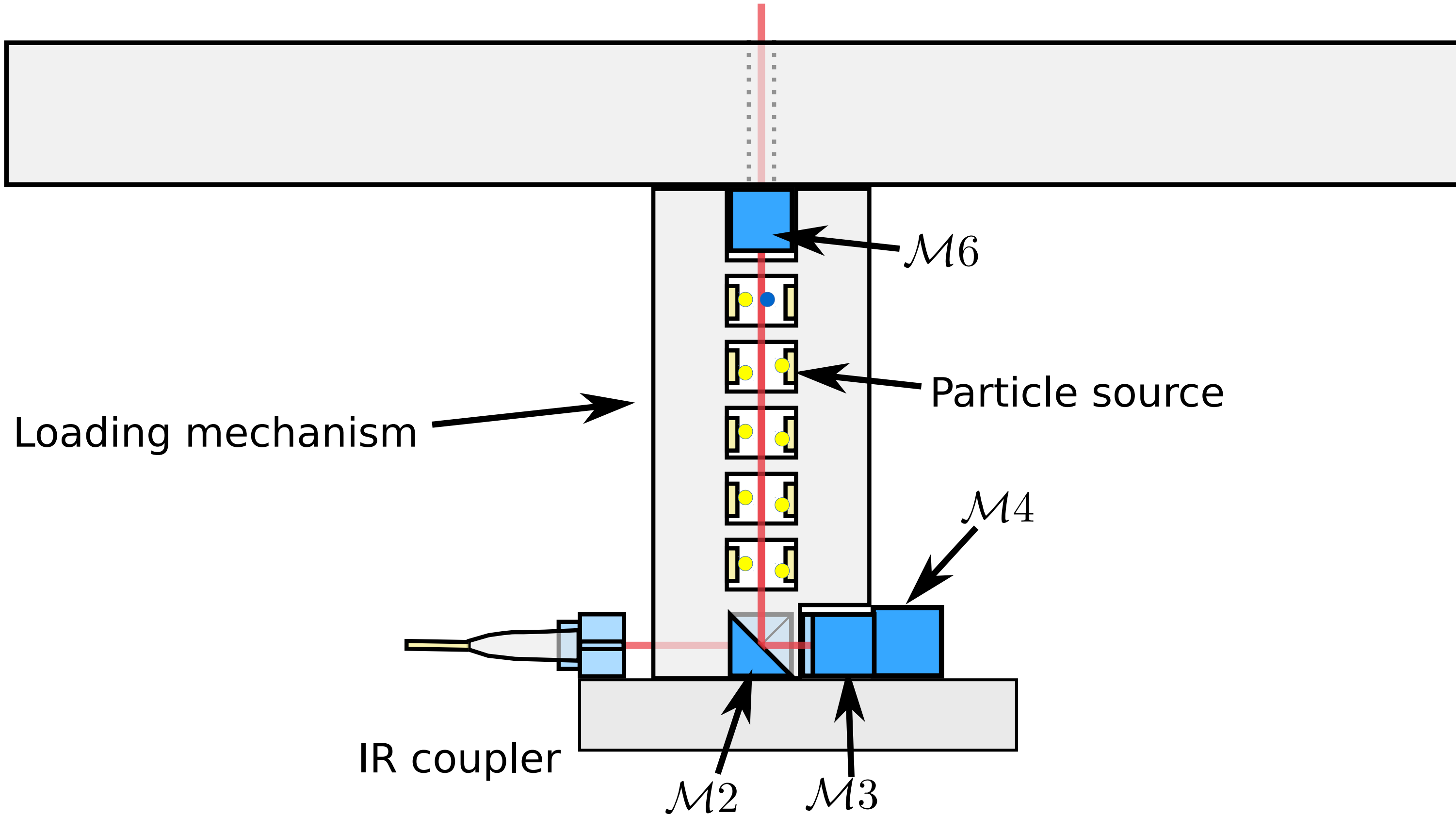
The loading mechanism



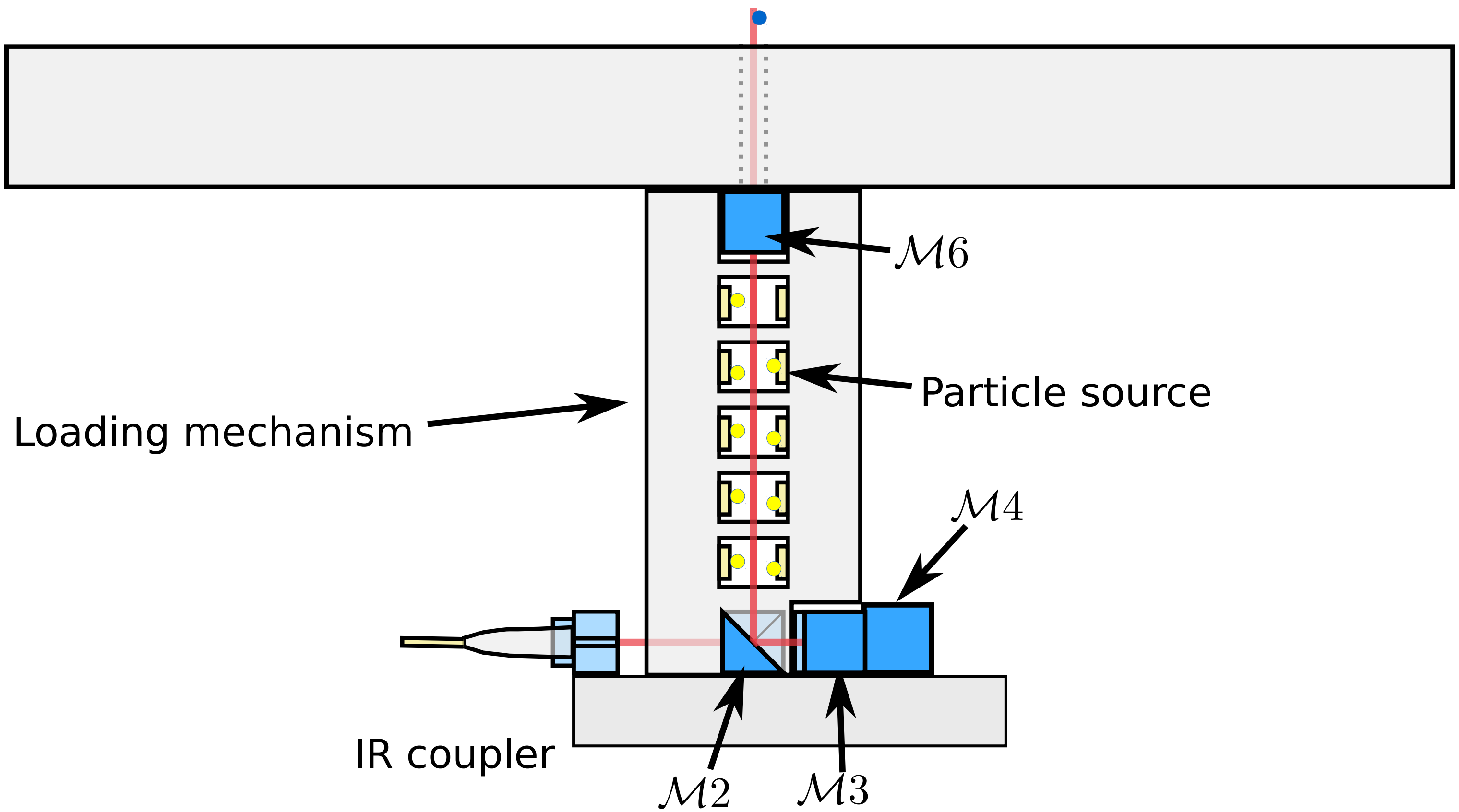
The loading mechanism



The loading mechanism

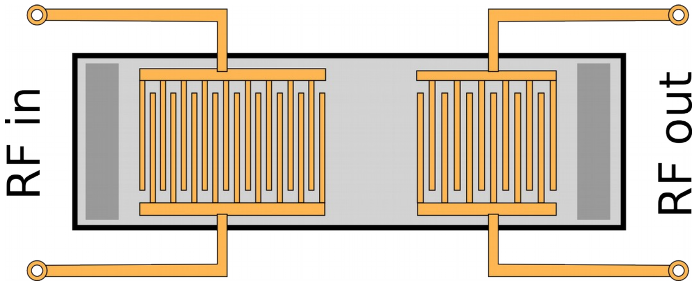


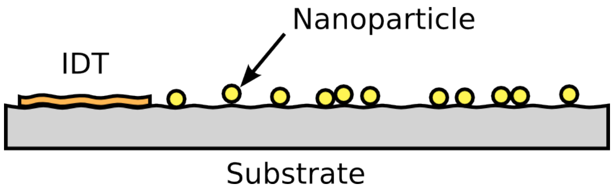
The loading mechanism



Surface acoustic waves

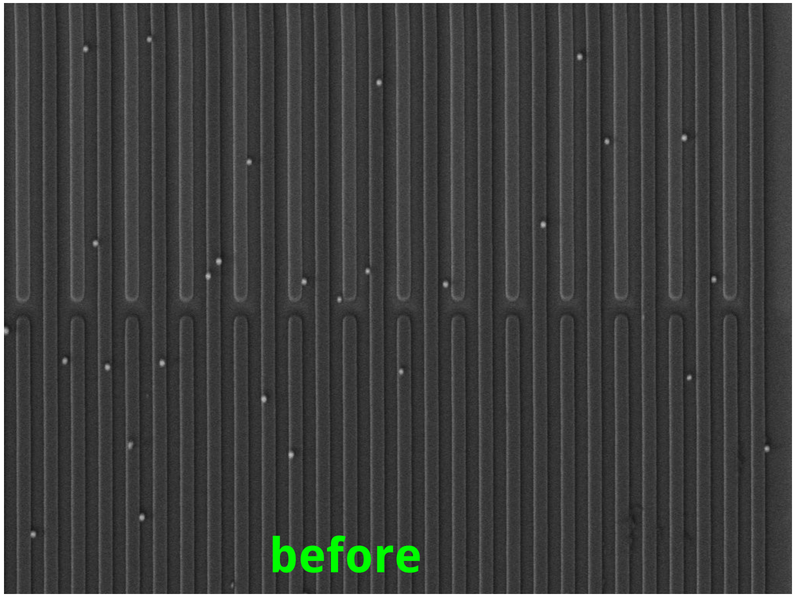
Surface Acousitc Wave (SAW) devices to release nanoparticles

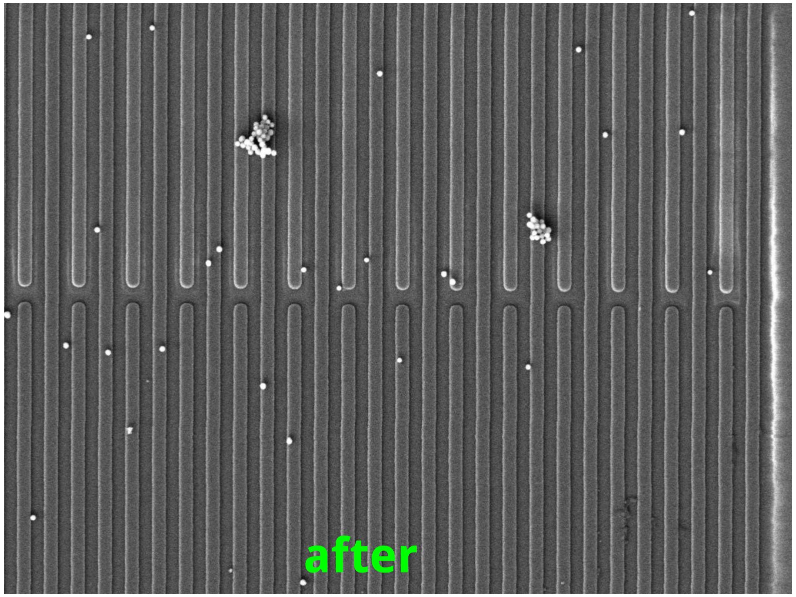




for $\nu = 915\,\mathrm{MHz}$ and $A = 3.5\,\mathrm{nm}$, we get $a_{\max} = A \times \omega^2 \sim 10^{11}\,\frac{\mathrm{m}}{\mathrm{s}^2}$

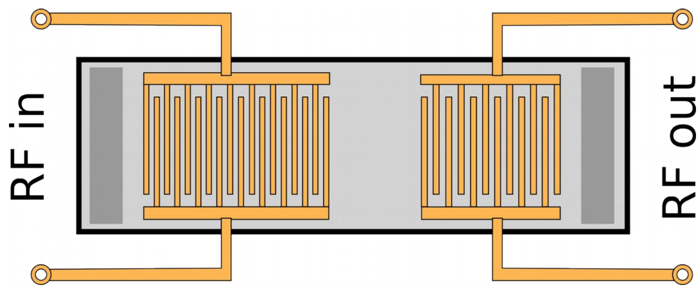
Scanning electron microscope (SEM) images

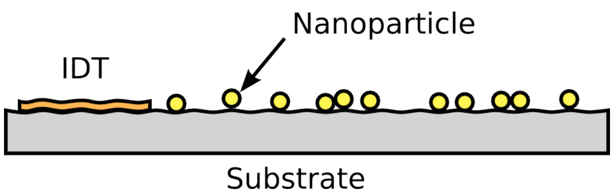




Surface acoustic waves

Surface Acousitc Wave (SAW) devices to release nanoparticles



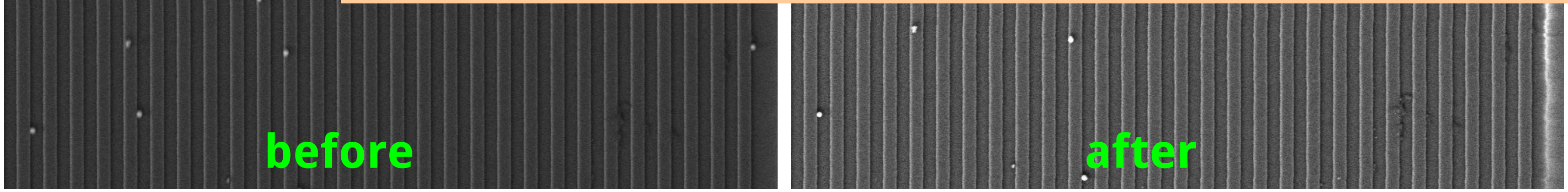


for $\nu = 915\,\mathrm{MHz}$ and $A = 3.5\,\mathrm{nm}$, we get $a_{\max} = A \times \omega^2 \sim 10^{11}\,\frac{\mathrm{m}}{\mathrm{s}^2}$

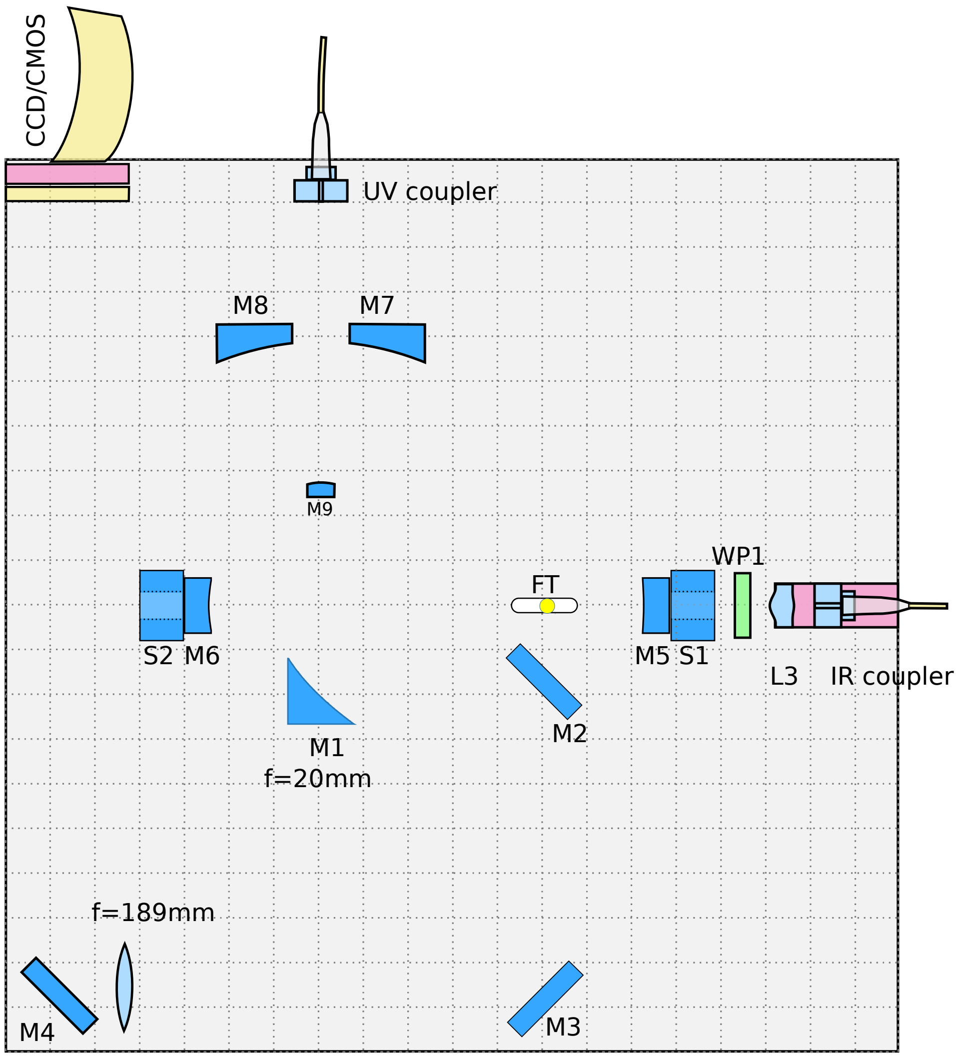
Scanning electron microscope (SEM) images

Benefits:

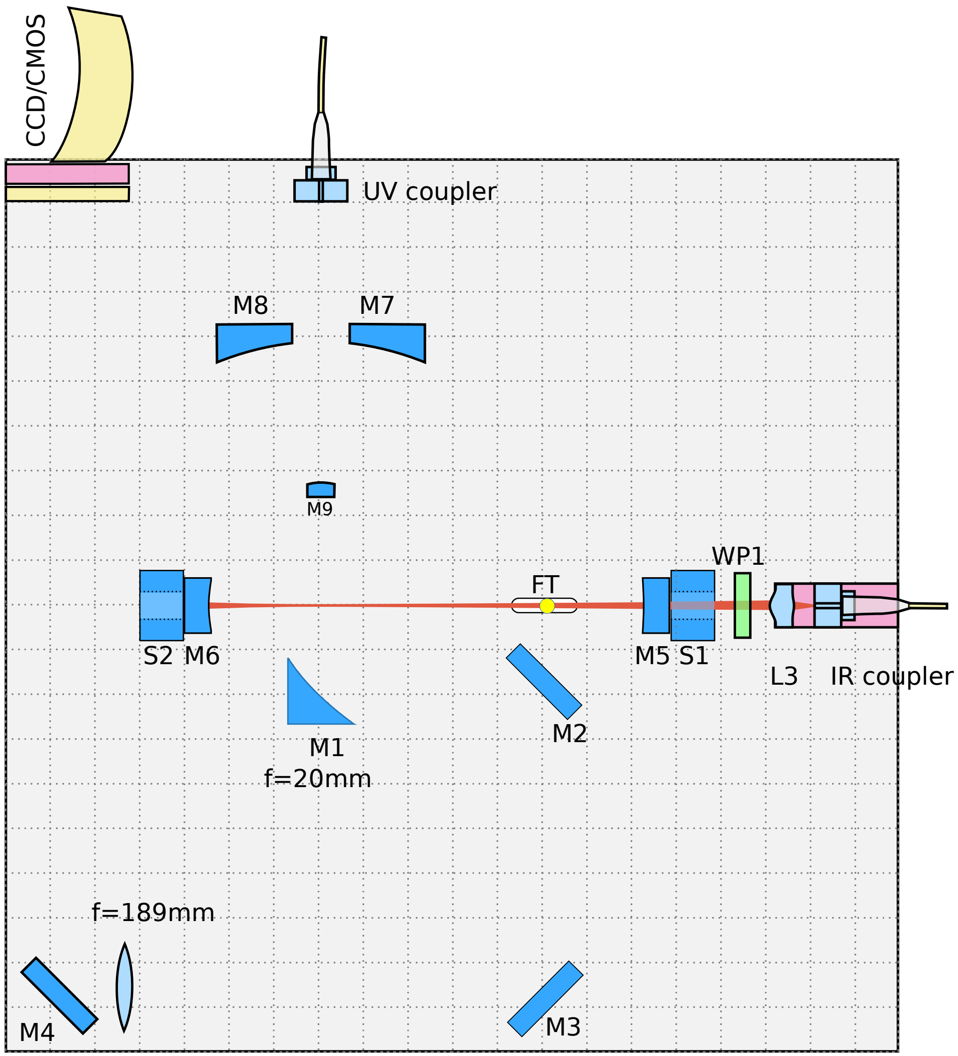
- Small
- low power
- redistribution on surface (slow bleaching)
- high TRL of SAW devices
- **But** do particles desorb?



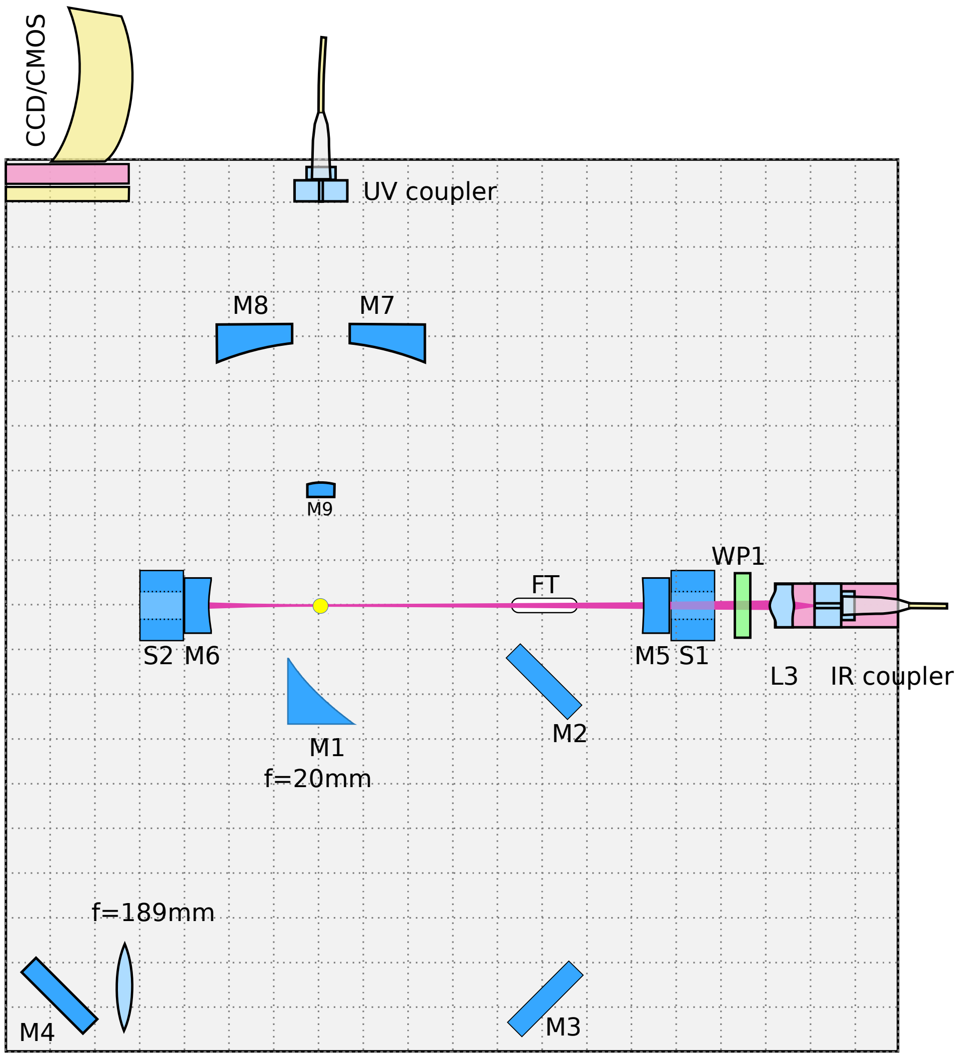
Optical bench



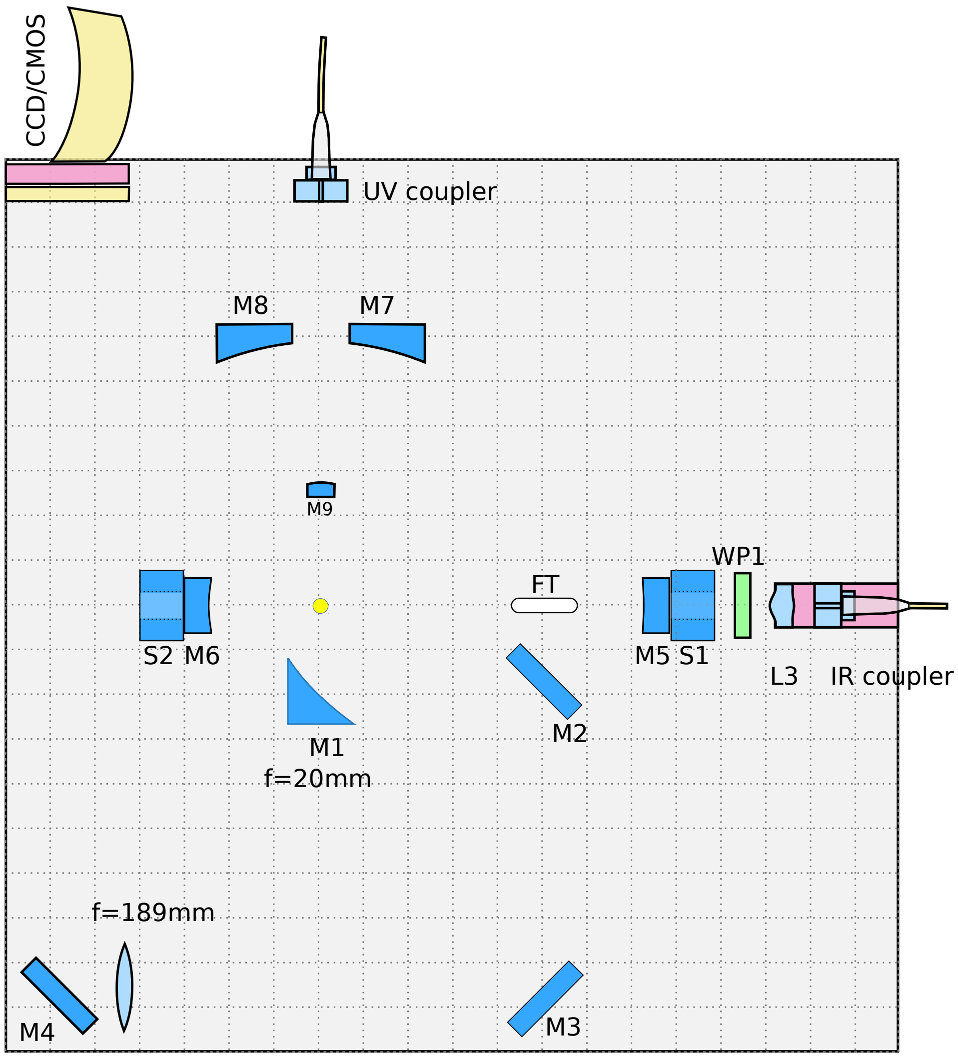
Optical bench



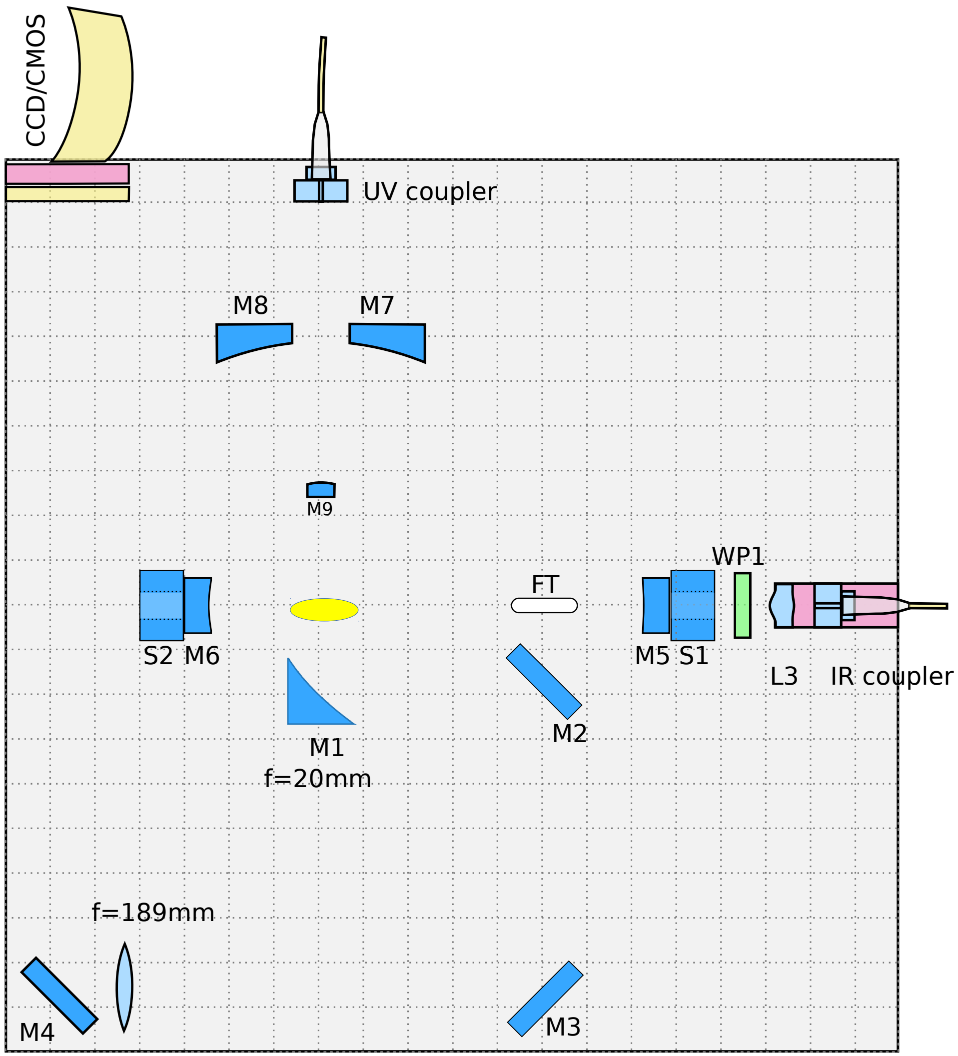
Optical bench



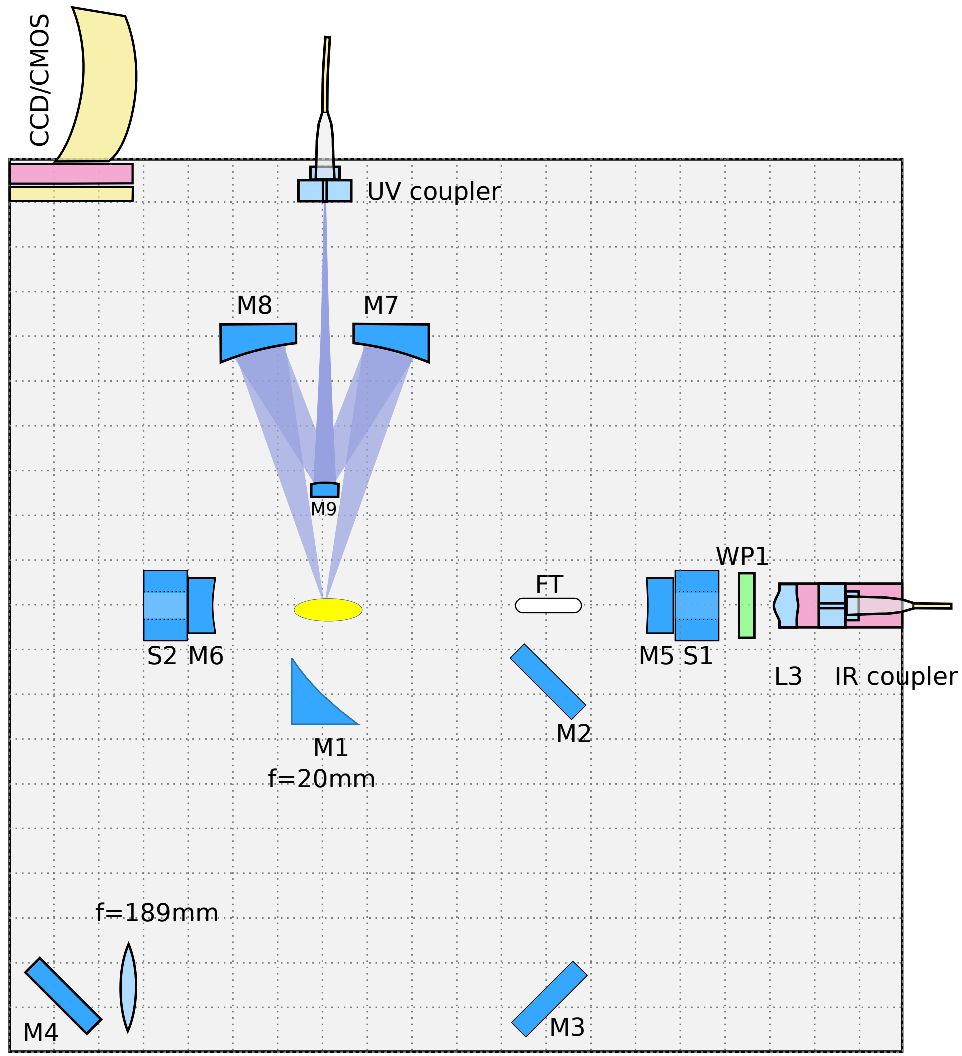
Optical bench



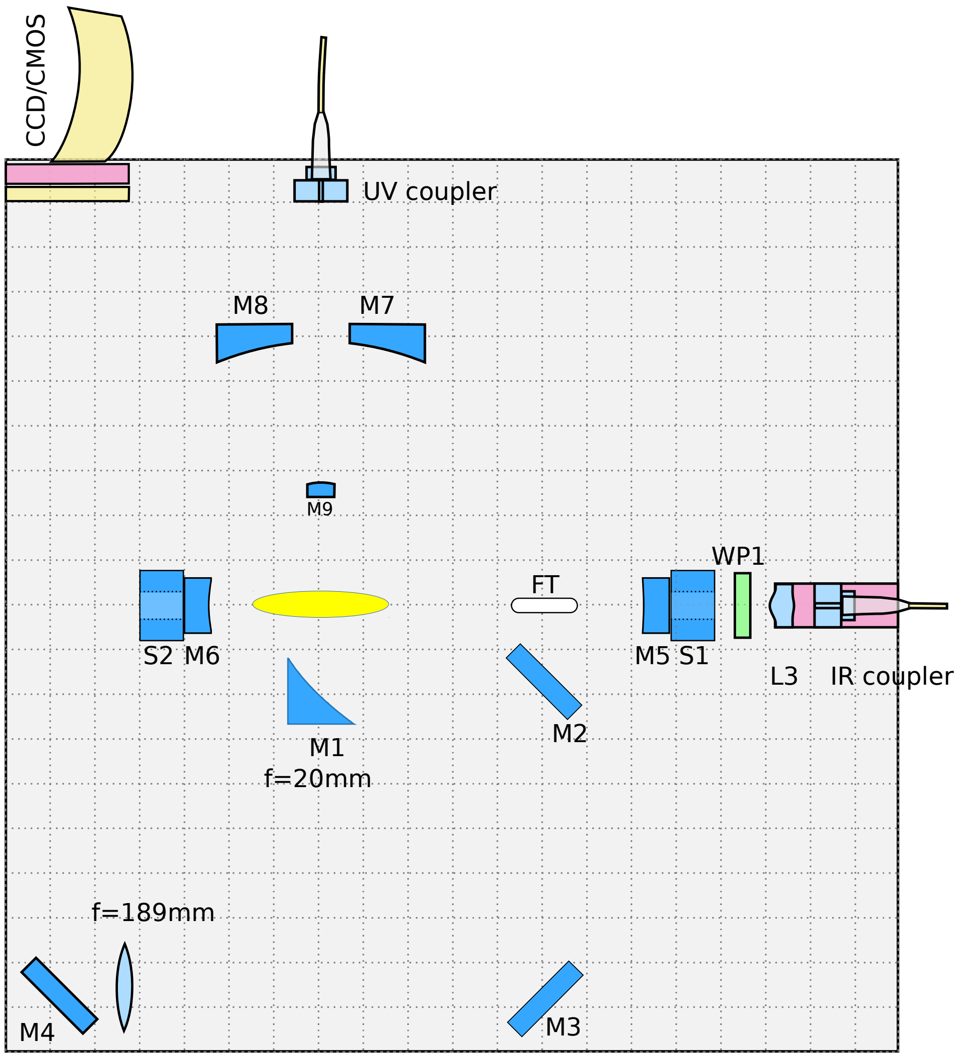
Optical bench



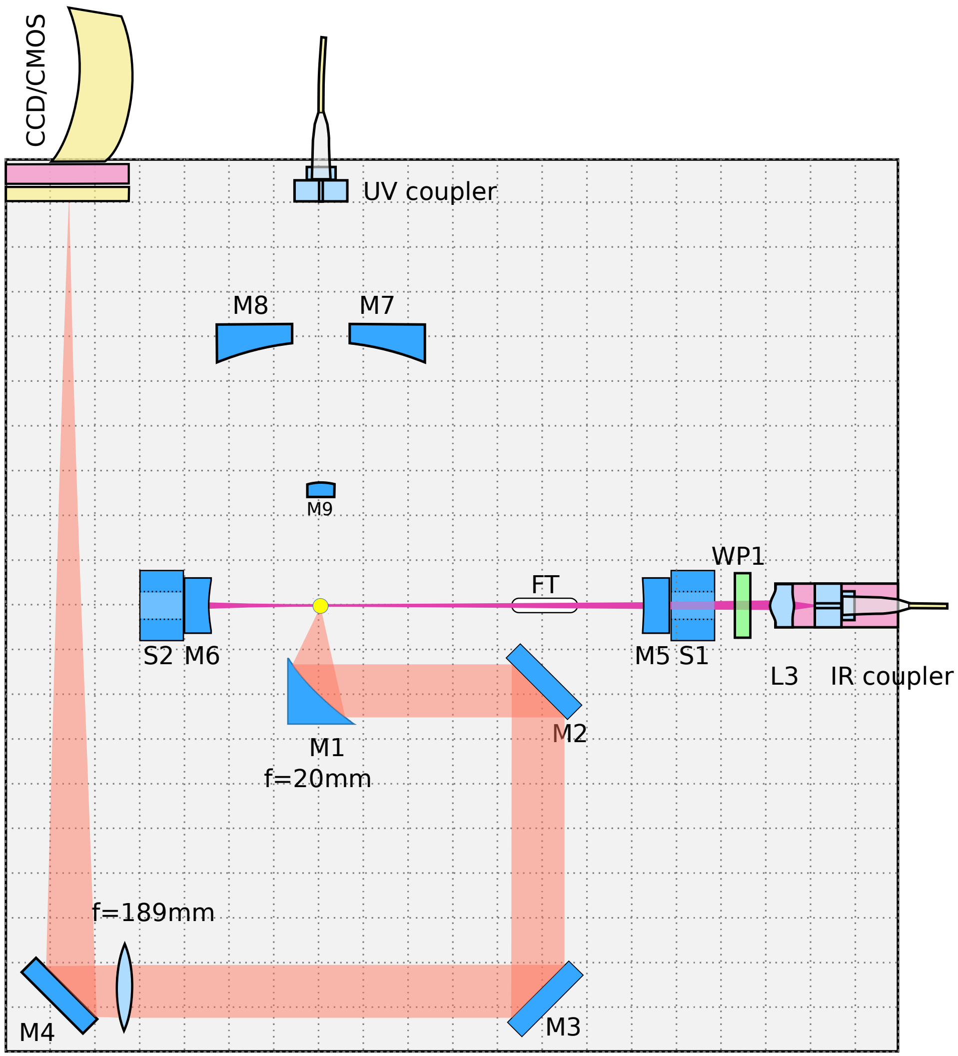
Optical bench



Optical bench



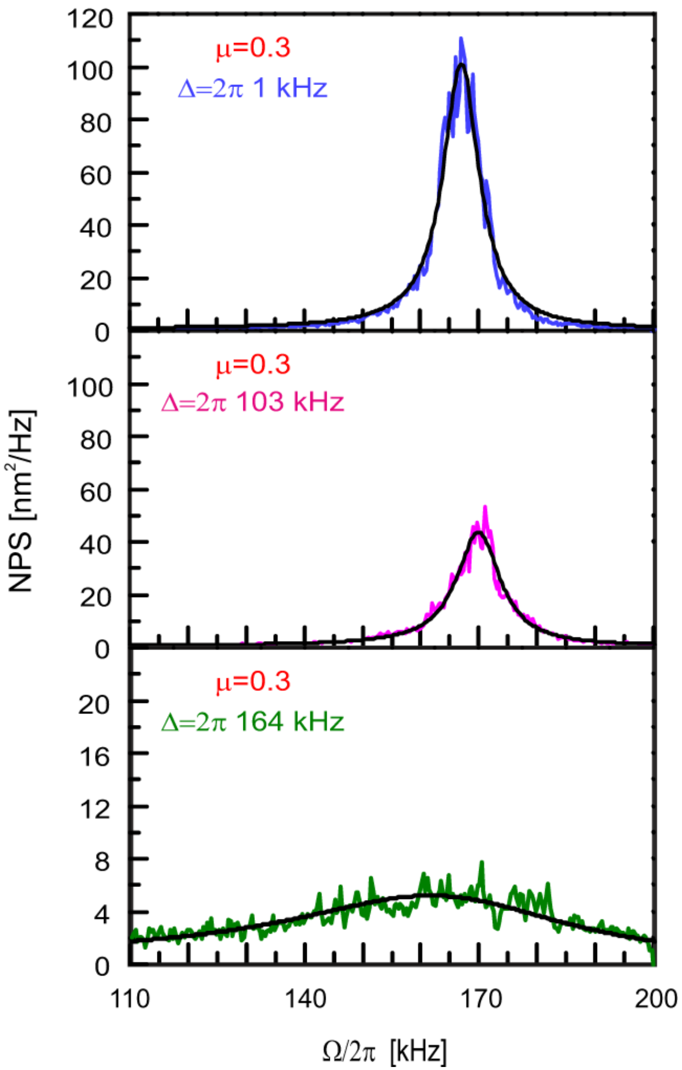
Optical bench



Cavity cooling in our lab

Vienna Center for Quantum Science and Technology

Cavity cooling

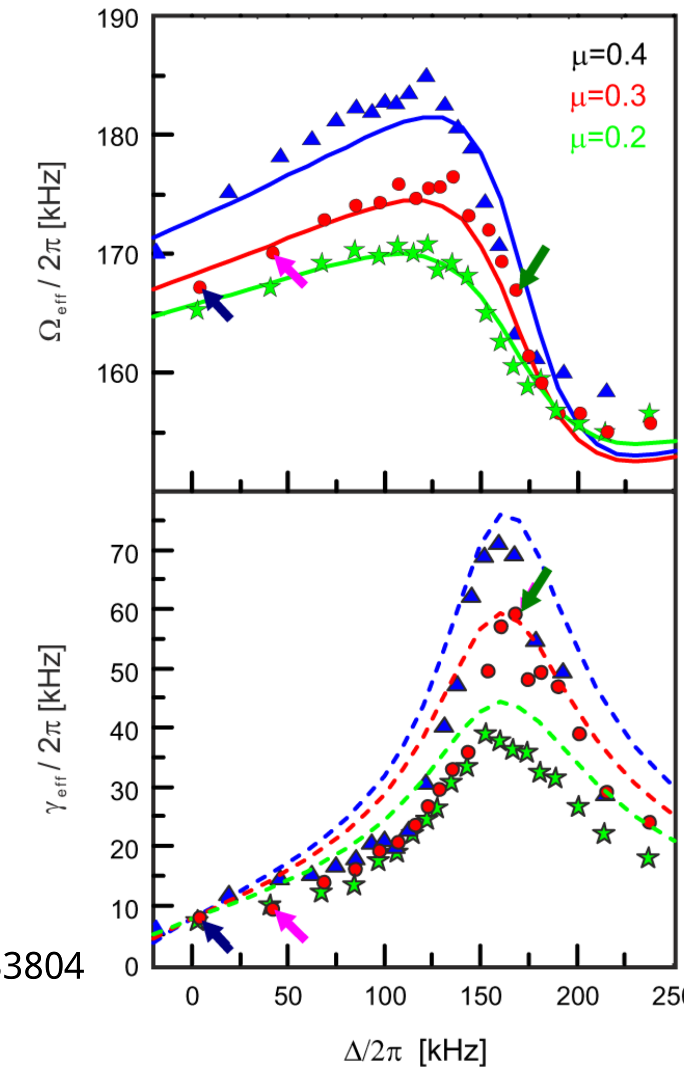


Cavity cooling of an optically levitated submicron particle
N. Kiesel, F. Blaser et al., PNAS **110**, 14180 (2013)

Optical spring
modification of mechanical frequency due to radiation pressure

Optical damping
modification of damping depending on detuning

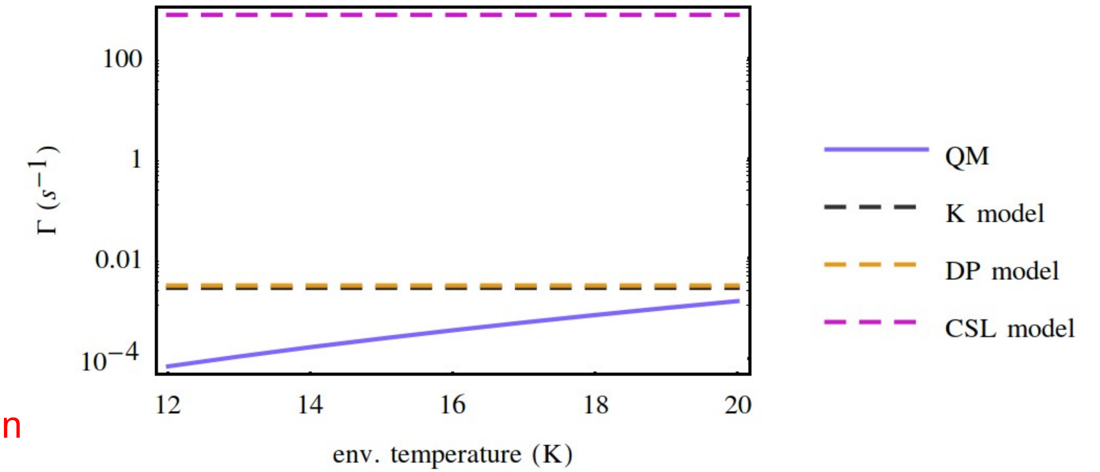
Theory:
Genes et al., PRA **77**, 033804



Detailed thermal analysis

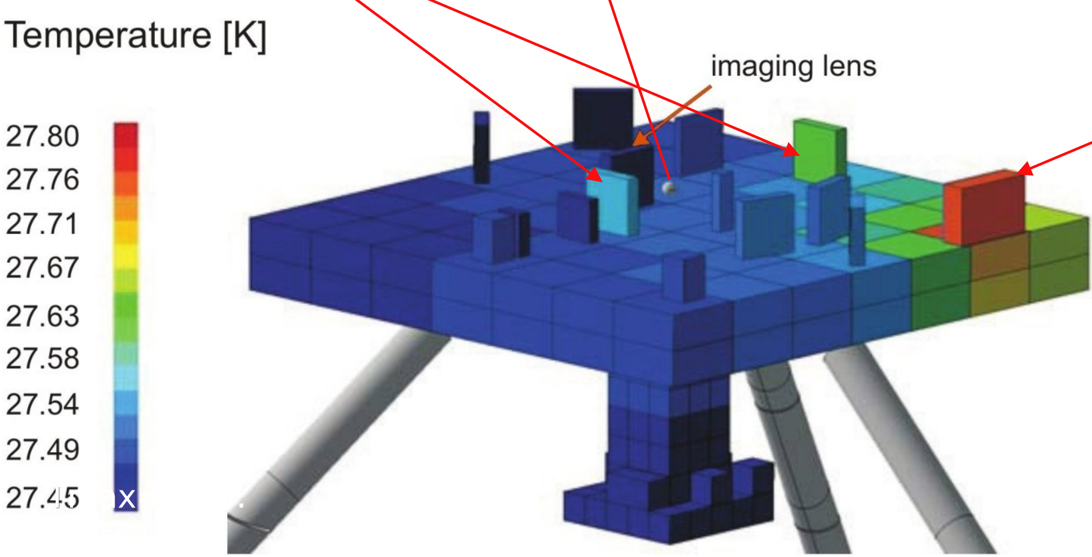
Analysis results:

- **16.42K** for test-volume
- **27.52K** optical Bench

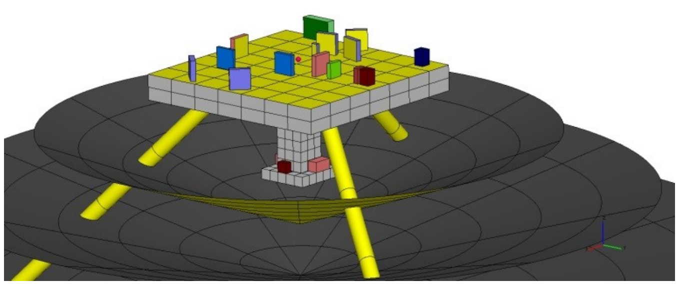


Cavity mirrors
(+0.1 K w.r.t. bench)

Test volume
(-11.1 K w.r.t. ben



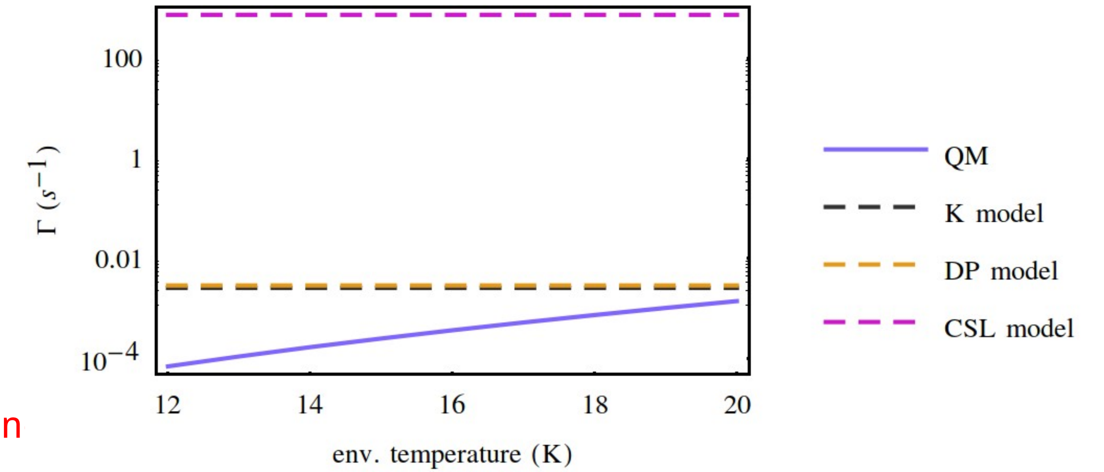
CCD head (+0.3 K w.r.t bench)



How cold can you get in space? Quantum physics as cryogenic temperatures in space,
G.. Hechenblaikner, F. Hufgard, J. Burkhardt, N. Kiesel, U. Johann, M. Aspelmeyer & R. Kaltenbaek, NJP **16**, 013058 (2014)

Detailed thermal analysis

Analysis results:
- **16.42K** for test-volume
- **27.52K** optical Bench

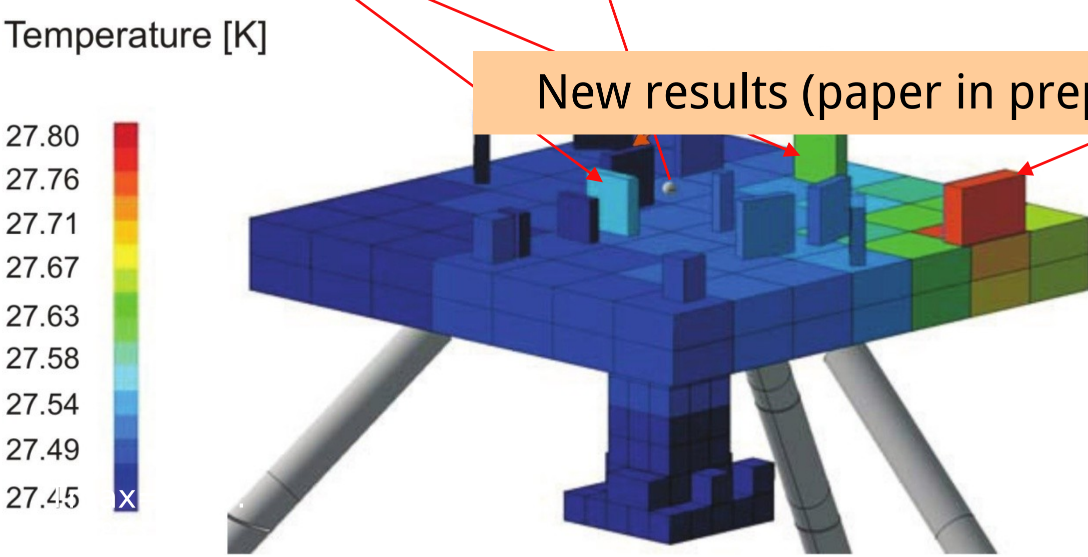


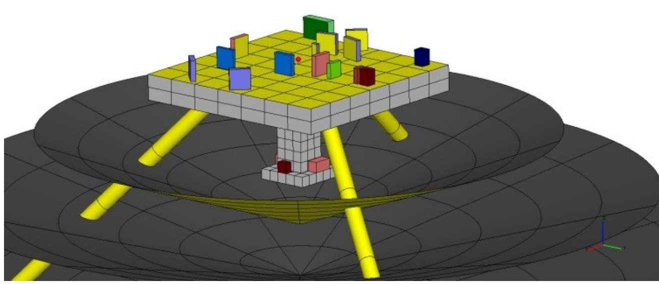
Cavity mirrors
(+0.1 K w.r.t. bench)

Test volume
(-11.1 K w.r.t. ben

New results (paper in preparation): ~12K

CCD head (+0.5 K w.r.t bench)

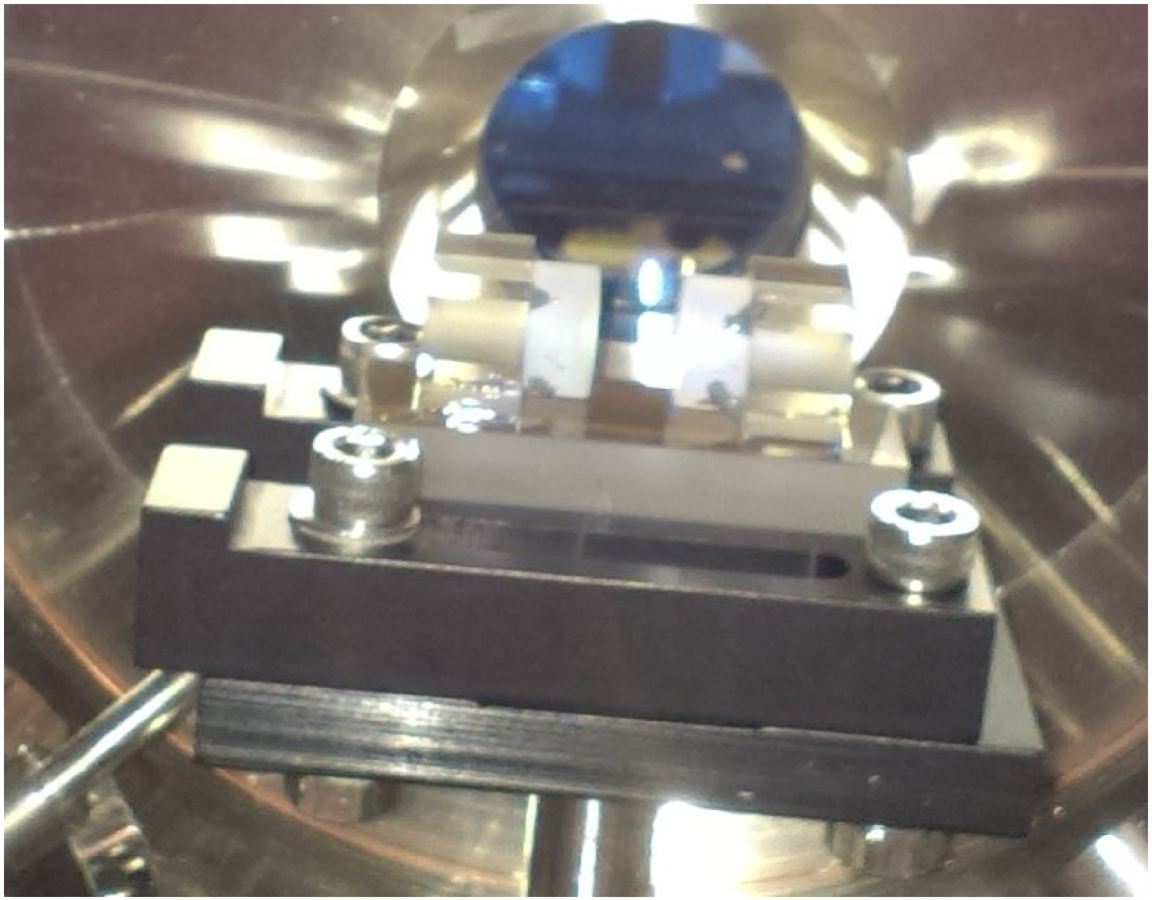




How cold can you get in space? Quantum physics as cryogenic temperatures in space,
G.. Hechenblaikner, F. Hufgard, J. Burkhardt, N. Kiesel, U. Johann, M. Aspelmeyer & R. Kaltenbaek, NJP **16**, 013058 (2014)

Space-proof cavity design

Test-cavity using space-proof gluing technology



Paper in preparation

Conclusions & Outlook

- Promising results
- Still a long way to go
- Open M4 Cosmic Vision call – launch ~2025?

MAQRO Consortium

Coordinator: R. Kaltenbaek

Member groups: M. Arndt (Vienna), M. Aspelmeyer (Vienna), P. Barker (London), A. Bassi (Trieste), K. Bongs (Birmingham), S. Bose (London), C. Braxmaier (Bremen), C. Brukner (Vienna, K. Dholakia (St. Andrews), W. Ertmer (Hannover), U. Johann (Astrium), C. Lämmerzahl (Bremen), M. Kim (London), A. Lambrecht (Paris), G. Milburn (Queensland), H. Müller (Berkley), L. Novotny (Zürich), M. Paternostro (Belfast), A. Peters (Berlin), E. Rasel (Hannover), S. Reynaud (Paris), O. Romero-Isart (Innsbruck), A. Roura (Ulm), W. Schleich (Ulm), J. Schmiedmayer (Vienna), K. C. Schwab (Caltech), M. Tajmar (Dresden), H. Ulbricht (Southhampton), V. Vedral (Oxford)

Thanks

MAQRO team at Aspelmeyer group:

R. Kaltenbaek

N. Kiesel

M. Aspelmeyer

EADS Astrium (Airbus D&S):

G. Hechenblaikner, J. Burkhardt, T. Schuldt, F. Hufgard, A. Pilan-Zanoni, T. Thuldt, M. Chwalla, C. Braxmaier, U. Johann

Thanks for discussions:

G. Cole

F. Blaser

D. Grass

M. Arndt

!THANK YOU!

Thanks for funding:

APART
Austrian Program for Advanced Research and Technology

ÖAW
Österreichische Akademie der Wissenschaften

Marie Curie FP7-PEOPLE-2010-RG
STREP MINOS
ERC Starting Grant

FWF
START
P15939
L426

ASAP project
Nr. 3589434
FFG