MAQRO
macrorealism or quantum physics?
A case for space

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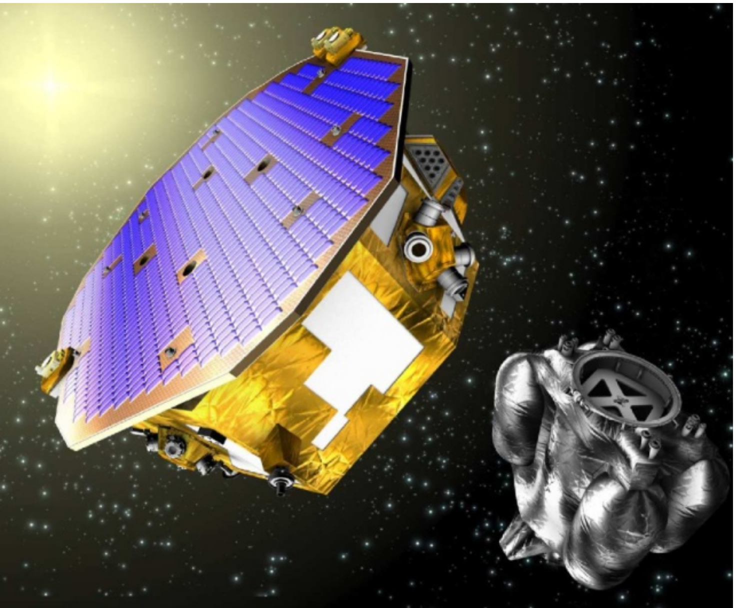
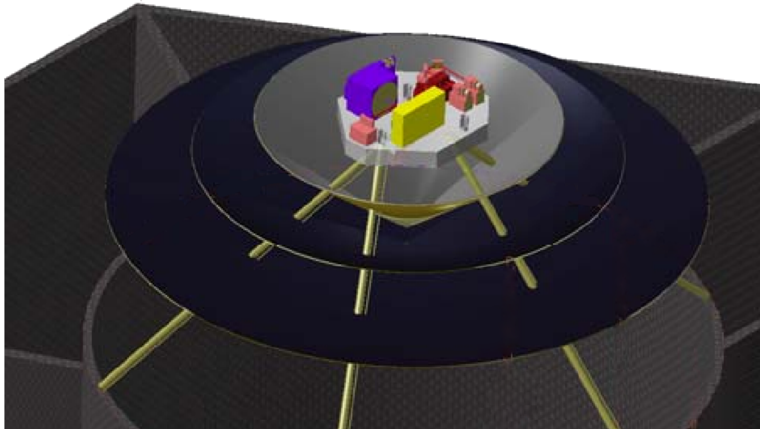
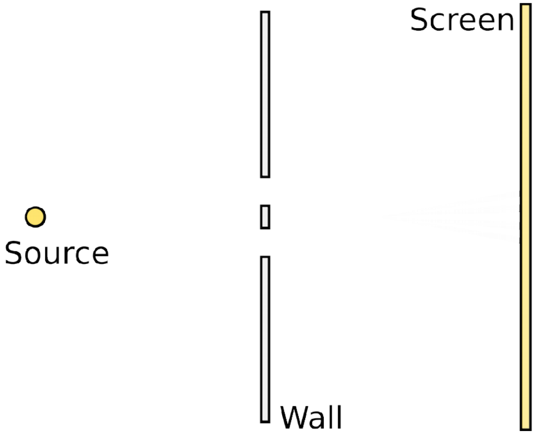
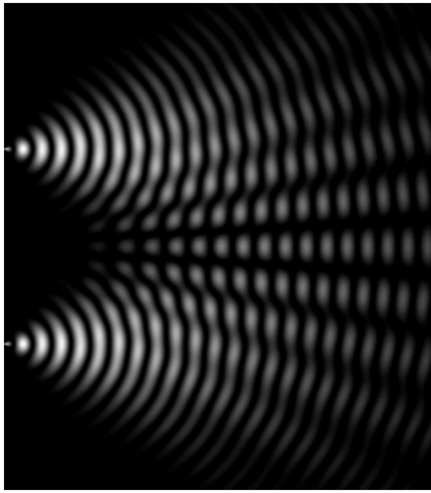




Double slit – classical vs. quantum

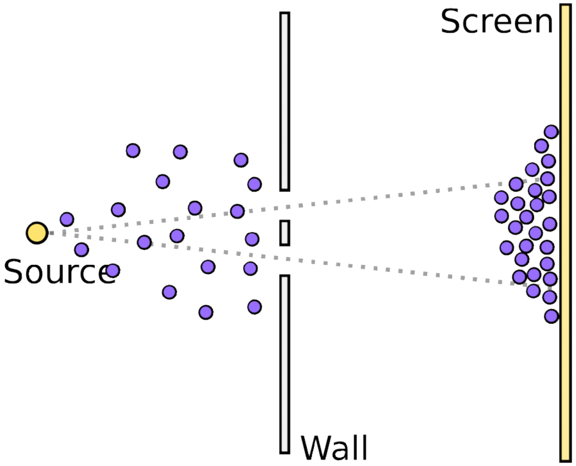


Classical Physics:
If we have waves: interference
If we have particles:
NO interference

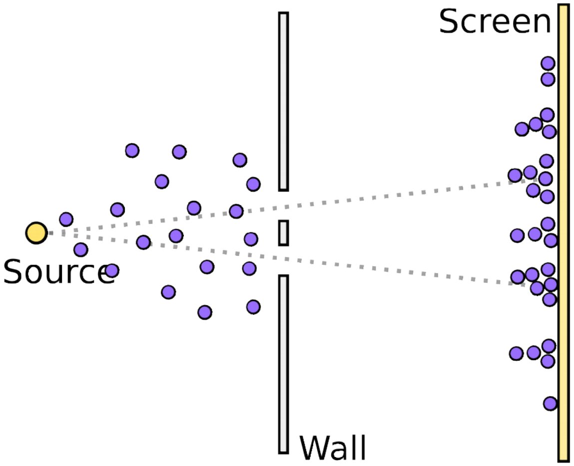


Quantum Mechanics:

There are no waves – only particles

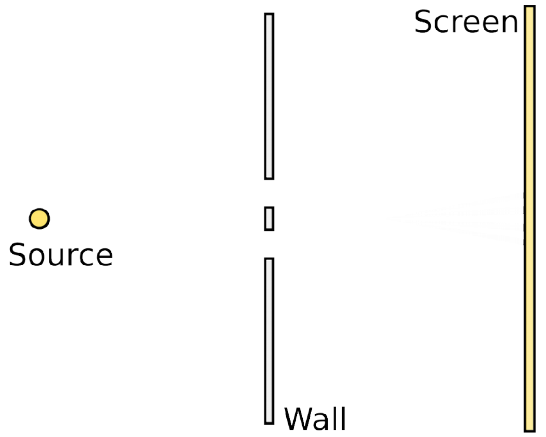


Classical physics



Quantum Theory

Double slit – classical vs. quantum



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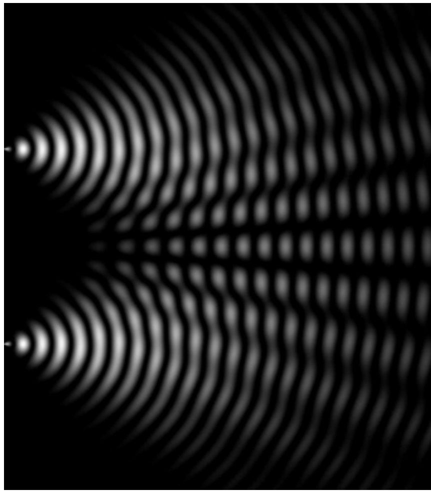

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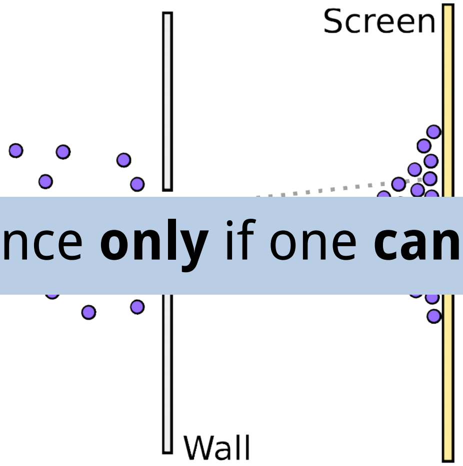
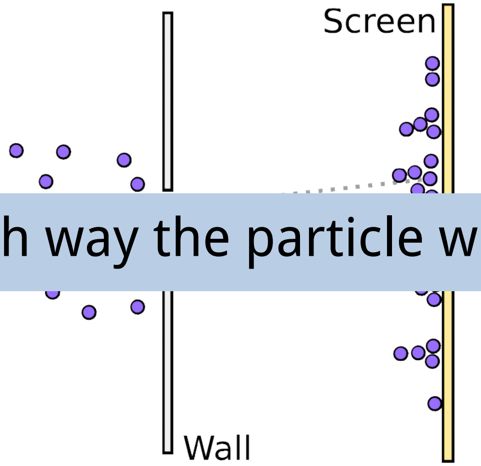


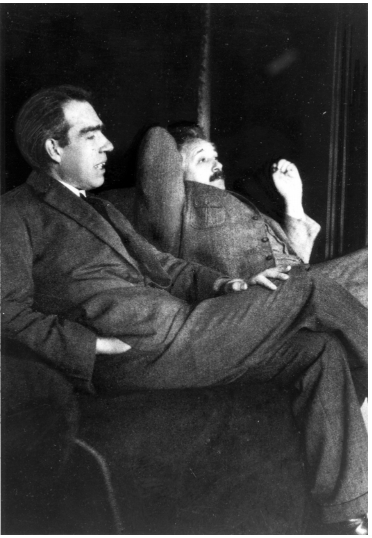


Interference **only** if one **cannot** tell which way the particle went.

Classical physics

Quantum Theory

But what is „really“ happening?



By Paul Ehrenfest

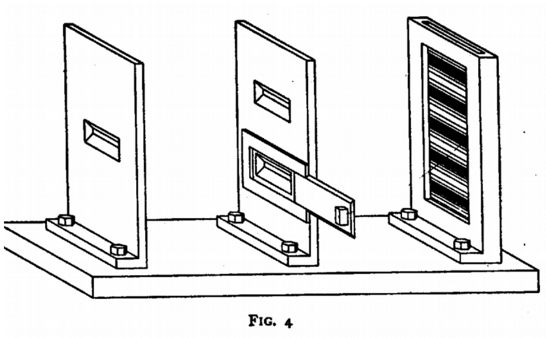
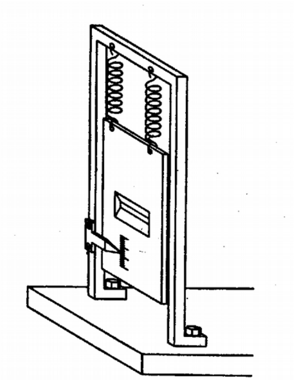


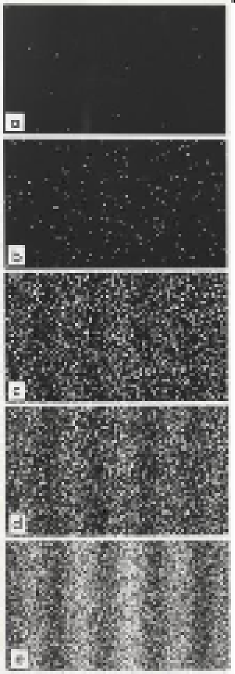
FIG. 4



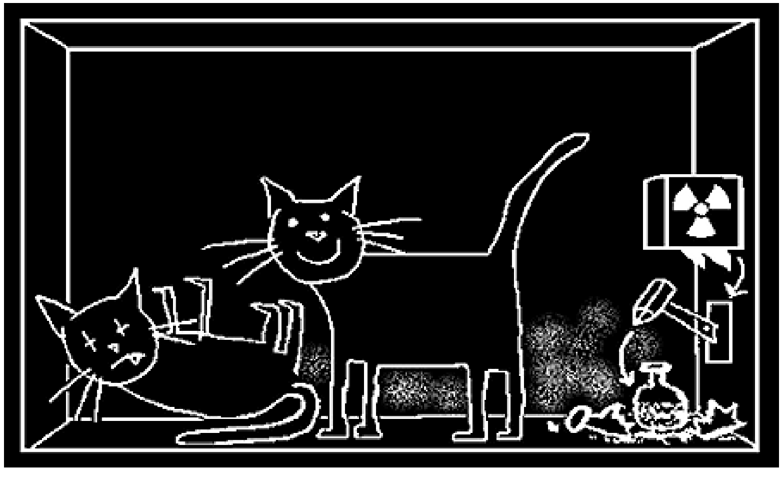
From J. D. Norton, Universtiy of Pittsburgh

FIG. 5

Interference for every single particle
not a statistical phenomenon



A. Tonomura et al., Amer. J. Phys. **57**, 117 (1989), Hitachi



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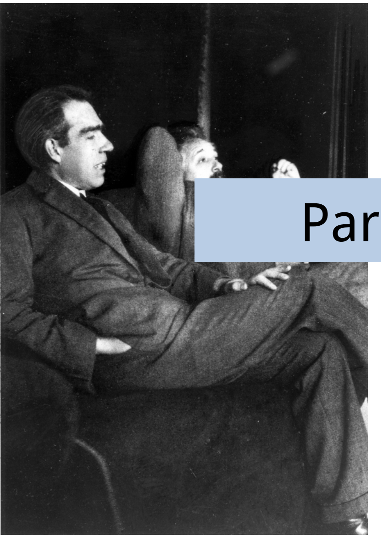

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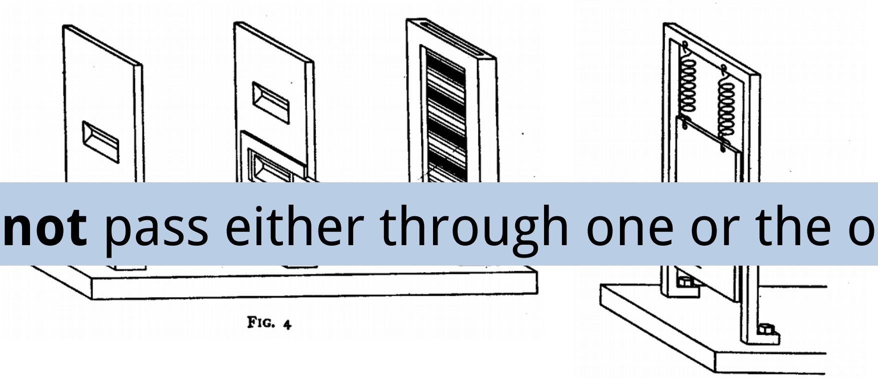
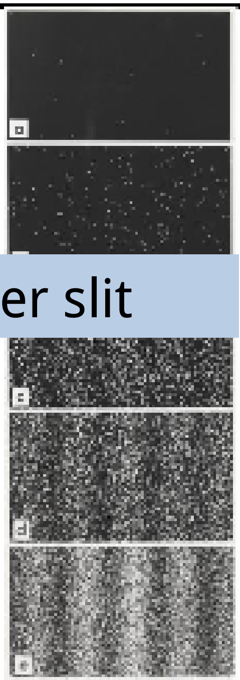


FIG. 4

FIG. 5

From J. D. Norton, Universtiy of Pittsburgh

Particles **do not** pass either through one or the other slit



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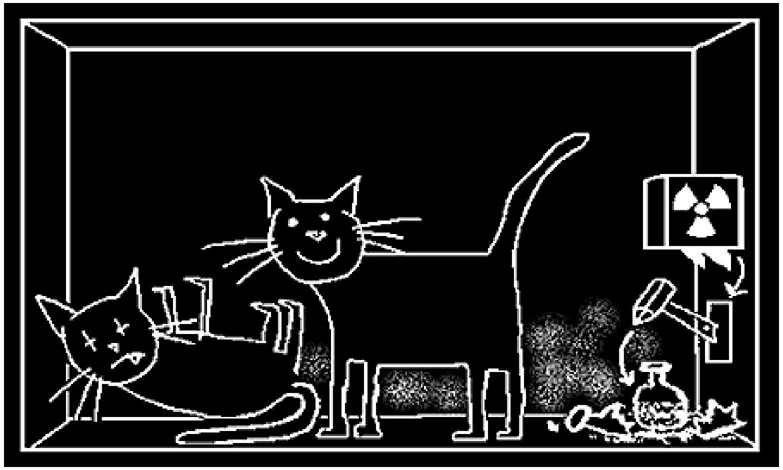

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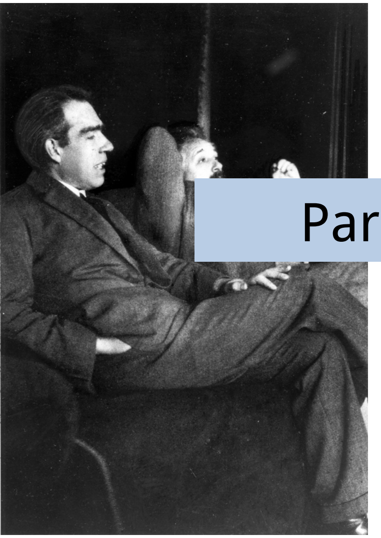
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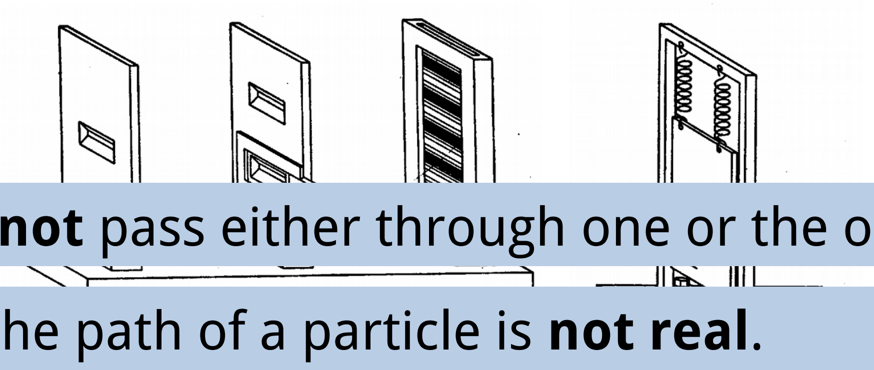
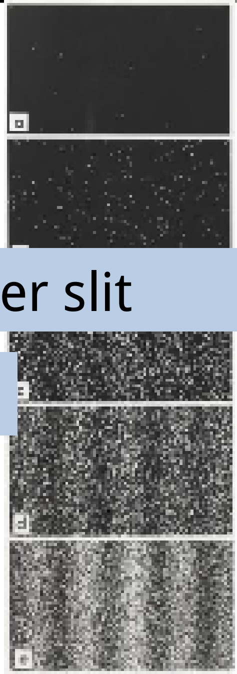

Particles **do not** pass either through one or the other slit

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

From J. D. Norton, Universtiy of Pittsburgh Fig. 5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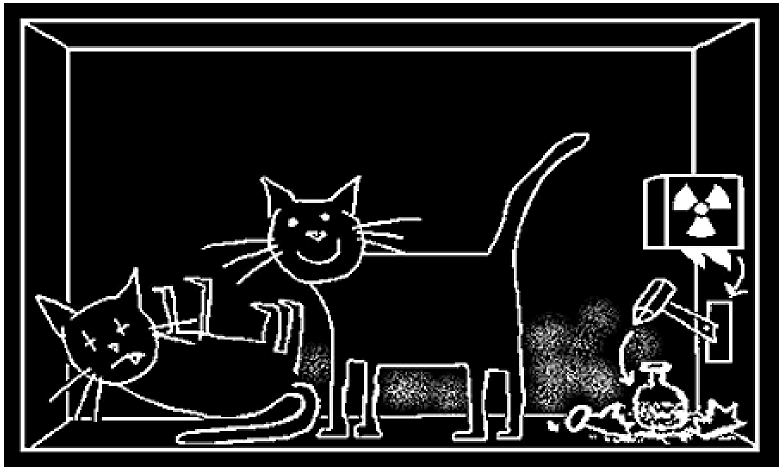

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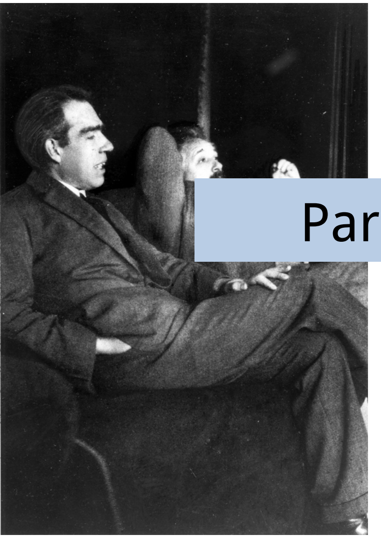

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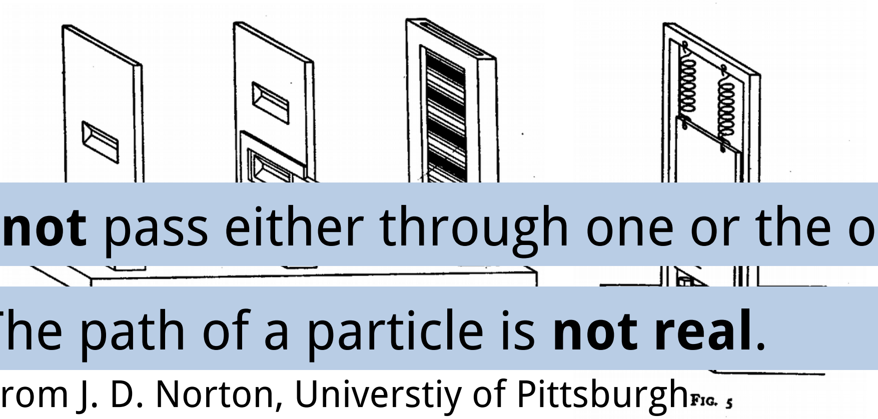

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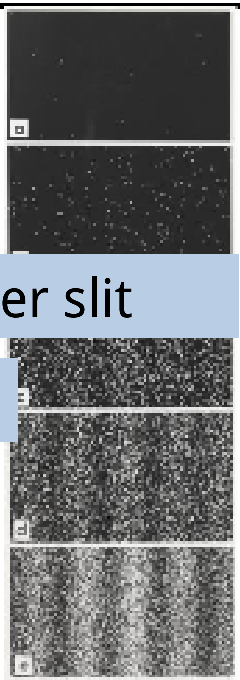

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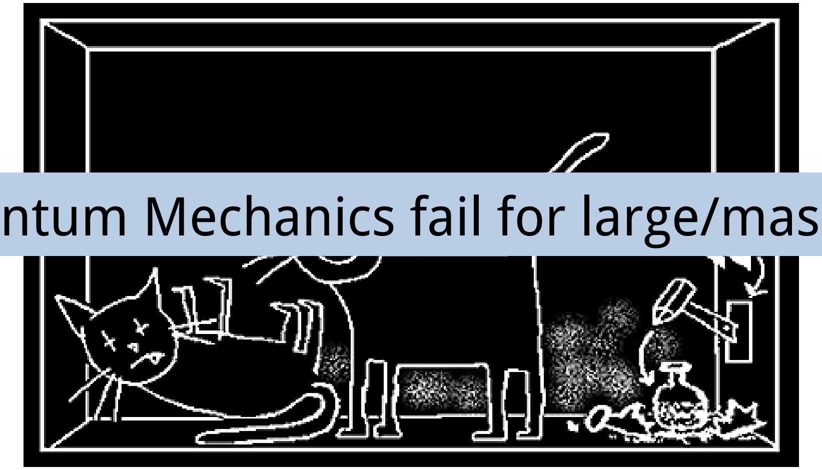
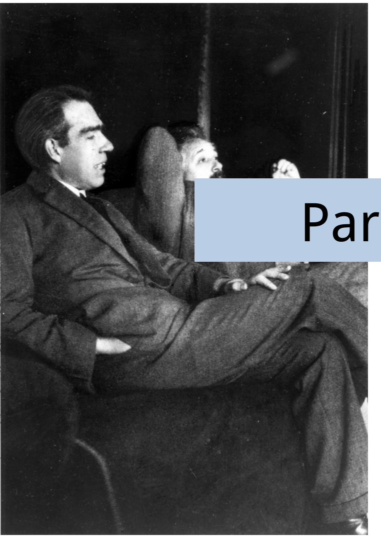


Does Quantum Mechanics fail for large/massive systems?

But what is „really“ happening?



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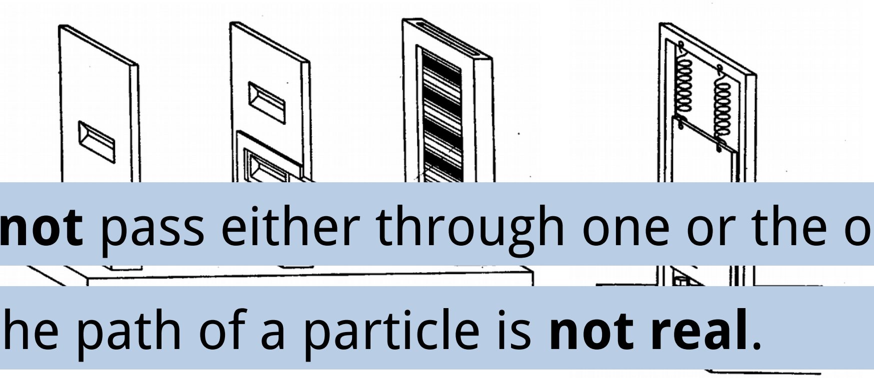

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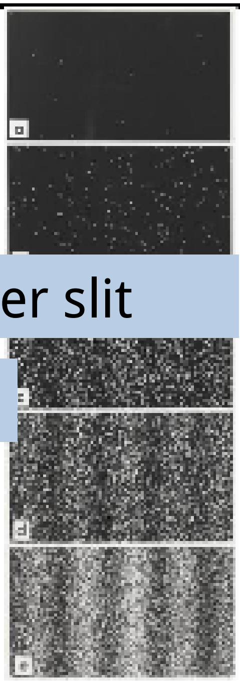

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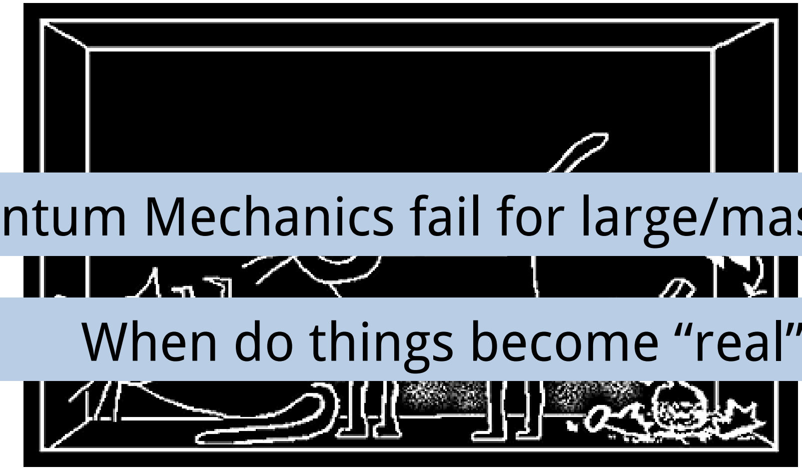


Does Quantum Mechanics fail for large/massive systems?

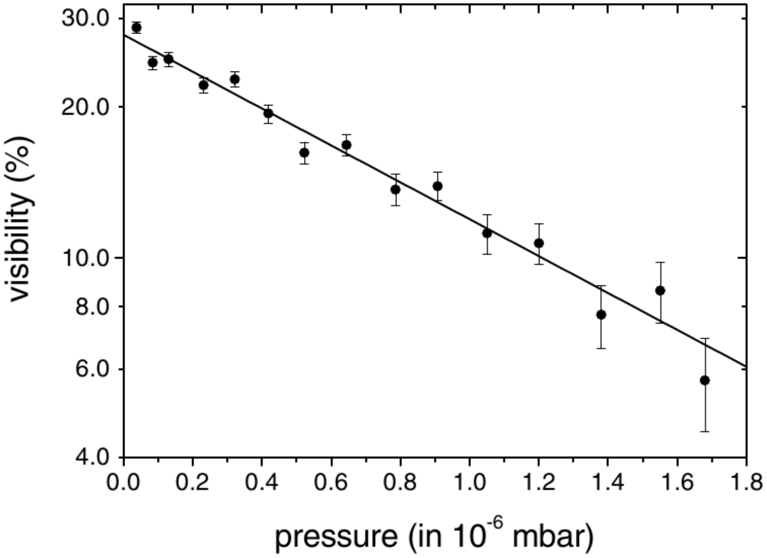
When do things become “real”?

The quantum answer

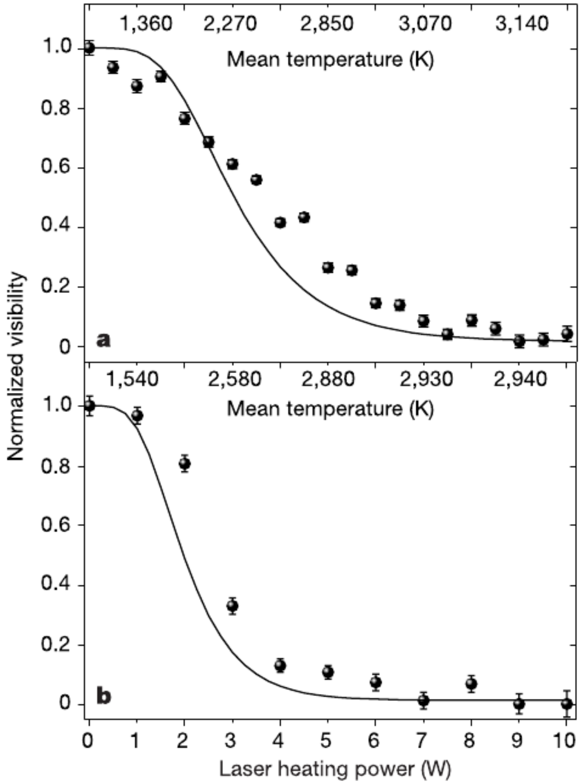
- Interference if there is no which-way information
- **BUT:** the larger the system the harder it is to isolate

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)

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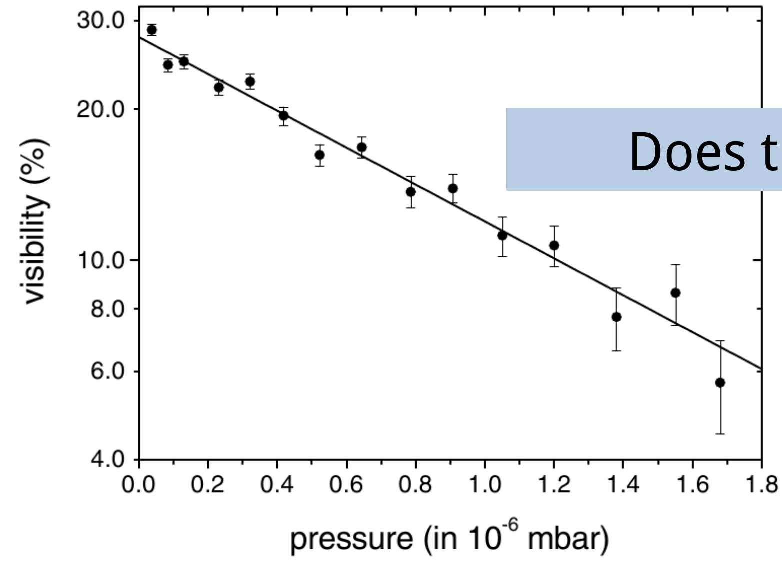

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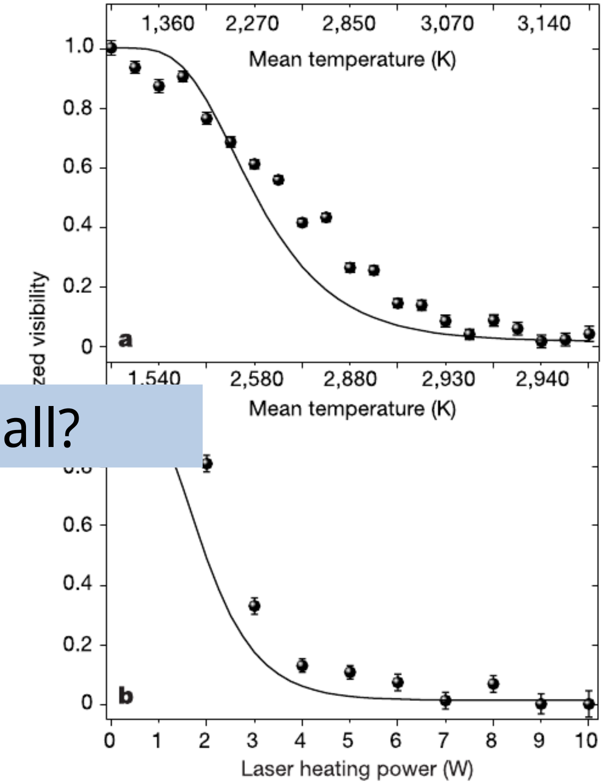
Does that explain it all?



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 sponataneous localization, Ghirardi, Pearle & Rimini, PRA 42, 78 (1990)
- Ellis, Mohanty, Nanopoulos, Phys. Lett. B 221, 113 (1989)

  - Heisenberg uncertainty → uncertainty in metric
  - randomizes phase for macroscopic superpositions

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- non-relativistic extension of QM to include Newtonian gravitation
- Schrödinger-Newton type of approach

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  - macroscopic superpositions → superposition of spacetimes
  - unstable → superposition collapses

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  - each constituent particle spontaneously collapses with rate λ
  - single collapse of constituent reduces DM of composite system

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- Ellis, Mohanty, Nanopoulos, Phys. Lett. B 221, 113 (1989)
  - quantum gravity → microscopic wormholes
  - motion of quantum system becomes entangled with wormholes – information lost in them

Decoherence

A word on notation: $\rho(\mathbf{x},\mathbf{x}') = \langle \mathbf{x}|\hat{\rho}|\mathbf{x}'\rangle = \rho(t,\mathbf{x},\mathbf{x}') = \langle \mathbf{x}|\hat{\rho}(t)|\mathbf{x}'\rangle$

$\Delta x \equiv |\mathbf{x}-\mathbf{x}'|^2$

General description (quantum theory and macrorealism):

$$\frac{\partial \rho(\mathbf{x},\mathbf{x}')}{\partial t} = \frac{1}{\mathrm{i}\hbar}\langle \mathbf{x}| \left[\hat{H},\hat{\rho}\right] |\mathbf{x}'\rangle - F(\mathbf{x}-\mathbf{x}')\cdot\rho(\mathbf{x},\mathbf{x}')$$

In the long-wavelength limit ($\lambda \gg \Delta x$):

$$\frac{\partial \rho(\mathbf{x},\mathbf{x}')}{\partial t} = -\Lambda\cdot(\mathbf{x}-\mathbf{x}')^2\cdot\rho(\mathbf{x},\mathbf{x}')$$

M. R. Gallis & G. N. Fleming, PRA **42**, 38 (1990) & G. N. Fleming, Found. Phys. **20**, 159 (1990)

- Macrorealism predicts decoherence **on top of** quantum decoherence.
- To test macrorealistic models, quantum decoherence has to be **very** low.

$\partial\hat{\rho}$ [redacted]

Decoherence

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In macrorealism: strongly dependent on mass

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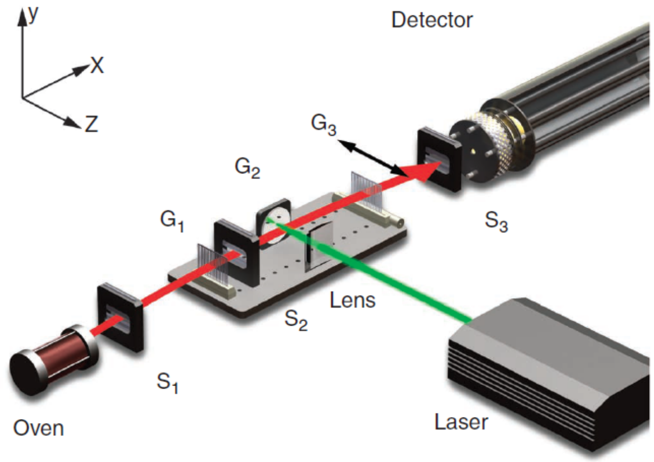
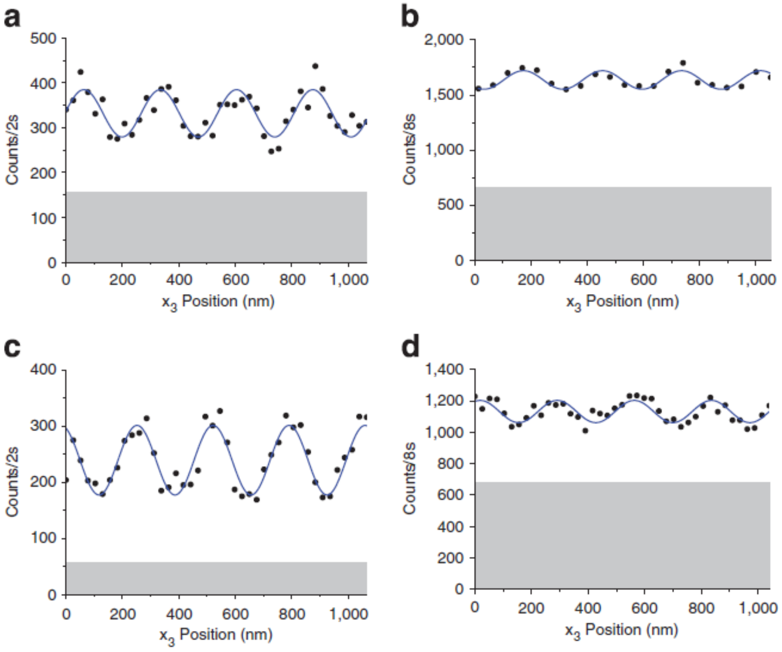
- To test macrorealistic models, quantum decoherence has to be **very** low.

Can we test it experimentally?

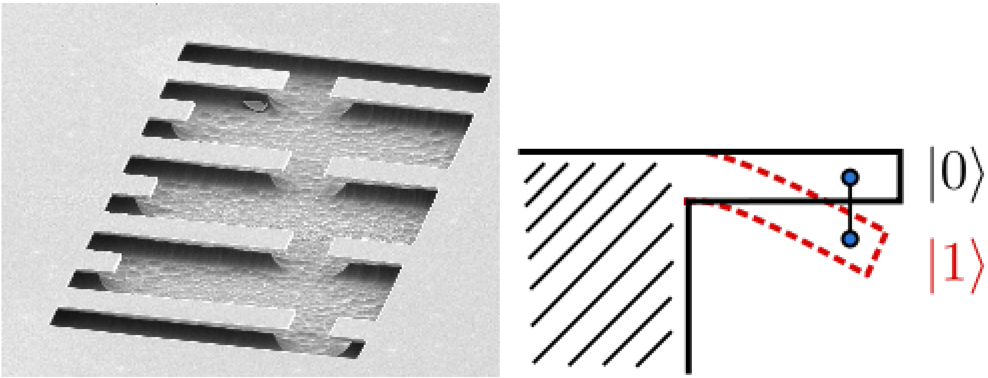
Matter-wave interferometry



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



Quantum Optomechanics



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

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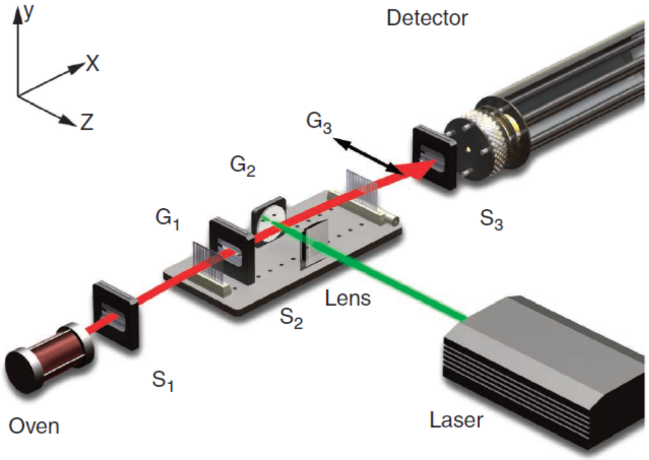

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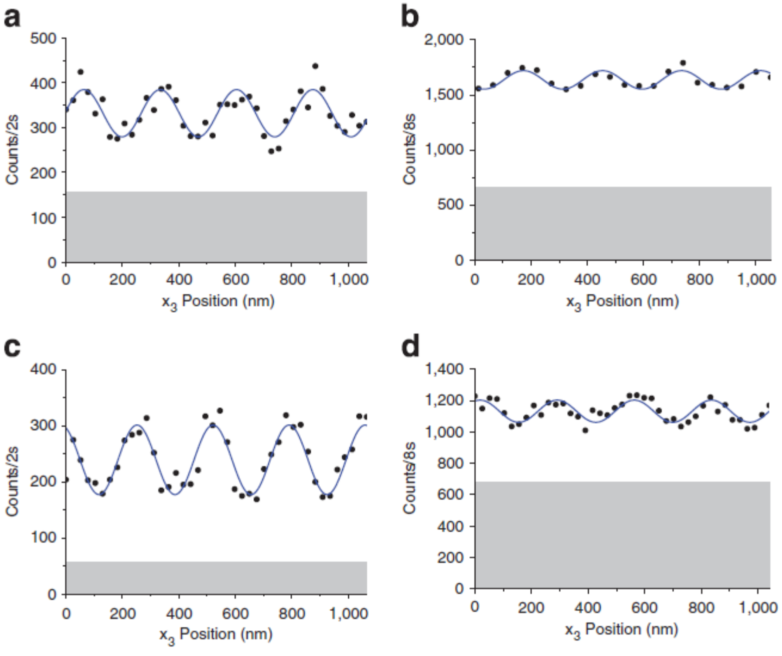

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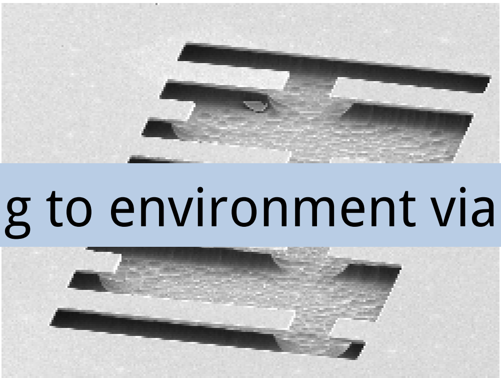
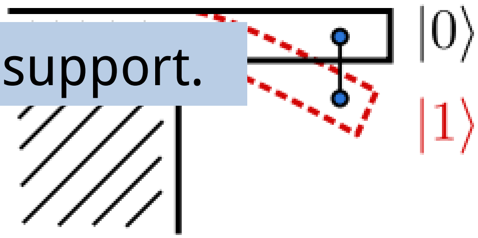




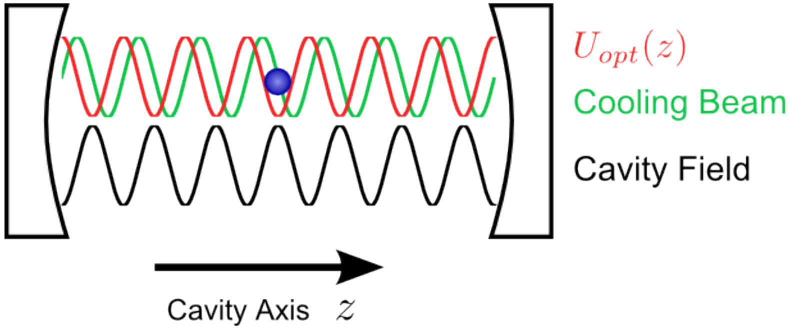
Disadvantage: coupling to environment via support.

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

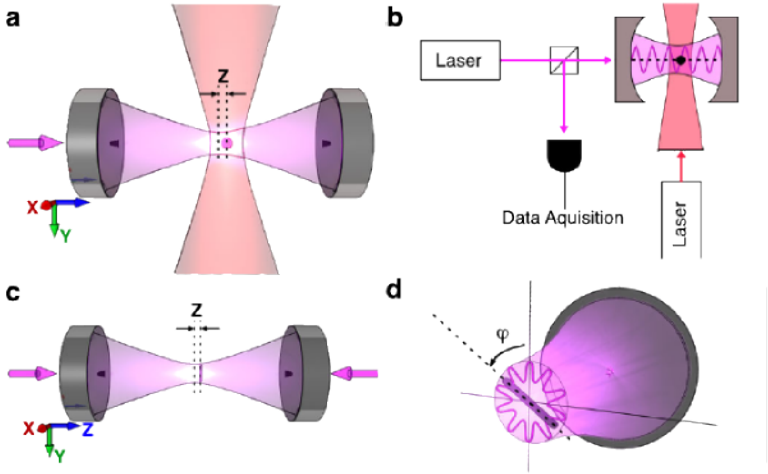
Optically trapped nanospheres

- 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)

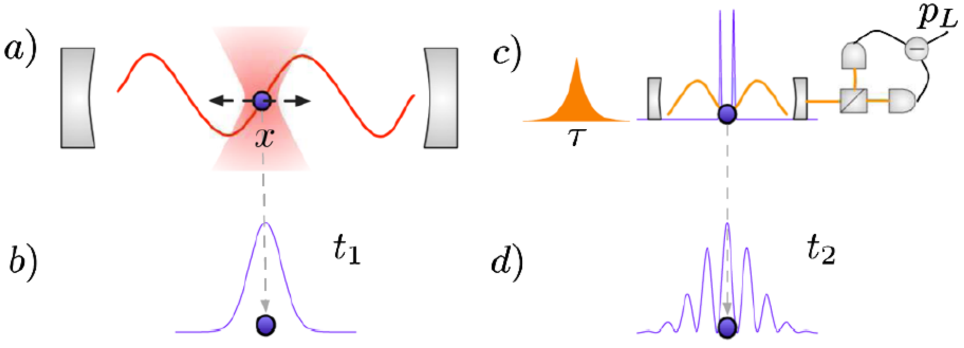


O. Romero-Isart et al., New J. Phys. 12, 033015 (2010)
O. Romero-Isart et al., PRA 83, 013803 (2011)

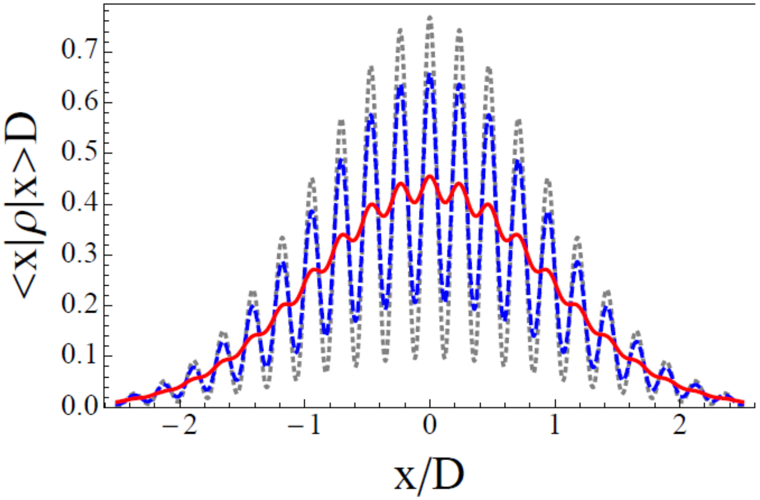


Double-slit with nanospheres

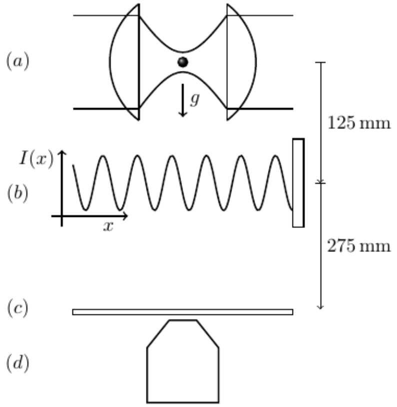
Ground-based experiments

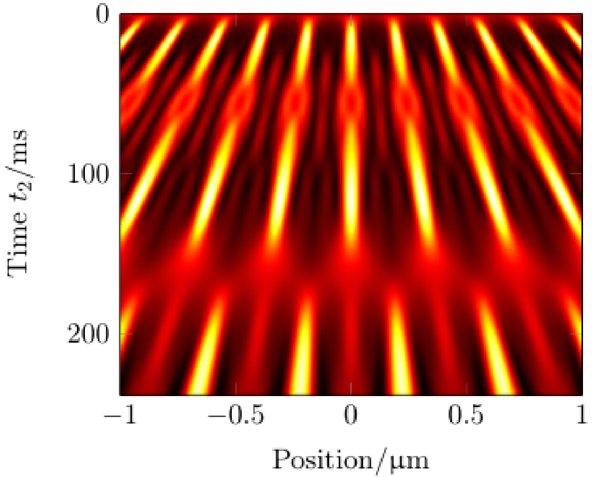


O. Romero-Isart , A. Pflanzer et al., PRL **107**, 020405 (2011)



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

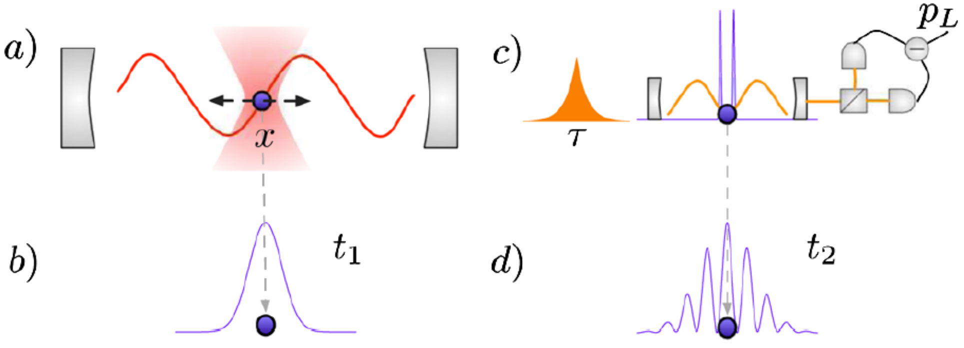




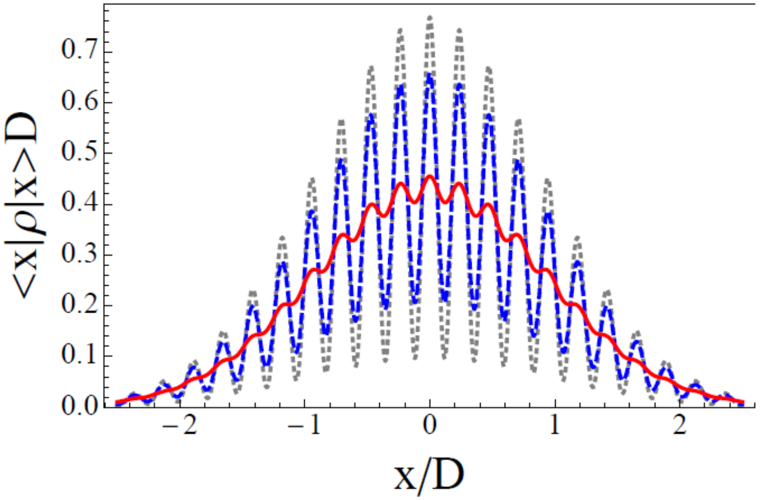
J. Bateman, S. Nimmrichter, K. Hornberger, H. Ulbricht
quant-ph/arXiv:1312.0500 (2013)

Double-slit with nanospheres

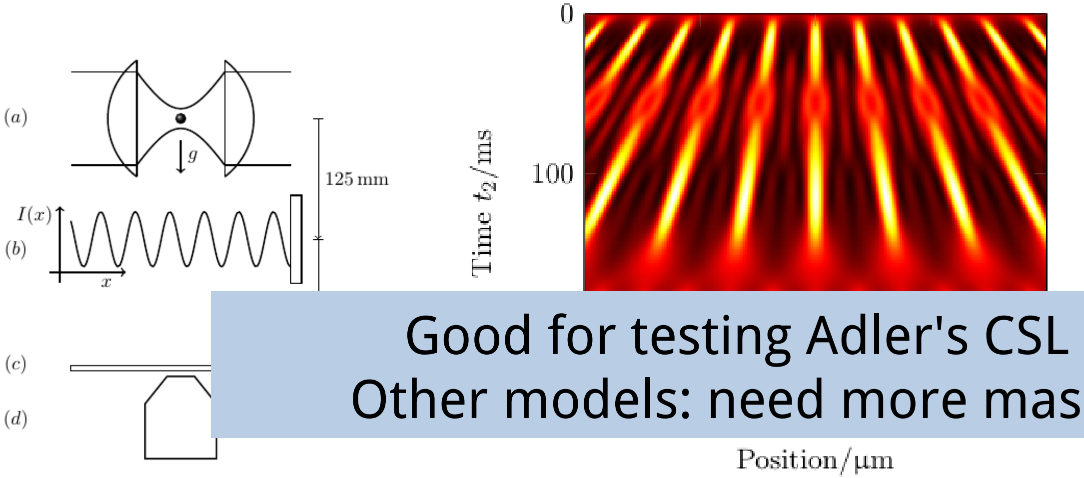
Ground-based experiments



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



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

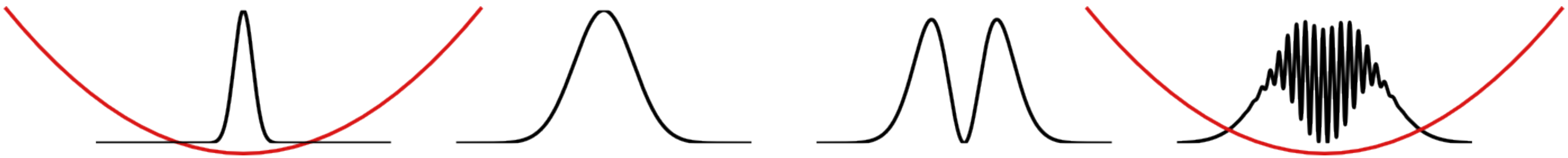


Good for testing Adler's CSL parameter
Other models: need more massive particles

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

Go to space → MAQRO

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



cool expand prepare expand, then measure

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 → space?

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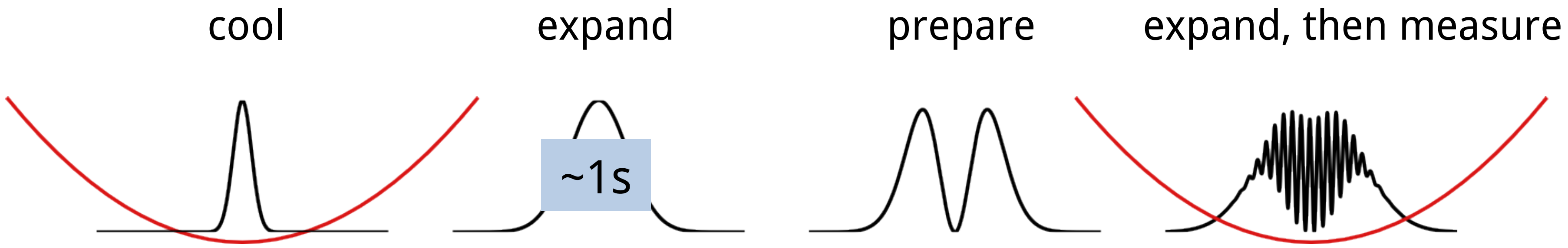

R. Kaltenbaek et al., Cosmic Vision proposal MAQRO (2010)
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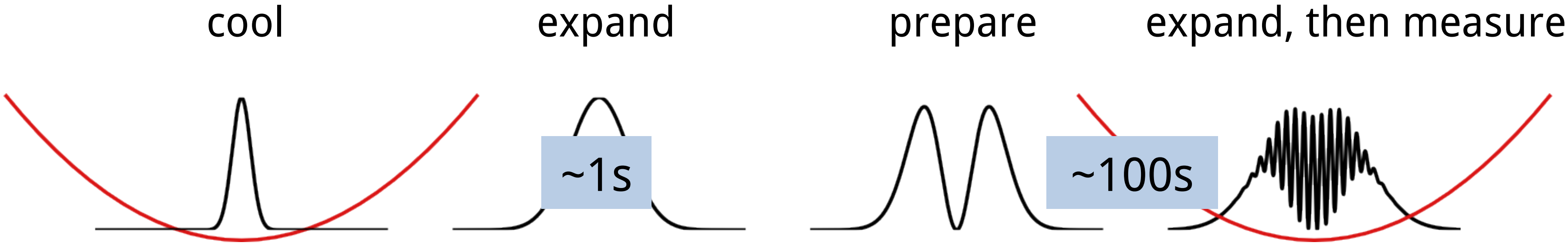
cool
expand
prepare
expand, then measure

~1s
~100s

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

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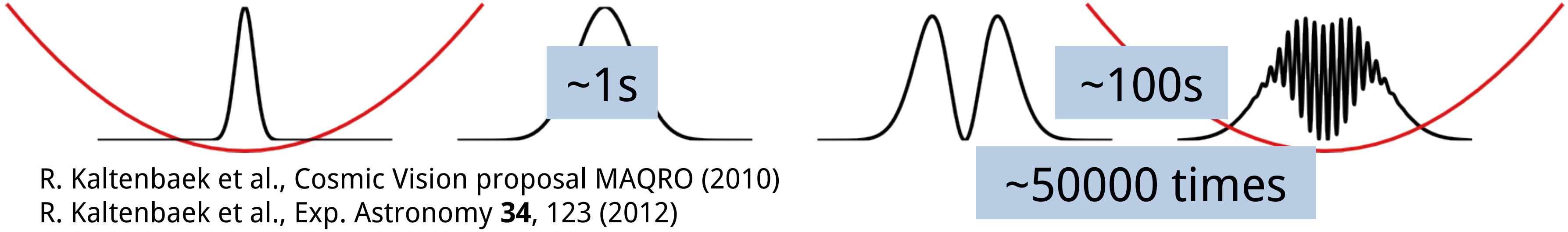

R. Kaltenbaek et al., Cosmic Vision proposal MAQRO (2010)
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The double slit in MAQRO

local decoherence via a short, tightly focused UV pulse

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

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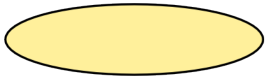

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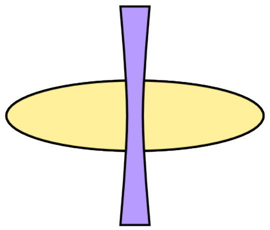

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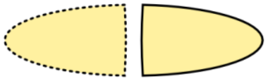
Localized

Incoherent mixture of two states



Superposition

The double slit in MAQRO

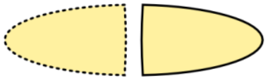
local decoherence via a short, tightly focused UV pulse

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

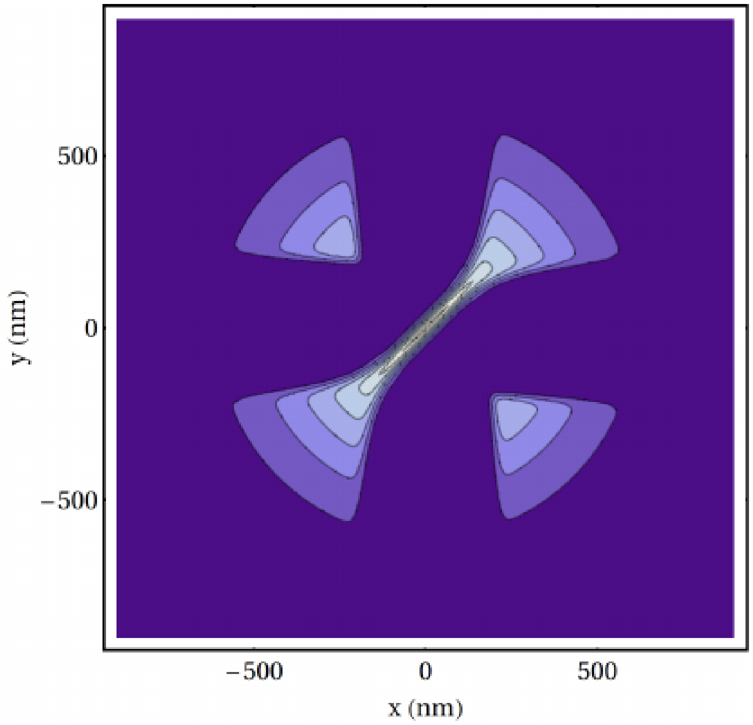
The density matrix: $\rho(x,y) = \langle x|\hat{\rho}|y\rangle$

Localized

Incoherent mixture of two states

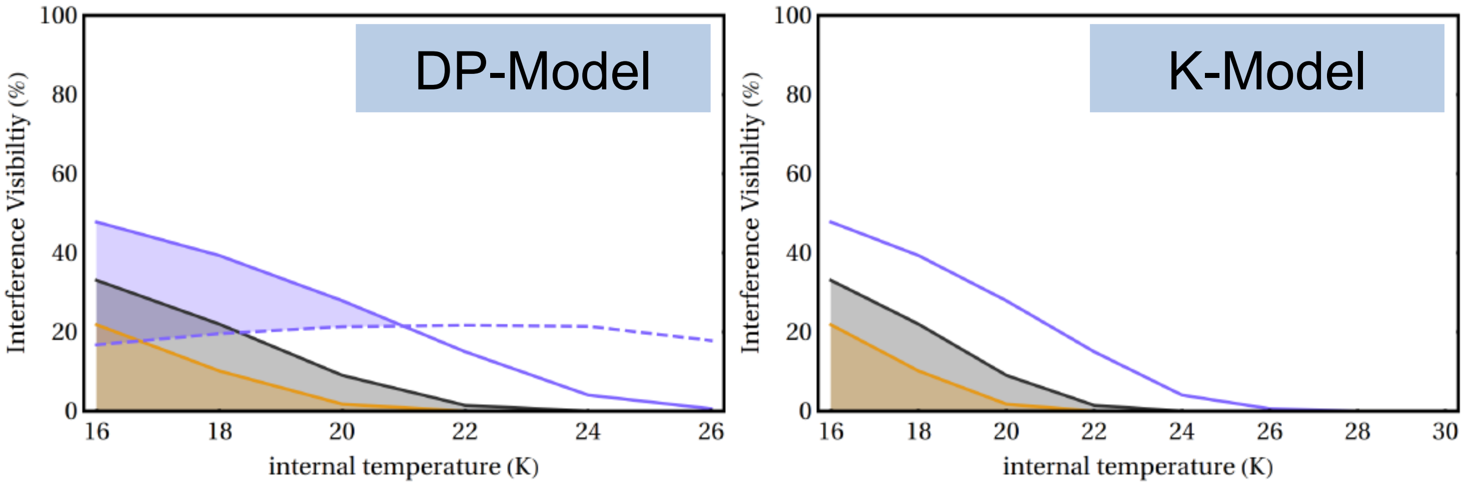


Superposition

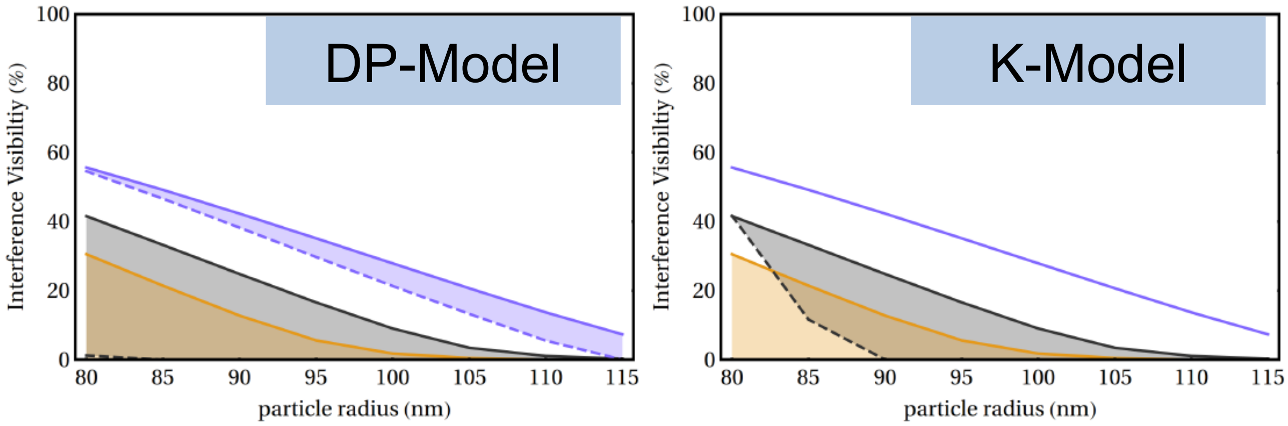


Theoretical estimates

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



Visibility over particle radius:



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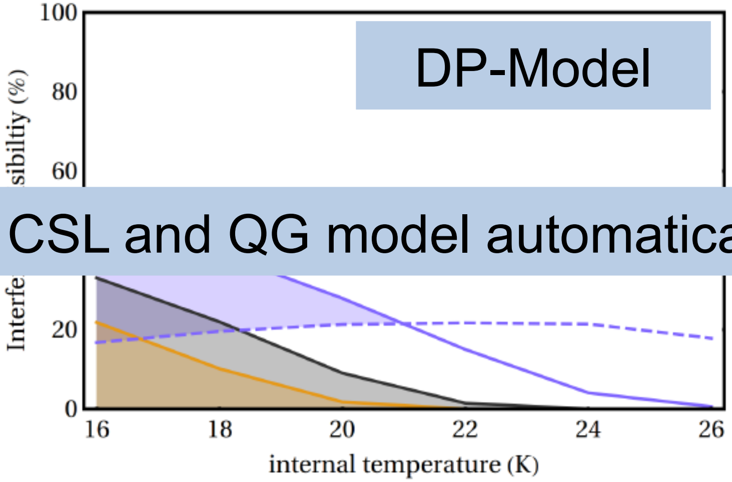
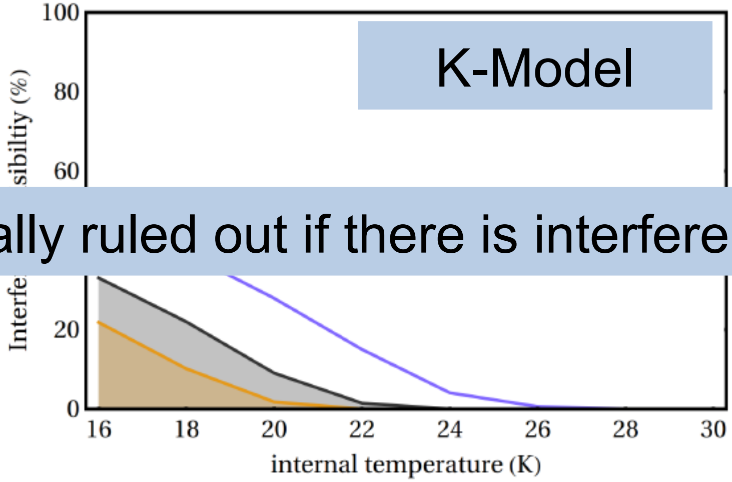
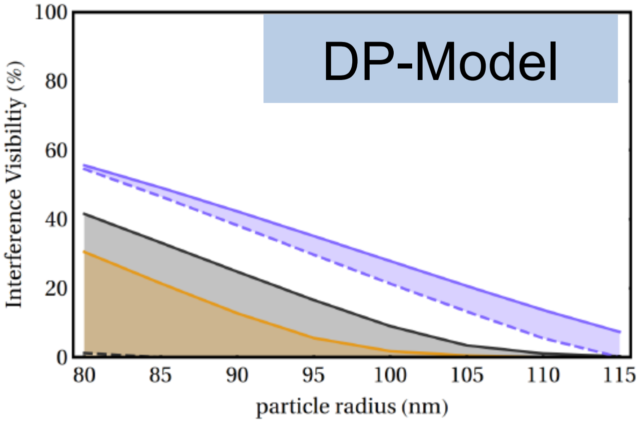
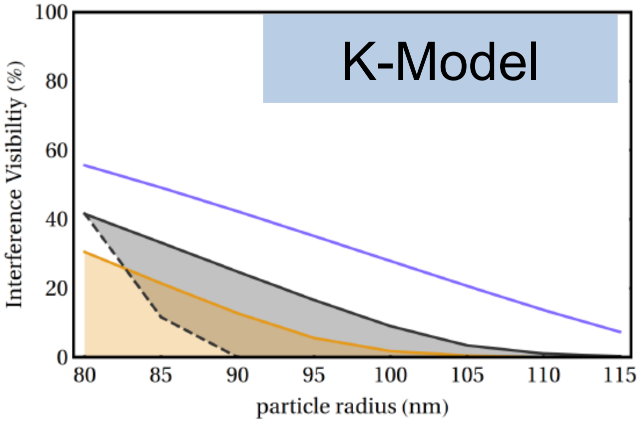




CSL and QG model automatically ruled out if there is interference

Visibility over particle radius:





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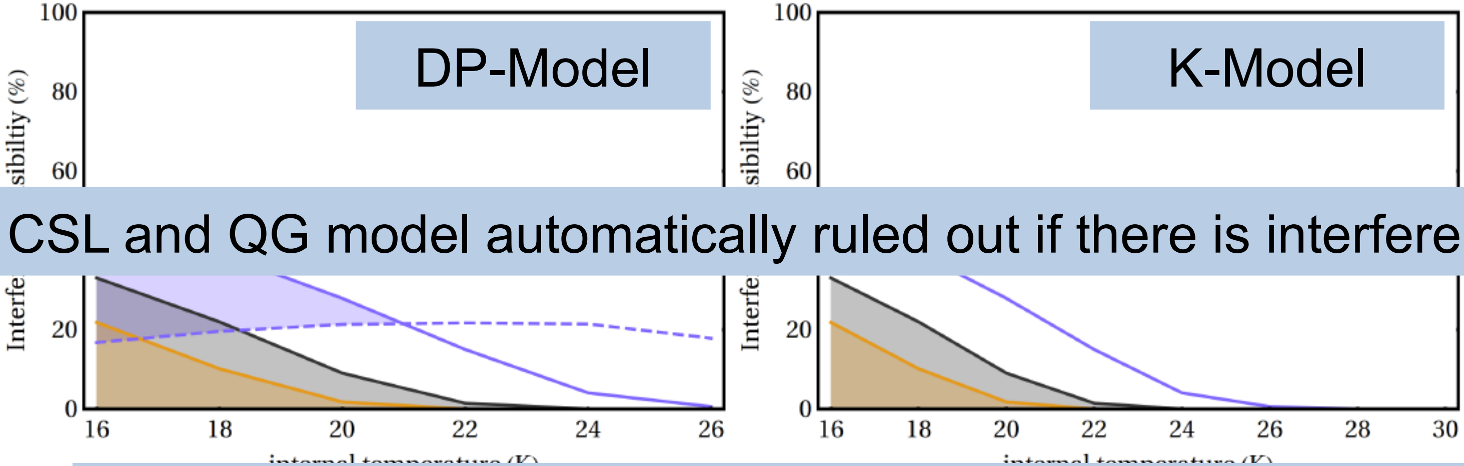
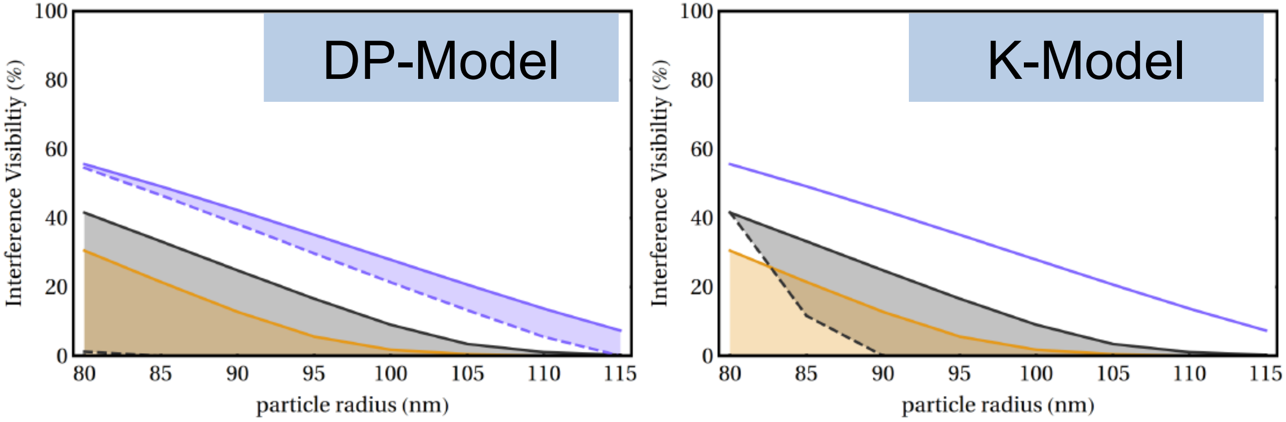


CSL and QG model automatically ruled out if there is interference

Visibility

Tests of K model only for high mass densities

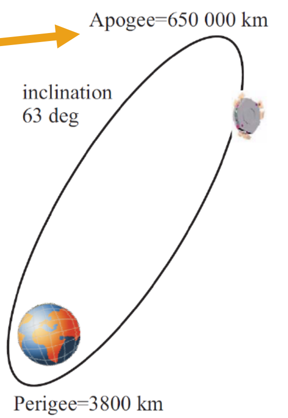


The (original) MAQRO mission proposal

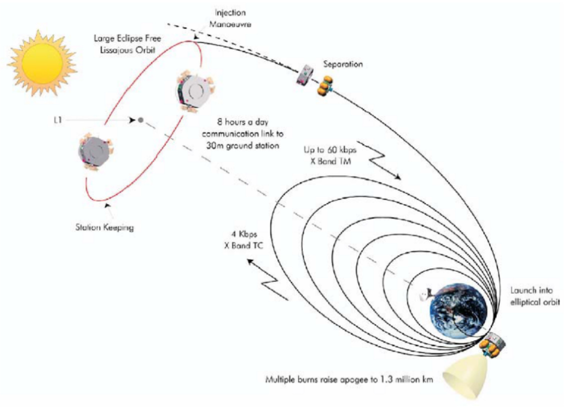
Two independent scientific instruments:

1. DECIDE (**dec**oherence **i**n a **d**ouble-slit **e**xperiment)
2. CASE (**c**omparative **a**cceleration **se**nsor)

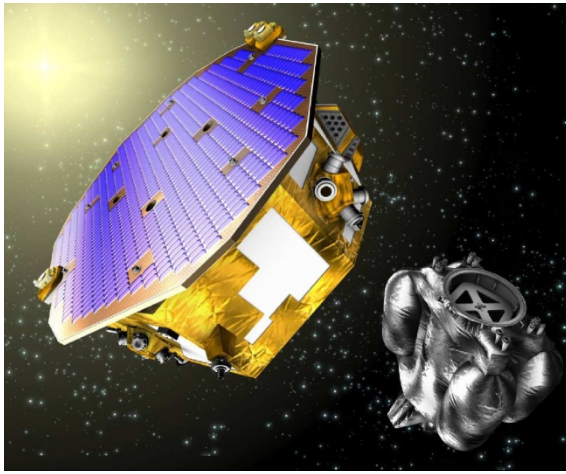
Highly eccentric orbit



L1- Lissajous orbit



- Spacecraft as in LISA Pathfinder
- Technological Heritage (LTP)
- L1 or L2 orbit ideal for DECIDE
- Alternative: highly-eccentric orbit



MAQRO, mission proposal 2010 - R. Kaltenbaek, G. Hechenblaikner, N. Kiesel, O. Romero-Isart, K. C. Schwab, U. Johann & M. Aspelmeyer, Exp. Astron. **34**, 123 (2012)

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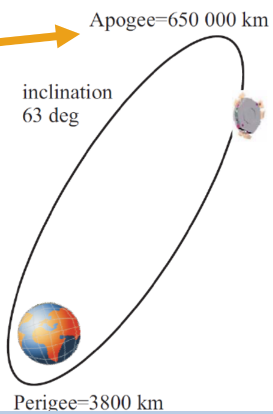

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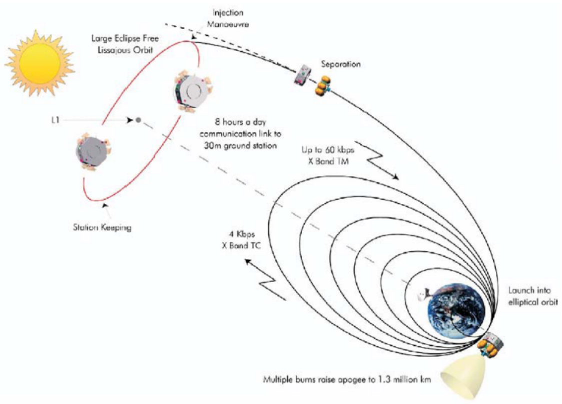
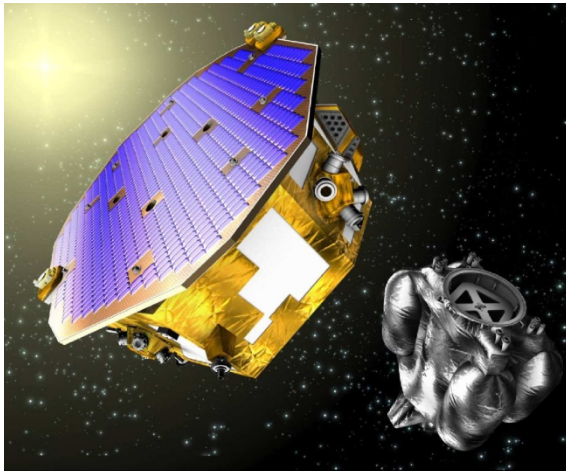


We concentrate on DECIDE

- Spacecraft as in LISA Pathfinder
- Technological Heritage (LTP)
- L1 or L2 orbit ideal for DECIDE
- Alternative: highly-eccentric orbit



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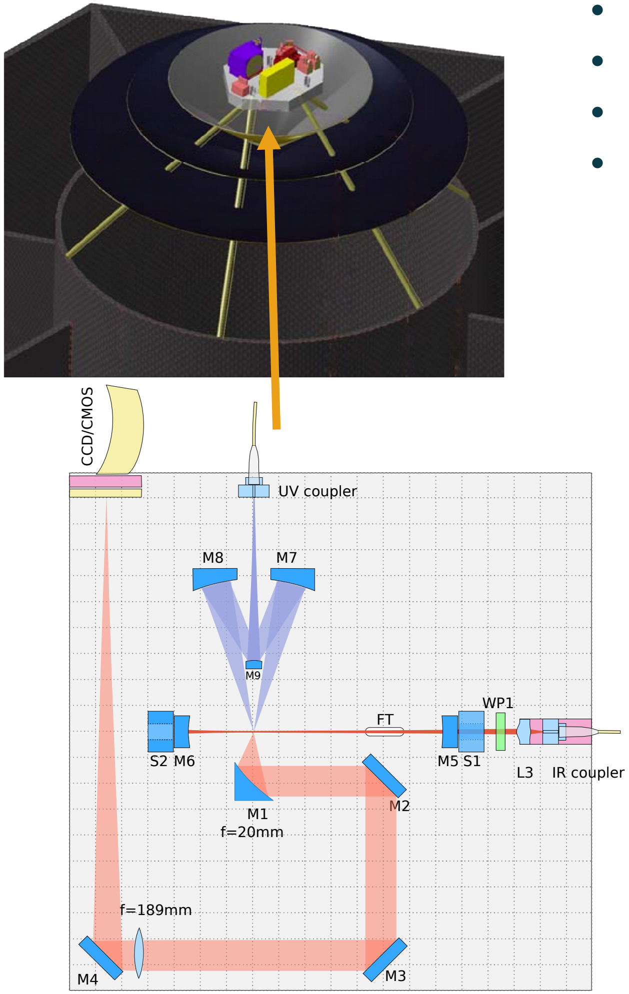
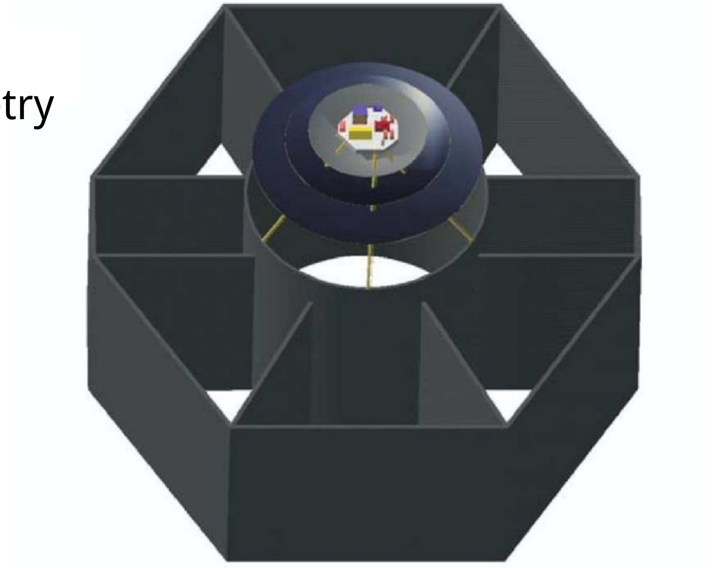
MAQRO mission design

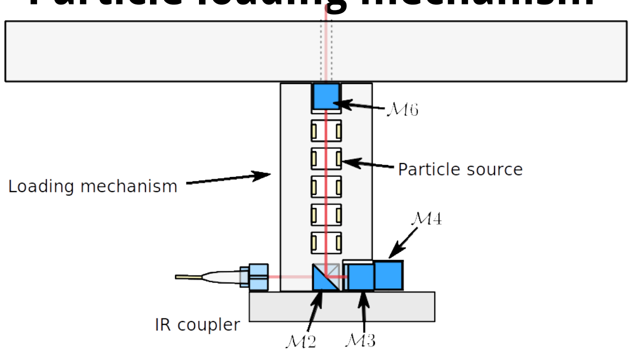


Matter-wave interferometry with massive particles (10^9 - 10^{11} amu)

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

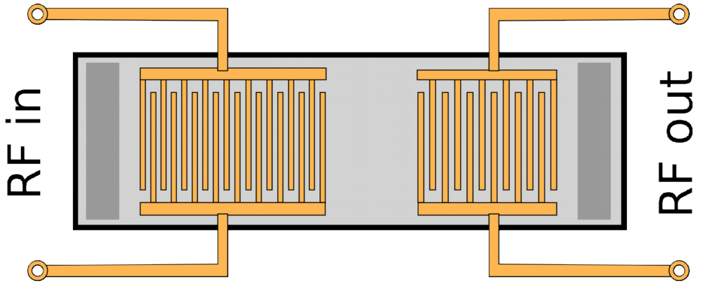


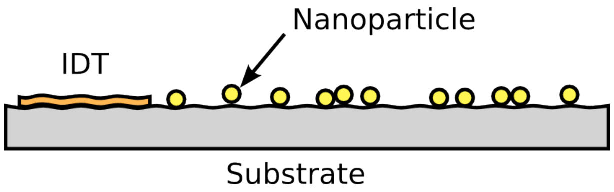
Particle loading mechanism



Surface acoustic waves

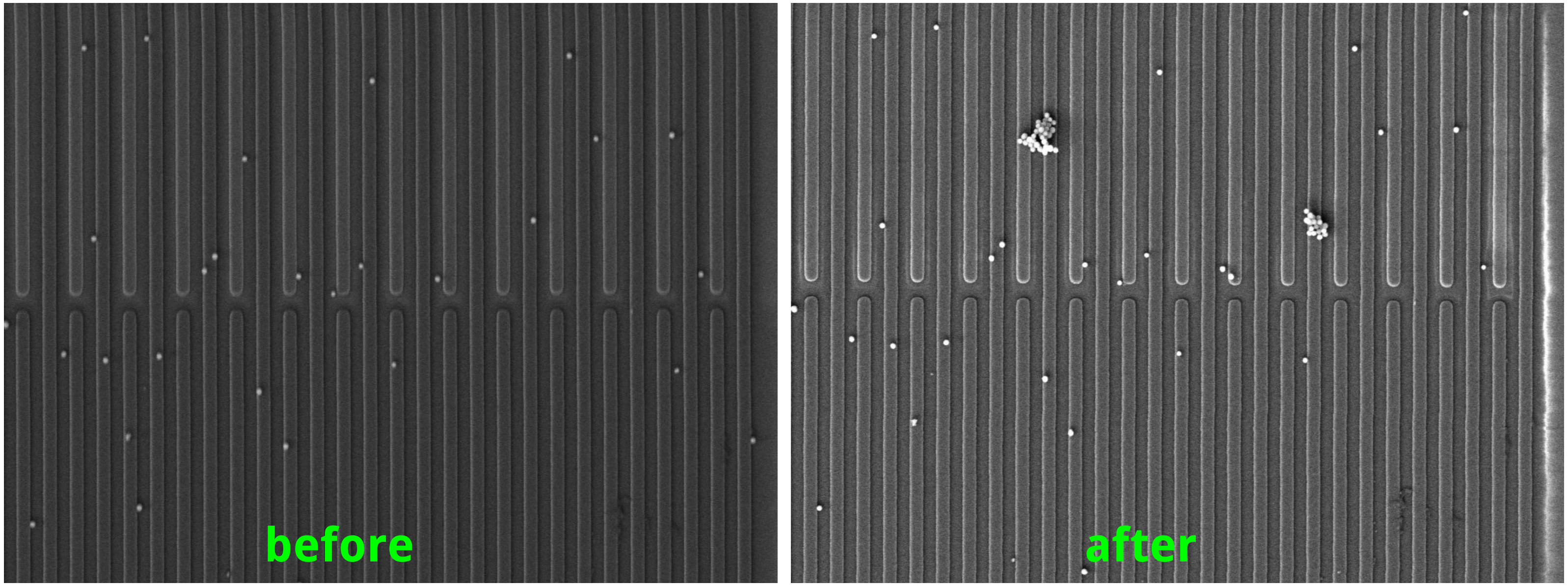
Surface Acousitc Wave (SAW) devices to release nanoparticles





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



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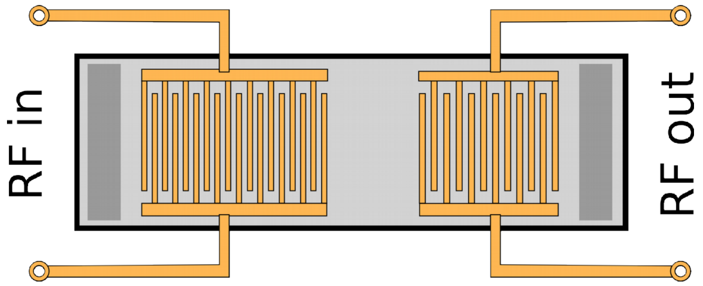

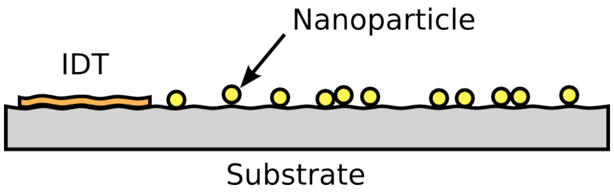

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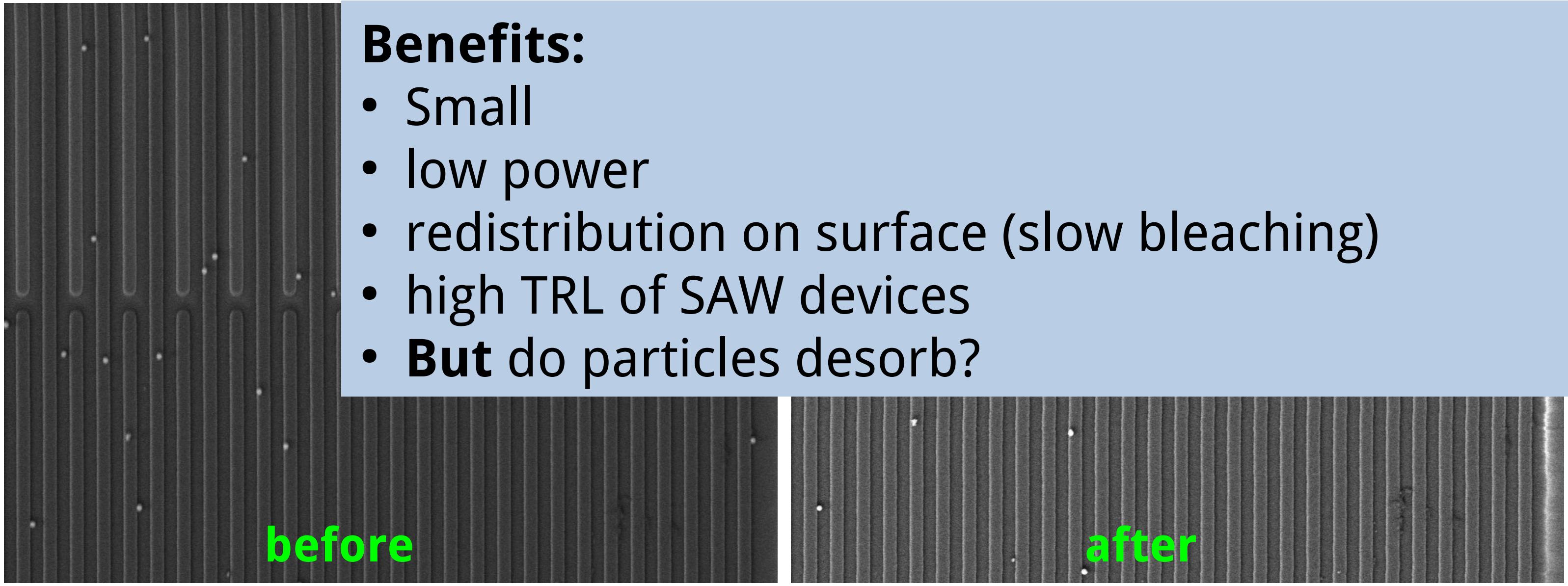
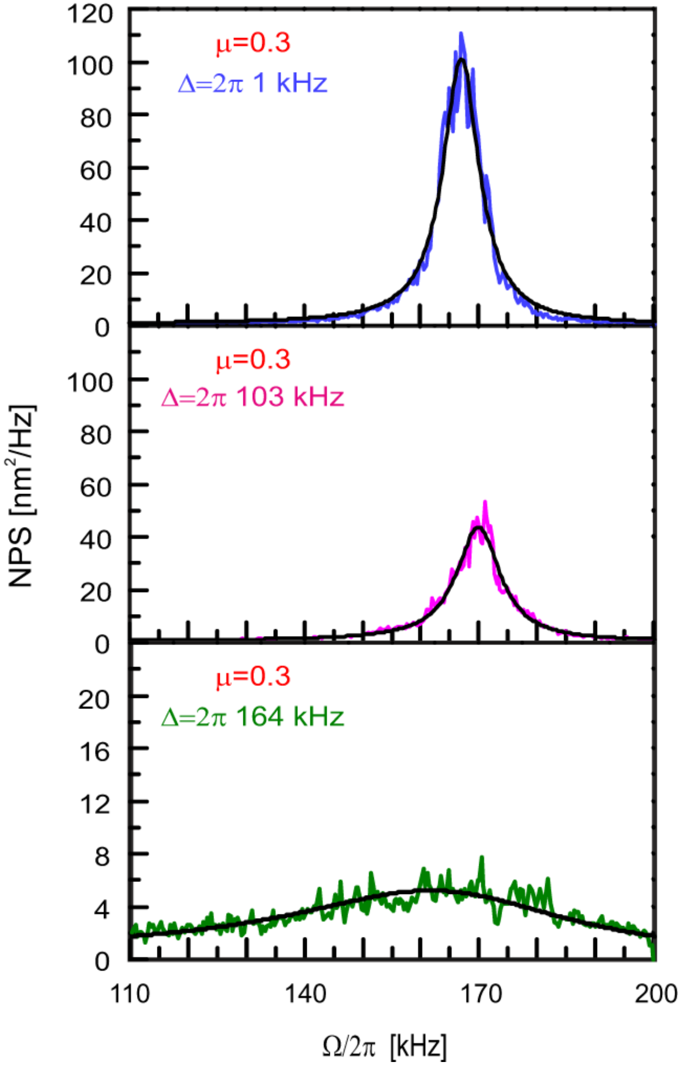


Benefits:
- Small
- low power
- redistribution on surface (slow bleaching)
- high TRL of SAW devices
- **But** do particles desorb?

Cavity cooling in our lab

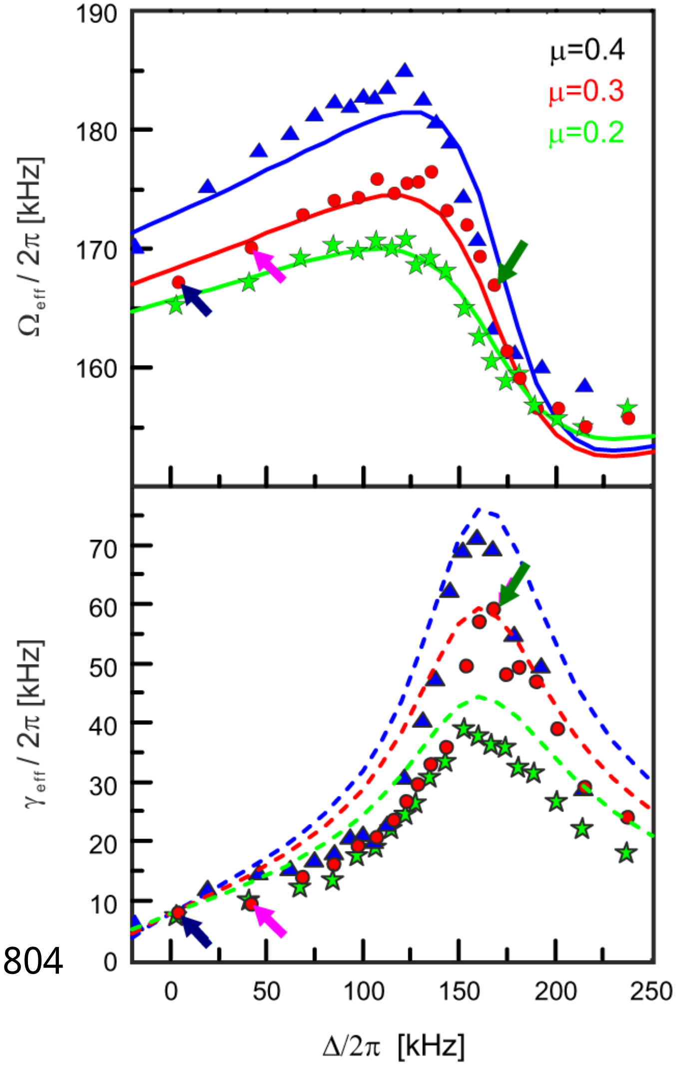
Cavity cooling



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



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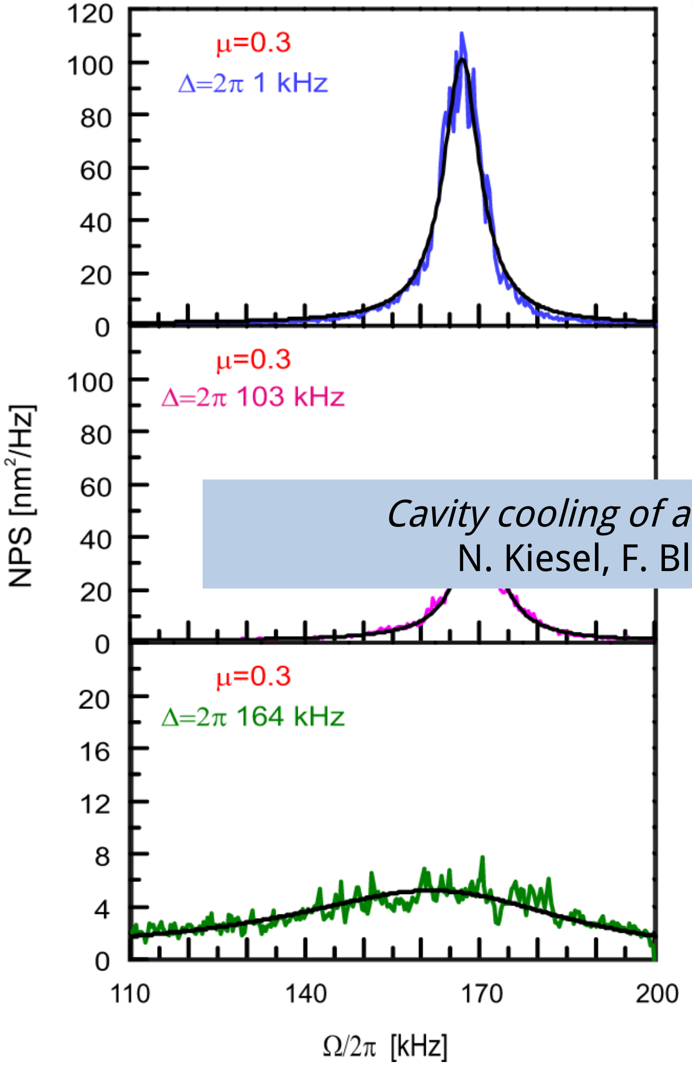

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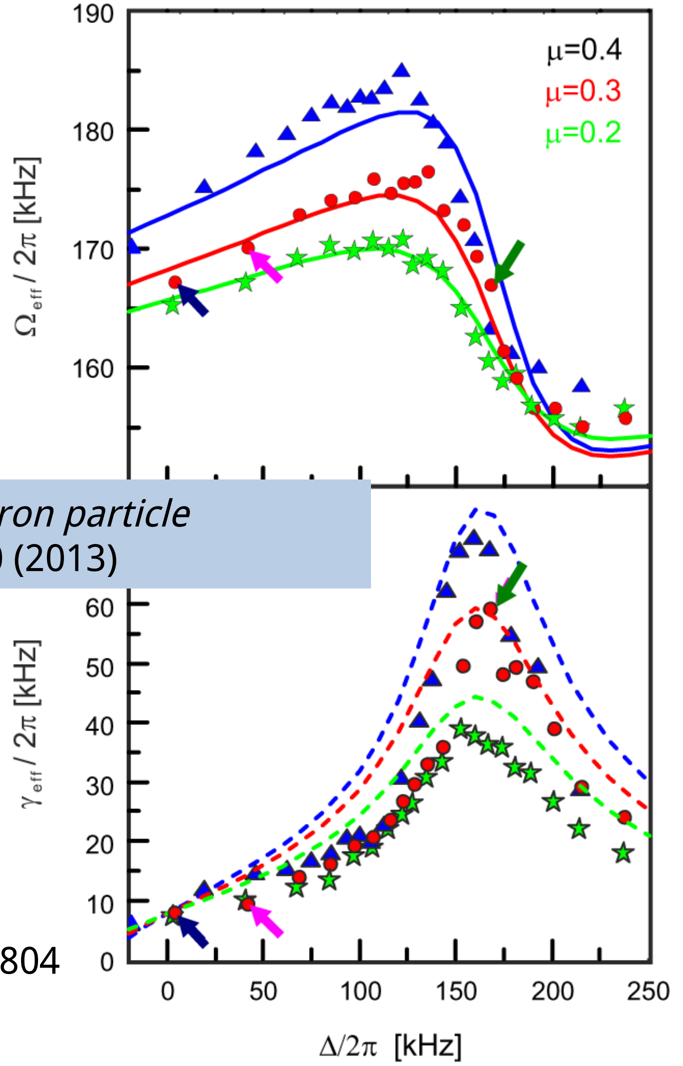


Cavity cooling of an optically levitated submicron particle
N. Kiesel, F. Blaser et al., PNAS **110**, 14180 (2013)

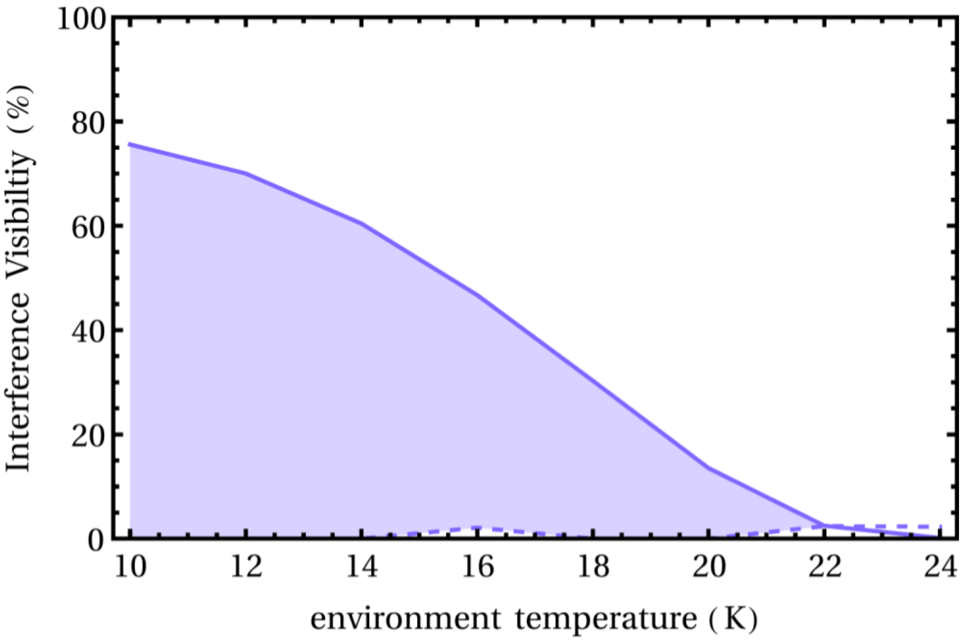
Optical damping
modification of damping depending on detuning

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

Detailed thermal analysis

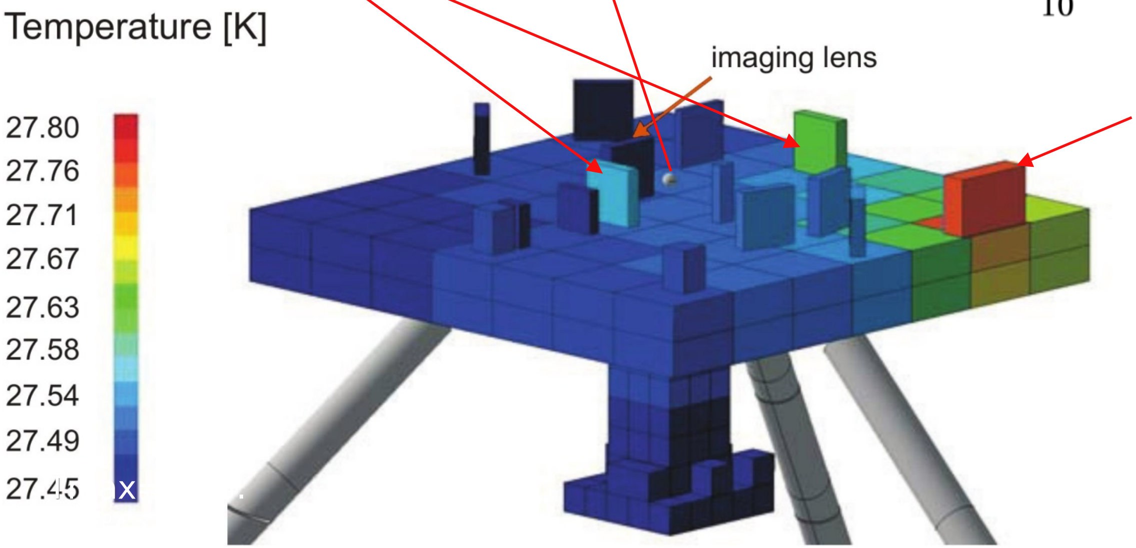
Analysis results:

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

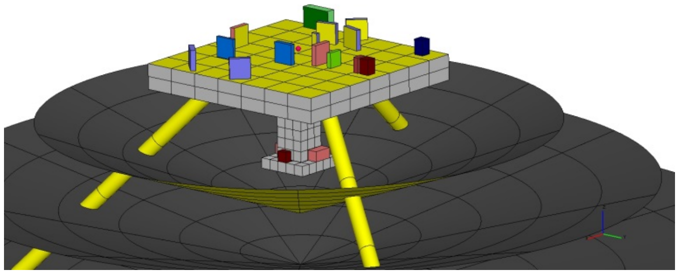


Cavity mirrors
(+0.1 K w.r.t. bench)

Test volume
(-11.1 K w.r.t. bench)



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)

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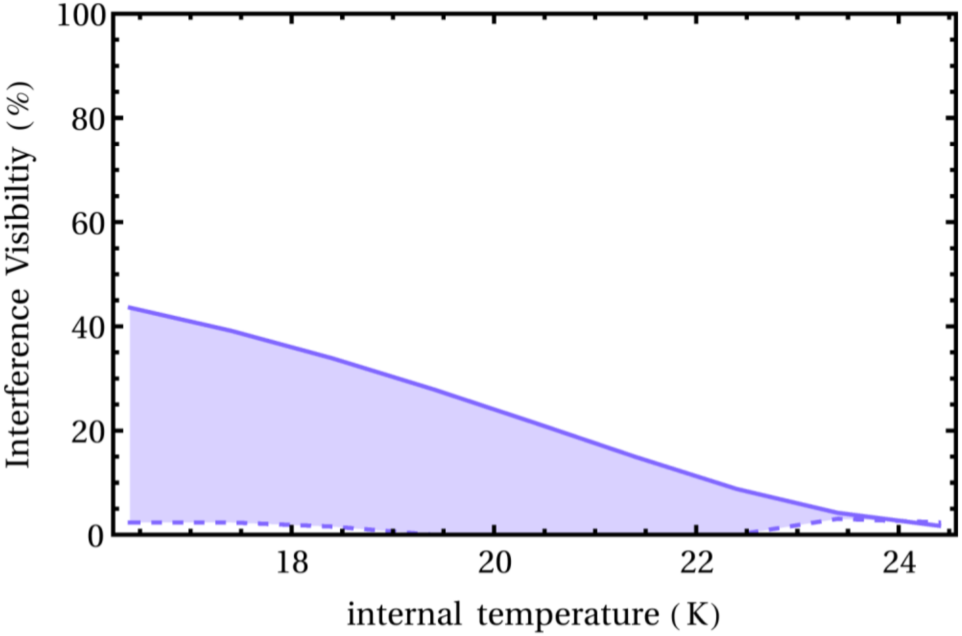

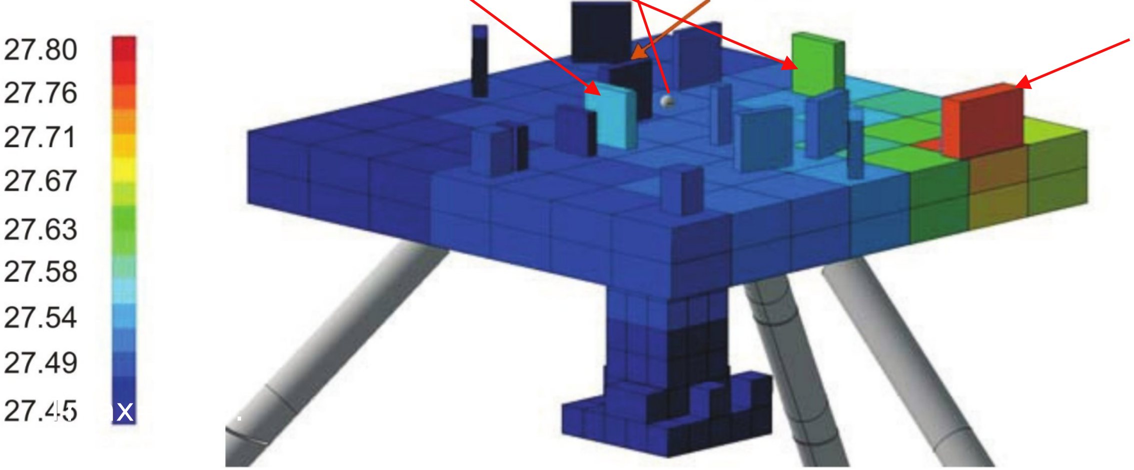

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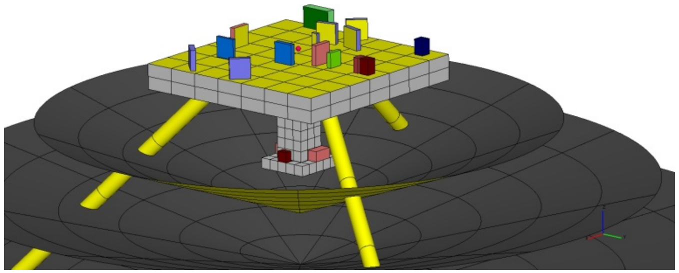

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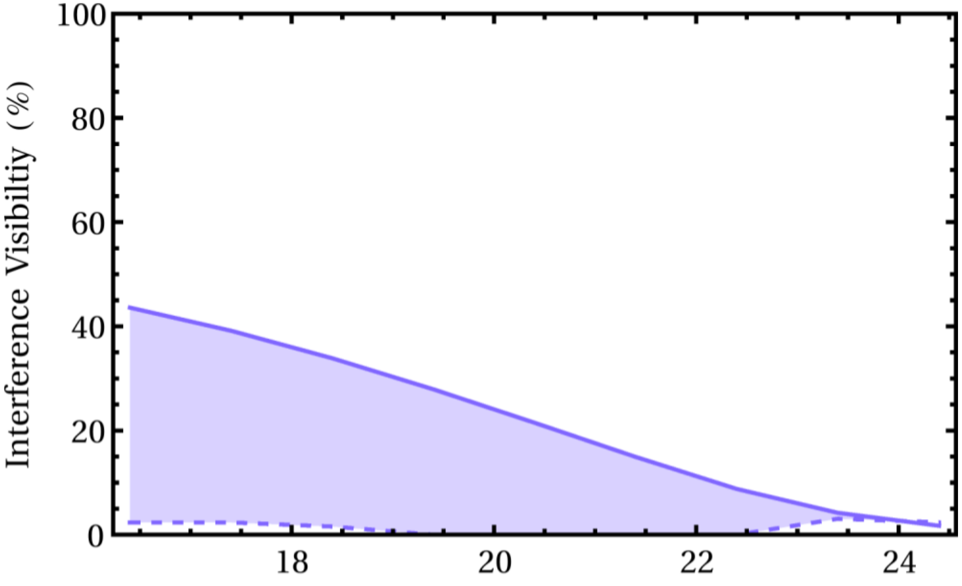

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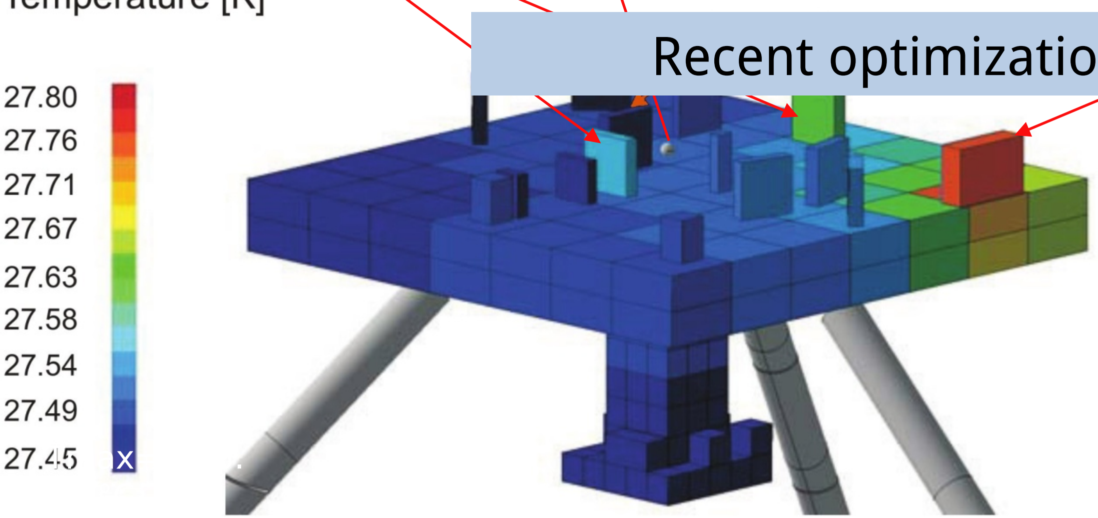
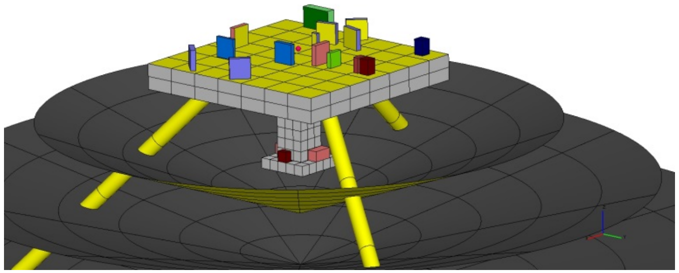
Test volume
(-11.1 K w.r.t. bench)

Recent optimization: ~ 12K

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

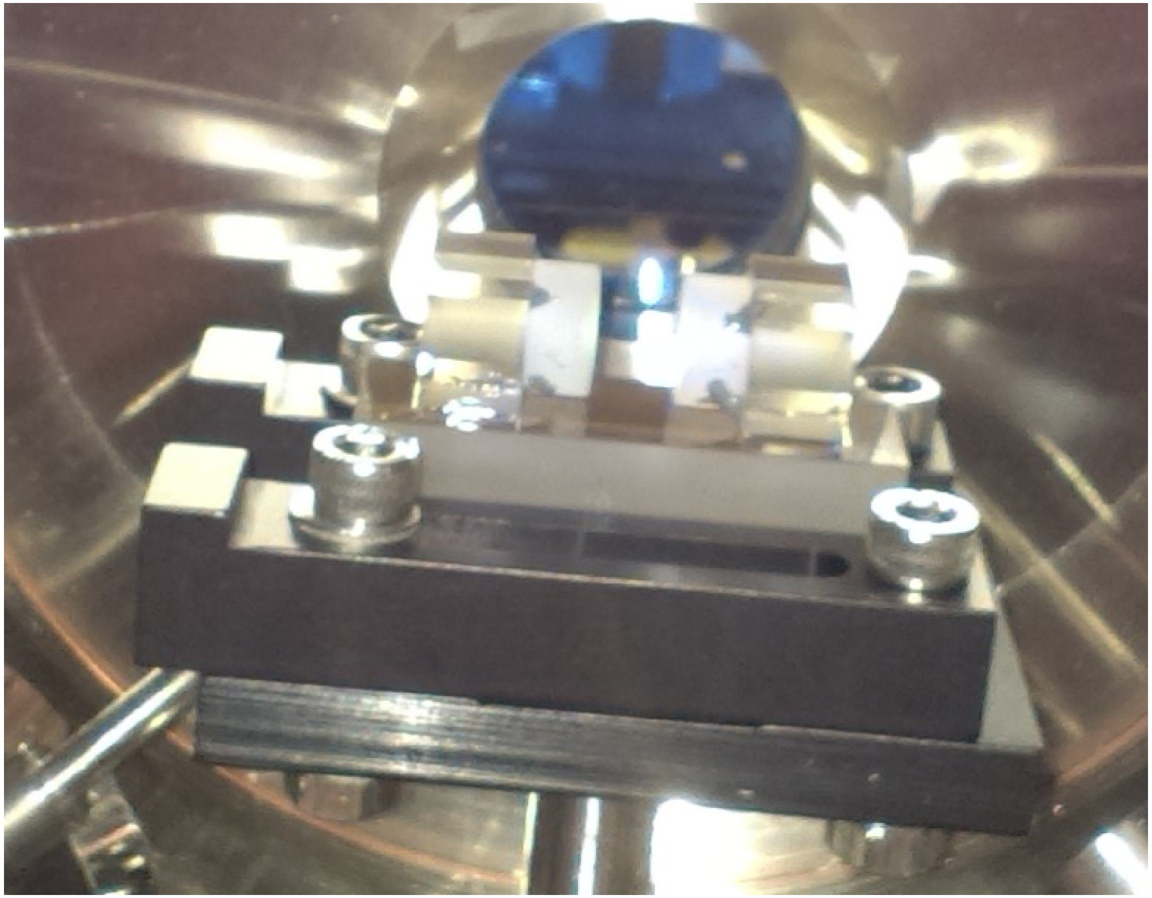




How cold can you get in space? Quantum physics as cryogenic temperatures in space,
G.. Hechenblaikner, F. Hufgard, J. Burkhardt, N. Kiesel, U. Johann, M. Aspelmeyer & R. Kaltenbaek, NJP **16**, 013058 (2014)

Space-proof cavity design

Test-cavity using space-proof gluing technology



Conclusions & Outlook

- Promising results
- Still a long way to go
- M4 Cosmic Vision call expected soon

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, C. Braxmaier, U. Johann

Thanks for discussions:

G. Cole

F. Blaser

D. Grass

M. Arndt

!THANK YOU!

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APART
Austrian Program for Advanced Research and Technology

ÖAW
Österreichische Akademie der Wissenschaften

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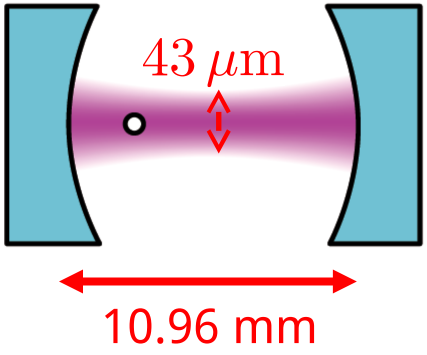
STREP MINOS
ERC Starting Grant

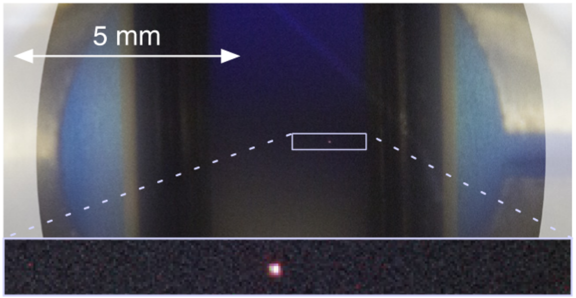
FWF
START
P15939
L426

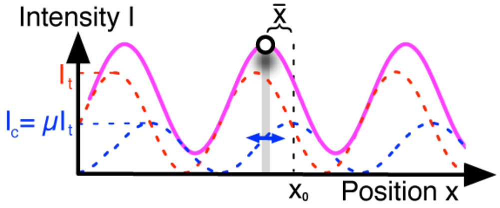
ASAP project
Nr. 3589434
FFG

Cavity cooling in our lab I/II

Near confocal cavity







Cavity Linewidth

$$\kappa = 180\,\mathrm{kHz}$$

Free Spectral Range

$$\mathrm{FSR} = 13.667\,\mathrm{GHz}$$

Finesse

$$\mathcal{F} = 78000$$