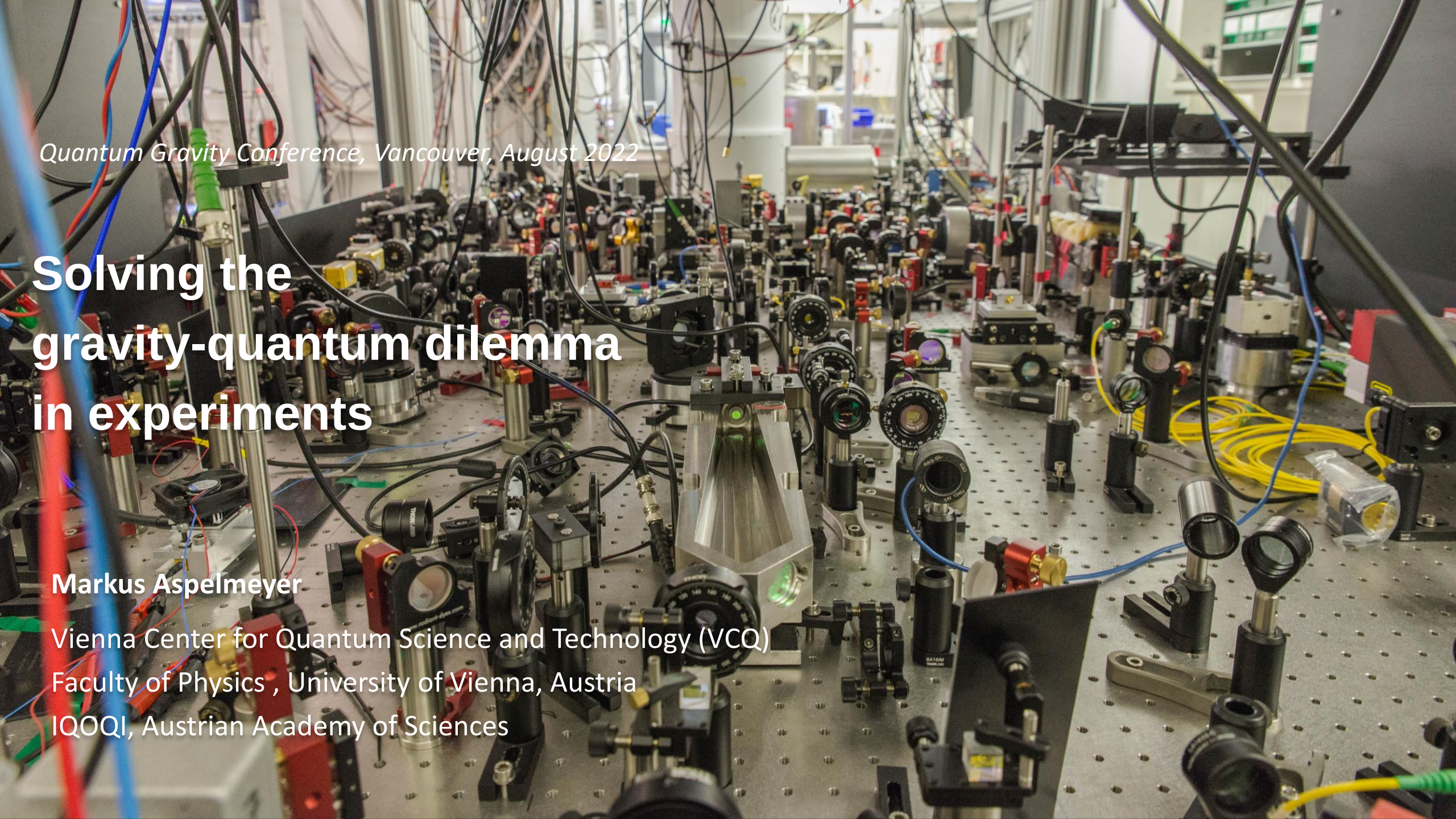


Quantum Gravity Conference, Vancouver, August 2022

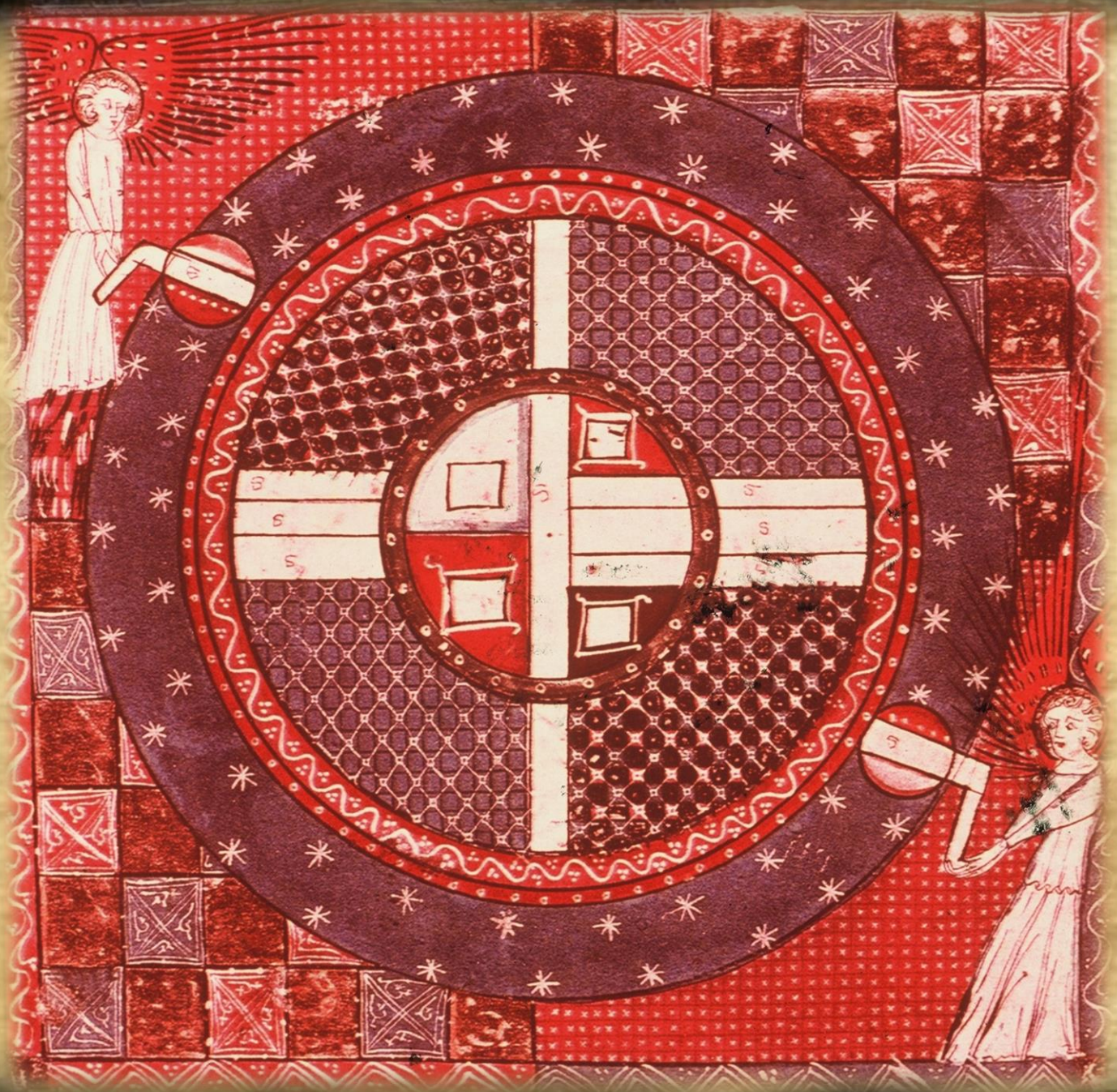
Solving the gravity-quantum dilemma in experiments

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)

Faculty of Physics , University of Vienna, Austria

IQOQI, Austrian Academy of Sciences



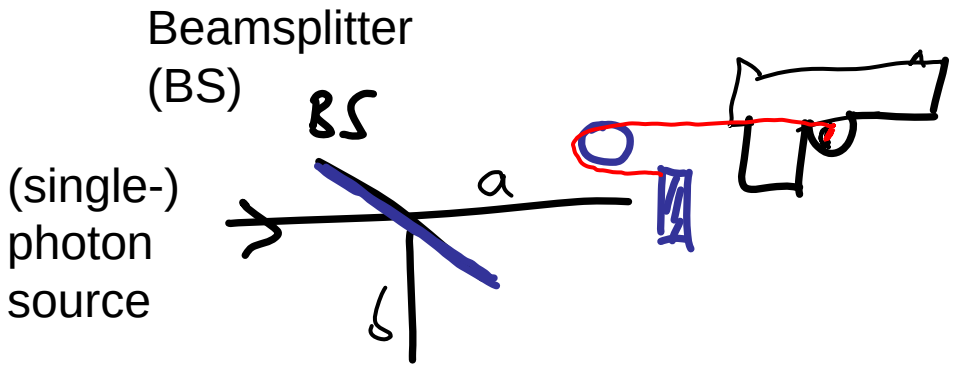
Old Lyme 8. VIII. 35.

Lieber Schrödinger!

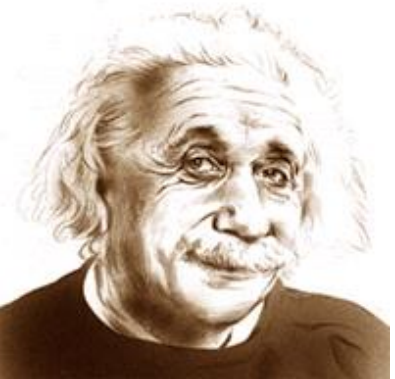
Du bist faktisch der einzige Mensch mit dem ich mich wirklich gerne auseinandersetze. Fast alle die Kerle sehen nämlich nicht von den Thatbeständen aus die Theorie sondern nur von der Theorie aus die Thatbestände; sie können aus ~~ihrem eigenen~~ dem einmal angenommenen Begriffensetz nicht heraus sondern nur possierlich darum herumzappeln. Du aber schaust es mir Wunder von aussen und von innen an. Dabei sind wir in der Auffassung des zu erwartenden Weges schärfste Gegensätze.

Albert Einstein to Erwin Schrödinger, 8.8.1935

Schrödinger‘s Cat: „a quite burlesque case“…



$$|0\rangle_a + |1\rangle_a \rightarrow |0\rangle_a |\text{cat}\rangle + |1\rangle_a |\text{cat}\rangle$$

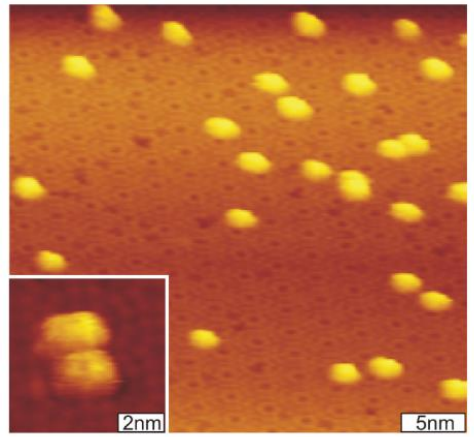


“By no art of interpretation can this Ψ-Function be made an adequate description of the real factual situation;…”

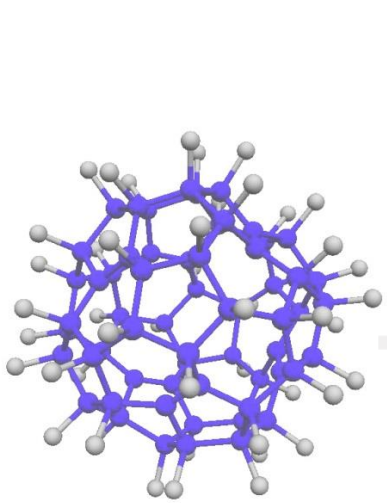
Einstein to Schrödinger (August 1935)

Which way?

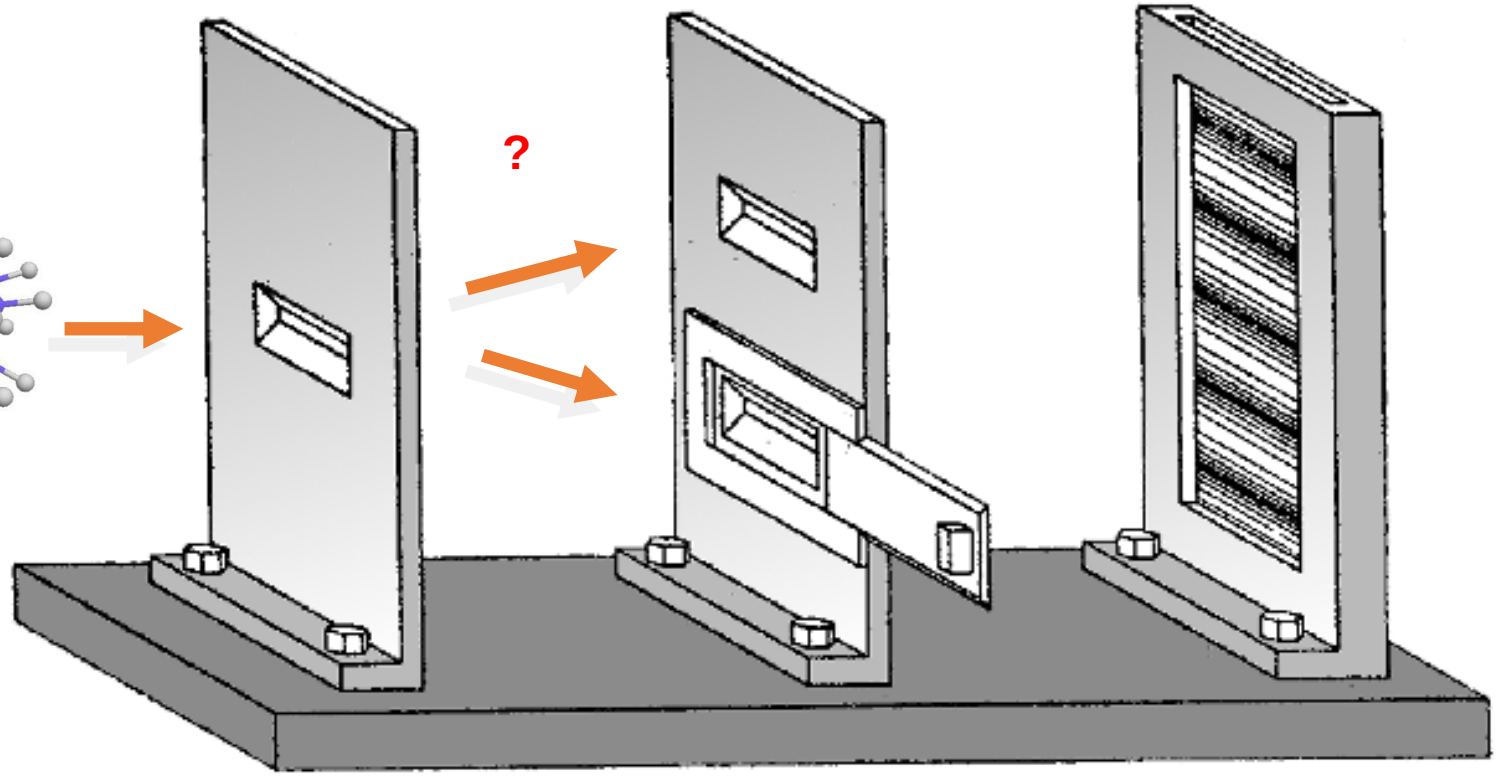
ONE molecule goes through **BOTH Slits?**
→Quantum-Superposition

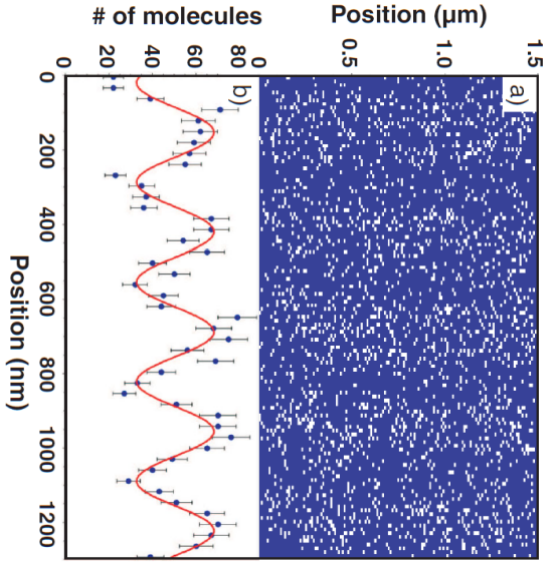


„particle“



$C_{60}F_{40}$





„wave“

Double-slit experiment with macro-molecules

Arndt, Zeilinger (1999, Uni Wien)

Quantum Superposition

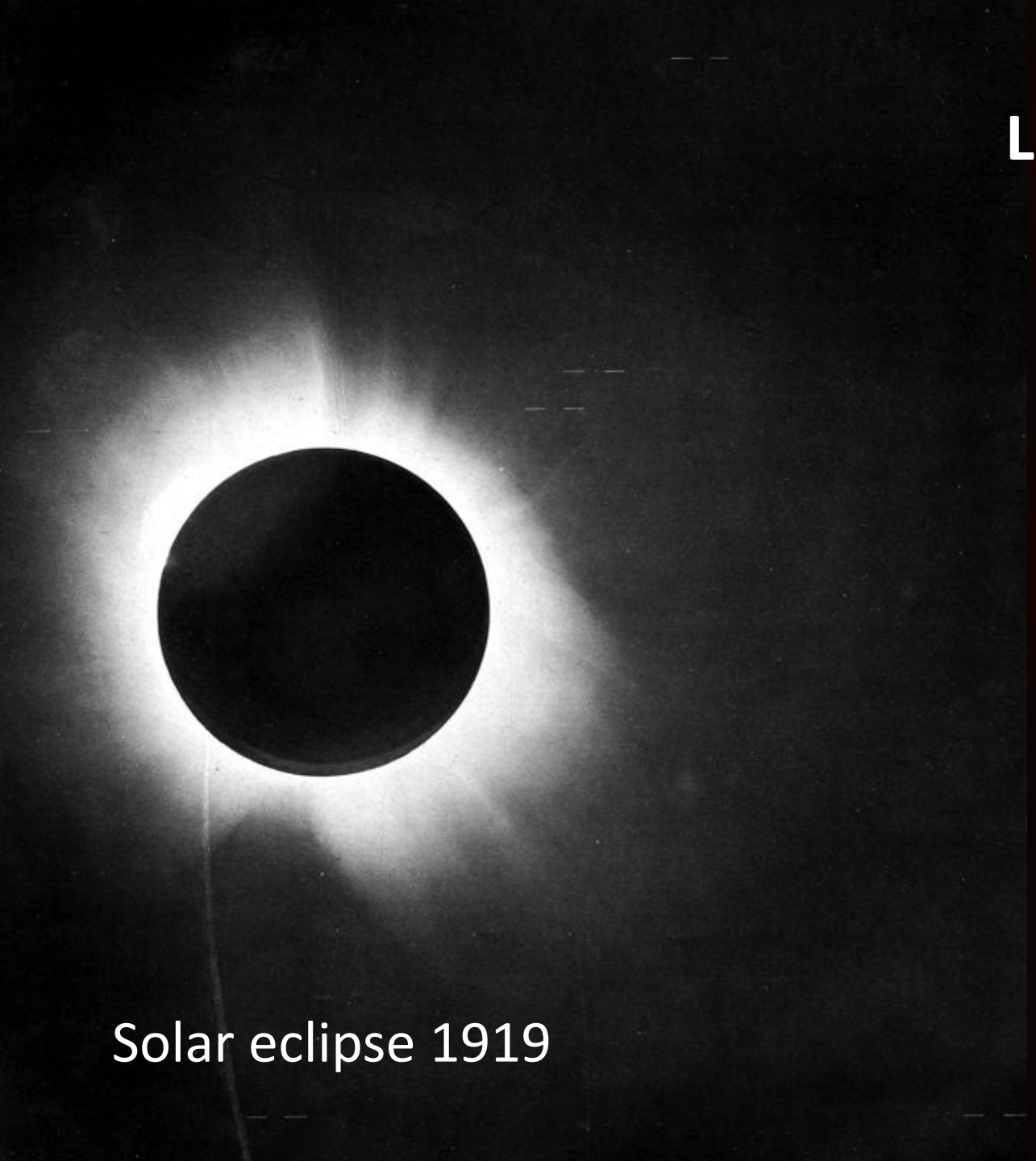
How is a consistent world-view possible?

What about gravity?

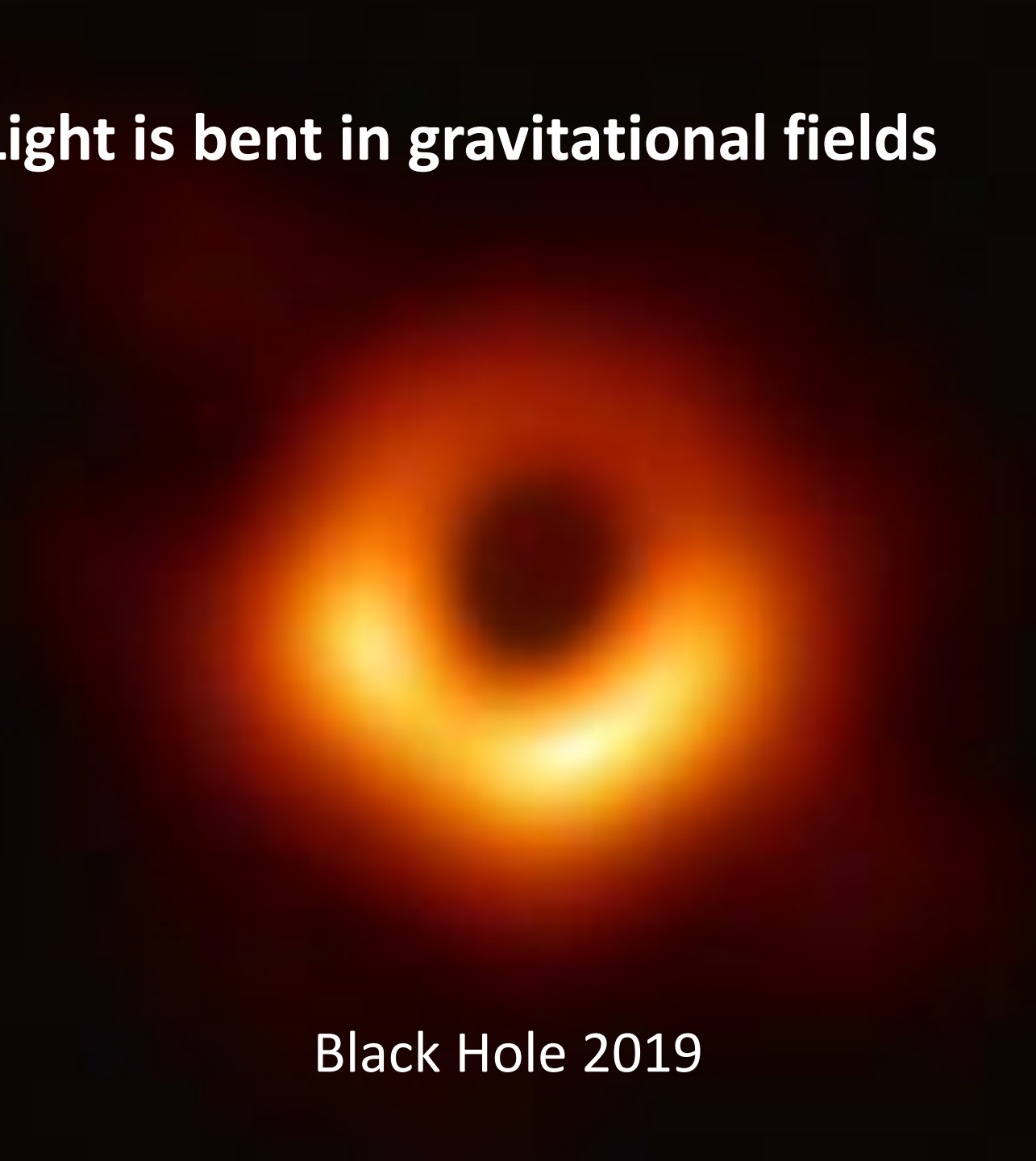
Einstein's general theory of relativity: curved space-time

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Light is bent in gravitational fields

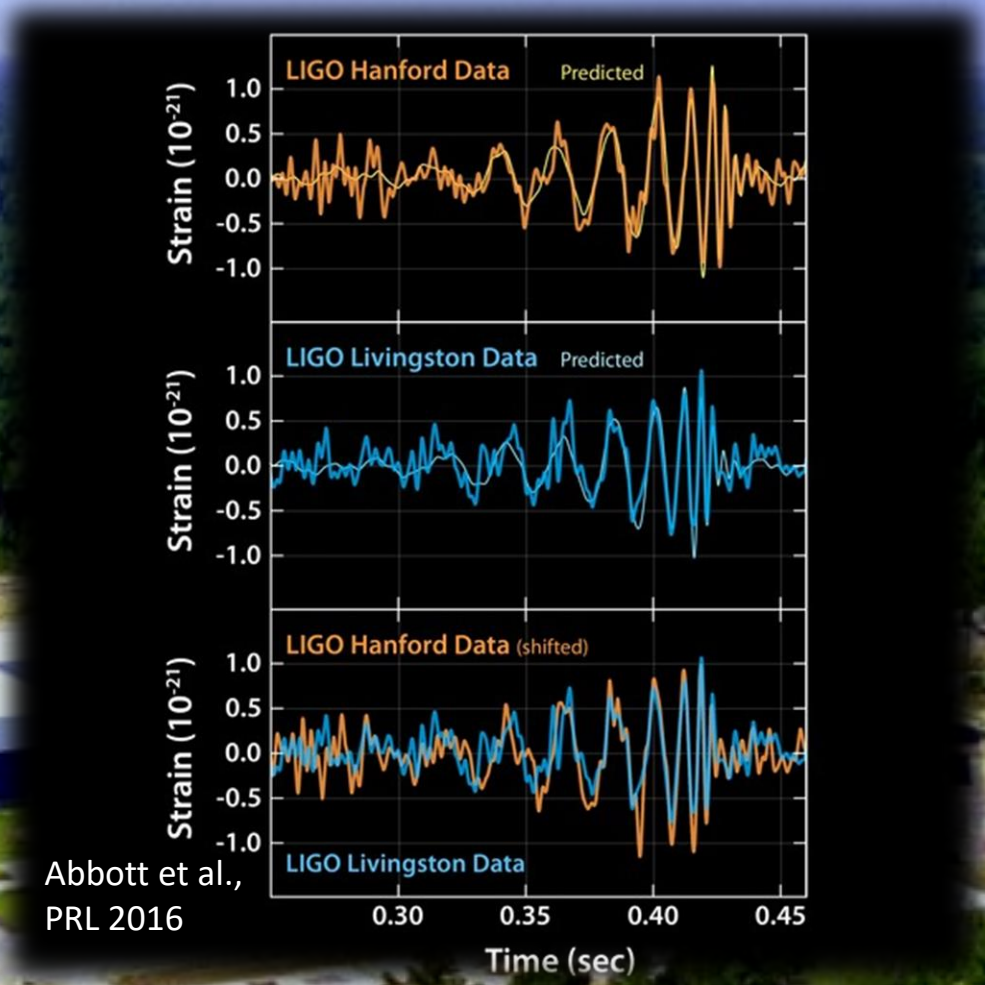


Solar eclipse 1919



Black Hole 2019

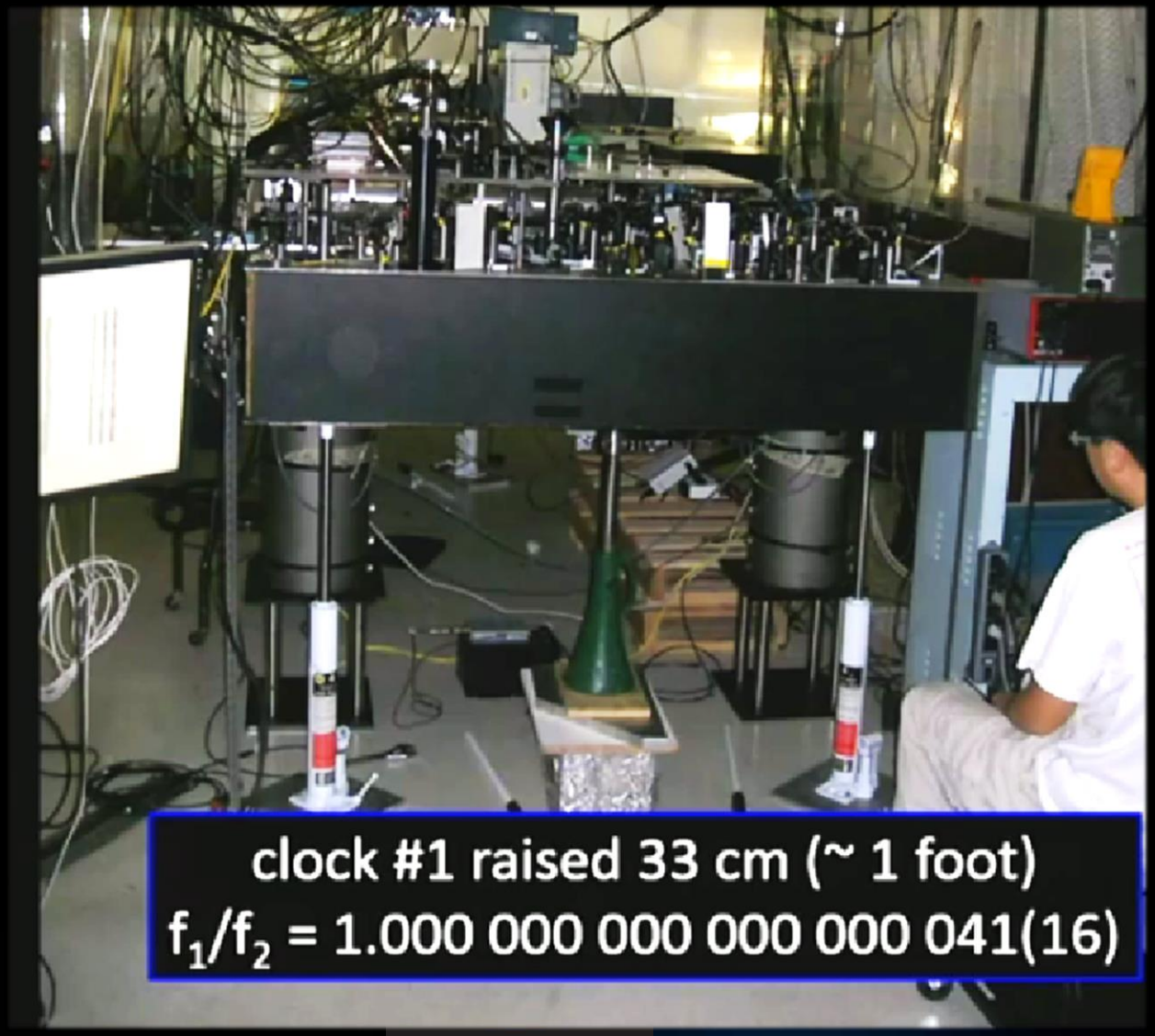
Gravitational energy is radiated via *gravitational waves*

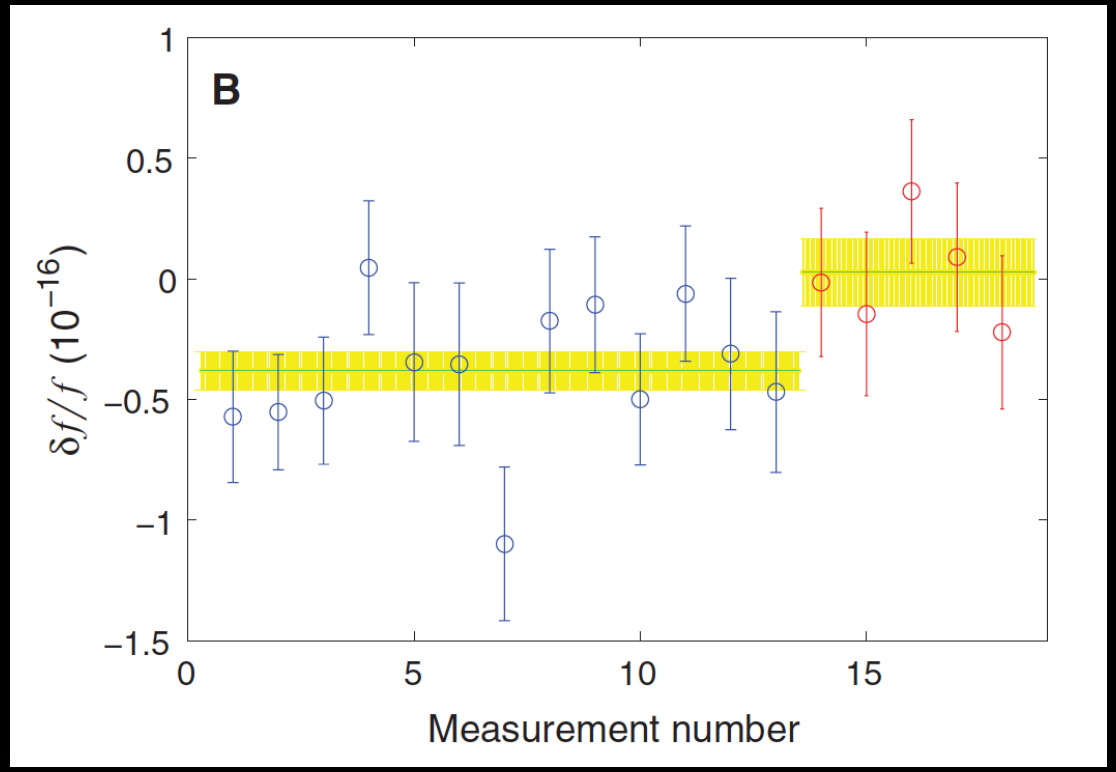


Abbott et al., PRL 2016

LIGO – Laser Interferometer Gravitational Wave Observatory

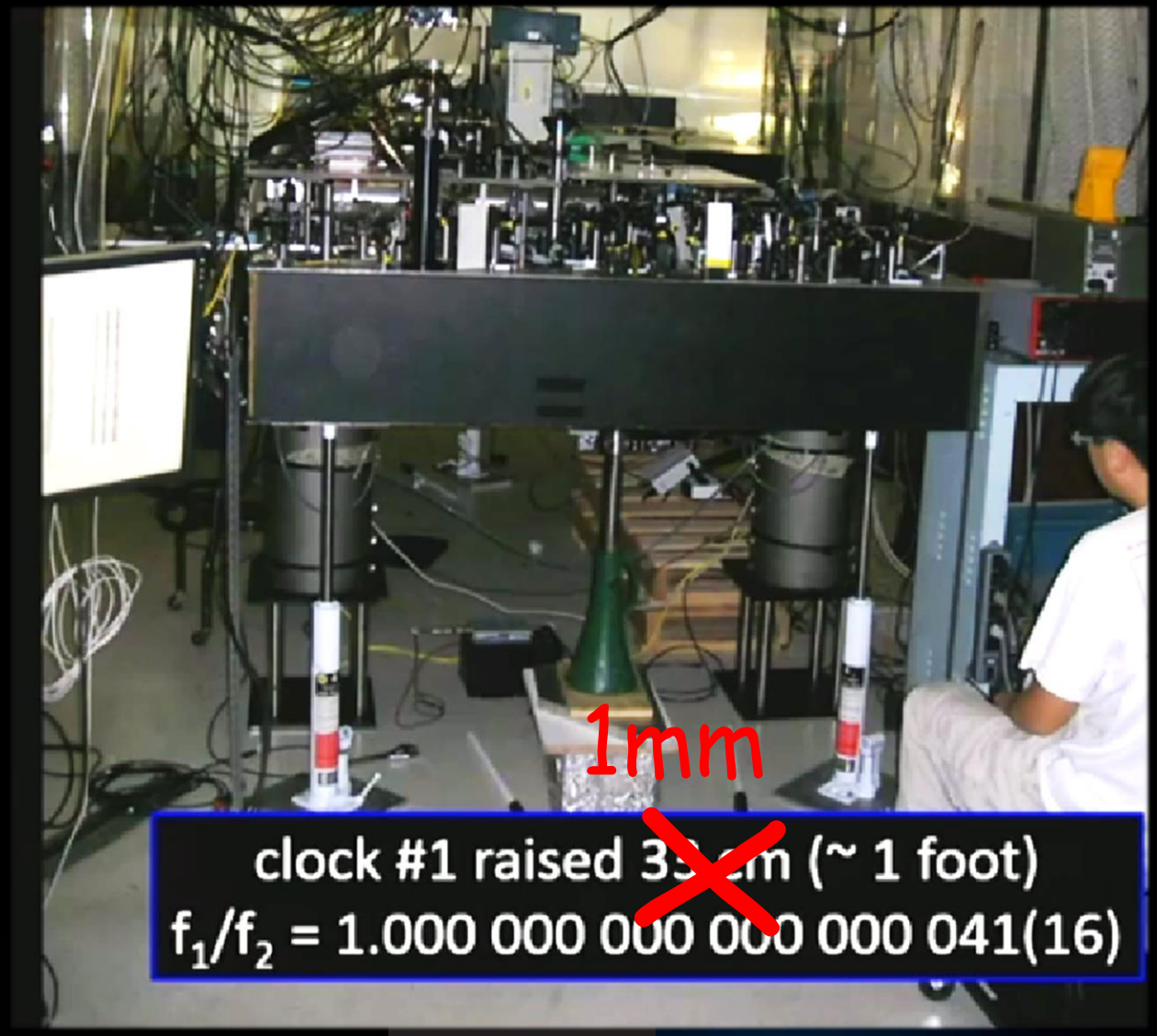
Gravitational time dilation

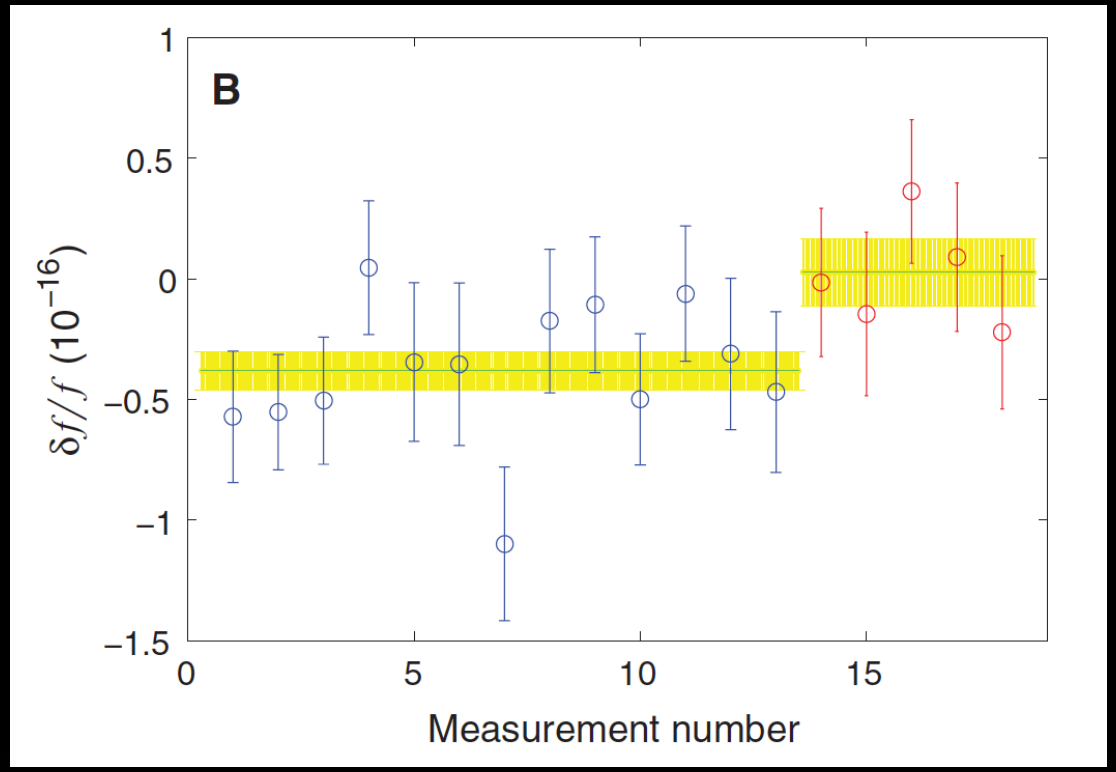




Wineland et al., Science 2012

Gravitational time dilation

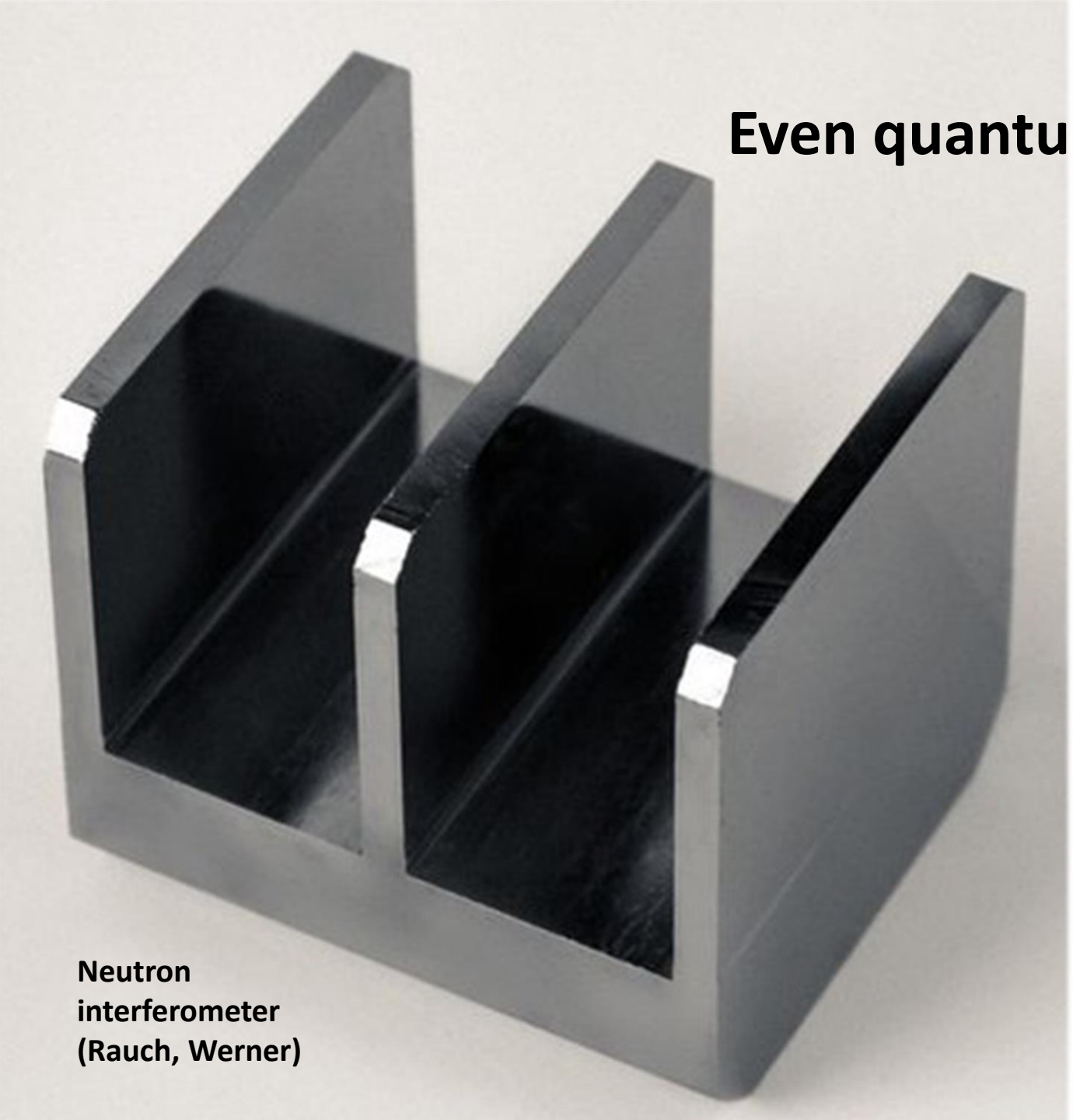




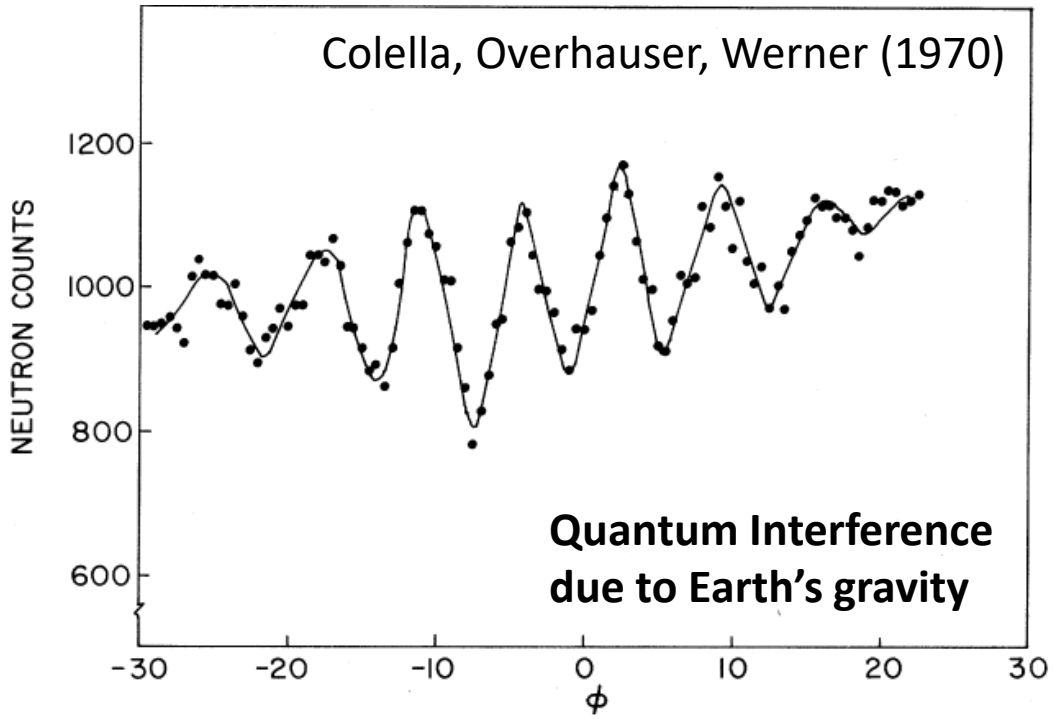
Wineland et al., Science 2012

Ye et al., Nature 2022

Even quantum systems interact with gravity

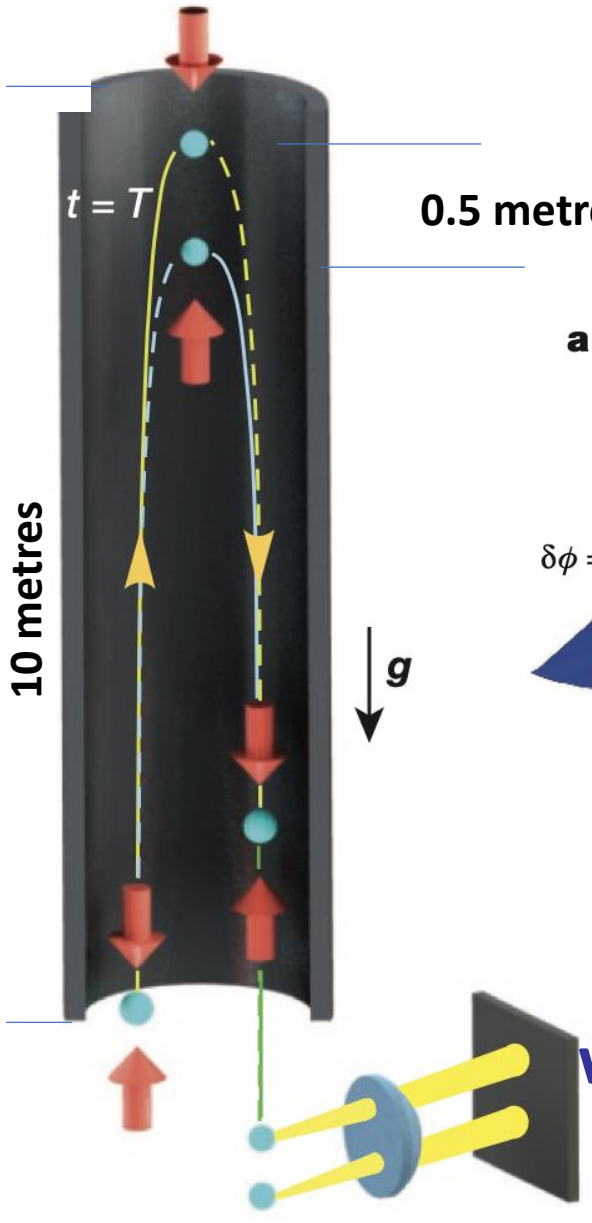


Neutron interferometer (Rauch, Werner)



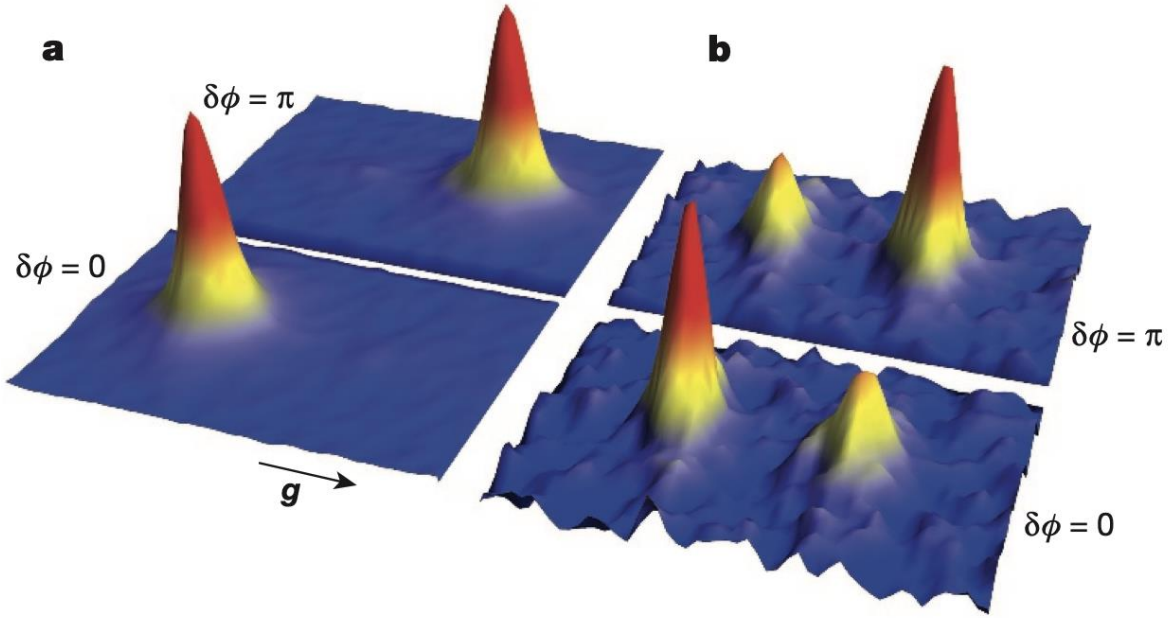
***Neutrons*: gravity impacts the wavefunction of a quantum particle**

Even quantum systems interact with gravity



Kasevich group (2015)

Quantum Superposition at the half-metre scale



***Atoms*: gravity impacts the wavefunction of a quantum particle**

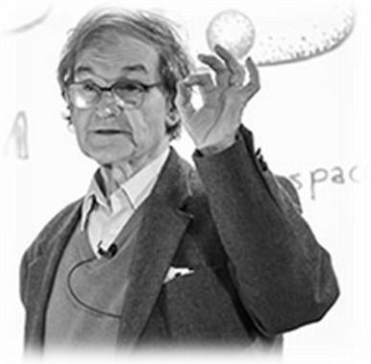
General Relativity works! As does Quantum Theory!

So what is the problem?

The underlying world views do not match!

If quantum physics holds, we need to radically re-think our notion of space and time (superposition of causal order / space-time / …)

Schrödinger: "*In quantum mechanics statements about what is "real" (…) are forbidden, they deal only with the relation object-subject - and obviously in a much more radical sense than any description of nature.*"

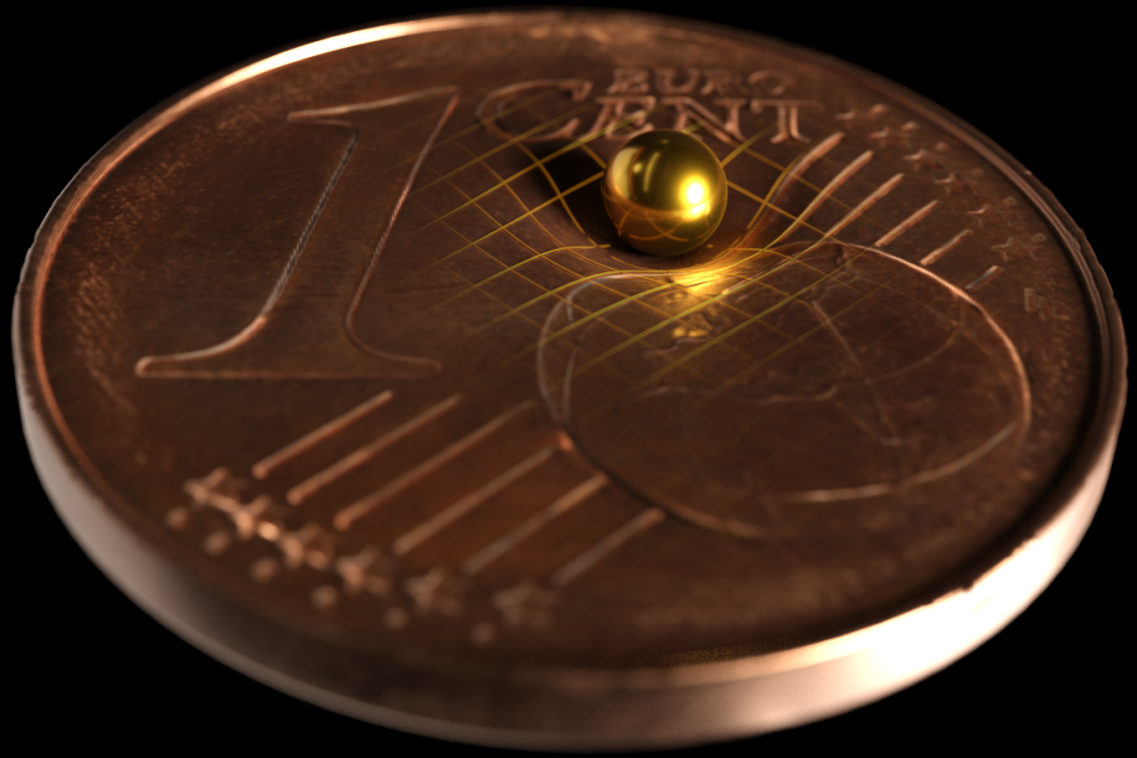


If general relativity holds, we need to radically re-think the role/relevance of quantum theory

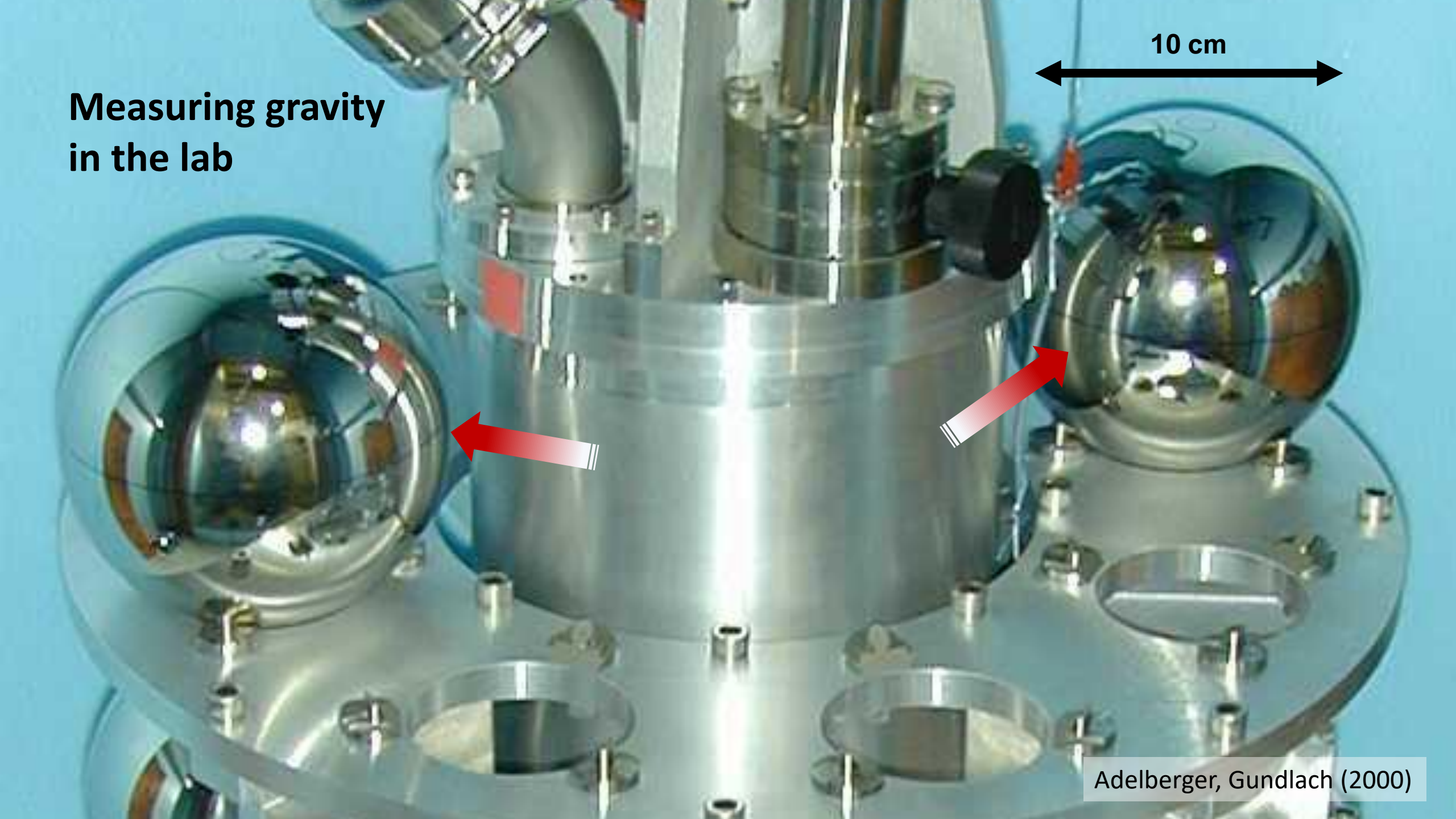
Penrose: "*There is a fundamental issue to be faced, when gravitational effects begin to become important (…). No fully satisfactory theory will be forthcoming until there is a revolution in the description of quantum phenomena that is of as great a magnitude as that which Einstein introduced (in the description of gravitational phenomena) with his general theory of relativity.*"

What about quantum systems as gravitational SOURCE masses?

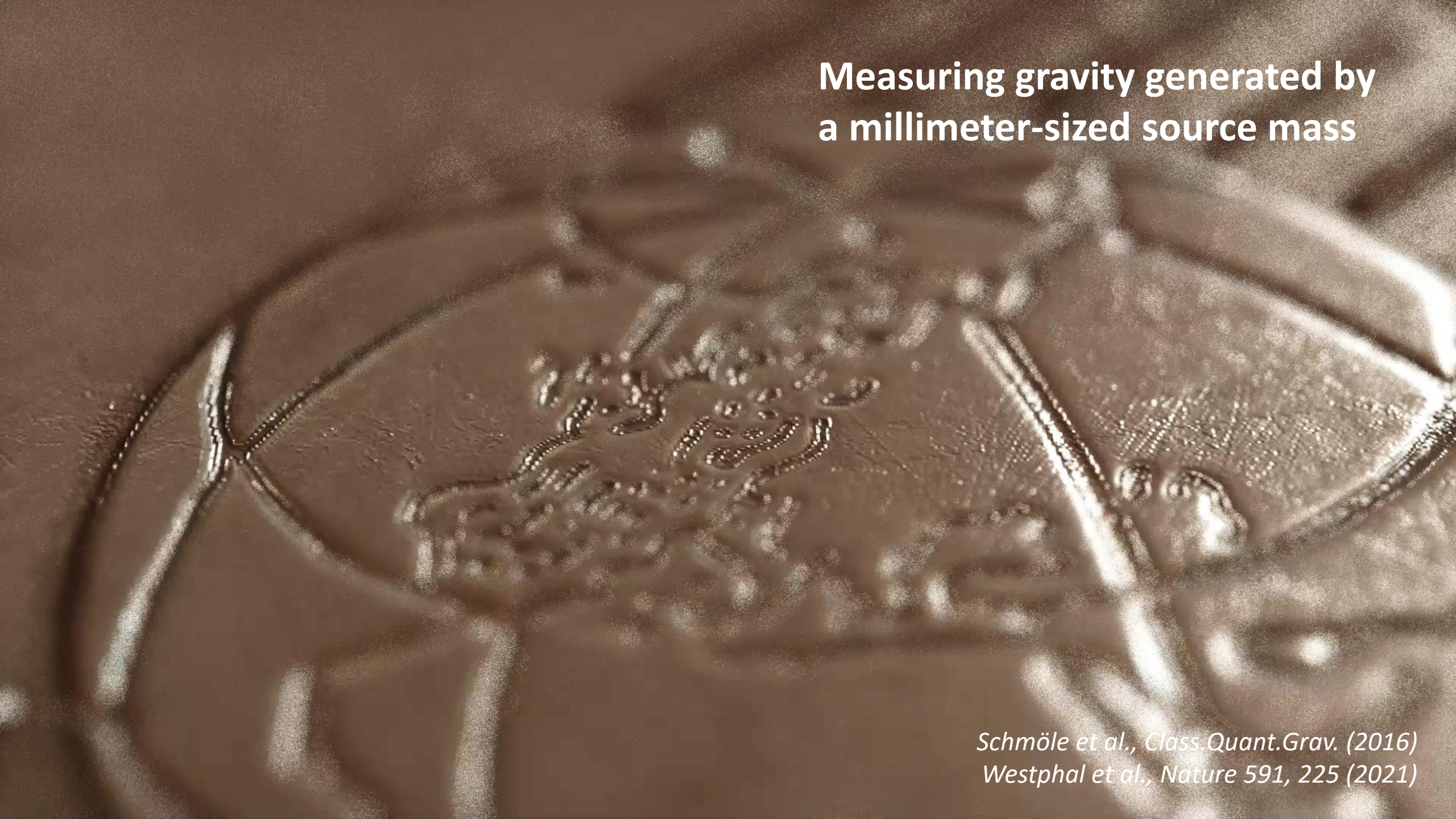
- How small can we make a source mass?
- How massive can we make a quantum system?



Measuring gravity in the lab



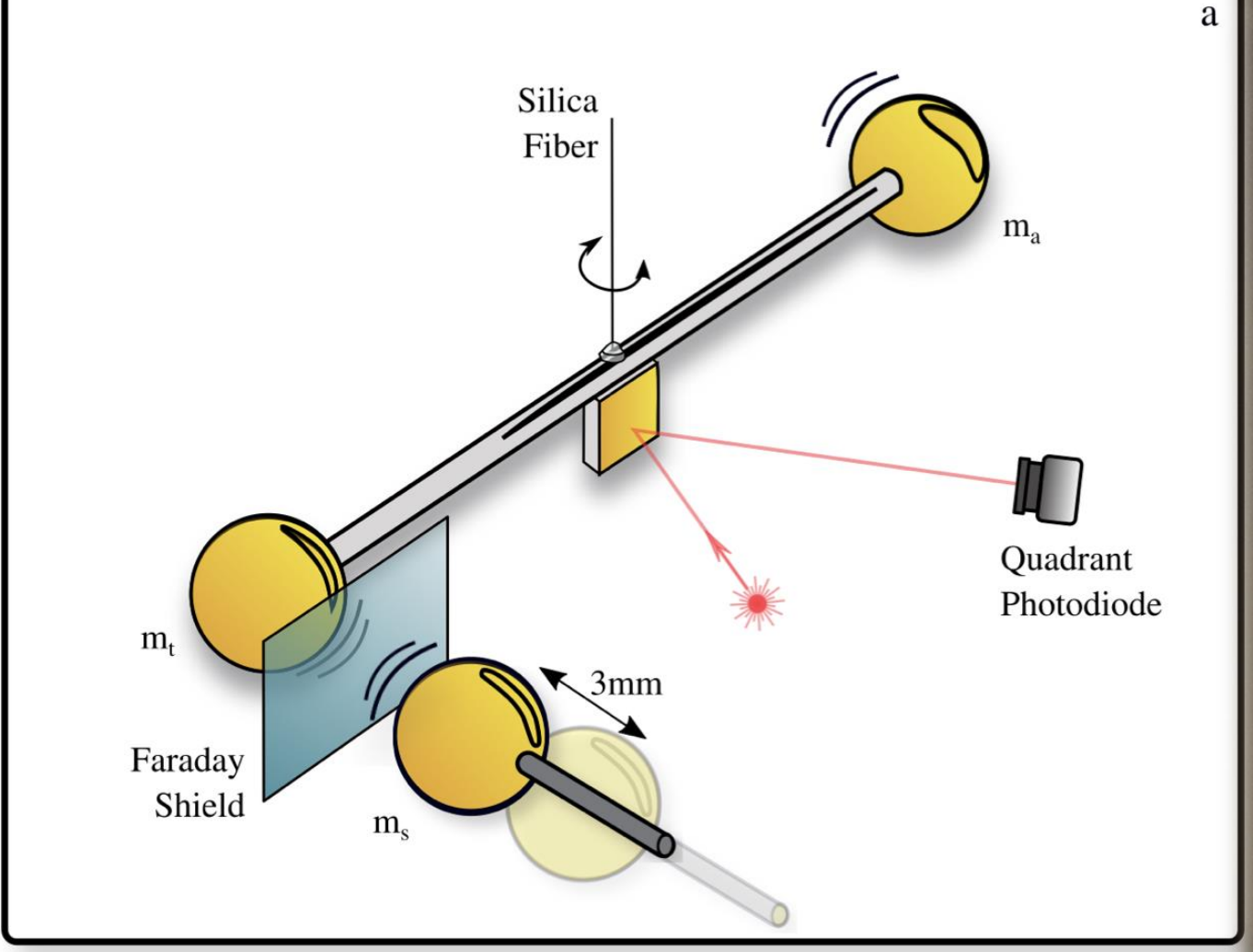
Adelberger, Gundlach (2000)

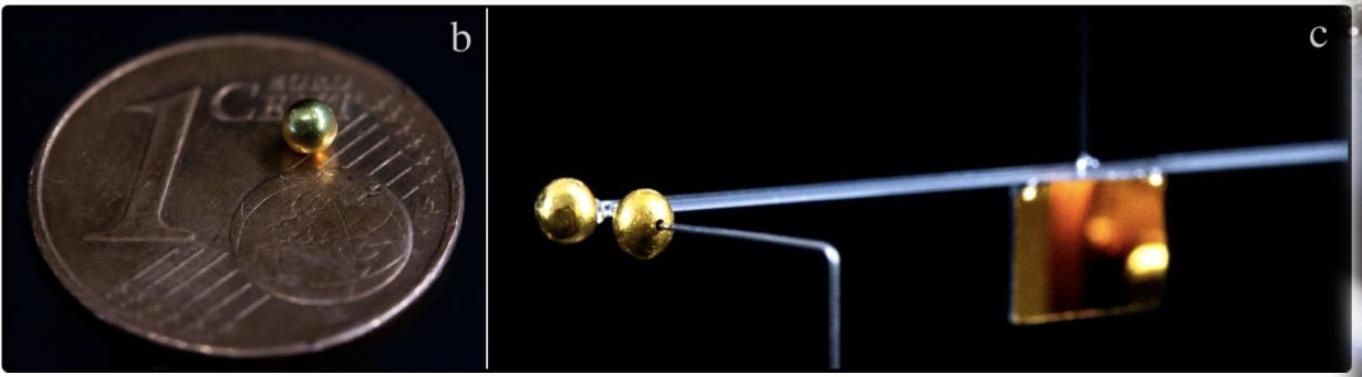


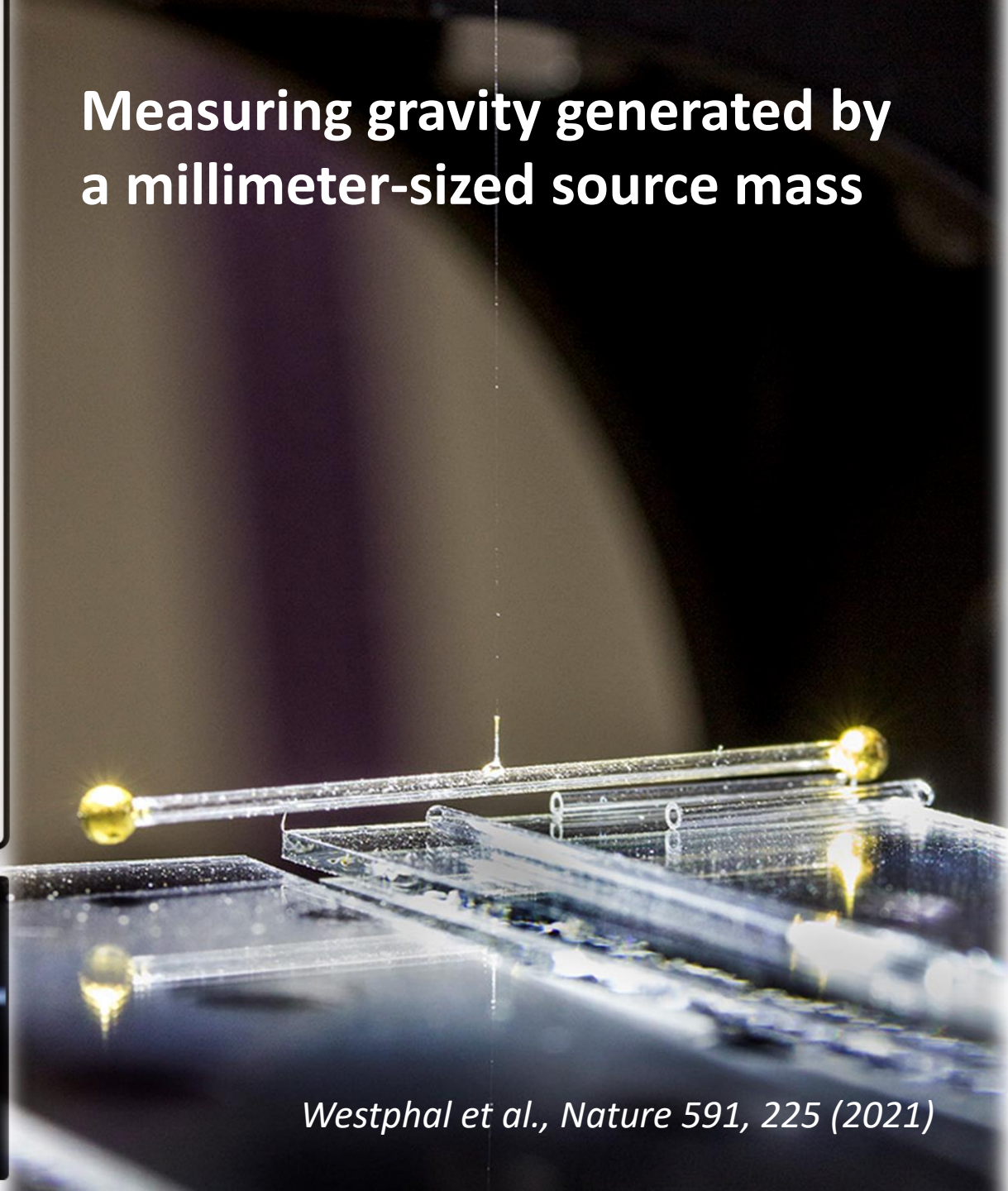
Measuring gravity generated by a millimeter-sized source mass

Schmöle et al., Class.Quant.Grav. (2016)
Westphal et al., Nature 591, 225 (2021)

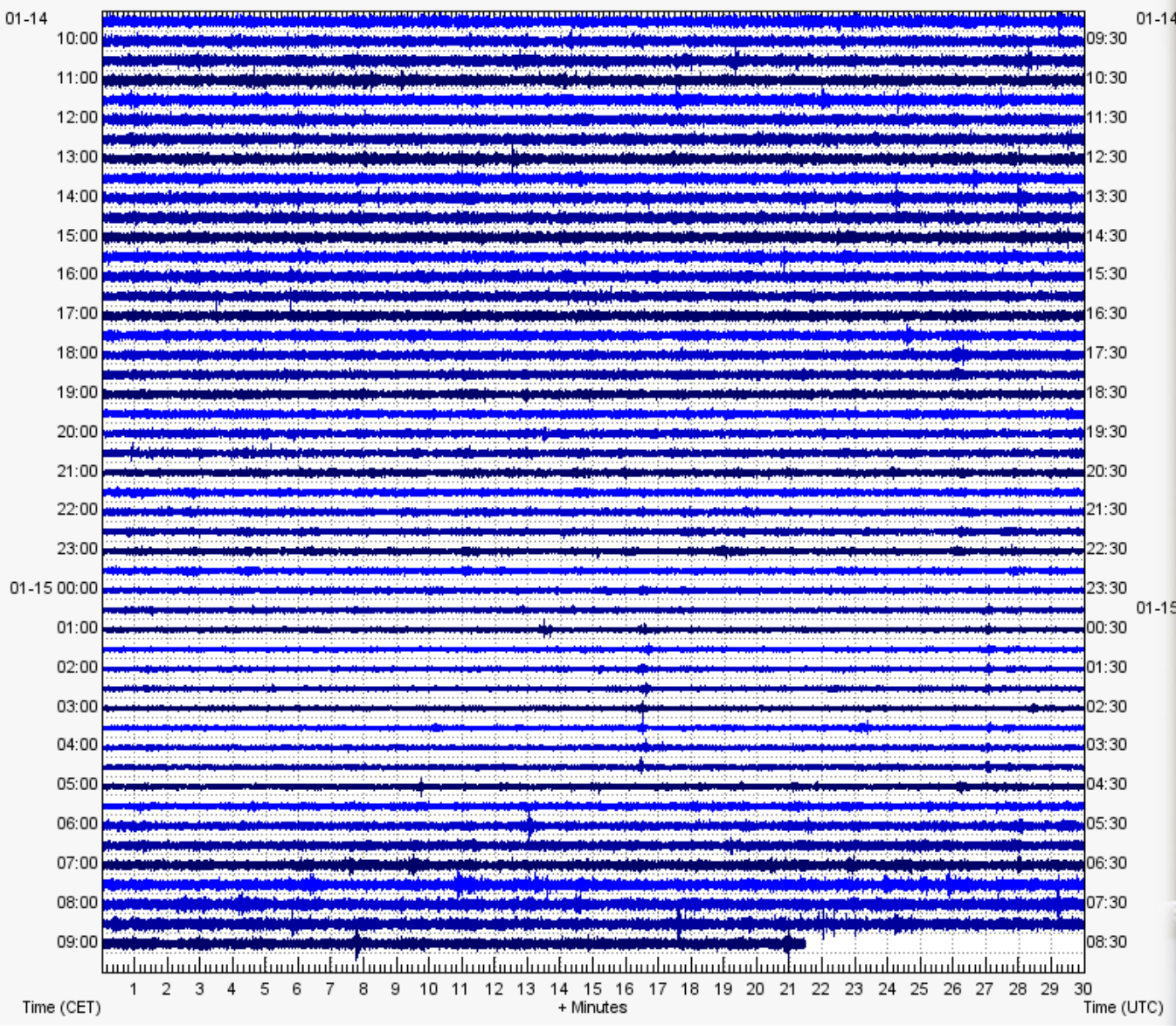
Measuring gravity generated by a millimeter-sized source mass



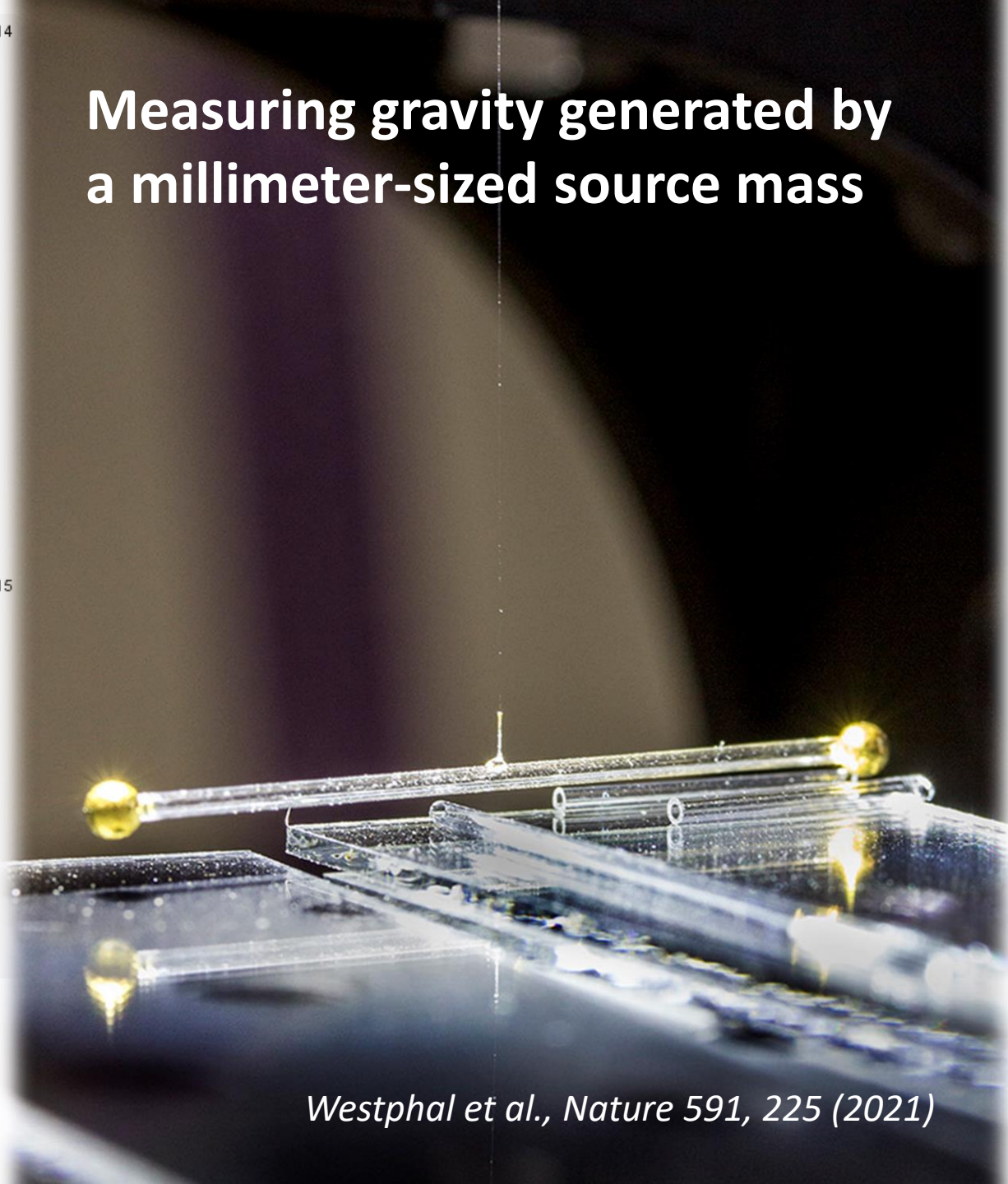




Westphal et al., Nature 591, 225 (2021)

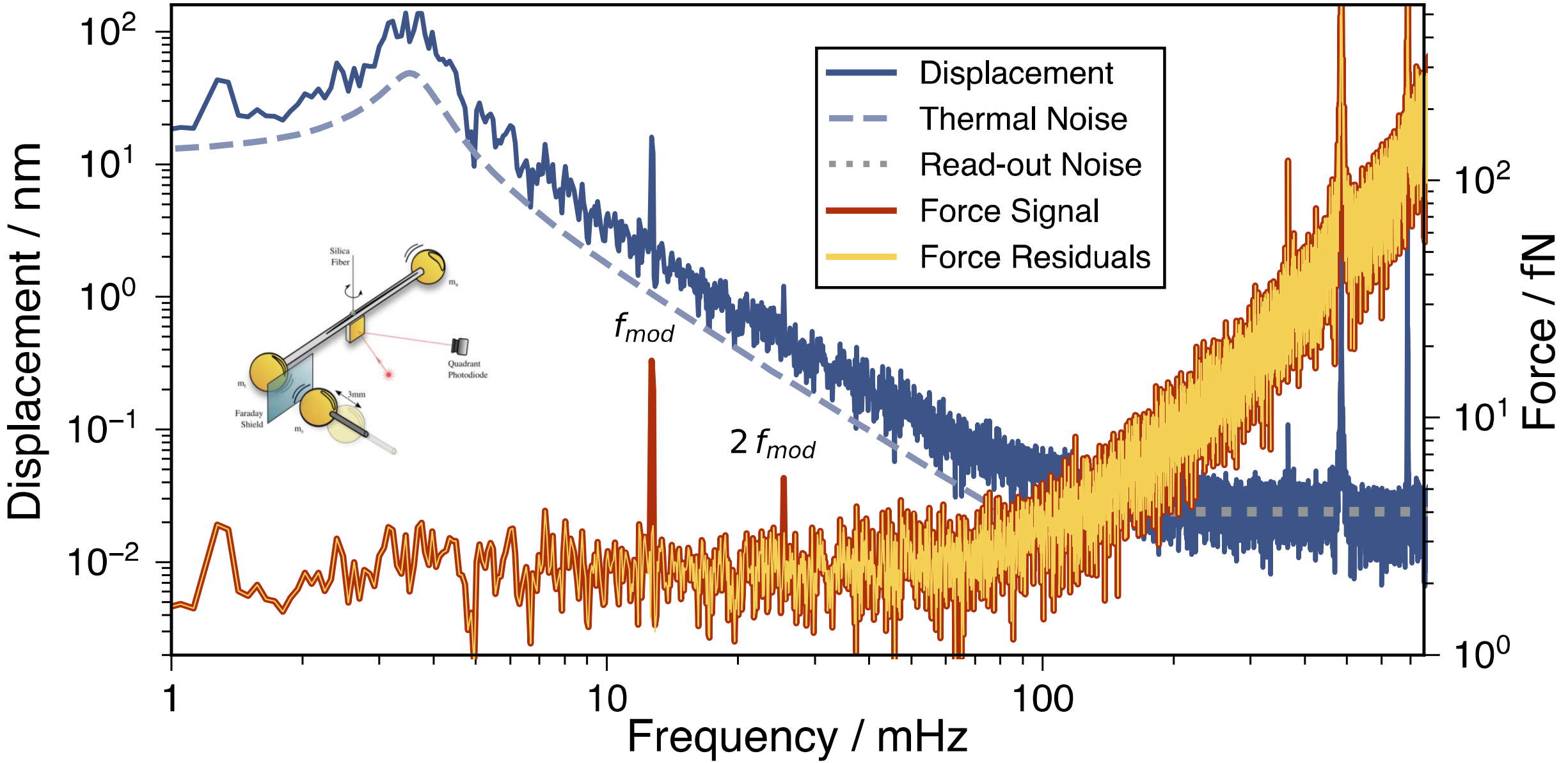


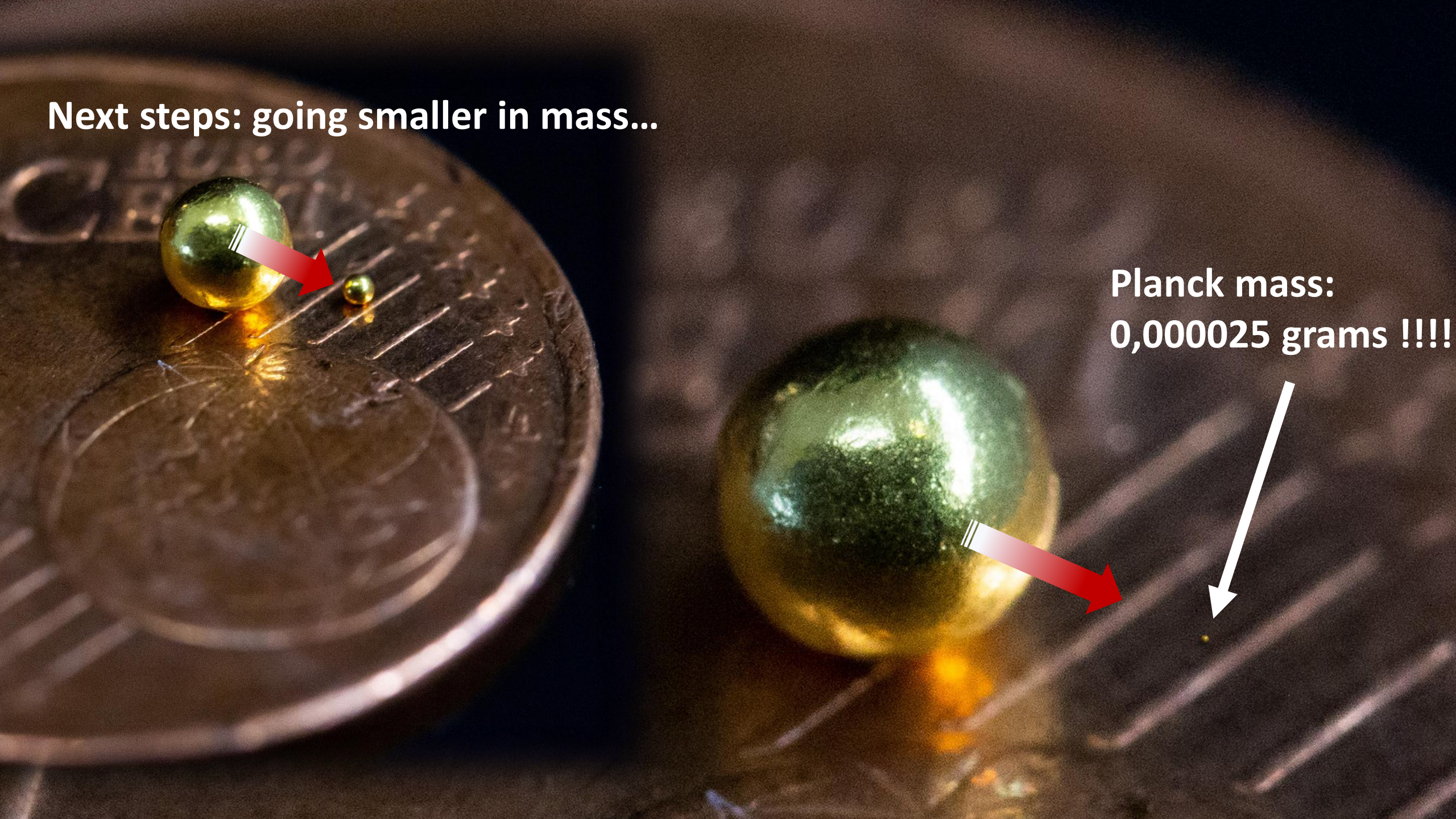
The challenge: how to NOT measure trams, marathon runners and night busses…



Silent Christmas night(s)

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



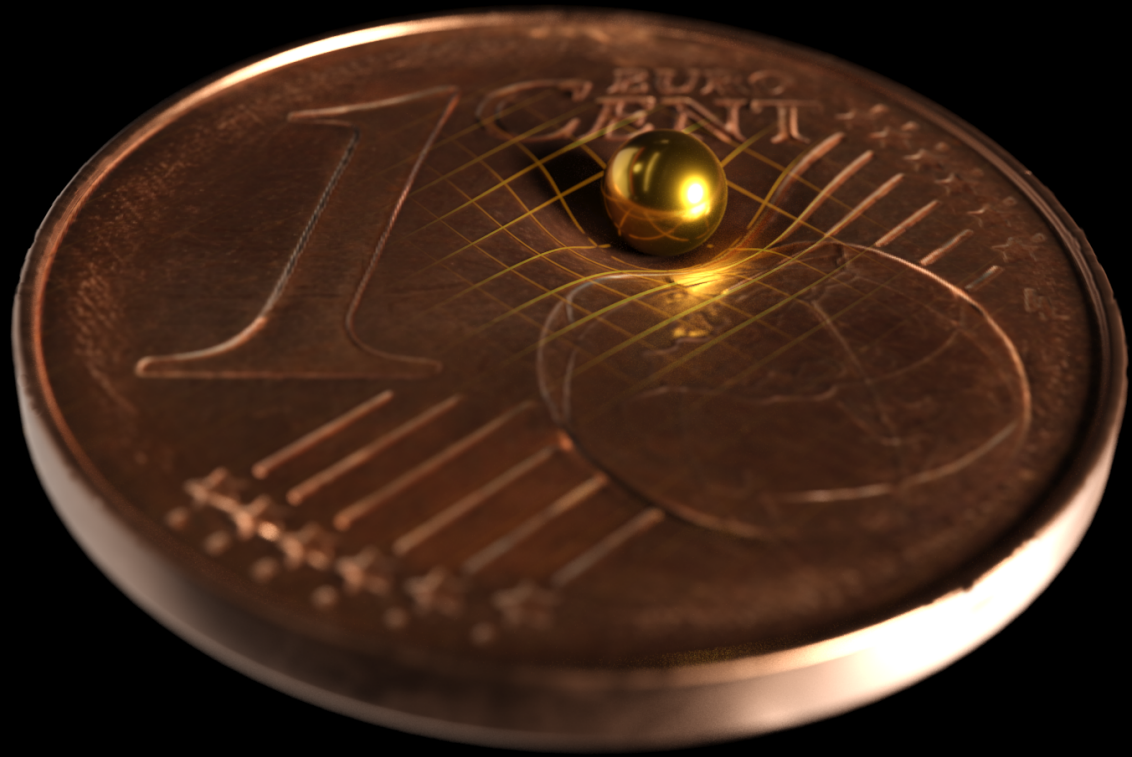

Next steps: going smaller in mass…
Planck mass:
0,000025 grams !!!!

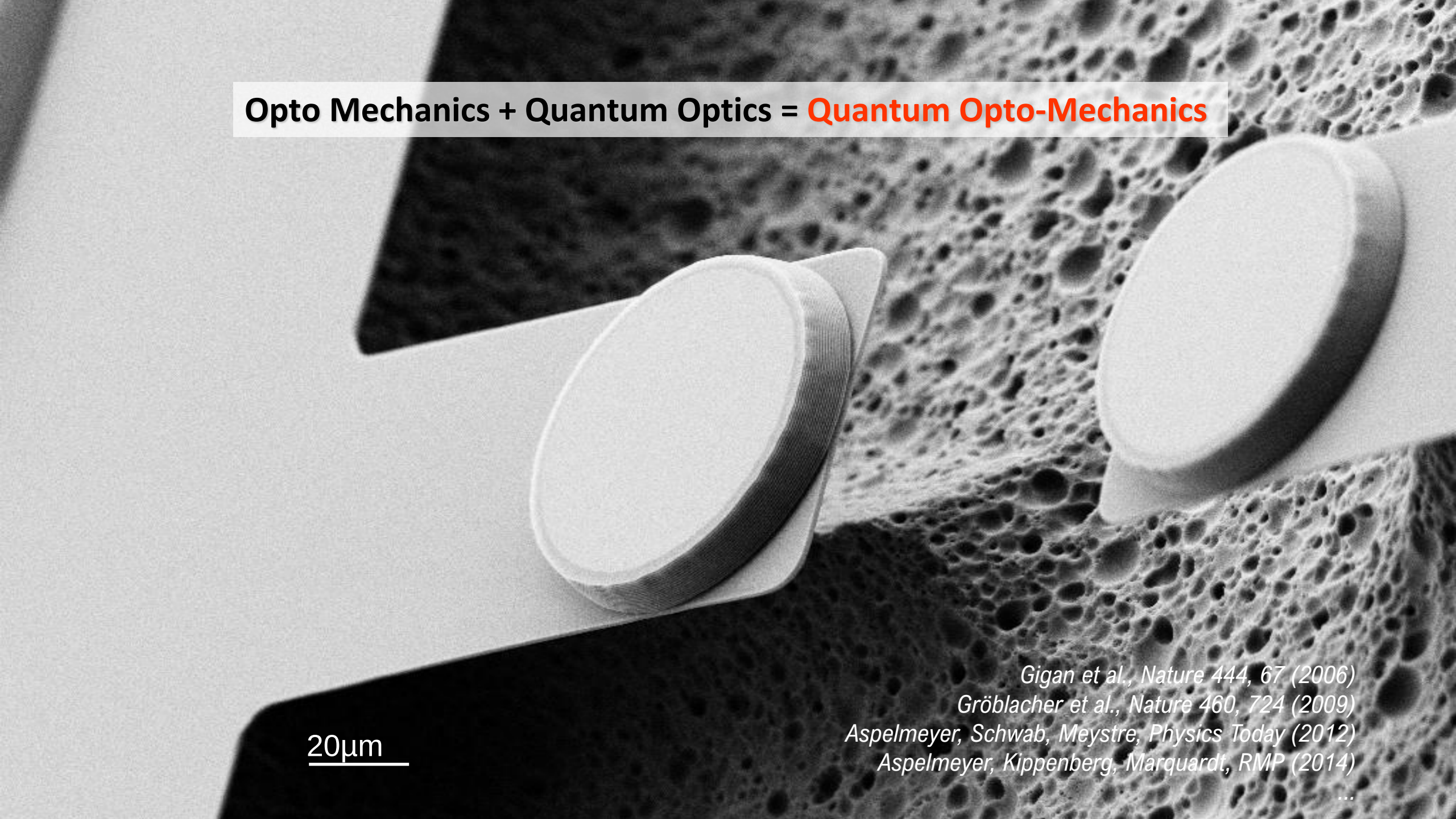
... by going underground

ZAMG
Zentralanstalt für
Meteorologie und Geodynamik

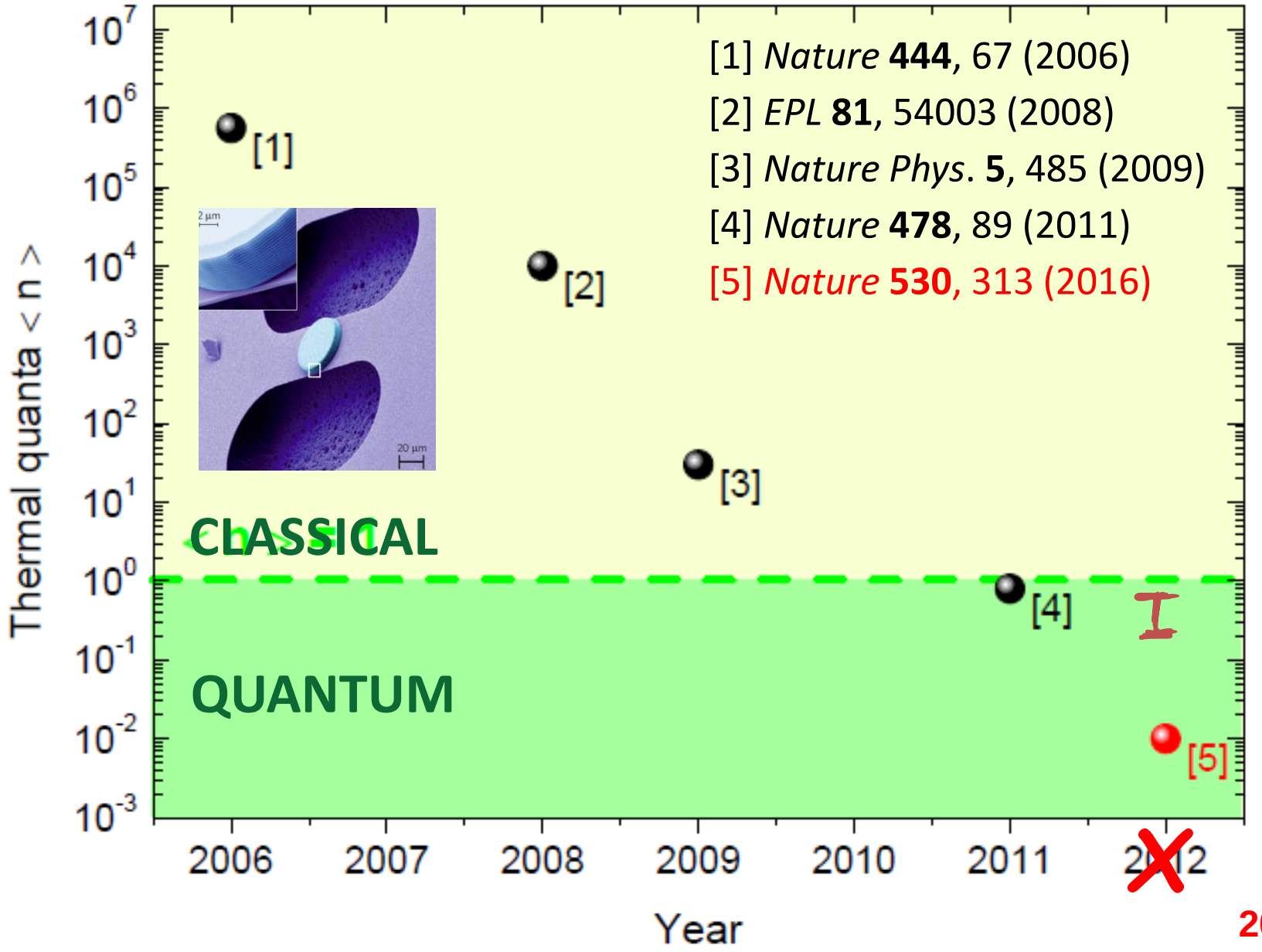
Conrad Observatorium

- How small can we make a source mass?
- How massive can we make a quantum system?

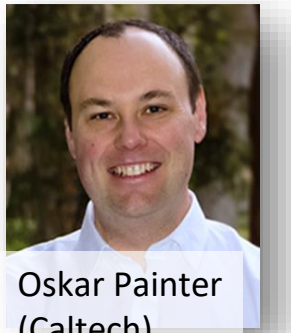



Opto Mechanics + Quantum Optics = Quantum Opto-Mechanics
20µm
Gigan et al., Nature 444, 67 (2006)
Gröblacher et al., Nature 460, 724 (2009)
Aspelmeyer, Schwab, Meystre, Physics Today (2012)
Aspelmeyer, Kippenberg, Marquardt, RMP (2014)
...

The Vienna quantum roadmap

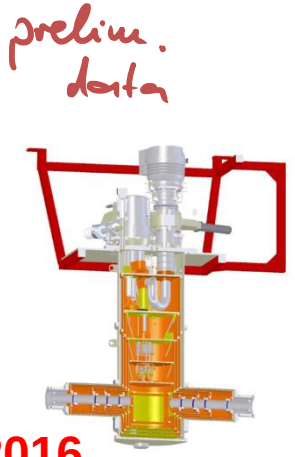


Our collaboration partners:



Oskar Painter
(Caltech)

Simon Gröblacher
(Delft)



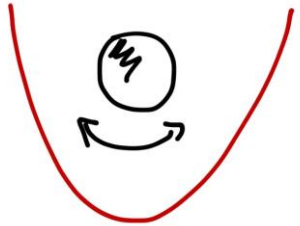
2016

Quantum controlling levitated solid-state objects

Combining LARGE MASSES with LONG COHERENCE TIMES and FUL MANIPULATION

+

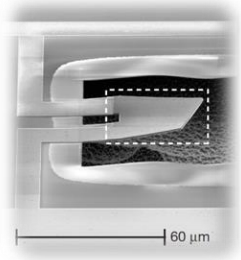
=

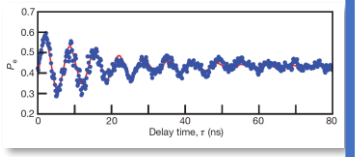


Solid-state mechanical quantum devices (clamped):

10^{10} – 10^{16} atoms

Coherence time
10^{-12} – 10^{-8} sec



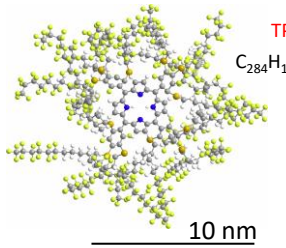


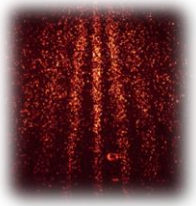
Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

10^{0} – 10^{4} atoms

Coherence time
10^{-3} – 10^{0} sec



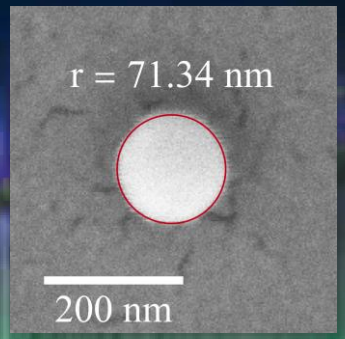


Nature Nanotech. 7, 297 (2012)

Levitated (opto-)mechanics

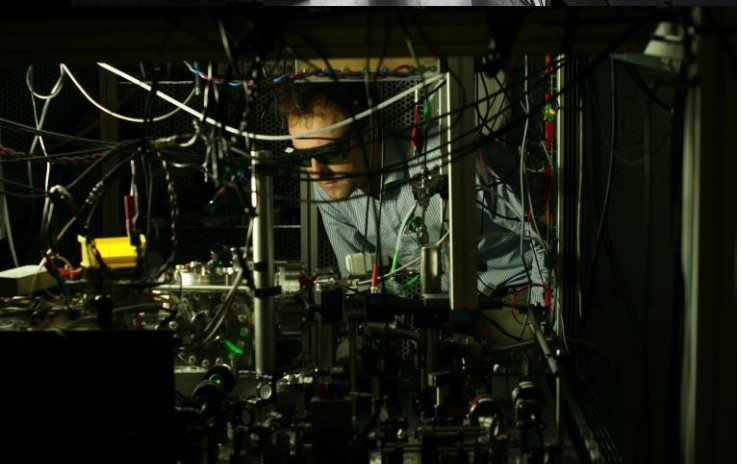
- Quantum control of a trapped solid state object >> 10^{10} atoms
- Long coherence times (up to seconds)

Optically levitated glass sphere



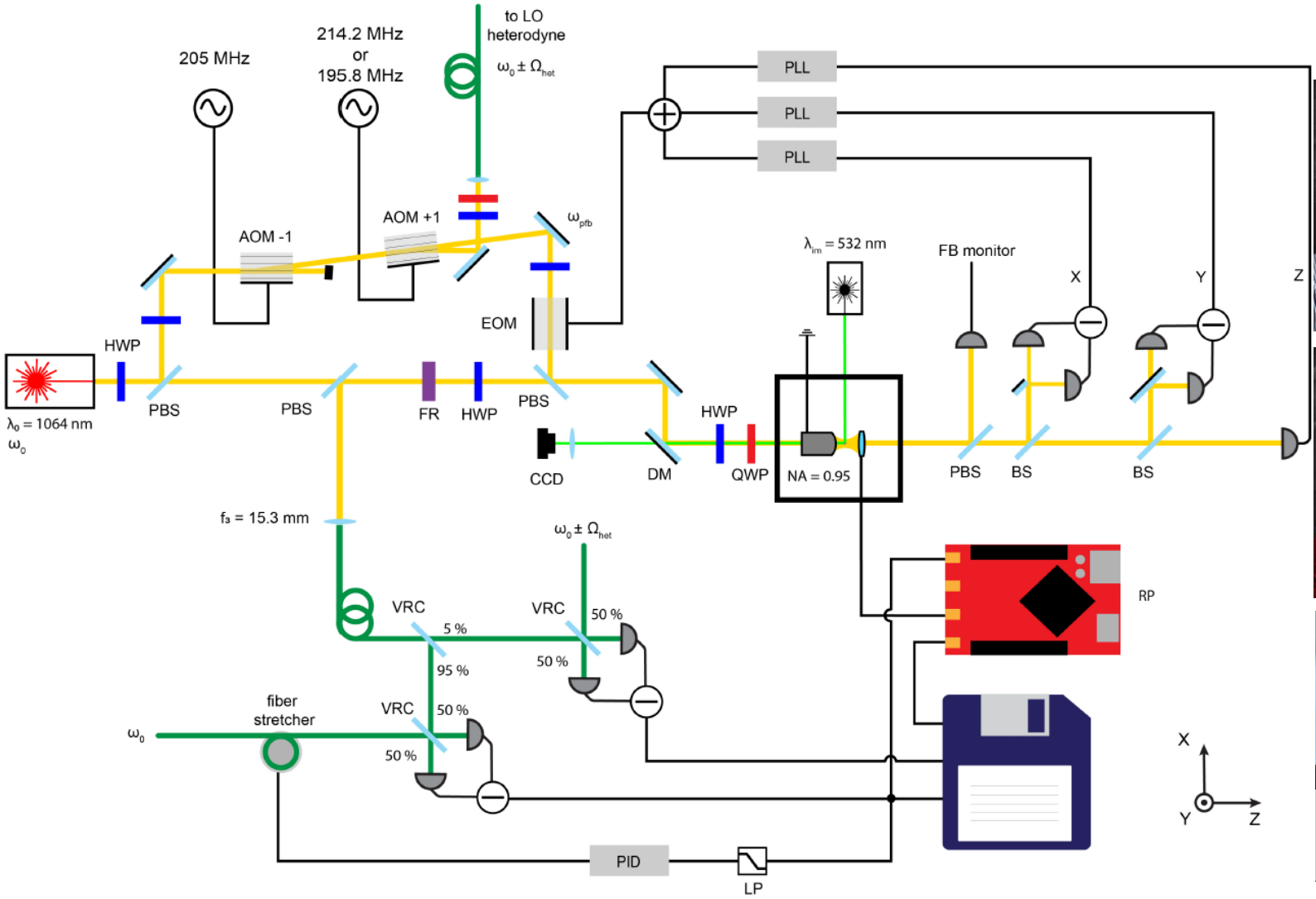
Pioneering work by Ashkin:
A. Ashkin, PRL 24, 156 (1970).
A. Ashkin, J. M. Dziedzic, APL 28, 333 (1976).

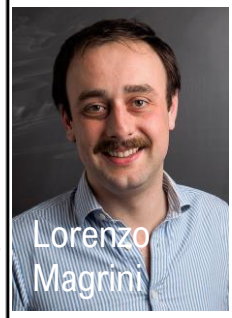
Magrini et al. 2018
(Scientific American)

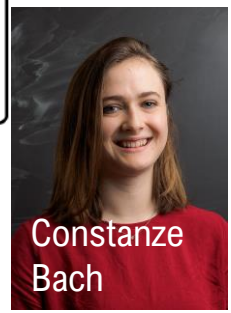


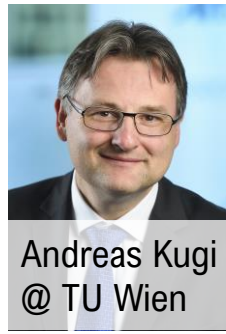
Looking behind the scenes: quantum Kalman Control

Magrini et al., Nature 595, 373 (2021)





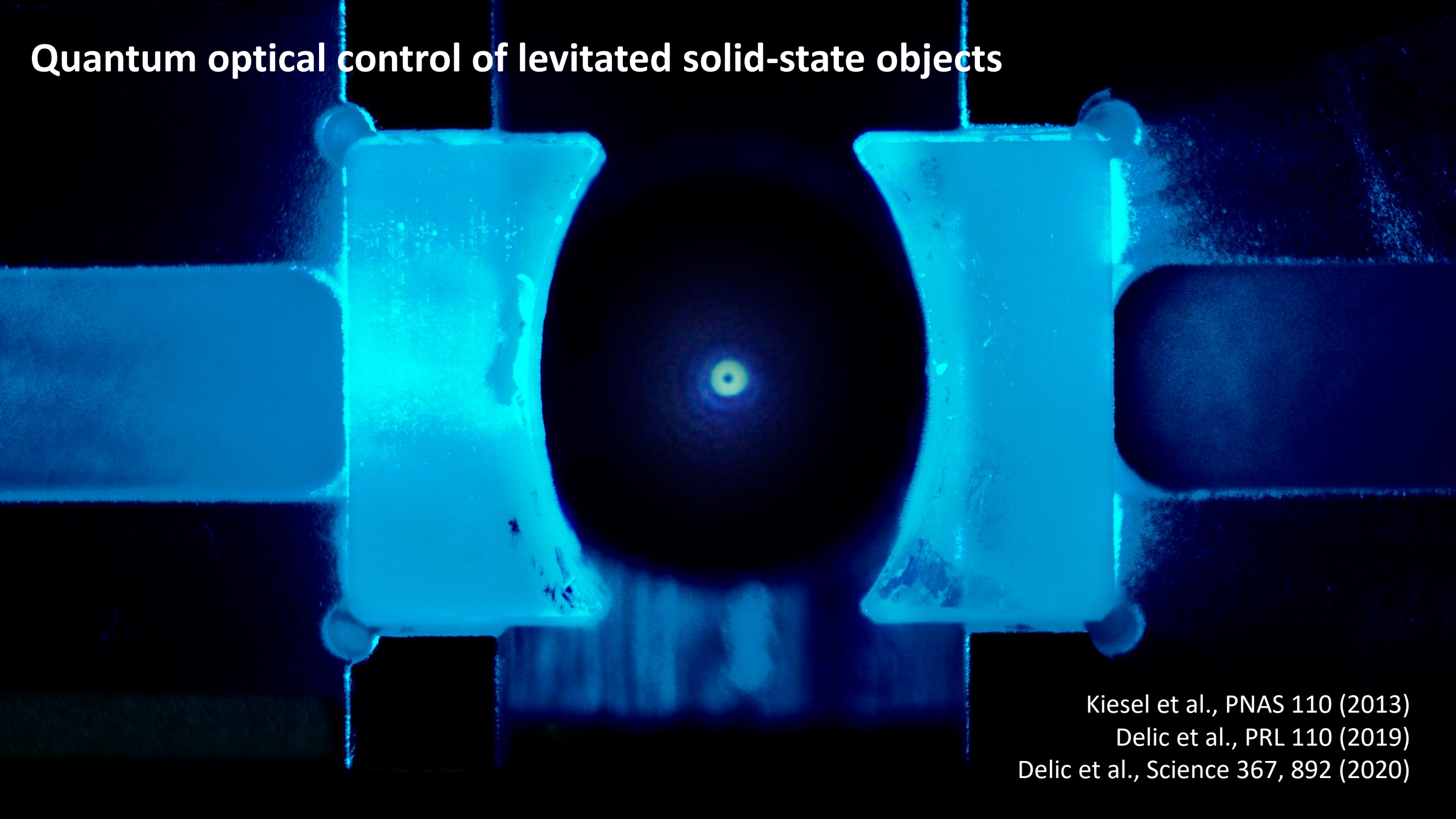




Lorenzo Magrini, Constanze Bach, Nikolai Kiesel
P. Rosenzweig, A. Deutschmann, A. Kugi (TU Wien)

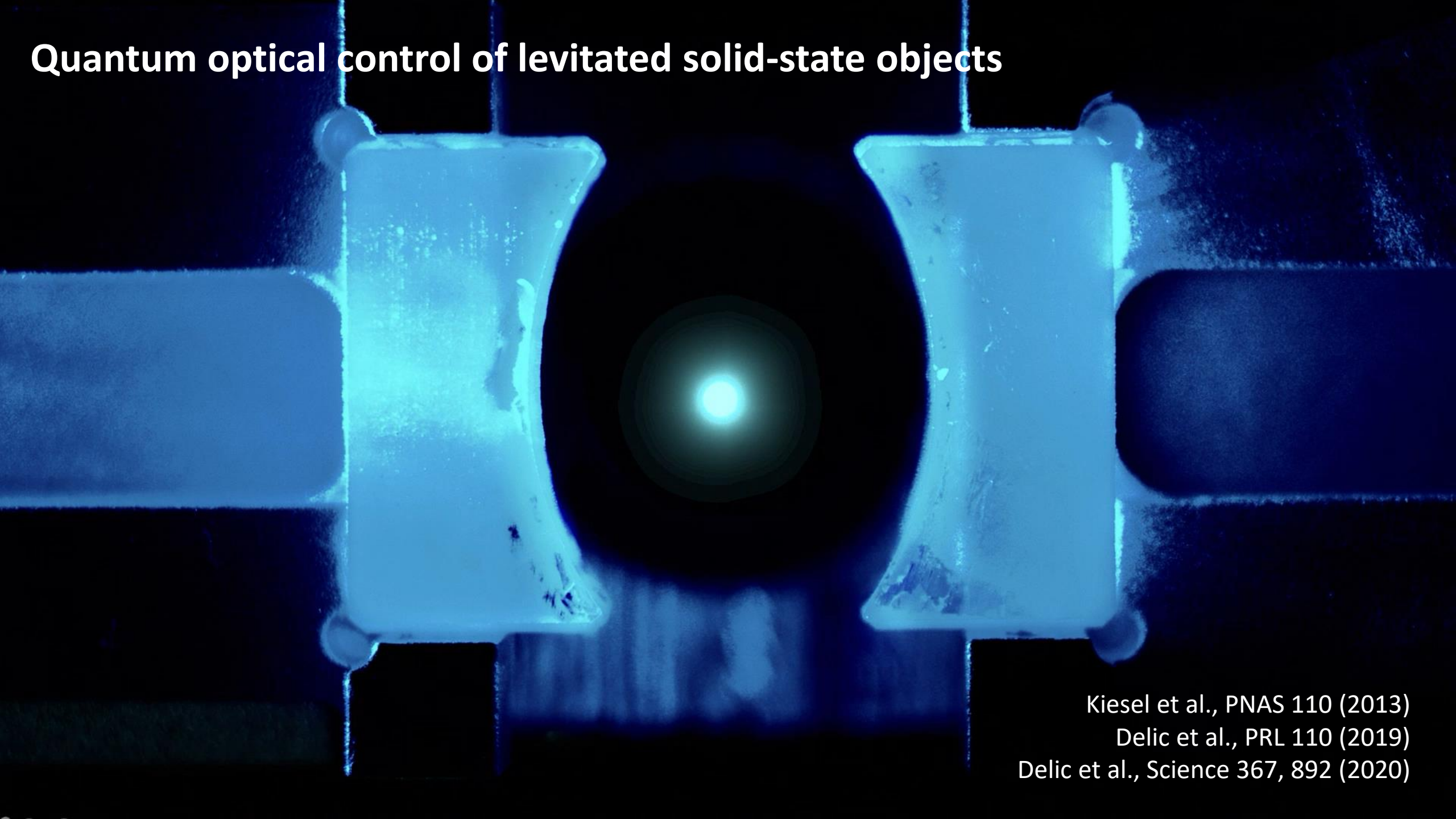
Image of a 150nm glass sphere in its quantum ground state of motion at a room temperature environment

Quantum optical control of levitated solid-state objects

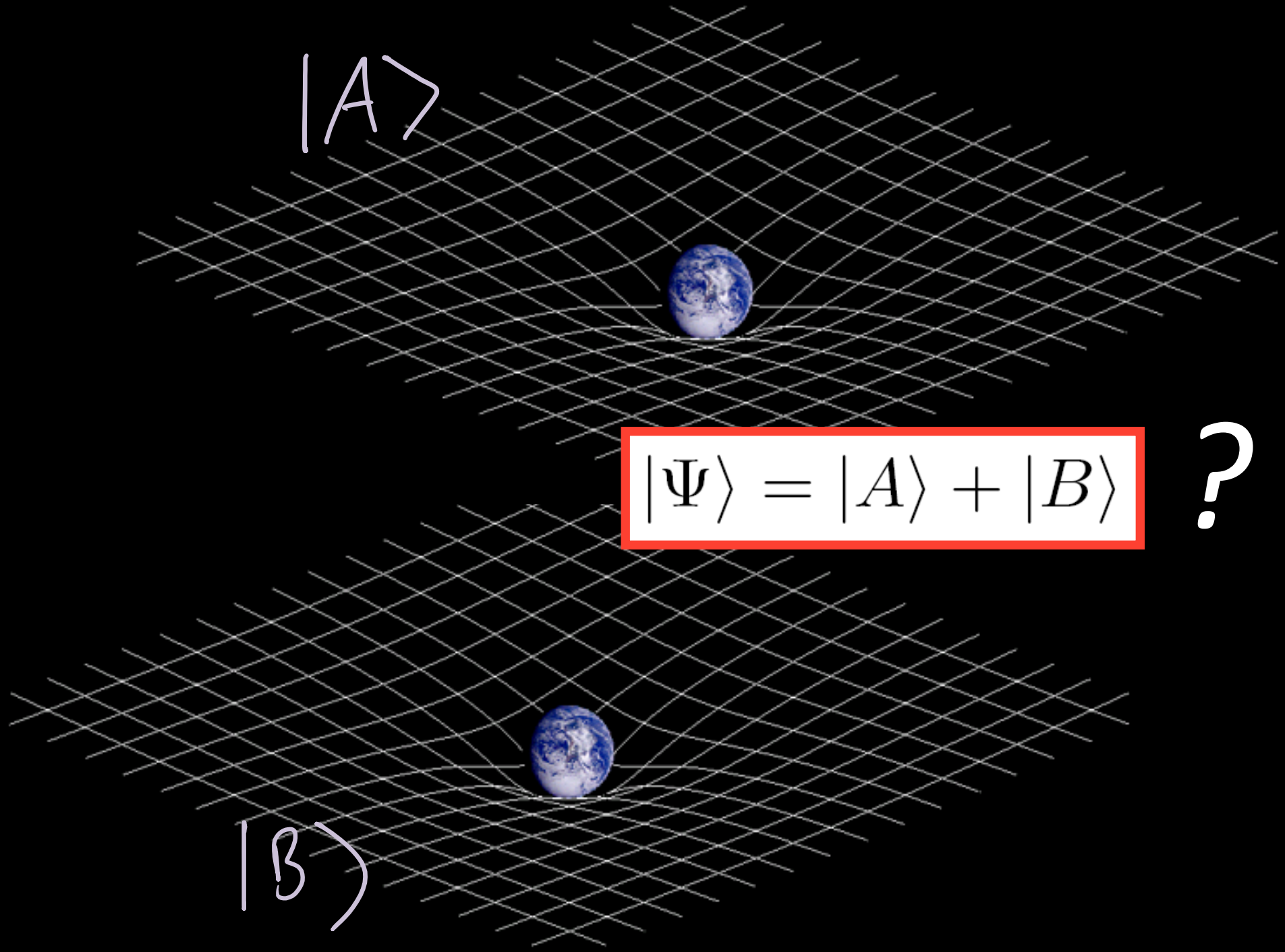


Kiesel et al., PNAS 110 (2013)
Delic et al., PRL 110 (2019)
Delic et al., Science 367, 892 (2020)

Quantum optical control of levitated solid-state objects



Kiesel et al., PNAS 110 (2013)
Delic et al., PRL 110 (2019)
Delic et al., Science 367, 892 (2020)


|A⟩
$|\Psi\rangle = |A\rangle + |B\rangle$
?
|B⟩

The 1957 Chapel Hill Conference

The absence of any paradox or discrepancy in gravitation theory at the human and astronomical levels creates an obligation to apply Einstein's ideas down to smaller and smaller distances. One must check as one goes, until one has either a successful extension to the very smallest distances, or a definite contradiction or paradox that will demand revision. ... The challenge cannot be evaded.

John A. Wheeler (letter to Bahnson, November 25, 1955)

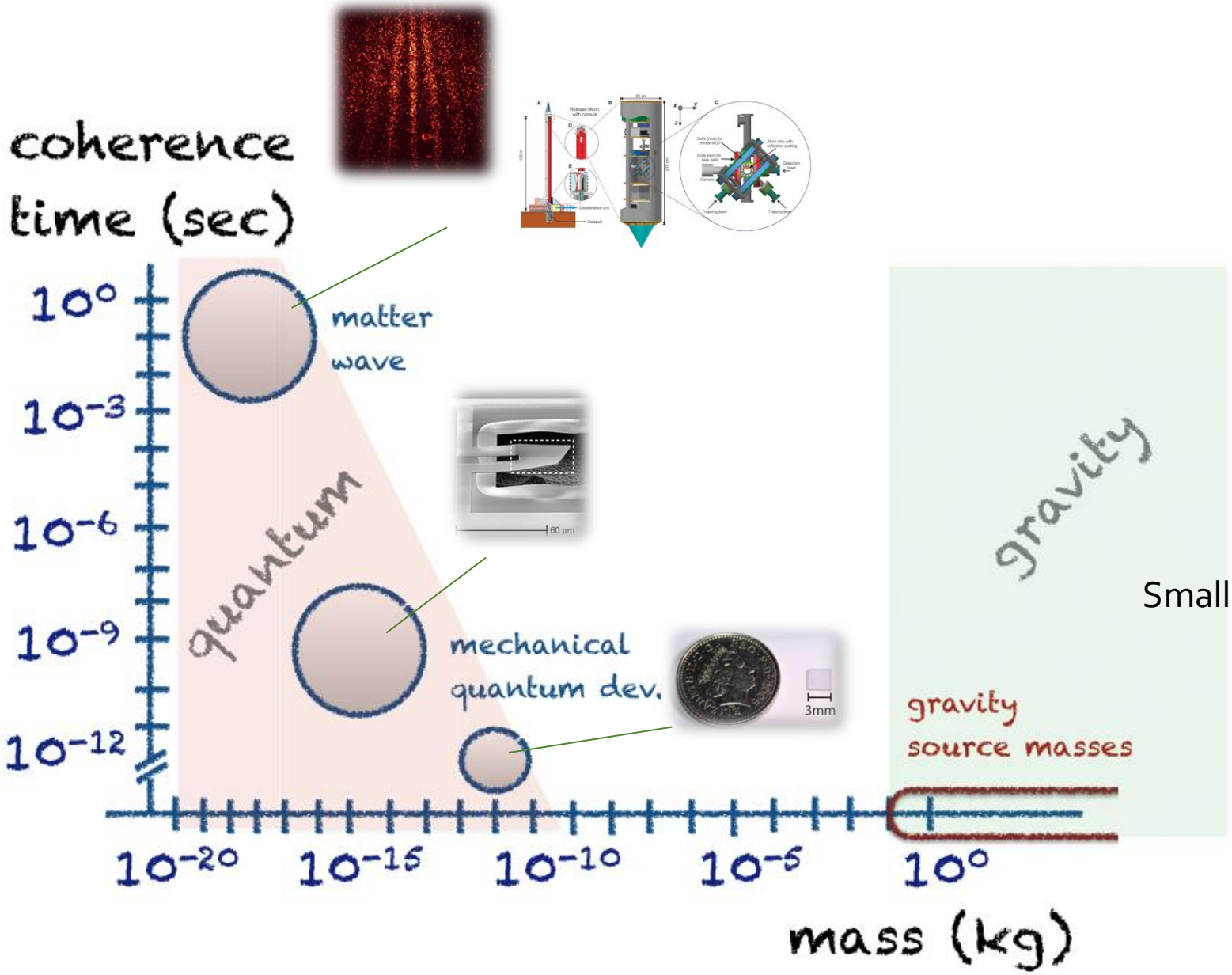
→ 1957 Chapel Hill Conference: The Role of Gravitation in Physics

Do gravitational waves exist?

Do we require a quantum description of gravity?

C. M. DeWitt, D. Rickles, Eds., The Role of Gravitation in Physics. Report from the 1957 Chapel Hill Conference (Max Planck Research Library for the History and Development of Knowledge, 2011).

The (experimental) challenge: quantum systems as gravitational source masses



- How small can we make a source mass?
- How massive can we make a quantum system?

Smallest source mass to date: **0.09 g**

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

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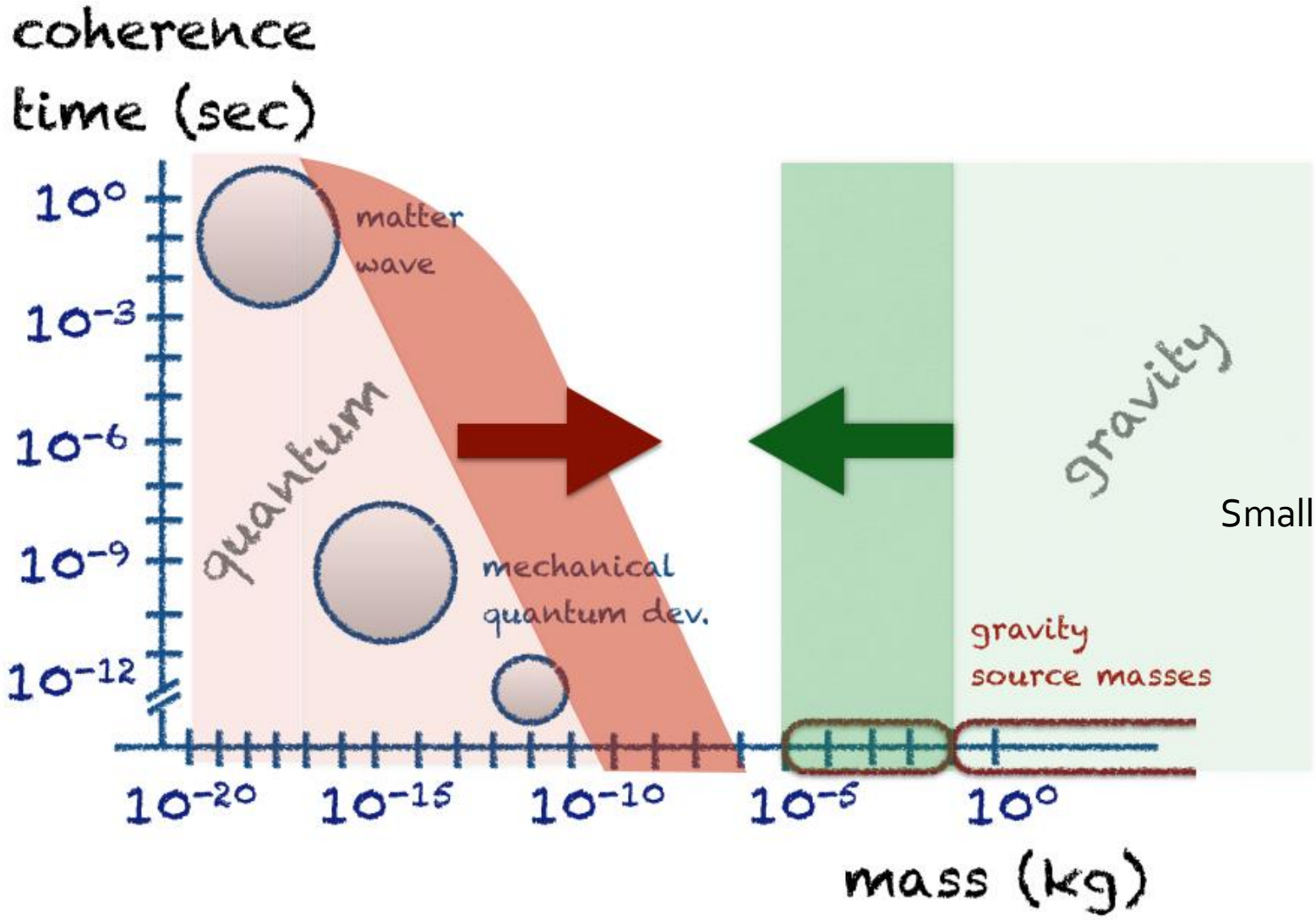

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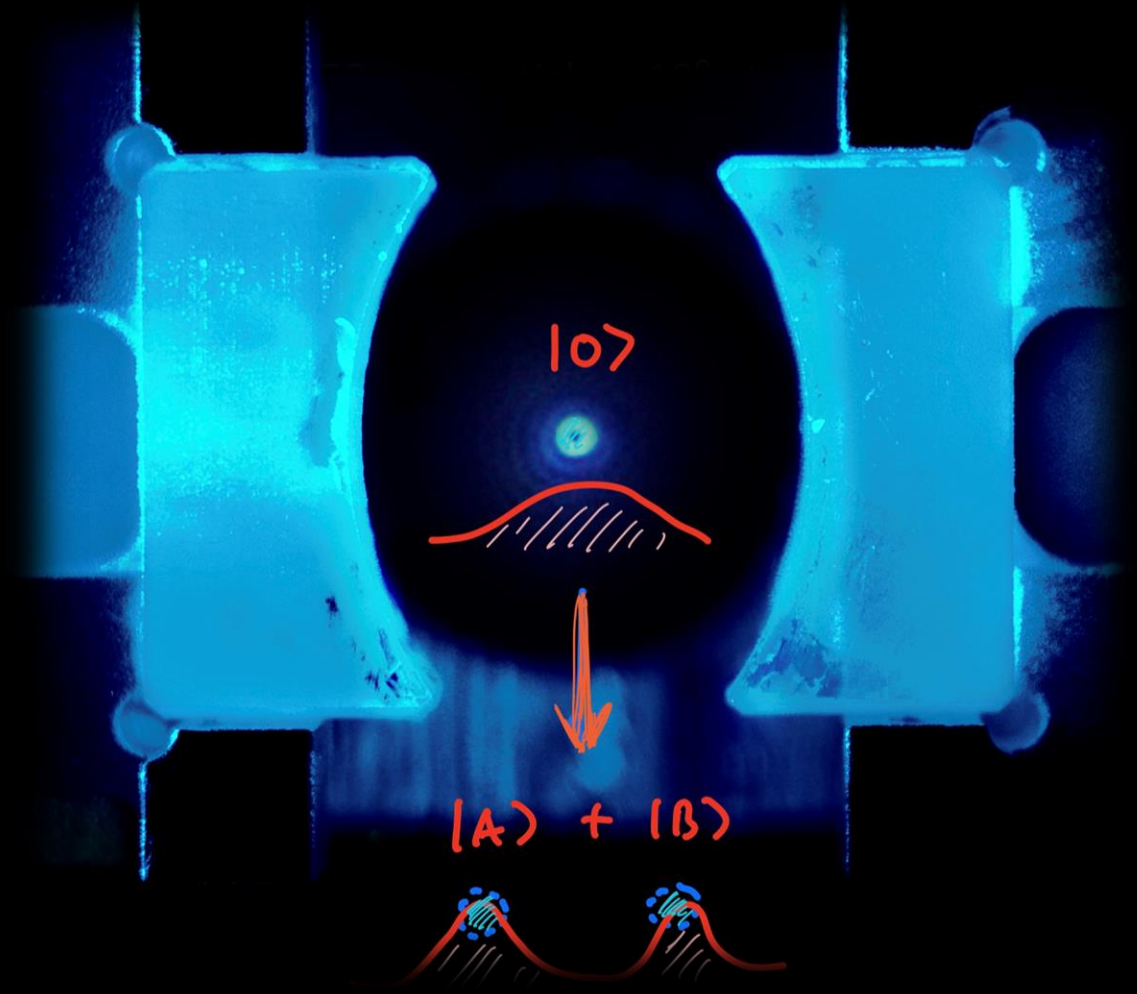
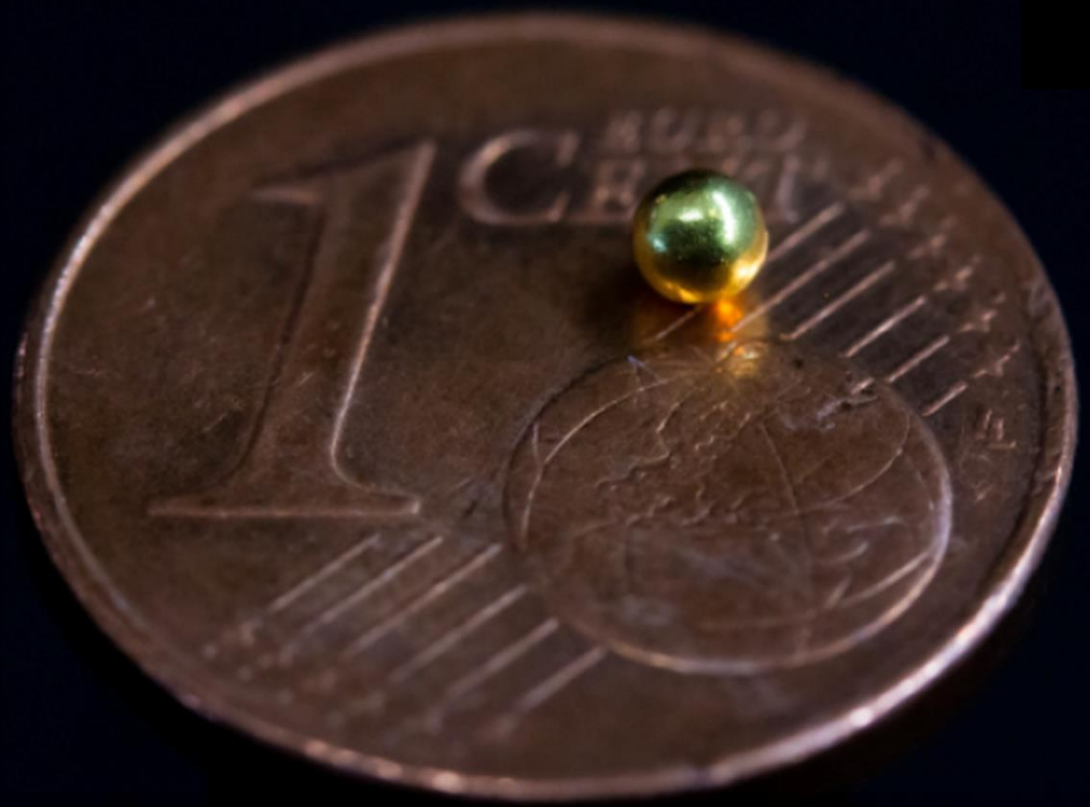
QUANTUM ⟷ GRAVITY



150 nm particle = 10^9 atoms



1 mm particle = 10^{21} atoms


USE BOTH EXITS
WHEN LEAVING
THE
PARKING STRUCTURE