Testing the Quantum Coherent Behaviour of Gravity

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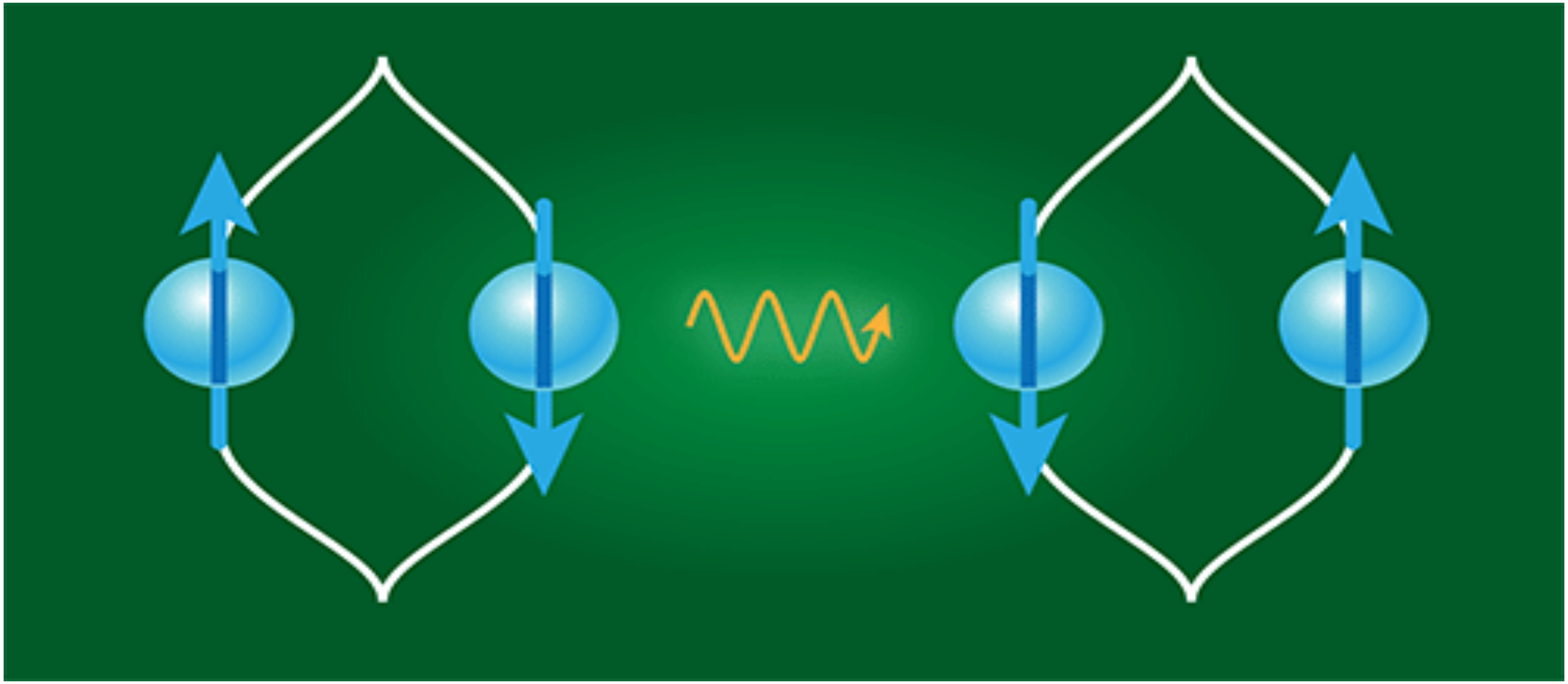
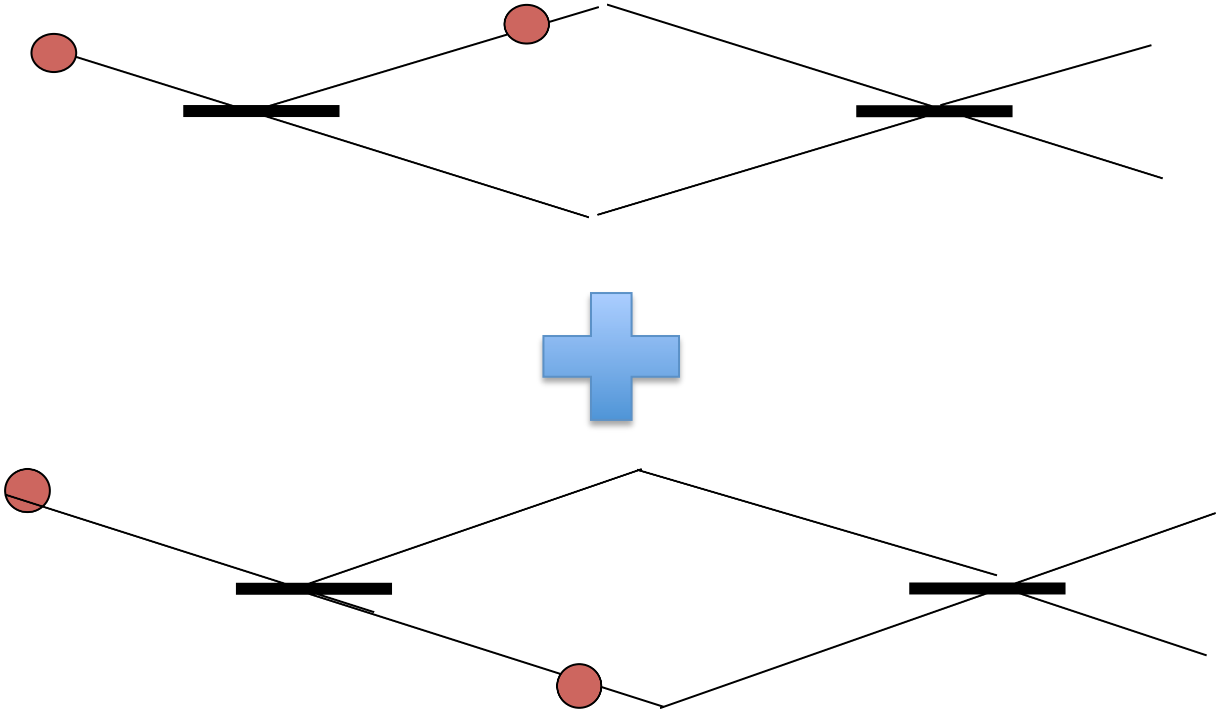
University College London

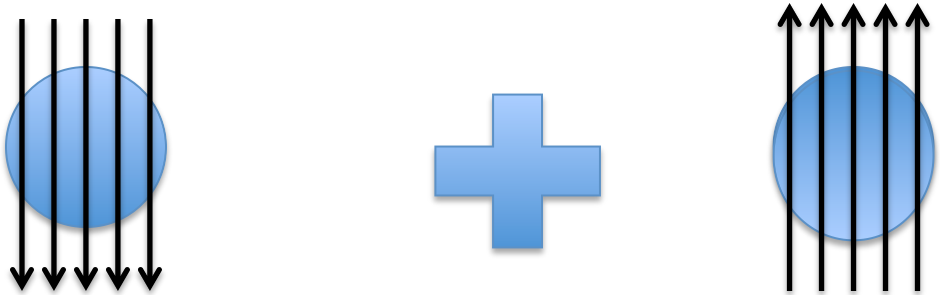


The Superposition Principle **Underpins** Quantum Mechanics

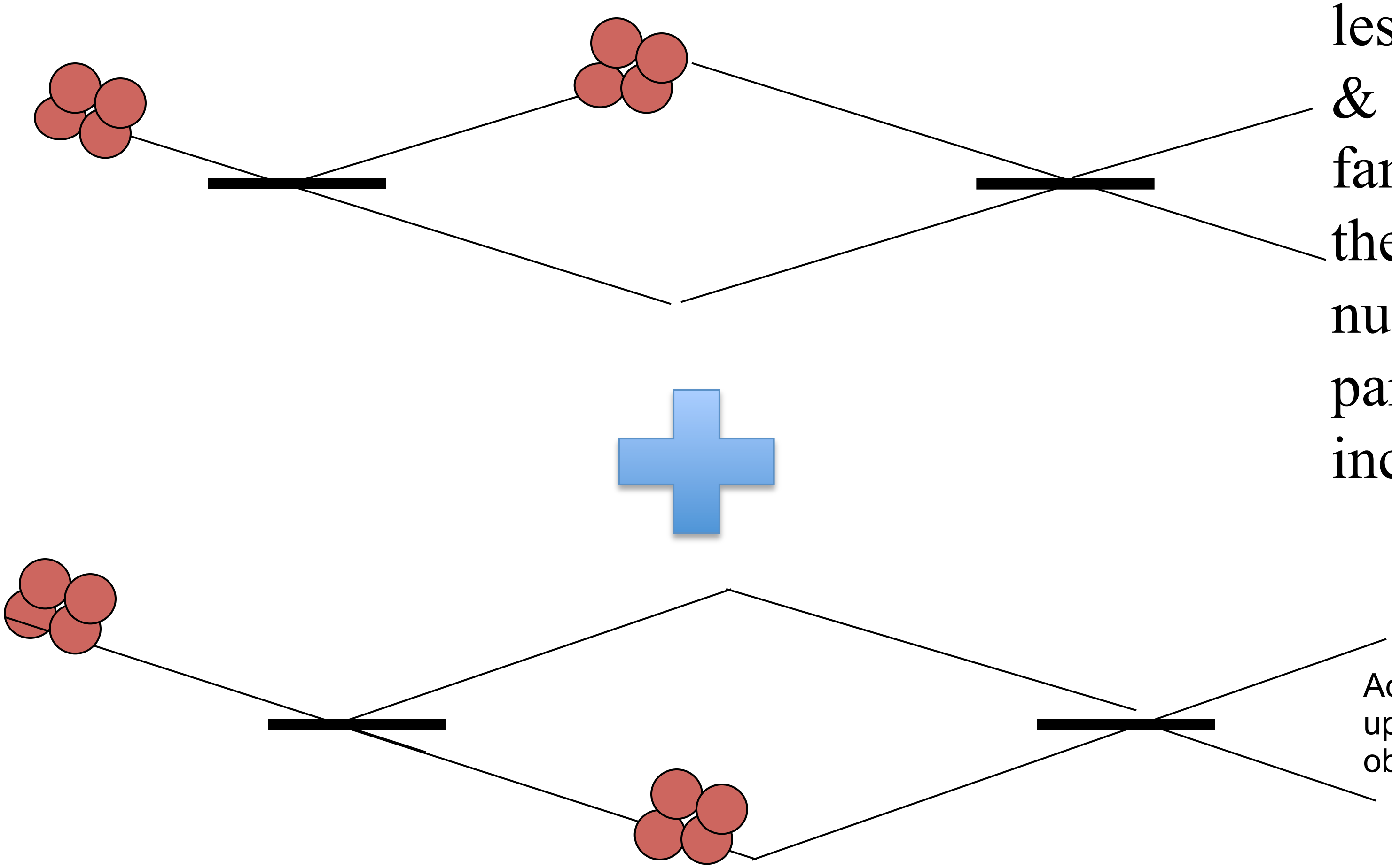
Very familiar
in experiments



Does gravity obey the quantum superposition principle?
To verify superpositions you need an interference experiment (to check for quantum coherence) — not clear in this case what to do.



Less familiar in experiments (becomes less & less familiar as the number of particles increase)

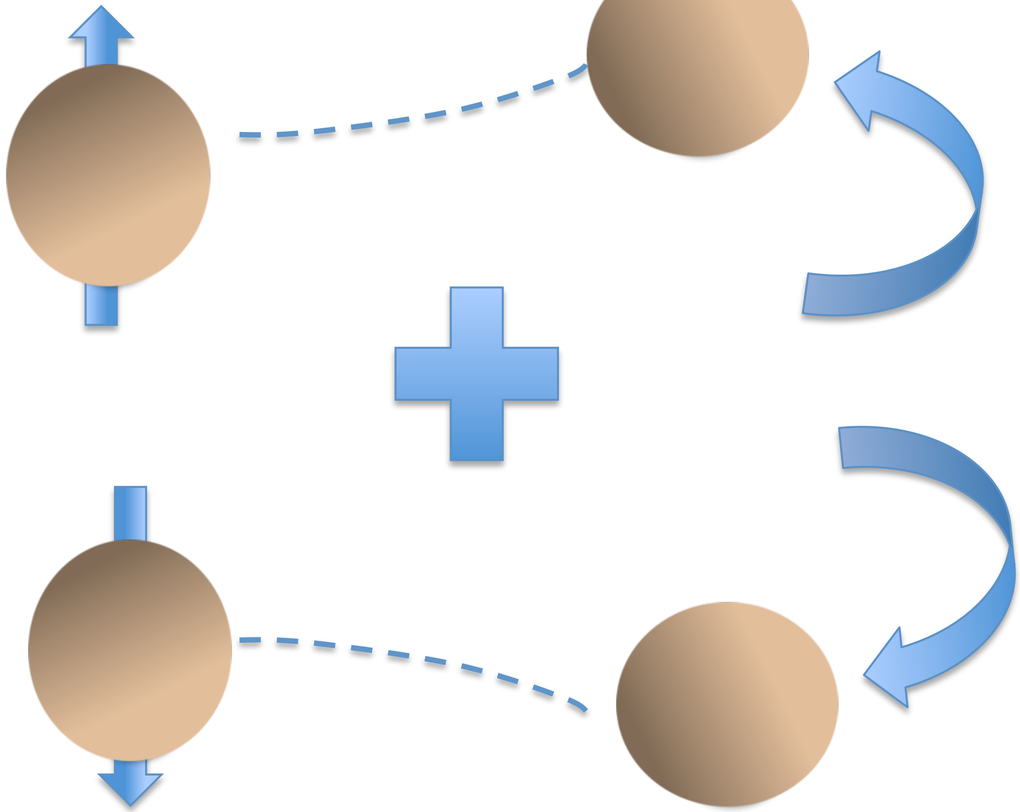


Accomplished up to 10^4 amu objects (Arndt et. al.)

Such superpositions are also called **GHZ** states or NOON states or **Schroedinger** Cat States

Feynman, 1954: Motivation – to argue about the necessity to quantize gravity: *" if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."*

Which aspect of the experiment not clarified

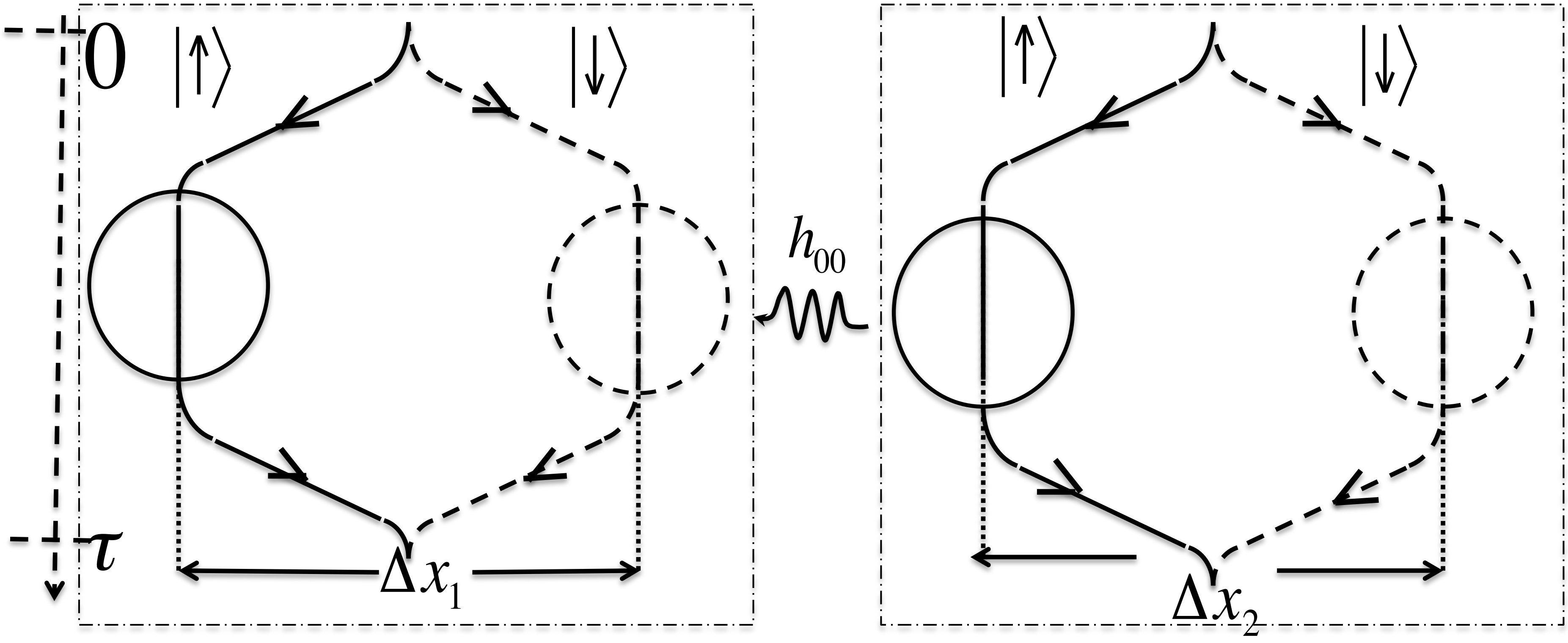


"The only way to avoid quantization of gravity can in principle no longer play a role beyond a certain point in the chain, and you are not allowed to use quantum mechanics on such a large scale. But I would say that this is the only 'out' if you don't want to quantize gravity."

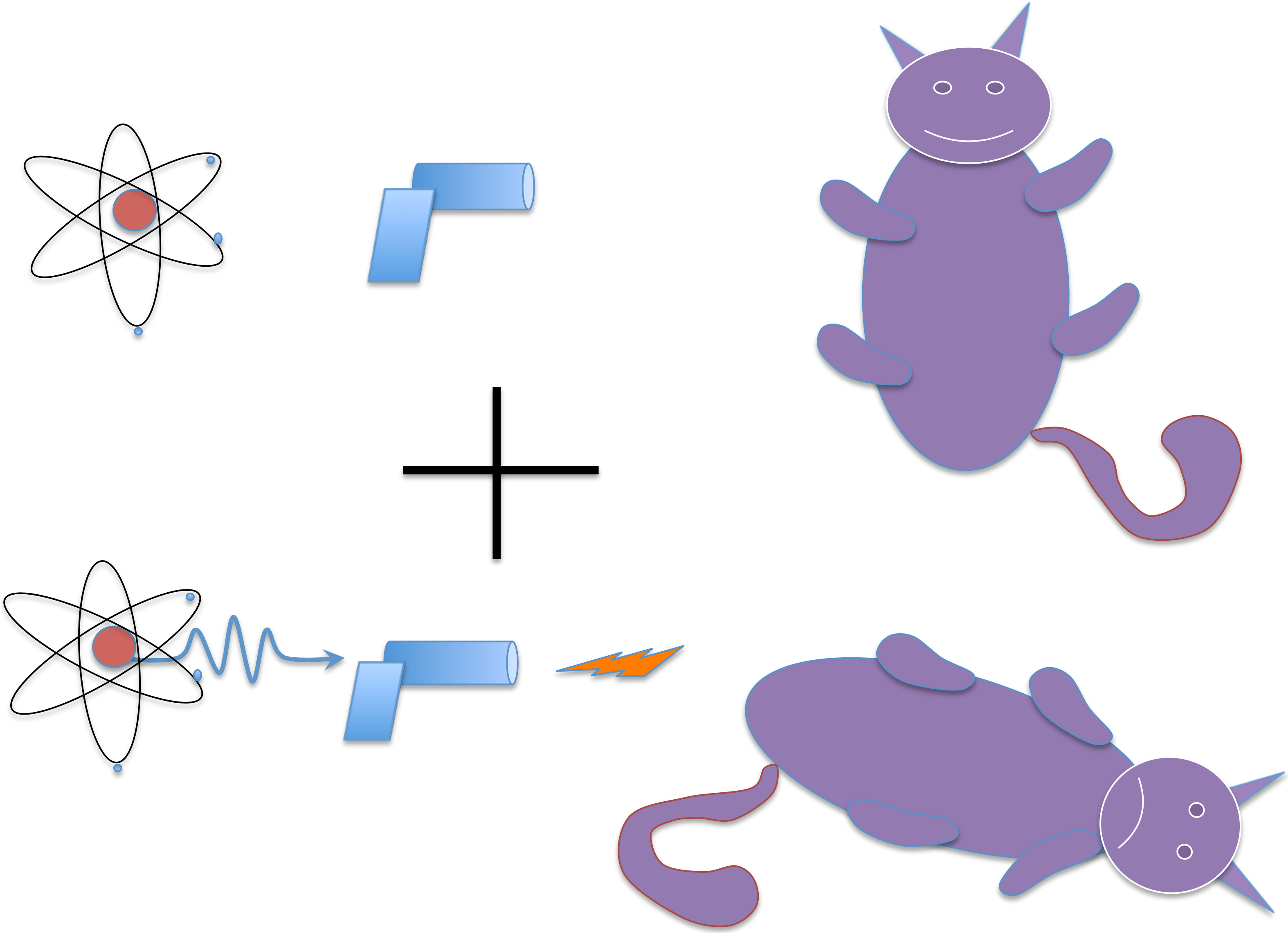
- Is Gravity a Quantum Entity?

- If Gravity Mediates Entanglement

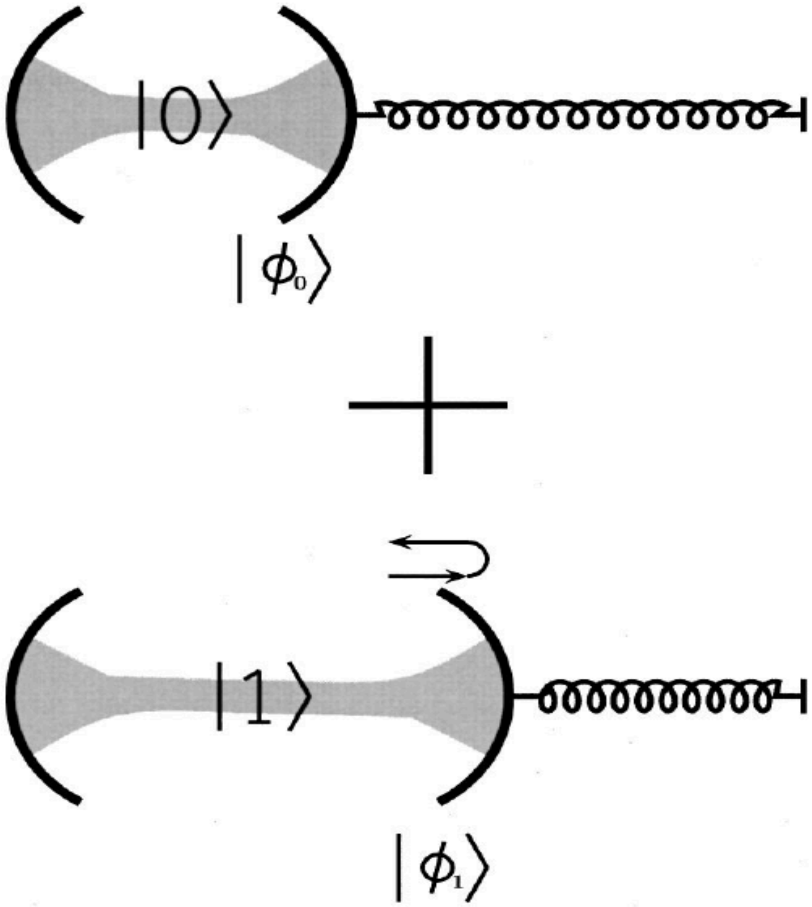
  → It must be quantum entity



How to create the macroscopic superpositions (earliest idea is Schroedinger’s Nucleo-Biological mechanism). **Coherent ancilla induced.**



Superpositions of States of a Macroscopic Object using an Ancillary Quantum System:



S. Bose, K. Jacobs, P. L. Knight,
Phys. Rev. A 59 (5), 3204 (1999). [arXiv: 1997].
Decoherence/partial coherence is used to certify superposition.

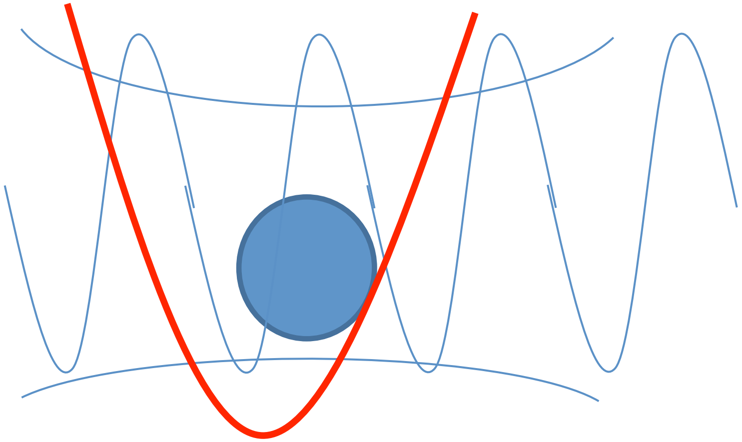
Armour, Blencowe, Schwab, PRL 2002.
Marshall, Simon, Penrose, Bouwmeester, PRL 2003.
Decoherence & Recoherence is used to certify superpositions

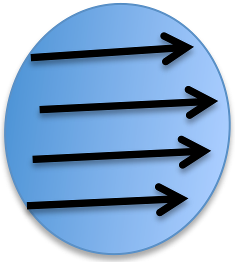
Bose, PRL 2006.

Ramsey Interferometry with a Levitated Thermal Mesoscopic Object

Diamond bead trapped in an optical trap. The bead contains a spin-1 NV center.

No cavity,
no cooling.

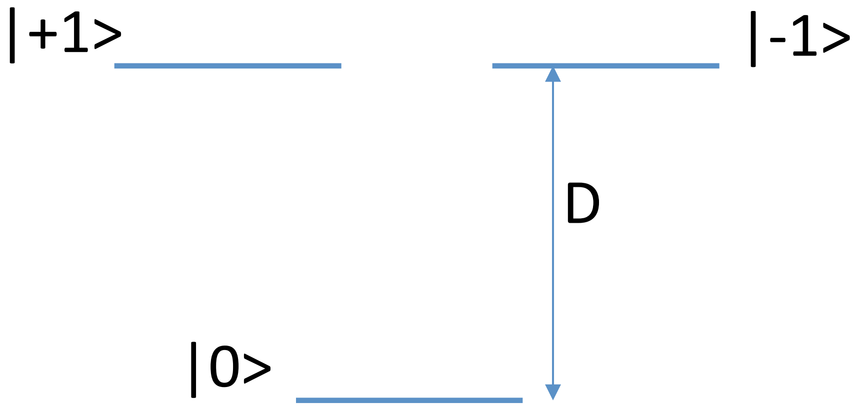




Exploits Spin-Motion coupling mechanism proposed by Rabl et.al. 2009.

Initial State:

$$|\beta\rangle|0\rangle$$



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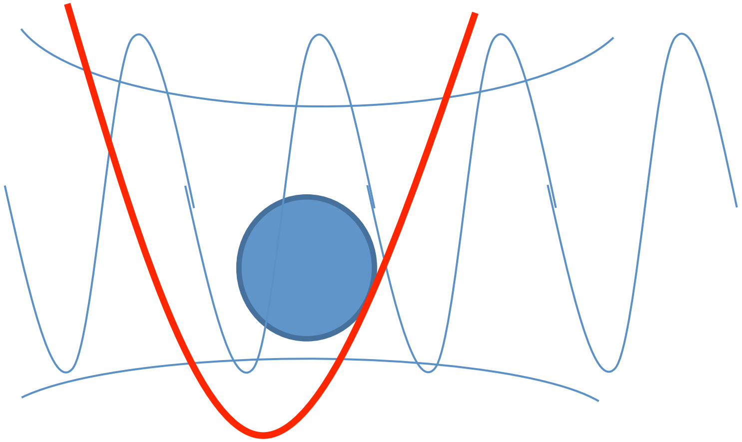
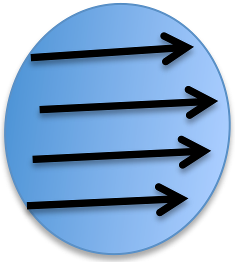
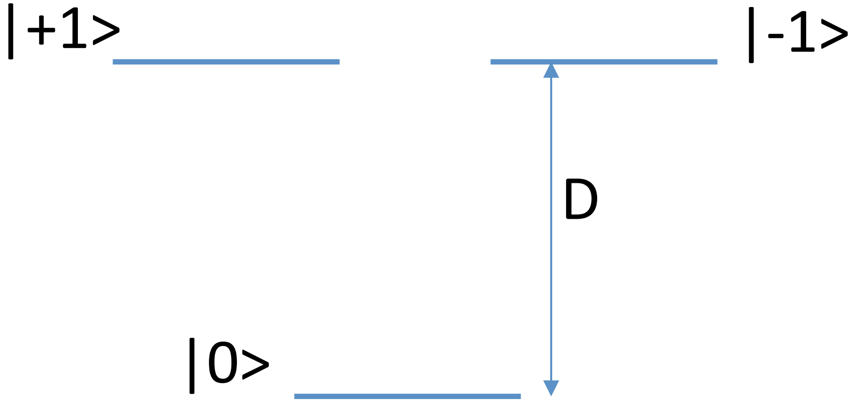




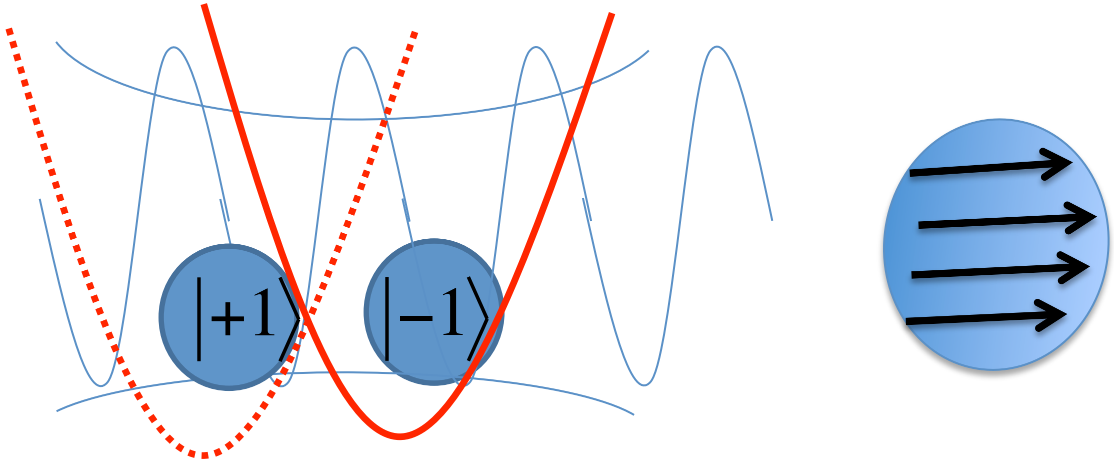
Step 1:

$$|\beta\rangle\left(|+1\rangle+|+1\rangle\right)$$



Ramsey Interferometry with a Levitated Thermal Mesoscopic Object

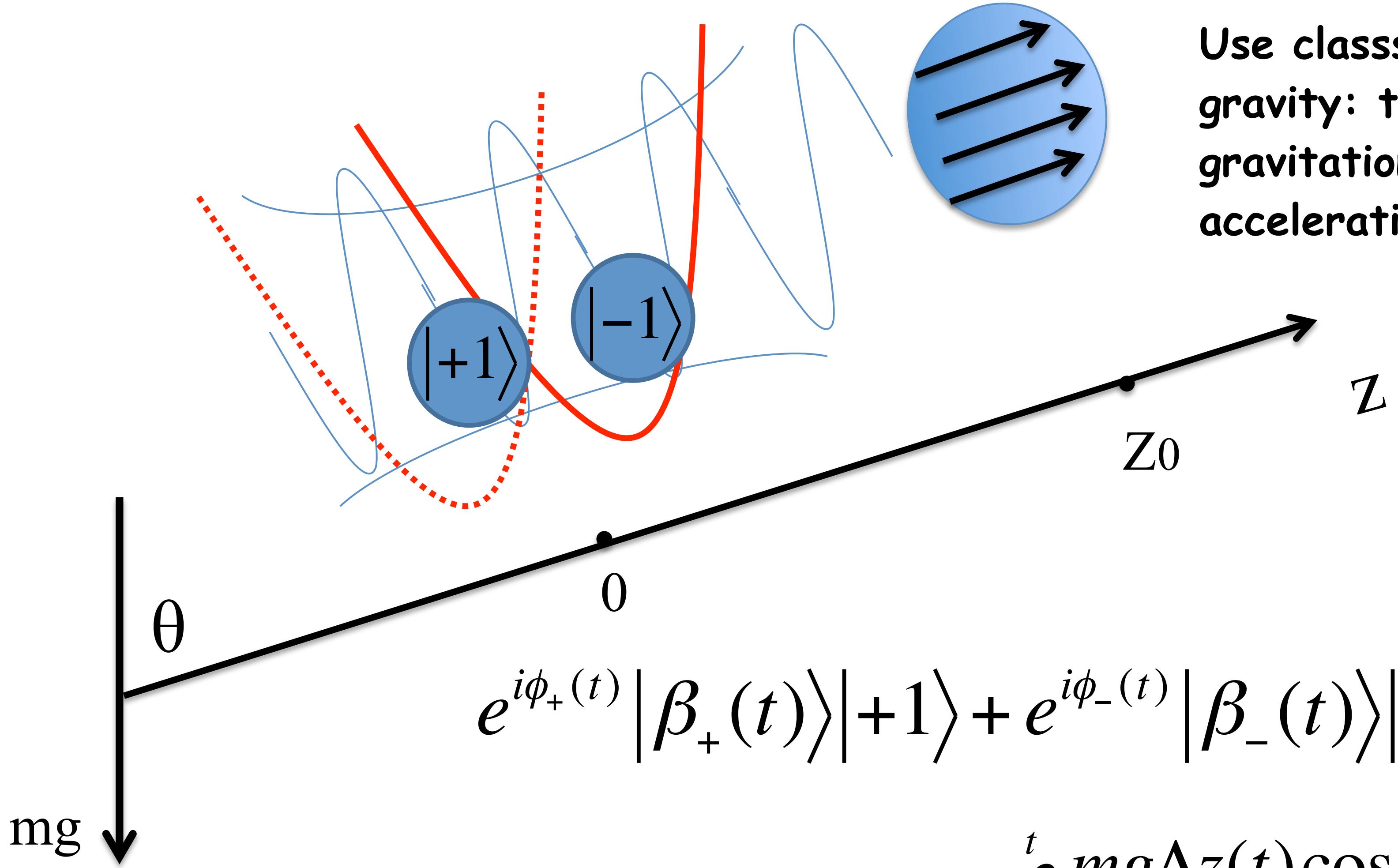
Diamond bead trapped in an optical trap. The bead contains a spin-1 NV center.



Time Evolution:

$$e^{i\phi_+(t)}\left|\beta_+(t)\right\rangle\left|+1\right\rangle + e^{i\phi_-(t)}\left|\beta_-(t)\right\rangle\left|-1\right\rangle$$

Ramsey Interferometry with a Levitated Thermal Mesoscopic Object



Use classsical gravity: the earth's gravitational acceleration as phase

$$e^{i\phi_+(t)}|\beta_+(t)\rangle|+1\rangle + e^{i\phi_-(t)}|\beta_-(t)\rangle|-1\rangle$$

$$\Delta\phi = \phi_+(t) - \phi_-(t) = \int_0^t \frac{mg\Delta z(t)\cos\theta}{\hbar}dt$$

Measuring the relative phase shift between superposed components

Step 3: apply the same very rapid mw pulse as in step 1,

The presence of $\Delta\phi$ gives a modulation of the population of $|S_z=0>$ according to:

$$\left|+1\right\rangle + e^{i\Delta\phi}\left|-1\right\rangle \rightarrow \cos\frac{\Delta\phi}{2}\left|0\right\rangle + \ldots$$

For *m*= 10^10 amu (nano-crystal), superposition over 1 pm,
the phase ~ O(1)

- M. Scala, M. S. Kim, G. W. Morley, P. F. Barker, S. Bose, Phys. Rev. Lett. **111**, 180403 (2013).
- Comment: F. Robicheaux, Phys. Rev. Lett. 118, 108901 (2017).
- Response: S. Bose et al, Phys. Rev. Lett. 118, 108902 (2017).

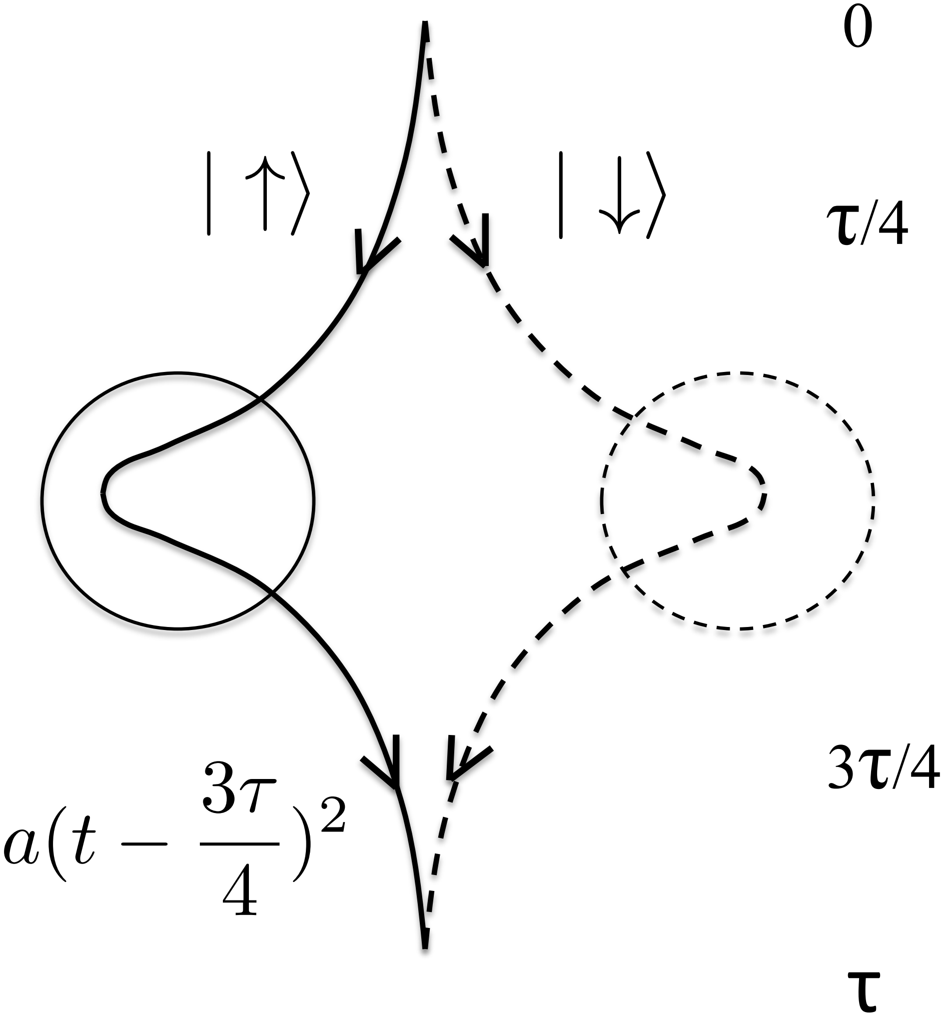
How can we increase the scale of the superposition?

Free particle in an inhomogeneous magnetic field (acceleration +*a* or –*a*)

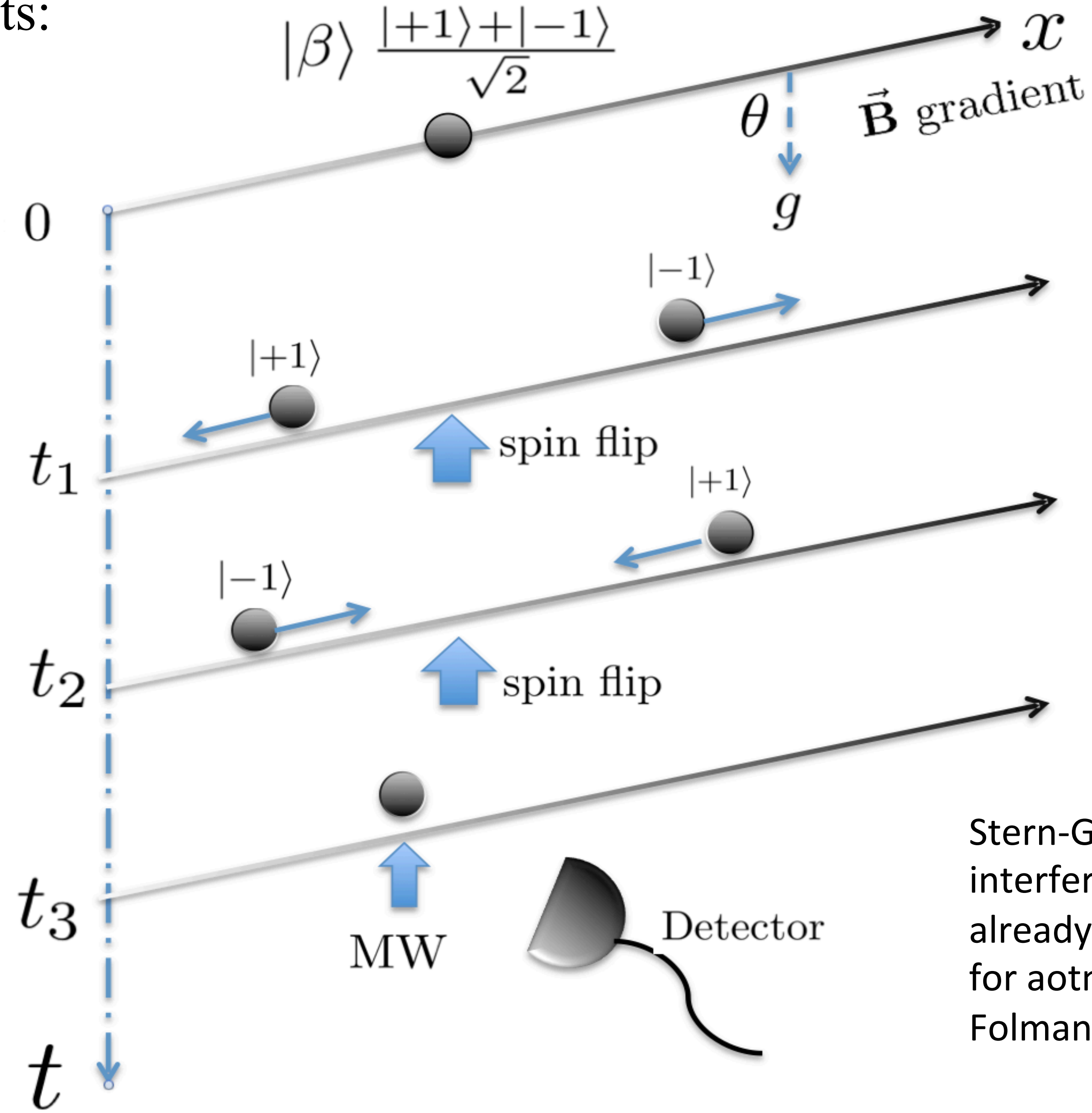
$$x_\sigma(t, j) = x_j(0) \pm \frac{1}{2}at^2$$

$$= \frac{a\tau}{4}(t - \frac{\tau}{4}) \mp \frac{1}{2}a(t - \frac{\tau}{4})^2$$

$$= \frac{1}{2}a(\frac{\tau}{4})^2 \mp \frac{a\tau}{4}(t - \frac{3\tau}{4}) \pm \frac{1}{2}a(t - \frac{3\tau}{4})^2$$



Free flight scheme able to achieve 100 nm separation among superposed components:



Stern-Gerlach interferometry already demonstrated for aotms by Folman et. al.

$$|\Psi(t_3)\rangle = \frac{1}{\sqrt{2}}|\psi(t_3)\rangle(|+1\rangle + e^{-i\phi_g}|-1\rangle)$$

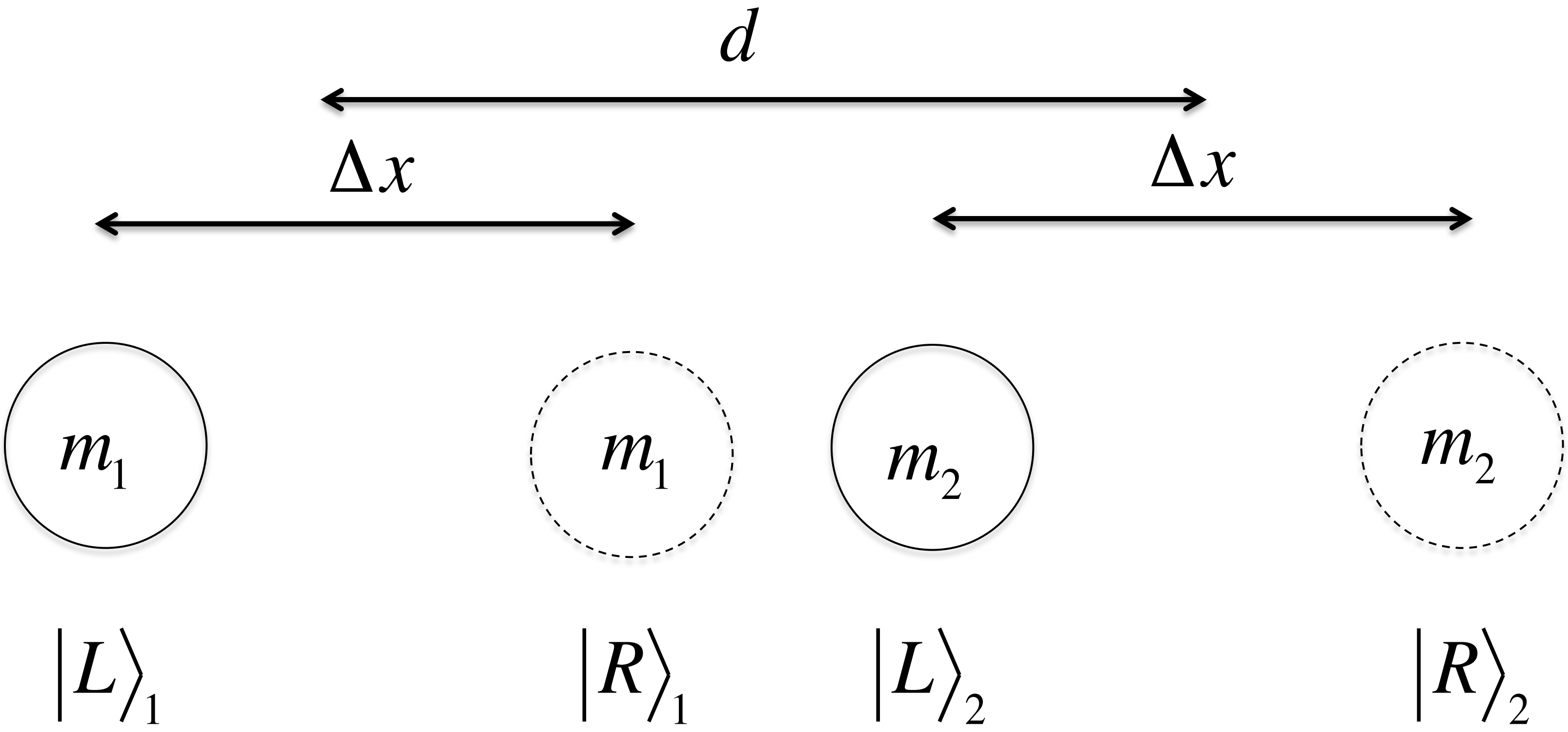
$$\langle x|\psi(t_3)\rangle = e^{-ip_0x}e^{-[(x-x_0-p_0t_3/m-g\cos\theta t_3^2/2)^2/2(\sigma')^2]}$$

$$\phi_g = (1/16\hbar)gt_3^3 g_{\mathrm{NV}}\mu_B(\partial B/\partial x)\cos\theta$$

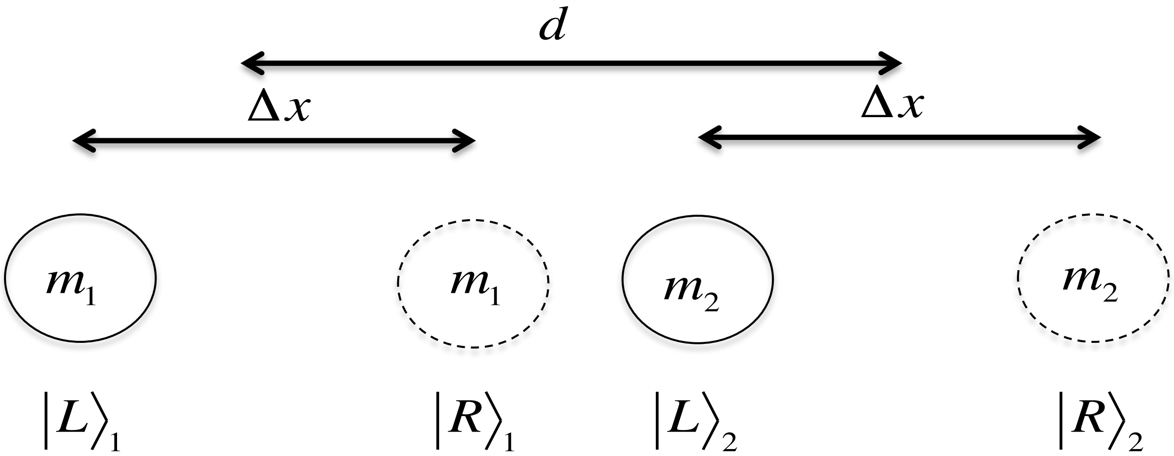
$$\Delta x_M = 2\times\frac{1}{2m}g_{\mathrm{NV}}\mu_B\frac{\partial B}{\partial x}(t_3/4)^2$$

10^10 amu mass can be placed in a superposition of states separated by 100 nm.

A Schematic of two matter-wave interferometers near each other



Consider two neutral test masses *held* in a superposition, each exactly as a path encoded qubit (states |L> and |R>), near each other.



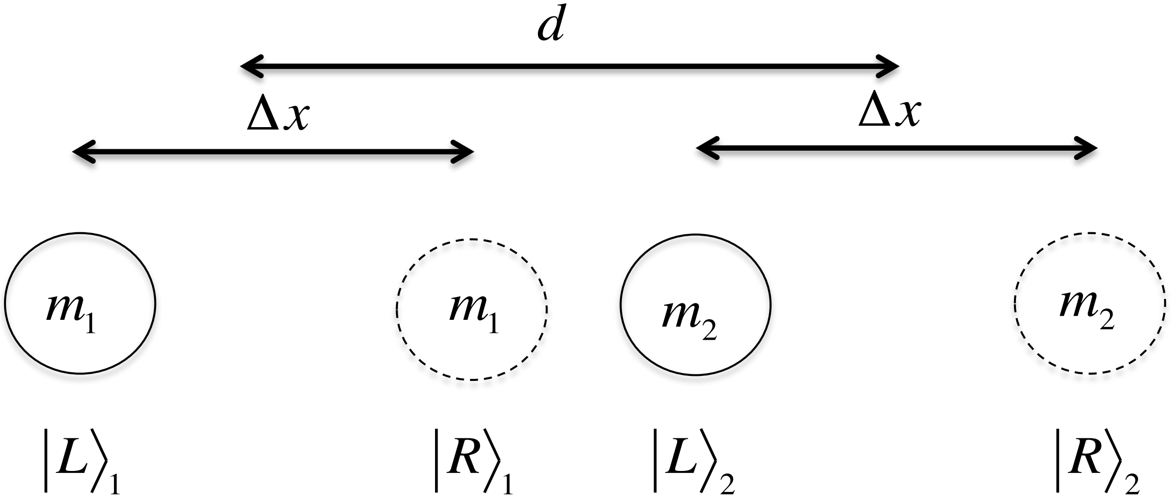
If they interact *only* through the gravitational force

$$
\begin{aligned}
|\Psi(t=0)\rangle_{12} &= \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2) \\
&= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2) \\
\rightarrow |\Psi(t=\tau)\rangle_{12} &= \frac{1}{2}(e^{i\phi_{LL}}|L\rangle_1|L\rangle_2 + e^{i\phi_{LR}}|L\rangle_1|R\rangle_2 \\
&\quad + e^{i\phi_{RL}}|R\rangle_1|L\rangle_2 + e^{i\phi_{RR}}|R\rangle_1|R\rangle_2),
\end{aligned}
$$

where

$$
\phi_{RL} \sim \frac{Gm_1m_2\tau}{\hbar(d-\Delta x)}, \phi_{LR} \sim \frac{Gm_1m_2\tau}{\hbar(d+\Delta x)},
$$

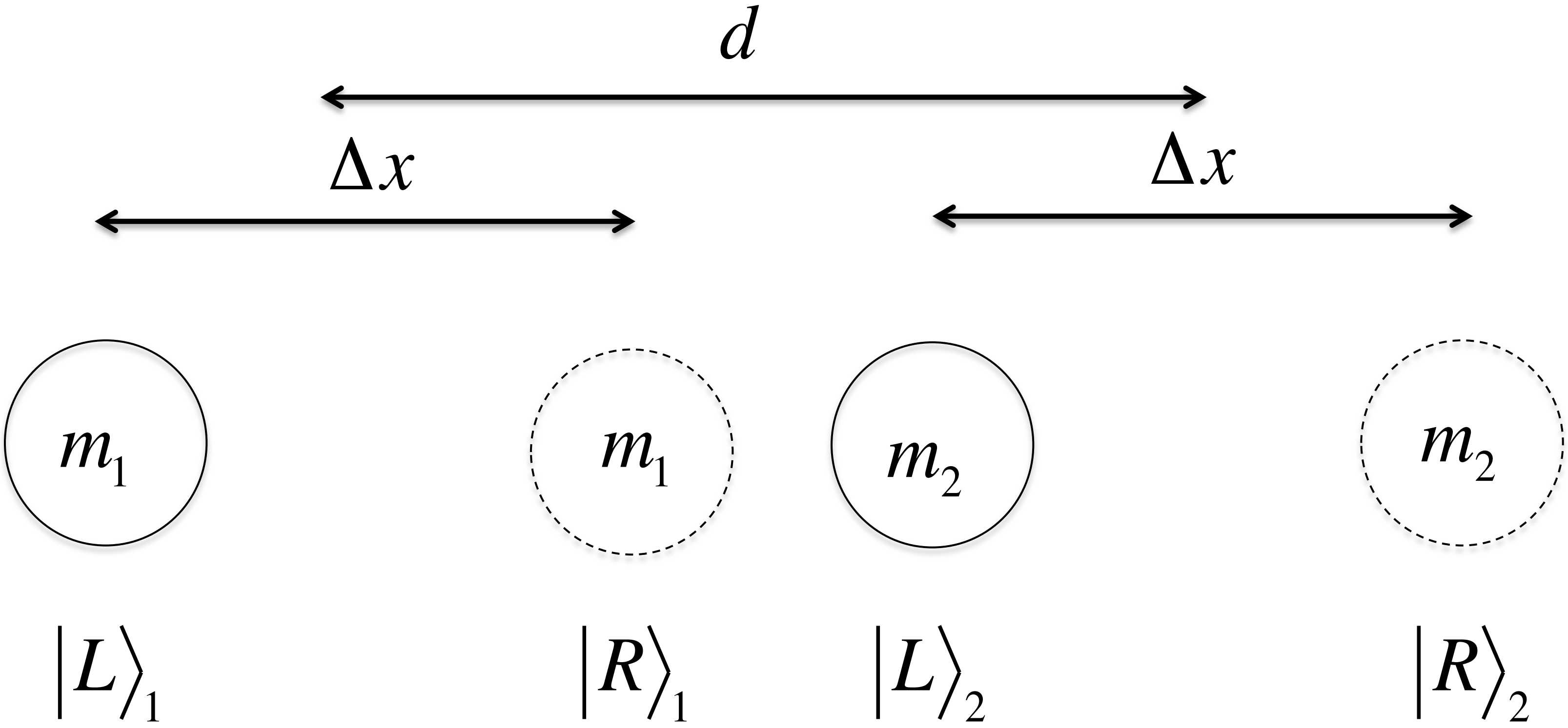
$$
\phi_{LL} = \phi_{RR} \sim \frac{Gm_1m_2\tau}{\hbar d}
$$



If they interact *only* through the gravitational force

$$
\begin{aligned}
|\Psi(t=\tau)\rangle_{12} &= \frac{1}{2}(e^{i\phi_{LL}}|L\rangle_1|L\rangle_2 + e^{i\phi_{LR}}|L\rangle_1|R\rangle_2 \\
&+ e^{i\phi_{RL}}|R\rangle_1|L\rangle_2 + e^{i\phi_{RR}}|R\rangle_1|R\rangle_2) \\
&= \frac{e^{i\phi_{RR}}}{\sqrt{2}}\{|L\rangle_1\frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2) \\
&+ |R\rangle_1\frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)\}
\end{aligned}
$$

The above state is maximally entangled when $\Delta\phi_{LR} + \Delta\phi_{RL} \sim \pi$.



For

$$d - \Delta x << d, \Delta x,$$

we have

$$\Delta\phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar(d - \Delta x)} >> \Delta\phi_{LR}, \Delta\phi_{LL}, \Delta\phi_{RR}$$

For

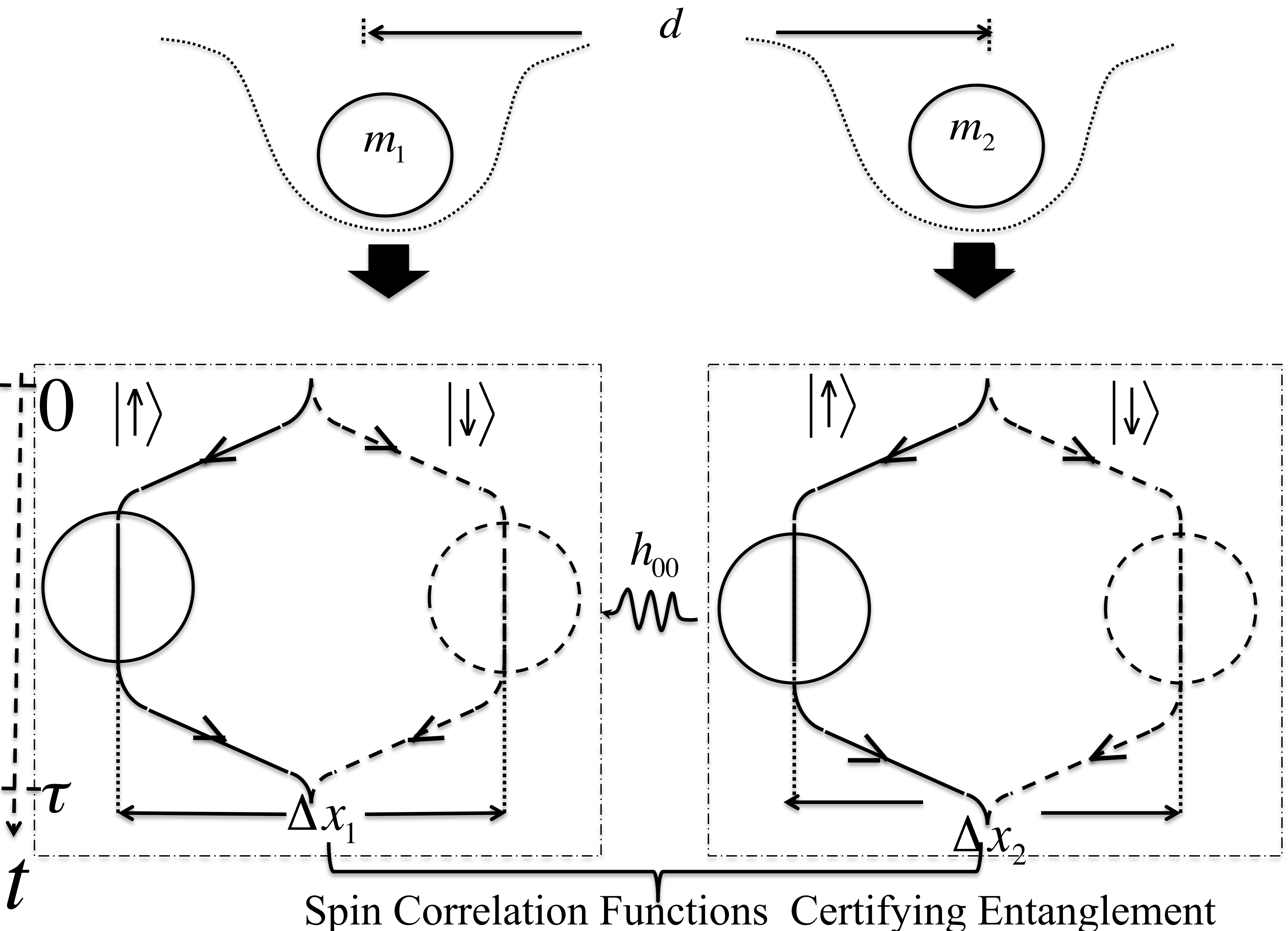
$$d - \Delta x << d, \Delta x,$$

we have

$$\Delta\phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar(d - \Delta x)} >> \Delta\phi_{LR}, \Delta\phi_{LL}, \Delta\phi_{RR}$$

For mass ~ 10^(-14) kg (microspheres), separation at closest approach of the masses ~ 200 microns (to prevent Casimir interaction), **time ~ 1 seconds**, gives:
Scale of superposition ~ 100 microns, **Delta phi_{RL} ~ 1**

Planck's Constant fights Newton's Constant!


d
m_1
m_2
0
$|\uparrow\rangle$
$|\downarrow\rangle$
$|\uparrow\rangle$
$|\downarrow\rangle$
h_{00}
τ
t
Δx_1
Δx_2
Spin Correlation Functions Certifying Entanglement

Spin Entanglement Witness:

Step 1: SG splitting:

$$|C\rangle_j \frac{1}{\sqrt{2}}(|\uparrow\rangle_j + |\downarrow\rangle_j) \rightarrow \frac{1}{\sqrt{2}}(|L,\uparrow\rangle_j + |R,\downarrow\rangle_j)$$

Step 2: Gravitational interaction induced phase accumulation on
the joint states of masses 1 &2 (*mapped to nuclear spins*)

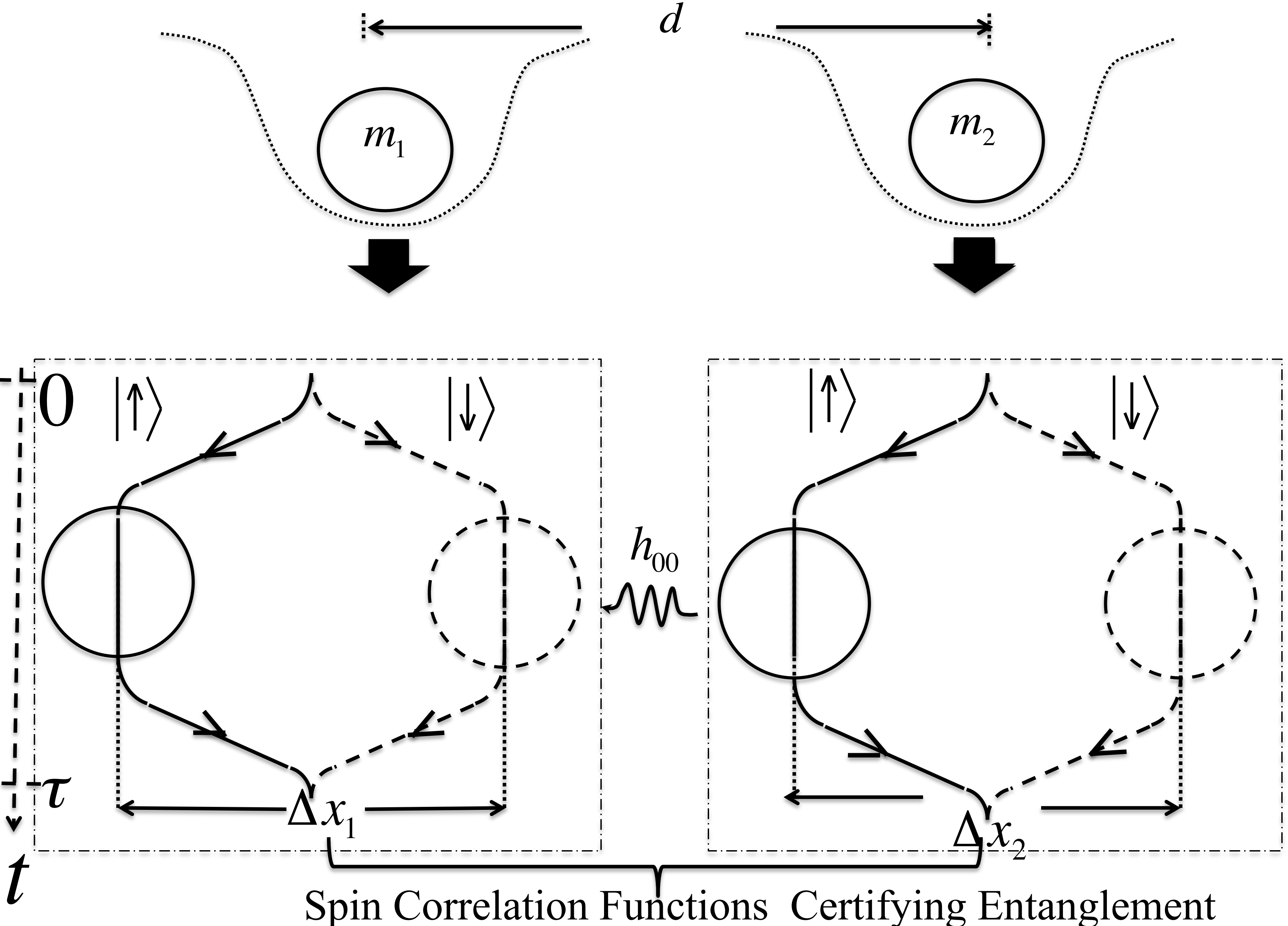
Step 3: SG recombination: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j,\ |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$

Step 4: Witness spin entangled state:

$$|\Psi(t=t_{\mathrm{End}})\rangle_{12} = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1 \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2)$$
$$+ |\downarrow\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2)\}|C\rangle_1|C\rangle_2$$

through the correlations:

$$\mathcal{W} = |\langle\sigma_x^{(1)} \otimes \sigma_z^{(2)}\rangle - \langle\sigma_y^{(1)} \otimes \sigma_z^{(2)}\rangle|$$


d
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Spin Correlation Functions Certifying Entanglement

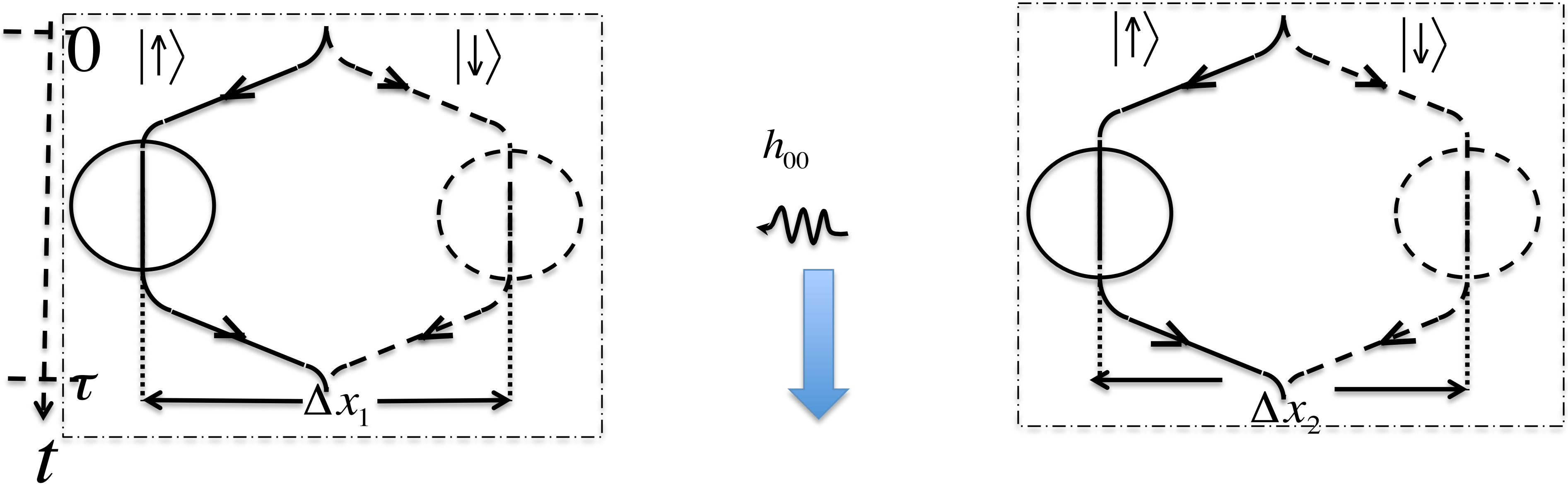
How is this related to Quantum Gravity?

LOCC Maps keep separable states separable (*cannot* create entanglement!)

Local Operations and Classical Communication (LOCC)

1. Unitary evolution
2. Measurement

Classical mediator of information/bits

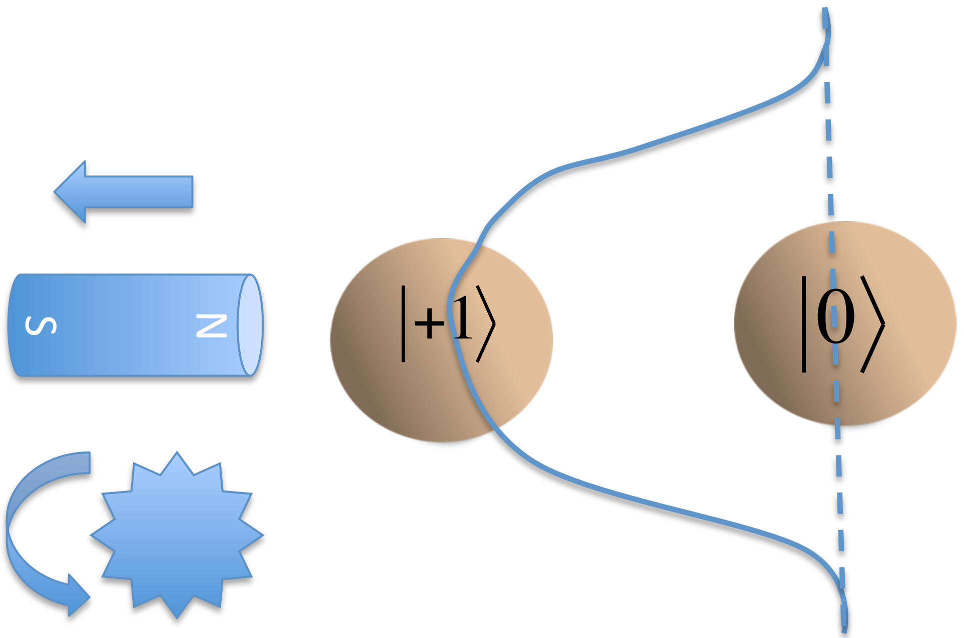


Must be quantum if the spins in the masses get entangled

Challenges (technical):

~ 200 micron superposition:

Literally pull one of the spin components?



Gavin Morley's idea

Other demands:

1. **Spin the masses to average charge multipoles.**
2. **Internal cooling to 77 K, External pressure 10^(-15) Pascal, 0.15 K temperature**

What does it imply in the context of **low energy effective field theory**?

$$\mathcal{H} = \sum_{j,\xi} m_j c^2 a^\dagger_{j,\xi} a_{j,\xi} + \sum_{\mathbf{k}} \hbar\omega_k b^\dagger_{\mathbf{k}} b_{\mathbf{k}}$$

$$- \hbar \sum_{j,\mathbf{k},\xi} g_{j,\mathbf{k}} a^\dagger_{j,\xi} a_{j,\xi} (b_{\mathbf{k}} e^{i\mathbf{k}.\mathbf{r}_{j,\xi}} + b^\dagger_{\mathbf{k}} e^{-i\mathbf{k}.\mathbf{r}_{j,\xi}})$$

Superposition

Coherent States of the gravitational field

$$|\Psi(t)\rangle_{\mathrm{mat+grav}} = \frac{1}{2} \sum_{\xi,\xi' \in \{L,R\}} a^\dagger_{1,\xi} a^\dagger_{2,\xi'} |0\rangle$$

$$\otimes \prod_{\mathbf{k}} e^{i\frac{(g_{1,\mathbf{k}} e^{i\mathbf{k}.\mathbf{r}_{1,\xi}} + g_{2,\mathbf{k}} e^{i\mathbf{k}.\mathbf{r}_{2,\xi'}})^2}{\omega_k} t} |\alpha_{\mathbf{k},\xi,\xi'}\rangle_{\mathbf{k}},$$

$$g_{j,\mathbf{k}} = m_j c^2 \sqrt{\frac{2\pi G}{\hbar c^3 k V}} \qquad \frac{g_{1,\mathbf{k}} g_{2,\mathbf{k}}}{\omega_k} \propto \frac{1}{k^2}$$

Superpositions of *distinct (?)* coherent states of the gravitational field

Summary

- Large mass, small scale of superpositions:

Stern-Gerlach based Ramsey interferometry in a trap:

M. Scala, M. S. Kim, G. W. Morley, P. F. Barker, S. Bose, Phys. Rev. Lett. 111, 180403 (2013). [related work by Tongcang Li et. al.]

- Large mass, large scale superpositions:

Free flight Stern-Grlach based Ramsey interferometry:

C. Wan, M. Scala, G. W. Morley, ATM. A. Rahman, H. Ulbricht, J. Bateman, P. F. Baker, S. Bose, M. S. Kim, Phys. Rev. Lett. 117, 143003 (2016).

- ***Spin Entanglement Witness for Quantum Gravity***:

S. Bose, A. Mazumdar, G. W.Morley, H. Ulbricht, M. Toros, M. Paternostro, P. F. Barker, A. Geraci, M. S. Kim, G. J. Milburn, Phys. Rev. Lett. 119, 240401 (2017). *Related work:* C. Marletto and V. Vedral