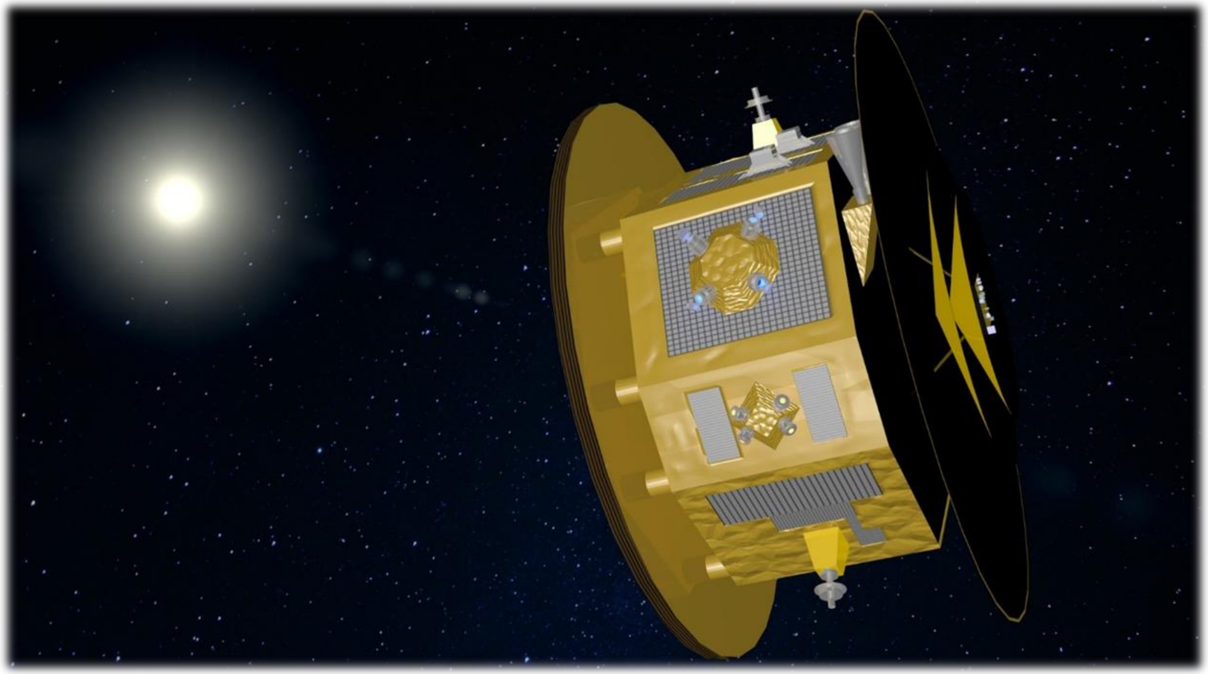
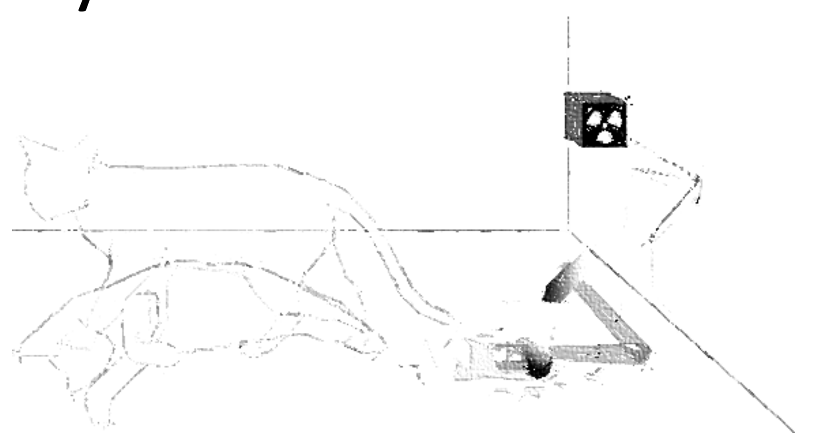


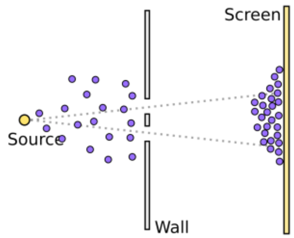
Towards a space platform for macroscopic tests of quantum physics

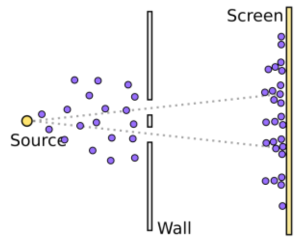
Rainer Kaltenbaek

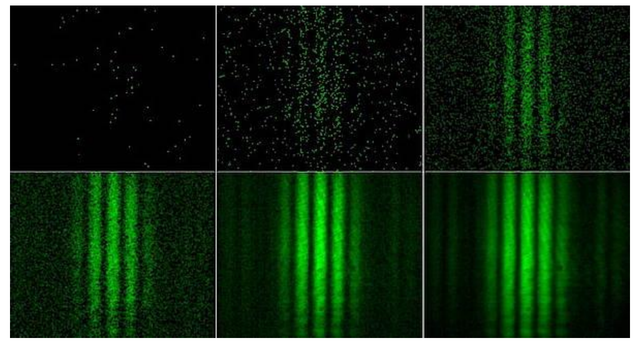


Science case

Testing quantum physics – the superposition principle

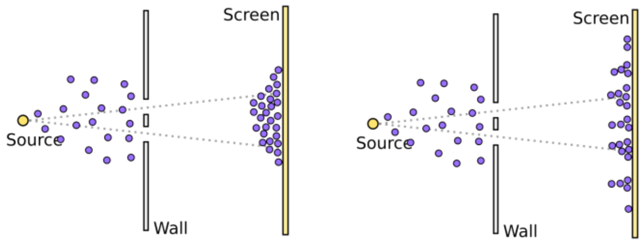


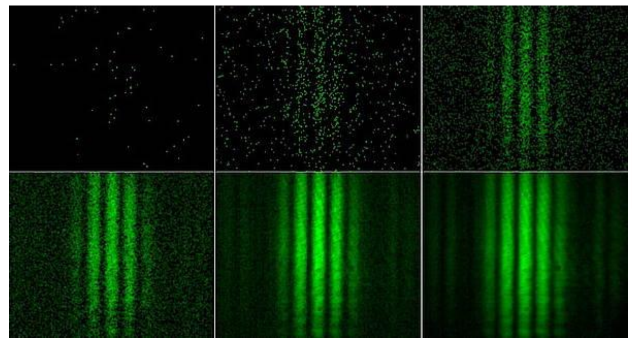




Science case

Testing quantum physics – the superposition principle

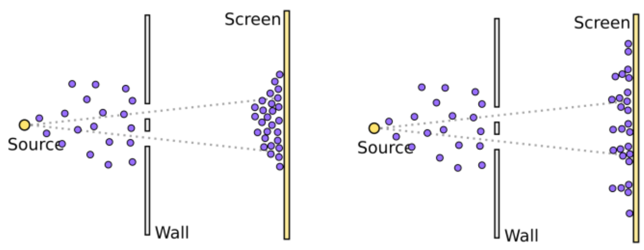


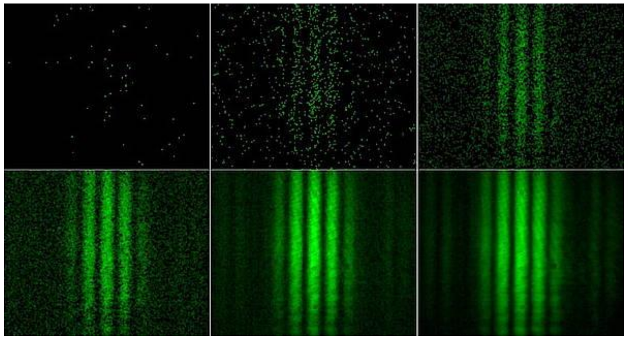


With high-mass particles

Science case

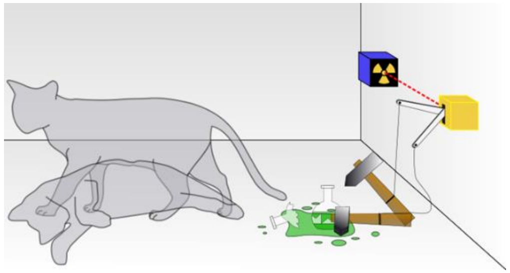
Testing quantum physics – the superposition principle



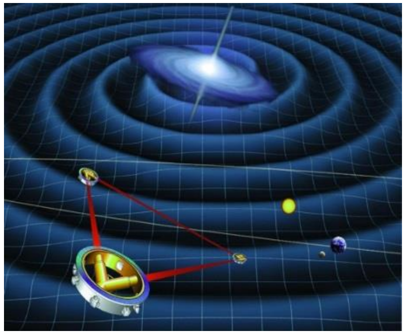


With high-mass particles

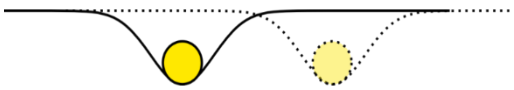
What could we learn?



Quantum – Classical



Gravitational decoherence?

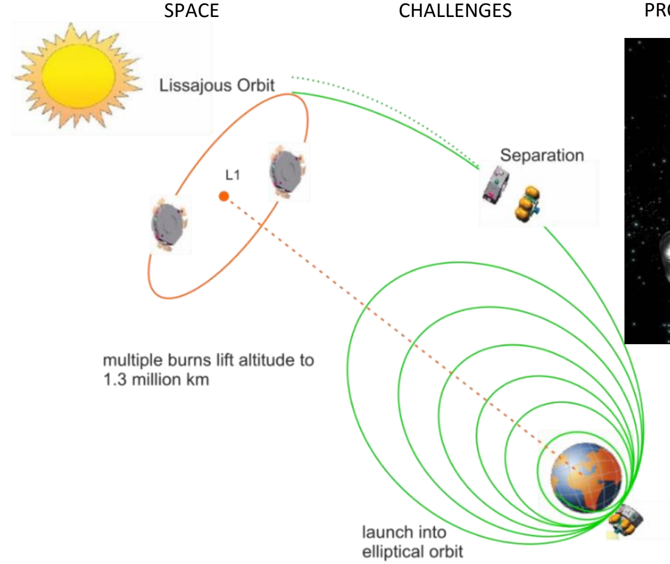


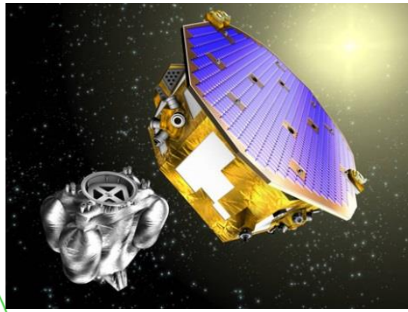
New physics?

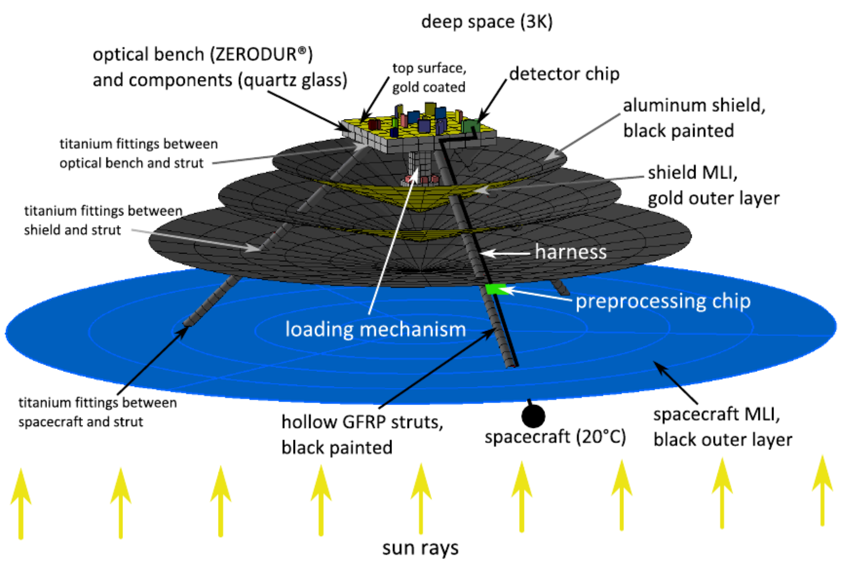
MAQRO – mission proposal

Platform to test quantum physics in space

2010 – first proposal ("M3")
2015 – updated proposal ("M4")
2016 – "New Science Ideas"
2018 – study at ESA's CDF







R. Kaltenbaek & MAQRO consortium,
EPJ Quantum Techn. **3**, 5 (2016)

A. Pilan Zanoni et al,
Appl. Therm. Engin. **107**, 689 (2016)

Launch & operation of LISA Pathfinder

Study at ESA‘s Concurrent Design Facility

Model-based study at ESA‘s CDF, 15.5.18 – 10.7.18.
”Phase 0“ mission analysis to identify

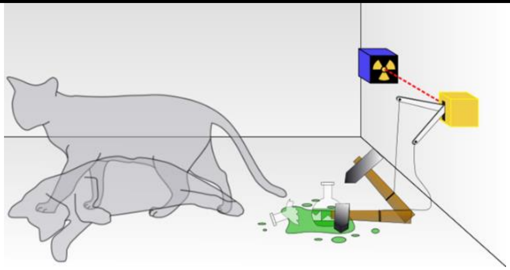
- Science goals
- Science requirements
- Experiments to be performed
- Case for space
- Critical challenges & technical solutions
- Technology to be developed
- Mission & orbit configuration

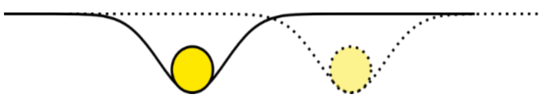
Quantum physics platform in space (QPPF)

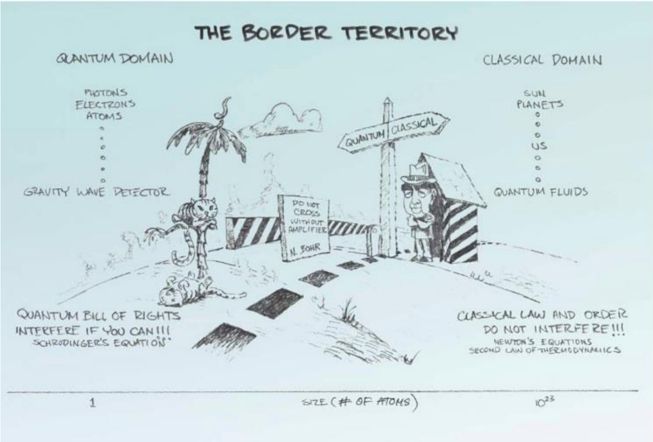
ESA’s “Concurrent Design Facility”

Science goals I/III – overview of objectives

Testing quantum physics – the superposition principle



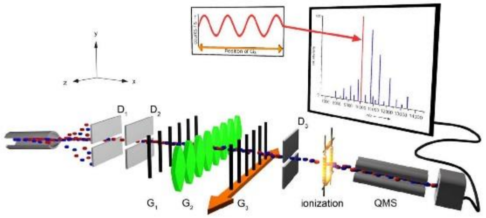




Classical to Quantum

Gravitational effects?

Quantum decoherence



Overlap with ground-based experiments

Science goals II/III

Test for deviations from quantum theory

Parametrization of deviations from coherent quantum evolution

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\widehat{H}, \hat{\rho}\right]$$

Test for deviations from quantum theory

Parametrization of deviations from coherent quantum evolution

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\hat{H},\hat{\rho}\right] - \Lambda\left[\hat{x},\left[\hat{x},\hat{\rho}\right]\right]$$

long-wavelength limit

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\hat{H},\hat{\rho}\right] - \gamma\hat{\rho}$$

short-wavelength limit

Science goals II/III

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Test for mass-dependent decoherence

- Particle size
- Mass
- Composition

Science goals II/III

Test for deviations from quantum theory

Parametrization of deviations from coherent quantum evolution

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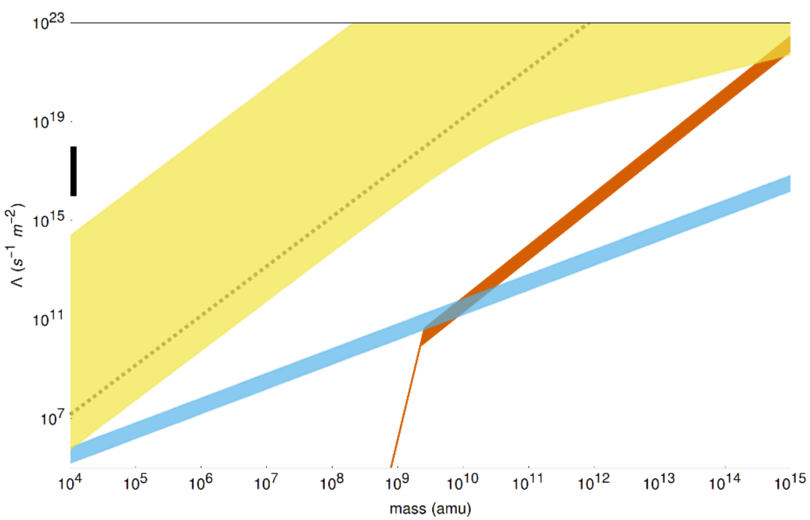


- Gray Dashed Line: QG Model (Ellis, Mohanty et al)
- Yellow: CSL model (Ghirardi, Rimini, Weber, Pearle, et al, $\lambda \in [10^{-8}, 2.2 \times 10^{-17}]$Hz, r_c=100nm)
- Blue: DP Model (Diósi, Penrose)
- Red: K Model (Károlyházy)
- ■ Current mass record: 10^4 atomic mass units (amu)

Coherent evolution of spherical test particle

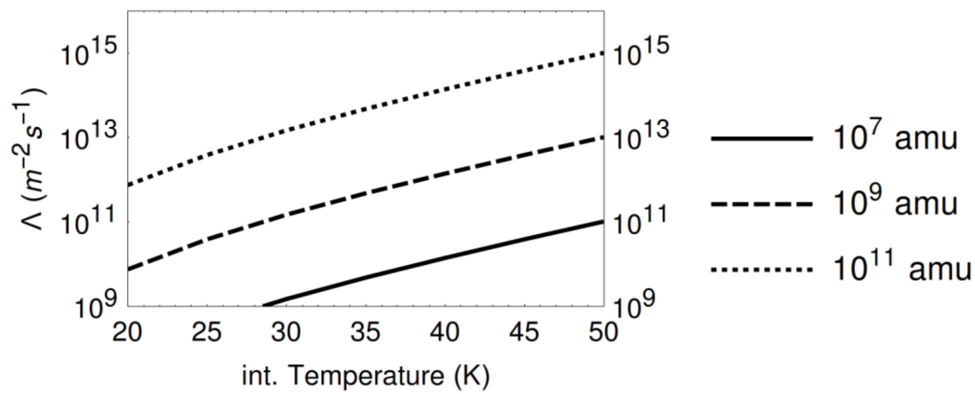
Science goals III/III

Testing quantum decoherence

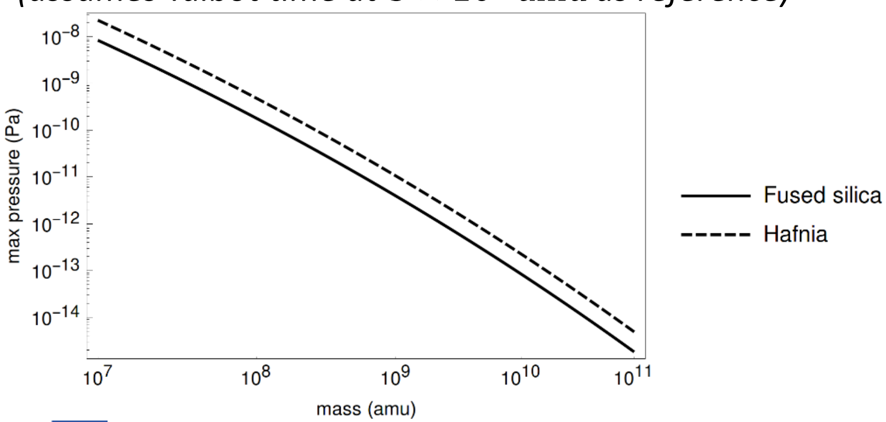
Test parameter dependence of known decoherence mechanisms

- particle size
- temperature
- polarizability
- vibrations
- pressure(?)
- charge(?)

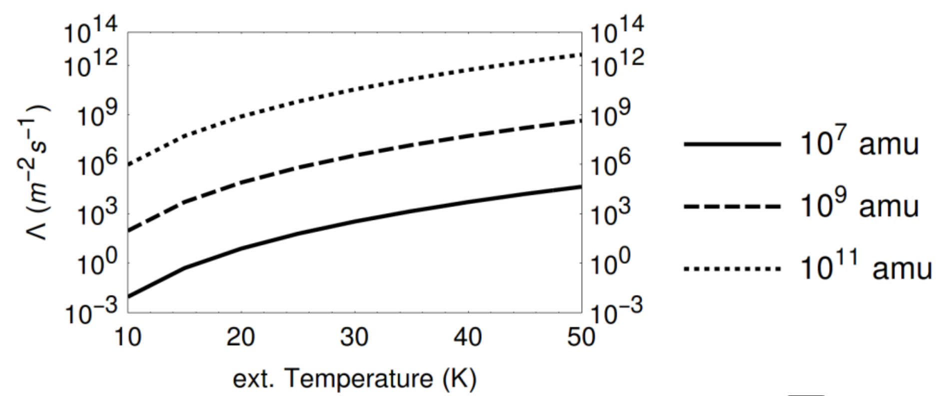
Emission of blackbody radiation (fused silica)



Avoiding particle collisions
(assumes Talbot time at 5×10^9 amu as reference)

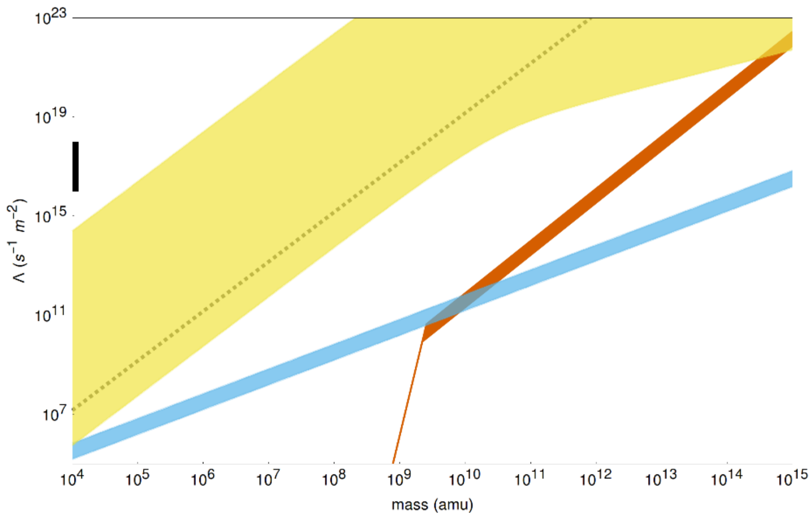


Scattering of blackbody radiation (fused silica)



Top-level science requirements

Test quantum physics with high test masses



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Top-level science requirements

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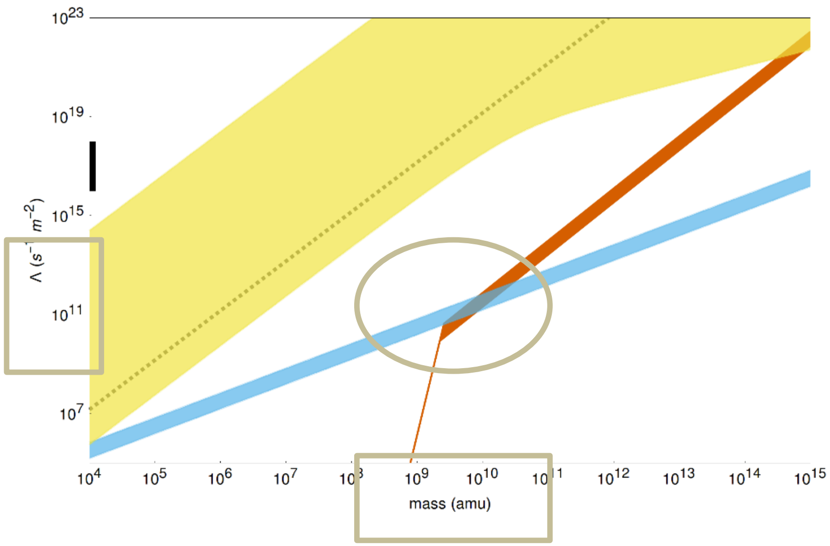

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Region of interest:

$$10^9\ \mathrm{m}^{-2}\mathrm{s}^{-1} \lesssim \Lambda \lesssim 10^{14}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$$

$$10^8\mathrm{amu} \lesssim m \lesssim 10^{11}\mathrm{amu}$$

- Perform experiments in this regime
- first deviations due to (quantum-)gravity?

Top-level science requirements

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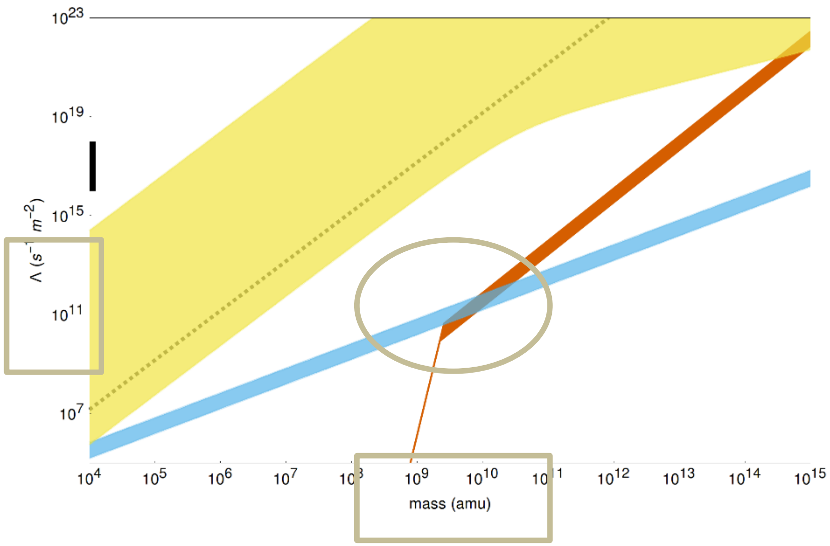

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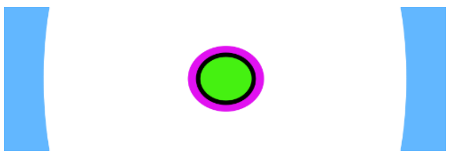
Parameter	Value	Driver/Justification
Λ_{env}	$\lesssim 10^9\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$	Standard decoherence must be less than decoherence tested for
Particle mass	$\gtrsim 10^8\mathrm{amu}$	Sensitive to gravitational deviations?

MAQRO – suggested experiments

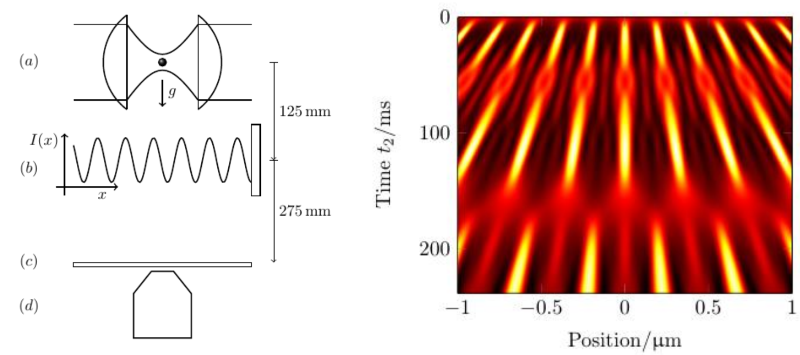
Free expansion of the wavefunction



- Additional decoherence?
- Schrödinger-Newton?

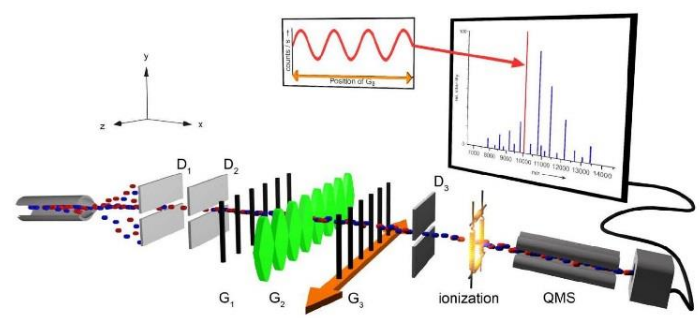
Suggested for MAQRO by RK in 2011

Matter-wave interference



Idea for ground-based experiments: J. Bateman et al. 2015
Adapted for MAQRO by RK in 2015/2016

Near-field Talbot interferometry as in record-holding experiment by S. Eibenberger in 2013



Free expansion of the wavefunction

MAQRO

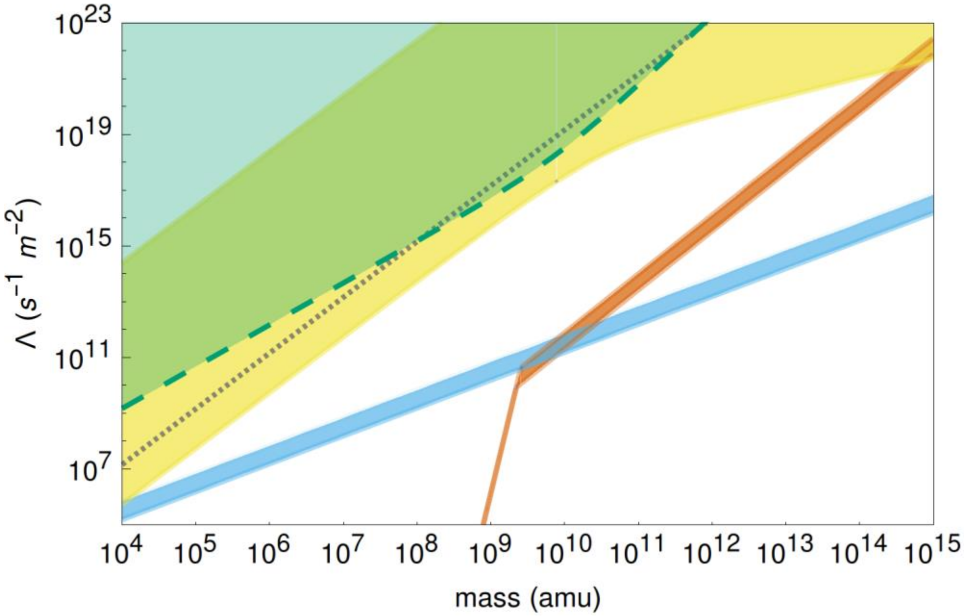
How well can we measure the width of the wavefunction?

$$w(t)^2 = \langle \hat{x}^2(0)\rangle + \frac{t^2}{m^2}\langle \hat{p}^2(0)\rangle + \frac{2\,\Lambda\,\hbar^2}{3\,m^2}t^3$$

$$w = \lim_{N\to\infty}\frac{1}{\sqrt{N-1}}\left(\sum_{j=1}^{N}(x_j-\bar{x})^2\right)^{1/2}.$$

$$\frac{\Delta w}{w} \cong (2\,N)^{-1/2} \text{ for } N \gg 1$$

$$\Lambda_{\min}(t) = 3\,m^2\,\frac{w^2(t)}{\sqrt{2\,N}\,\hbar^2\,t^3} \cong 3\,m^2\,\frac{w_S^2(t)}{\sqrt{2\,N}\,\hbar^2\,t^3}$$



Assuming $\omega = 10^5$ rad/s, 0.3 occupation at $m = 5\times 10^9$amu, fused-silica particle, 30-day measurement run, 100s per measurement

Narrow the gap between existing experiments & „quantum-gravity“ regime

Free expansion of the wavefunction

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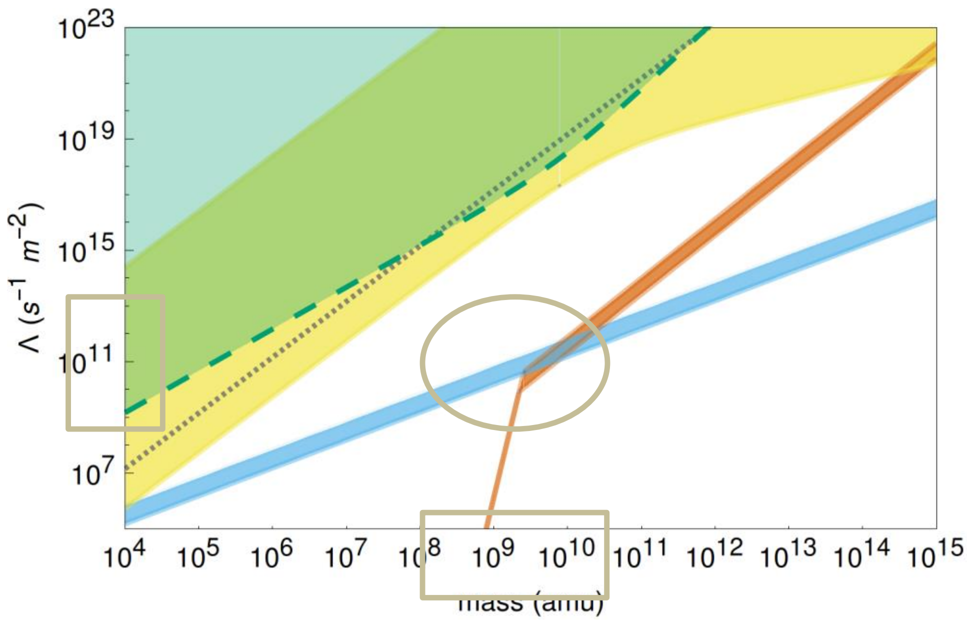

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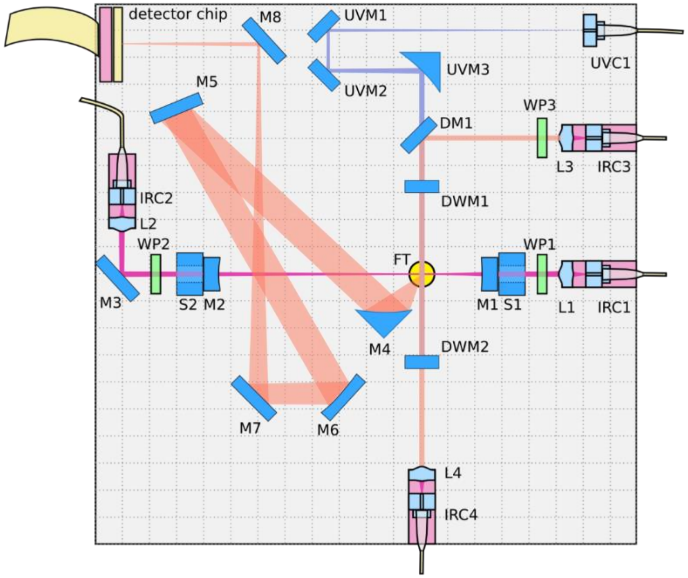
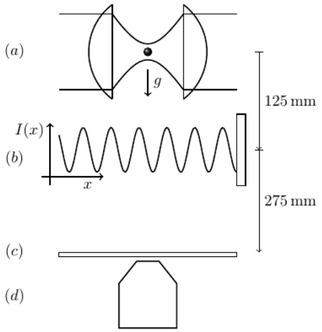
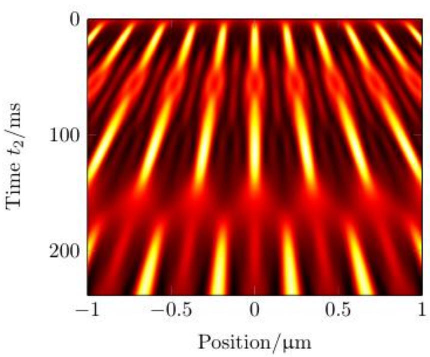
Narrow the gap between existing experiments & „quantum-gravity“ regime

Matter-wave interferometry I/II

Working principle







Matter-wave interferometry I/II

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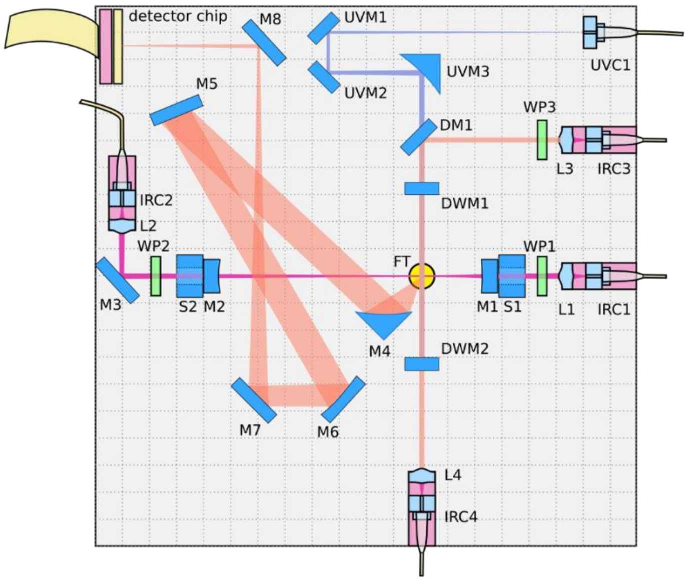
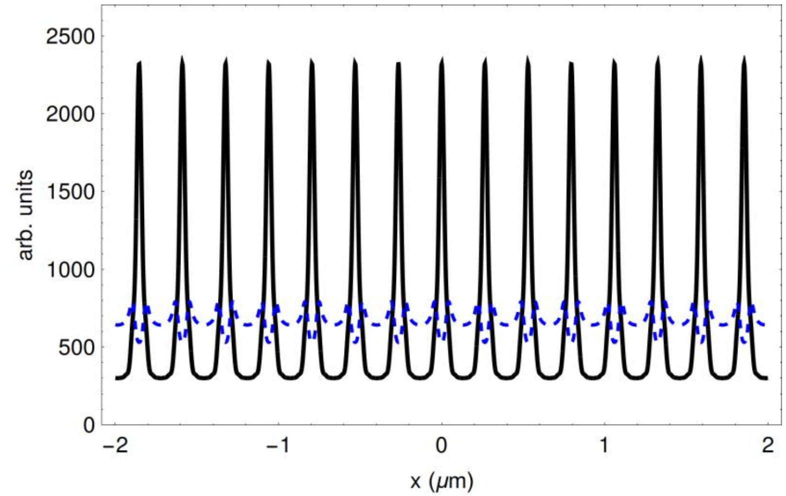
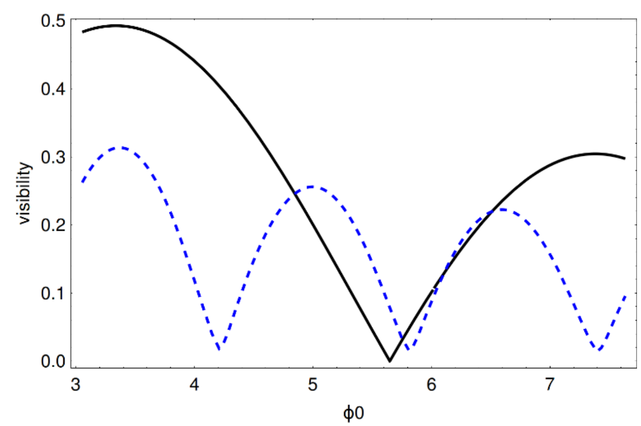




- Blue, dashed: classical Moire shadowing
- Black, solid: quantum prediction

(mass: 10^9 amu, T=100s, $\lambda_g = 100\text{nm}, \phi_0 = 5\pi$)



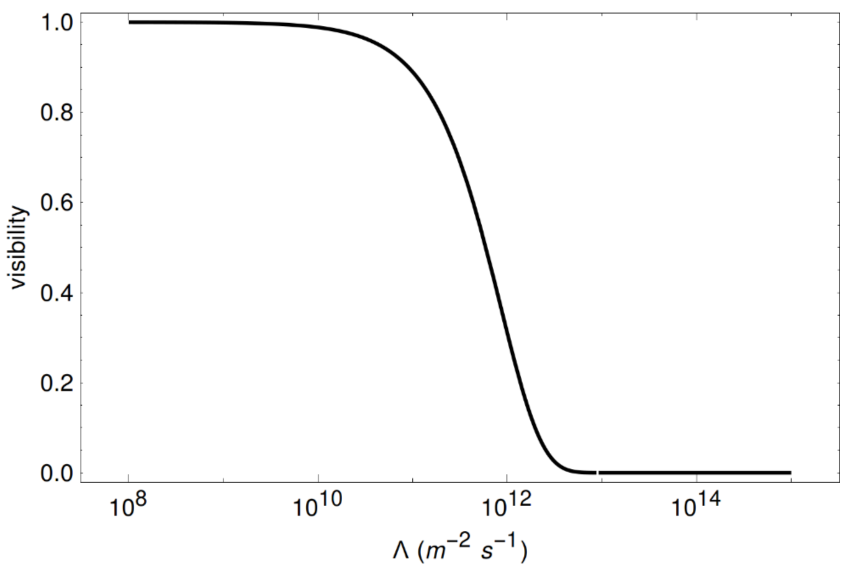
Pattern:

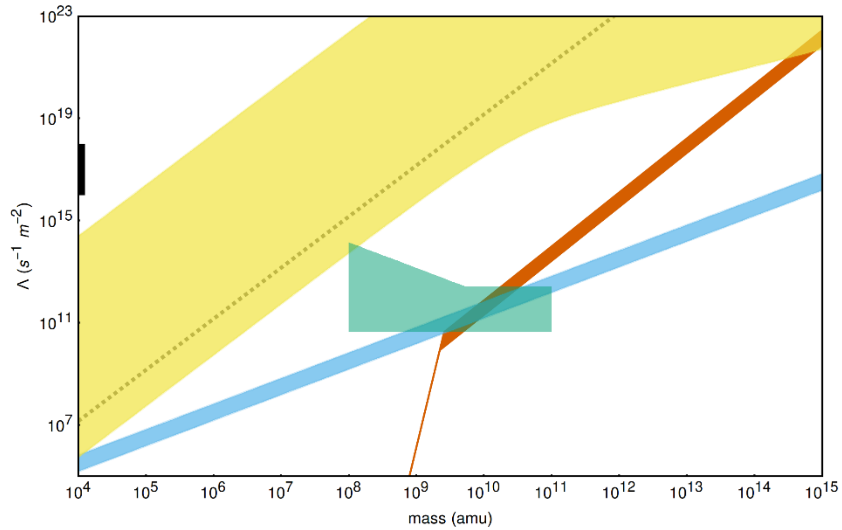
$$P(x) = g_1 \exp\left(-\frac{x^2}{2\, g_2}\right)\left(\frac{1}{2} + \sum_{n=1}^{\infty} J_n(\phi_0 \sin(n\, g_3)) \cos(n\, x\, g_4) \exp(-n^2 g_5)\right)$$

Matter-wave interferometry II/II

Sensitivity

Reduction of interference visibility for increasing Λ for 100s free fall & 1e9 amu





Matter-wave interferometry II/II

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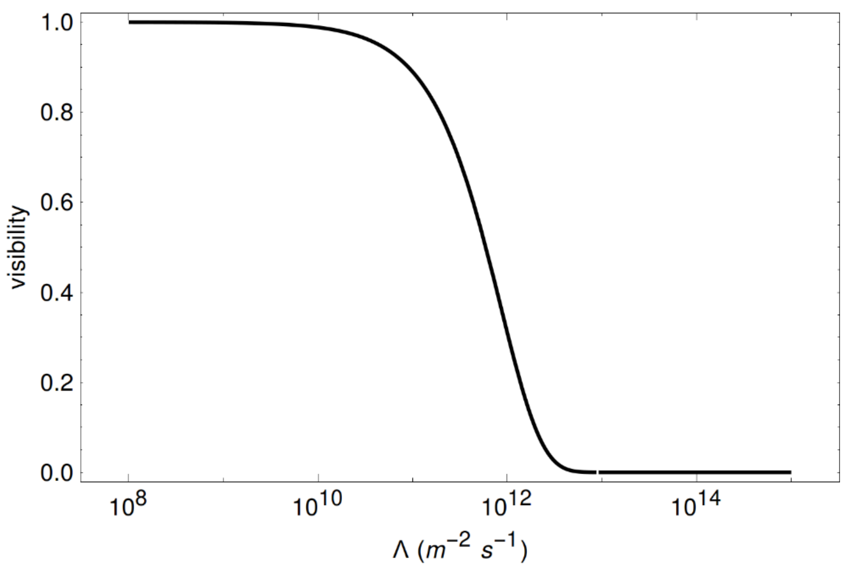

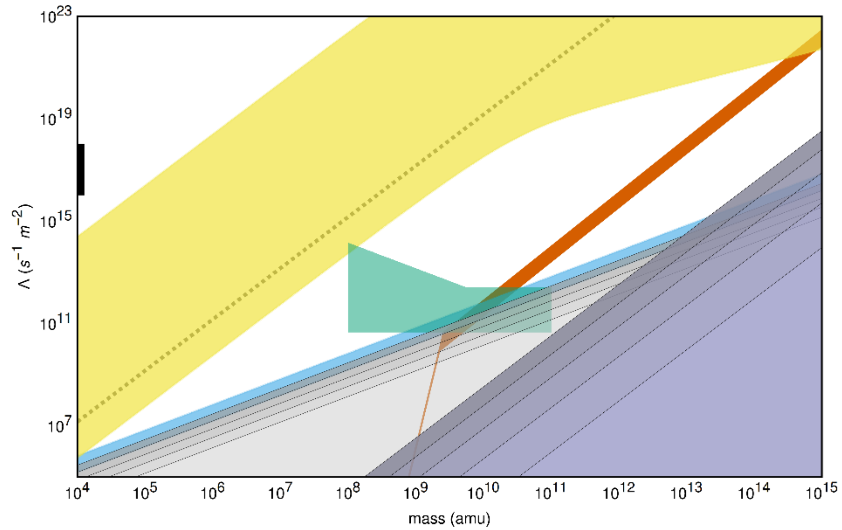

- **Blue-gray:** scattering for environment temperature in 5K steps [10K,30K]
- **Gray:** absorption/emission for temp. in 2K steps [16k,24K]

Matter-wave interferometry II/II

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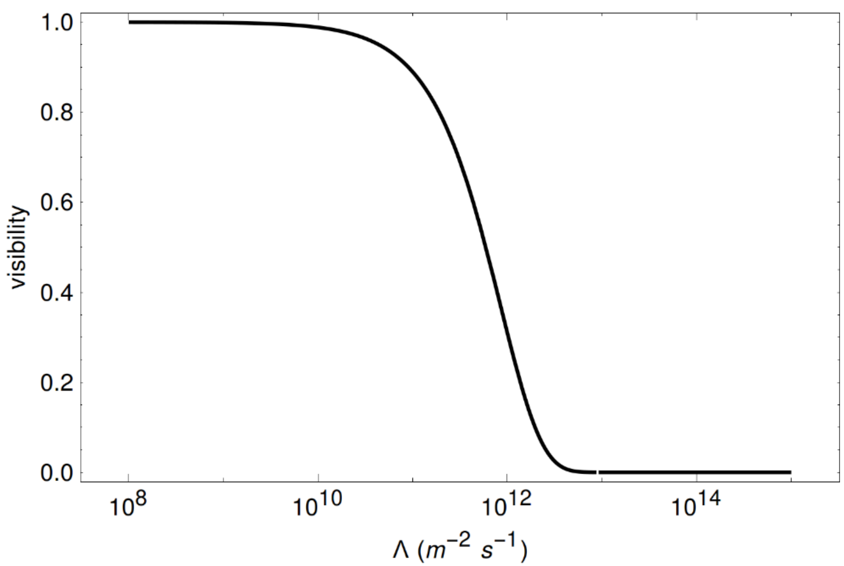
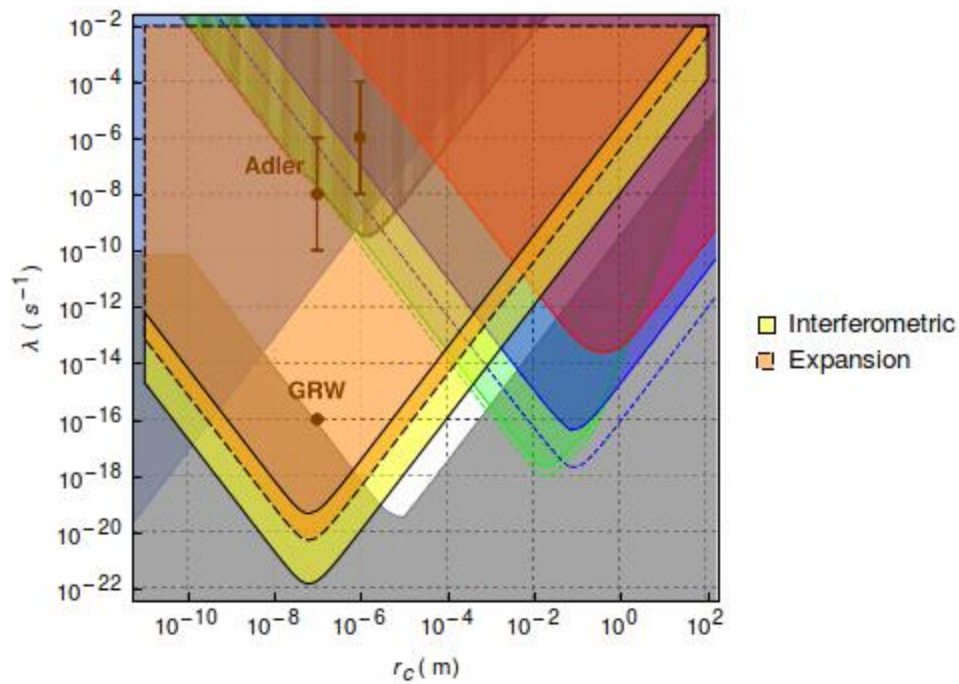
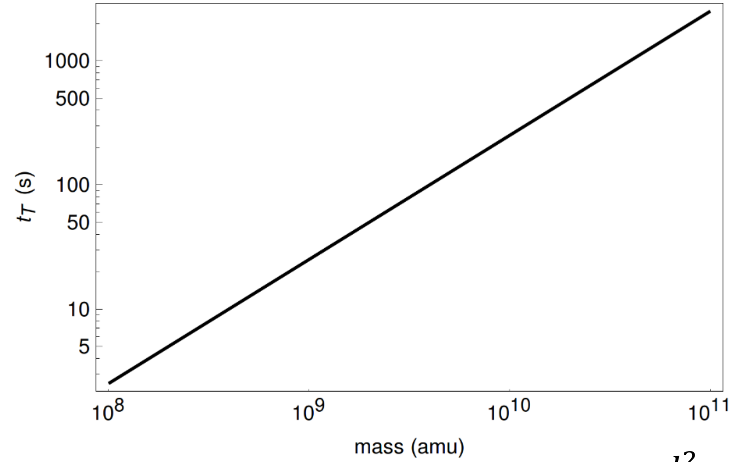




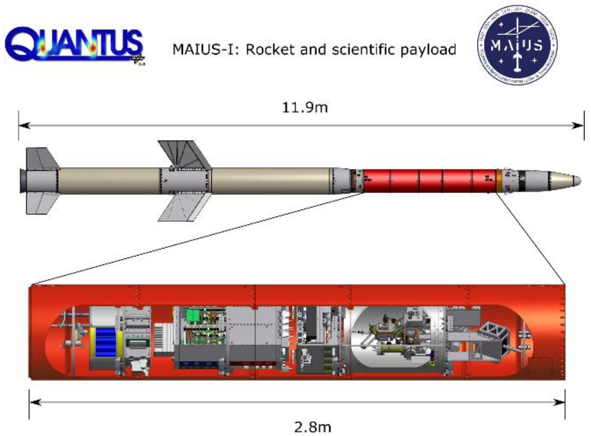
Case for space

- Free-fall time (~ 100 s)
- Micro-gravity / vibrations ($\sim 10^{-9}$ g)
- Statistics ($\gtrsim 10^4$ data points per meas.)

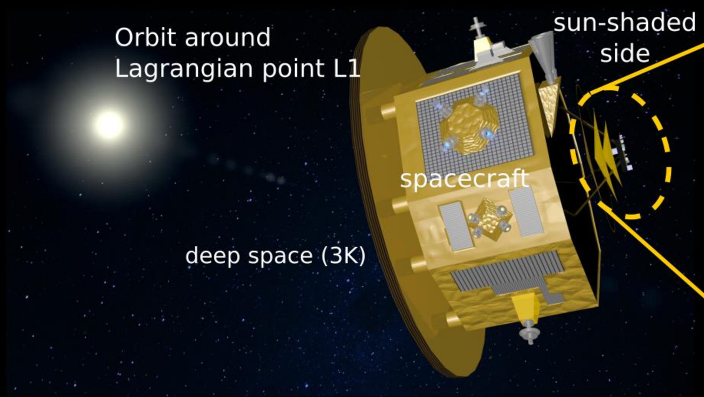


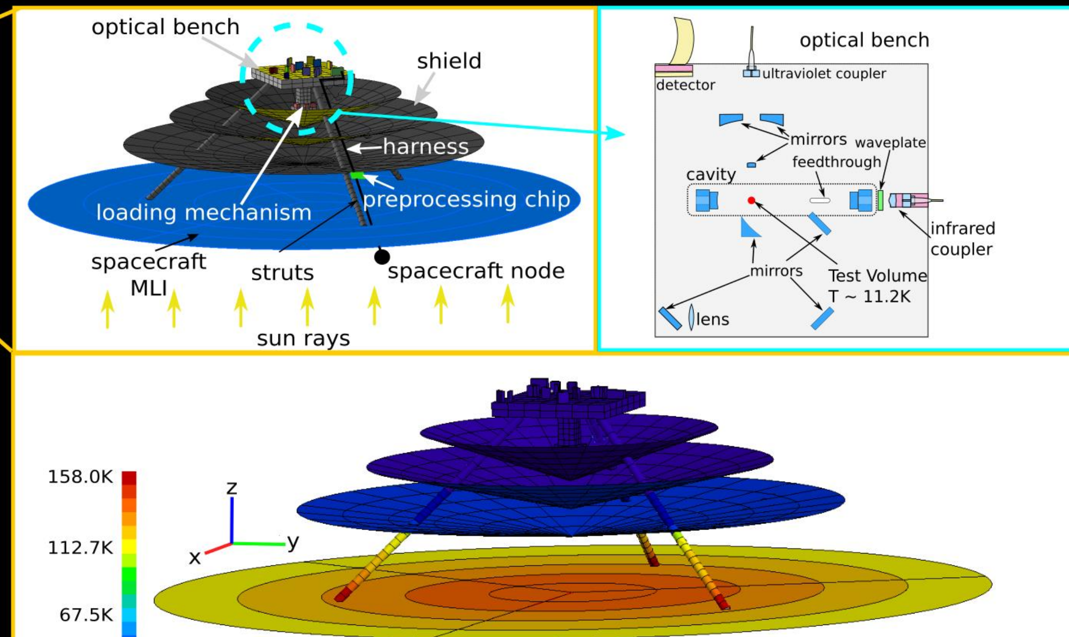
Interferometry – Talbot time: $t_T = \frac{md^2}{h}$

Wavepacket expansion: $\Lambda_{\min}(t) \cong 3\, m^2 \frac{w_S^2(t)}{\sqrt{2}\, N\, \hbar^2\, t^3}$

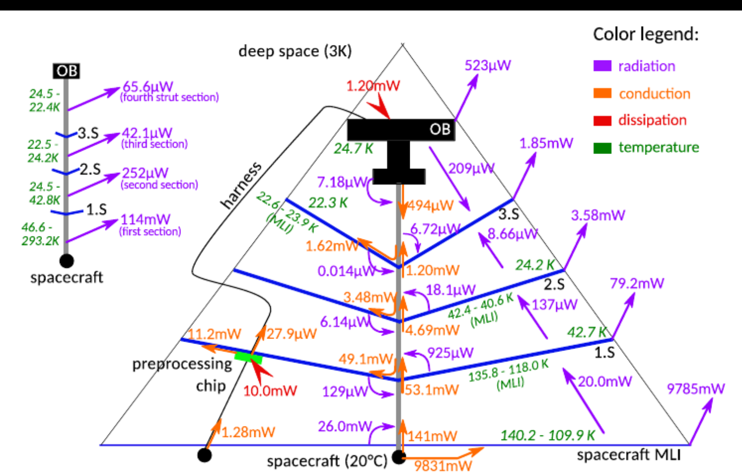


Before QPPF study: passive radiative cooling





A. Pilan Zanoni et al, Appl. Therm. Engin. **107**, 689 (2016)

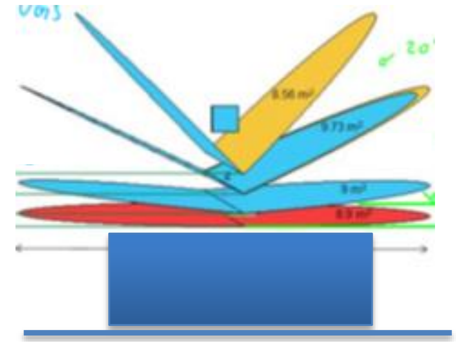


+ Low vibrations
+ “unlimited” lifetime
+ Outgassing to space

- Electron bombardment
- Not easily testable
- Outgassing plume

New spacecraft & orbit configuration

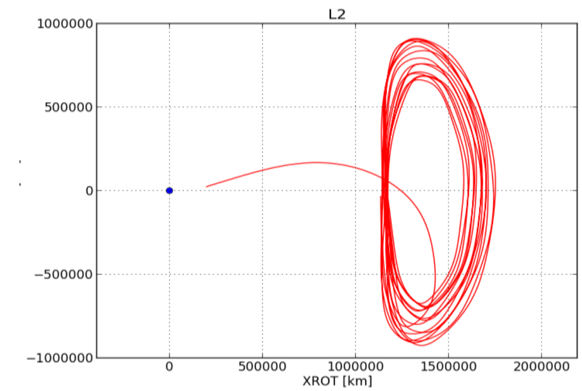
- Optical bench enclosed in protective cover
- Hydrogen sorption cooler between v-grooves
- Passive + active cooling → 20 K on bench



Sketch of QPPF S/C configuration, courtesy: ESA

New spacecraft & orbit configuration

- Orbit around L2, direct injection
- Better science-wise: Earth trailing, but limited data-rate and lifetime



JAN 2030

Launch to L2
Ariane 6.2

JAN 2030

LEOP and Commissioning
- *Transfer Correction Manouvres*
- *Cooling of Payload (1 month)*

MAR 2030

Payload Commissioning
- *Calibrate temperature*
- *Test Free Fall*
- *Test Collision rate*

APR 2030

Science Phase
- *3 years*
- *1 month per batch - 3 weeks of science 1 week of communications*

APR 2033

Disposal

Science Phase

Number of Test Batches (combination of 1e8amu and 1e9amu)	15
No. of Test Samples per Batch (@ 80%Pr of <2 collisions)	10000 valid 12500 actual
Test Duration (s) per Test Sample	100s 40s free fall - 60s prep

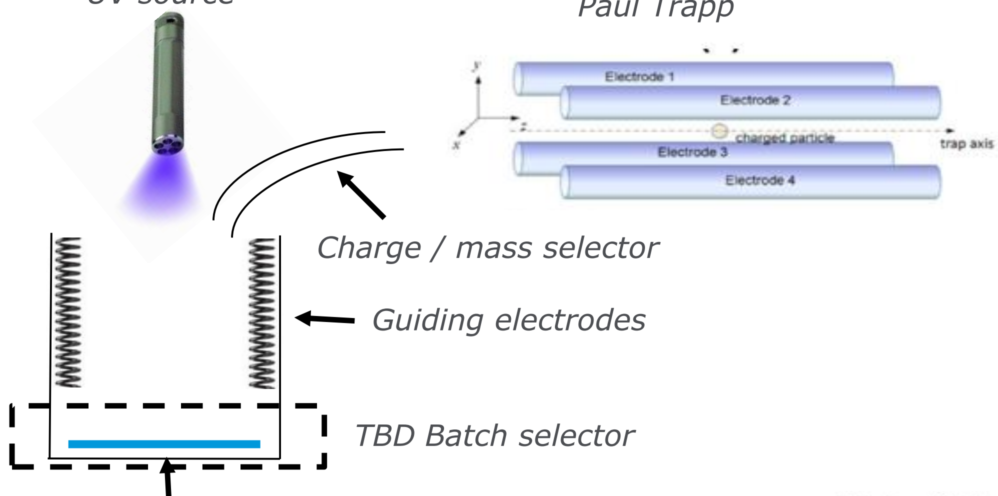
Critical challenge I/II: particle loading

Particle Transportation Sequence:

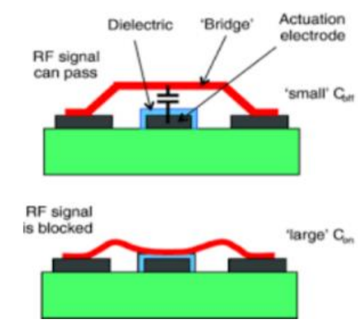
1. Select Batch
2. UV Active Paul Trapp
3. LED fires at particle
4. Particle(s) absorb energy and remove from surface, charged negatively
5. Electrodes guide charged particle into piping
6. Particles travel through charge/mass selection piping
7. Particle arrives into Paul Trap
8. Transferred into optical trap
9. Particle discharged using UV light

UV source

Paul Trapp

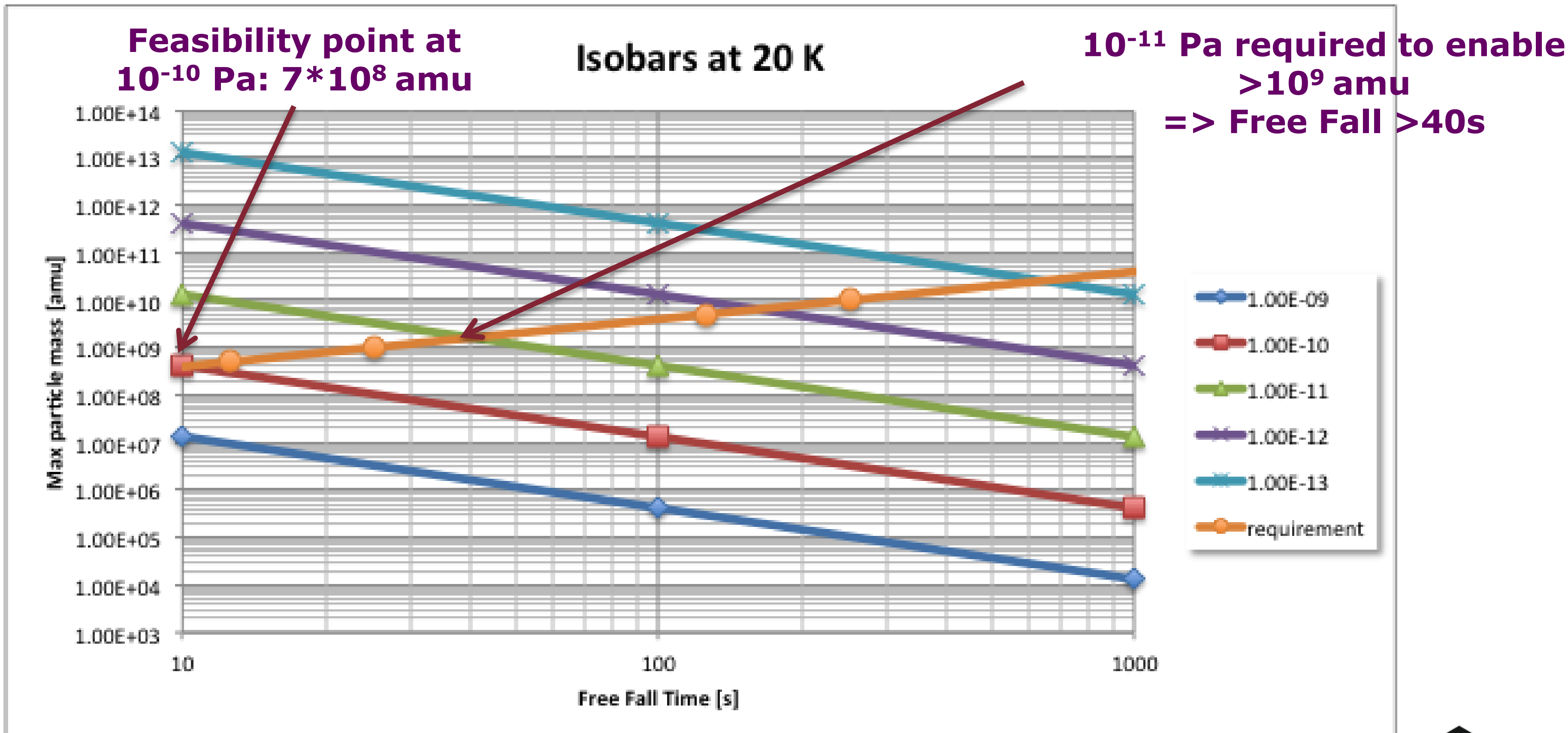


Option: Replace surface coating with a MEMS modulator



Critical challenge II/II: vacuum

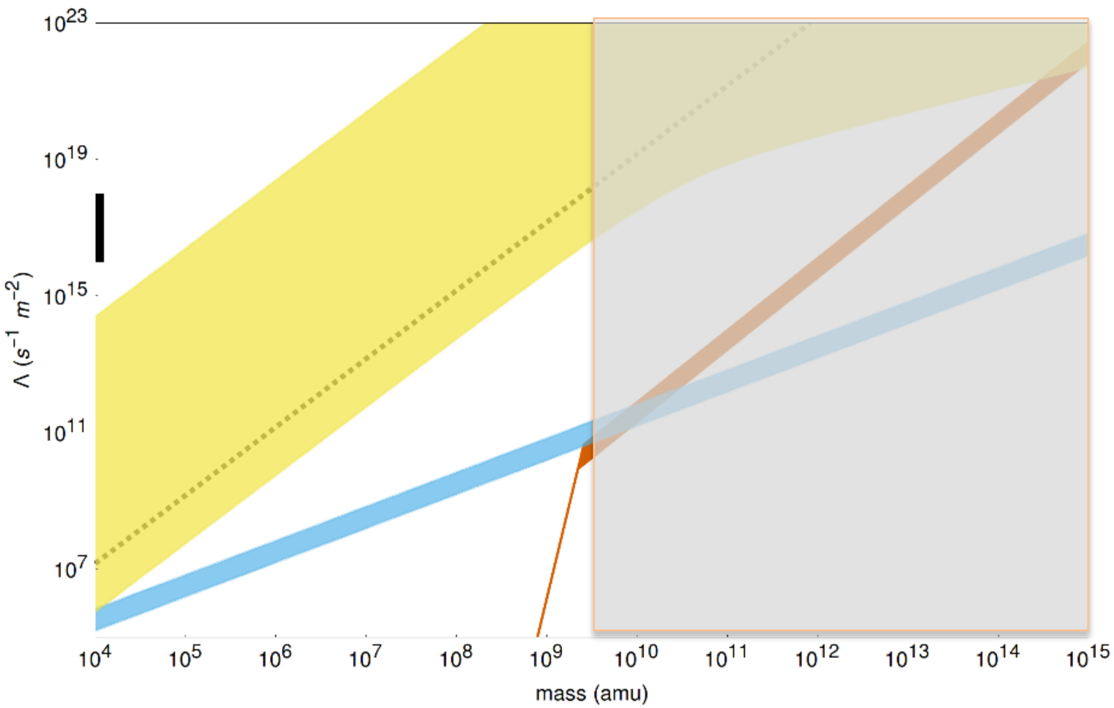
Limit number of collisions during Talbot time $$t_T = \frac{md^2}{h}$$



Critical challenge II/II: vacuum

Accessible decoherence regimes with current baseline

- Gray: QG Model (Ellis, Mohanty et al)
- Yellow: CSL model (Ghirardi, Rimini, Weber, Pearle, et al, $\lambda \in [10^{-8}, 2.2 \times 10^{-17}]$Hz, r_c=100nm)
- Blue: DP Model (Diósi, Penrose)
- Red: K Model (Károlyházy)



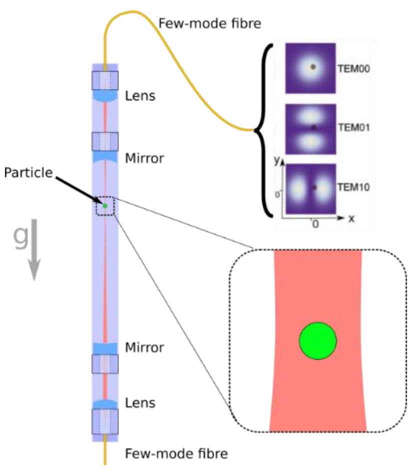
■ Current mass record: 10^4 atomic mass units (amu)

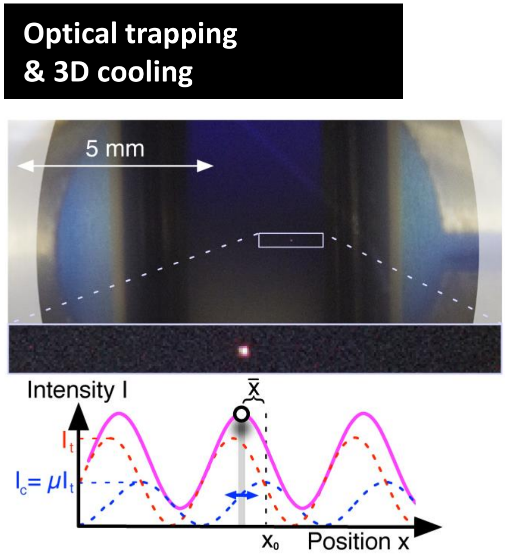
”Normal” Challenges for payload

- Consolidation of science requirement on pressure
- Technology development of payload components:
  - High-finesse cavities
  - interferometric position measurement of test-particle
  - GHz EOMs
  - AOMs
  - DUV laser/grating
  - cooling with multiple cavity modes
  - spatial mode multiplexers
  - narrow-band fiber Bragg filters
  - low-noise amplifiers
  - homodyne detection
- Acquiring/testing >10^5 particles with ‘identical’ (< few %) properties within batch
- Long term degradation of particles?
- Particle disposal

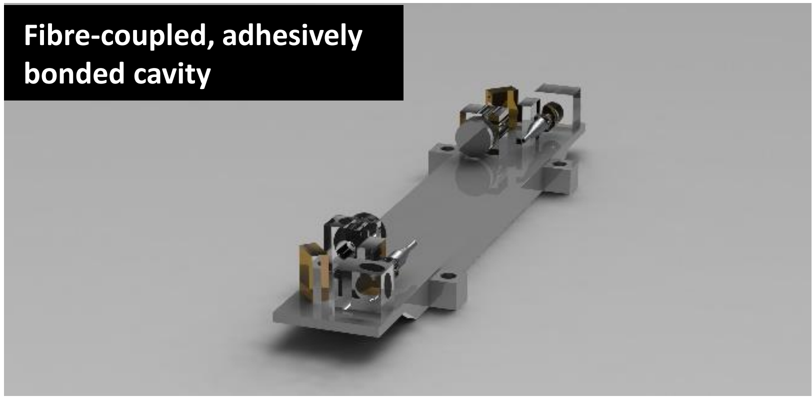
Proof-of-principle experiments I/III

- Develop optomechanical platform using optically trapped particles
- 3D optomechanical cooling and control
- non-classical state preparation
- free-fall experiments in the lab
- quantum state tomography





N. Kiesel et al, PNAS (2013)



Proof-of-principle experiments I/III

- Develop optomechanical platform using optically trapped particles
- 3D optomechanical cooling and control
- non-classical state preparation
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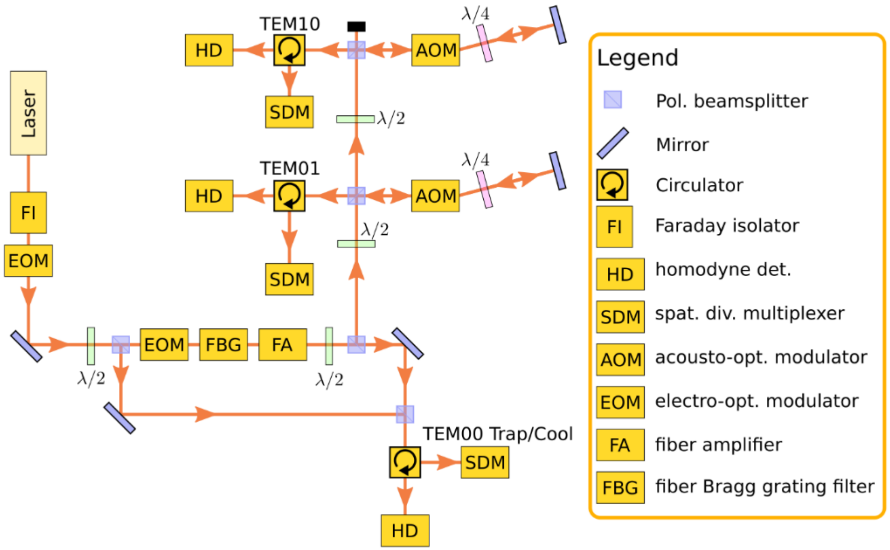
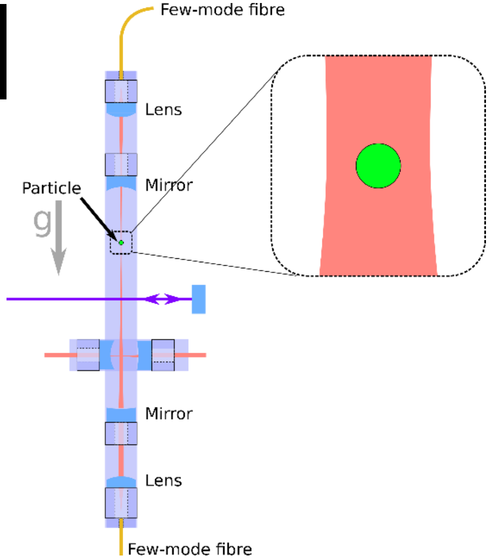
- quantum state tomography

Proof-of-principle experiments II/III

Stable, fiber-integrated optomechanical setup



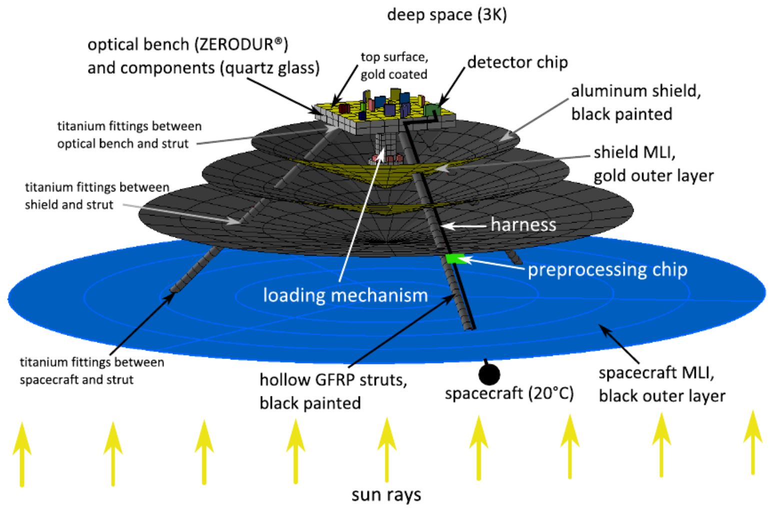
Free-fall experiments with UV phase grating



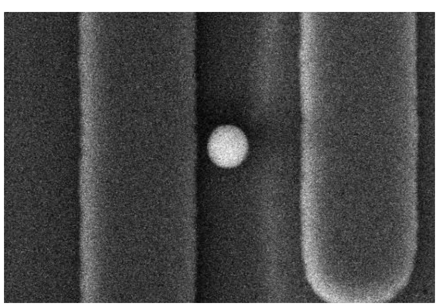
Proof-of-principle experiments III/III

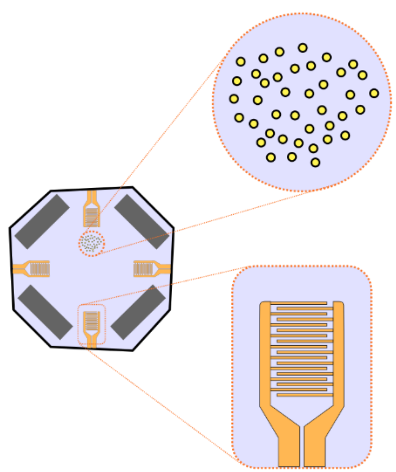
MAQRO

- Demonstrator for passive radiative cooling
- Lab / cubesat
- Extremely high vacuum
- Pressure sensors

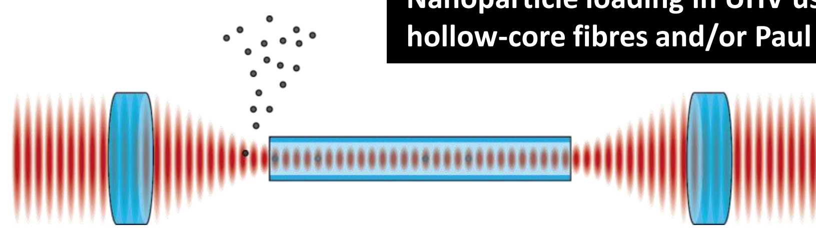


Nanoparticle loading in UHV using SAW chips





Nanoparticle loading in UHV using hollow-core fibres and/or Paul traps



Loading & guiding with hollow-core photonic crystal fibres
D. Grass et al., Appl. Phys. Lett. **108**, 221103 (2016)

Discharging particles using DUV light?

Conclusion & Outlook

- ESA find's the topic of macroscopic tests of quantum physics very interesting
- → New Science Ideas – topic of interest for future space missions
- QPPF → possible to realize a platform for such experiments

QPPF Final Presentation:
22/11/2018

Next steps

- Structure consortium, working groups, regular meetings
- Address challenges & develop technologies
- Increase TRL of core technologies
- Demonstration experiments (lab, drop-tower, cubesat)

MAQRO next-steps meeting:
early 2019

PI – Rainer Kaltenbaek

PM – Angelo Bassi

WG1 – Theory
M. Paternostro & C. Brukner

WG2 – Experiment
H. Ulbricht

WG3 – Technology
J. Bateman & T. Schuldt

WG4 – Space
U. Johann & D. Gerardi

THANKS

QTSpace COST action (CA15220)
10/16 – 10/20
26 countries

www.maqro-mission.org

Austrian Research Promotion Agency
(MAQROsteps, Project no. 840089)
(ULE-Cavity-Access, Project no. 854036)
(QuantumShield, Project no. 865996)

MQES study (ESA contract Po P5401000400)
NanoTrapS project (ESA contract 4000105799/127NL/Cbi)
QPPF CDF Study 2018