La force et l’accélération

Culture scientifique en L3

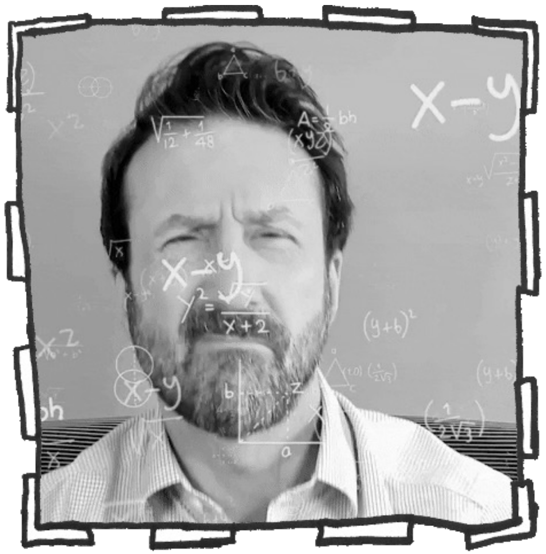
Institut Villebon-Charpak, Julien Bobroff

La force

expliquez à un enfant
de 10 ans ce que c’est

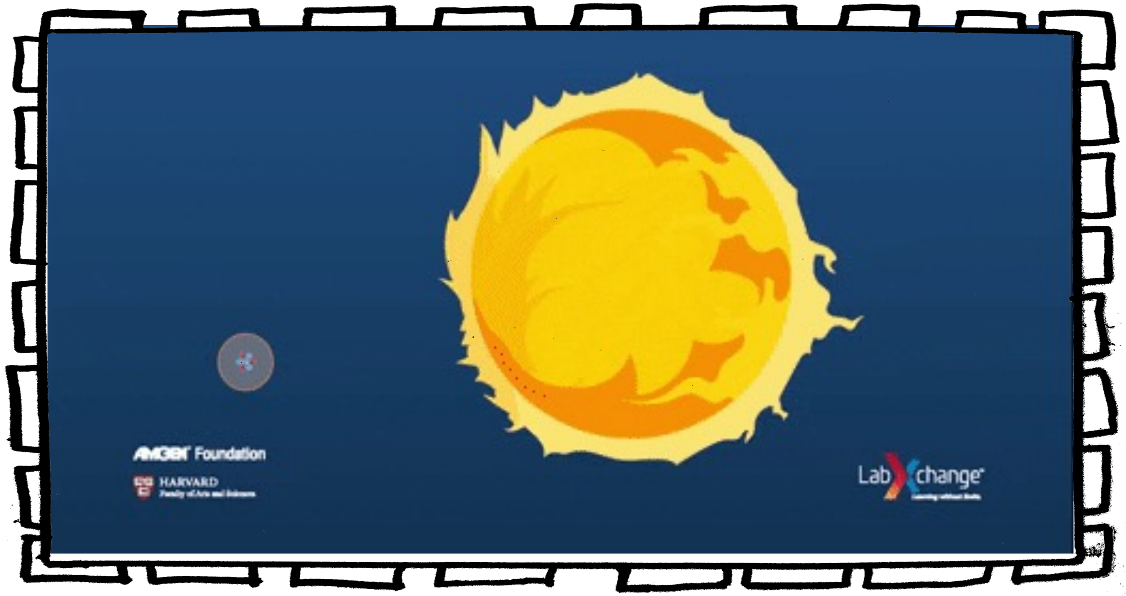
La force

quelles équations ?



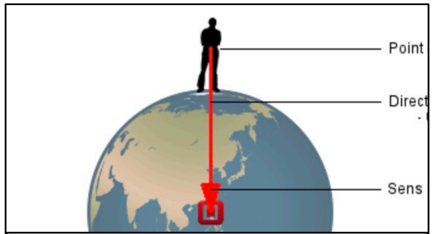
La force et l’accélération

les ordres de grandeur



classer l'accélération de la plus faible à la plus forte (en m/s²)

roller coaster



gravité

voiture accélère de 0 à 100km/h

escargot accélère à sa vitesse max.

F1 accélération moyenne

Terre vers Soleil

TGV à vitesse constante

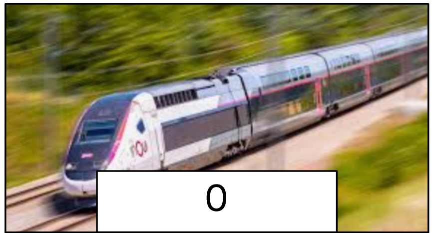
balle de baseball

protons au LHC

puce quand elle saute

classer l’accélération de la plus faible à la plus forte (en m/s²)

$a = dv/dt$

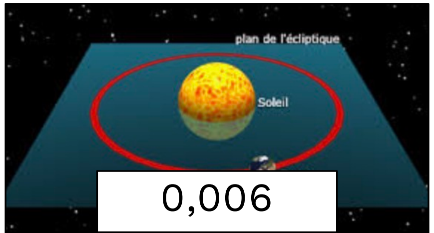


0

TGV à vitesse constante

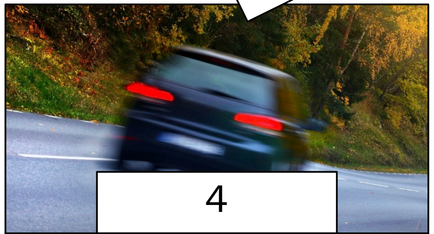
0,002

escargot va à sa vitesse max.



0,006

Terre vers Soleil



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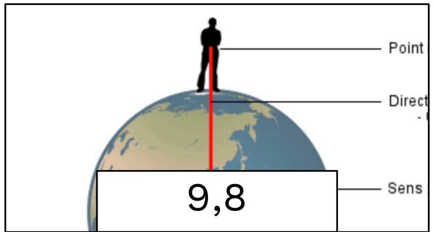
voiture va de 0 à 100km/h



9,8

gravité

30

roller coaster

60

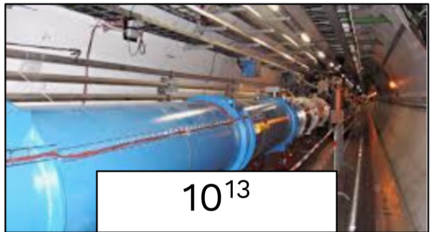
F1 accélération moyenne

2000

puce quand elle saute

30 000

balle de baseball



10^{13}

protons au LHC

Les quatre grandes forces

4 interactions fondamentales

- interaction **électromagnétique** : tout ce qui est électrique ou magnétique
- interaction **faible** : à l'origine de la désintégration de certains noyaux radioactifs.
- interaction **forte** : permet de maintenir la cohésion des noyaux.
- interaction **gravitationnelle**

La gravité

deux points de vue

- **Newton :** mécanique classique
  La gravité est liée à une force d'attraction entre masses

- **Einstein :** relativité générale
  La gravité est liée à une courbure de l'espace-temps.

La force

recherches récentes

recherches récentes

1. mesurer une petite force
2. tester la loi de gravitation
3. tester le principe d'équivalence
4. l'accélération chez la puce

recherches récentes

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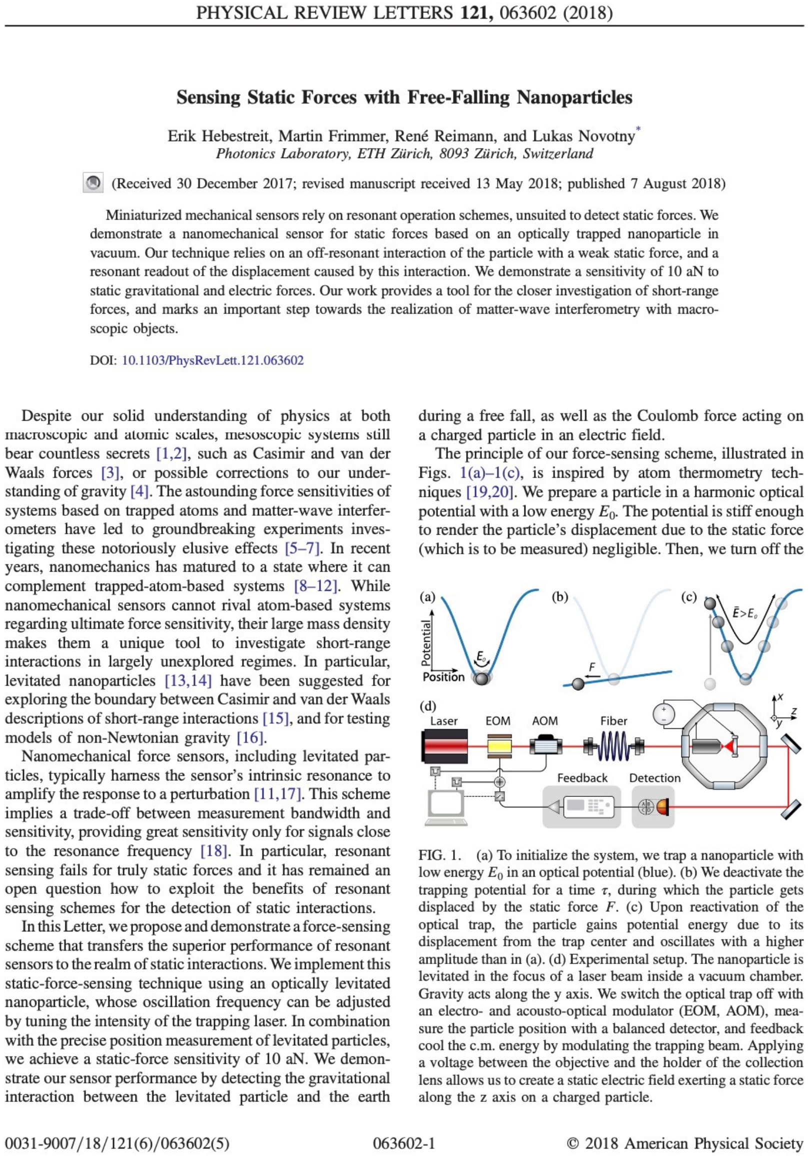

Sensing Static Forces with Free-Falling Nanoparticles

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(Received 30 December 2017; revised manuscript received 13 May 2018; published 7 August 2018)

Miniaturized mechanical sensors rely on resonant operation schemes, unsuited to detect static forces. We demonstrate a nanomechanical sensor for static forces based on an optically trapped nanoparticle in vacuum. Our technique relies on an off-resonant interaction of the particle with a weak static force, and a resonant readout of the displacement caused by this interaction. We demonstrate a sensitivity of 10 aN to static gravitational and electric forces. Our work provides a tool for the closer investigation of short-range forces, and marks an important step towards the realization of matter-wave interferometry with macroscopic objects.

DOI: 10.1103/PhysRevLett.121.063602

Despite our solid understanding of physics at both macroscopic and atomic scales, mesoscopic systems still bear countless secrets [1,2], such as Casimir and van der Waals forces [3], or possible corrections to our understanding of gravity [4]. The astounding force sensitivities of systems based on trapped atoms and matter-wave interferometers have led to groundbreaking experiments investigating these notoriously elusive effects [5–7]. In recent years, nanomechanics has matured to a state where it can complement trapped-atom-based systems [8–12]. While nanomechanical sensors cannot rival atom-based systems regarding ultimate force sensitivity, their large mass density makes them a unique tool to investigate short-range interactions in largely unexplored regimes. In particular, levitated nanoparticles [13,14] have been suggested for exploring the boundary between Casimir and van der Waals descriptions of short-range interactions [15], and for testing models of non-Newtonian gravity [16].

Nanomechanical force sensors, including levitated particles, typically harness the sensor's intrinsic resonance to amplify the response to a perturbation [11,17]. This scheme implies a trade-off between measurement bandwidth and sensitivity, providing great sensitivity only for signals close to the resonance frequency [18]. In particular, resonant sensing fails for truly static forces and it has remained an open question how to exploit the benefits of resonant sensing schemes for the detection of static interactions.

In this Letter, we propose and demonstrate a force-sensing scheme that transfers the superior performance of resonant sensors to the realm of static interactions. We implement this static-force-sensing technique using an optically levitated nanoparticle, whose oscillation frequency can be adjusted by tuning the intensity of the trapping laser. In combination with the precise position measurement of levitated particles, we achieve a static-force sensitivity of 10 aN. We demonstrate our sensor performance by detecting the gravitational interaction between the levitated particle and the earth during a free fall, as well as the Coulomb force acting on a charged particle in an electric field.

The principle of our force-sensing scheme, illustrated in Figs. 1(a)–1(c), is inspired by atom thermometry techniques [19,20]. We prepare a particle in a harmonic optical potential with a low energy E_0. The potential is stiff enough to render the particle's displacement due to the static force (which is to be measured) negligible. Then, we turn off the

FIG. 1. (a) To initialize the system, we trap a nanoparticle with low energy E_0 in an optical potential (blue). (b) We deactivate the trapping potential for a time τ, during which the particle gets displaced by the static force F. (c) Upon reactivation of the optical trap, the particle gains potential energy due to its displacement from the trap center and oscillates with a higher amplitude than in (a). (d) Experimental setup. The nanoparticle is levitated in the focus of a laser beam inside a vacuum chamber. Gravity acts along the y axis. We switch the optical trap off with an electro- and acousto-optical modulator (EOM, AOM), measure the particle position with a balanced detector, and feedback cool the c.m. energy by modulating the trapping beam. Applying a voltage between the objective and the holder of the collection lens allows us to create a static electric field exerting a static force along the z axis on a charged particle.

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Hebestreit et al.

Physical review letters 063602 (2018)

Zurich, Suisse

2018

détecter des forces de 10 aN avec des billes en lévitation

Mesurer une petite force

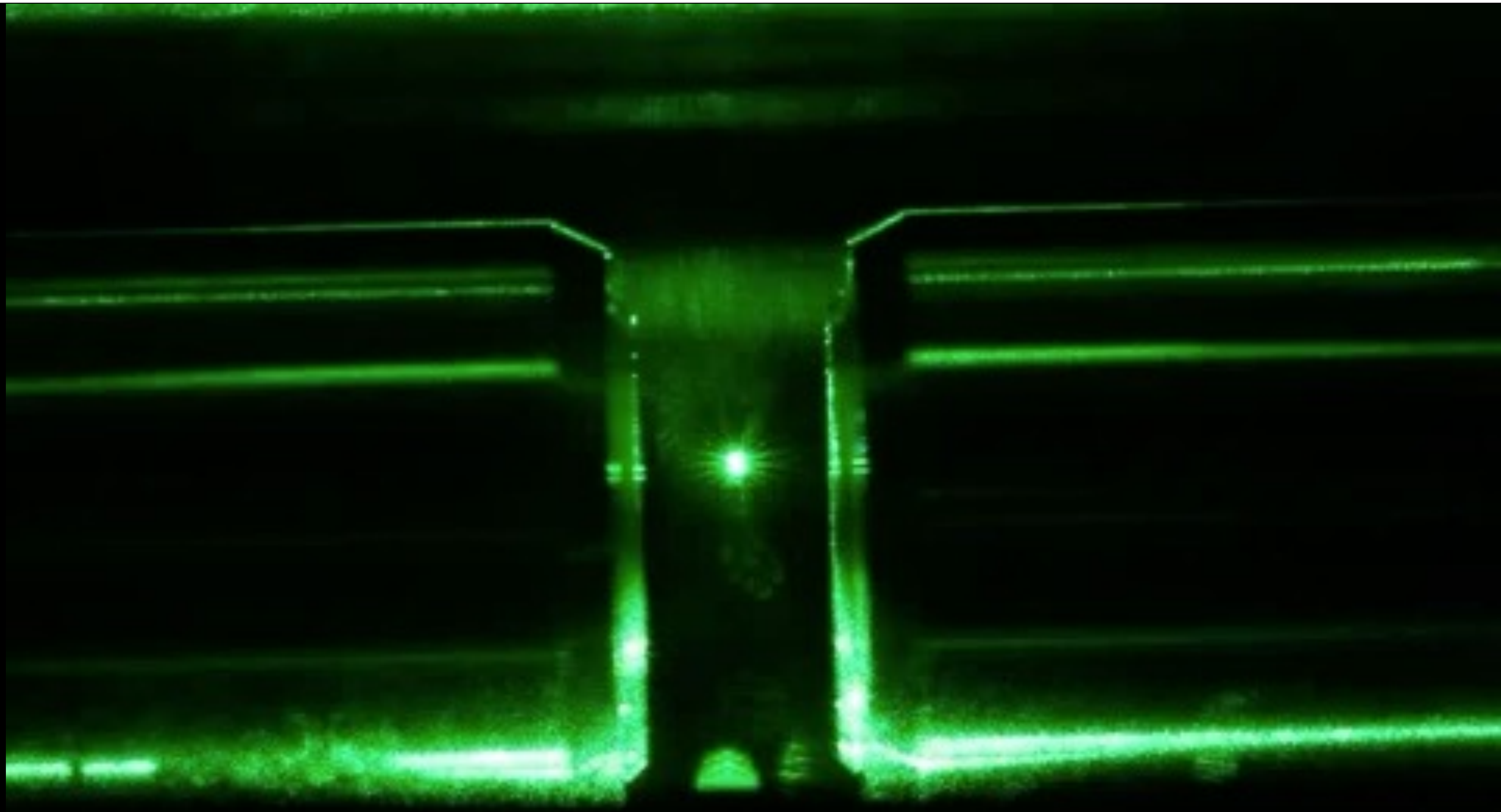
On utilise la **lévitodynamique** :
lévitation et contrôle d'objets microscopiques dans le vide

Pour faire léviter, on utilise :

Piège optique : avec des lasers, on joue sur les forces dipolaires électriques entre le laser et un objet diélectrique

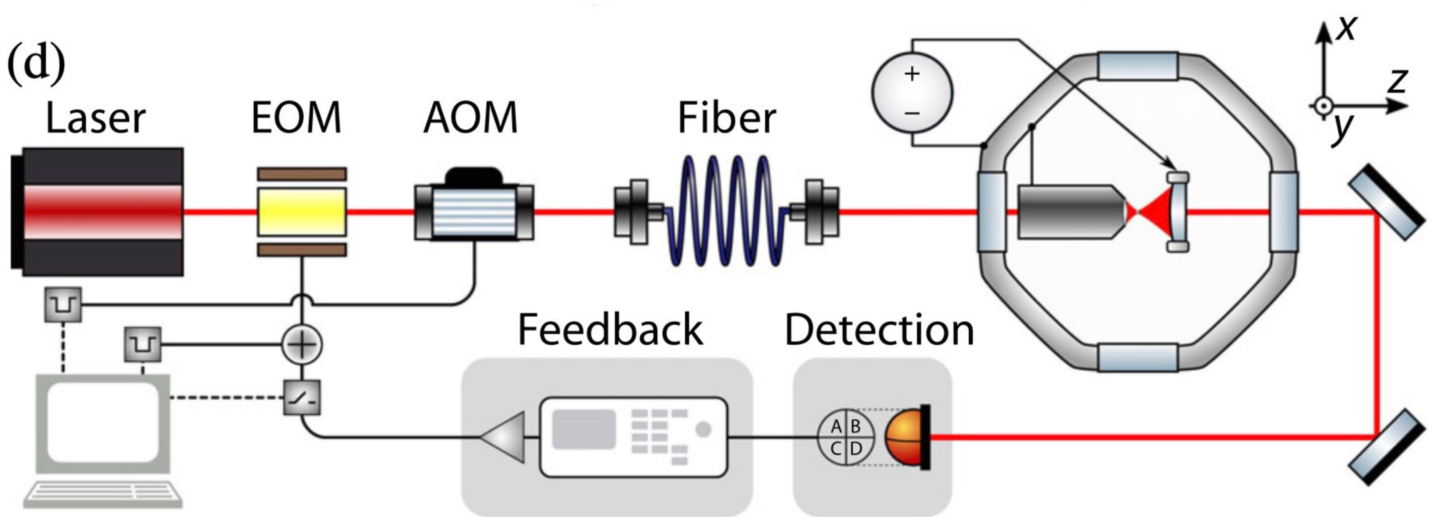
Piège électrique : avec des champs radiofréquences sur un objet électrisé

Magnétique : avec des champs magnétiques sur un objet magnétique



levitation optique d’une goutte de glycérol

on piège une petite bille par des lasers : pinces optiques



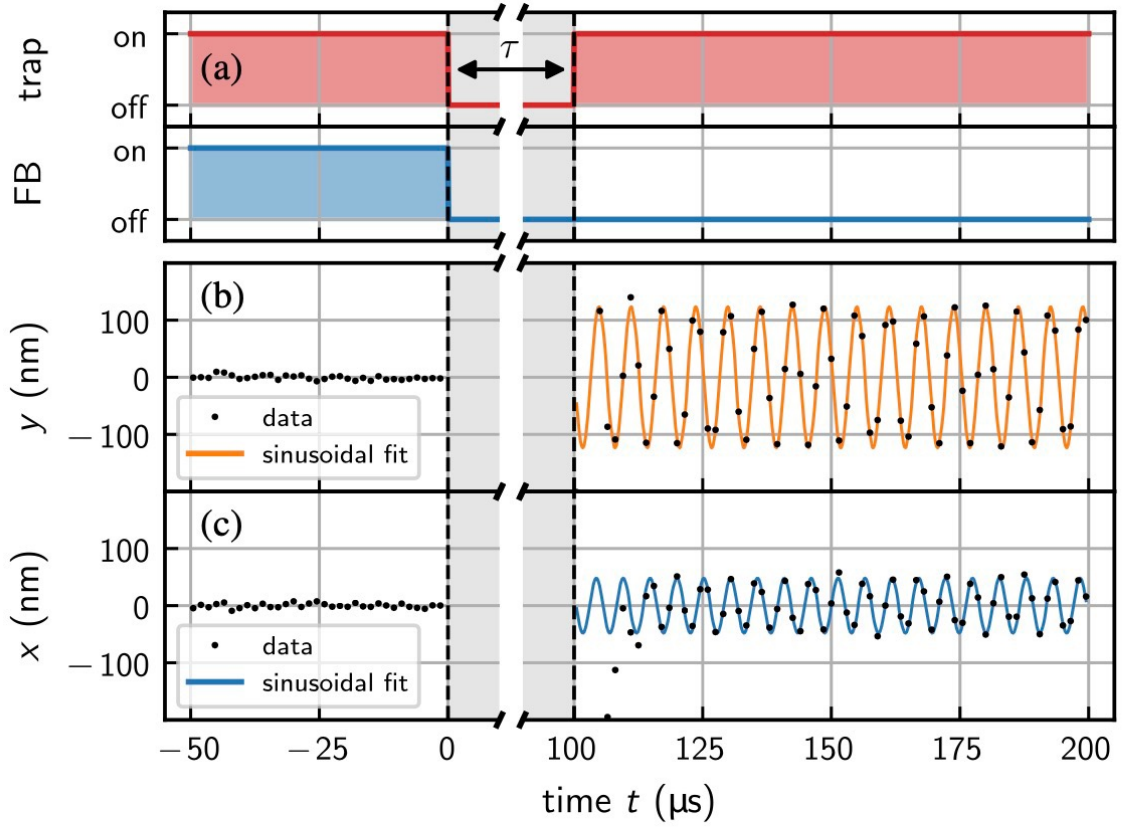
bille en silicium de rayon 58nm et masse 2 fg = 2 10^{-15}g

si on veut mesurer la gravité, on doit détecter une force :
F = P = mg = 9,8 * 2 10^{-18} kg = 2 10^{-17} N = 20 aN

pour mesurer la force :

- on arrête le piège
- la bille est sensible à la force seulement
- on redémarre le piège et on regarde la bille « rebondir »
- on déduit des oscillations l'amplitude de la force

→ ils trouvent g=10.4+-1.8 m/s²



sensibilité : 10 aN = 10^{-17} N

Si on peut encore mieux calmer la sphère, on pourrait atteindre une sensibilité de 1 zN = 10^{-21}N

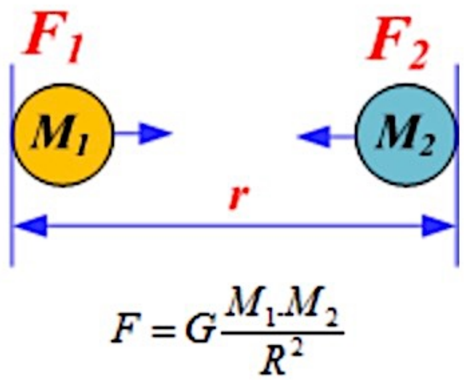
recherches récentes

1. mesurer une petite force
2. tester la loi de gravitation
3. tester le principe d'équivalence
4. l'accélération chez la puce

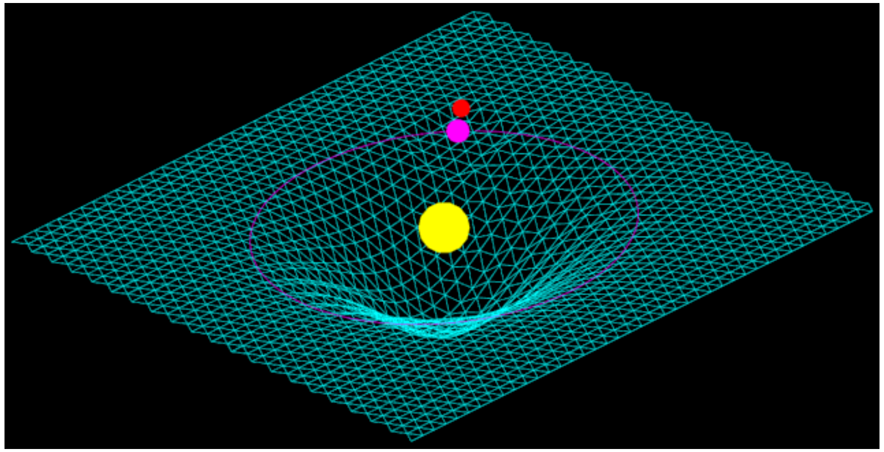
La gravité

deux points de vue

- mécanique classique (Newton) :
  Gravité liée à une force d'attraction
  entre masses



- relativité générale (Einstein) :
  La matière déforme l'espace
  ce qui crèe les effets de gravité.



Tester la loi de gravitation

Des théories au delà du « modèle standard » suggèrent des nouveaux effets liés à la gravité à des échelles petites (dans la théorie des cordes, ou dans d'autres théories à particules exotiques).

Tous ces effets crèeraient des déviations à la loi de gravitation via un terme exponentiel :

loi gravitationnelle :

$$V(r) = -G\frac{m_1 m_2}{r}$$

loi gravitationnelle modifiée :

$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

Article

Measurement of gravitational coupling between millimetre-sized masses

https://doi.org/10.1038/s41586-021-03250-7

Received: 17 September 2020

Accepted: 18 January 2021

Published online: 10 March 2021

Check for updates

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Gravity is the weakest of all known fundamental forces and poses some of the most important open questions to modern physics: it remains resistant to unification within the standard model of physics and its underlying concepts appear to be fundamentally disconnected from quantum theory[1–4]. Testing gravity at all scales is therefore an important experimental endeavour[5–7]. So far, these tests have mainly involved macroscopic masses at the kilogram scale and beyond[8]. Here we show gravitational coupling between two gold spheres of 1 millimetre radius, thereby entering the regime of sub-100-milligram sources of gravity. Periodic modulation of the position of the source mass allows us to perform a spatial mapping of the gravitational force. Both linear and quadratic coupling are observed as a consequence of the nonlinearity of the gravitational potential. Our results extend the parameter space of gravity measurements to small, single source masses and low gravitational field strengths. Further improvements to our methodology will enable the isolation of gravity as a coupling force for objects below the Planck mass. This work opens the way to the unexplored frontier of microscopic source masses, which will enable studies of fundamental interactions[9–11] and provide a path towards exploring the quantum nature of gravity[12–15].

The last decades have seen numerous experimental confirmations of Einstein's theory of relativity, our best working theory of gravity, by observing massive astronomical objects and their dynamics[5,16]. This culminated in the recent direct detection of gravitational waves from the merger of two black holes[17] and the direct imaging of a supermassive black hole[18]. Meanwhile, Earth-bound experiments have been continuously increasing their sensitivity to gravity phenomena at laboratory scales, including general relativistic effects[19,20], tests of the equivalence principle[6,21], precision measurements of Newton's constant[22–24] and tests of the validity of Newton's law at micrometre-scale distances[25–27]. Although test masses in such experiments span the whole range from macroscopic objects to individual quantum systems[19–21,24,28], the gravitational source is typically either Earth or masses at the kilogram scale and beyond[8]. This is contrasted by an increasing interest to study gravitational phenomena originating from quantum states of source masses, for example, in the form of 'quantum Cavendish experiments'[1,12–14,29]. Because quantum coherence is easily lost for increasing system size, it is important to isolate gravity as a coupling force for as small objects as possible.

Experiments with smaller source masses are much more difficult—the gravitational force generated at a given distance by a spherical mass of radius R shrinks with R^{-3}—and hence only few experiments have so far observed gravitational signatures of gram-scale mass configurations[27,30,31]. In one case, a hole pattern in a rotating, 5-cm-diameter attractor disk made from platinum generated a periodic mass modulation of a few hundred milligrams, which was resolved in a torsional balance measurement[27]. In another case, a single 700-mg tungsten sphere was used to resonantly excite a torsion pendulum[31]. Isolating gravitational interactions generated by even smaller, single source-mass objects is a challenging task because it requires increasing efforts to shield residual contributions from other sources of acceleration, in particular of seismic and electromagnetic nature[32]. In addition, resonant detection schemes, which are typically employed to amplify the signal above the readout noise, amplify displacement noise as well, and hence do not yield any gain in terms of separating the signal from other force noise sources. Here we overcome this limitation by combining time-dependent gravitational accelerations with an off-resonant detection scheme of a well balanced differential mechanical mode and independent noise estimation. In this way, we can measure the gravitational field of single source masses smaller than 100 mg.

Experiment

In our experiment, the gravitational source is a nearly spherical gold mass of radius $R = 1.07 \pm 0.04$ mm and mass $m_s = 92.1 \pm 0.1$ mg. A similarly sized gold sphere acts as a test mass of $m_t = 90.7 \pm 0.1$ mg. The idea is that a periodic modulation of the position of the source mass generates a time-dependent gravitational potential at the location of the test mass, the acceleration of which is measured in a miniature torsion pendulum configuration (Fig. 1). The experiment is conducted in high vacuum (6×10^{-7} mbar), which minimizes residual noise from acoustic coupling and momentum transfer of gas molecules[32] (see Methods). To prevent nonlinear coupling of high-frequency vibrations into the relevant low-frequency measurement band around the modulation frequency $f_{mod} = 12.7$ mHz, the support structure of the pendulum rests on soft, vacuum-compatible rubber feet[33].

We optically monitor the angular deflection of the pendulum, which provides a calibrated readout of the motion of the test mass with a

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Westphal et al., Nature 591, 225 (2021)

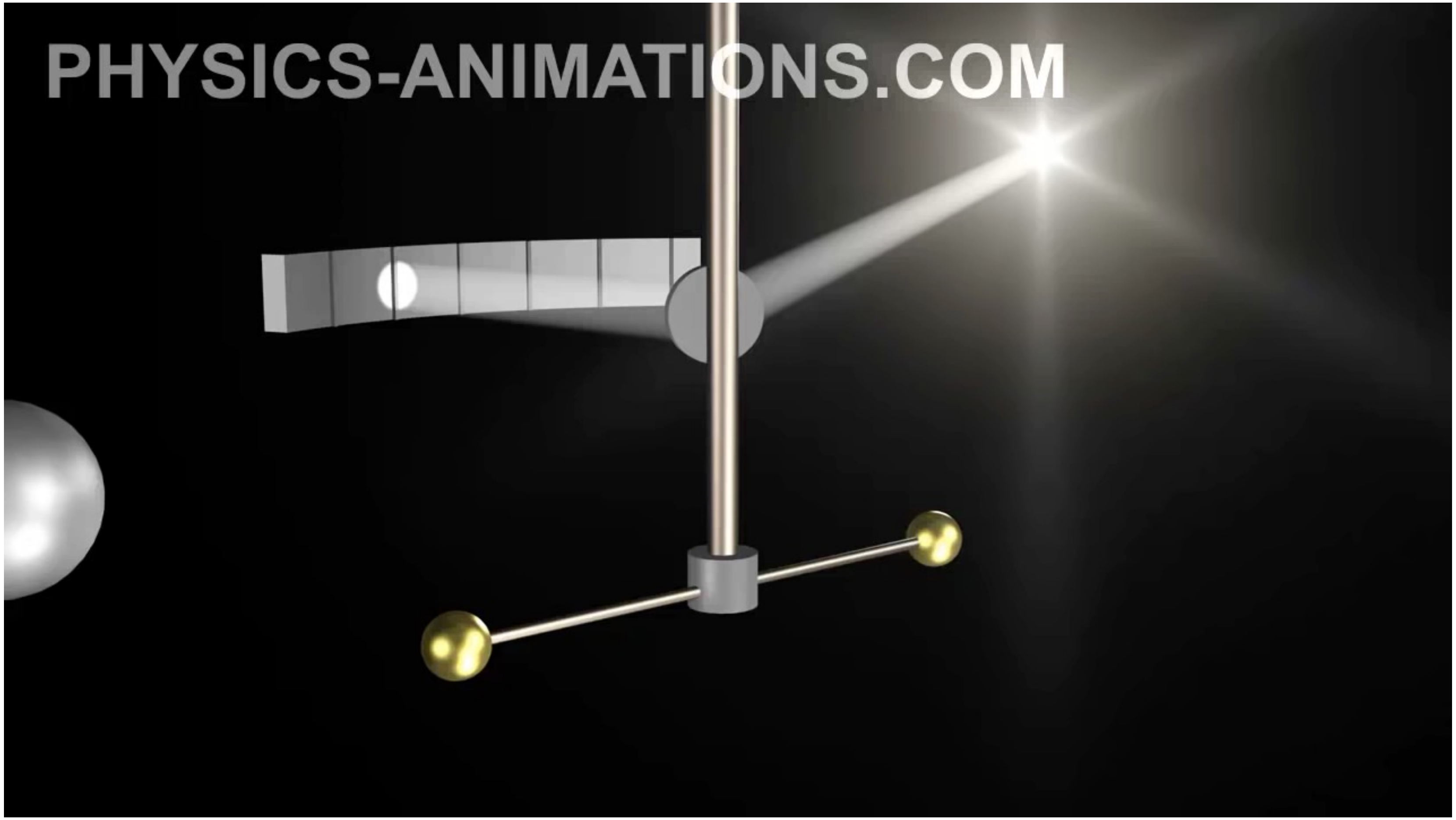
Vienne, Autriche

2021

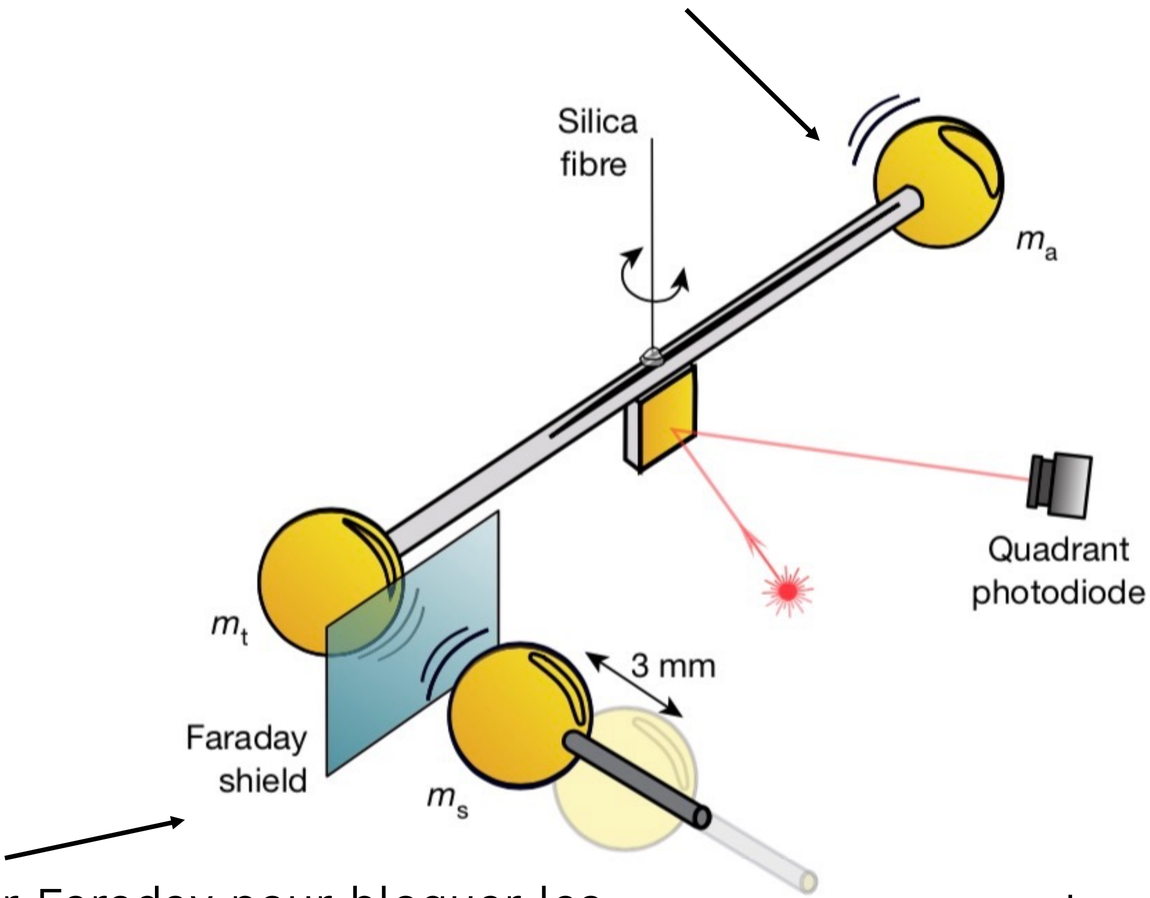
mesurer la gravitation entre masses de quelques mm et mg

but : mesurer l’effet gravitationnel d’une bille d’or de 1mm de rayon de 92mg sur une autre identique, à qq mm, donc une force de l’ordre de 10^{-14}N

principe : la balance de Cavendish

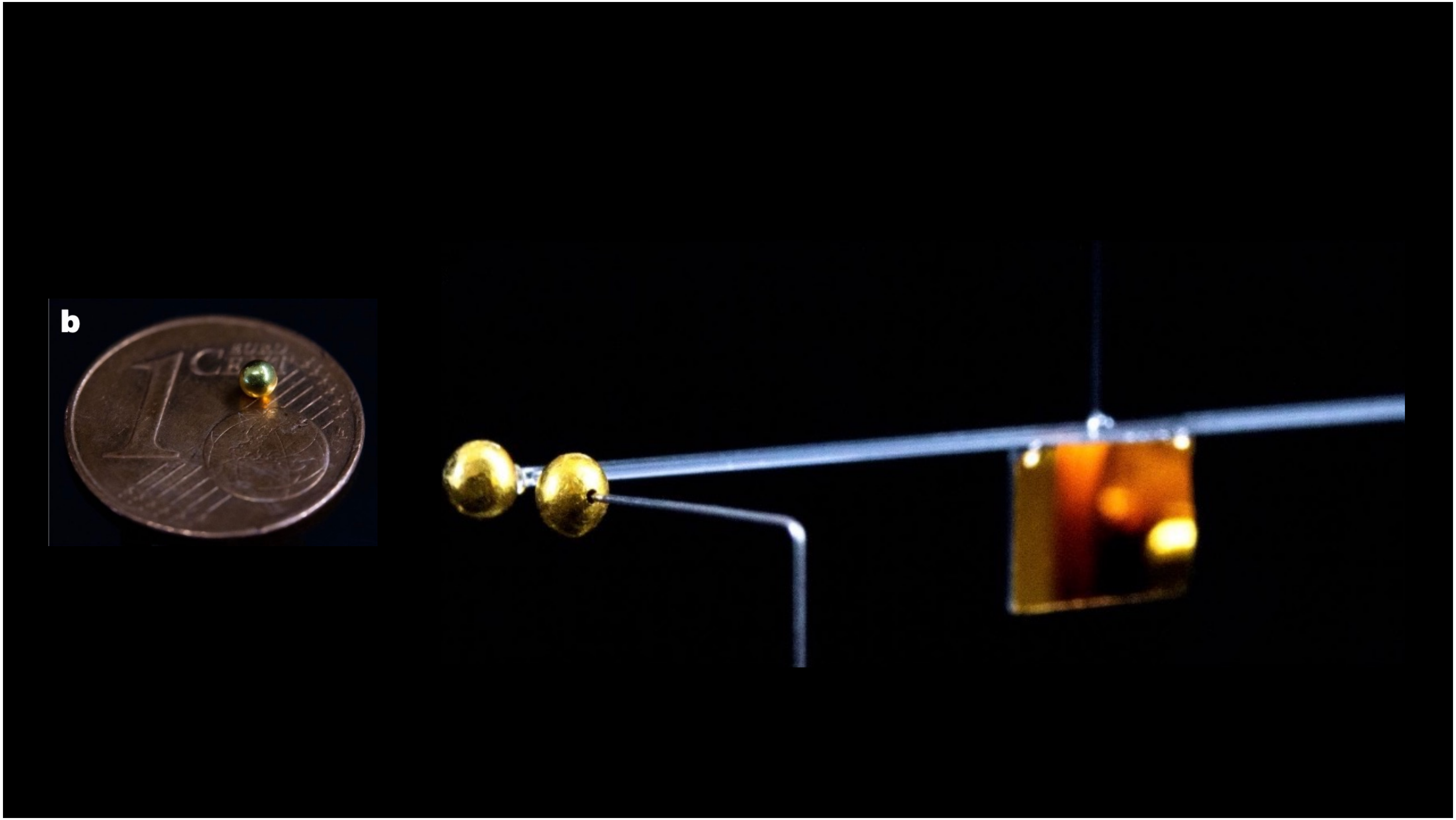


sphère de 92 mg



bouclier Faraday pour bloquer les effets electromagnétiques

on approche périodiquement une 3ème sphère
->effet périodique

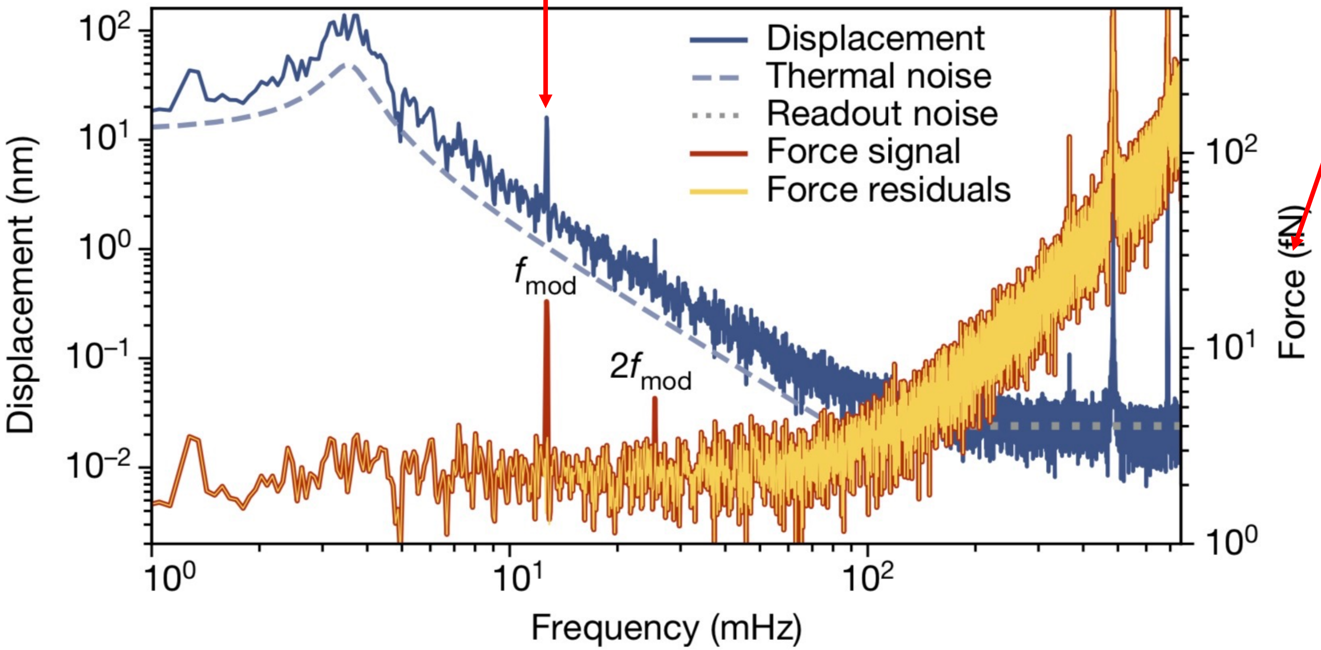

b

Mesure du déplacement des sphères et de la force correspondante parmi le bruit :

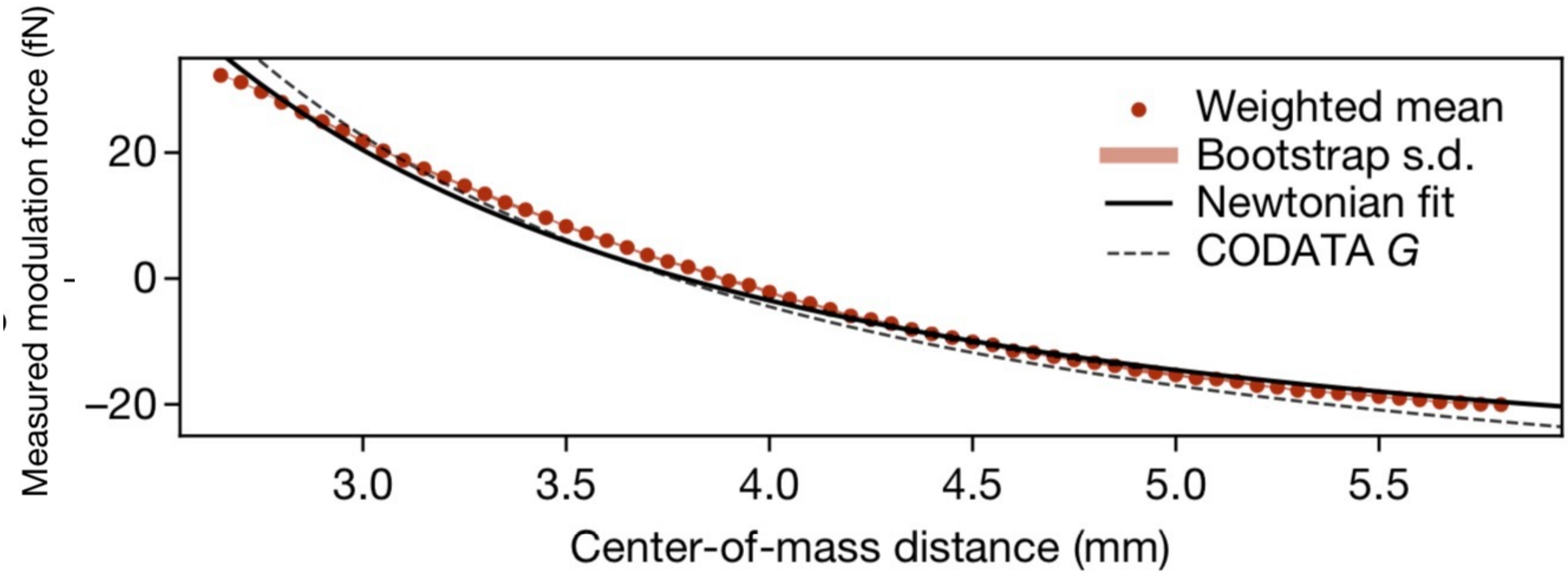
la fréquence
de l’oscillation

$fN=10^{-15}N$

on mesure des
nanomètres



correspond à une accélération de $3x10^{-10}m/s^2$



la loi $V(r) = -G\frac{m_1 m_2}{r}$ est bien vérifiée dans l'intervalle d'incertitude.

recherches récentes

1. mesurer une petite force
2. tester la loi de gravitation
3. **tester le principe d’équivalence**
4. l’accélération chez la puce

tester le principe d’équivalence

La relativité générale implique le principe d'équivalence : tous les corps tombent de la même manière dans un champ gravitationnel lorsqu'aucune autre force n'agit sur eux, indépendamment de leurs masses et constitutions internes.

Mais des théories alternatives prévoient que ce principe ne soit plus vérifié.

PHYSICAL REVIEW LETTERS **129,** 121102 (2022)

Editors' Suggestion | Featured in Physics

MICROSCOPE Mission: Final Results of the Test of the Equivalence Principle

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(Received 27 January 2022; revised 10 March 2022; accepted 30 March 2022; published 14 September 2022)

The *MICROSCOPE* mission was designed to test the weak equivalence principle (WEP), stating the equality between the inertial and the gravitational masses, with a precision of 10^{-15} in terms of the Eötvös ratio η. Its experimental test consisted of comparing the accelerations undergone by two collocated test masses of different compositions as they orbited the Earth, by measuring the electrostatic forces required to keep them in equilibrium. This was done with ultrasensitive differential electrostatic accelerometers onboard a drag-free satellite. The mission lasted two and a half years, cumulating five months worth of science free-fall data, two-thirds with a pair of test masses of different compositions—titanium and platinum alloys—and the last third with a reference pair of test masses of the same composition—platinum. We summarize the data analysis, with an emphasis on the characterization of the systematic uncertainties due to thermal instabilities and on the correction of short-lived events which could mimic a WEP violation signal. We found no violation of the WEP, with the Eötvös parameter of the titanium and platinum pair constrained to $\eta(\mathrm{Ti,Pt}) = [-1.5 \pm 2.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^{-15}$ at 1σ in statistical errors.

DOI: 10.1103/PhysRevLett.129.121102

General relativity (GR) offers a remarkable description of gravitational interactions, successfully tested in the anomalous precession of the perihelion of Mercury, the bending of light in a gravitational field, the gravitational redshift, the Shapiro time delay and the change in the periods of binary pulsars from the emission of gravitational waves [1–10]. Gravitational waves from the coalescence of neutron stars and very massive black holes have been observed recently, providing evidence for the existence of black holes and ruling out many beyond-GR models [11–19].

A building block of general relativity is the equivalence principle (EP), according to which all bodies fall in the same way in a gravitational field when no other forces are acting on them, independently of their masses and internal constitutions. First observed by Galileo and Newton and tested by Eötvös *et al.* at the 5×10^{-9} level [20], the

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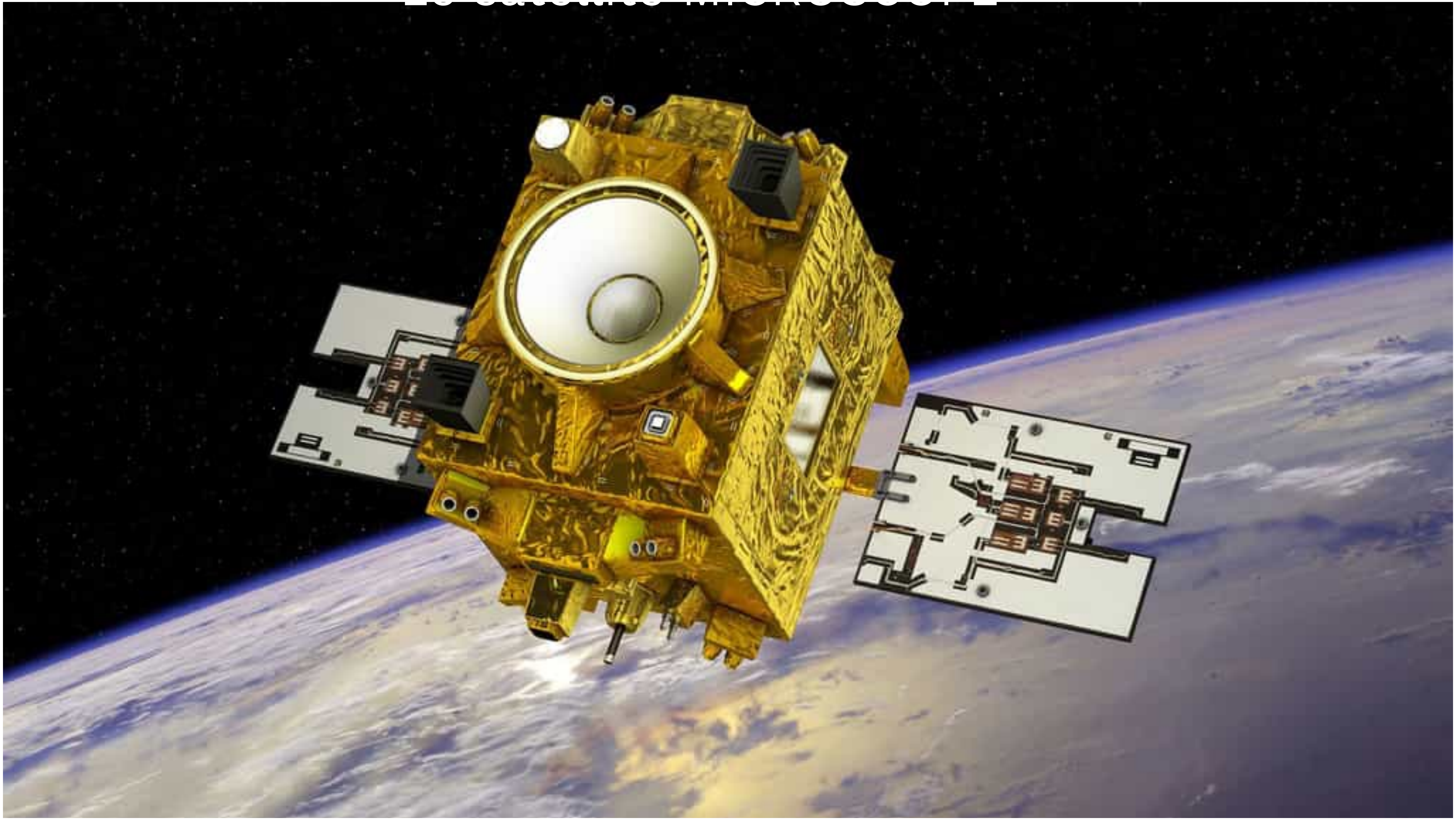
Touboul et al.

Physical review letters 121102 (2022)

international

2022

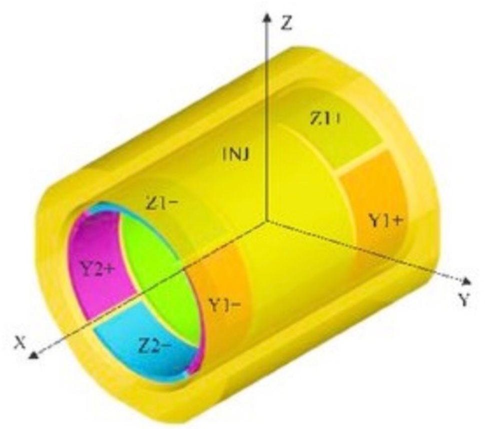
tester le principe d'équivalence,
soit en gros la chute des corps.



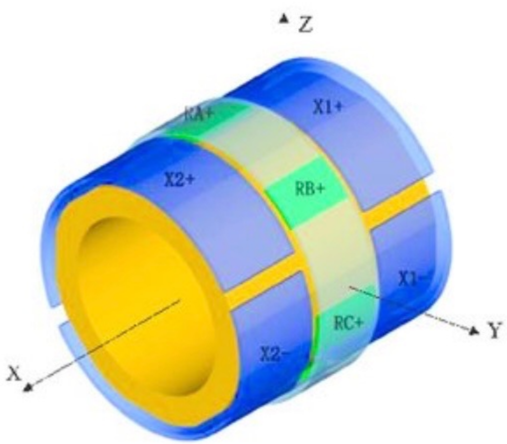
tester le principe d’équivalence

L’expérience : un acceléromètre différentiel mesure deux tubes de masse différente concentriques, en Pt et Ti, dans le satellite en chute libre autour de la Terre.

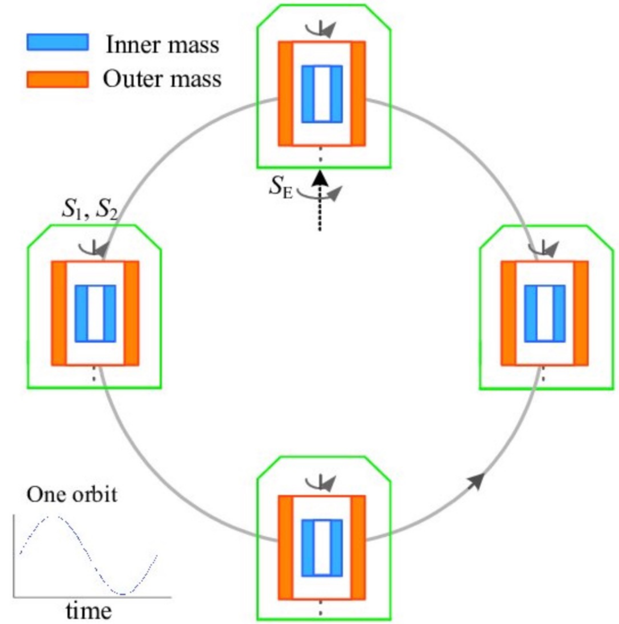
Comment ? Des champs electriques corrigent en permanence la position des tubes pour les maintenir au même point. On compare ces champs entre les 2 tubes.

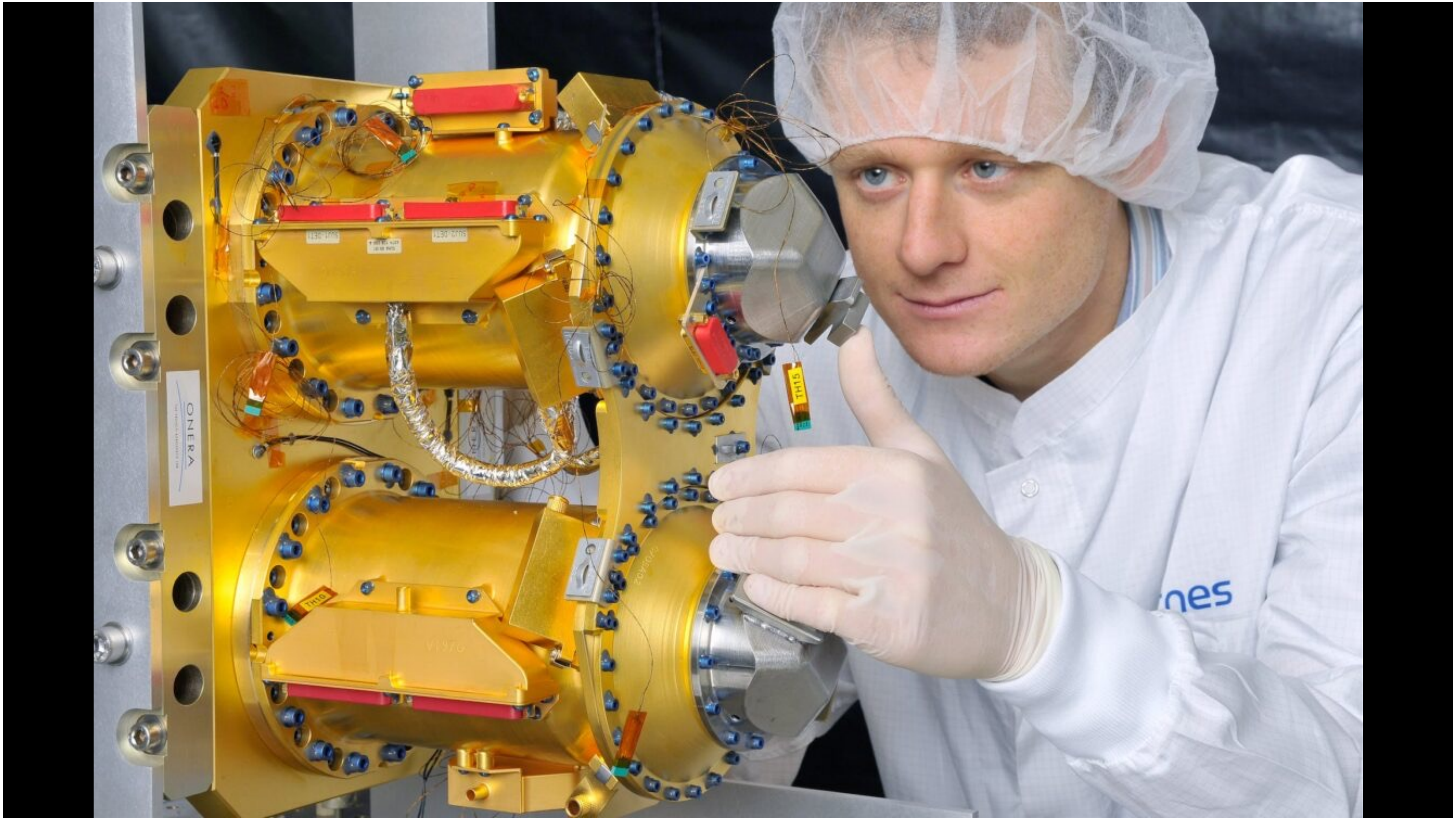


(a) Inner cylinder electrodes



(b) Outer cylinder electrodes




ONERA
TH15
TH10

tester le principe d'équivalence

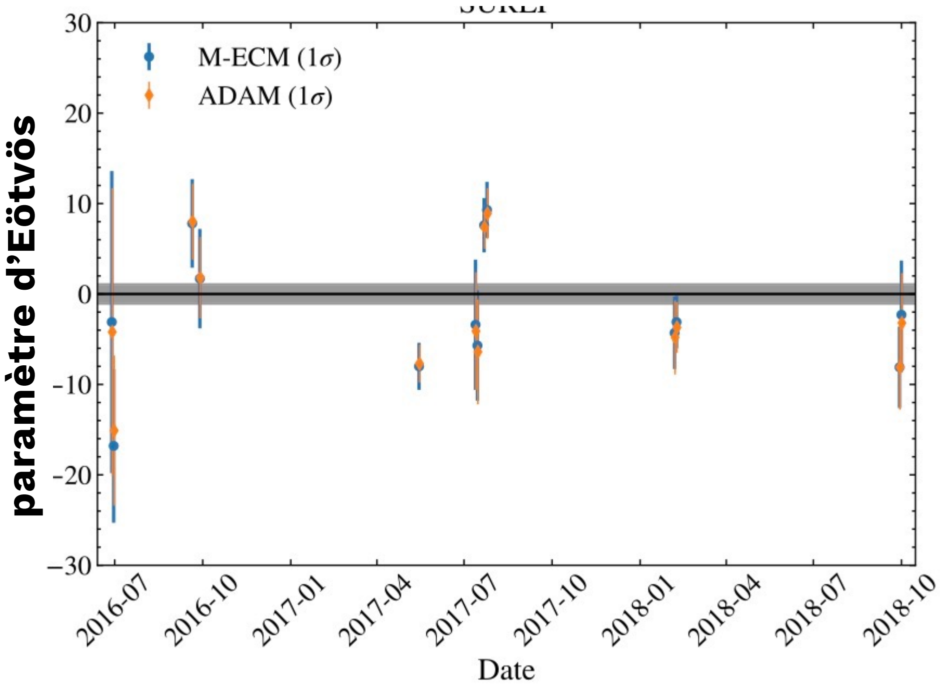
mesure via le paramètre d'Eötvös :

$$\eta = \frac{2[(m_g/m_i)_A - (m_g/m_i)_B]}{[(m_g/m_i)_A + (m_g/m_i)_B]}$$

m_i masse inertielle
m_g masse gravitationnelle

Ce paramètre vaut 0 si le principe d'équivalence est vérifié.

mesure
sur 2 ans



tester le principe d’équivalence

Résultat :

Putting these results together, *MICROSCOPE*’s new constraint on the validity of the WEP is

$$\eta(\mathrm{Ti}, \mathrm{Pt}) = [-1.5 \pm 2.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^{-15}, \qquad (5)$$

Vérification du principe d’équivalence et de l’indépendance de la chute des corps à la masse à 10^{-15}

PHYSICAL REVIEW LETTERS **127,** 100401 (2021)

Editors' Suggestion | Featured in Physics

Collective-Mode Enhanced Matter-Wave Optics

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(Received 13 November 2020; revised 14 June 2021; accepted 25 June 2021; published 30 August 2021)

In contrast to light, matter-wave optics of quantum gases deals with interactions even in free space and for ensembles comprising millions of atoms. We exploit these interactions in a quantum degenerate gas as an adjustable lens for coherent atom optics. By combining an interaction-driven quadrupole-mode excitation of a Bose-Einstein condensate (BEC) with a magnetic lens, we form a time-domain matter-wave lens system. The focus is tuned by the strength of the lensing potential and the oscillatory phase of the quadrupole mode. By placing the focus at infinity, we lower the total internal kinetic energy of a BEC comprising 101(37) thousand atoms in three dimensions to $3/2\, k_B \cdot 38^{+6}_{-7}$ pK. Our method paves the way for free-fall experiments lasting ten or more seconds as envisioned for tests of fundamental physics and high-precision BEC interferometry, as well as opens up a new kinetic energy regime.

DOI: 10.1103/PhysRevLett.127.100401

Optics with matter waves shares many analogies with its counterpart for light. However, matter can interact via electromagnetic forces: a well known fact in electron or ion optics, where the Coulomb repulsion causes particle beams to diverge, deteriorating their quality [1]. Similarly, interactions accelerate the expansion of a repulsive quantum gas in free fall and, moreover, become dominant at ultralow temperatures, setting a lower limit to the internal kinetic energy of the gas [2].

So far, evaporative cooling [3] and spin gradient cooling [4] permitted to reach three-dimensional internal kinetic energies below 500 and 350 pK, respectively. In terms of effective temperatures, employing matter-wave lenses based on magnetic [5–7], electrostatic [8], or optical [9] forces made it possible to reduce the internal kinetic energy of a BEC to about 50 pK [10], albeit only in two dimensions.

We tailor the expansion of a ^{87}Rb BEC by exploiting a collective-mode excitation in the BEC [11,12] in combination with a magnetic lens. Both act together like a time-domain matter-wave lens system for all three spatial dimensions. The focus of the lens system can be tuned by releasing the BEC at an appropriate phase of the collective-mode oscillation and the strength of the lensing potential. When focusing at infinity, we achieve a total internal kinetic energy in three dimensions of as low as $3/2\, k_B \cdot 38^{+6}_{-7}$ pK.

Such atomic ensembles allow for placing better experimental constraints on proposed modifications of quantum theory [13–15], predicting tiny deviations from the standard expansion of a quantum gas. Moreover, for the first time, they fulfill the strict requirements imposed by atom interferometers exploiting free-fall times of tens of seconds [16–18] as needed, e. g. for a stringent quantum test of the equivalence principle [19–21], gravitational wave detection [22,23], or the determination of the gravitational constant [24] and the photon recoil [25]. In these precision experiments, the residual motion of the atoms couples to rotations [26–28] or to wave-front distortions of the interferometry light beam [29–31], leading to a phase noise or bias in the interferometer. Additionally, the atomic expansion limits the efficiency of large momentum beam splitters proposed for high-precision experiments [32–35].

Our matter-wave lens system is implemented using an atom chip [Fig. 1(a)], which permits us to excite the BEC to perform collective-mode oscillations [Fig. 1(b)] to release it at a specific phase and to shape it with a magnetic lens. Figures 1(c)–1(e) compare the simulated absorption images

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Deppner et al., PRL 127, 100401 (2021)

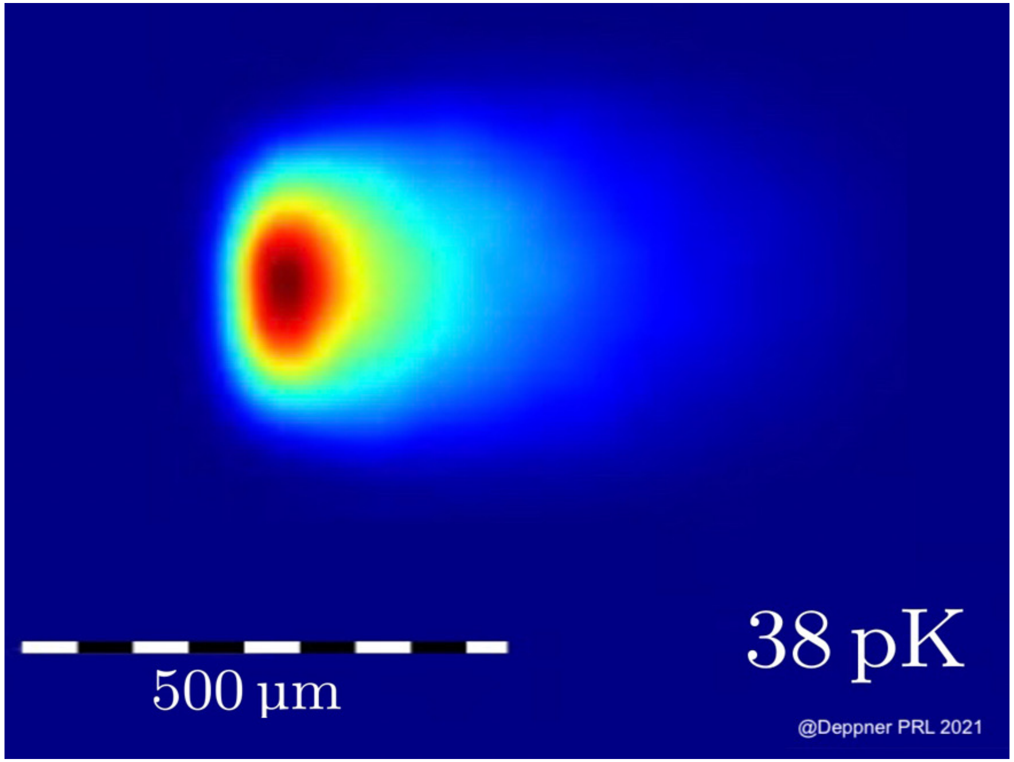
Brême, Allemagne

2021

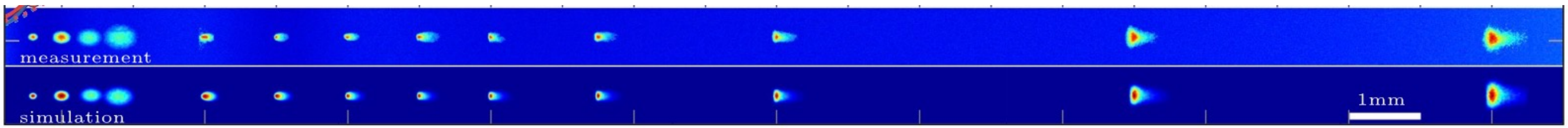
mesurer la chute libre d'un nuage d'atomes

tester le principe d'équivalence

Test sur un nuage d'atomes en chute libre dans la tour de Brême (120m)

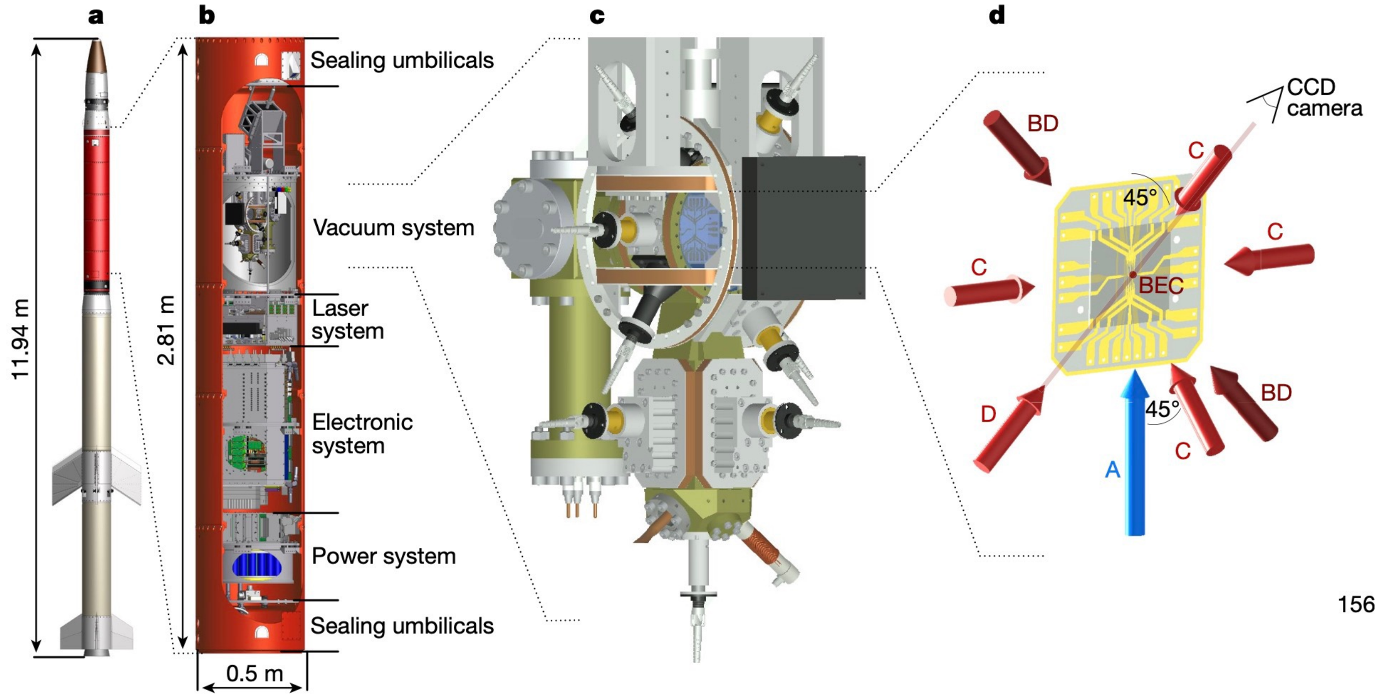


pendant la chute :



tester le principe d’équivalence

Test sur un nuage d’atomes en chute libre dans le Cold Atom Lab de l’ISS



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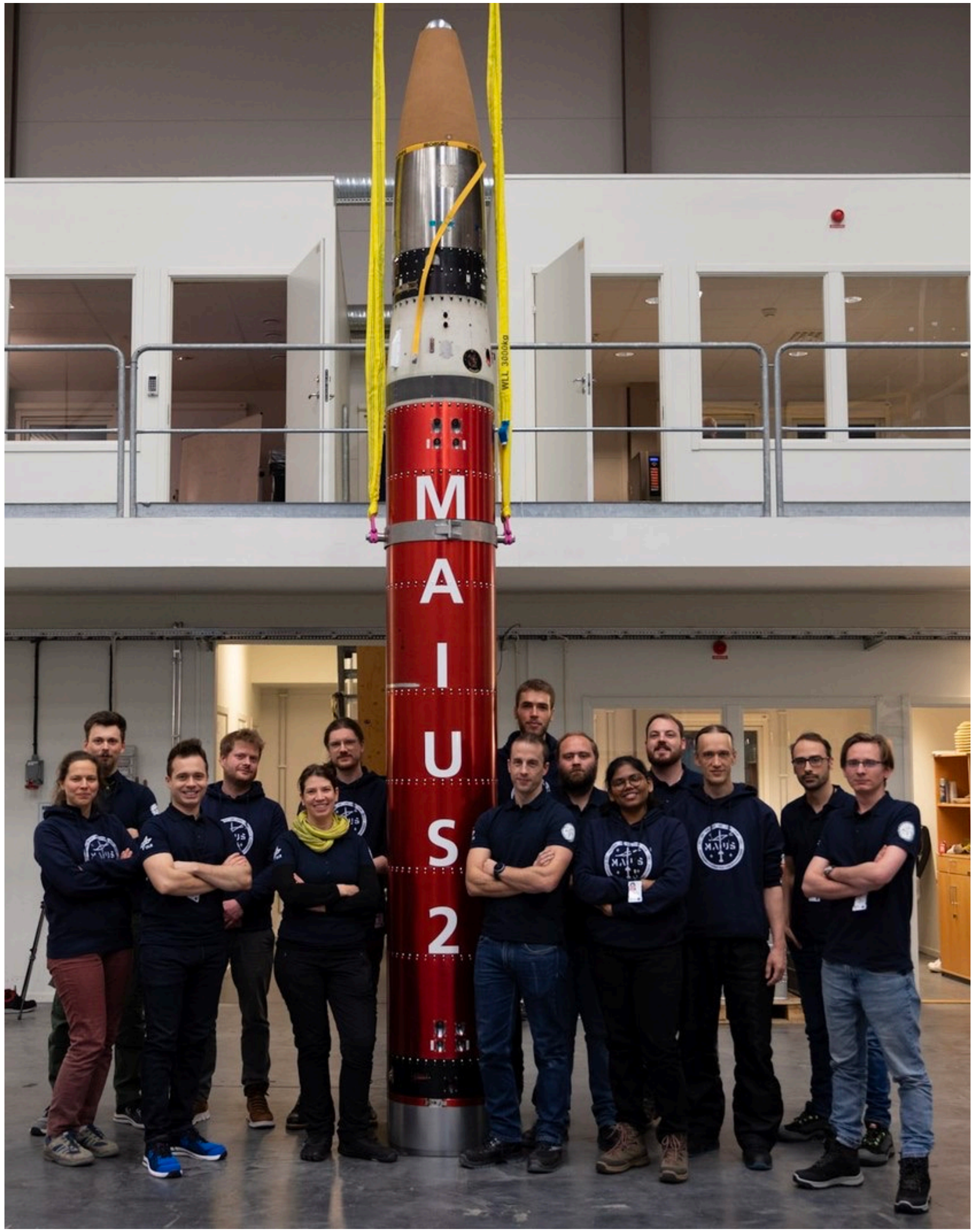


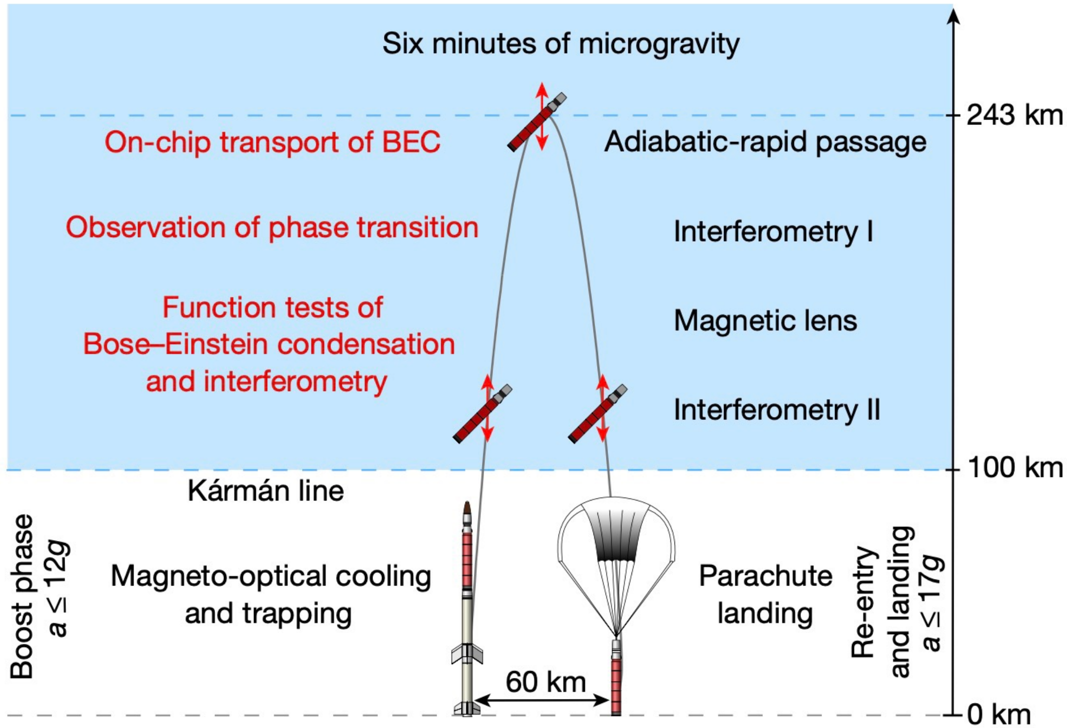


Fig. 2 | Schedule for the MAIUS-1 sounding-rocket mission. During the boost phase (bottom left) and the 6 min of space flight (blue-shaded region), 110 atom-optics experiments were performed. Those discussed here are printed in red. In space (above the Kármán line, 100 km above the ground), inertial perturbations are reduced to a few parts per million of gravity, the pointing of the length axis is stabilized with respect to gravity (indicated by the red arrows) and the spin of the rocket is suppressed to about 5 mrad s^{-1} owing to rate control. During re-entry, the peak forces on the payload (a) exceed the gravitational force on the ground (g) by a factor of up to 17.

tester le principe d’équivalence

Test sur un nuage d’atomes en chute libre
dans le Cold Atom Lab de l’ISS

recherches récentes

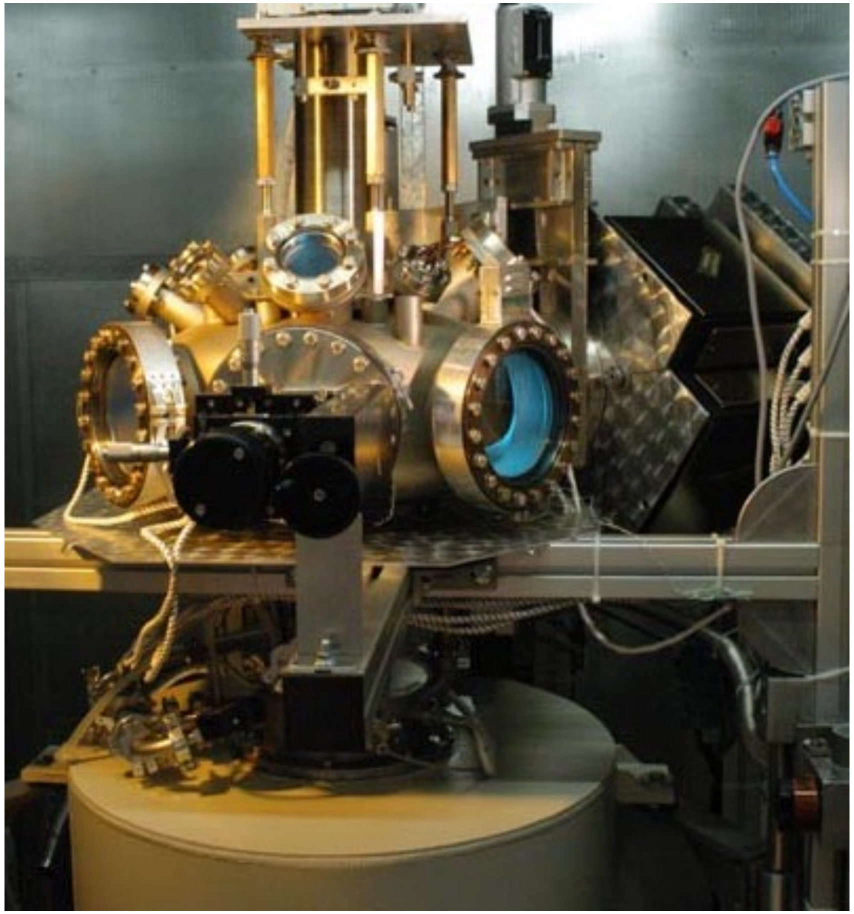
1. mesurer une petite force
2. tester la loi de gravitation
3. **tester le principe d’équivalence**
4. l’accélération chez la puce

mesurer des forces de surface

laisser glisser une pointe et regarder
comment elle est déviée par le relief

mesurer des forces de surface

microscopes à force atomique (AFM)



AFM filmé par
un microscope électronique

@DME-GmbH

recherches récentes

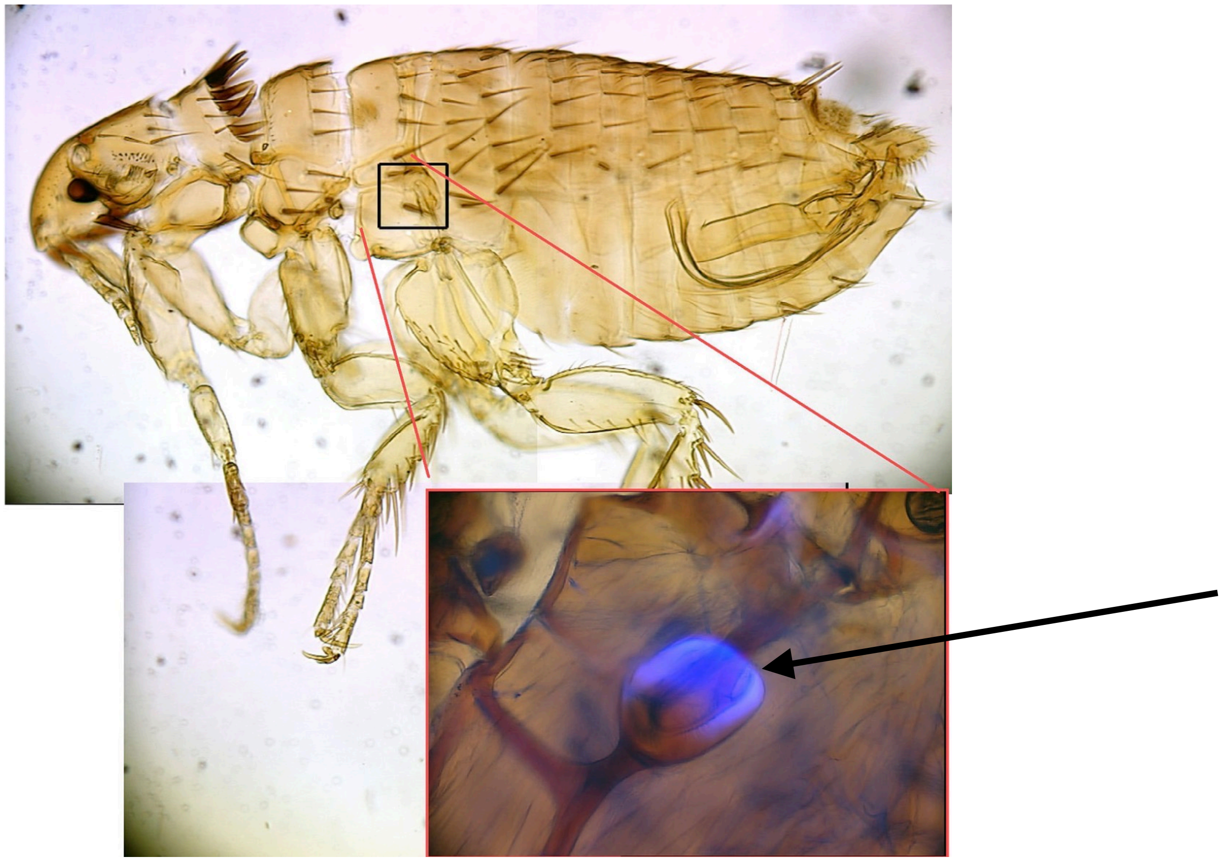
1. mesurer une petite force
2. tester la loi de gravitation
3. tester le principe d'équivalence
4. **l'accélération chez la puce**

l’accélération chez la puce

saut de qq centimètres en moins d’1 msec
vitesse finale 1 à 2 m/s
→ acceleration jq 3000 m/s^2 ?

l’accélération chez la puce

mécanisme : compression d’un coussin de resiline



l'accélération chez la puce

mécanisme : compression d'un coussin de resiline

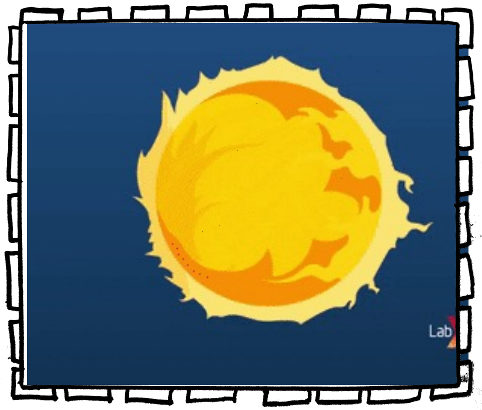
La force et l’accélération

Qu’avez-vous retenu ?

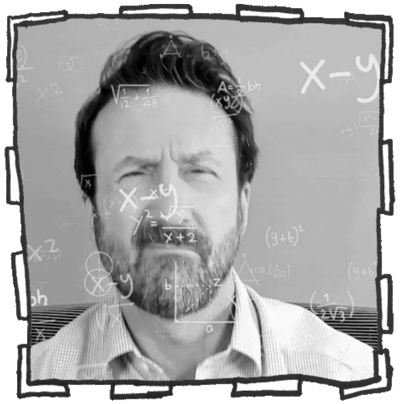
La force et l’accélération

Cachez vos notes, et tentez d’écrire en quelques mots…

1 ou 2 ordres de grandeur



un truc que vous avez retenu sur la physique associée



un résultat de recherche récente