Les Houches Summer School “Quantum Optomechanics and Nanomechanics” August 2015

Is the Moon there when nobody looks ?

Fluctuations in vacuum, gravitational waves, and decoherence

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M.-T. Jaekel (LPT-ENS Paris),
P.A. Maia Neto (UF Rio de Janeiro),
B. Lamine (IRAP Toulouse),
and the HYPER, SAGAS, MWXG, GAUGE and MAQRO collaborations

Outline :

- Quantum / classical border and decoherence
- Ultimate fluctuations for optomechanics in vacuum
- Decoherence induced by the scattering of gravitational waves backgrounds

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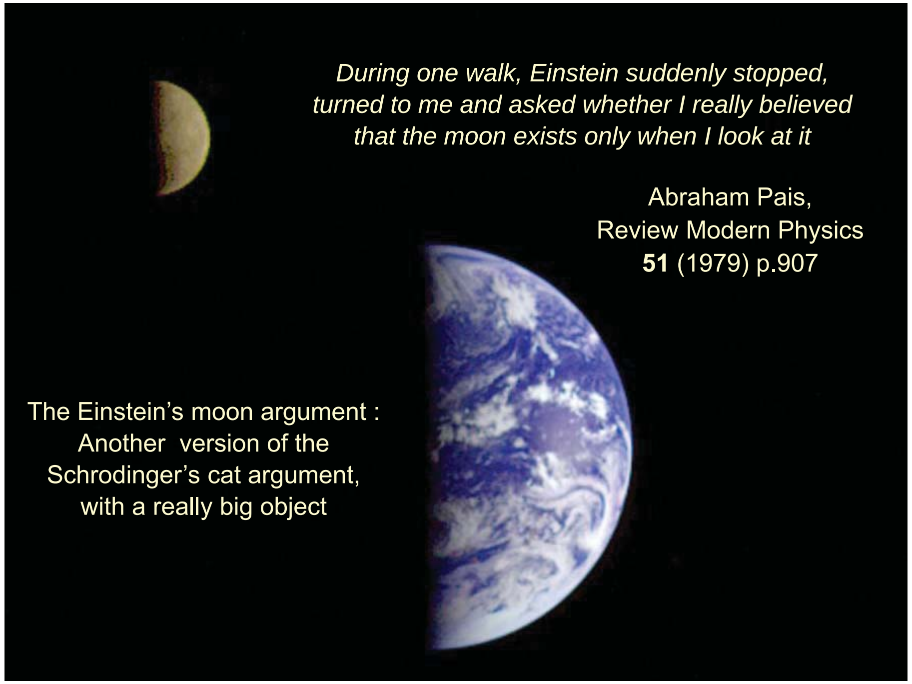


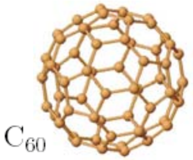
During one walk, Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it

Abraham Pais,
Review Modern Physics
51 (1979) p.907

The Einstein’s moon argument :
Another version of the
Schrodinger’s cat argument,
with a really big object

Quantum / classical border and decoherence

Quantum domain



Microscopic objects (electrons, photons, atoms & molecules...) show interferences

Classical domain

Macroscopic bodies (soccer balls, cats, moons & planets...) do not !

This is explained by quantum decoherence:
W. H. Zurek, Physics Today (October 1991) 36
W. H. Zurek, Rev. Mod. Phys. 75 (2003) 715
S. Haroche, Physics Today (July 1998) 36
S. Haroche, Nobel Lecture, Rev. Mod. Phys. 85 (2013) 1083

Is there a universal borderland ?

- Planck mass scale has a value between microscopic and macroscopic masses
  - Is this an accidental coincidence ?
  - Or a hint that space-time fluctuations are the origin of some universal decoherence mechanism ?

$$m_{\mathrm{P}} = \sqrt{\frac{\hbar c}{G}} \simeq 22\mu\mathrm{g}$$

- Planck time and length scales are extremely small !

$$t_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^5}} \simeq 5 \times 10^{-44}\mathrm{s} \qquad \ell_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \simeq 10^{-35}\mathrm{m}$$

- But the Planck scales could be seen by comparing the Compton length $\ell_C = \frac{\hbar}{mc}$ to the Planck length $\ell_P = \frac{\hbar}{m_P c}$

$$m < m_P \quad \Leftrightarrow \quad \ell_C > \ell_P \quad / \quad m > m_P \quad \Leftrightarrow \quad \ell_C < \ell_P$$

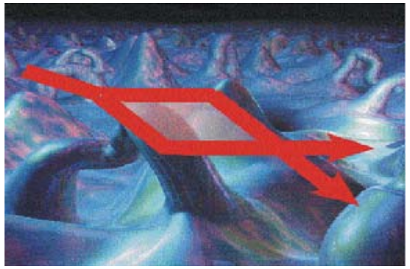
R.P. Feynman, *Lectures on Gravitation* (1962)

Can we explore it in new experiments ?

- Would it be possible to prove the existence of fluctuations of space-time by observing some universal Planck scale diffusion ?

- The situation would be analogous to that which allowed physicists to prove the existence of atoms by observing Brownian diffusion in the beginning of the 20th century

F. Karolyhazy (1966), L. Diósi (1984),
M. Jaekel & S. Reynaud (1994),
R. Penrose (1996)



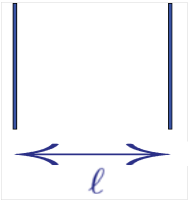
Decoherence of an atomic interferometer, an artist's view : HYPER, W. Ertmer et al

- Could this be feasible with state-of-the-art matter-wave interferometers ?

I. Percival & W. Strunz (1997)

A motivation for several space projects over the last 15 years
– HYPER, SAGAS, MWXG, GAUGE and now MAQRO –

A nice version of Feynman's argument : optomechanics in vacuum



- Analysis of ultimate limits in the sensitivity of interferometric detection of gravitational waves (analysis focused on questions of principle)
- Length ℓ of the cavity read out as a phase
- Optimization involves
  Optical phase noise & Radiation pressure noise

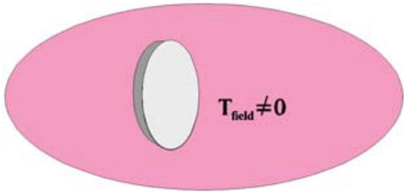
M. Jaekel & S. Reynaud, Europhys. Lett. **13** (1990) 301 *quant-ph/0101104*

- Taking into account the effect of gravitational wave noise in vacuum on the geodesic distance between the two mirrors reproduces the main elements of the Feynman's argument
- Gravitational fluctuations dominant for macroscopic masses

M. Jaekel & S. Reynaud, Phys. Lett. **A 185** (1994) 143 *quant-ph/9801074*

M. Jaekel & S. Reynaud, Quant. Semiclass. Optics **7** (1995) 639 *quant-ph/9506007*

Classical fluctuations-dissipation relations for a mirror in a field at thermal equilibrium



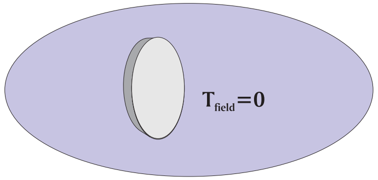
- A mirror at rest in a thermal field experiences fluctuations of the radiation pressure
  → noise spectrum $C_{FF}[\omega]$ (Fourier Transf. of the correlation function)
- A mirror moving in a thermal field experiences a friction force → mean force given by a linear susceptibility $\langle \delta F \rangle [\omega] = \chi_{FF}[\omega] \delta q[\omega]$
- Classical fluctuations-dissipation relations (Einstein 1909, 1917)
  → written here for a perfect mirror in 1-dimensional (1d) space

$$C_{FF}[\omega] = 2\gamma T \qquad \gamma = \frac{3\pi k_B^2 T^2}{2\hbar c^2}$$

$$\chi_{FF}[\omega] = i\gamma\omega$$

Friction force proportional to the velocity $\langle \delta F \rangle (t) = -\gamma \delta q'(t)$

Quantum fluctuations-dissipation relations for a mirror in vacuum



- Dissipative force in vacuum : linearization of the Fulling-Davies force, proportional to the derivative of the acceleration

$$\langle \delta F \rangle (t) = \frac{\hbar}{6\pi c^2} \delta q'''(t)$$

S.A. Fulling, P.C.W. Davies, PRS **348** (1976) 393

Again the simplest model : perfect mirror in 1d space

- A mirror at rest in vacuum also experiences radiation pressure fluctuations related to dissipation by quantum FD relations

$$\chi_{FF}[\omega] = \frac{i\hbar\omega^3}{6\pi c^2}$$

$$C_{FF}[\omega] = \frac{\hbar^2\omega^3}{3\pi c^2} \theta(\omega)$$

$$\xi_{FF}[\omega] = \frac{C_{FF}[\omega] - C_{FF}[-\omega]}{2\hbar} = \operatorname{Im} \chi_{FF}[\omega]$$

M. Jaekel & S. Reynaud, Quantum Optics **4** (1992) 39 *quant-ph/0101068*

Instability problem and its solution

- Same dependence as the radiation reaction force for an electron in 3d electromagnetic vacuum
  → same instability problem
- Problem solved by considering "real mirrors" transparent at high frequencies
- FD relations still valid

$$\xi_{FF}[\omega] = \mathrm{Im}\chi_{FF}[\omega] = \frac{\chi_{FF}[\omega]-\chi_{FF}[-\omega]}{2i}$$

$$C_{FF}[\omega] = 2\hbar\xi_{FF}[\omega]\theta(\omega)$$

- Linear susceptibility varying less rapidly at high frequencies, which cures the instability problem associated with perfect mirrors
- Fluctuations and dissipation at mechanically accessible frequencies remaining the same as for a perfect mirror
- In particular, dissipative force remaining null for a mirror with constant velocity (no term proportional to ω - this is a consequence of Lorentz invariance of vacuum)

Fluctuations of a mirror in vacuum

- Equation of motion accounting for the reaction of vacuum written in terms of a mechanical impedance *Z* or admittance *Y*

$$-i\omega q[\omega] = Y[\omega]F_A[\omega]$$

$$\frac{1}{Y[\omega]} = Z[\omega] = \frac{k}{-i\omega} - im\omega + \frac{\chi_{\mathrm{FF}}[\omega]}{i\omega}$$

- Vacuum state of the coupled system described by the admittance function

$$C_{qq}[\omega] = 2\hbar\xi_{qq}[\omega]\theta(\omega)$$

$$\xi_{qq}[\omega] = \mathrm{Re}\frac{Y[\omega]}{\omega} = \mathrm{Im}\frac{1}{k-m\omega^2-\chi_{\mathrm{FF}}[\omega]}$$

- Noise spectrum containing narrow peaks at the eigenvalues of the suspension system, corresponding to usual quantum fluctuations, above a small and broad background induced by vacuum radiation pressure fluctuations

M. Jaekel & S. Reynaud, J. Physique **I-3** (1993) 1 *quant-ph/0101115*

Compton and Planck lengths

$$\boxed{\omega \gg \sqrt{k/m}}$$

- At high frequencies, quantum diffusion
- Magnitude determined by the Compton length

$$C_{qq}[\omega] = \frac{\ell_{\mathrm{C}}^2}{3\pi\omega}\theta(\omega)$$

$$\ell_{\mathrm{C}} = \frac{\hbar}{mc}$$

- To be compared to the fluctuations of the geodesic distance between the two mirrors used for the measurement
- Considering here the vacuum fluctuations of the metric field registered as phase variations in the measurement

$$\boxed{\omega \gg c/\ell}$$

- At high frequencies, form of the noise spectrum similar to the previous one
- Magnitude determined by the Planck length

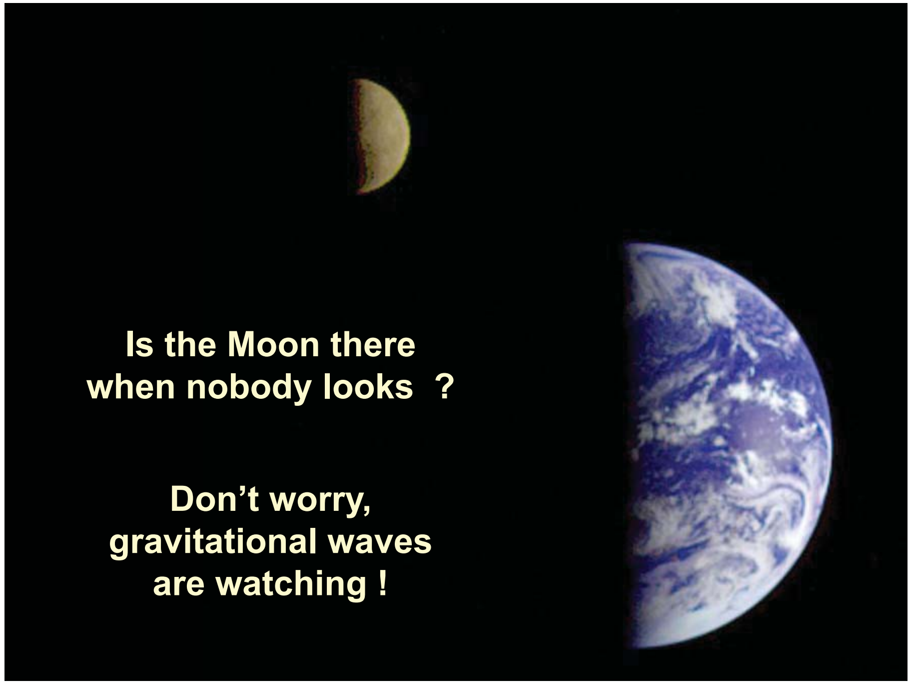
$$C_{\ell\ell}[\omega] \propto \frac{\ell_{\mathrm{P}}^2}{\omega}\theta(\omega)$$

$$\ell_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} = \frac{\hbar}{m_{\mathrm{P}}c}$$

- Gravity contribution dominant for macroscopic masses $m \gg m_{\mathrm{P}}$

M. Jaekel & S. Reynaud, Phys. Lett. **A185** (1994) 143 *quant-ph/9801074*

- Model not realistic : gravitational field is not in its vacuum state !



Is the Moon there when nobody looks ?

Don't worry, gravitational waves are watching !

Decoherence induced by the scattering of stochastic gravitational waves backgrounds

- A well-defined problem which can be completely calculated
  - general relativity is the effective theory of gravity at frequencies of experimental interest
  - the associated intrinsic fluctuations are known as the stochastic backgrounds of gravitational waves (GW)
  - one also knows how to calculate their effects

➡ We don’t have to wait for a full theory of quantum gravity

- Stochastic gravitational waves radiated by masses moving in the Galaxy and the Universe define a universal environment
  - all motions are affected – no shielding possible

S. Reynaud, B. Lamine, M.-T. Jaekel, Fermi School lectures, *arXiv:0801.3411*

Gravitational wave backgrounds

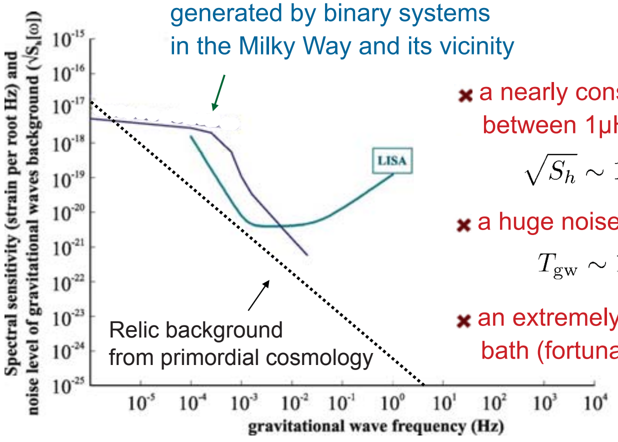
- GW backgrounds characterized by
  - the spectral density of the strain fluctuations *h* (one of metric components)
  - or the number of gravitons per mode $S_h[\omega] = \frac{16G}{5c^5}\hbar\omega n_{\text{gw}}$
  - or the equivalent noise temperature $S_h[\omega] = \frac{16G}{5c^5}k_{\text{B}}T_{\text{gw}}$

$$\boxed{S_h[\omega] \equiv C_{hh}[\omega]}$$

- They correspond to a huge number of gravitons per mode, *i.e.* a huge temperature, but an extremely weak coupling
  - *T* is certainly not an equilibrium temperature !
  - this is the ideal situation to study decoherence

S. Reynaud, B. Lamine, M.-T. Jaekel, Fermi School lectures, *arXiv:0801.3411*

Galactic and cosmic backgrounds



Binary confusion background, generated by binary systems in the Milky Way and its vicinity

Relic background from primordial cosmology

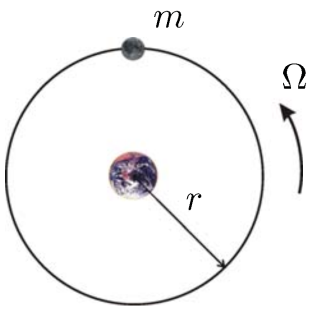
- a nearly constant spectrum between 1µHz and 1mHz
  $\sqrt{S_h} \sim 10^{-17}\text{Hz}^{-\frac{1}{2}}$
- a huge noise temperature
  $T_{\text{gw}} \sim 10^{41}\text{K}$
- an extremely weakly coupled bath (fortunately !)

B. Schutz, Class. Quant. Grav. **16** (1999) A131 *gr-qc/9911034*

GW and the Earth-Moon system

- Mean motion of Earth-Moon system damped by GW emission
  - Damping rate calculated by “quadrupole radiation formula” (Einstein 1918)

$$\Gamma_{\text{gw}} = \frac{64Gmr^2\Omega^2}{5c^5}$$



- Much smaller than the effects of electromagnetic scattering and dominant tide mechanism (interaction of Earth and Moon tides)

$$\boxed{\Gamma_{\text{gw}} \simeq 2\times10^{-34}\,\text{s}^{-1} \simeq 10^{-16}\times\Gamma_{\text{tides}}}$$

$$\boxed{\Gamma_{\text{em}} \ll \Gamma_{\text{tides}}} \qquad \boxed{\Gamma_{\text{tides}} \simeq 2\times10^{-18}\,\text{s}^{-1}}$$

GW and momentum diffusion

- With the simple model of constant noise temperature, stochastic GW induce a Brownian momentum diffusion

$$\Delta p^2 = D_{\mathrm{gw}}\tau$$

τ time of exposition
D_{gw} momentum diffusion coefficient

- The momentum diffusion coefficient may be obtained by writing a (classical) fluctuation-dissipation relation

$$D_{\mathrm{gw}} = m\Gamma_{\mathrm{gw}}k_{\mathrm{B}}T_{\mathrm{gw}}$$

Γ_{gw} damping rate
T_{gw} effective noise temperature

- Due to the huge value of the noise temperature, GW induced contribution dominates other contributions

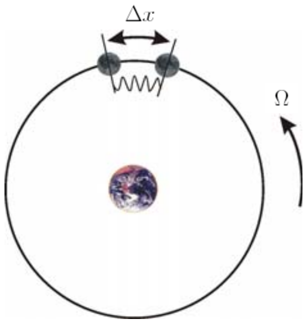
$$T_{\mathrm{gw}} \sim 10^{41}\mathrm{K} \ggg T_{\mathrm{tides}}\,,\, T_{\mathrm{em}}$$

$$D_{\mathrm{gw}} \gg D_{\mathrm{tides}}\,,\, D_{\mathrm{em}}$$

Reynaud, Maia Neto, Lambrecht & Jaekel, Europhys. Lett. **54** (2001) 135

GW and decoherence

- An hypothetical Schrödinger's Moon (coherent superposition of two positions) would be decohered on an extremely short time by the scattering of GW



$$\langle e^{i\delta\Phi_{\mathrm{gw}}}\rangle = \exp\left(-\frac{\Delta\Phi_{\mathrm{gw}}^2}{2}\right)$$

$$\frac{\Delta\Phi_{\mathrm{gw}}^2}{2} = \frac{D_{\mathrm{gw}}}{\hbar^2}\tau\,\Delta x^2$$

- As expected, coherences not observable in this case

$$\frac{D_{\mathrm{gw}}}{\hbar^2} \sim 10^{75}\,\mathrm{s}^{-1}\,\mathrm{m}^{-2}$$

Reynaud, Maia Neto, Lambrecht & Jaekel, Europhys. Lett. **54** (2001) 135

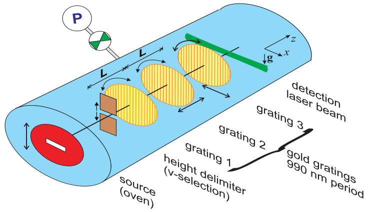
Experiments on GW induced decoherence ?

- GW induced decoherence difficult to observe
  - It is extremely rapid for macroscopic objects
  - It is very slow for microscopic objects

A challenge : design experiments allowing one to explore the transition on "mesoscopic" objects

- A few ideas already explored
  - Matter-wave interferometry with larger and larger masses
    B. Lamine et al, PRL **96** (2006) 050405 (next slides)
  - EPR correlations on larger and larger distances
    B. Lamine et al, EPL **95** (2011) 20004
  - Synchronization between remote clocks
    S. Reynaud et al, Phys. Rev. **D77** (2008) 122003

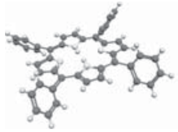
MW interferometry with large molecules .. ..



Talbot-Lau interferometer @ Vienna
Markus Arndt *et al*

Molecules that showed quantum interferences
with this interferometer

C_{60}



$C_{44}H_{30}N_4$

$C_{60}F_{48}$

Arndt *et al*, Nature **401** (1999) 680 Brezger *et al*, PRL **88** (2002) 100404

Hornberger *et al*, PRL **90** (2003) 160401 Hackermüller *et al*, Nature **427** (2004) 711

.. MW interferometry with large molecules ..

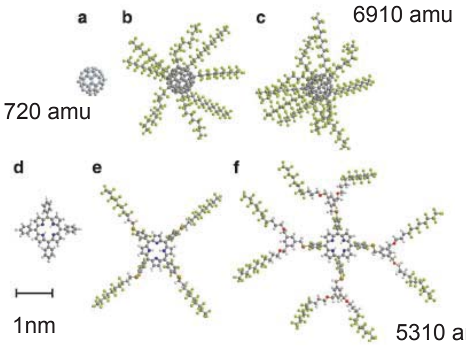


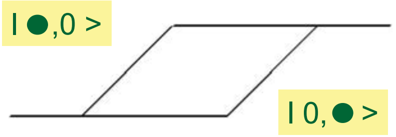
Figure 1 | Gallery of molecules used in our interference study. (**a**) The fullerene C_{60} ($m = 720$ AMU, 60 atoms) serves as a size reference and for calibration purposes; (**b**) The perfluoroalkylated nanosphere PFNS8 ($C_{60}[C_{12}F_{25}]_8$, $m = 5{,}672$ AMU, 356 atoms) is a carbon cage with eight perfluoroalkyl chains. (**c**) PFNS10 ($C_{60}[C_{12}F_{25}]_{10}$, $m = 6{,}910$ AMU, 430 atoms) has ten side chains and is the most massive particle in the set. (**d**) A single tetraphenylporphyrin TPP ($C_{44}H_{30}N_4$, $m = 614$ AMU, 78 atoms) is the basis for the two derivatives (**e**) TPPF84 ($C_{84}H_{26}F_{84}N_4S_4$, $m = 2{,}814$ AMU, 202 atoms) and (**f**) TPPF152 ($C_{168}H_{94}F_{152}O_8N_4S_4$, $m = 5{,}310$ AMU, 430 atoms). In its unfolded configuration, the latter is the largest molecule in the set. Measured by the number of atoms, TPPF152 and PFNS10 are equally complex. All molecules are displayed to scale. The scale bar corresponds to 10 Å.

Light standing wave for the middle grating
Kapitza-Dirac-Talbot-Lau interferometer
Markus Arndt *et al* @ Vienna

Gerlich *et al*, Nature Communications **2** (2011) 263

.. .. MW interferometry with large molecules

- Detailed calculations of the reduction of the fringe contrast
- Mach-Zehnder geometry
- Simple model of a constant noise temperature



$$\Delta\Phi^2_{\mathrm{gw}} = (2\Omega \sin\alpha)^2\, S_h\, 2\tau \quad , \quad \Omega = \frac{m_{\mathrm{at}} v^2_{\mathrm{at}}}{2\hbar}$$

Relevant parameters

✖ kinetic energy	$\hbar\Omega$
✖ geometry	aperture angle α
✖ GW noise spectrum	S_h
✖ exposition time	τ

- For all MW interferometry experiments studied to date, GW-induced decoherence remains undetectable

B. Lamine, R. Hervé, A. Lambrecht, S. Reynaud, PRL **96** (2006) 050405

Discussion

- Need to go to much larger masses with much longer diffusion times in a well-controlled environment …

MAQRO

- Numbers are also improved if there are non standard mechanisms inducing more fluctuations than general relativity

Example : “Spontaneous localization theories”

P. Pearle, PRA **39** (1989) 2277
G.C. Ghirardi, P. Pearle and A. Rimini, PRA **42** (1990) 78

Constraints on these models could be obtained with masses between 10^6 and 10^8 amu, which should be feasible with levitated nanospheres

O. Romero-Isart , A. Pflanzer et al., PRL **107** (2011) 020405
S. Nimmrichter, K. Hornberger, P. Haslinger and M. Arndt, PRA **83** (2011) 043621

J. Bateman, S. Nimmrichter, K. Hornberger, H. Ulbricht, Nature Comm. **5** (2014) 4788

MAQRO proposal

MAQRO

MAQRO Consortium
Coordinator: R. Kaltenbaek (Vienna)
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), P.-F. Cohadon (Paris), A. M. Cruise (Birmingham), K. Dholakia (St. Andrews), W. Ertmer (Hannover), A. Heidmann (Paris), 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), M. Rodriguez (Onera), 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)

R. Kaltenbaek, G. Hechenblaikner, N. Kiesellmeyer et al,
Exp. Astron. **34** (2012) 123; *arXiv:1201.4756*

R. Kaltenbaek, M. Arndt, M. Aspelmeyer et al (2015) *arXiv:1503.02640*

Thanks for your attention