Sensing Quantum Gravity & Gravitational Waves with Mesoscopic Superpositions

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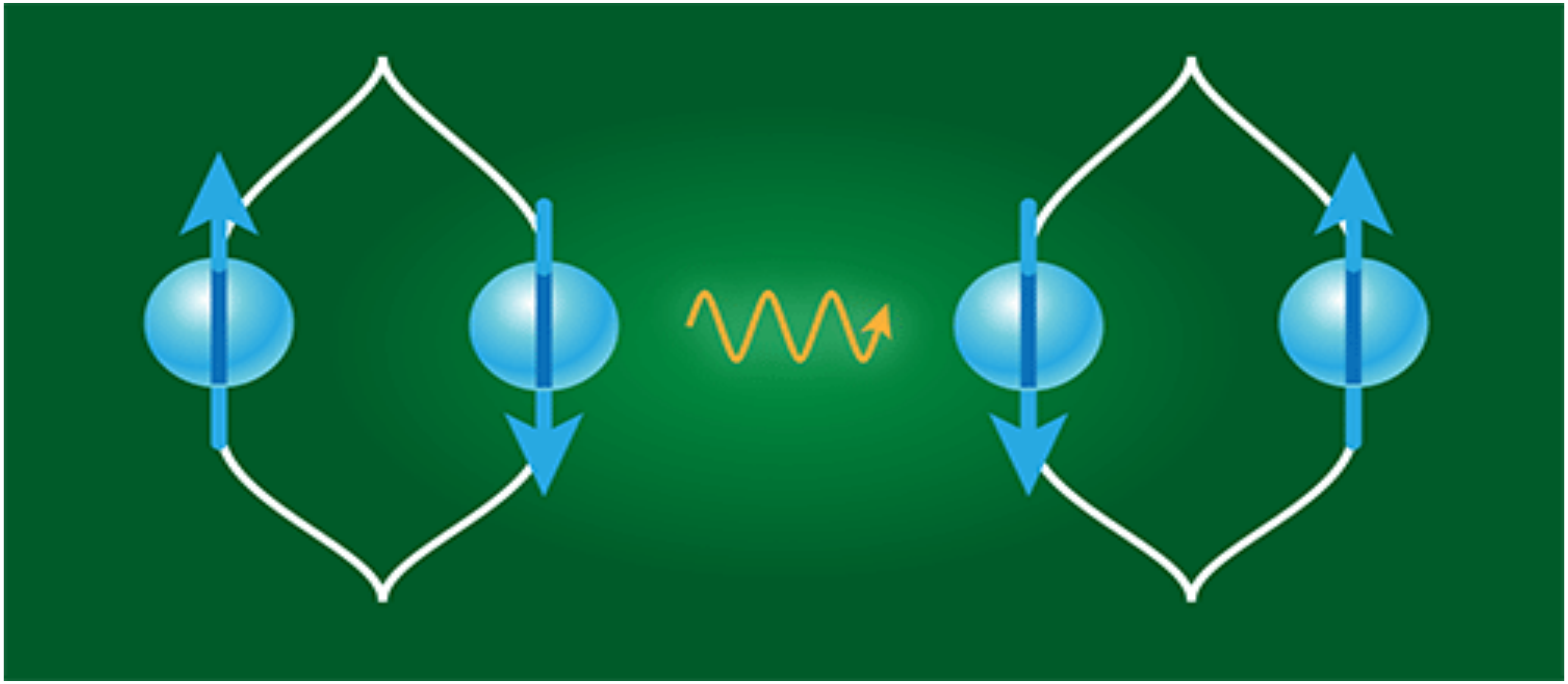
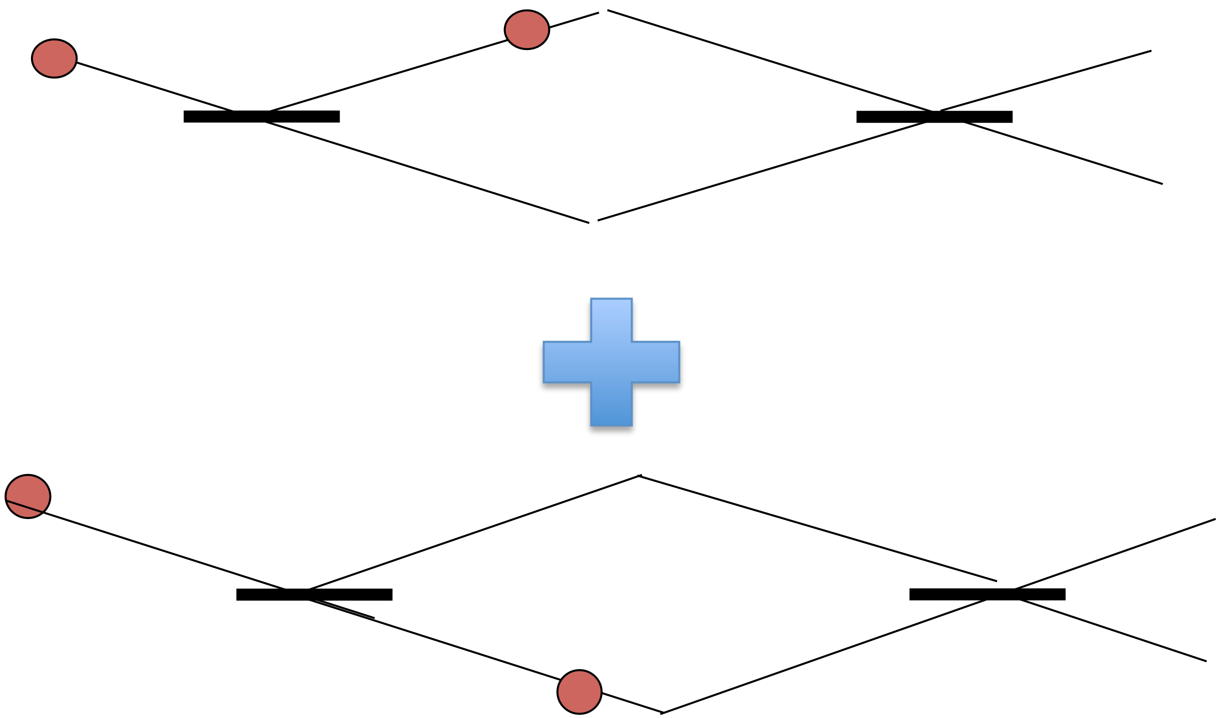


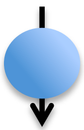
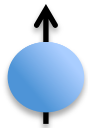
The Superposition Principle **Underpins** Quantum Mechanics

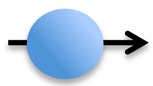
Very familiar
in experiments

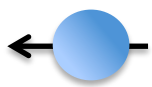


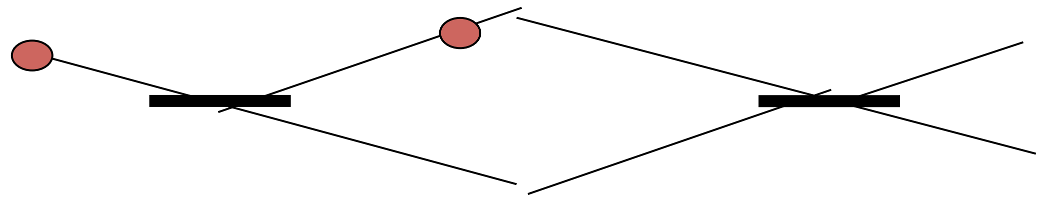
If you *decohere* (kill superpositions) nonclassical features of quantum mechanics go away.

To understand/evidence superposition you have to control the phase

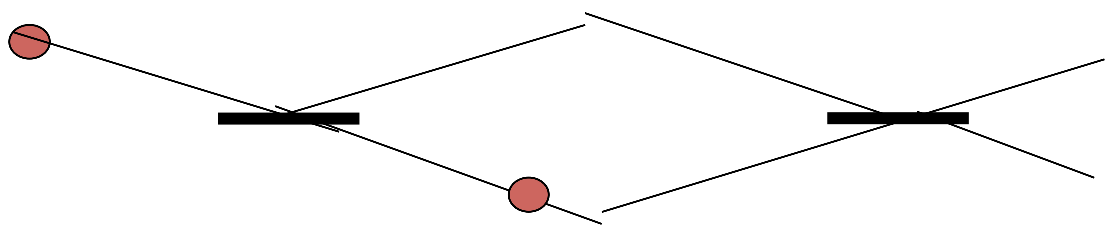
 + $e^{i\phi}$ 

For $\phi = 0$ 

For $\phi = \pi$ 

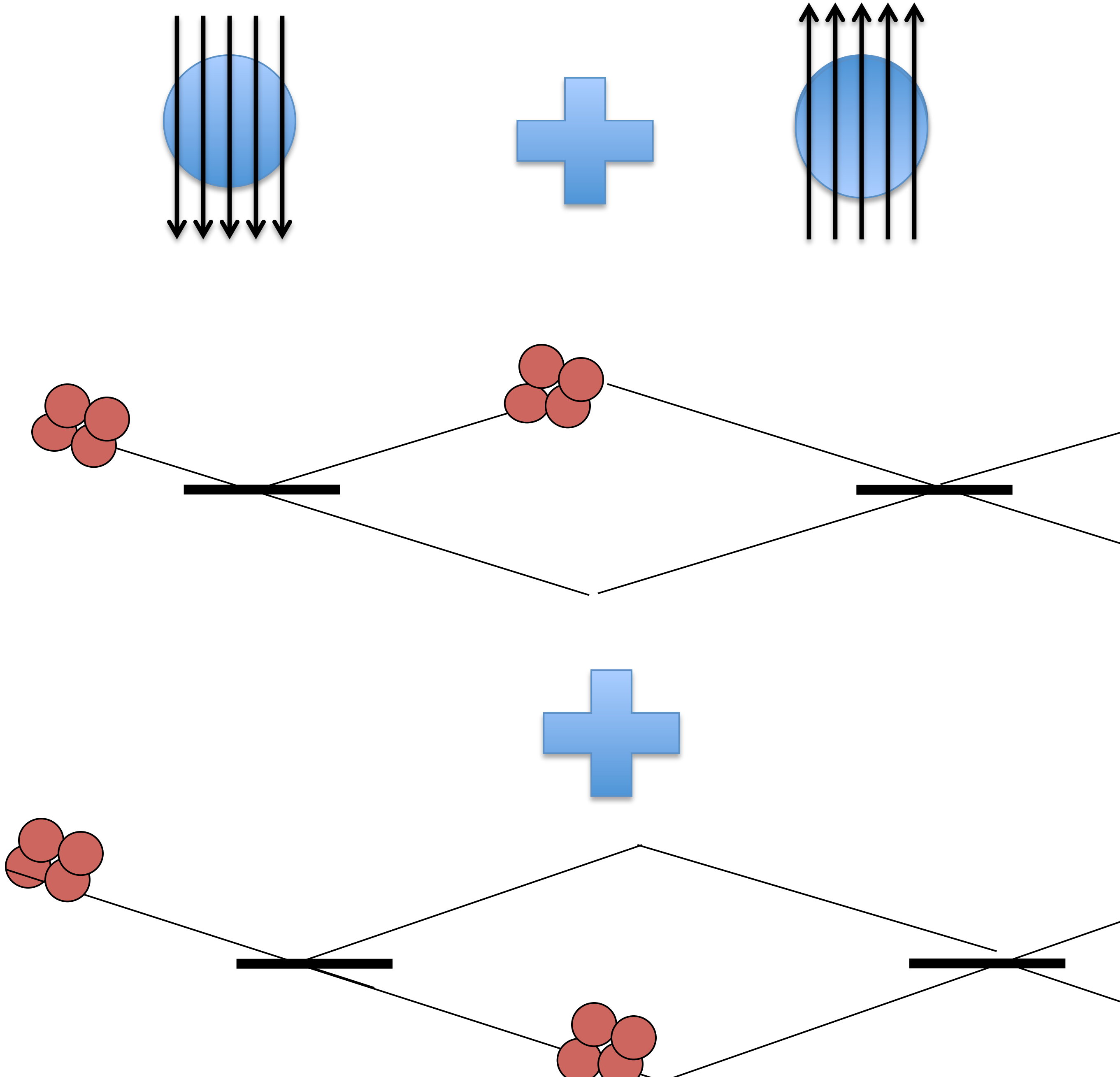


+ $e^{i\phi}$



For $\phi = 0$ D1 Clicks

For $\phi = \pi$ D2 Clicks



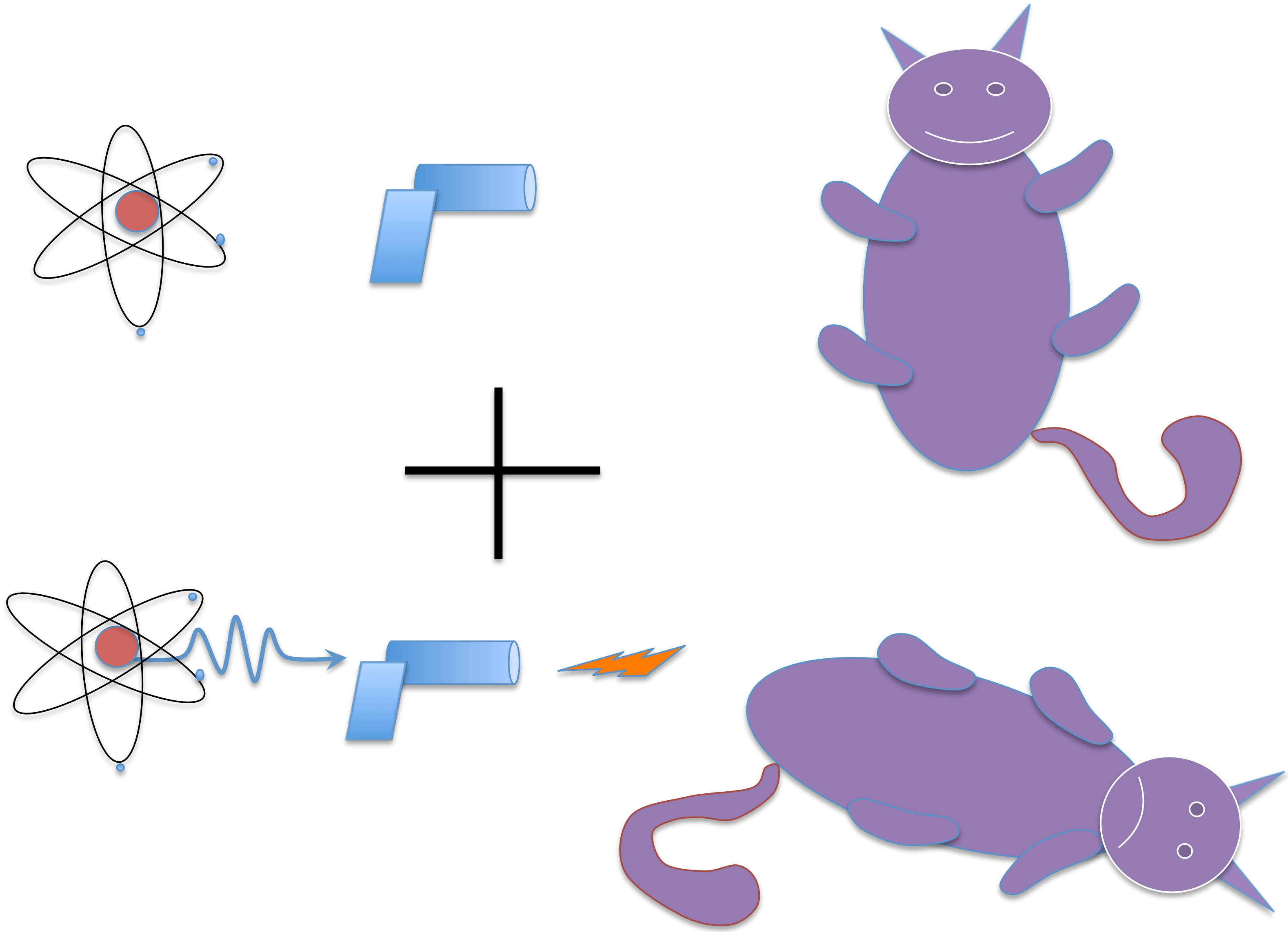
Less familiar superposition: Higher the N in NOON Gets!

Can we Generate NOON States with $N \sim 10^{10}$- 10^{13} atoms?

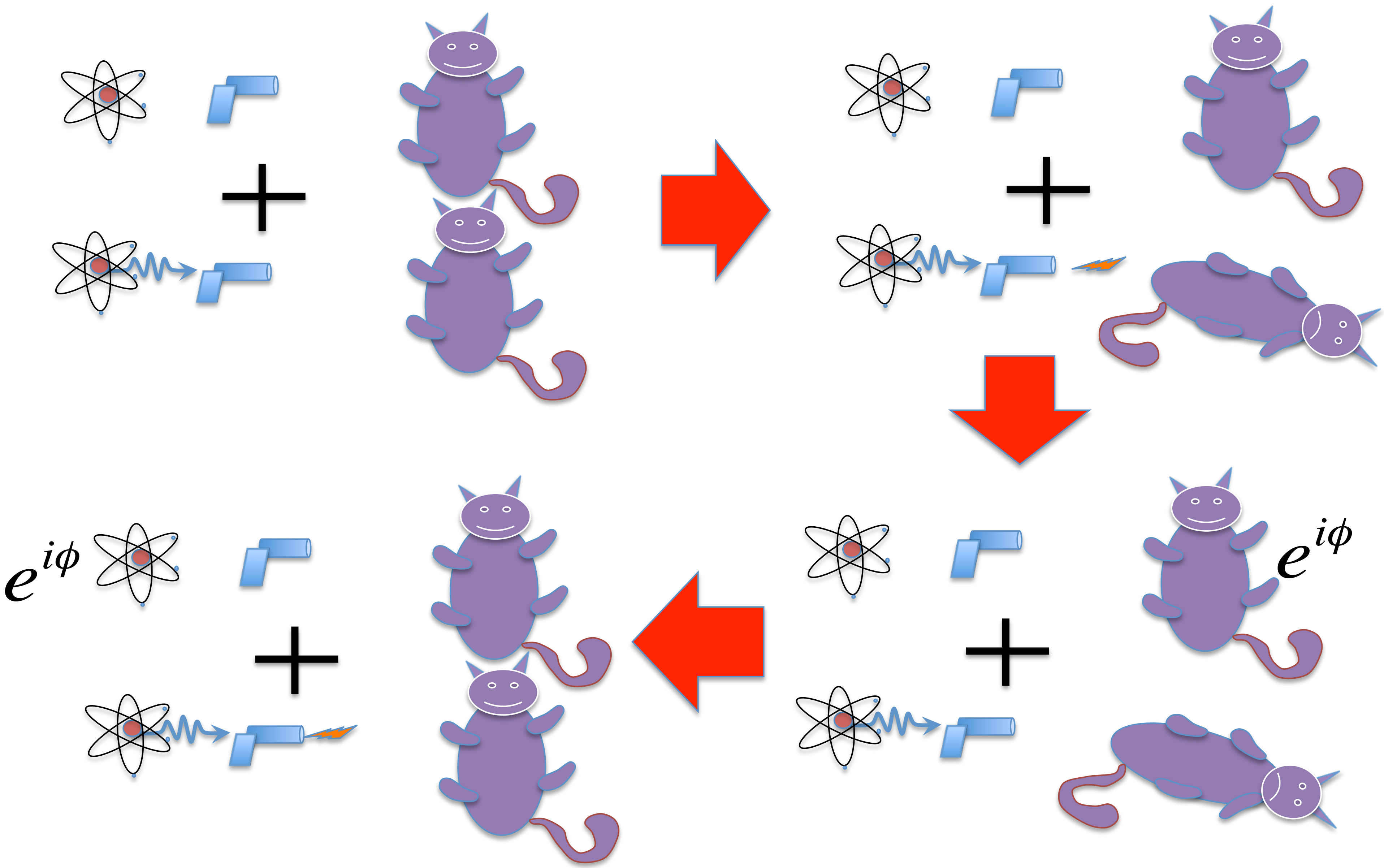
If so what are the Applications?

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

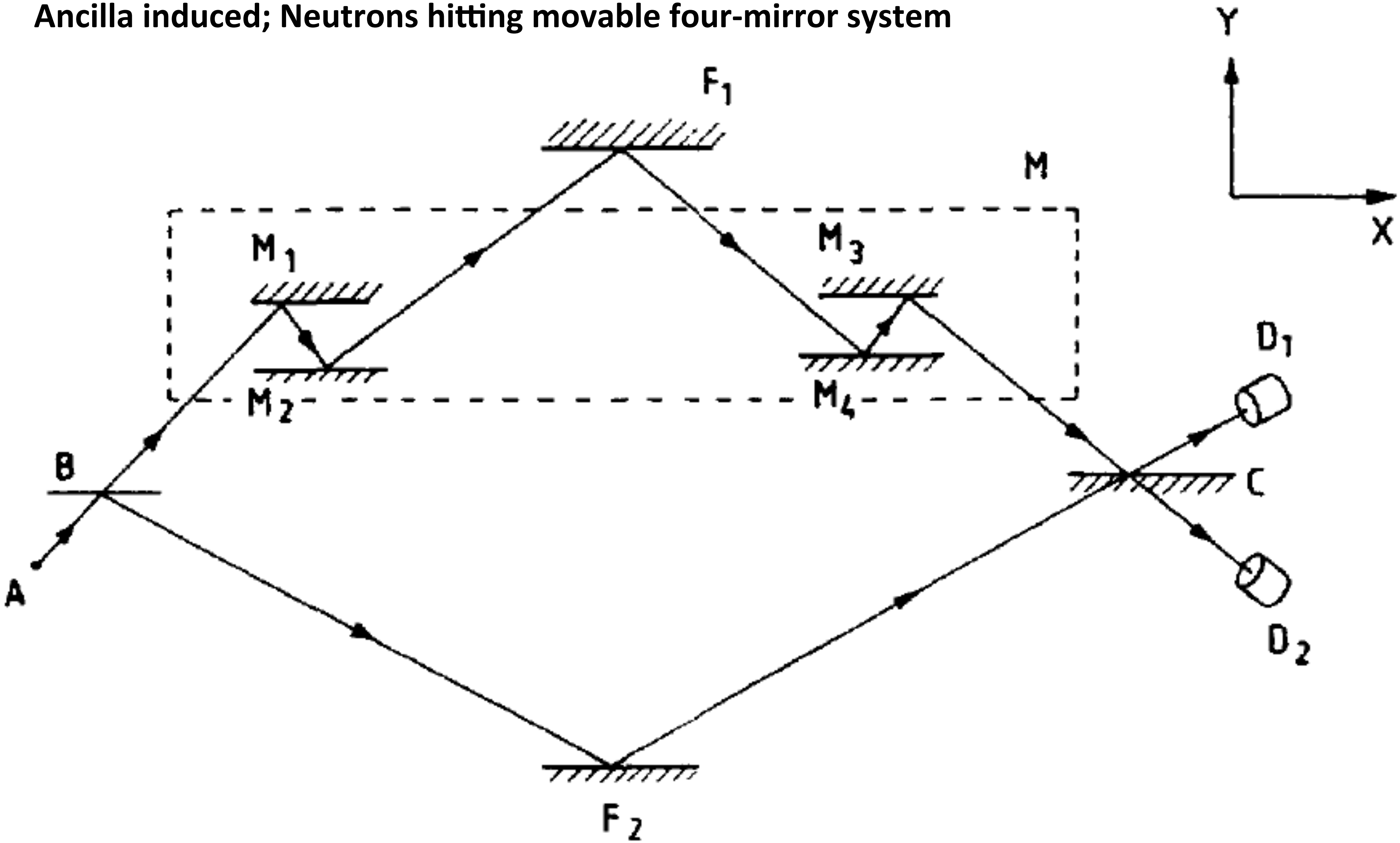
How to create the macroscopic superpositions (earliest idea is Schroedinger's Nucleo-Biological mechanism). **Coherent ancilla induced.**



Ancilla Induced AND Ancilla Probed Superposition:

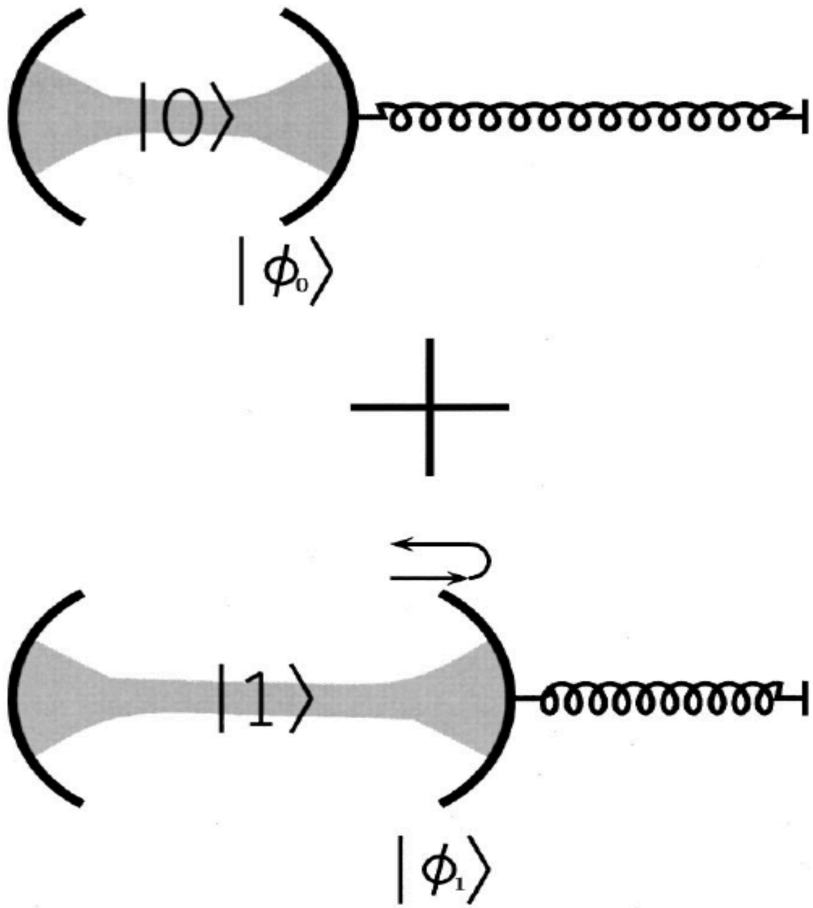


Ancilla induced; Neutrons hitting movable four-mirror system



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:



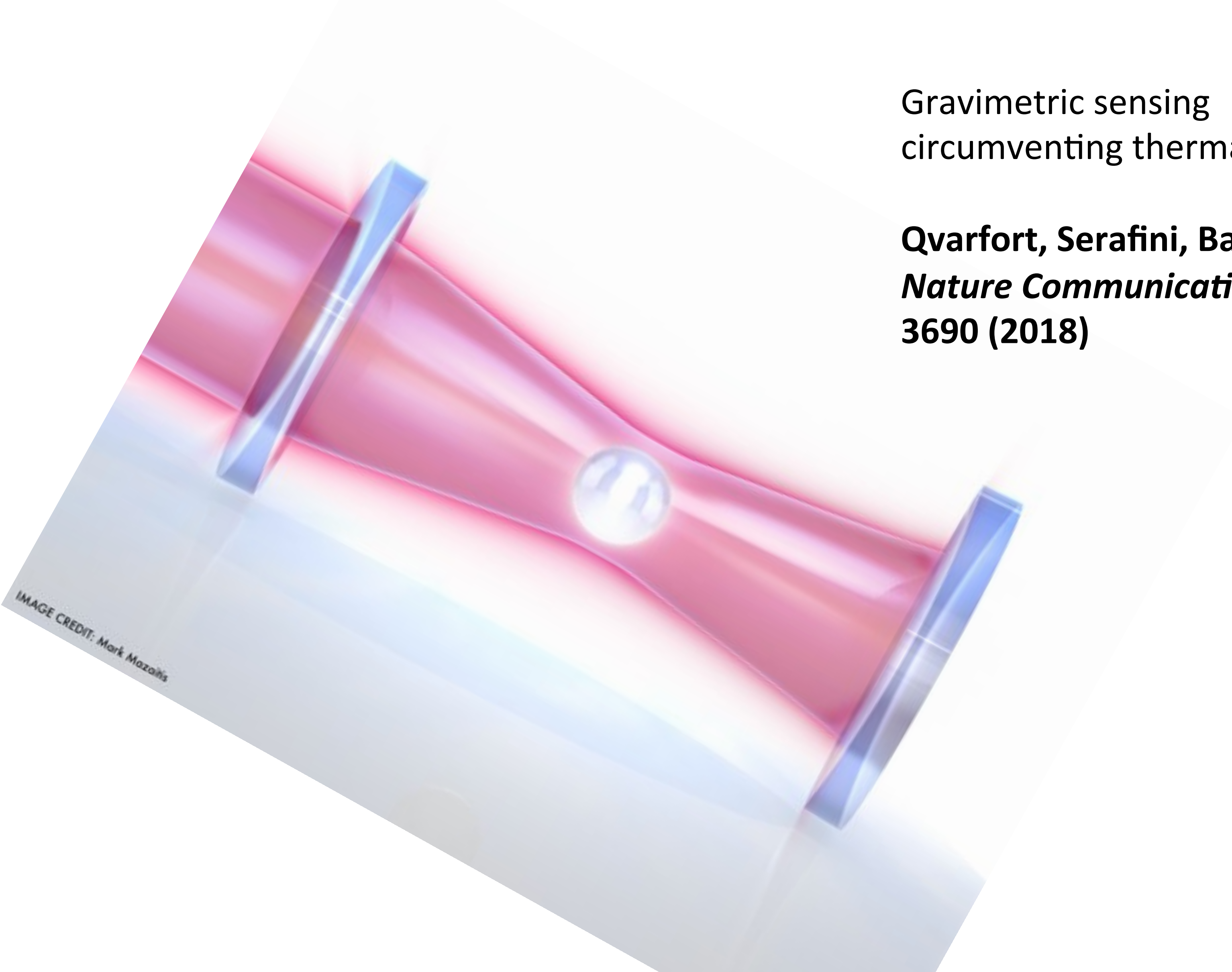
S. Bose, K. Jacobs, P. L. Knight,
Phys. Rev. A 59 (5), 3204 (1999). [arXiv: 1997].
Decoherence/partial coherence is used to certify superposition.

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

Bose, PRL 2006.

Gravimetric sensing circumventing thermal noise.

Qvarfort, Serafini, Barker, Bose, *Nature Communications* 9, 3690 (2018)

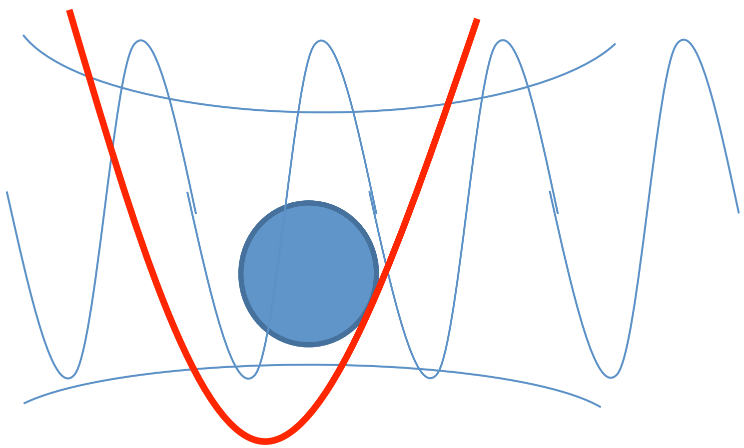


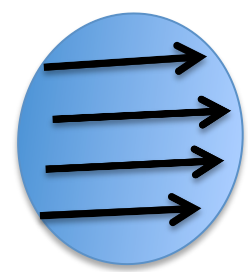
Possible to sense acceleration 10^(-15) ms^(-2)/root(Hz) via optomechanical entanglement

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.

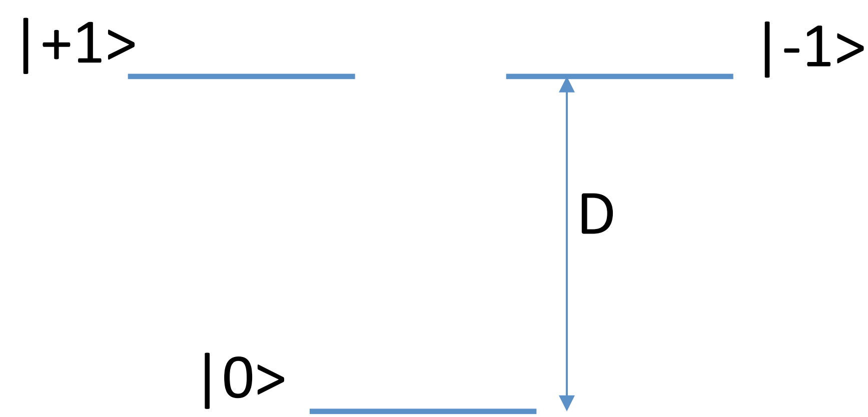




Exploits Spin-Motion coupling mechanism proposed by Rabl et.al. 2009.
van Wezel & Oosterkamp, 2011.

Initial State:

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



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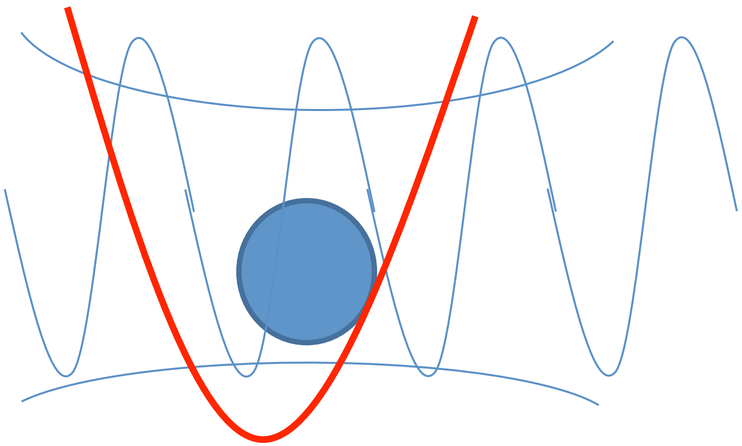
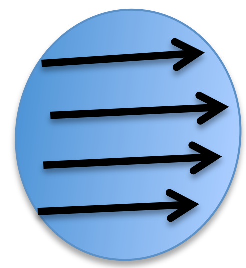
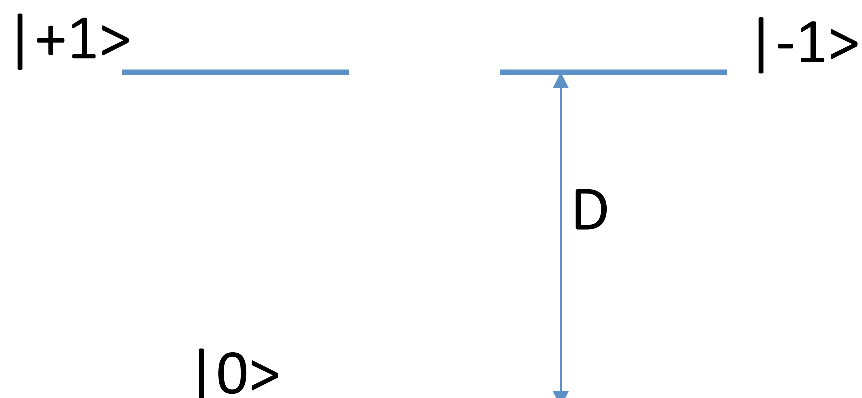




Step 1:

$$|\beta\rangle\big(|+1\rangle + |+1\rangle\big)$$



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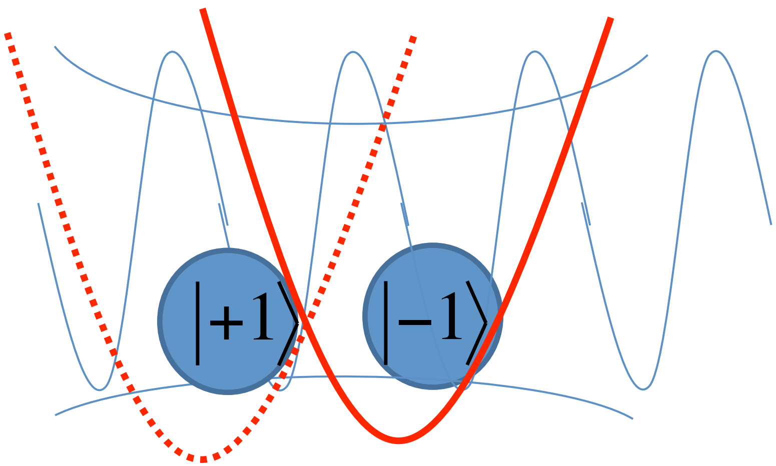
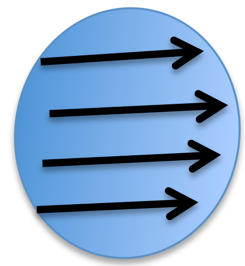
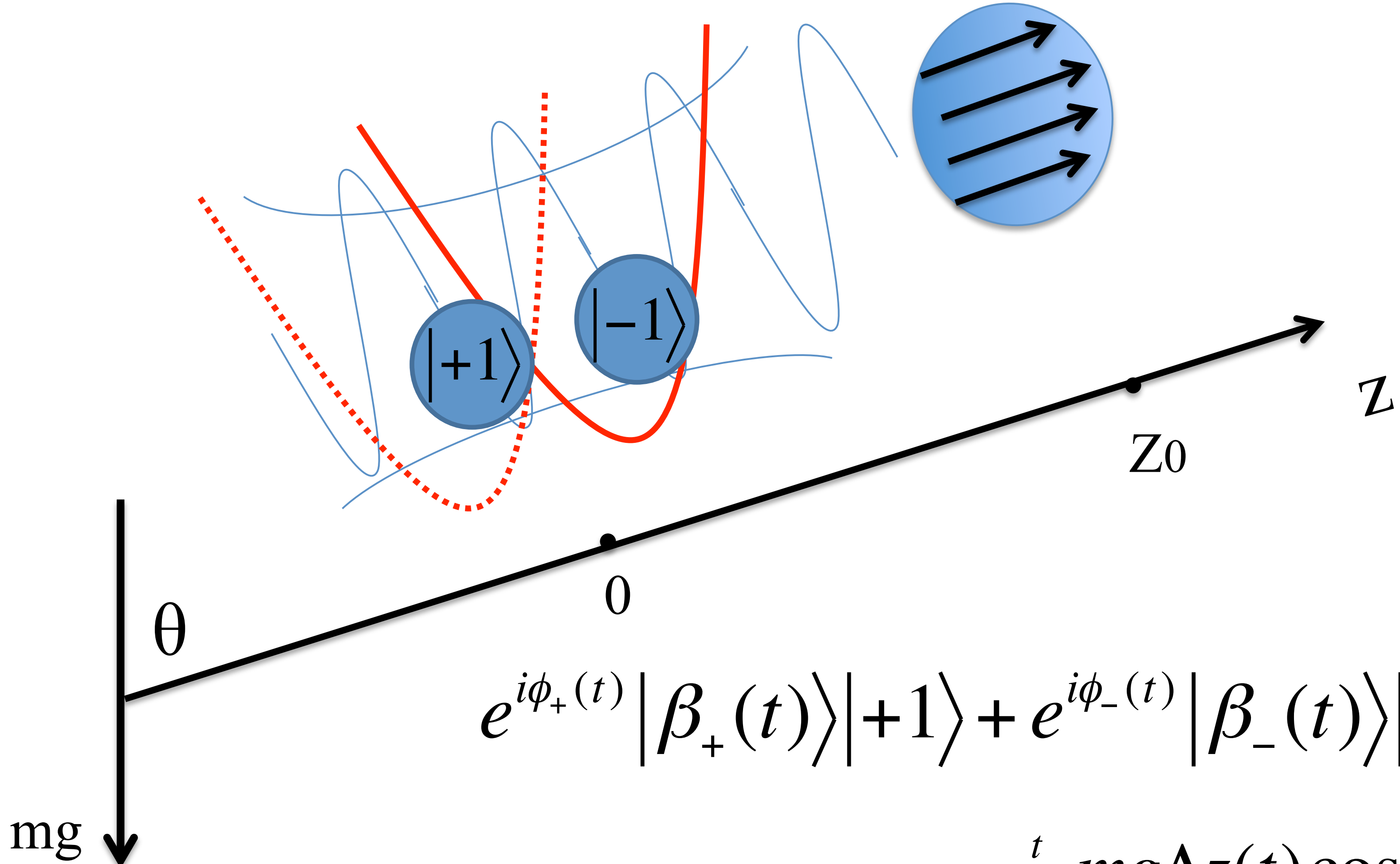




Time Evolution:

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

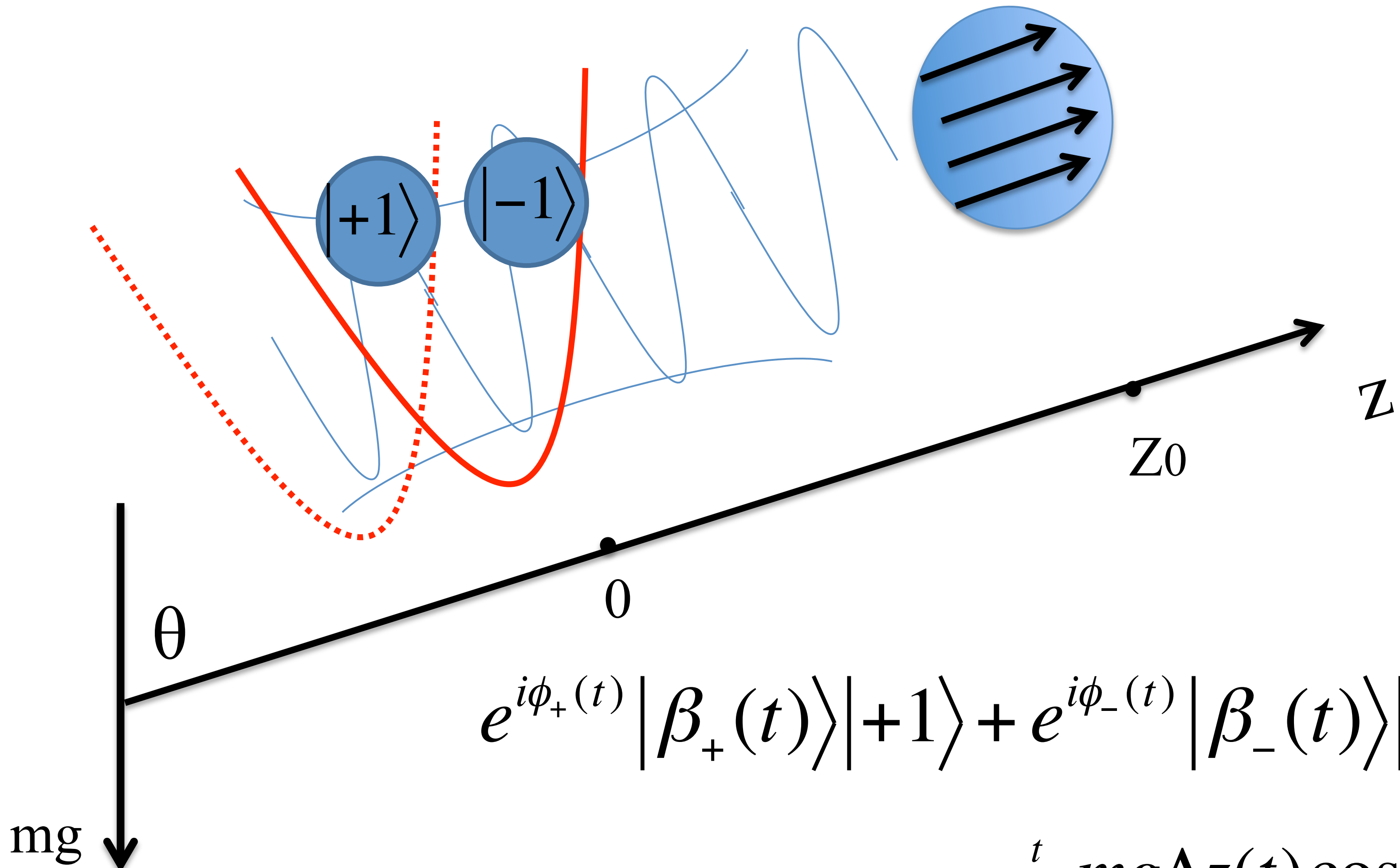
Ramsey Interferometry with a Levitated Thermal Mesoscopic Object



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

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

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 $|S_z=0\rangle$ 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?

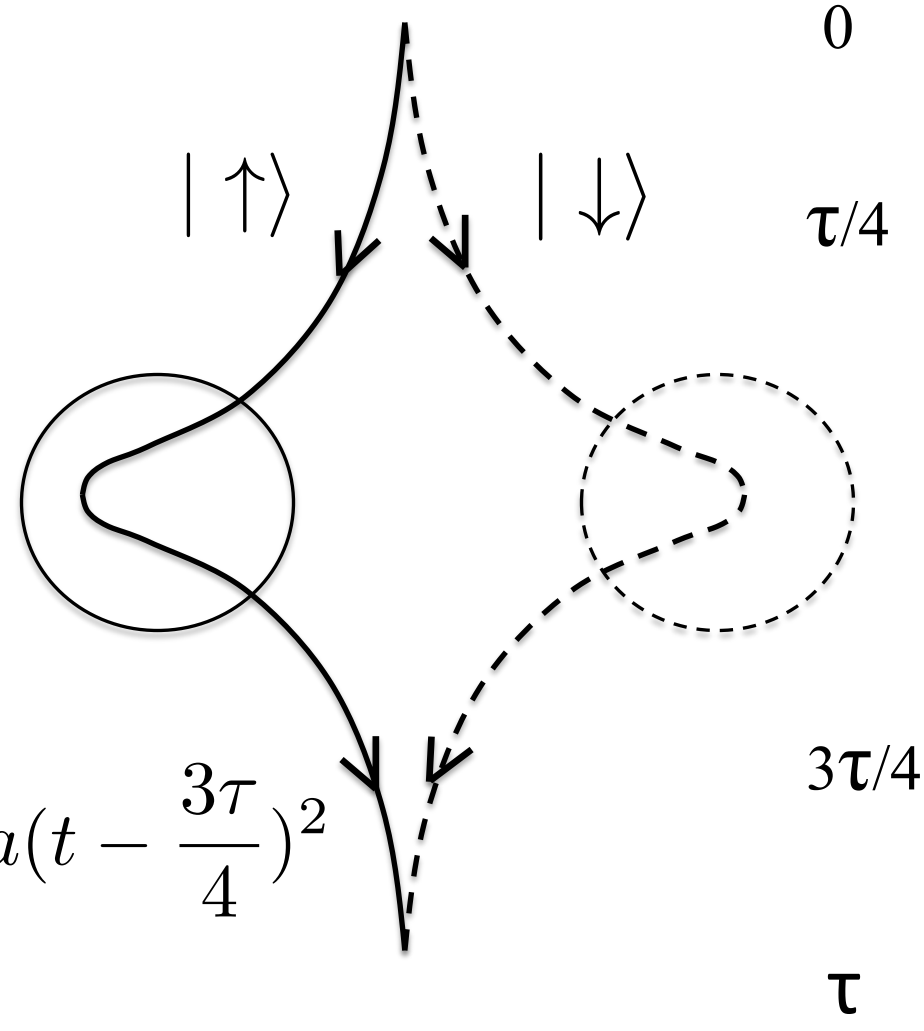
Already done by Ron Folman for atoms!!!: 1. Machluf et. al. Nature Comm. 2013, 2. Margalit et. al. 2018

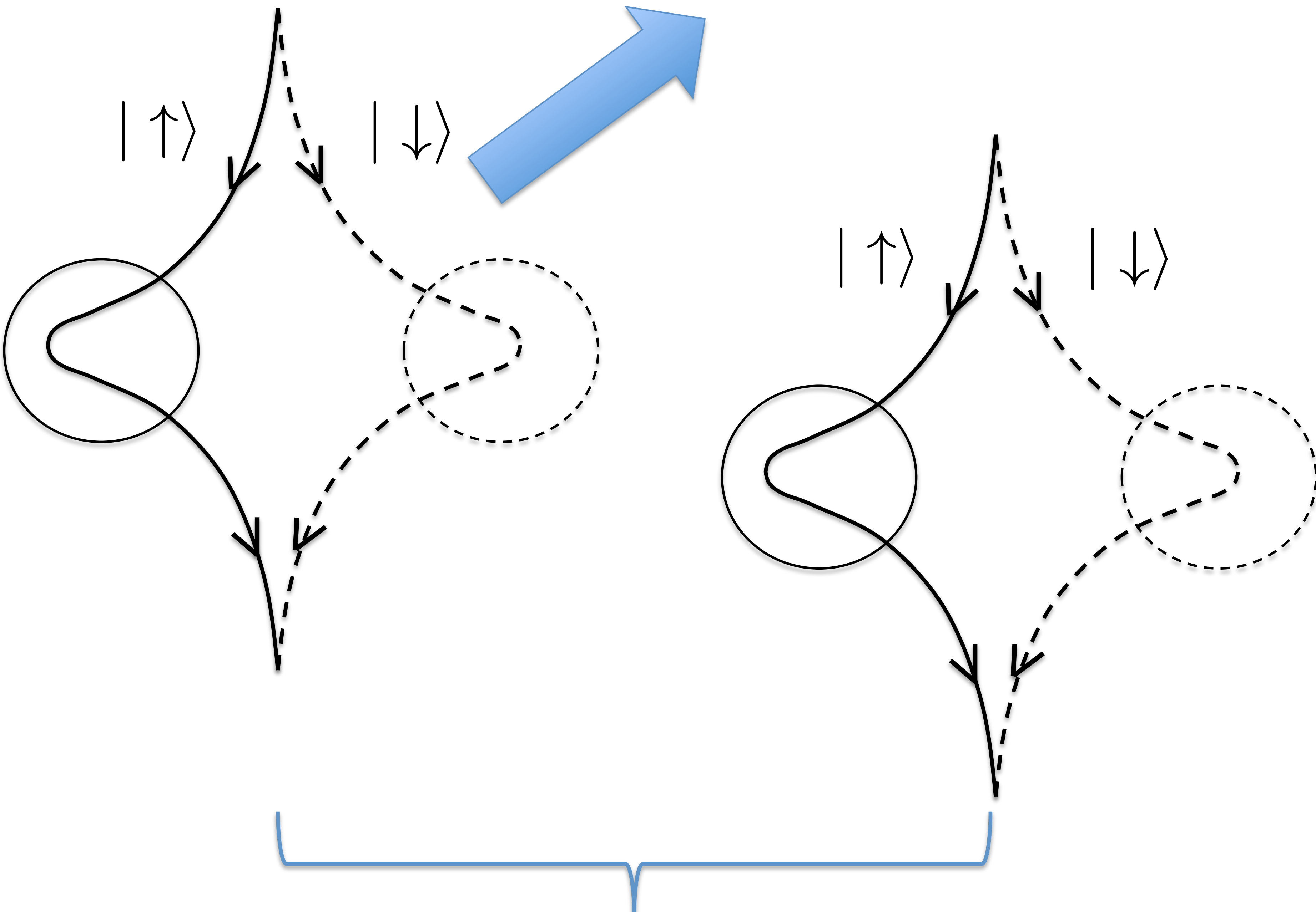
Free particle in an inhomogeneous magnetic field (acceleration +*a* or –*a*)

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

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

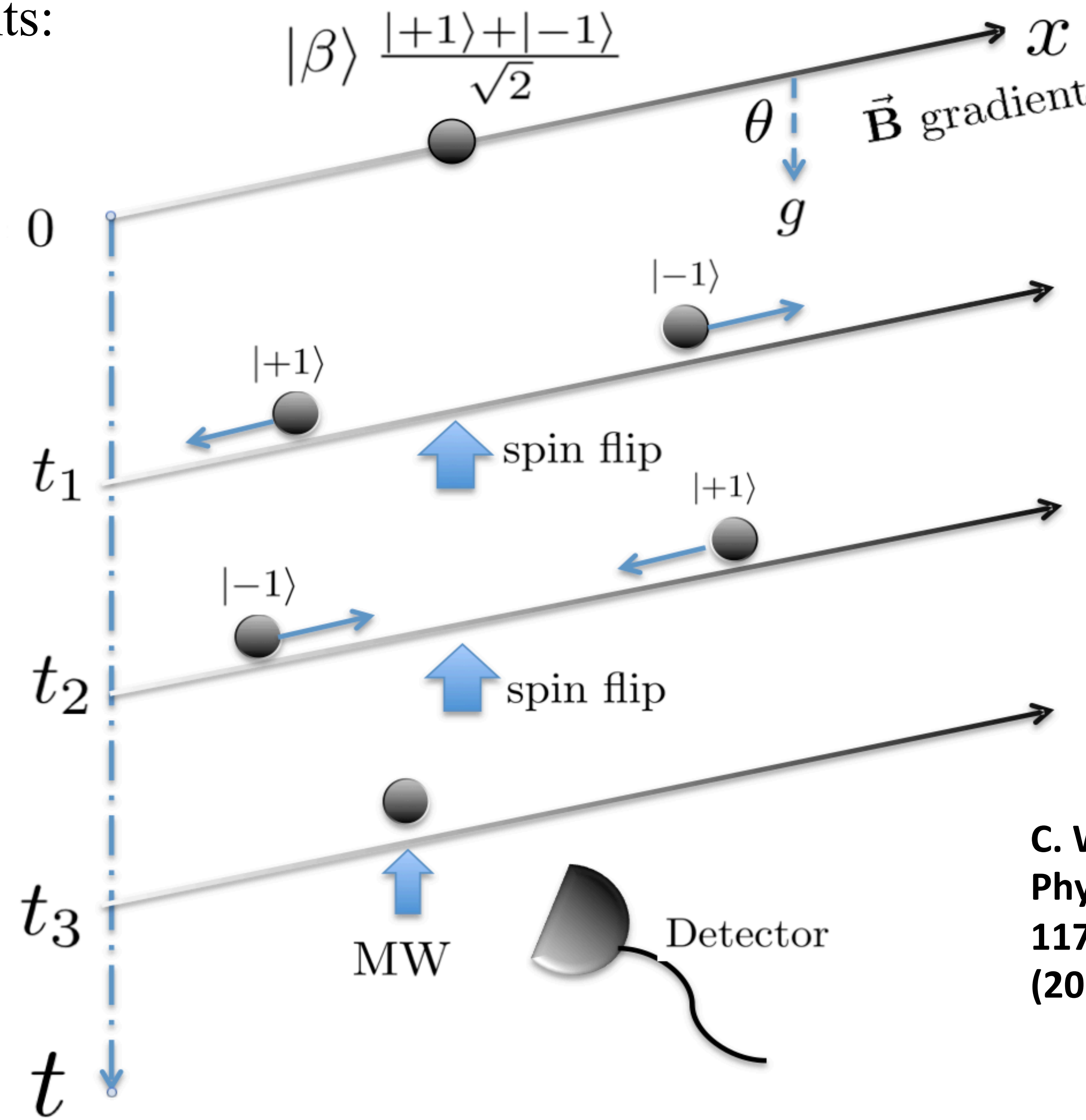
$$= \frac{1}{2}a(\frac{\tau}{4})^2 \mp \frac{a\tau}{4}(t - \frac{3\tau}{4}) \pm \frac{1}{2}a(t - \frac{3\tau}{4})^2$$





Same spin signal as long as the same field gradient gives the relative phase

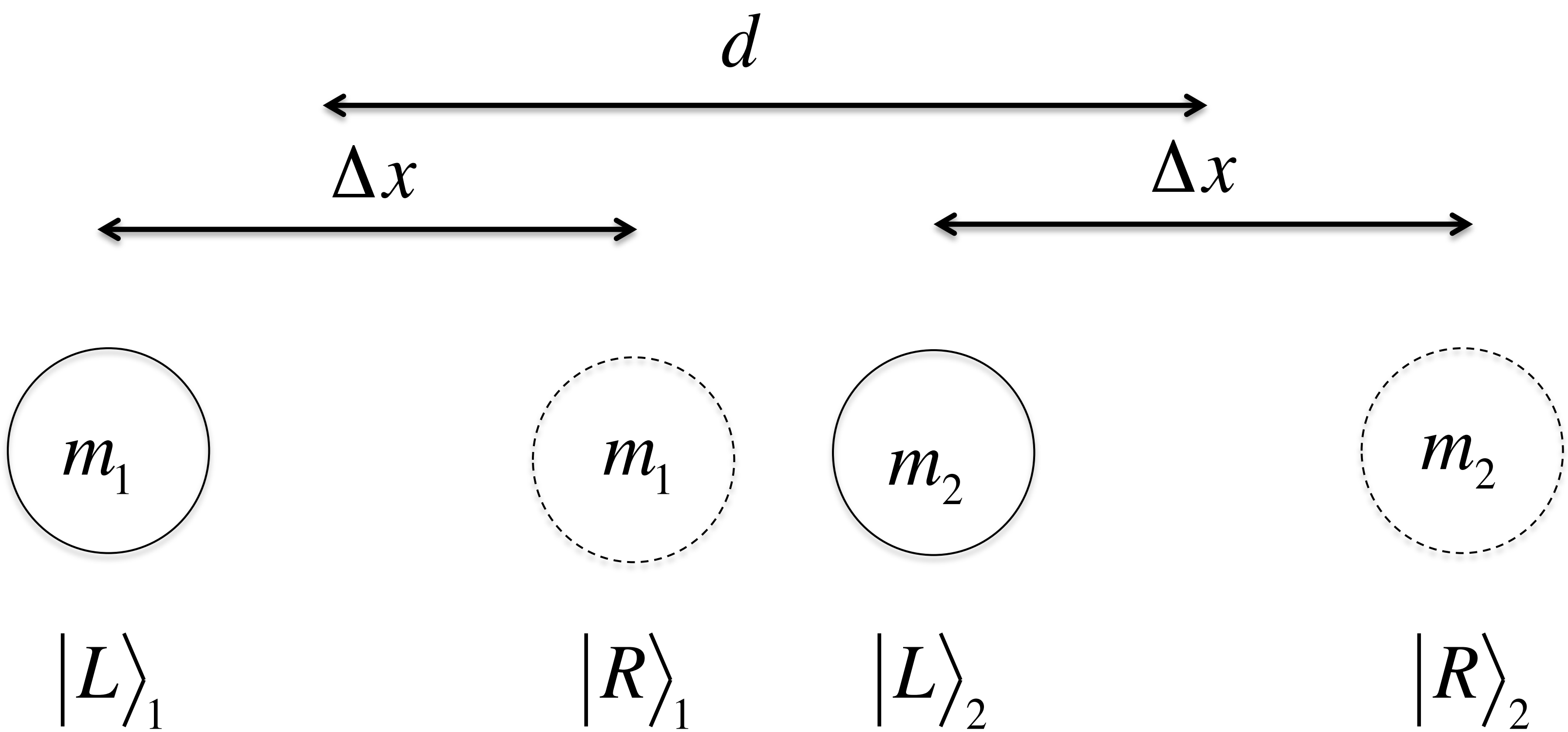
Free flight scheme able to achieve 100 nm separation among superposed components:



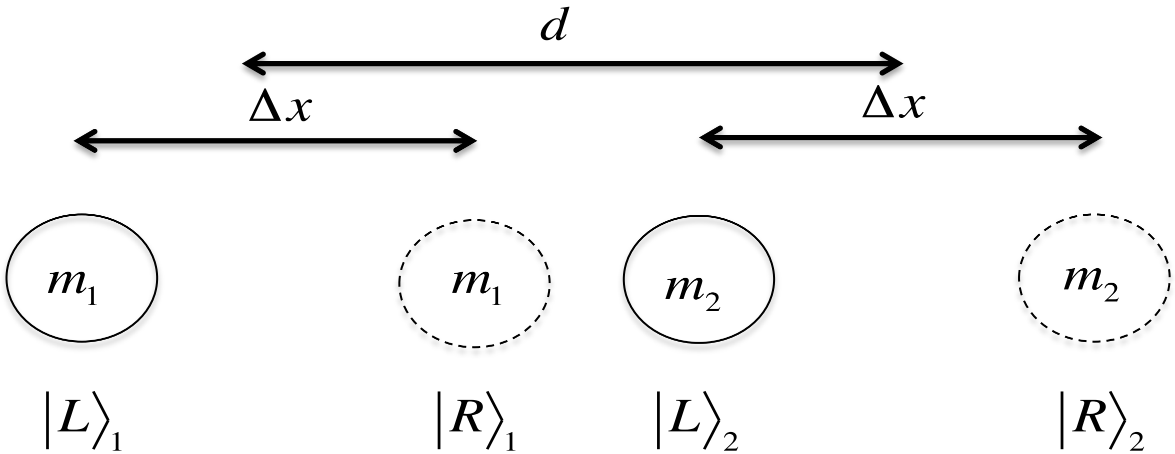
C. Wan et. al. , Phys. Rev. Lett. 117, 143003 (2016).

Two gravitationally interacting matter-wave interferometers

S. Bose *et. al.*, Phys. Rev. Lett. 119, 240401 (2017);
C. Marletto and V. Vedral, Phys. Rev. Lett. 119, 240402 (2017)



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

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

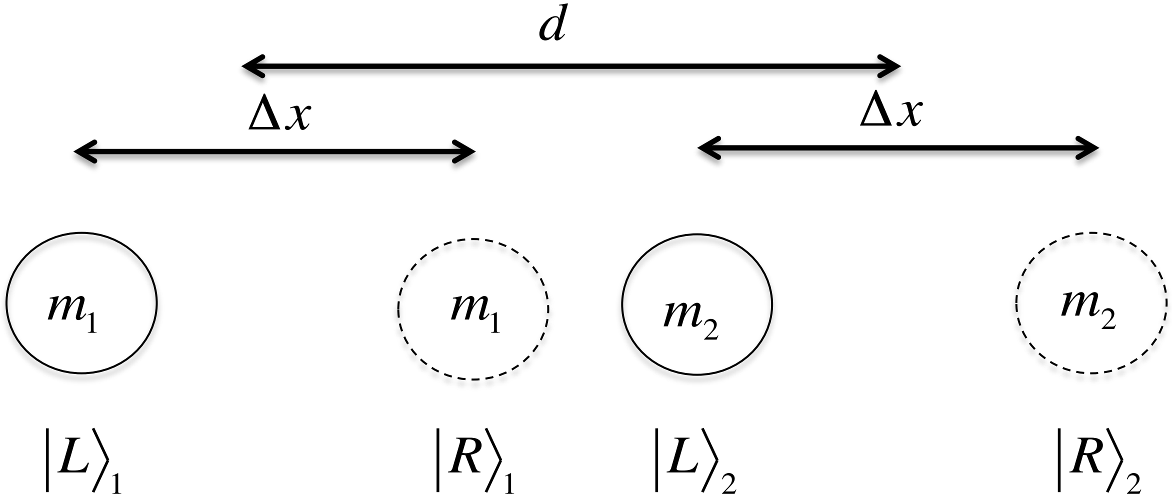
$$= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2)$$

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

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

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

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 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!

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*)

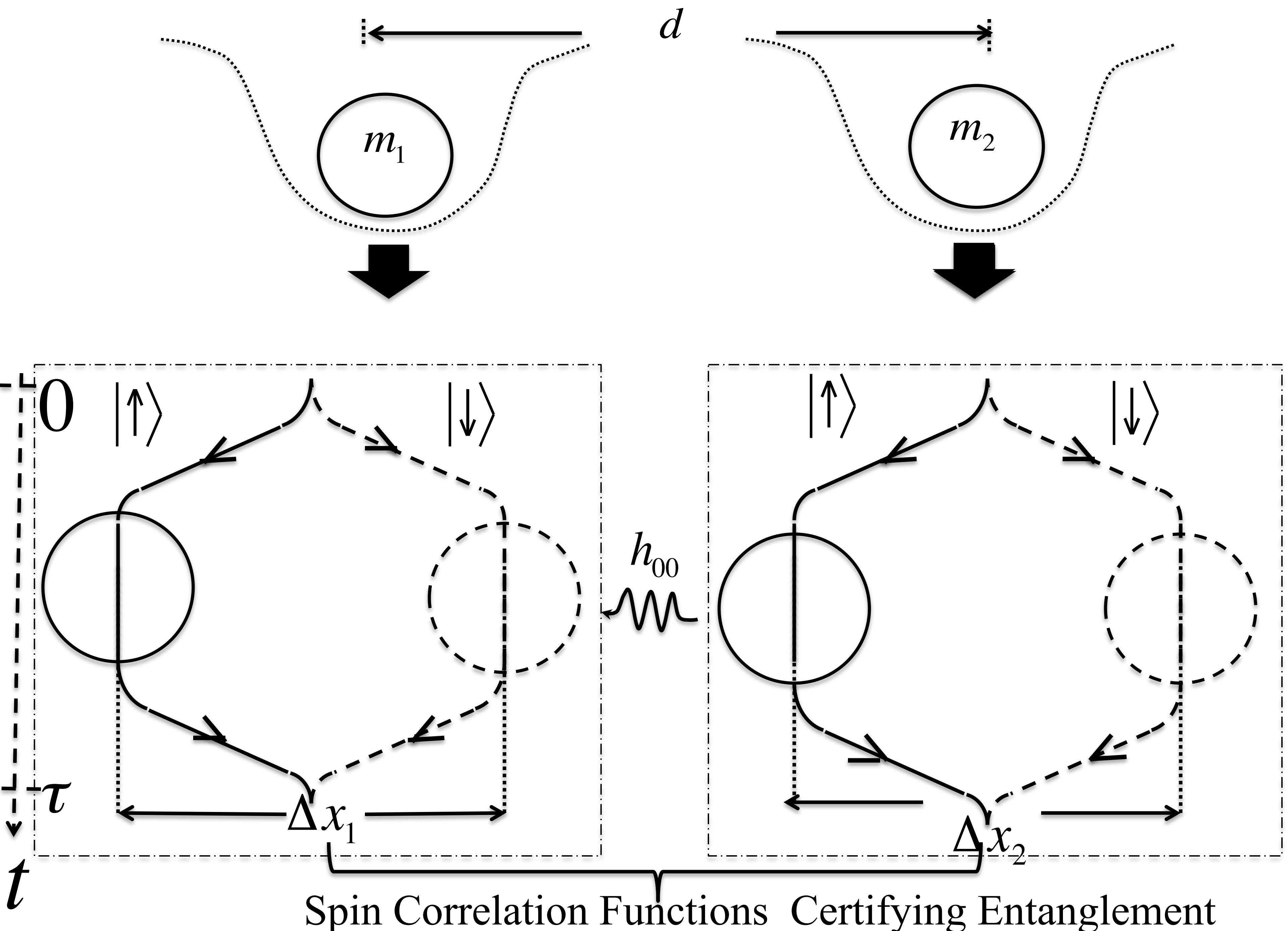
Step 3: SG recombination: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j, \; |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$

Step 4: Witness spin entangled state:

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

through the correlations:

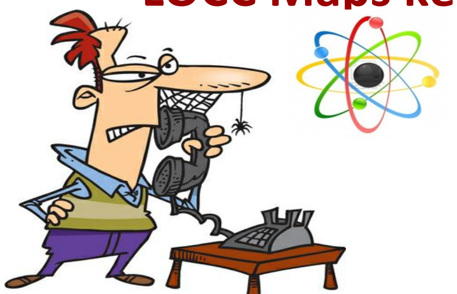
$$\mathcal{W} = |\langle\sigma_x^{(1)} \otimes \sigma_z^{(2)}\rangle - \langle\sigma_y^{(1)} \otimes \sigma_z^{(2)}\rangle|$$



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 the *non-classicality* of Gravity?

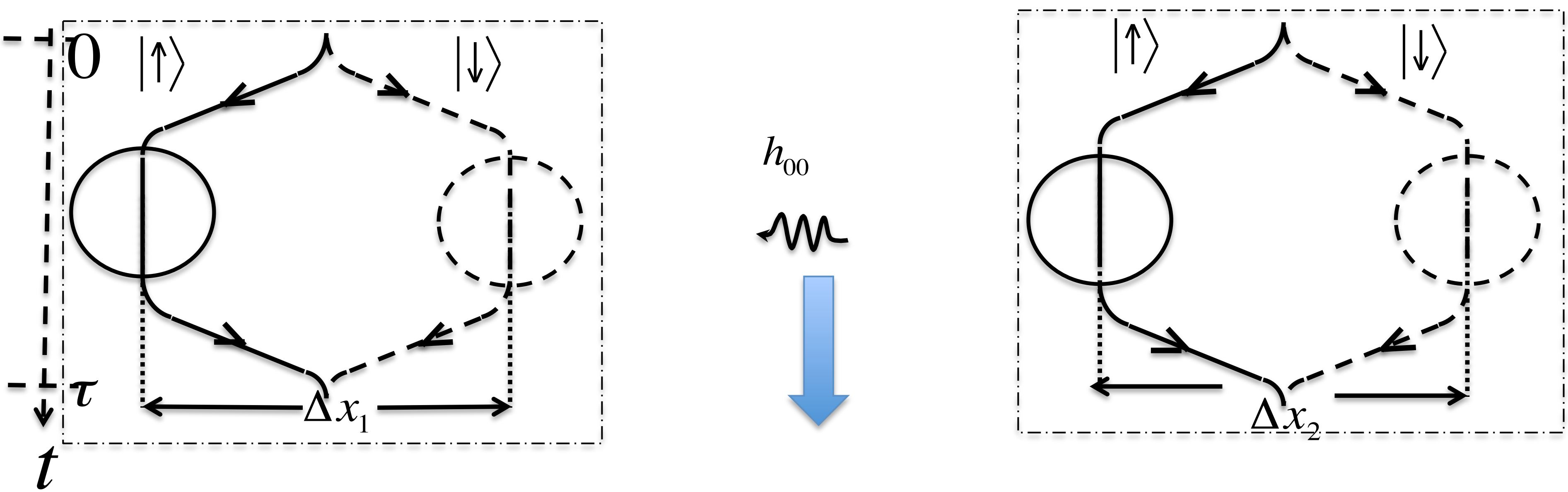
LOCC Maps keep separable states separable (*cannot* create entanglement!)



Local Operations and Classical Communication (LOCC)

1. Unitary evolution
2. Measurement

Classical mediator of information/bits



Cannot be classical if the spins in the masses get entangled

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

$$|\Psi(t)\rangle_{\mathrm{mat+grav}} = \frac{1}{2} \sum_{\xi,\xi' \in \{L,R\}} a^\dagger_{1,\xi} a^\dagger_{2,\xi'} |0\rangle \otimes \prod_{\mathbf{k}} e^{i\frac{(g_{1,\mathbf{k}} e^{i\mathbf{k}.\mathbf{r}_{1,\xi}} + g_{2,\mathbf{k}} e^{i\mathbf{k}.\mathbf{r}_{2,\xi'}})^2}{\omega_k} t} |\alpha_{\mathbf{k},\xi,\xi'}\rangle_{\mathbf{k}},$$

Supplementary Materials of Bose et. al. PRL 2017

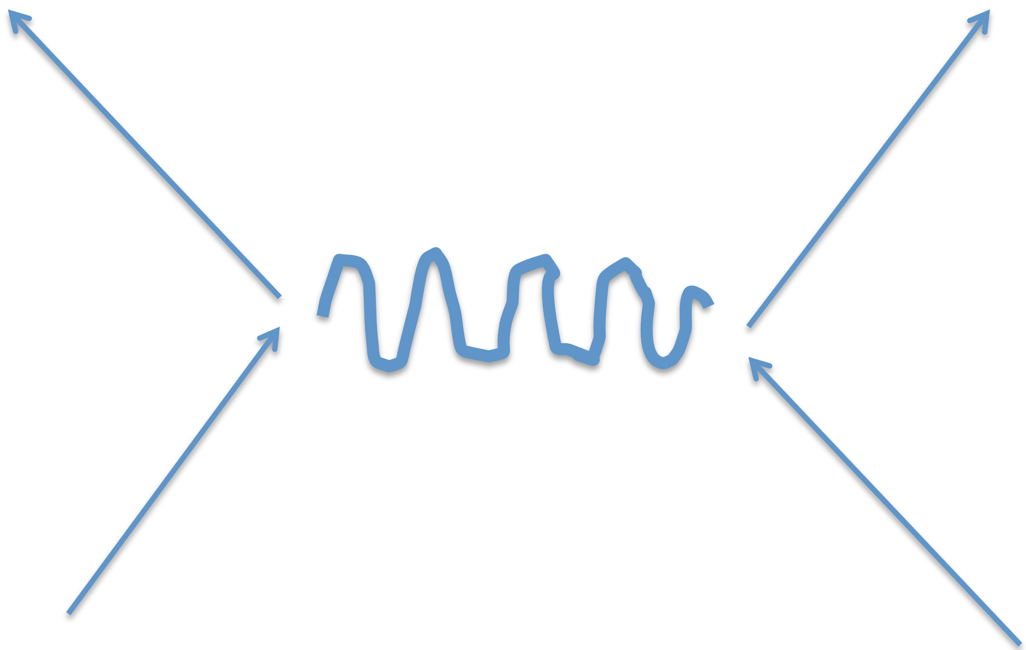
$$g_{j,\mathbf{k}} = m_j c^2 \sqrt{\frac{2\pi G}{\hbar c^3 k V}} \qquad \frac{g_{1,\mathbf{k}} g_{2,\mathbf{k}}}{\omega_k} \propto \frac{1}{k^2}$$

Superpositions of coherent states of the gravitational field

See also: Christodoulou & Rovelli, 2018 – Space-time superpositions

Marletto & Vedral, PRL 2017 — Mediator must have noncommuting variables.

Newtonian potential can be thought to be originating from the exchange of virtual (*off-shell*) gravitons (e.g., Quantum Field Theory in a Nutshell – A. Zee)



$$W(T) = -\frac{1}{2}\int \frac{d^4k}{(2\pi)^4} T^{00}(k)^* \frac{1+1-\frac{2}{3}}{k^2 - m^2 + i\varepsilon} T^{00}(k)$$

Based on this, a fully covariant treatment can be made:
Marshman, Mazumdar, Bose, arXiv:1907.01568

How do we know whether the above process is right (i.e. something quantum is exchanged?)

3 assumptions (which were implicit in our proposal):

- **Locality** of Physical Interactions:

$$\kappa^2 h_{\mu\nu}(\vec{r},t)T^{\mu\nu}(\vec{r},t)$$

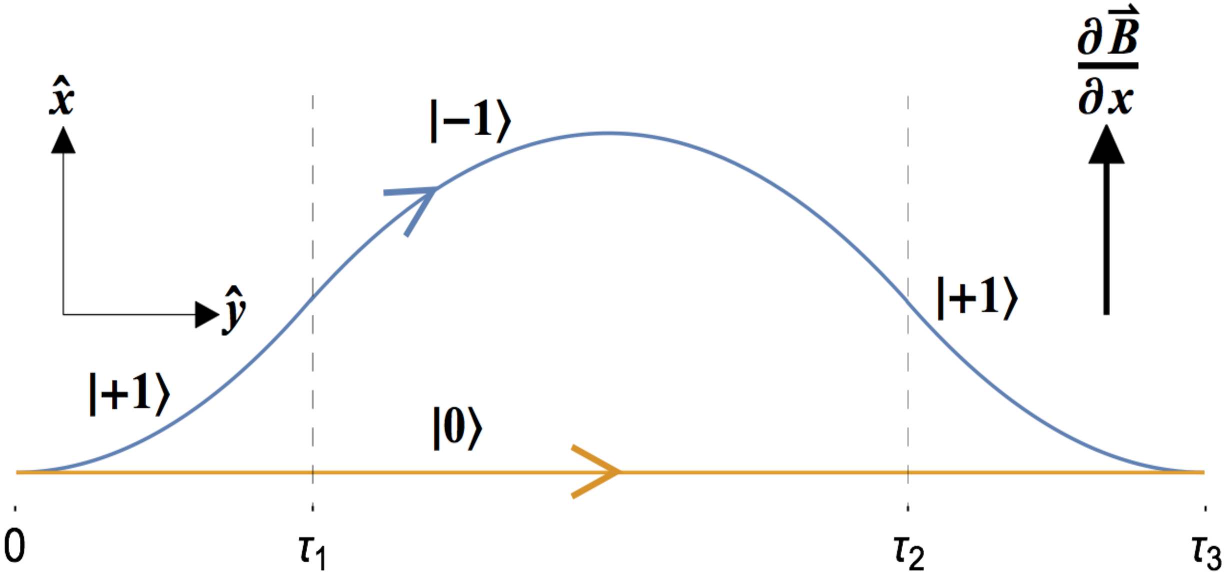
- Linearized Gravity (not sure this assumption is needed, but safe);

$$g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu} \qquad |\kappa h_{\mu\nu}| \ll 1$$

- A reasonable definition of classicality:

$$P_j \ , \ \{|j\rangle\langle j|, h^j_{\mu\nu}\}$$

Marshman, Mazumdar, Bose, arXiv:1907.01568



Compact meter scale detectors for Gravitational waves:

Ryan J. Marshman, Anupam Mazumdar, Gavin W. Morley, Peter F. Barker, Steven Hoekstra, Sougato Bose, arXiv:1807.10830

$$S \approx m \int \left[c^2 \left(1 - \frac{h_{00}}{2} \right) - c h_{0j} v^j - (\eta_{ij} + h_{ij}) \frac{v^i v^j}{2} \right] dt$$

$$\Delta S\left(h_{00}\right) = mc^2 a\tau_1^3\left(\partial_x h_{00} + \frac{23}{60}a\tau_1^2\partial_x\partial_x h_{00} + ...\right),$$

$$\Delta S\left(h_{0j}\right) = mcav_y\left(-2\tau_1^3\partial_y h_{0x} + 2\tau_1^3\partial_x h_{0y}\right.$$

$$\left. + \frac{23}{30}a\tau_1^5\partial_x\partial_x h_{0y} + ...\right),$$

$$\Delta S\left(h_{ij}\right) = \frac{-2}{3}h_{xx}ma^2\tau_1^3 + ... = \frac{-2}{3}h_{xx}mv_x^2\tau_1 + ...$$

a mass of 10^{-16}kg in a $\sim$ 1mm interferometer with interrogation time $\tau_1 \sim 100$ms gives a detection of acceleration with sensitivity down to $10^{-16}\text{ms}^{-2}\text{Hz}^{-1/2}$ when a flux of $N = 200$ objects

Compact meter scale detectors for Gravitational waves:

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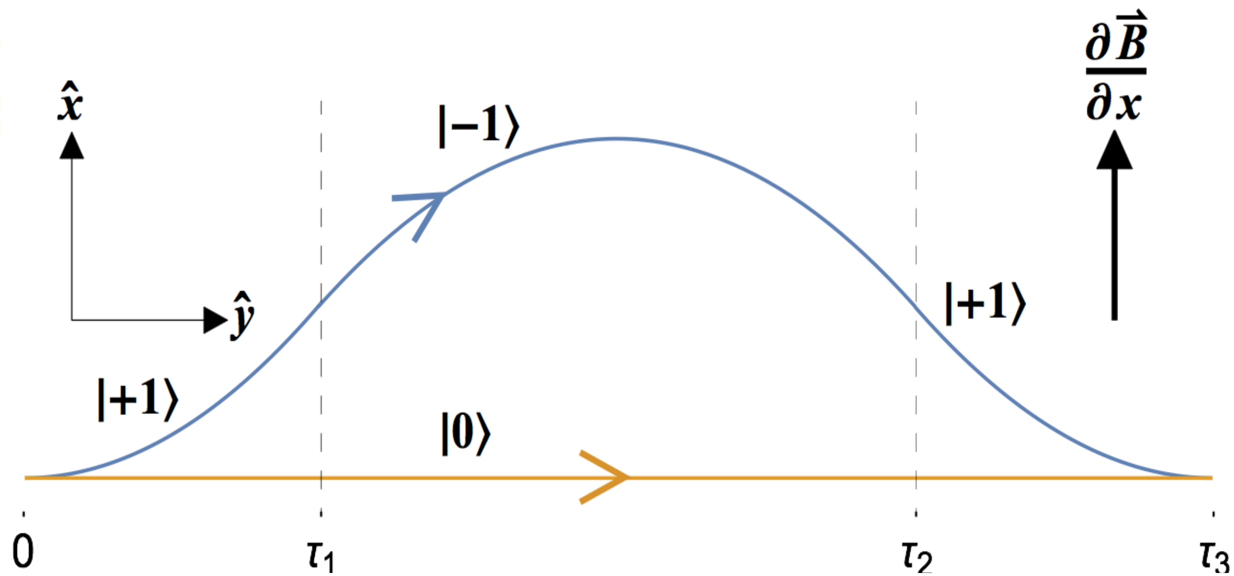
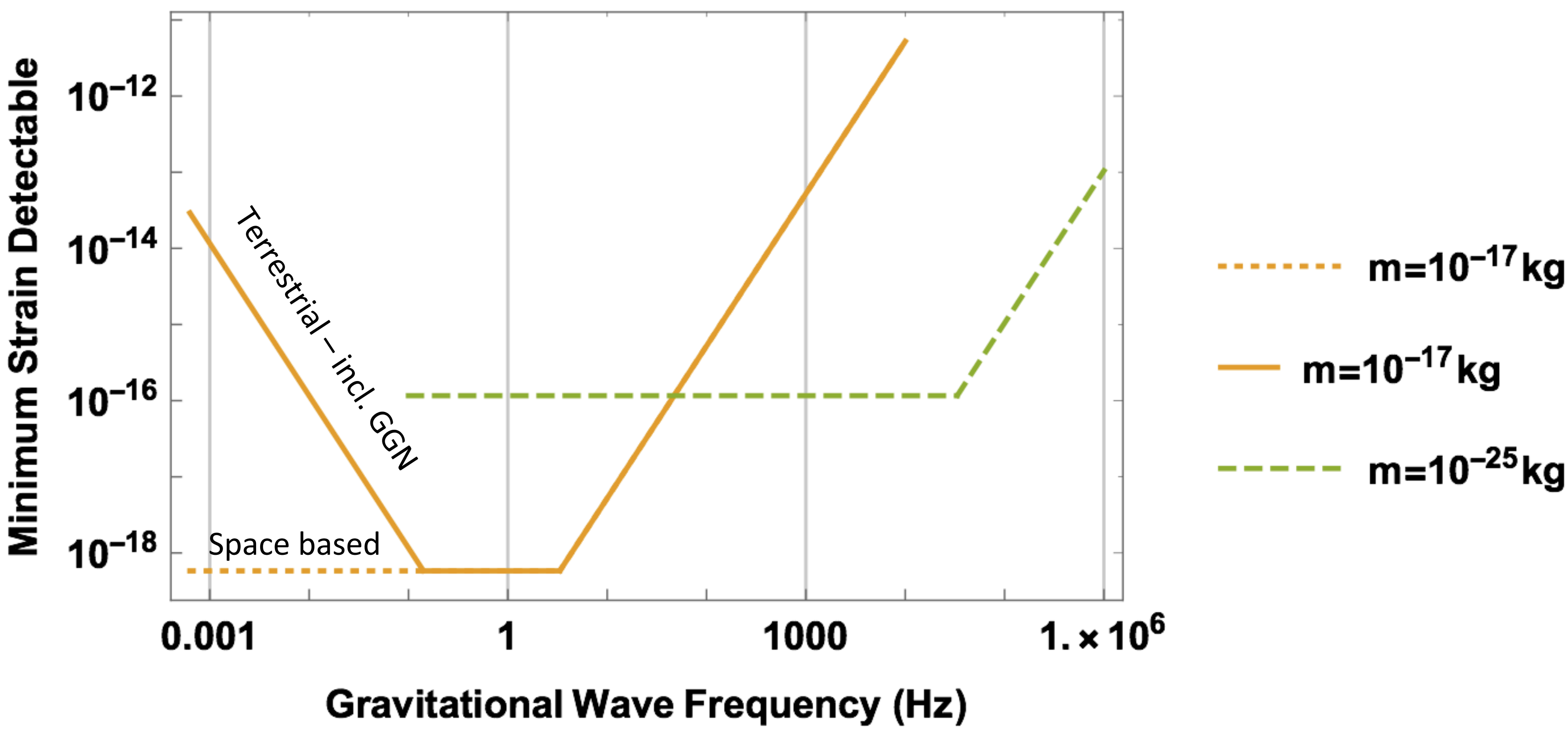
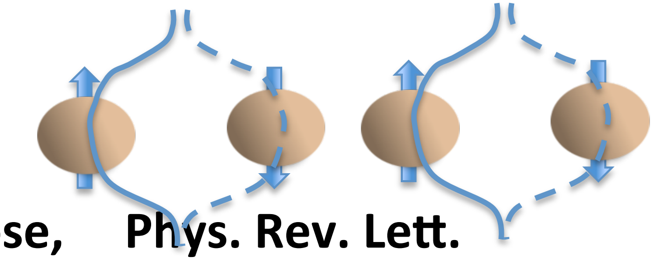




Some papers



- Large mass, small scale of superpositions:

M. Scala, M. S. Kim, G. W. Morley, P. F. Barker, S. Bose, Phys. Rev. Lett. 111, 180403 (2013).

- Large mass, large scale superpositions:

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