Title: Quantum / optical mechanical sensors

Speakers: Markus Aspelmeyer

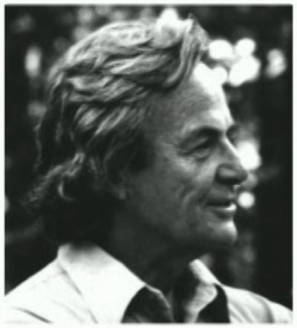
Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 22, 2022 - 9:15 AM

URL: https://pirsa.org/22090020

e.g. Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)

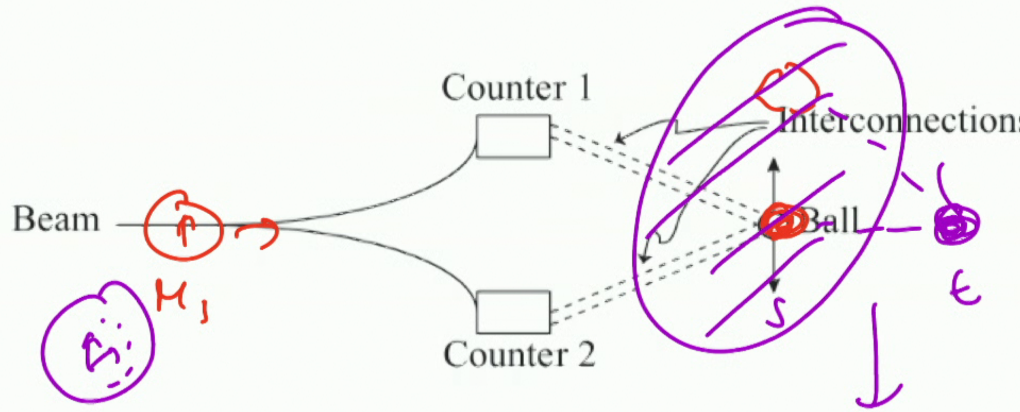
How does gravity react to quantum systems?



R P Feynman

"One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference"

Chapel Hill Conference 1957



$$\left(|x_u\rangle_s + |x_d\rangle_s\right) \otimes |x_0\rangle_t$$

$$t \downarrow \quad a_G^{I,II} = G \frac{m_s}{d^2_{I,II}}$$

$$|x_u\rangle_s |x_u\rangle_t + |x_d\rangle_s |x_d\rangle_t$$

ENTANGLED iff $\langle x_u | x_d \rangle_t \ll 1$

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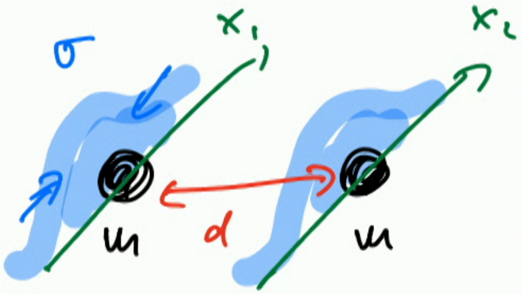
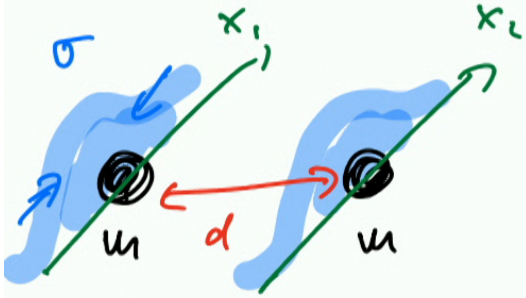


$$H_{int} \sim G\frac{m^2}{r} = G\frac{m^2}{\sqrt{d^2+(x_1-x_2)^2}}$$

$$\approx G\frac{m^2}{d}\left(1-\frac{(x_1-x_2)^2}{2d^2}+\dots\right)$$

$$= G\frac{m^2}{d}\left(1-\frac{x_1^2}{2d^2}-\frac{x_2^2}{2d^2}+\frac{x_1x_2}{d^2}+\dots\right)$$

$$\rightarrow H_{int} = G\frac{m^2}{d^3}x_1x_2$$



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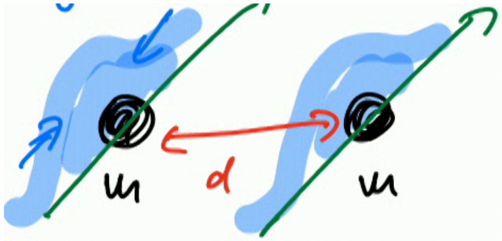
$$\rightarrow \hat{H}_{int} = G\frac{m^2}{d^3}\hat{x}_1\hat{x}_2 \qquad \hat{x} = \sigma(\hat{a}+\hat{a}^\dagger)$$

$$= G\frac{m^2}{d^3}\sigma^2(\hat{a}+\hat{a}^\dagger)(\hat{b}+\hat{b}^\dagger)$$



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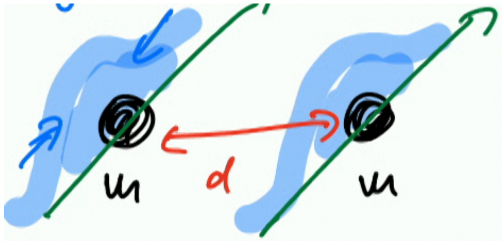

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$$\rightarrow \boxed{g = \frac{G}{\hbar}\frac{m^2}{d}\frac{\sigma^2}{d^2}}$$

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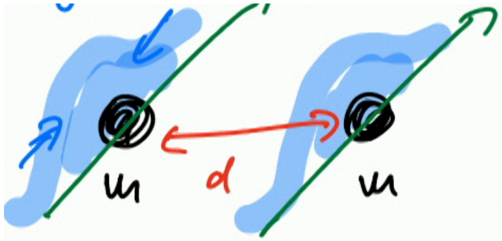

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Examples: 1) 2 ATOMS separated by $1\,\mu m$, $\sigma = \sqrt{\frac{\hbar}{m\Omega}} \sim 10^{-7}\,m$

$$g = 2\pi\, 10^{23}\, \frac{10^{-52}}{10^{-6}}\, 10^{-2} \sim 10^{-25}\ \text{Hz}$$

$$\rightarrow \tau_{ent} \sim 10^{25}\ \text{sec.} \sim 10^{8}\ T_{Un.}$$

2) 2 PLANCK MASSES,

18

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Examples: 1) 2 ATOMS separated by 1 μm, $\sigma = \sqrt{\frac{\hbar}{m\Omega}} \sim 10^{-7}$ m

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2) 2 PLANCK MASSES, $d \sim 100\,\mu m$, $\sigma \sim 1\,nm$

$$g = 2\pi\, 10^{23}\, \frac{10^{-16}}{10^{-4}}\, 10^{-6} \sim$$

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$\rightarrow \boxed{g = \frac{G}{\hbar} \frac{m^2}{d} \frac{\sigma^2}{d^2}}$ ≡ ENTANGLEMENT RATE

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2) 2 PLANCK MASSES, $d \sim 100\,\mu m$, $\sigma \sim 1\,\mu m$

$$g = 2\pi\, 10^{23} \frac{10^{-16}}{10^{-4}} 10^{-10} \sim 10 \text{ Hz}$$

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18

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$\frac{\sigma}{d} \sim 10^{-2}$, $d \sim 10\,\mu m$

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$< g$

$$\rightarrow \boxed{g = \frac{G}{\hbar}\frac{m^2}{d}\frac{\sigma^2}{d^2}} > \Gamma_{dec.}$$

$\equiv$ ENTANGLEMENT RATE

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$$g \overset{!}{>} 1$$

$$m^2 > \frac{\hbar}{G} d \left(\frac{d}{\sigma}\right)^2$$

$$10^{-23}\ 10^{-5}\ 10^{4}$$

$$\sim (10^{-12})^2$$

2) 2 PLANCK MASSES, $d \sim 100\,\mu m$, $\sigma \sim 1\,nm$

$$g = 2\pi\, 10^{23} \frac{10^{-16}}{10^{-4}} 10^{-10} \sim 10\ Hz$$

$$\Rightarrow \rho > \frac{m}{d^3} \sim \frac{10^{-12}}{10^{-15}} \sim 10^3 \frac{kg}{m^3}$$

$$\rightarrow \tau_{ent} \sim 100\,ms$$

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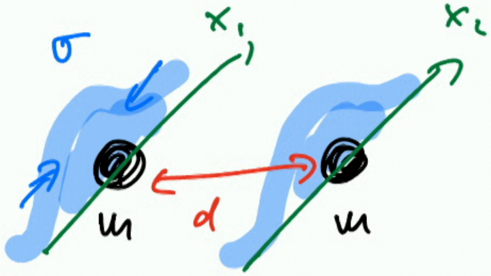

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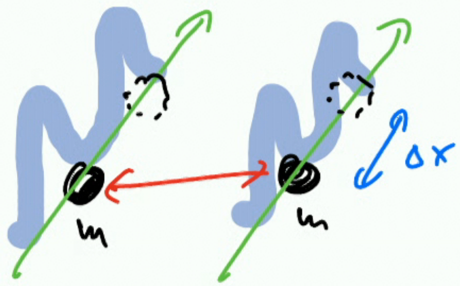

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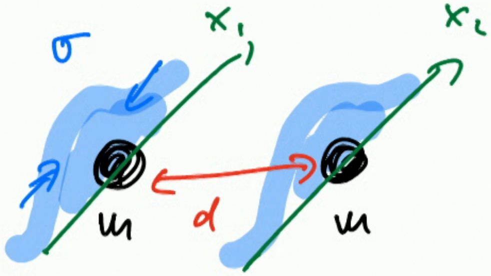

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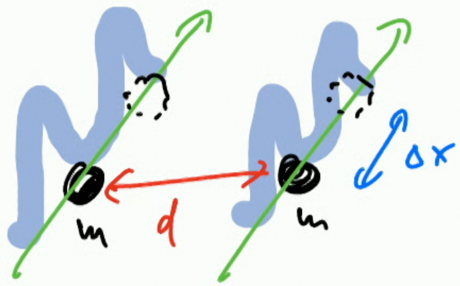

$$\to \hat{H}_{int} = G\frac{m^2}{d^3}\hat{x}_1\hat{x}_2 \qquad \hat{x} = \sigma(\hat{a}+\hat{a}^\dagger)$$

$$\varphi = \frac{1}{\hbar}\int m\phi\, dt$$

$$\downarrow$$

$$\phi = G\frac{m}{r}$$

$$= G\frac{m^2}{d^3}\sigma^2(\hat{a}+\hat{a}^\dagger)(\hat{b}+\hat{b}^\dagger)$$

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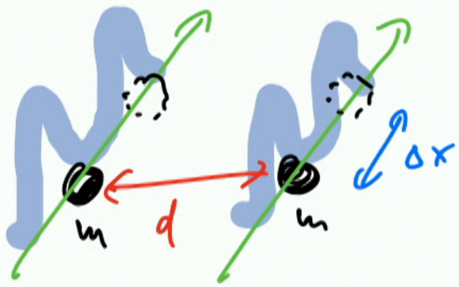


$$|\psi_0\rangle = (|x_L\rangle_1 + |x_R\rangle_1) \otimes (|x_L\rangle_2 + |x_R\rangle_2)$$

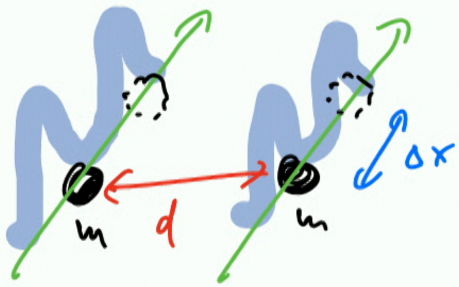
$$\Big\downarrow t$$

$$\varphi = \frac{1}{\hbar}\int m\,\phi\, dt$$

$$\phi = G\frac{m}{r}$$

$$r_{\underline{\pm}} = d$$

$$r_{\underline{\pi}} = \sqrt{d^2 + \Delta x^2}$$



$$\varphi = \frac{1}{\hbar}\int m\,\Phi\,dt$$

$$\Phi = G\,\frac{m}{r}$$

$$r_{I} = d$$

$$r_{II} = \sqrt{d^2 + \Delta x^2}$$

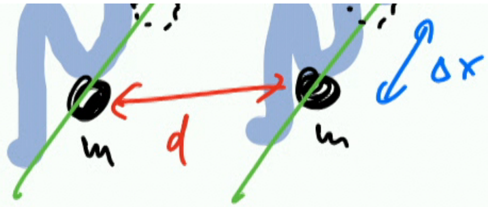
$$|\psi_0\rangle = \left(|x_L\rangle_1 + |x_R\rangle_1\right) \otimes \left(|x_L\rangle_2 + |x_R\rangle_2\right)$$

$$\big\downarrow t$$

$$e^{i\varphi_1}\Big(|x_L\rangle_1 \overbrace{\left(|x_L\rangle_2 + e^{i\Delta\varphi}|x_R\rangle_2\right)}^{|\tilde{x}_L\rangle_2} + |x_R\rangle_1 \underbrace{\left(|x_R\rangle_2 + e^{i\Delta\varphi}|x_L\rangle_2\right)}_{|\tilde{x}_R\rangle_2} \Big)$$

ENTANGLED iff $\langle \tilde{x}_L | \tilde{x}_R \rangle = 0 = \left| e^{i\Delta\varphi} + e^{-i\Delta\varphi} \right|$

$\sim \cos\Delta\varphi$



$$\varphi = \frac{1}{\hbar}\int m\,\phi\,dt$$

$$\phi = G\frac{m}{r}$$

$$r_{\underline{I}} = d$$

$$r_{\underline{II}} = \sqrt{d^2 + \Delta x^2}$$

$$\Delta\varphi = \frac{1}{\hbar}\left(G\frac{m^2}{d}\left(1 + \frac{\Delta x^2}{d^2} - 1\right)\right)\cdot t$$

$$g_{ent} = \frac{d}{dt}\Delta\varphi = \frac{G}{\hbar}\frac{m^2}{d}\left(\frac{\Delta x}{d}\right)^2$$

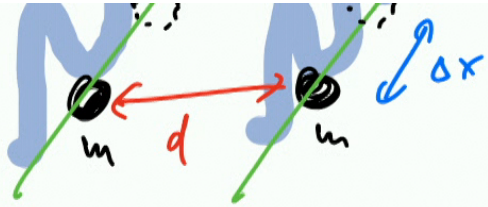
$$\Big\downarrow t$$

$$e^{i\varphi_1}\Big(|x_L\rangle_1 \overbrace{\big(|x_L\rangle_2 + e^{i\Delta\varphi}|x_R\rangle_2\big)}^{|\tilde{x}_L\rangle_2}$$

$$+ |x_R\rangle_1 \underbrace{\big(|x_R\rangle_2 + e^{i\Delta\varphi}|x_L\rangle_2\big)}_{|\tilde{x}_R\rangle_2}\Big)$$

ENTANGLED iff $\langle \tilde{x}_L | \tilde{x}_R\rangle = 0 = |e^{i\Delta\varphi} + e^{-i\Delta\varphi}|$

$$\sim \cos\Delta\varphi$$



$$\varphi = \frac{1}{\hbar}\int m\,\phi\, dt$$

$$\phi = G\frac{m}{r}$$

$$r_{\underline{+}} = d$$

$$r_{\underline{\pi}} = \sqrt{d^2 + \Delta x^2}$$

$$e^{i\varphi_1}\Big(|x_L\rangle_1 \overbrace{\left(|x_L\rangle_2 + e^{i\Delta\varphi}|x_R\rangle_2\right)}^{|\tilde{x}_L\rangle_2} + |x_R\rangle_1 \underbrace{\left(|x_R\rangle_2 + e^{i\Delta\varphi}|x_L\rangle_2\right)}_{|\tilde{x}_R\rangle_2}$$

$\downarrow t$

ENTANGLED iff $\langle \tilde{x}_L | \tilde{x}_R \rangle = 0 = |e^{i\Delta\varphi} + e^{-i\Delta\varphi}|$

$$\sim \cos\Delta\varphi$$

$$\Delta\varphi = \frac{1}{\hbar}\left(G\frac{m^2}{d}\left(1 + \frac{\Delta x^2}{d^2} - 1\right)\right)\cdot t$$

$$g_{ent} = \frac{d}{dt}\Delta\varphi = \frac{G}{\hbar}\frac{m^2}{d}\left(\frac{\Delta x}{d}\right)^2 \Rightarrow \text{maximize } \frac{m^2\Delta x^2}{d^3}\cdot\tau_{coh.}$$

Current experiments involving delocalization of massive objects

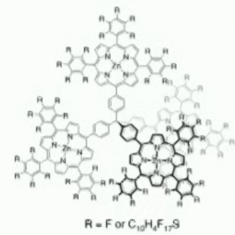
Superposition of single systems (beyond atoms & neutrons)

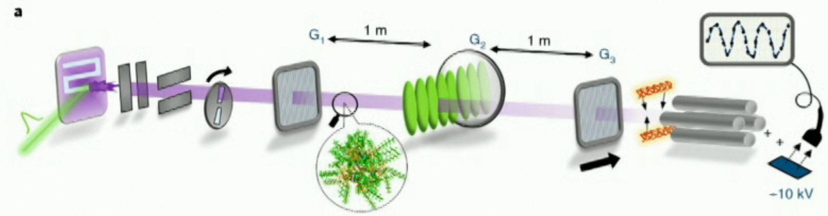
$\Delta x \cdot M \approx 10^{-29}$ [m · kg]

Macro-molecules

matter-wave interference; 2,000 atoms; M = 25,000 a.m.u. = 4e-23 kg; particle size D=5nm; superposition size Δx > 500 nm

Y. Y. Fein *et al.*, *Nat. Phys.* **15**, 1242–1245 (2019)

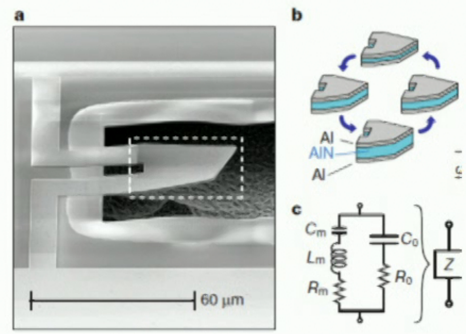




Solid-state mechanical oscillators

Ramsey interference 0+1 between ground state (0) and single-phonon (1) Fock state (6 GHz acoustic mode); 1e13 atoms, M = 8e-13 kg, SiO2/AlN slab (60umx10umx700nm), superposition size Δx = 2e-16 m (thickness oscillation)

A. D. O'Connell et al., Nature 464, 697–703 (2010)



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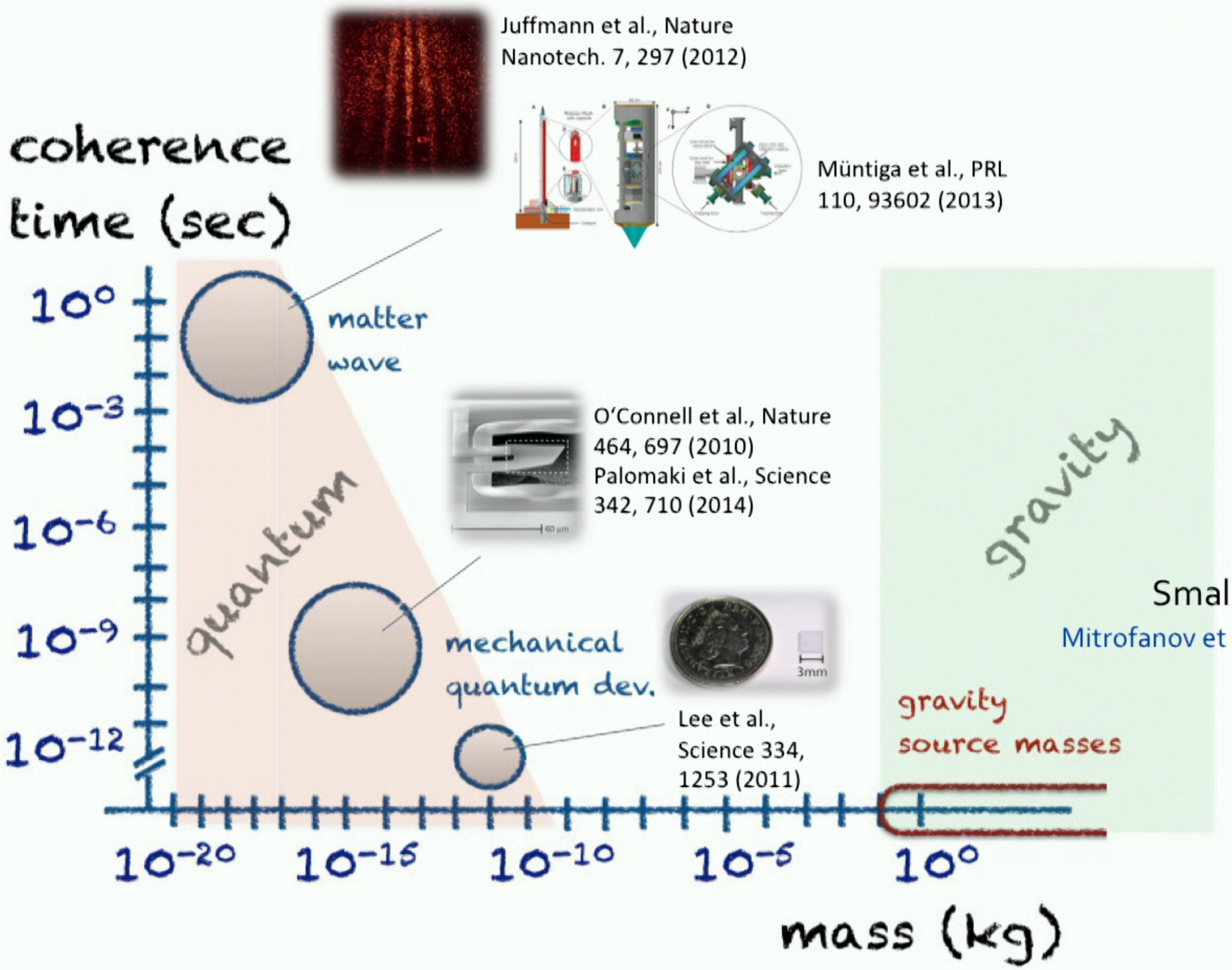
Reality check: quantum systems as gravitational source masses?

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



Smallest source mass to date: **0.7 g**

Mitrofanov et al., Zh. Eksp. Teor. Fiz. 94,16-22 (1988)

Lee et al., PRL 124, 101101 (2020)

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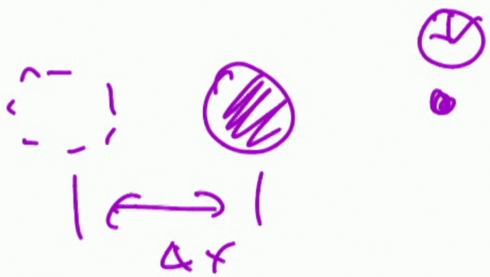
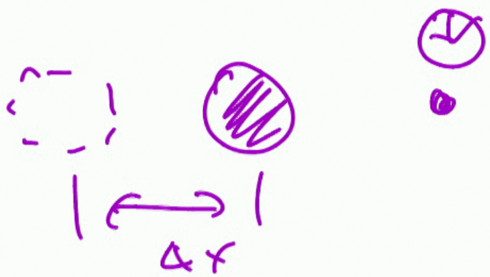
$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot} \right)$$



$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot}\right) = |\Psi\rangle_t$$



$$\rho_m = \mathrm{Tr}_{\odot} |\Psi\rangle\langle\Psi|$$

$$= |\tilde{\Psi}_L\rangle\langle\tilde{\Psi}_L| + |\tilde{\Psi}_R\rangle\langle\tilde{\Psi}|_R$$

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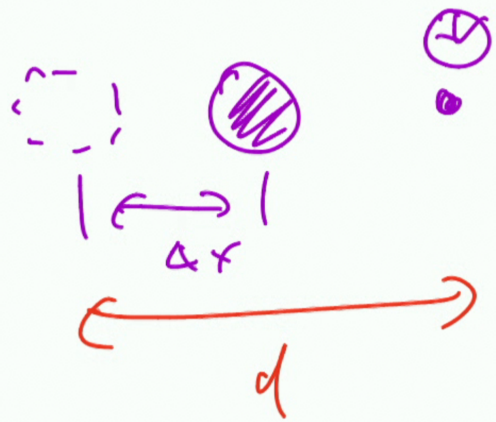
$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot} \right) = |\Psi\rangle_+$$

$m = M_p$, $d \sim 10^{-5}\,\mathrm{m}$, $\frac{\Delta x}{d} \sim 10^{-2}$

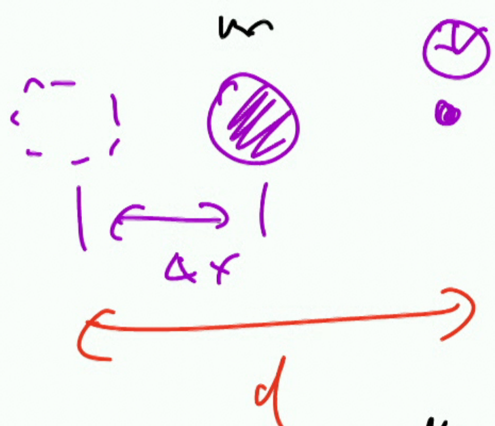


$$\rho_m = \mathrm{Tr}_{\odot} |\Psi\rangle\langle\Psi|$$

$$= |\tilde{\Psi}_L\rangle\langle\tilde{\Psi}_L| + |\tilde{\Psi}_R\rangle\langle\tilde{\Psi}|_R$$

$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot} \right) = |\Psi\rangle_t$$

$$m = M_p \,, \quad d \sim 10^{-5}\,\mathrm{m} \,, \quad \frac{\Delta x}{d} \sim 10^{-2} \qquad \frac{\Delta \nu}{\nu} = \frac{\Delta U}{c^2}$$



$$\rho_m = \mathrm{Tr}_{\odot} |\Psi\rangle\langle\Psi|$$

$$= |\tilde{\Psi}_L\rangle\langle\tilde{\Psi}_L| + |\tilde{\Psi}_R\rangle\langle\tilde{\Psi}|_R$$

$$\Delta U = -G\frac{m}{d} + G\frac{m}{d-\Delta x}$$

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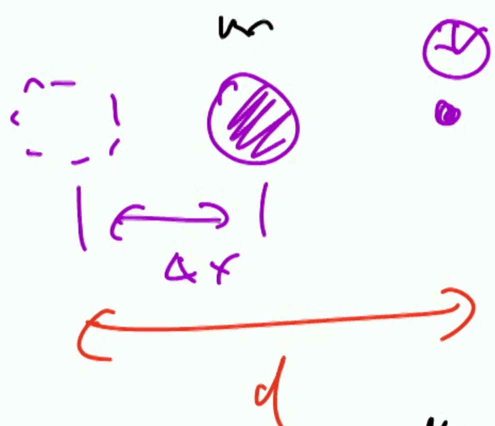
$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot} \right) = |\Psi\rangle_t$$

$m = M_P$, $d \sim 10^{-5}\,\mathrm{m}$, $\frac{\Delta x}{d} \sim 10^{-2}$ $\qquad \frac{\Delta \nu}{\nu} = \frac{\Delta U}{c^2}$



$$\rho_m = \mathrm{Tr}_{\odot} |\Psi\rangle\langle\Psi|$$

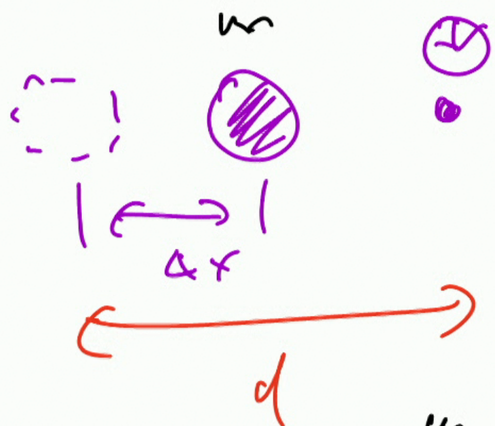
$$= |\tilde{\Psi}_L\rangle\langle\tilde{\Psi}_L| + |\tilde{\Psi}_R\rangle\langle\tilde{\Psi}_R|$$

$$\Delta U = -G\frac{m}{d} + G\frac{m}{d-\Delta x} = G\frac{m}{d}\frac{\Delta x}{d}$$

$$\left(|x_L\rangle_m |\alpha_L\rangle_g |\tau_L\rangle_{\odot} + |x_R\rangle_m |\alpha_R\rangle_g |\tau_R\rangle_{\odot}\right) = |\Psi\rangle_t$$

$$m = M_p\,,\quad d \sim 10^{-5}\,m\,,\quad \frac{\Delta x}{d} \sim 10^{-2}$$

$$\frac{\Delta\nu}{\nu} = \frac{\Delta U}{c^2} = \frac{10^{-16}}{10^{16}} \sim 10^{-32}$$



$$\rho_m = \mathrm{Tr}_{\odot}\, |\Psi\rangle\langle\Psi|$$

$$= |\tilde{\Psi}_L\rangle\langle\tilde{\Psi}_L| + |\tilde{\Psi}_R\rangle\langle\tilde{\Psi}_R|$$

$$\Delta U = -G\frac{m}{d} + G\frac{m}{d-\Delta x} = G\frac{m}{d}\frac{\Delta x}{d} = 6\cdot 10^{-11}\,\frac{10^{-8}}{10^{-5}}\,10^{-2} \sim 10^{-16}$$

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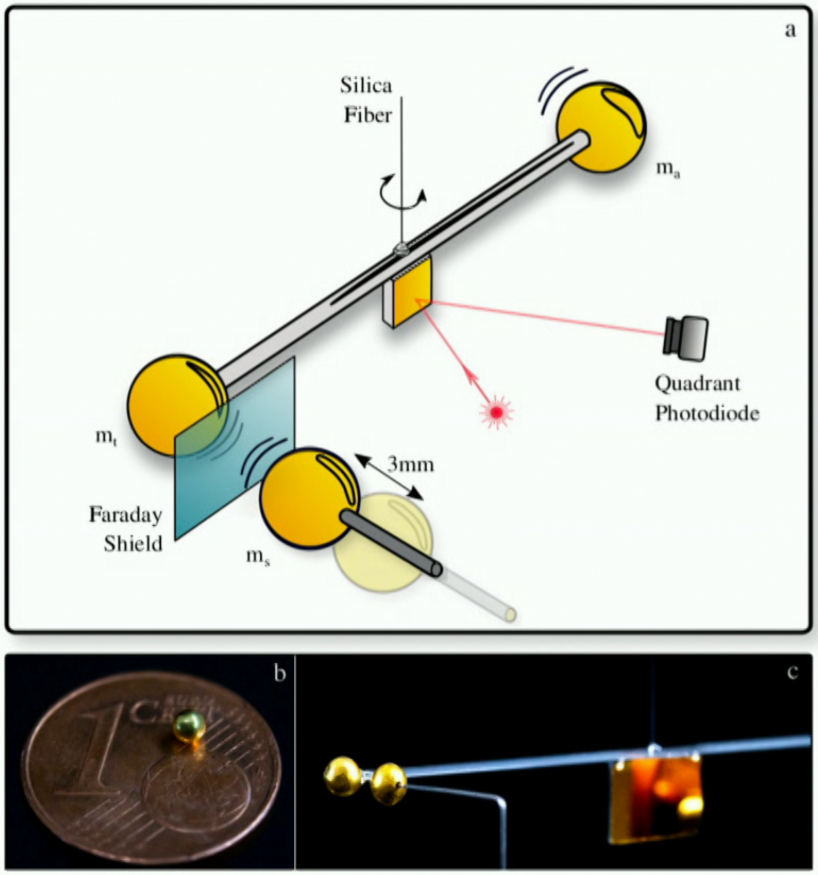
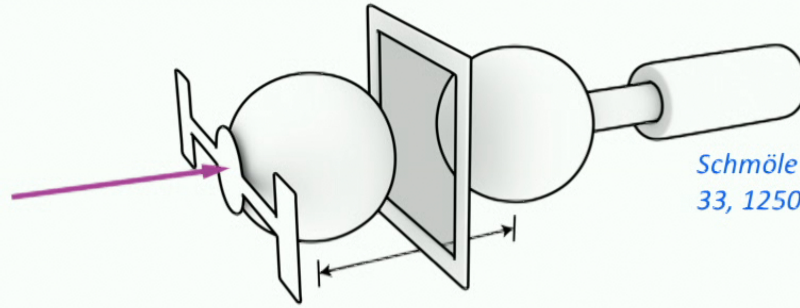
How small can we go? The idea:



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



Schmöle et al., Class. Quant. Grav. 33, 125031 (2016)

- periodic modulation of a source mass @ f_mod
- generates a test mass acceleration @ n x f_mod (n=1,2, …)
- fundamental limit: thermal noise of test mass oscillator

$$d(t) = d_0 + d_m \cos \Omega t$$

$$a(t) = G \frac{m}{d(t)^2} = G \frac{m}{d_0^2} \left(1 - 2 \frac{d_m}{d_0} \cos \Omega t + 3 \left(\frac{d_m}{d_0}\right)^2 \cos^2 \Omega t + \dots \right)$$

$$\left. \begin{array}{l} m_s \sim 9 \cdot 10^{-5}\ \mathrm{kg} \\ d_0 \sim 4\ \mathrm{mm} \\ d_m \sim 1.6\ \mathrm{mm} \end{array} \right\} a \sim 3 \cdot 10^{-10}\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

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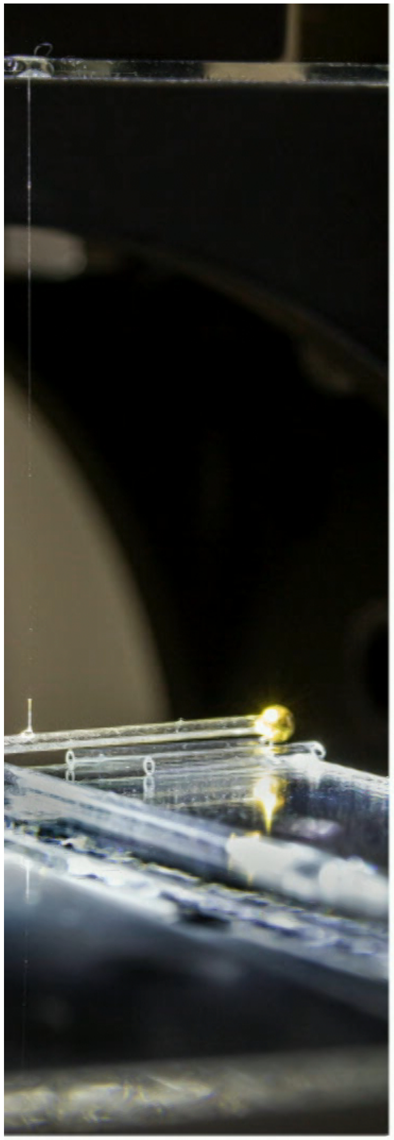
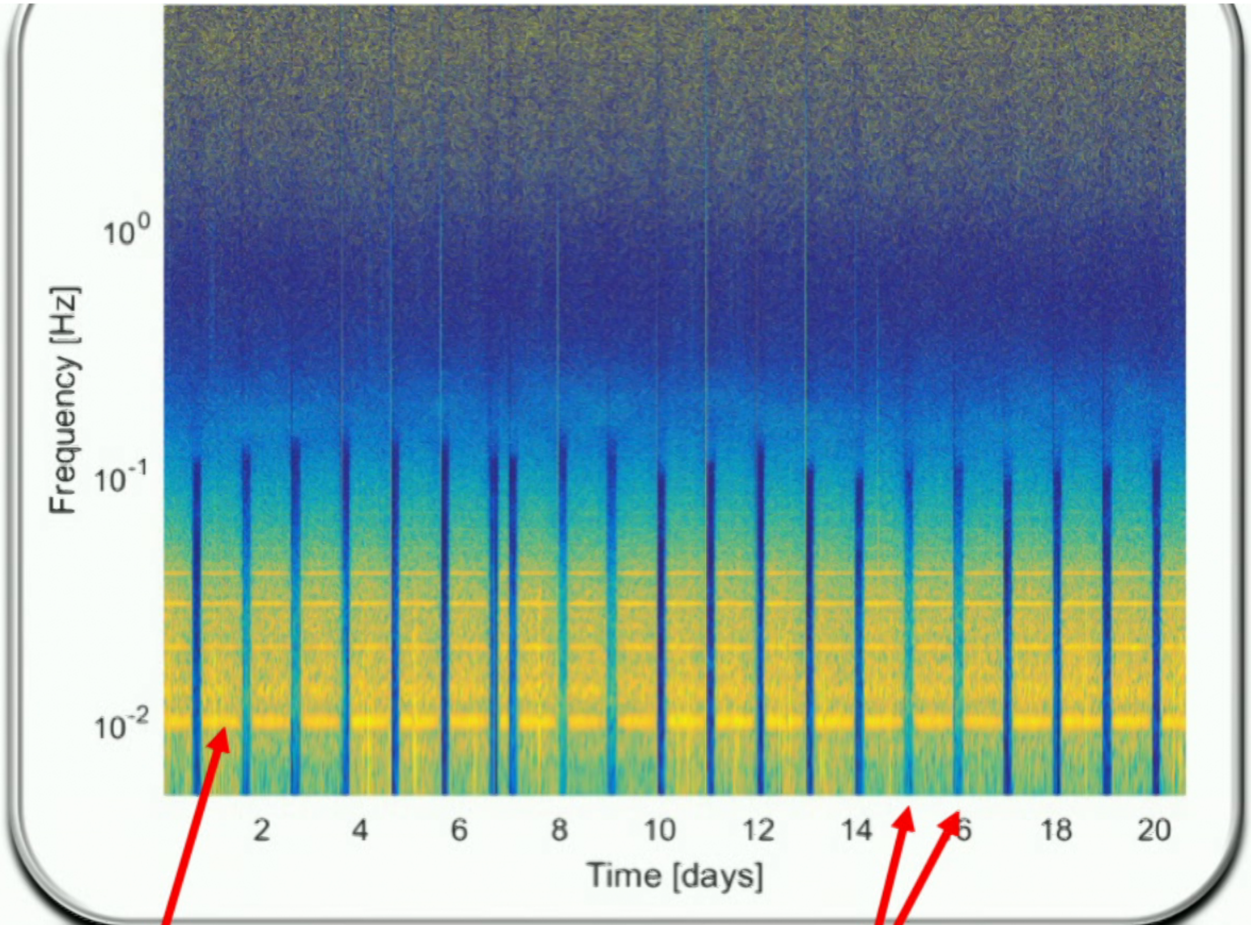


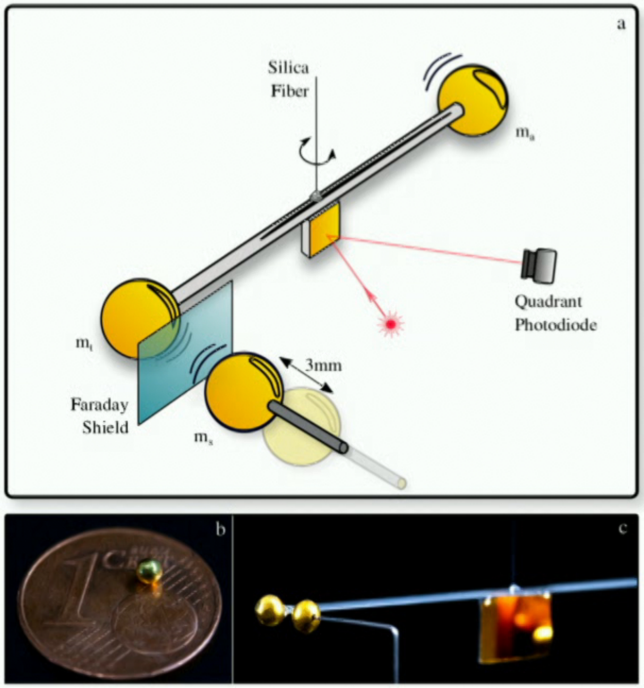


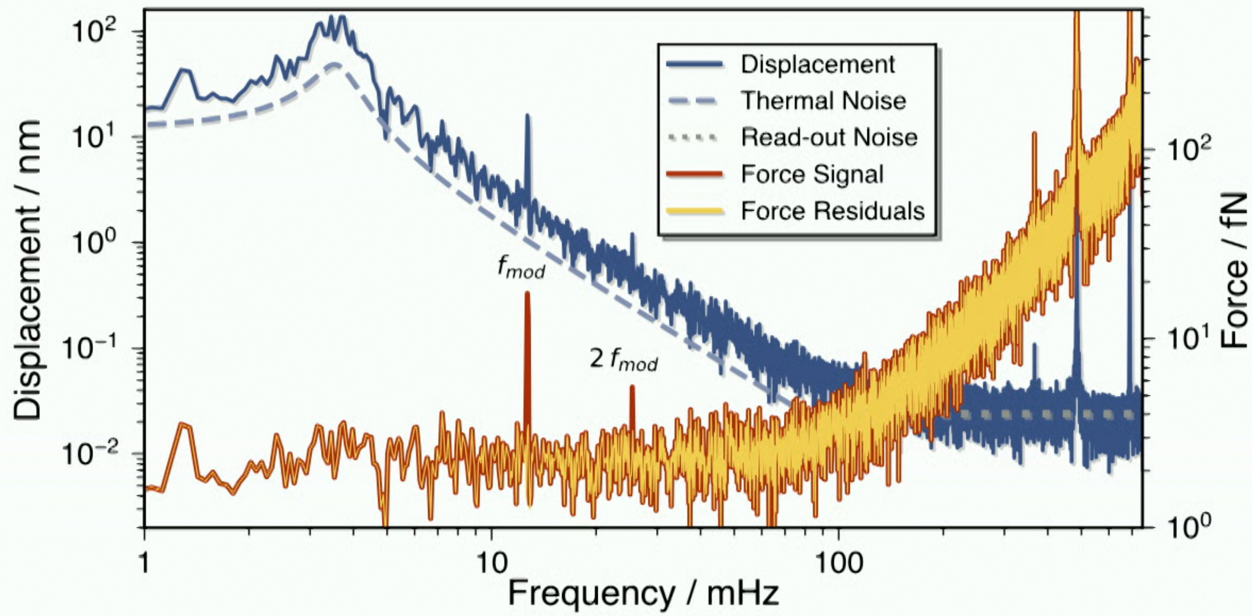
10 mHz = traffic light cycle
Nussdorfer Str @
Währinger Str

Friday & Saturday night
= party night

Results

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





- We observe a linear and quadratic acceleration modulation (at f_mod and 2f_mod) produced from a **90mg source mass**
- We resolve an **acceleration modulation of 3e-10 m/s^2** with an accuracy of 10% and a **precision of 1% (3e-12 m/s^2)**
- The observed coupling deviates from the CODATA value for Newton's constant by 9%, which is covered in the known systematic uncertainties of our experiment (i.e. interaction is >90% gravitational)

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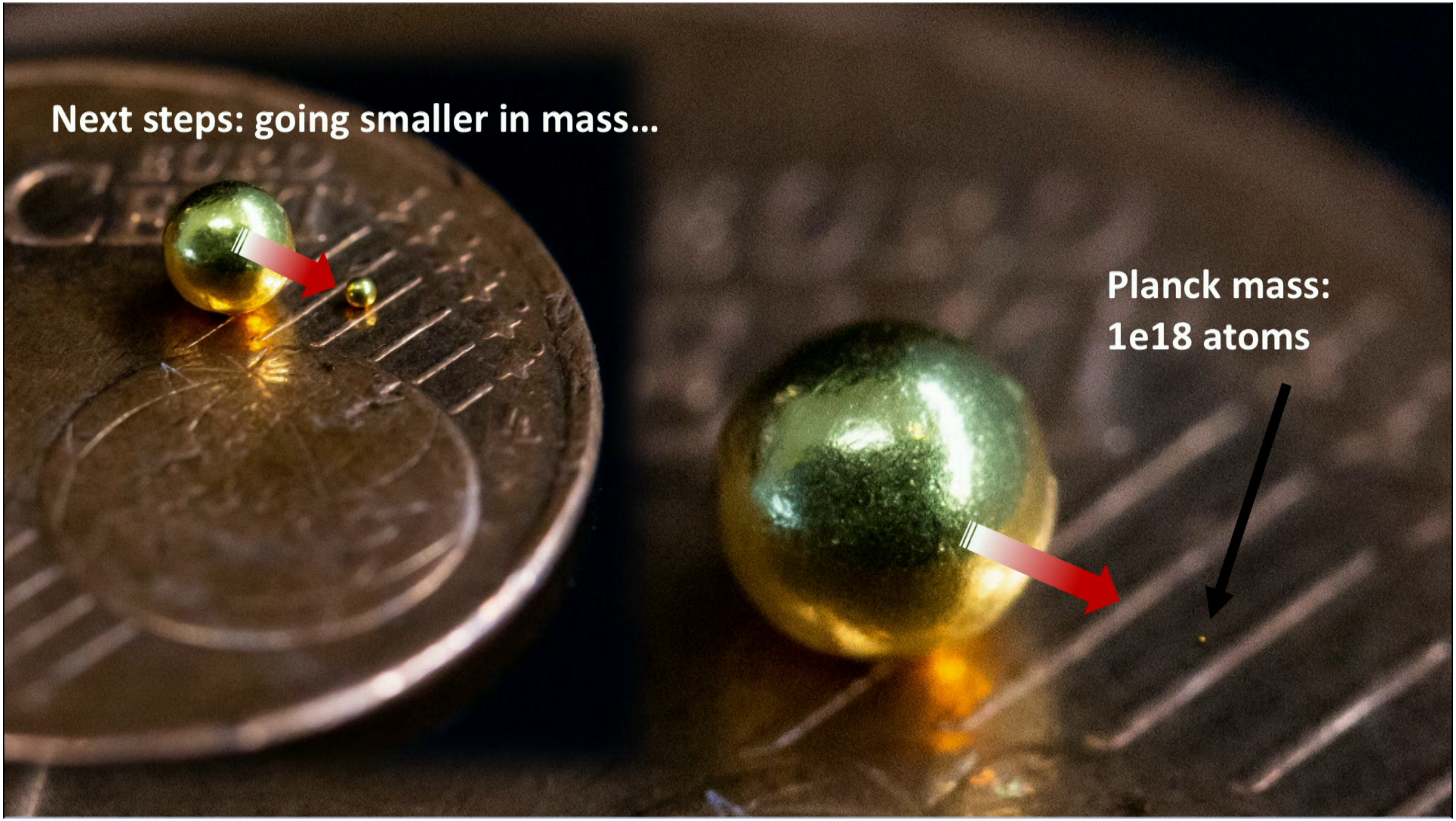

Next steps: going smaller in mass…
Planck mass:
1e18 atoms

... by going underground

Quantum controlling levitated solid-state objects

Combining LARGE MASSES with LONG COHERENCE TIMES and FULL MANIPULATION

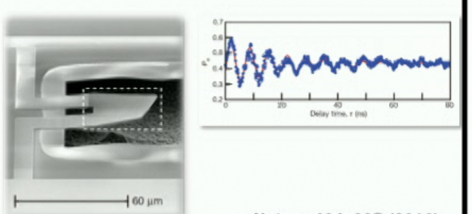
+

=

Solid-state mechanical quantum devices (clamped):

$10^{10} - 10^{16}$ atoms

Coherence time
$10^{-12} - 10^{-8}$ sec

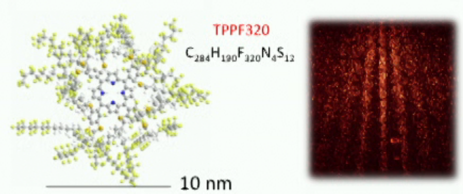


Nature 464, 697 (2010)

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)
- Exceptional force sensitivity
- Externally engineerable (and controllable) arbitrary potential landscape

recent review:
Gonzalez-Ballestero et al., Science **374**, 168 (2021)

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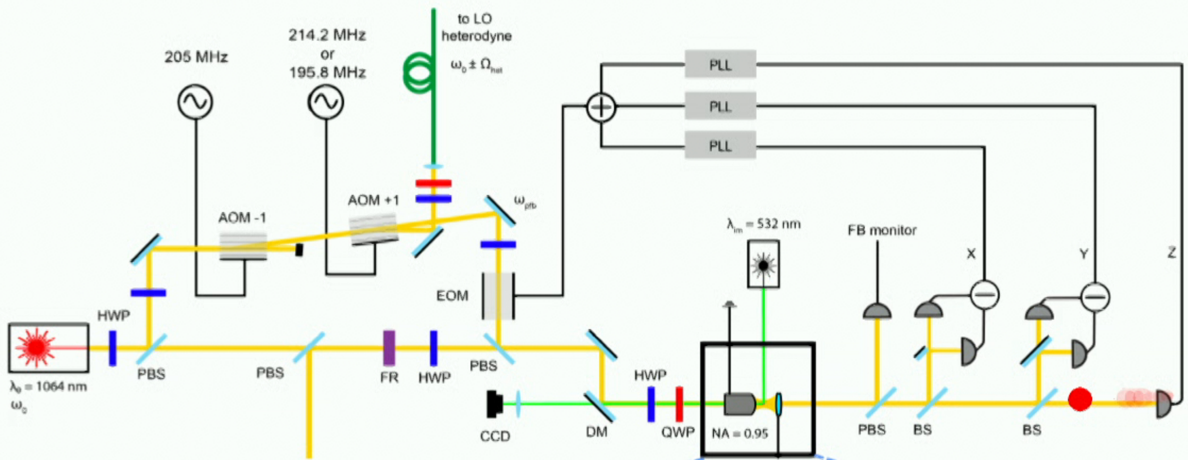
Keeping a particle in high vacuum: feedback control

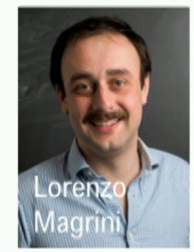
Magrini et al., Nature 595, 373 (2021)

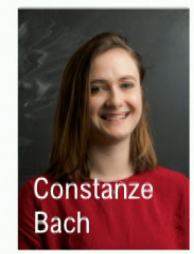
see also

F. Tebbenjohanns et al., PRL 124, 013603 (2020)

F. Tebbenjohanns et al., Nature 595, 378 (2021)

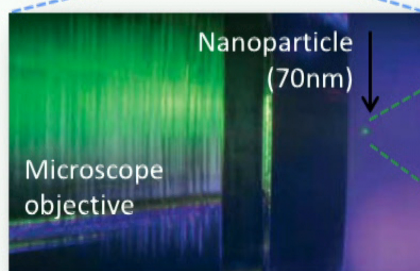


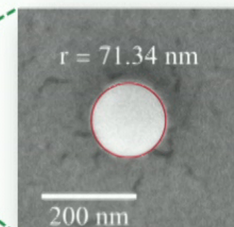




3d parametric feedback stabilizes the particle @ 9e-9 mbar

see also Gieseler et al., Phys. Rev. Lett. 109, 103603 (2012)

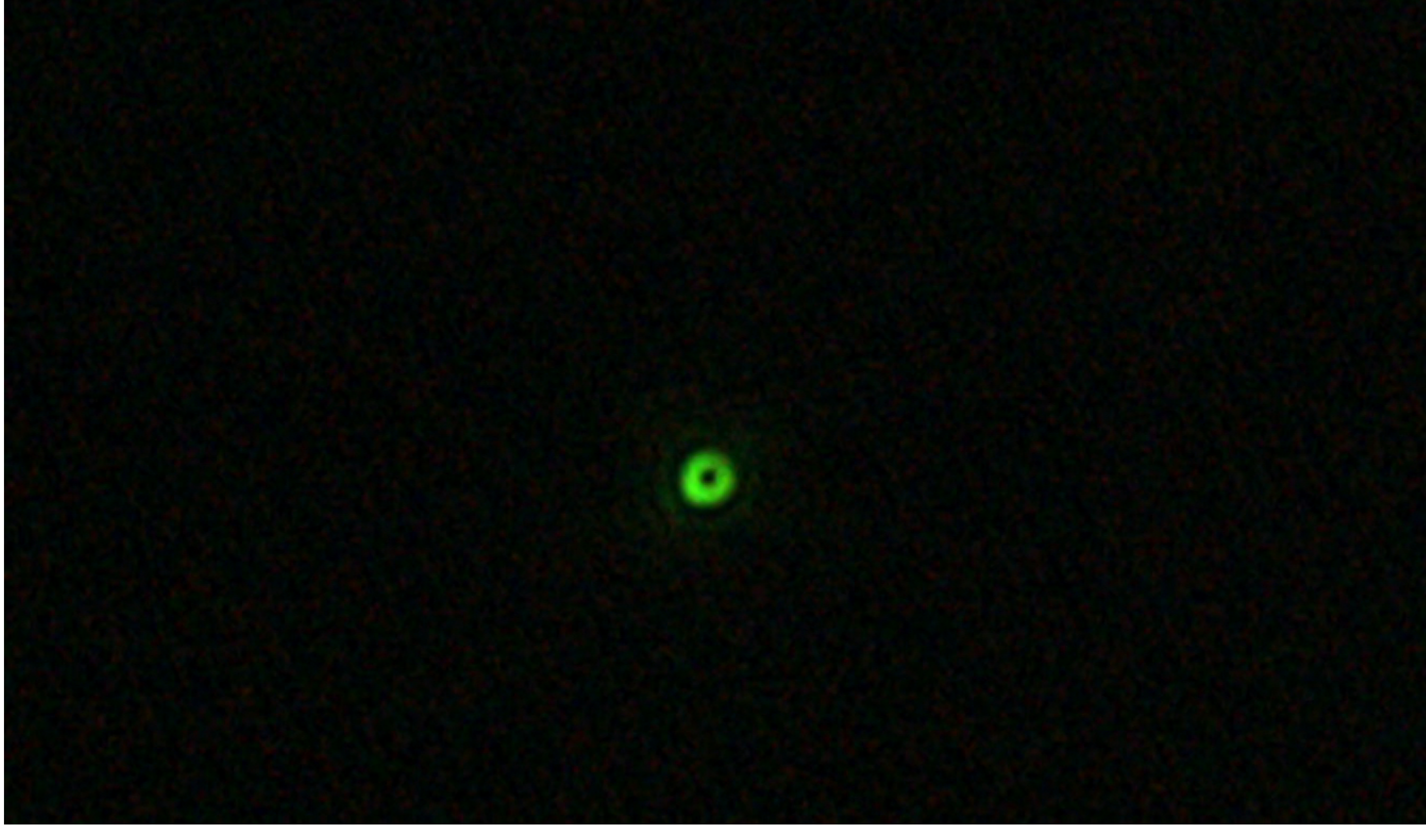


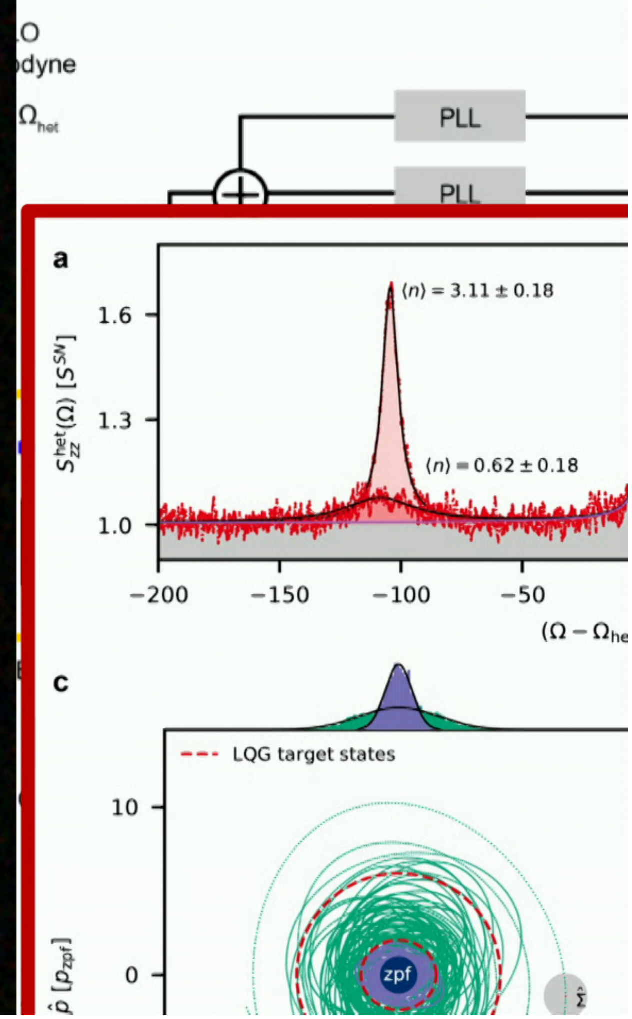


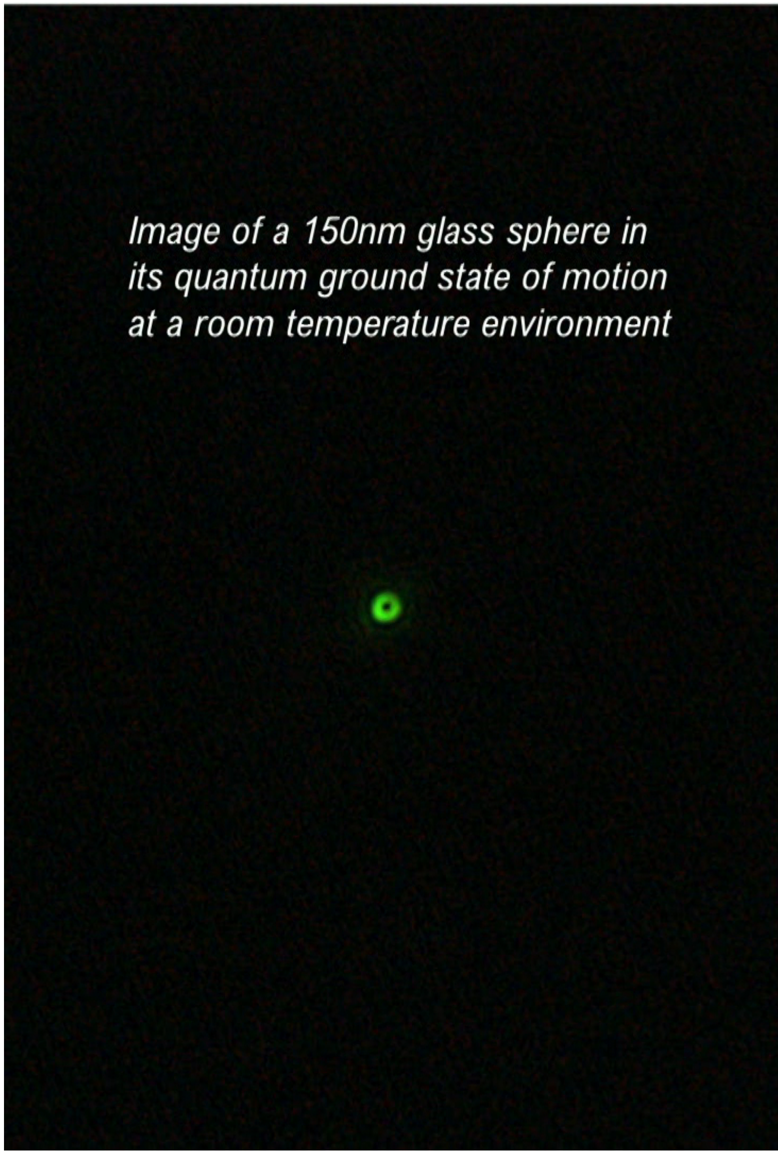
Lorenzo Magrini, Constanze Bach

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

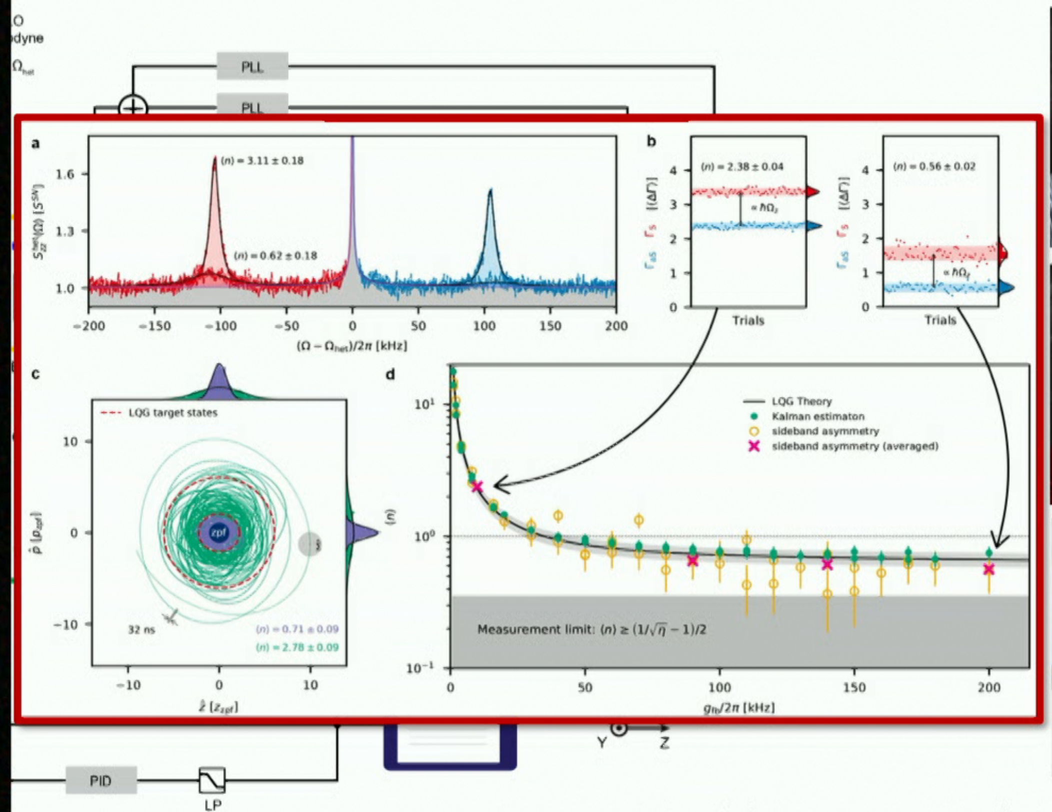






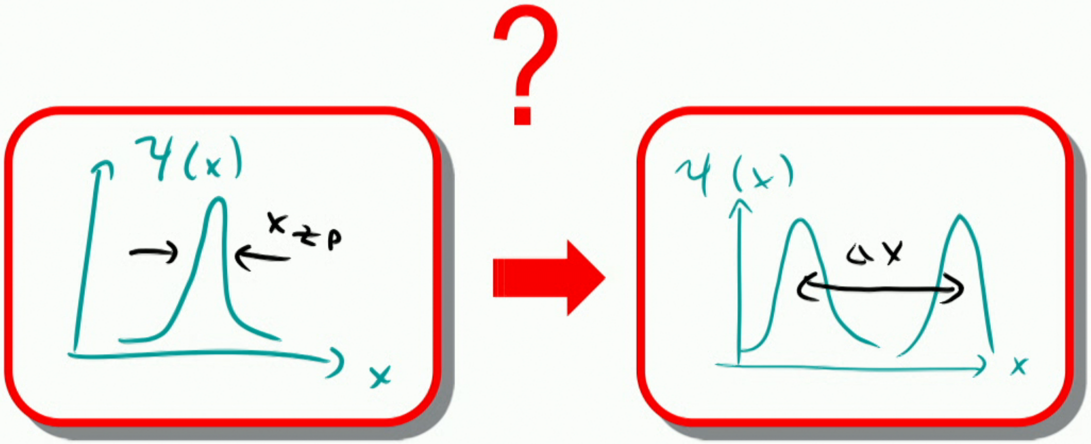
ground-state cooling

Magrini et al., Nature 595, 373 (2021)
see also
F. Tebbenjohanns et al., PRL 124, 013603 (2020)
F. Tebbenjohanns et al., Nature 595, 378 (2021)



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

Towards „large“ quantum superposition states?



How to prepare “macroscopic superpositions”?

Find at least 2 possible ways of realizing them.

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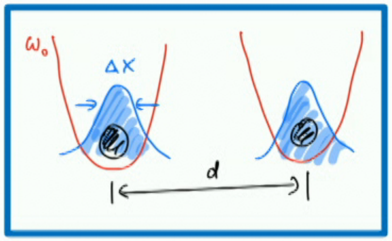
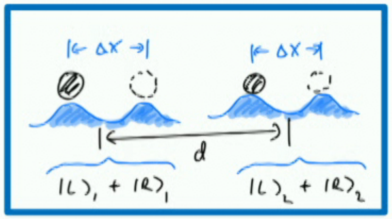
The decoherence challenge...





What are the main sources of decoherence?

How to estimate them?

How to avoid them?

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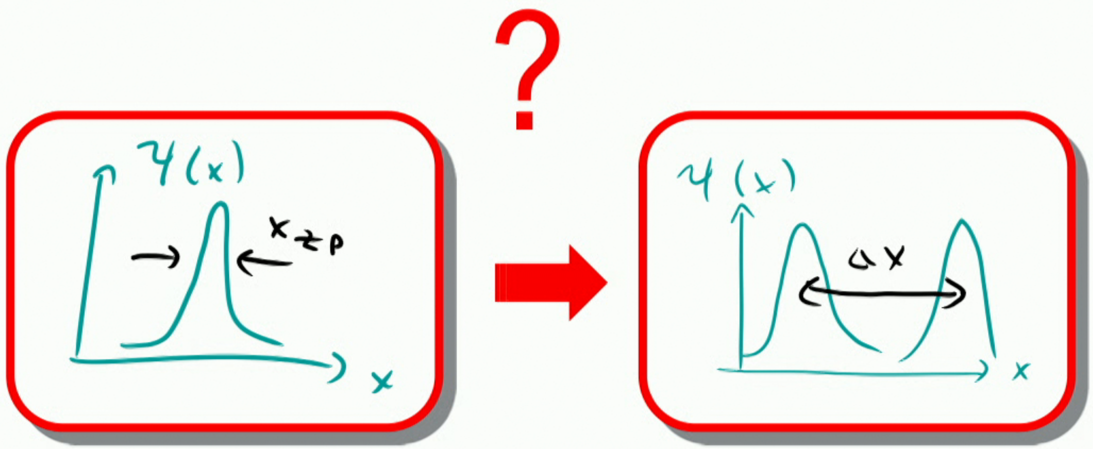
Towards „large“ quantum superposition states?



How to prepare “macroscopic superpositions”?

Find at least 2 possible ways of realizing them.

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