From Macroscopic Superpositions to Quantum Gravity

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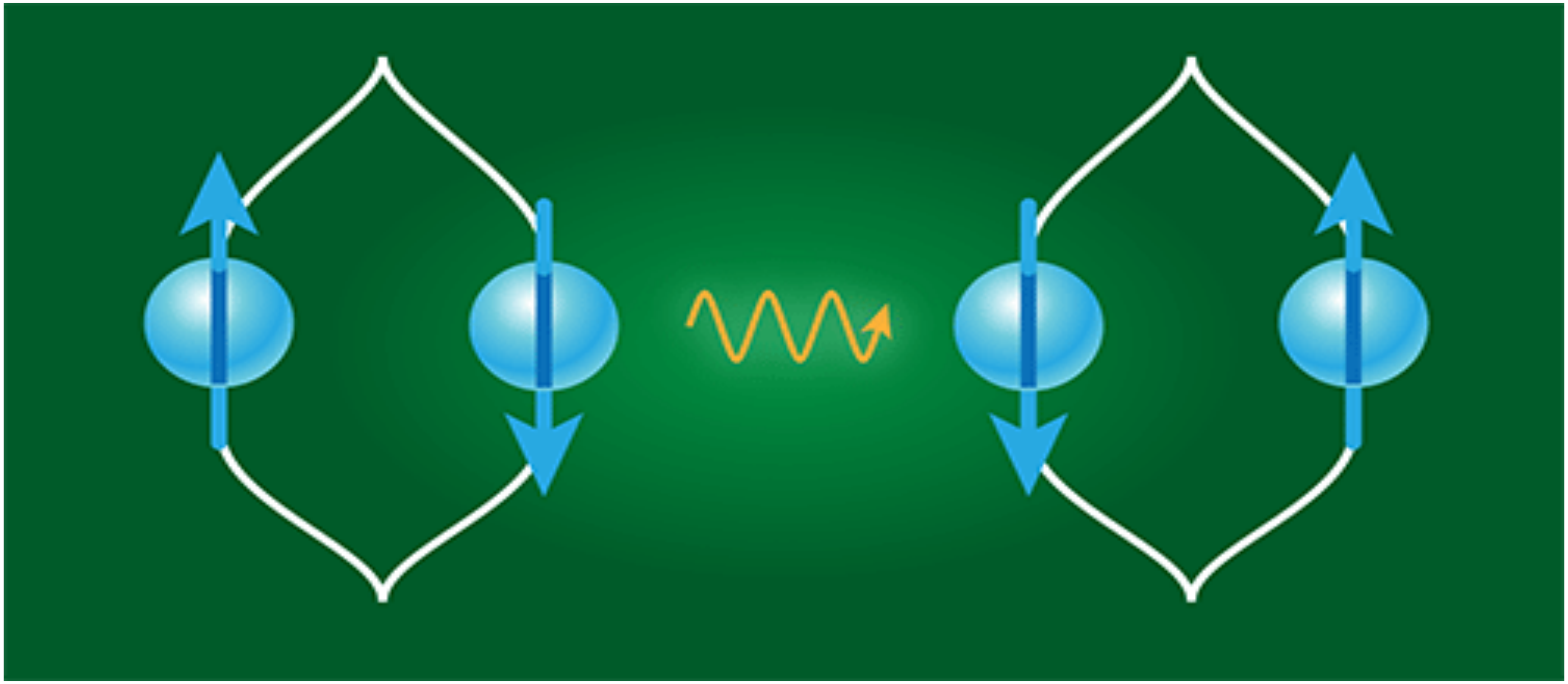
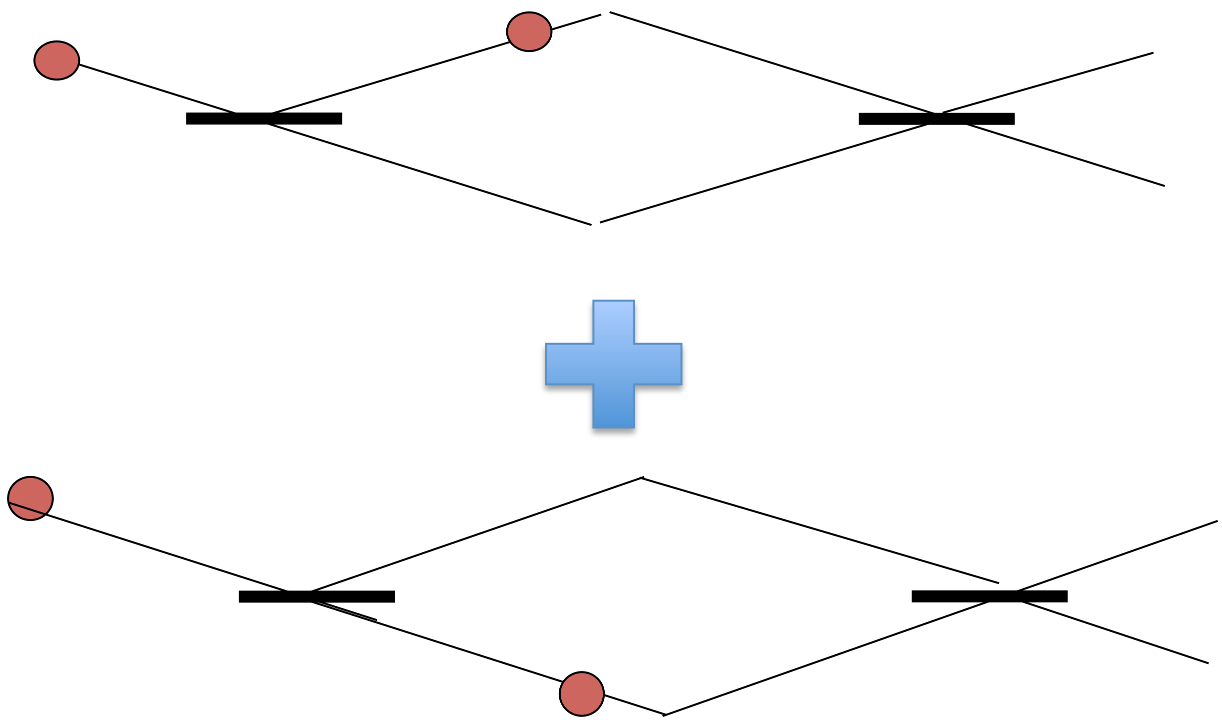
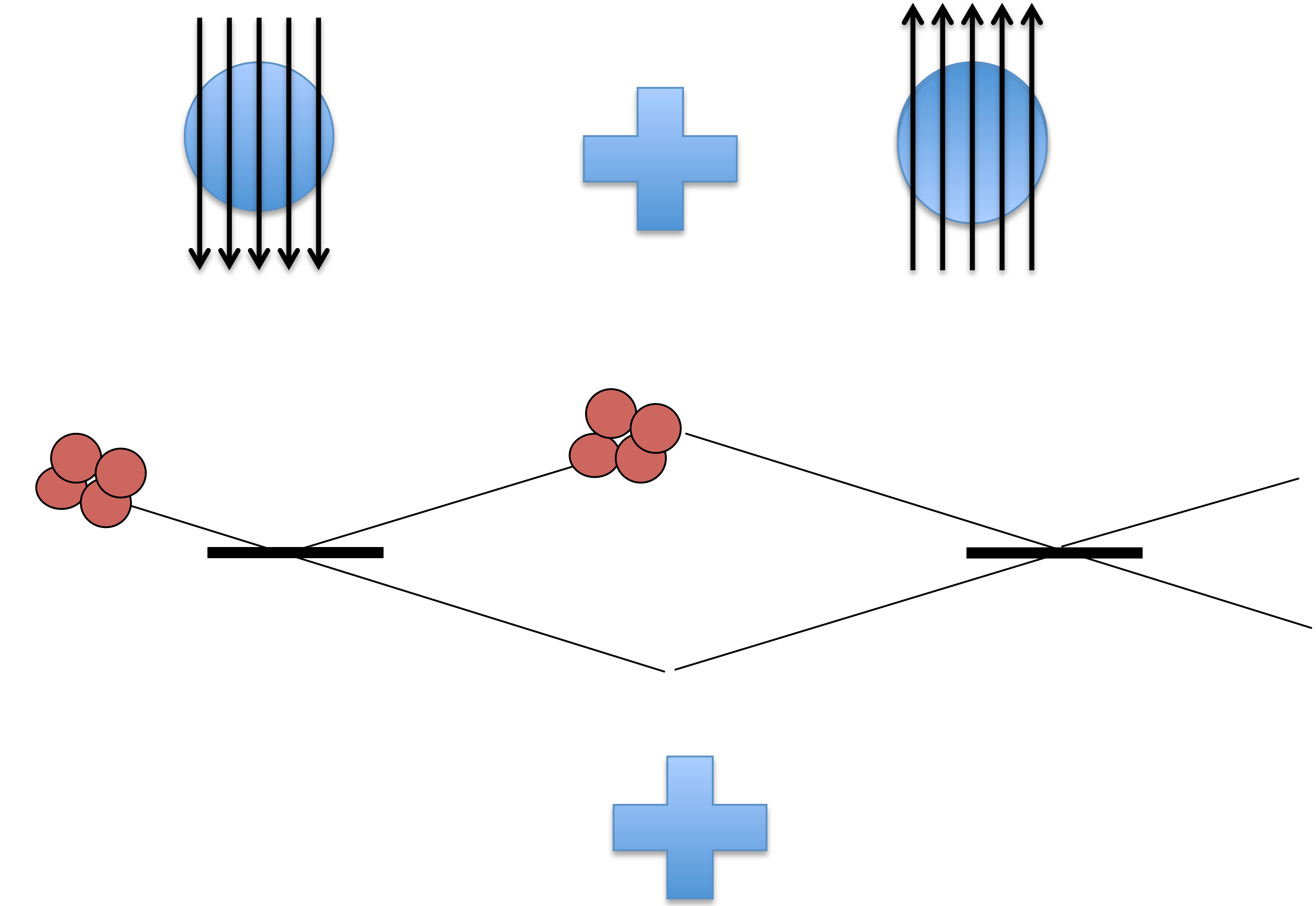


The Superposition Principle **Underpins** Quantum Mechanics

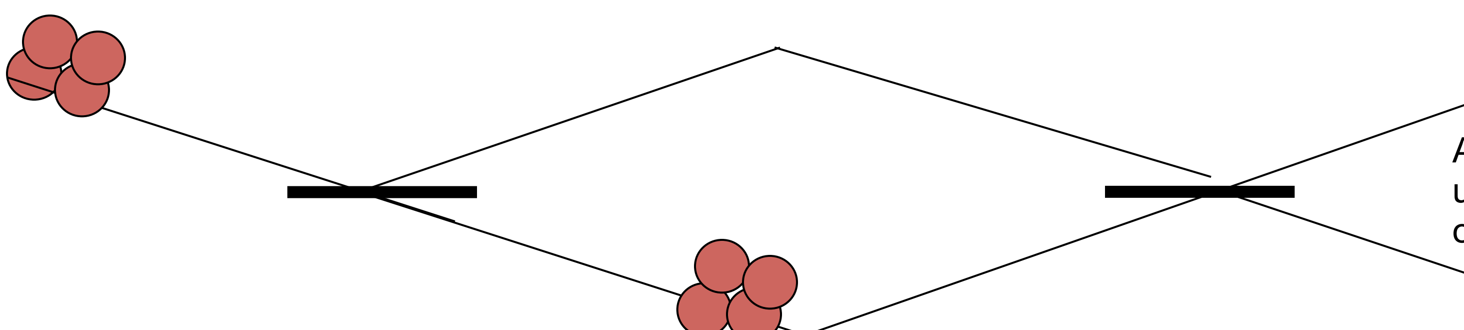
Very familiar
in experiments



If you *decohere* (kill superpositions) nonclassical features of quantum mechanics go away.
Even old quantum mechanics: the right difference between energy levels obtained only through a superposition of localized states.



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

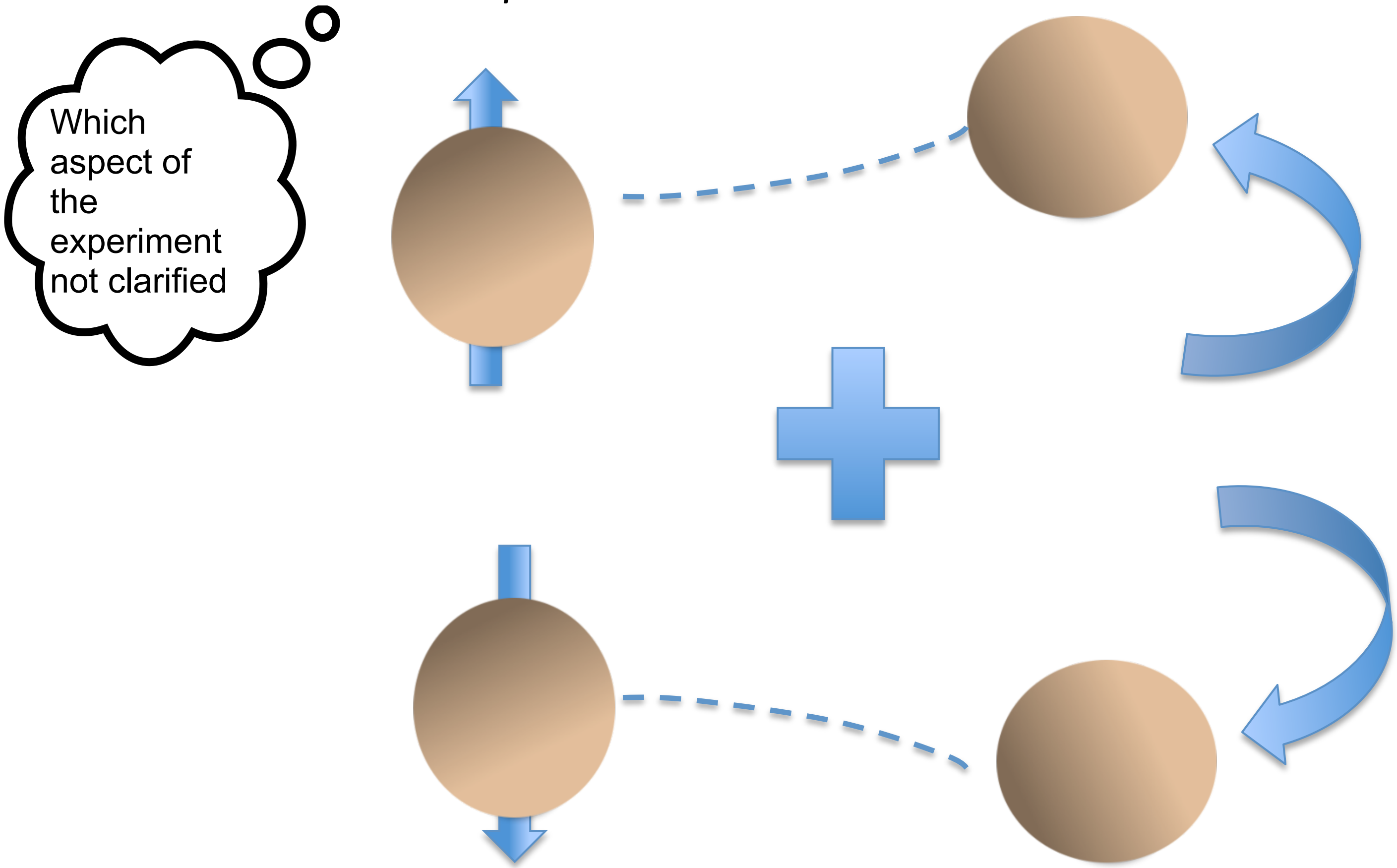
Why do we need to stretch the domain of the superposition principle?

(a) We need to understand whether it has any boundaries or whether it holds at all scales (there are strong beliefs on either side – better to be agnostic and look for experiments).

(b) It is always a winning game: If we can
extend one aspect of the domain, we can extend certain other aspects as well (i.e., use those tools
to stretch quantum attributes further. Eg. Applications to testing **quantum indistinguishability** and **quantum gravity**).

(c) Obvious sensing applications.

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."*

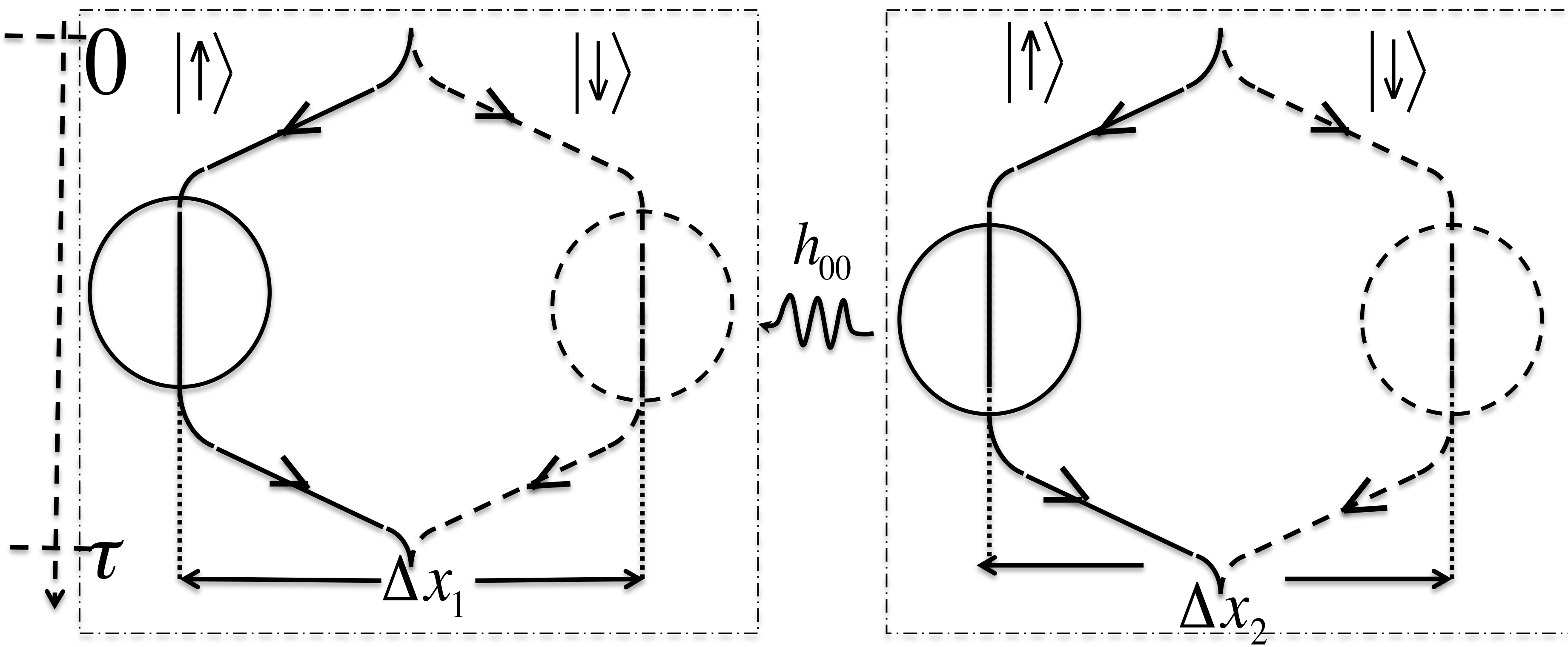


"The only way to avoid quantization of gravity can in principle no longer play a role beyond a certain point in the chain, and you are not allowed to use quantum mechanics on such a large scale. But I would say that this is the only 'out' if you don't want to quantize gravity."

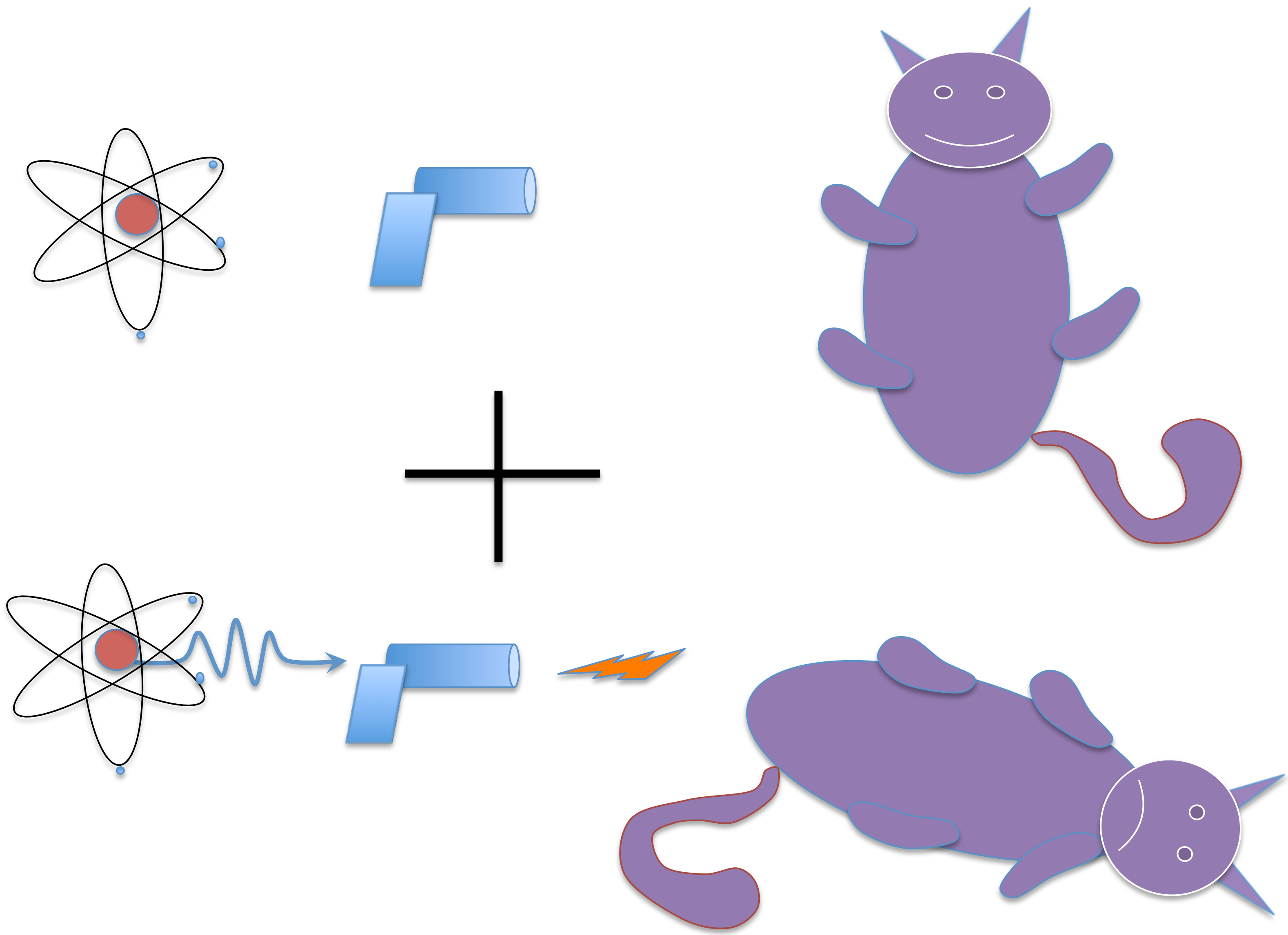
- Is Gravity a Quantum Entity?

- If Gravity Mediates Entanglement

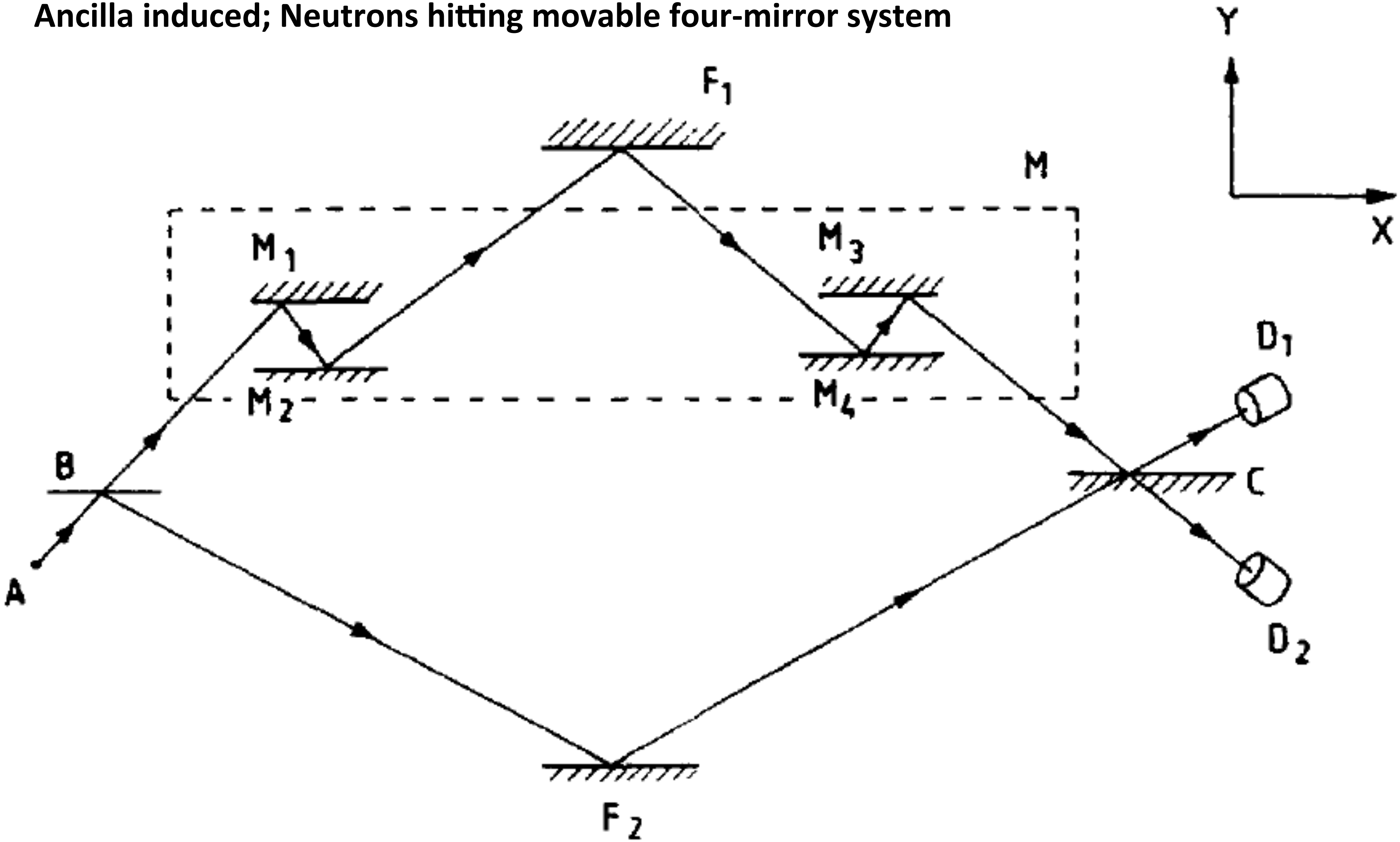
It must be quantum entity



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

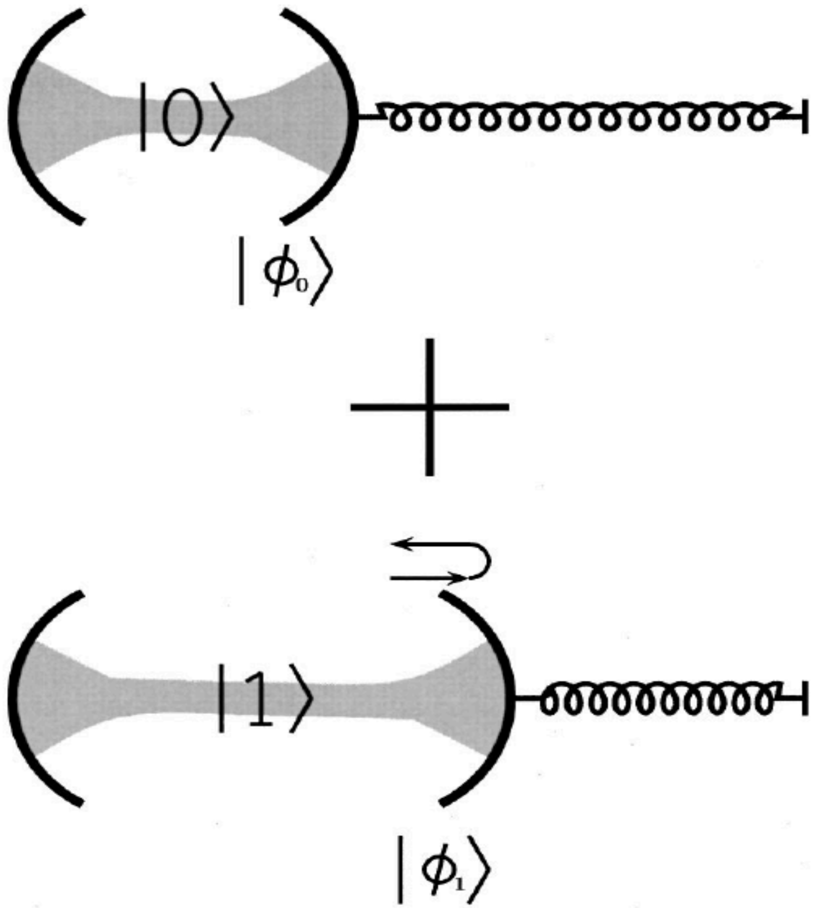


Ancilla induced; Neutrons hitting movable four-mirror system



D. Home & S. Bose, Physics Letters A **217,** 209 (1996); Based on quantum erasure setup of Greenberger and Yasin.

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



Ancilla-only probing: Difficult to satisfy a skeptical person: Alternatives --Asadian, Brukner, Rabl. PRL 2013

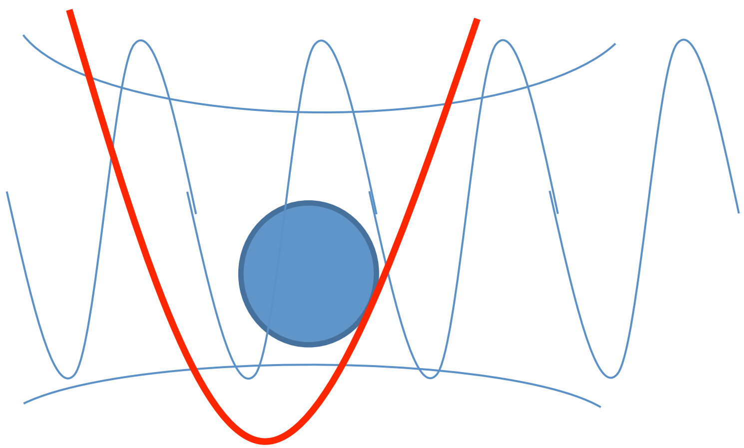
S. Bose, K. Jacobs, P. L. Knight,
Phys. Rev. A 59 (5), 3204 (1999). [arXiv: 1997].
Decoherence/partial coherence is used to certify superposition.

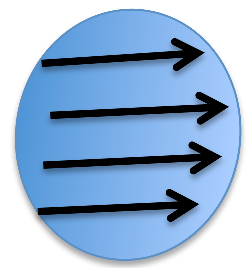
Armour, Blencowe, Schwab, PRL 2002.
Marshall, Simon, Penrose, Bouwmeester, PRL 2003.
Decoherence & Recoherence is used to certify superpositions

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.



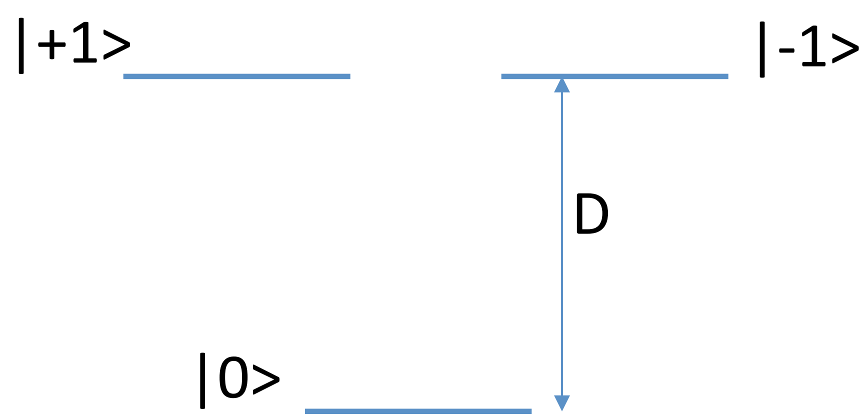


No cavity, no cooling.

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

Initial State:

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



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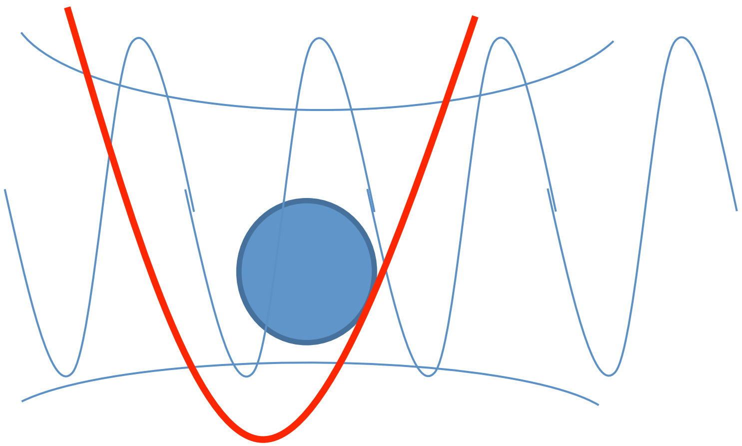
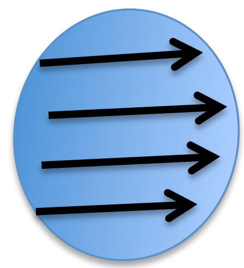
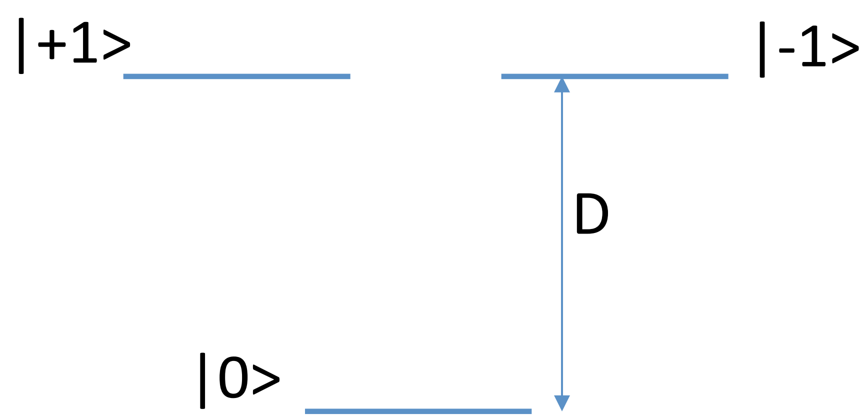




Step 1:

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



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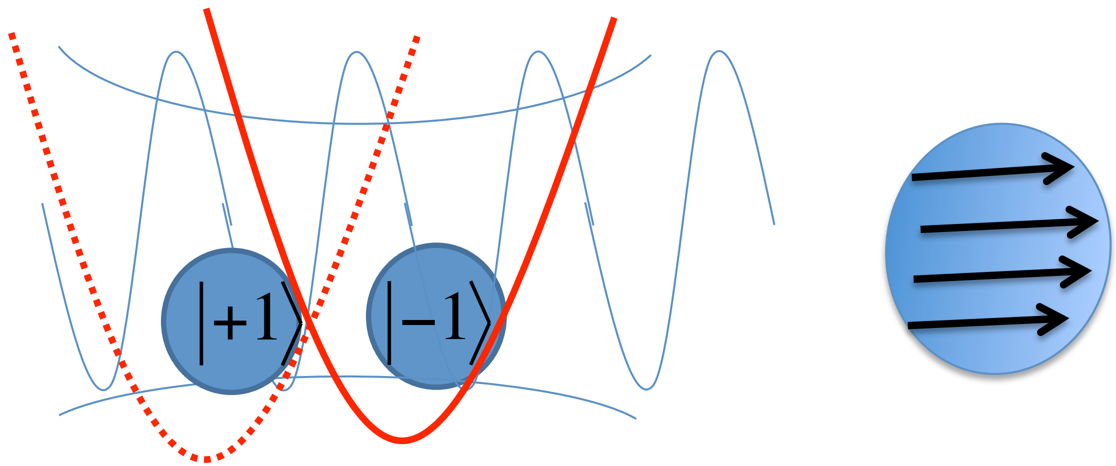
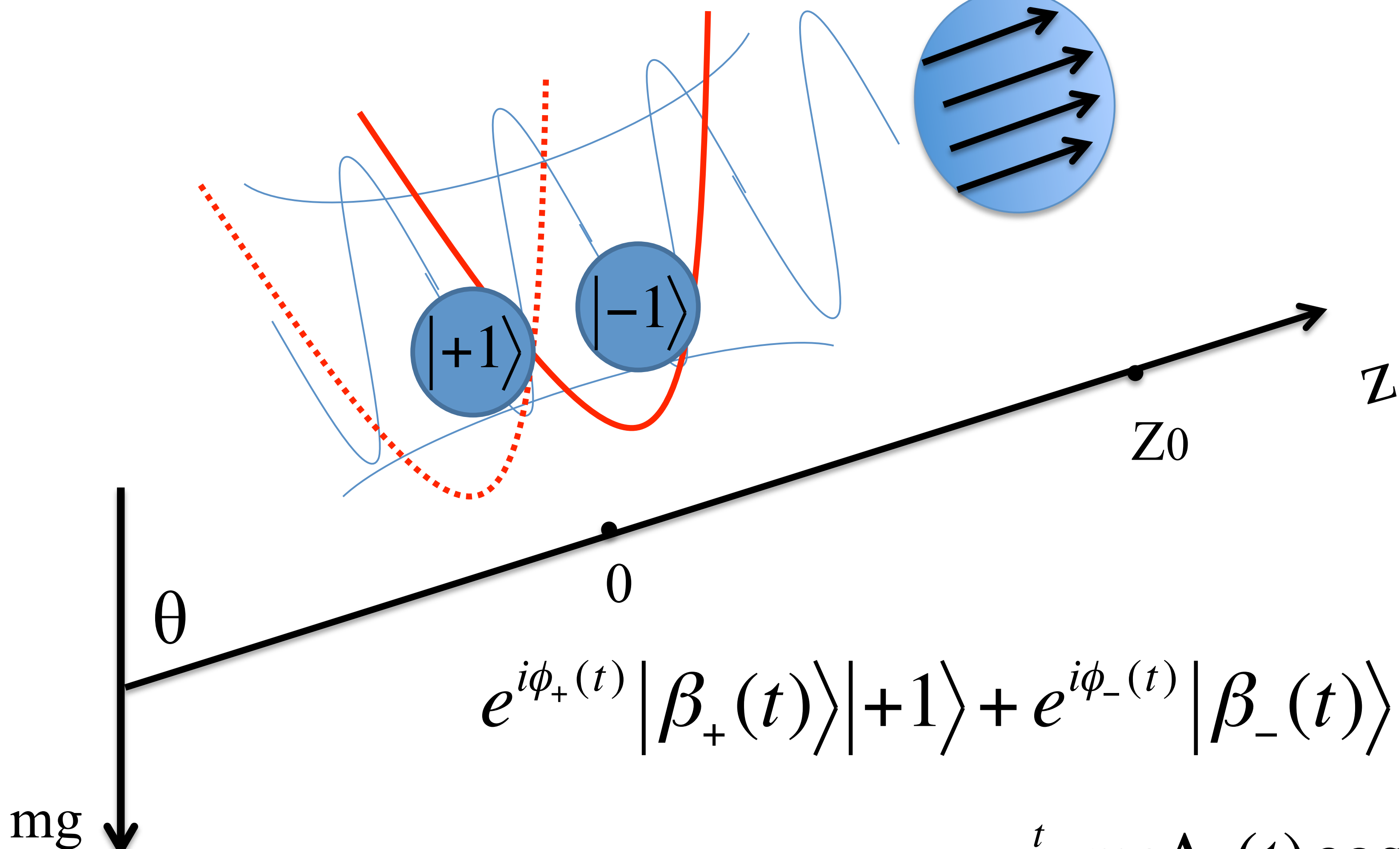


Time Evolution:

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

Ramsey Interferometry with a Levitated Thermal Mesoscopic Object



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

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

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).

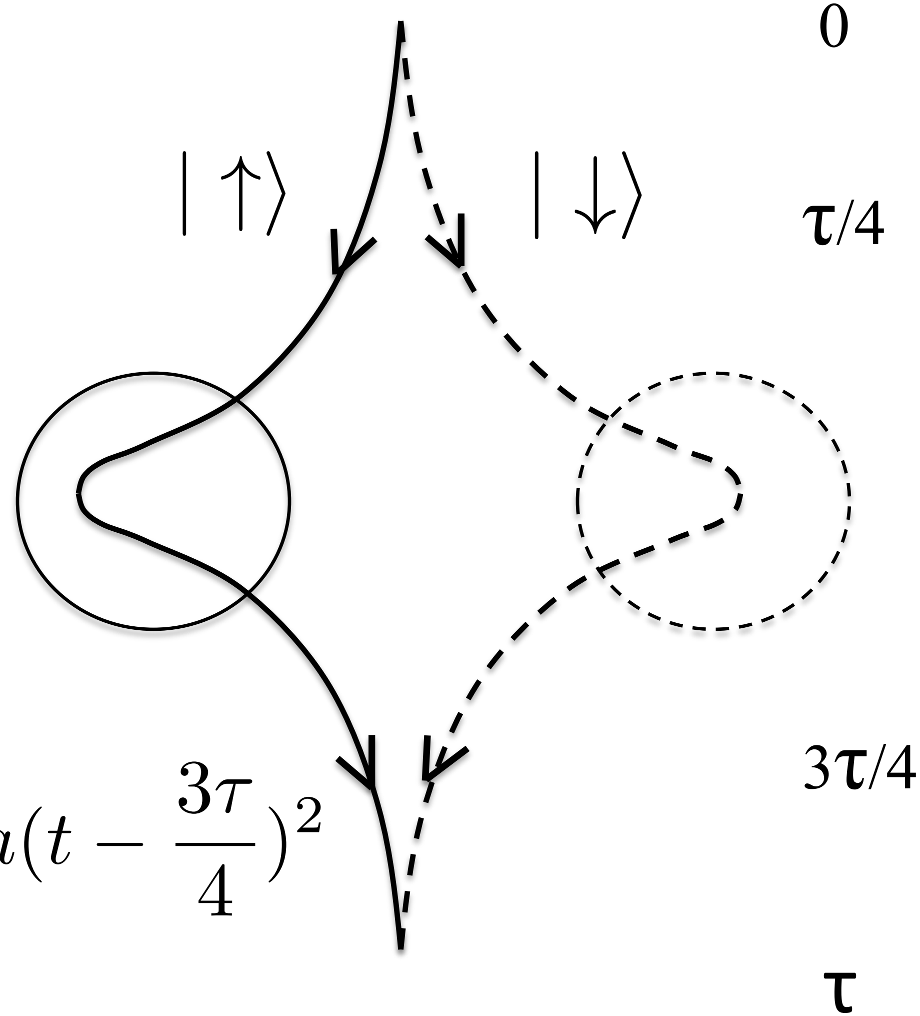
How can we increase the scale of the superposition?

Free particle in an inhomogeneous magnetic field (acceleration $+a$ or $-a$)

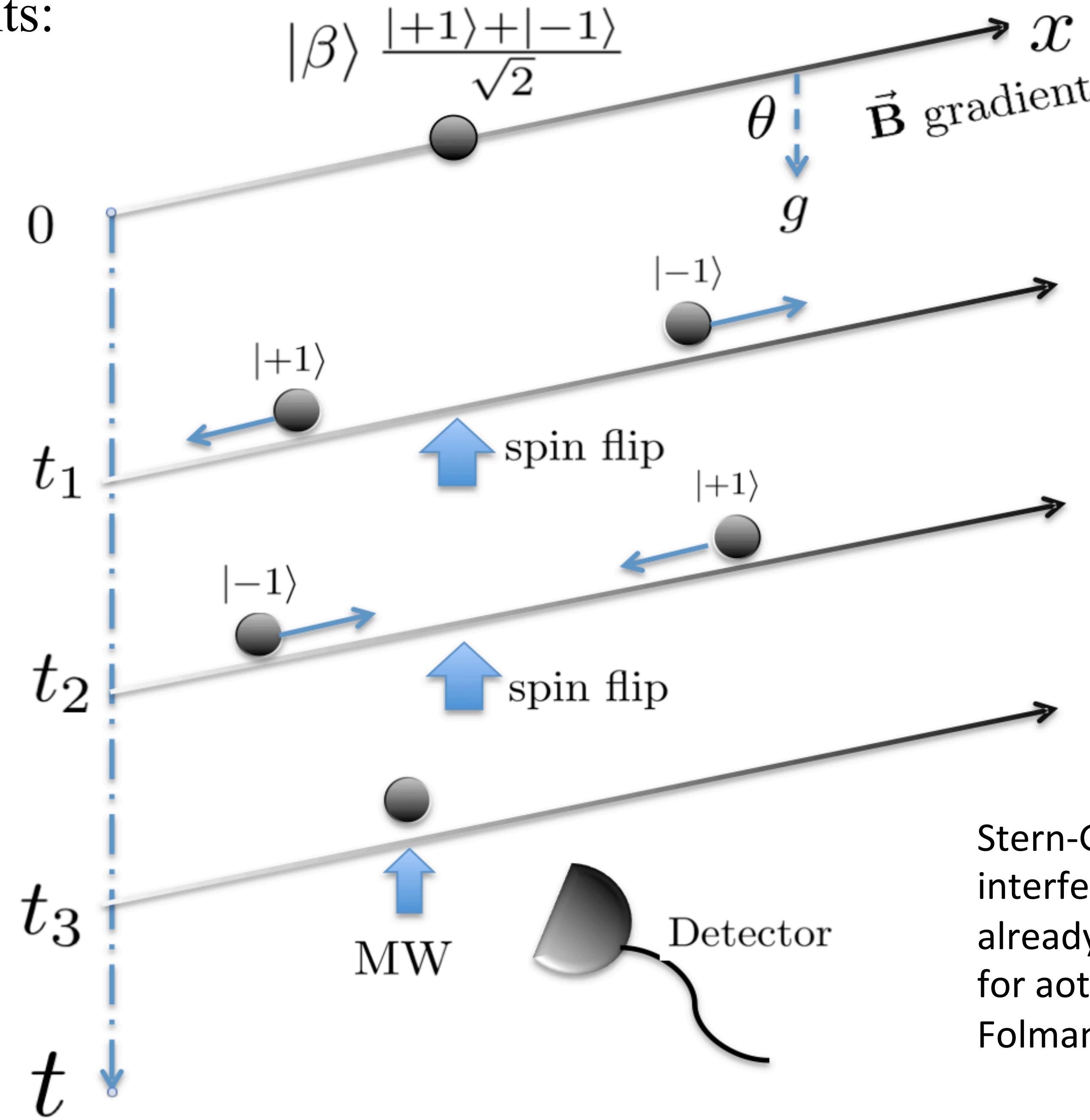
$$x_\sigma(t, j) = x_j(0) \pm \frac{1}{2}at^2$$

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

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



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



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

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

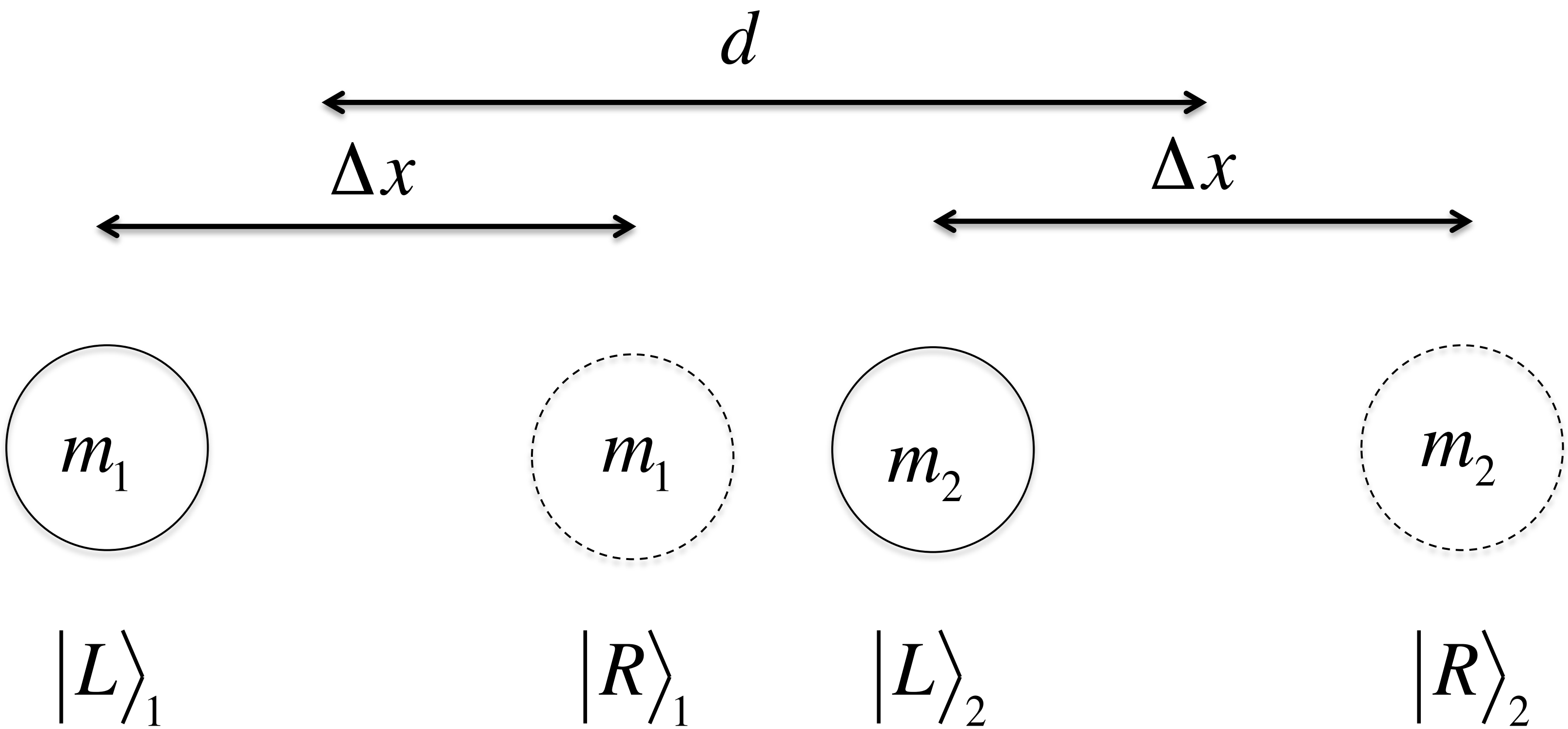
$$\langle x|\psi(t_3)\rangle = e^{-ip_0x}e^{-[(x-x_0-p_0t_3/m-g\cos\theta t_3^2/2)^2/2(\sigma')^2]}$$

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

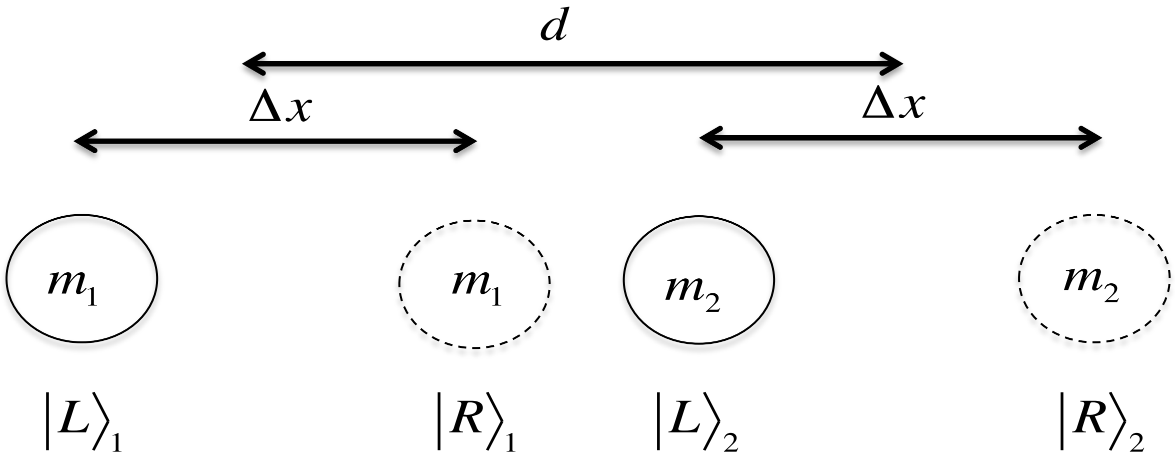
$$\Delta x_M = 2\times\frac{1}{2m}g_{\rm NV}\mu_B\frac{\partial B}{\partial x}(t_3/4)^2$$

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

$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2)$$

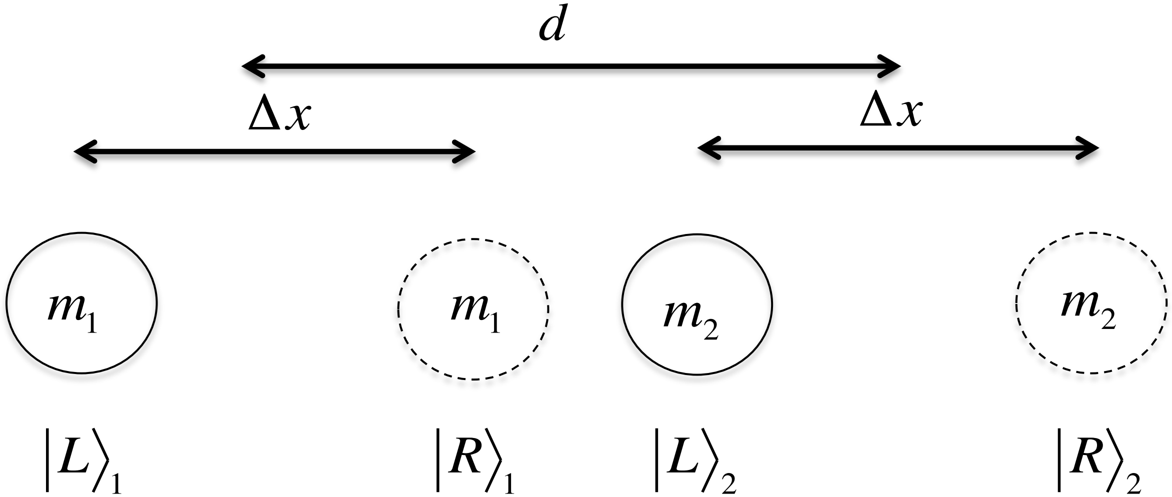
$$= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2)$$

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

where

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

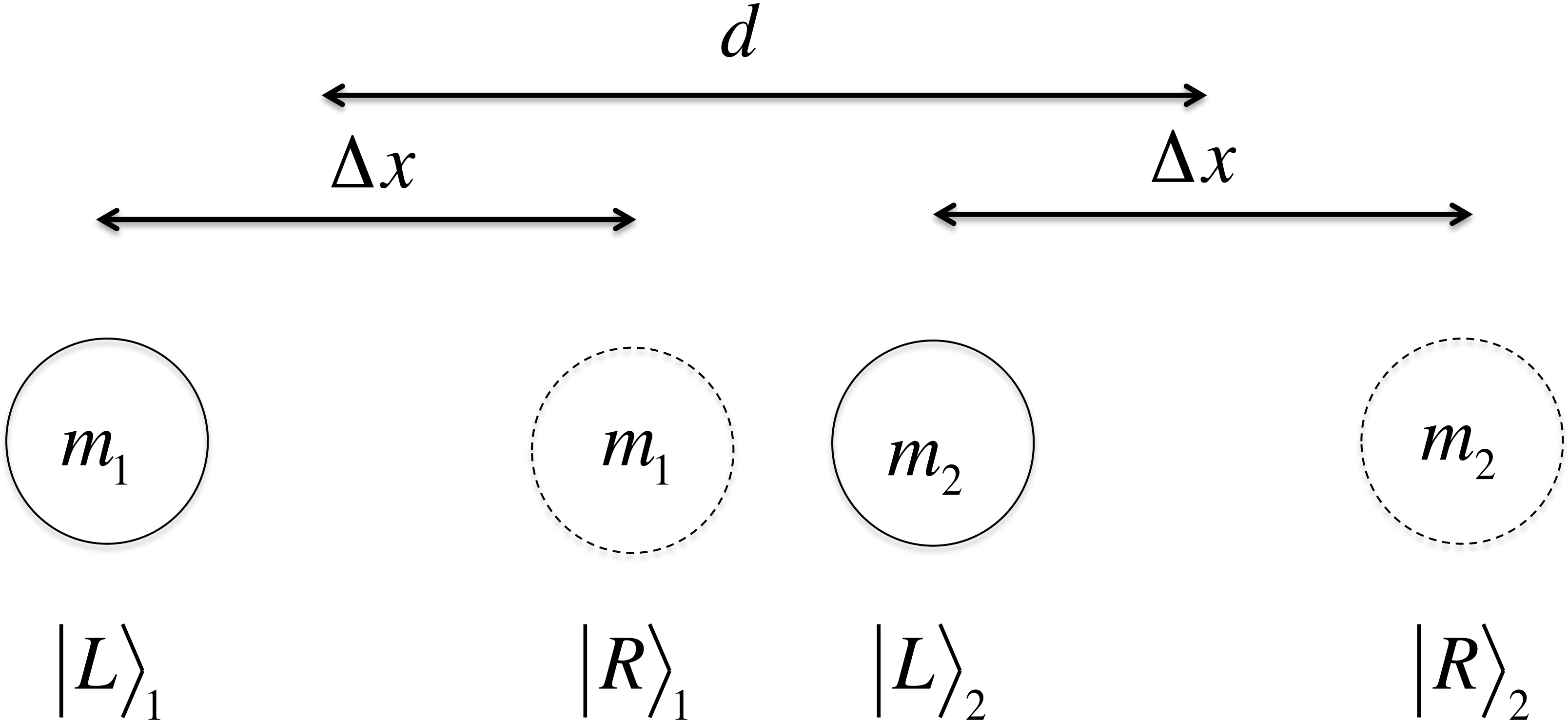
$$\phi_{LL} = \phi_{RR} \sim \frac{Gm_1m_2\tau}{\hbar d}$$



If they interact *only* through the gravitational force

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

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

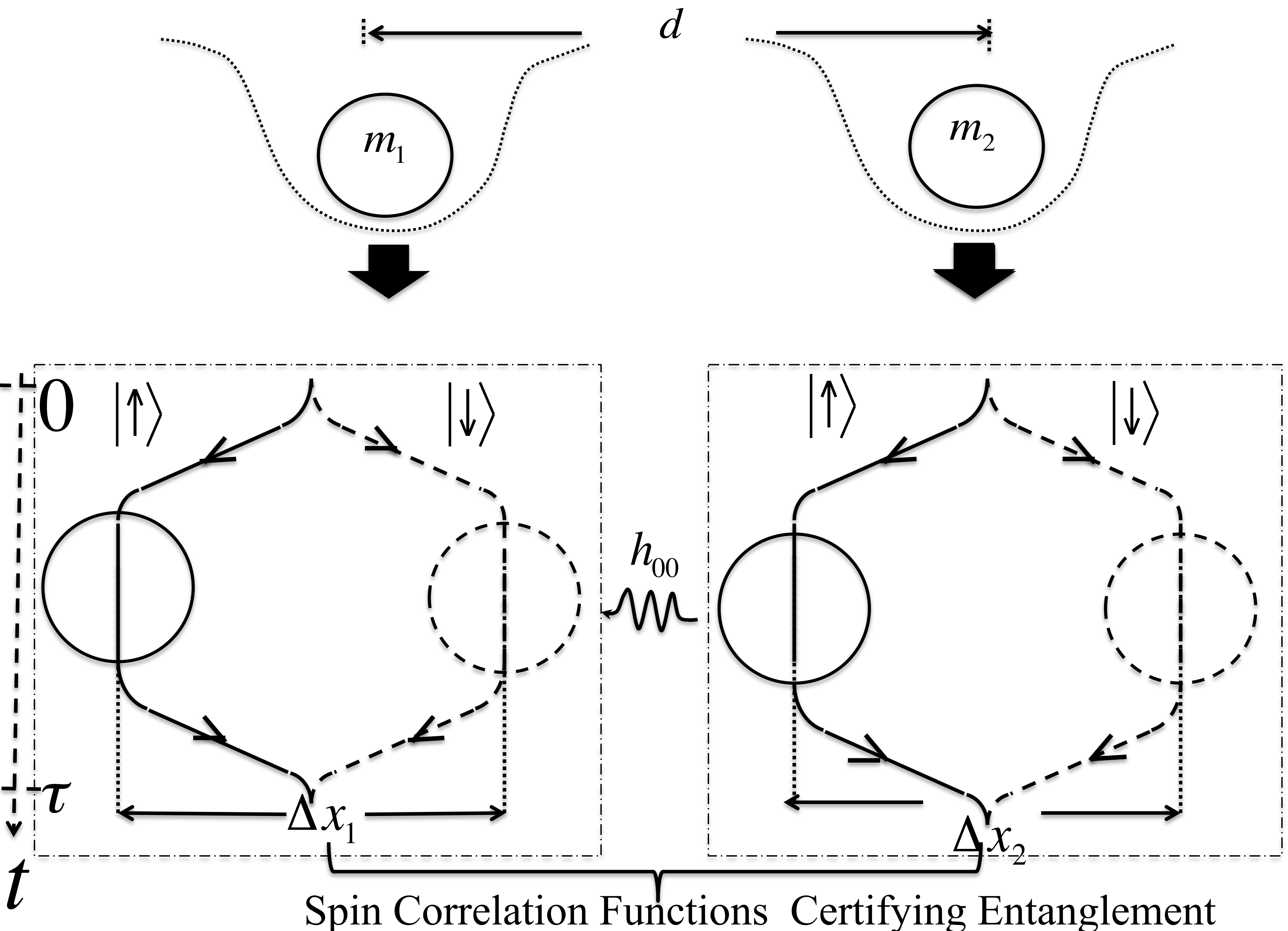
$$d - \Delta x << d, \Delta x,$$

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
Δx_1
Δx_2
t
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*)

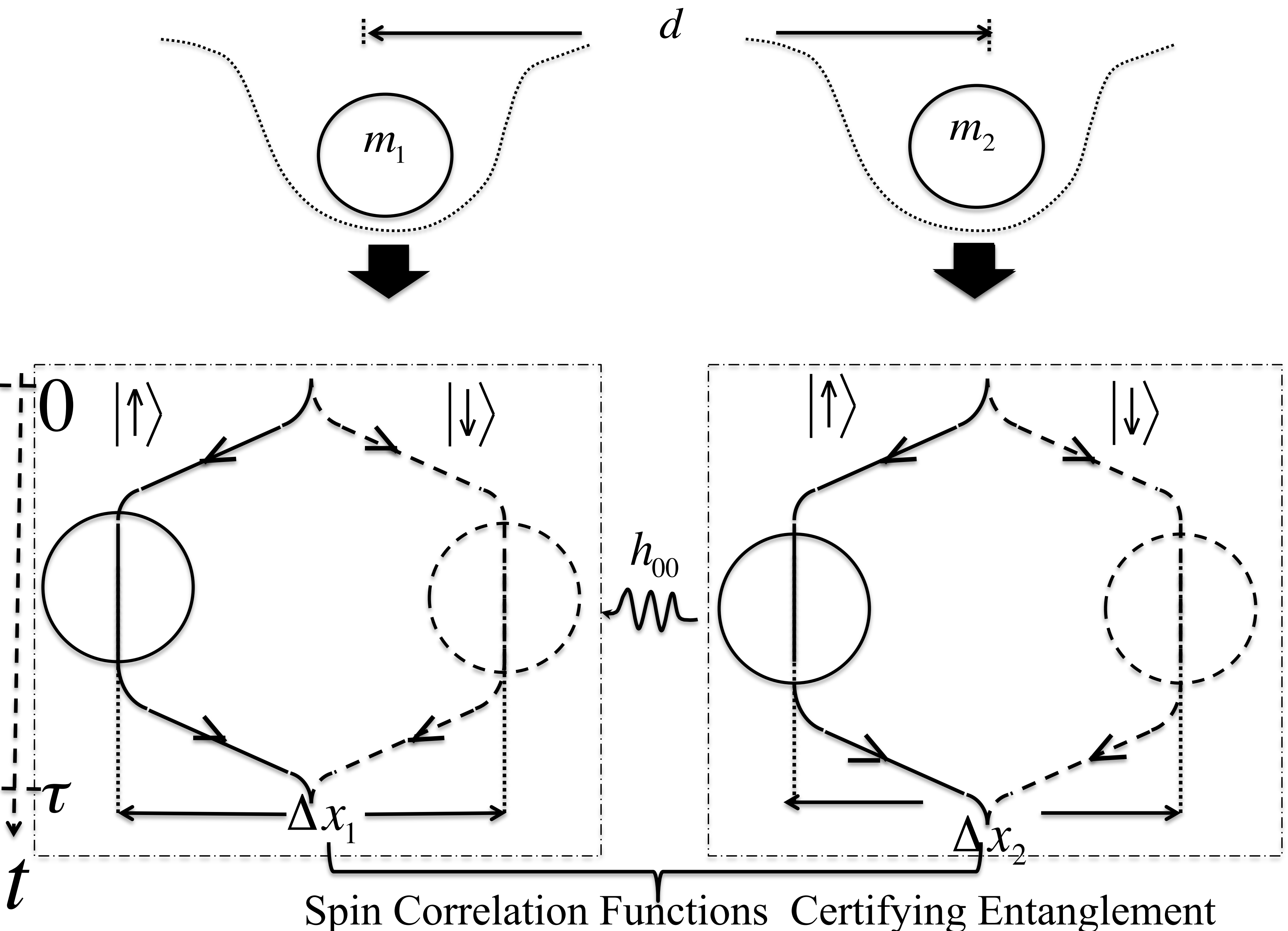
Step 3: SG recombination: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j, \ |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$

Step 4: Witness spin entangled state:

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

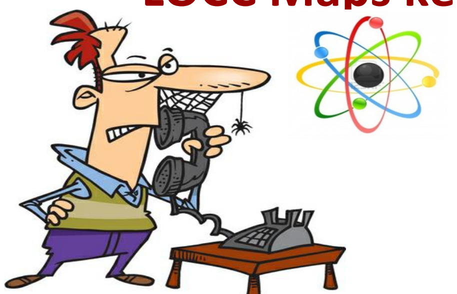
through the correlations:

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


d
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

How is this related to Quantum Gravity?

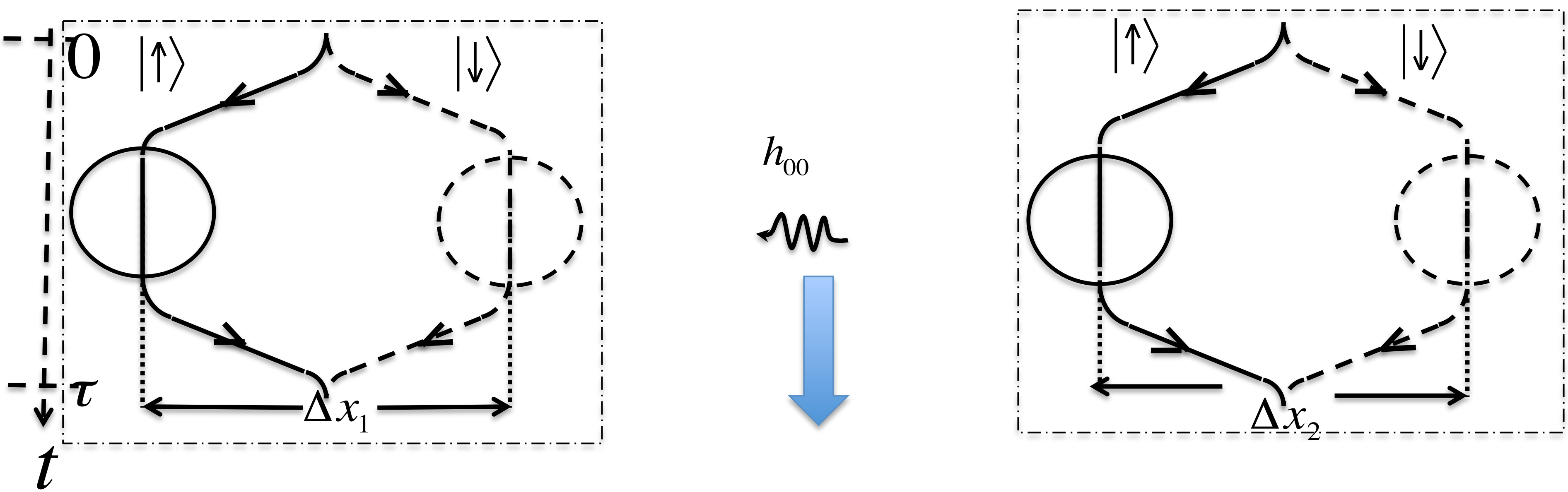
LOCC Maps keep separable states separable (*cannot* create entanglement!)



Local Operations and Classical Communication (LOCC)

1. Unitary evolution
2. Measurement

Classical mediator of information/bits

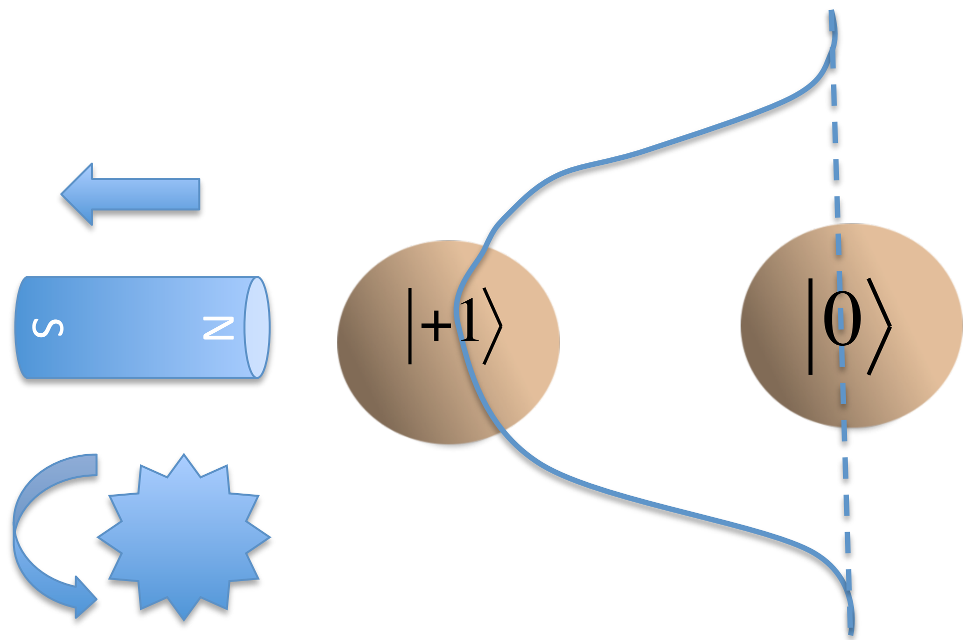


Must be quantum if the spins in the masses get entangled

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 Phys. Rev. Lett. 119, 240402 (2017)