Quantum Superpositions of Macroscopic Objects as Probes for Fundamental Physics

Sougato Bose

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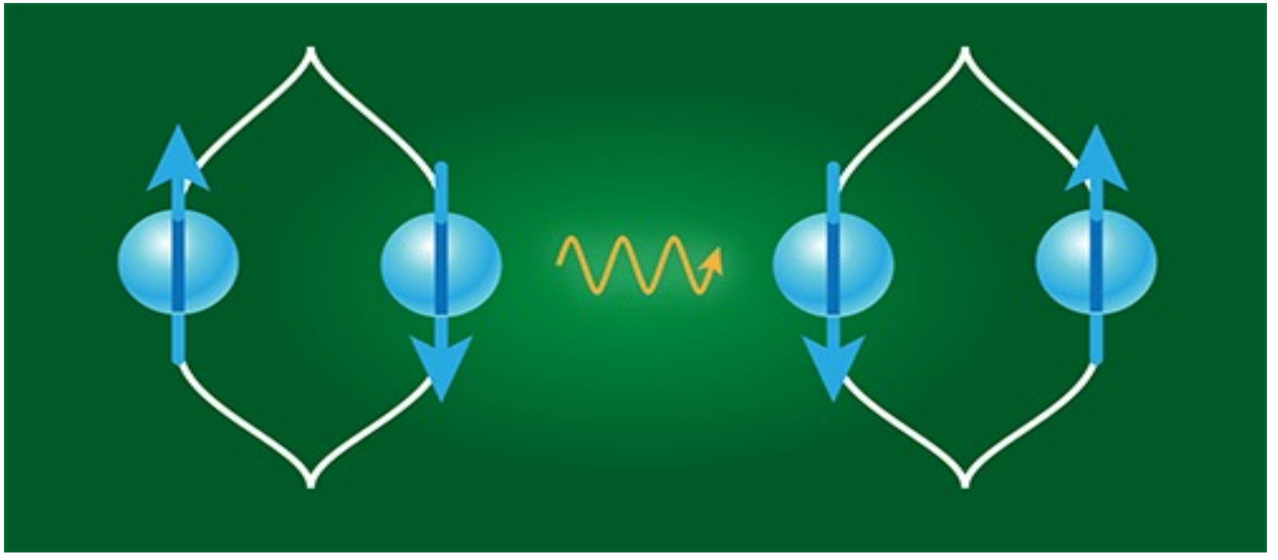
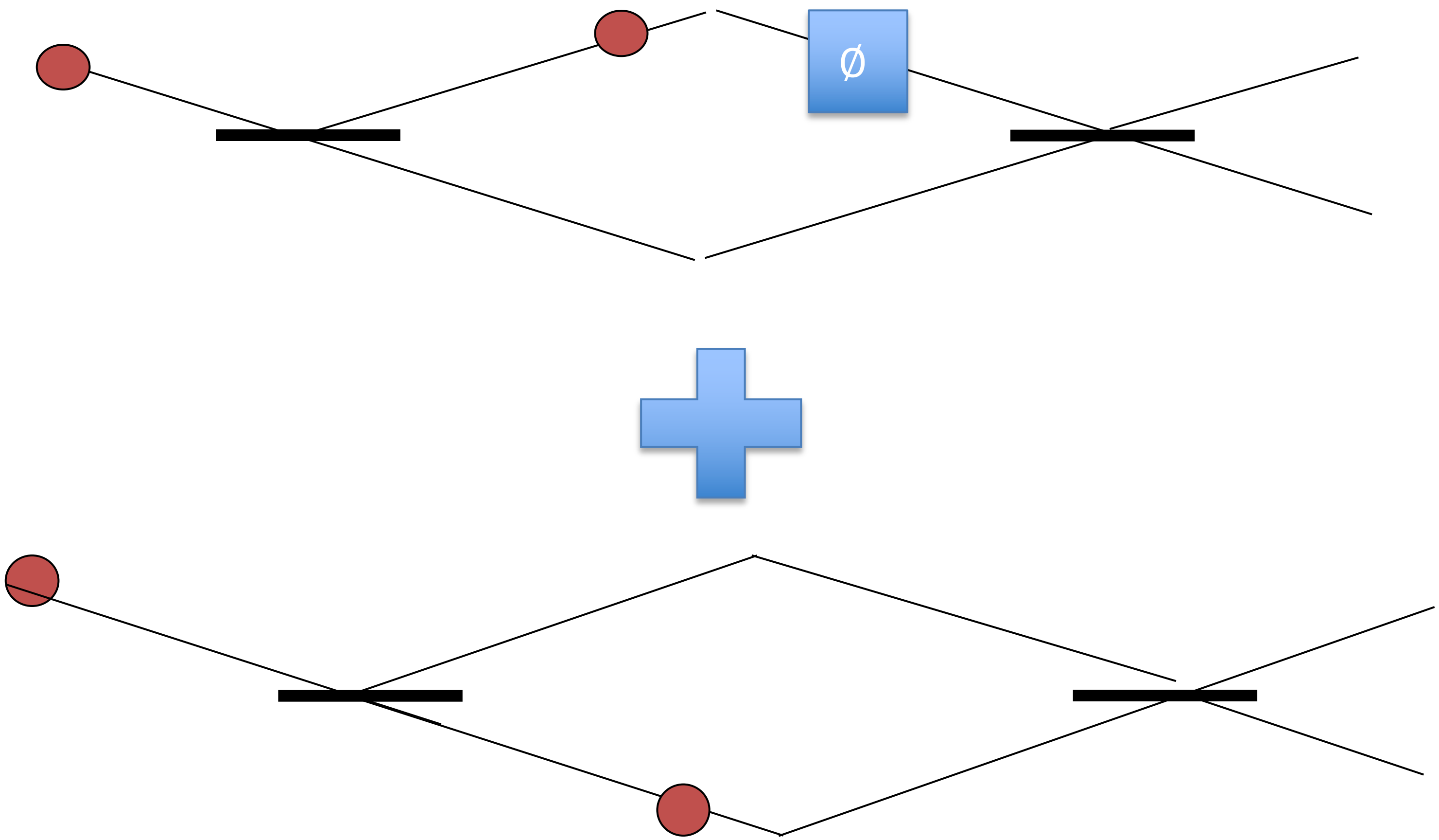


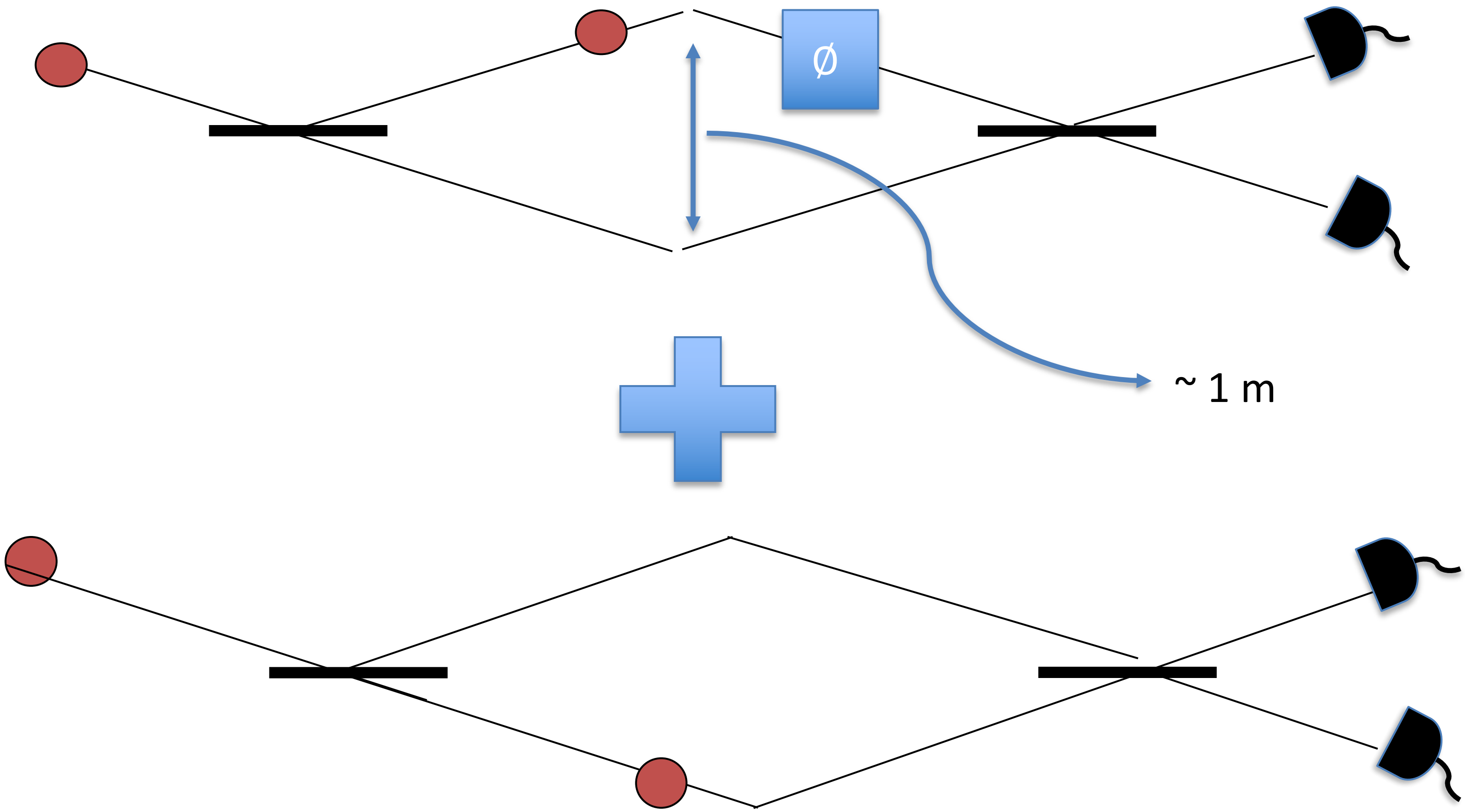
Talk to KCL theory, 2023

The type of experiment needed for the demonstration of quantum superpositions



Different from testing energy level quantization (?).
Different from testing higher order corrections (?).

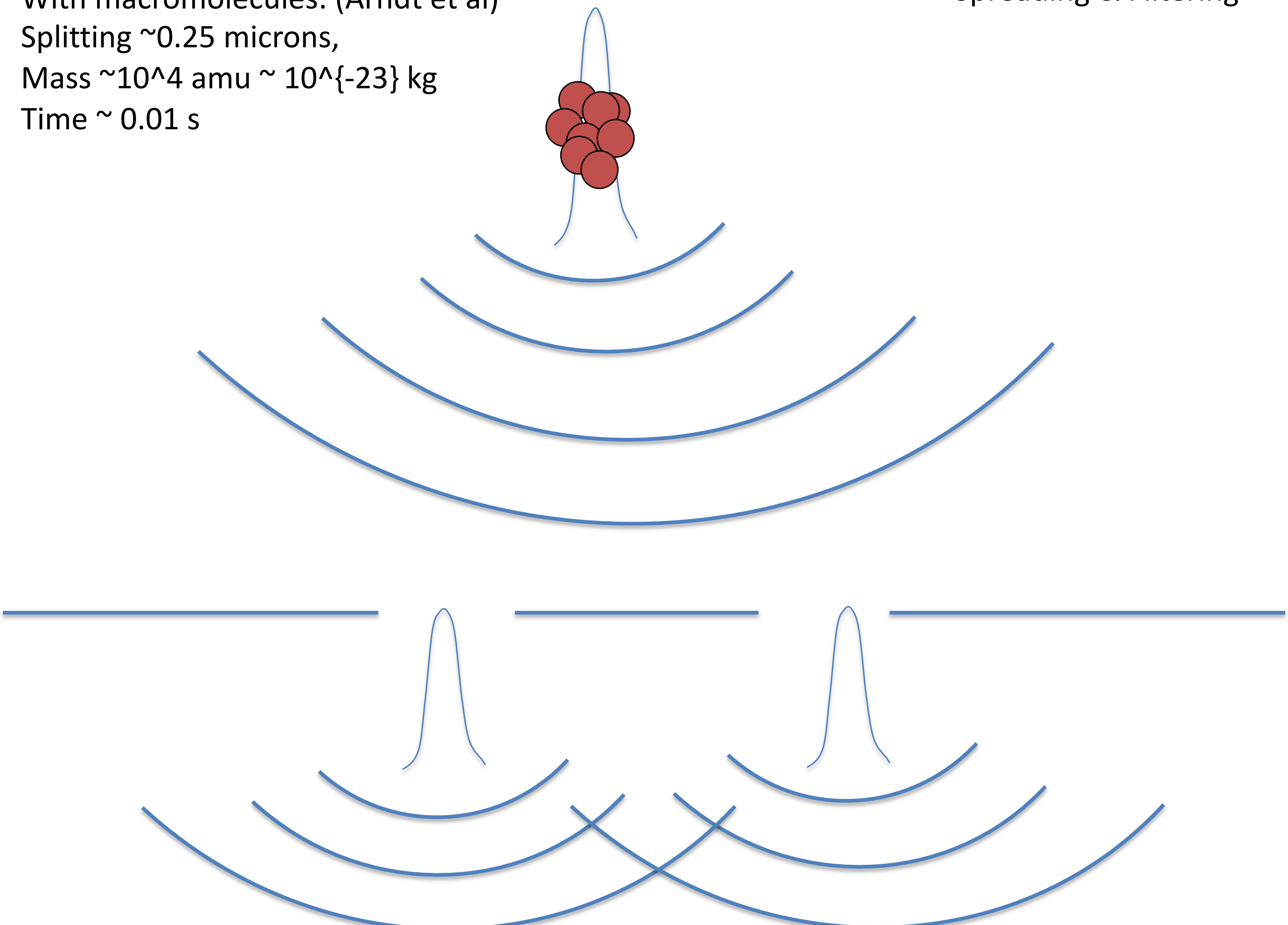
With atoms: (Kovachy, Asenbaum, Kasevich et al). [With internal states – Ramsay-Borde; Also Stern-Gerlach possible, described later]



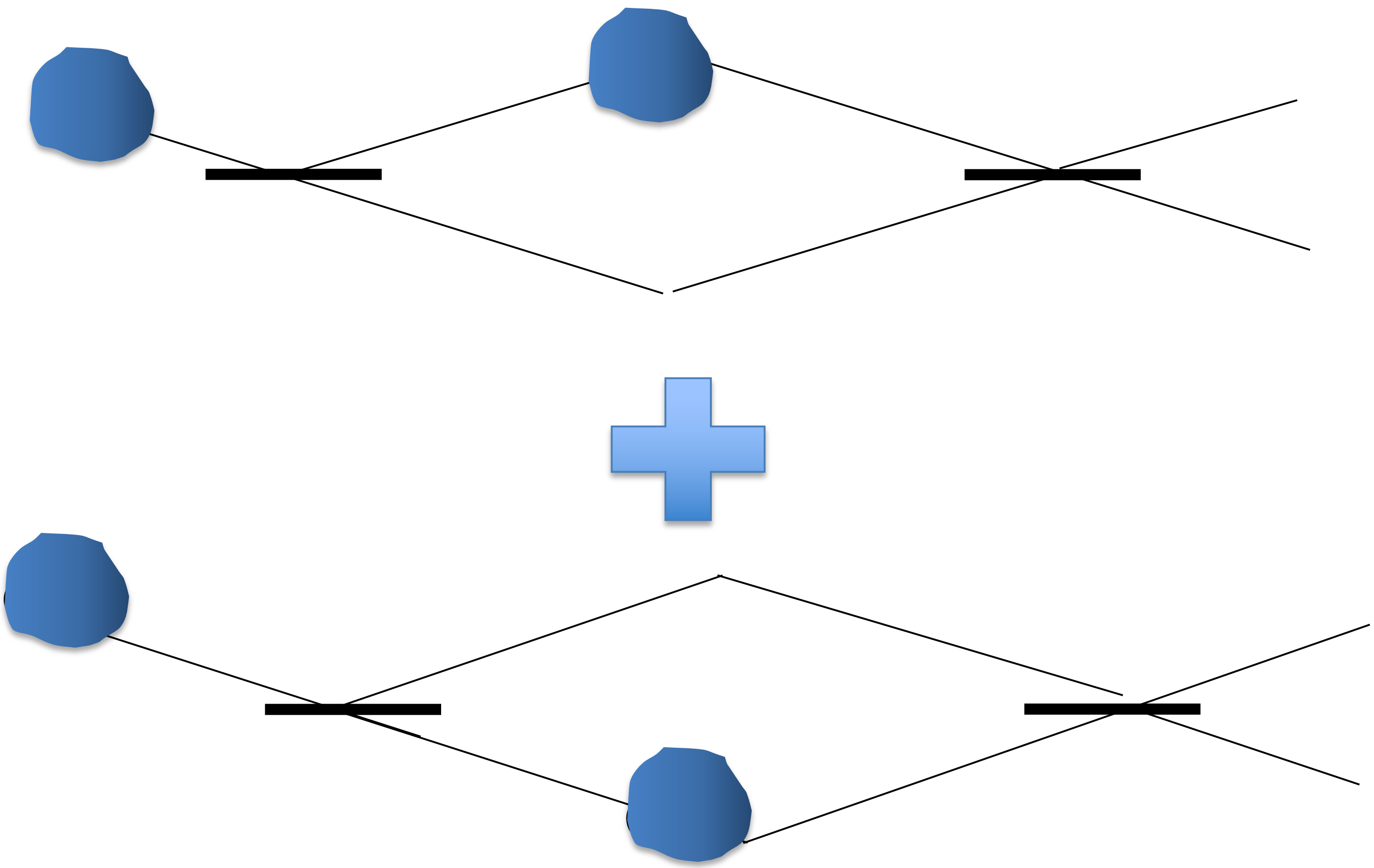
Splitting ~ 1 m, Mass ~ 100 amu ~ 10^{-25} kg, Time ~ 1 s

With macromolecules: (Arndt et al)
Splitting ~0.25 microns,
Mass ~10^4 amu ~ 10^{-23} kg
Time ~ 0.01 s

Spreading & Filtering



What we want [Just to ***extend*** the boundaries of QM):



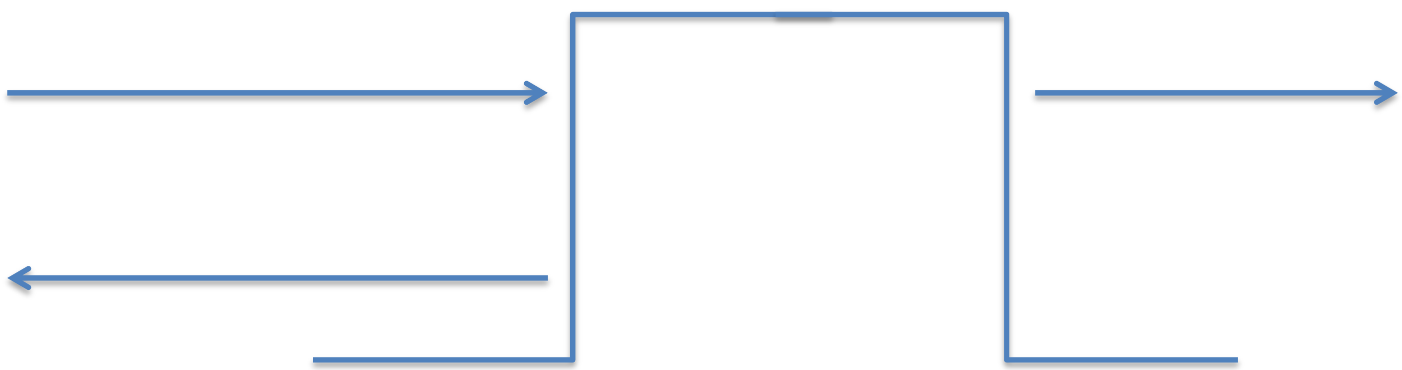
What we require in *each interferometer* are NOON States!

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

Coherent states, such as in a BEC interferometer do not suffice!
You just cannot *assume* a Mach-Zhender interferometer of 10^{-15} kg objects!

We first concentrate just on creating the LMLSLD interferometry (thinking of coherence later)

Ideal Superposition generation mechanism (not possible for large masses and distances):



$$e^{-\frac{\sqrt{2mV}}{\hbar}\Delta x}$$

For 10^{-15} kg masses over 10 microns distances, V ~ initial KE ~ 10^{-24} eV.

Another technique (as used for macro-molecules): not too bad, but requires more Initial squeezing. Spreading of the wavepacket, followed by measurement/filtering.

$$\delta x(t) \sim \frac{\hbar t}{2m\delta x(0)}$$

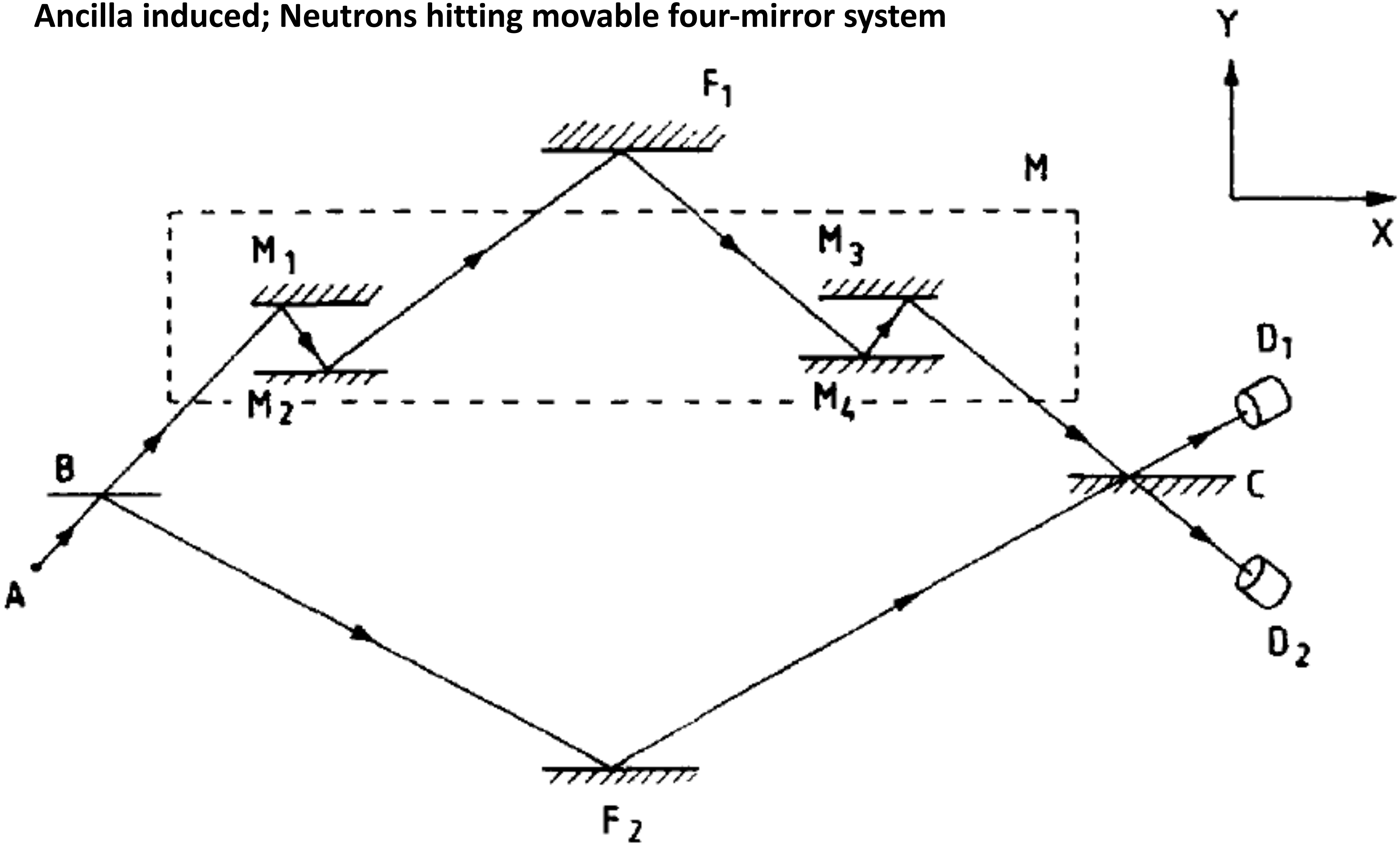
We need squeezing to 10 fm for it to expand to 10 microns in 1s.

If measuring by light, this requires, 10^16 photons. These number

of photons will still heat the diamond to 10,000 K

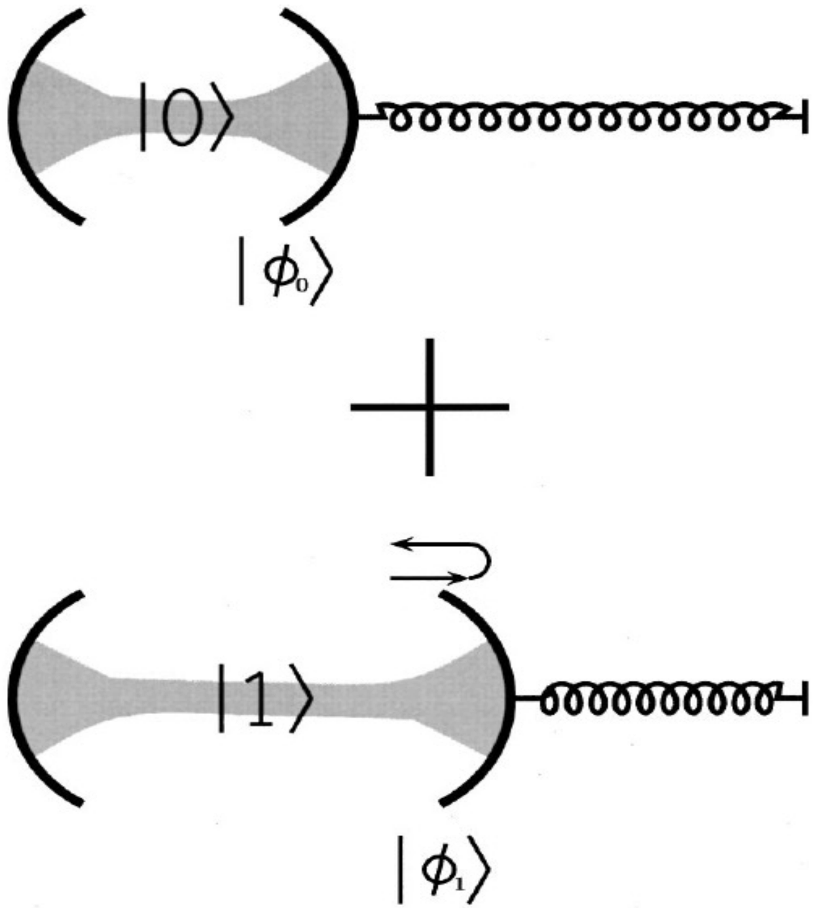
$$\Delta T \sim \frac{(1 - e^{\frac{r}{l_{abs}}}) n_{phot} \hbar \omega_{phot}}{m C_v}$$

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.

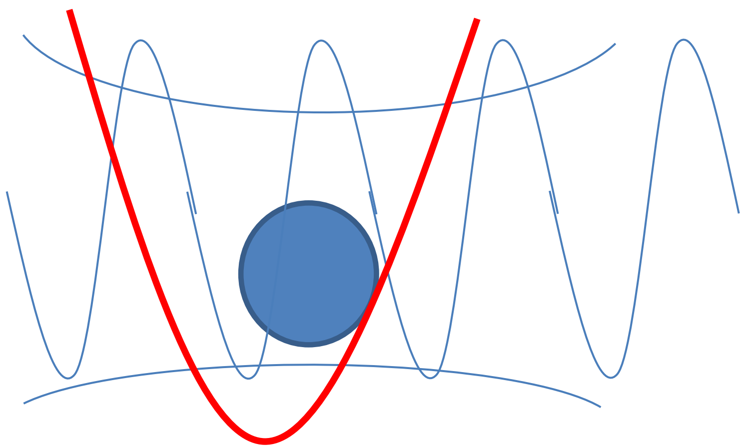
Armour, Blencowe, Schwab, PRL 2002.
Marshall, Simon, Penrose, Bouwmeester, PRL 2003.
Decoherence & Recoherence is used to certify superpositions

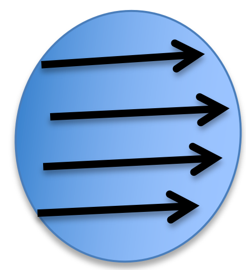
Bose, PRL 2006.

Interferometry with a Levitated (trapped) Thermal Mesoscopic Object

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

No cavity,
no cooling.

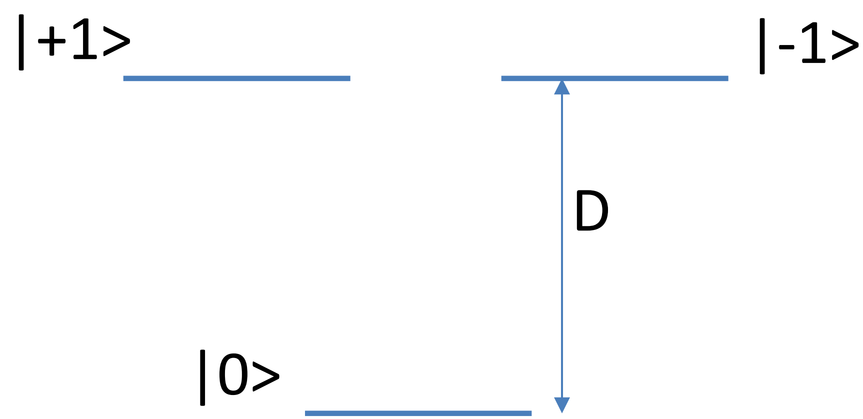




$$F = \sigma_z \mu_B \frac{\partial B}{\partial x}$$

Initial State:

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



Scala et al PRL 2013

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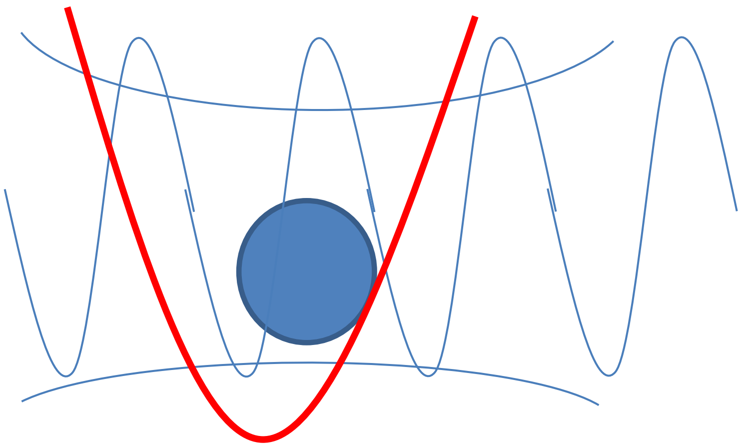
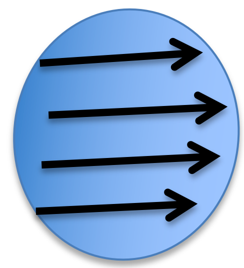
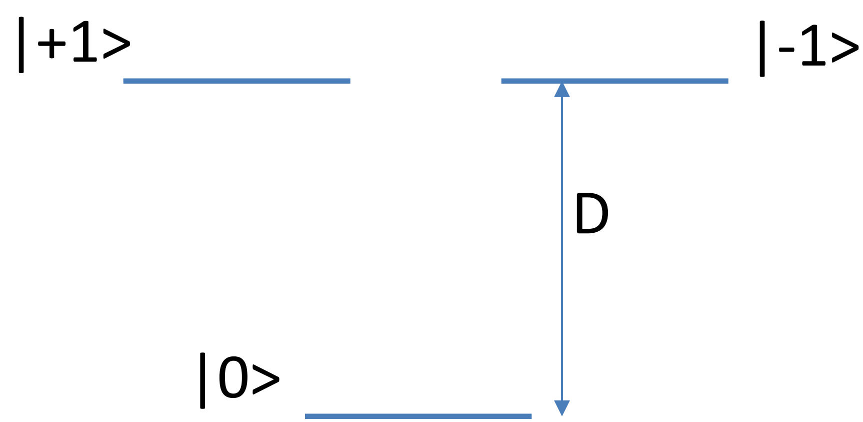




$$F = S_z \mu_B \frac{\partial B}{\partial x}$$

Step 1:

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



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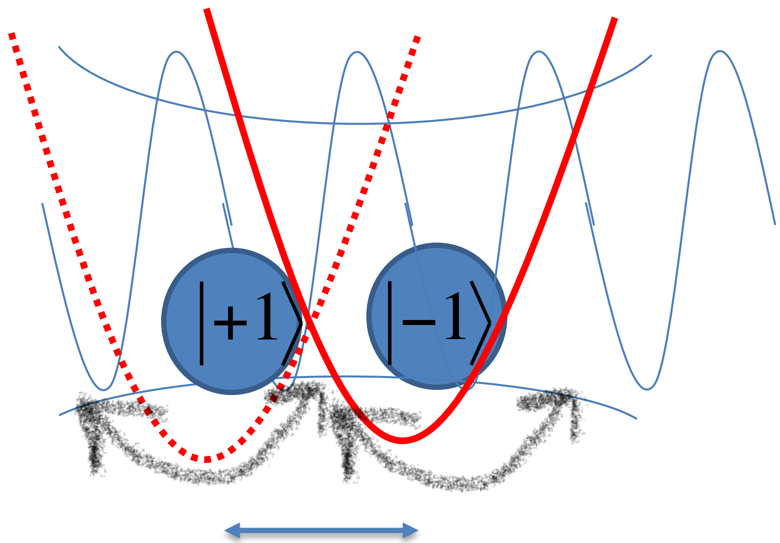
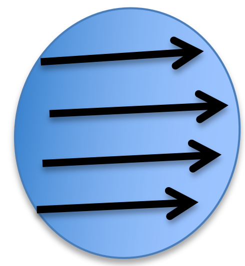


$$\Delta x = \frac{F}{m\omega_m^2}$$



Advantage: Interferometry naturally completed

Disadvantage: Acceleration not always present

Scala et al PRL 2013. (Restricted to 10 pm for a 10^{-17} kg mass)

Time Evolution:

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

Stern-Gerlach Interferometry of an untrapped (*free*) object can increase the scale of the superposition

Y Margalit et. al.,Science advances 7, eabg2879 (2021); S Machluf, Y Japha, R Folman, Nature communications 4, 1-9 (2013).

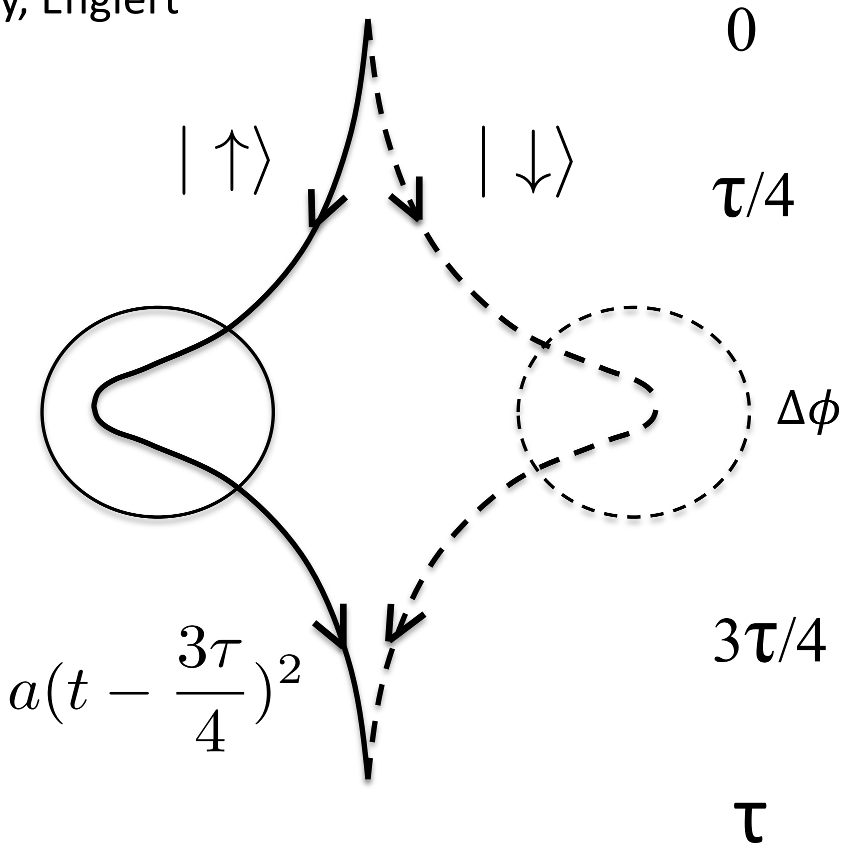
C. Wan, M. Scala, G. W. Morley, ATM. A. Rahman, H. Ulbricht, J. Bateman, P. F. Baker, S. Bose, M. S. Kim, Phys. Rev. Lett. 117, 143003 (2016).

The Humpty-Dumpty effect (Schwinger, Scully, Englert

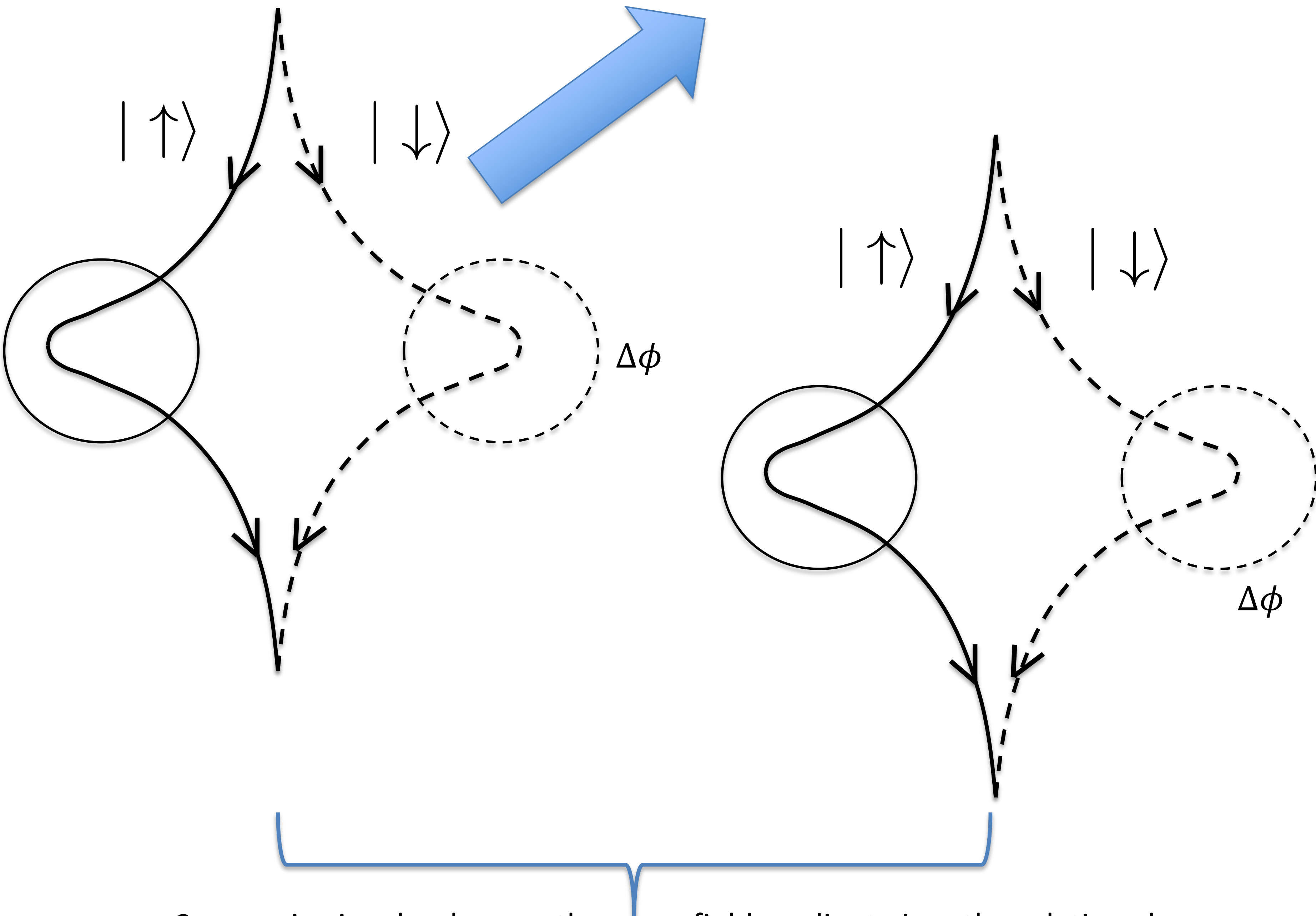
$$x_\sigma(t,j) = x_j(0) \pm \frac{1}{2}at^2$$

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

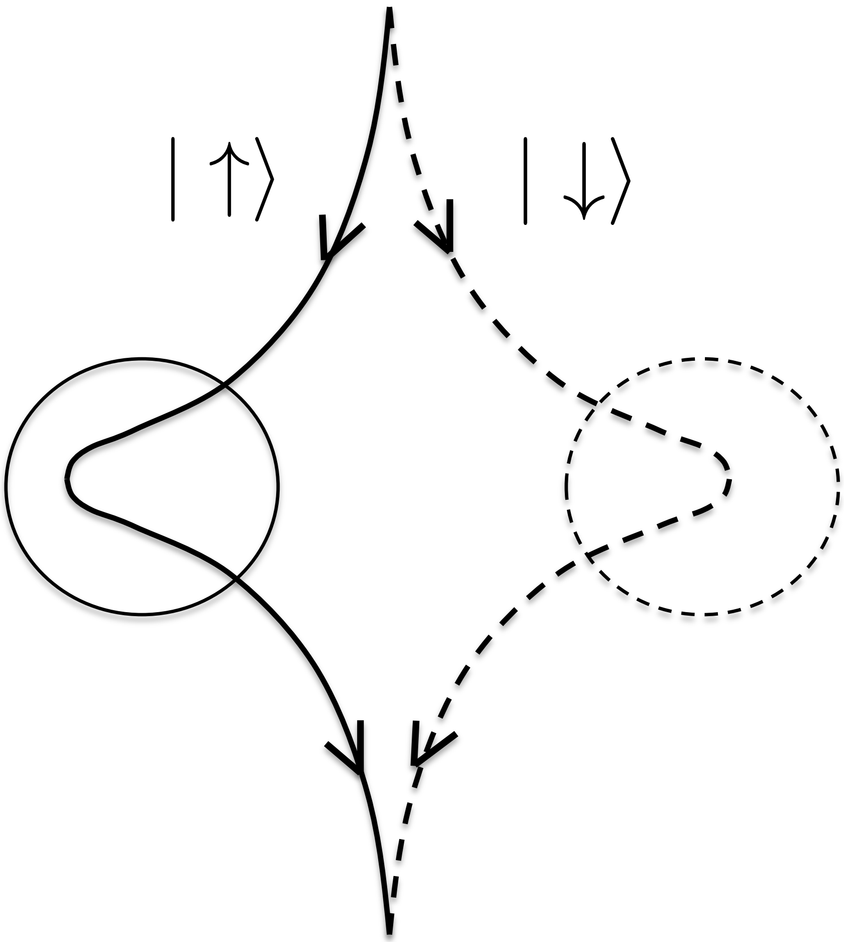
$$= \frac{1}{2}a(\frac{\tau}{4})^2 \mp \frac{a\tau}{4}(t-\frac{3\tau}{4}) \pm \frac{1}{2}a(t-\frac{3\tau}{4})^2$$



A very important effect was forgotten here!



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



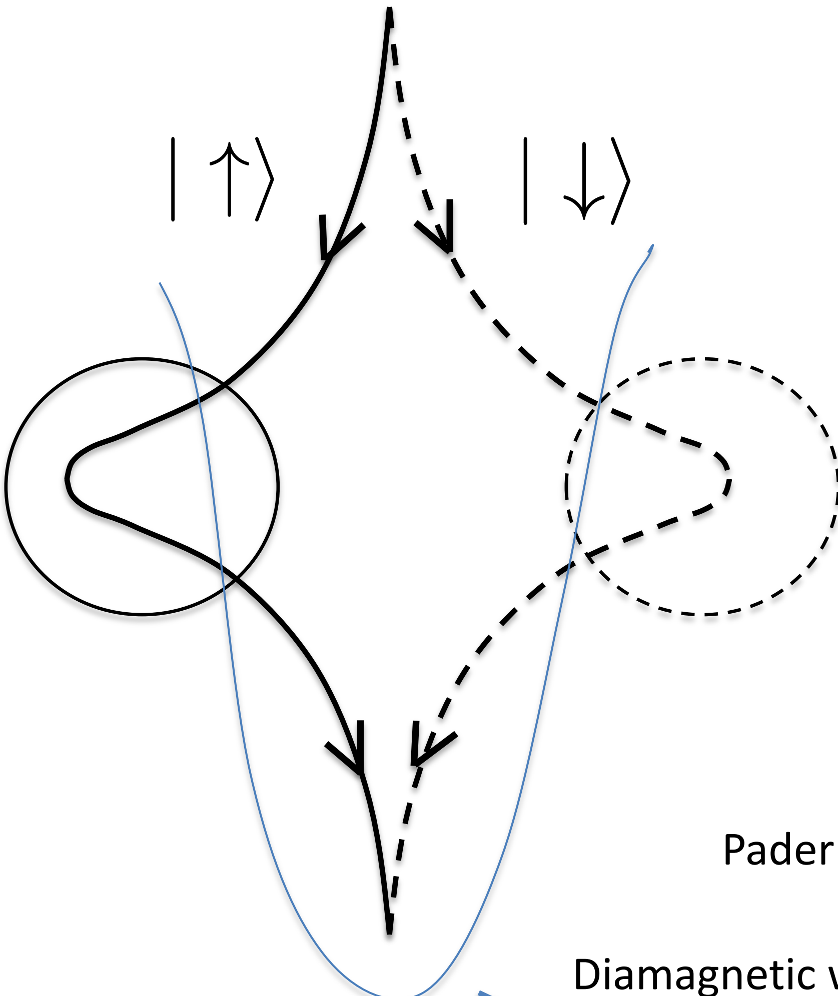
10^{-23}   10^{5}

$$\Delta x \sim \frac{F}{m}\tau^2 = \frac{\mu_B \frac{\partial B}{\partial x}}{m}\tau^2$$

10^{-14}   1

Wan et al, 2016; Bose et al 2017.

But ….



$$\Delta x \sim \frac{F}{m\omega_m^2} = \frac{\mu_B \frac{\partial B}{\partial x}}{m \frac{\chi_m}{\mu_0}\left(\frac{\partial B}{\partial x}\right)^2}$$

$$\Delta v \sim \frac{F}{m\omega_m} = \frac{\mu_B}{m}\sqrt{\frac{\mu_0}{\chi_m}}$$

10^{-23}

10^{-6}

10^{-15}

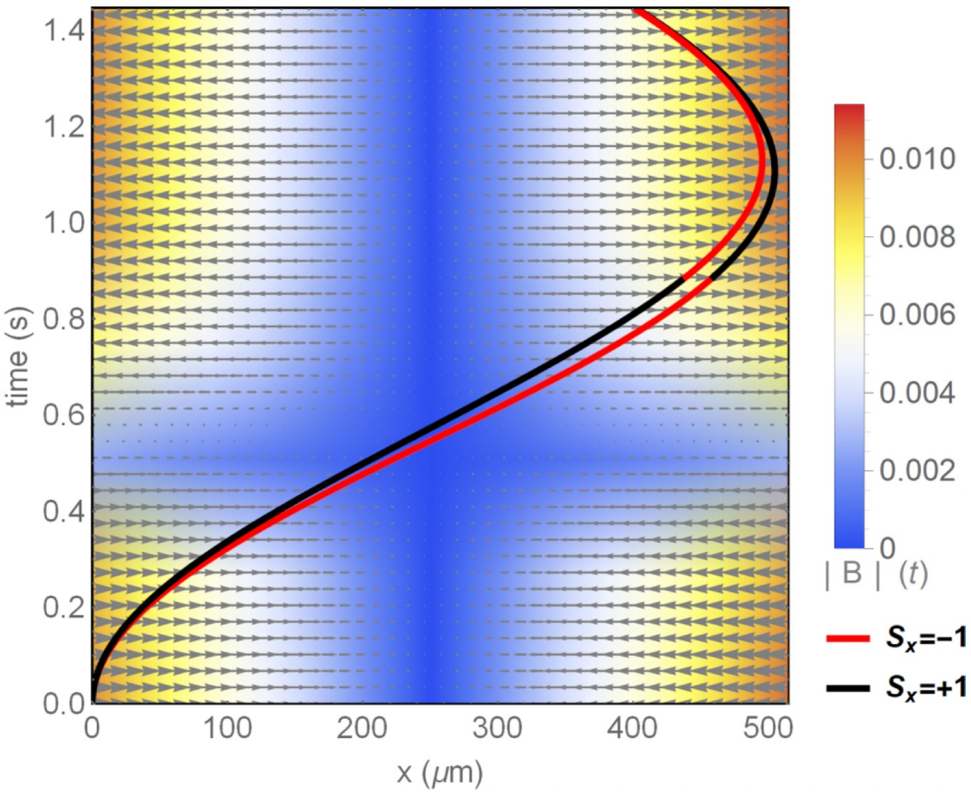
10^{-8}

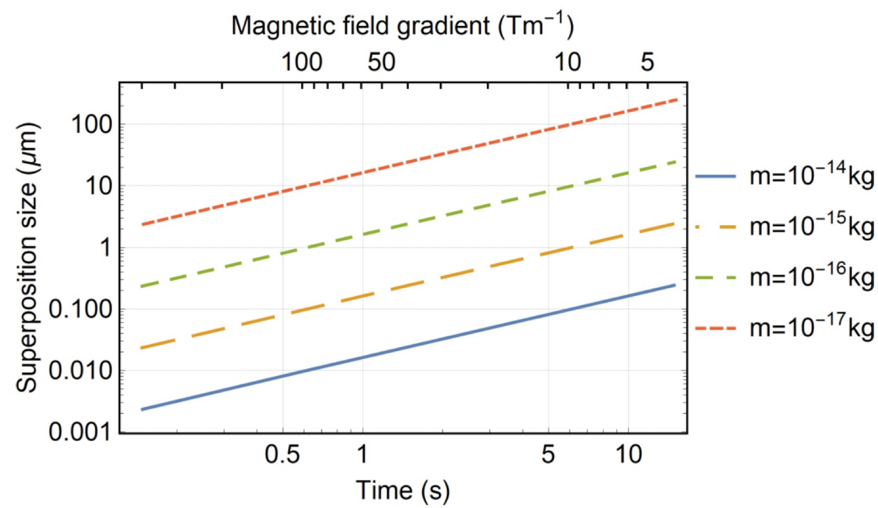
Padernalles et al, PRL 2020; **Marshman et al PRR 2021.**

Diamagnetic well

$$\frac{1}{2} m\chi_m \frac{\left(\frac{\partial B}{\partial x}\right)^2}{\mu_0} x^2 \Rightarrow \omega_m = \frac{\partial B}{\partial x}\sqrt{\frac{\chi_m}{\mu_0}}$$

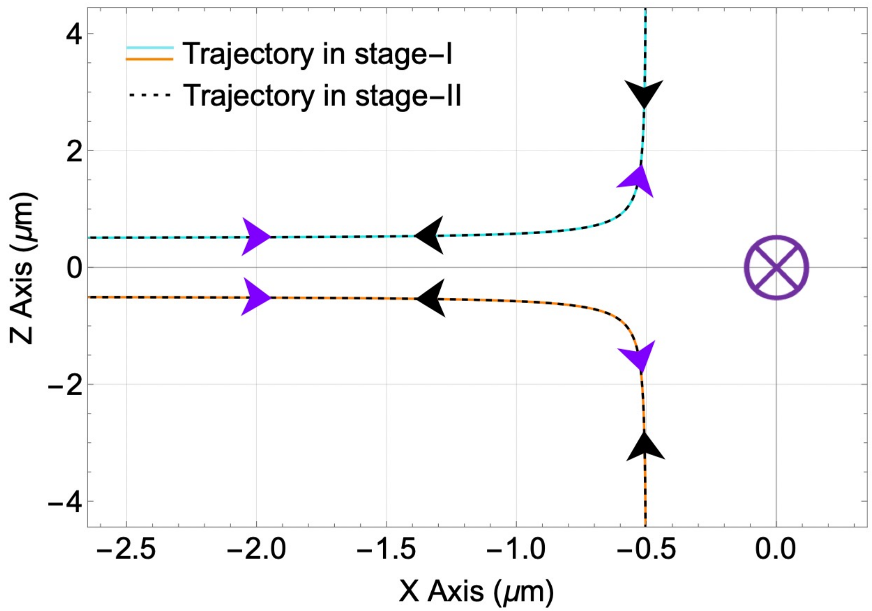
SGI including diamagnetism





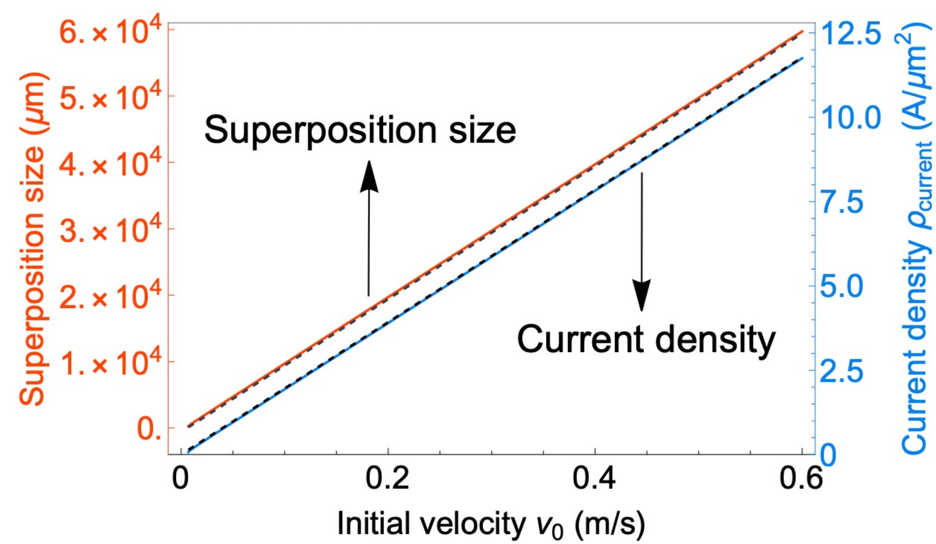
Marshman et al PRR 2021.

Mass-Independent Splitting
R. Zhao et al arXiv:2210.05689



0.1 s

$$\Delta Z_{maxR} = v_0\tau - 2x_0.$$

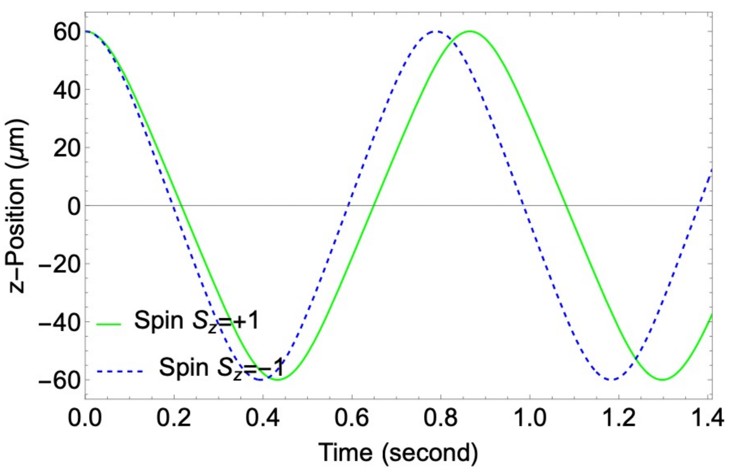


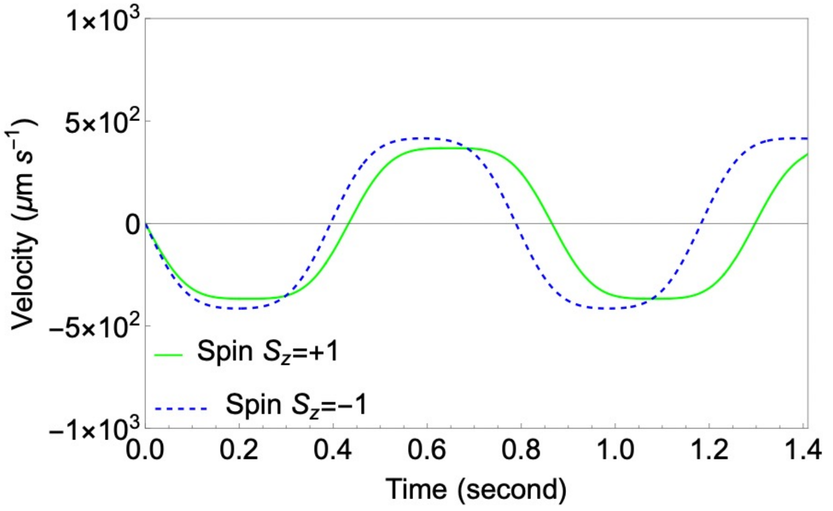
Going beyond SGI: Nonlinear gradients

(R. Zhou et al 2022 PRR (to appear))

$$\boldsymbol{B} = (B_0 + \eta z^2 - \eta x^2)\hat{\boldsymbol{z}} - 2\eta z x \hat{\boldsymbol{x}}.$$

$$a_z = \left(\frac{\chi_m}{\mu_0}(B_0 + \eta z^2) 2\eta z - S_z \frac{g e \hbar}{m m_e} \eta z \right) \hat{\boldsymbol{z}}$$





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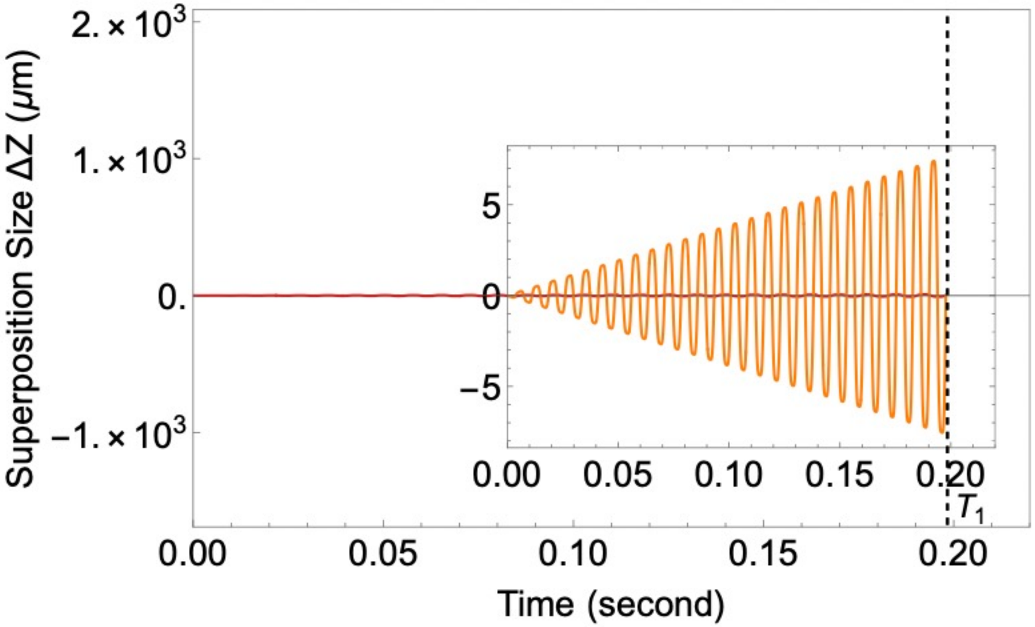
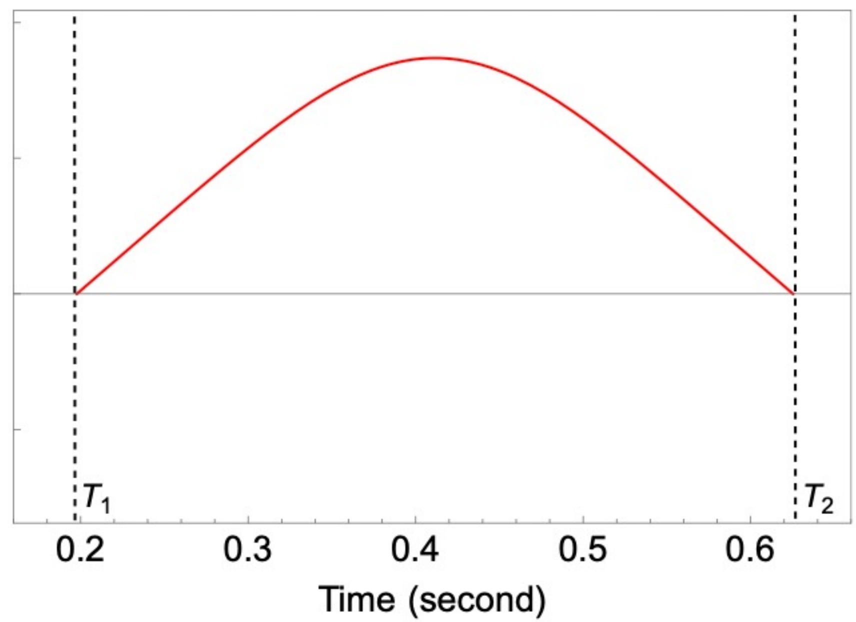
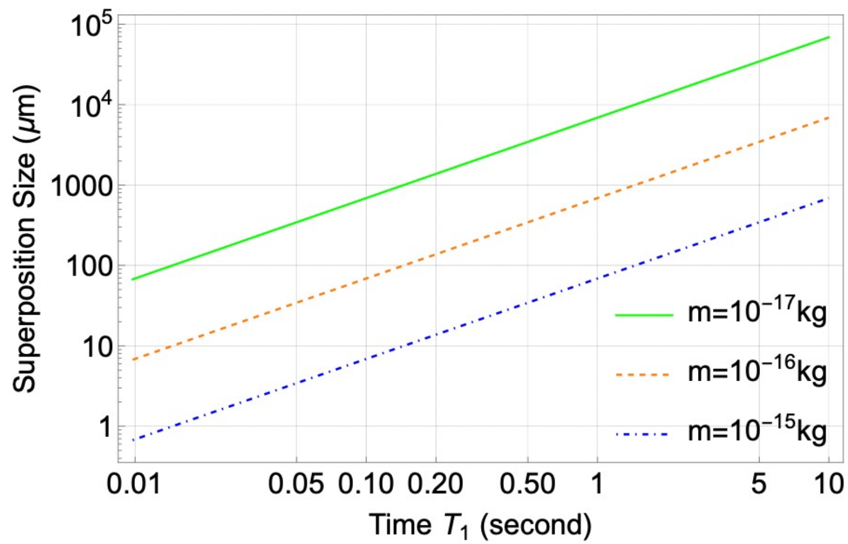




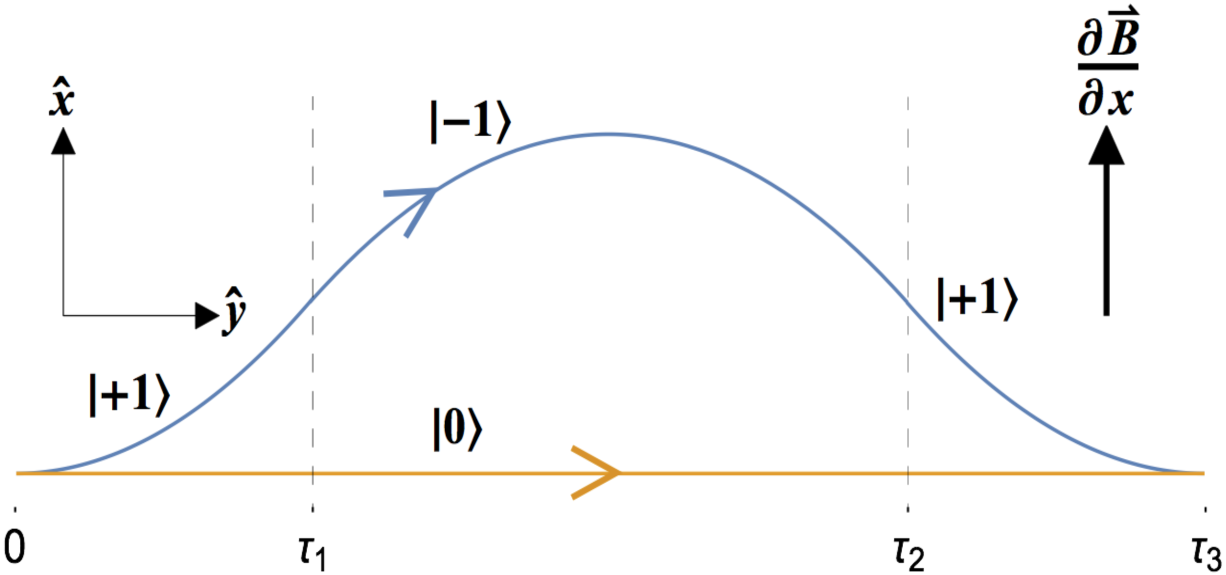


Applications: 1. Acceleration Detection

$$\delta\Delta\Phi_{eff} \sim \frac{m\,\delta g\,\Delta x\,\tau}{\hbar}$$

m	Δx	τ	δg
10^{-17} kg	10^{-7} m	10^{-6} s	10^{-4} ms^{-2}
10^{-15} kg	10^{-5} m	1 s	10^{-14} ms^{-2}

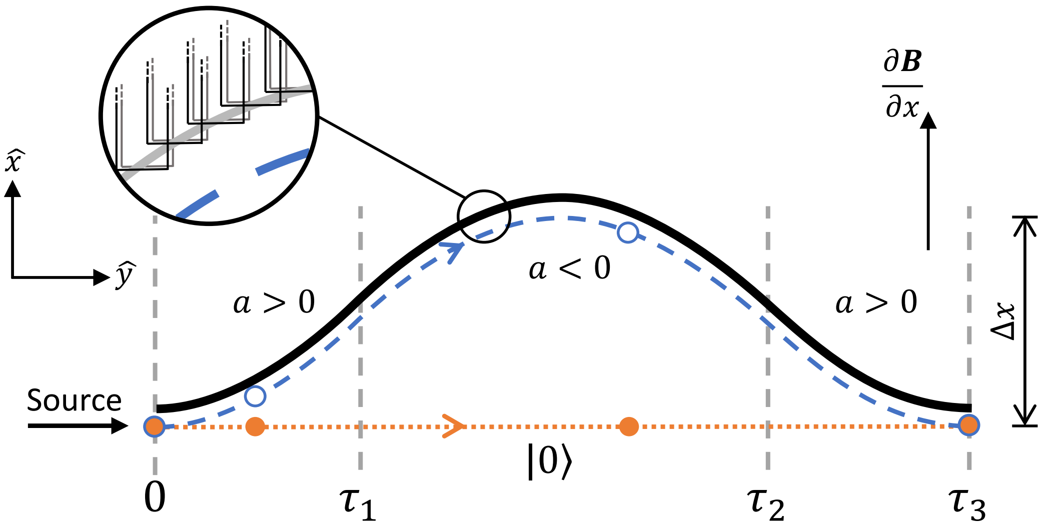
Qvarfort et al Nat Comm 2018; Marshman et al New J Phys 2020



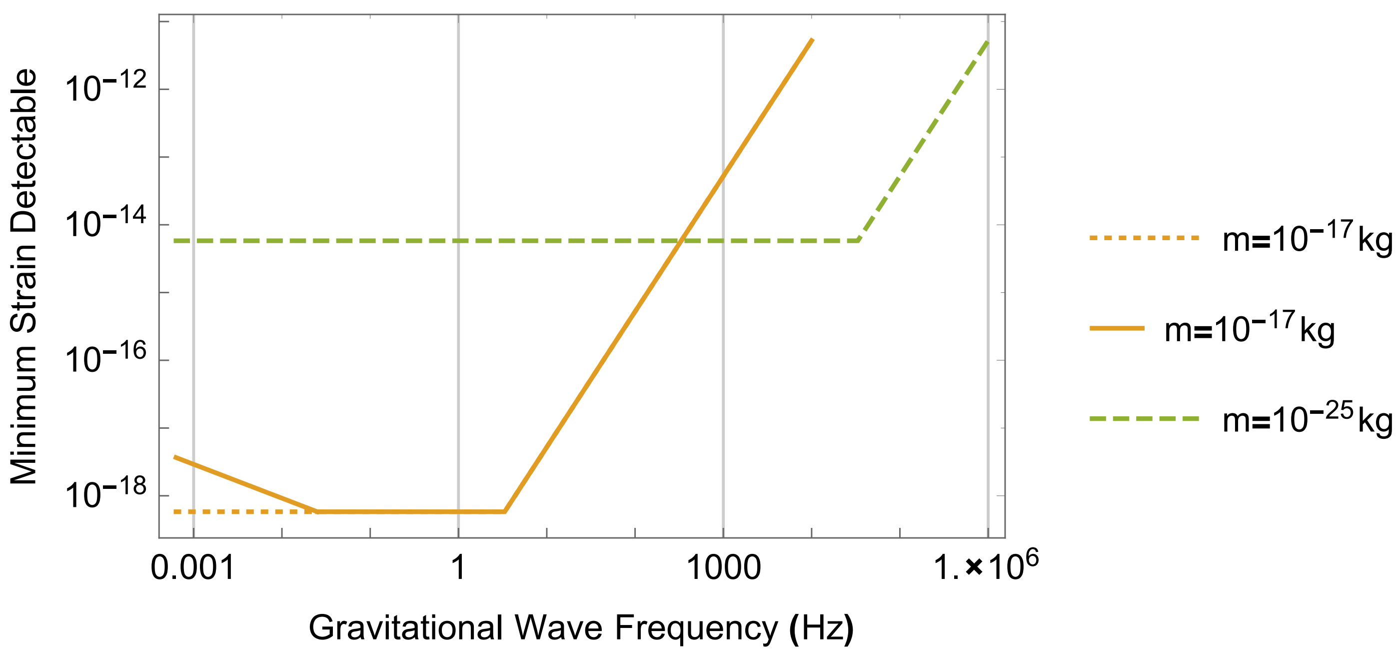
App 2: Compact meter scale detectors for Gravitational waves (MIMAC):

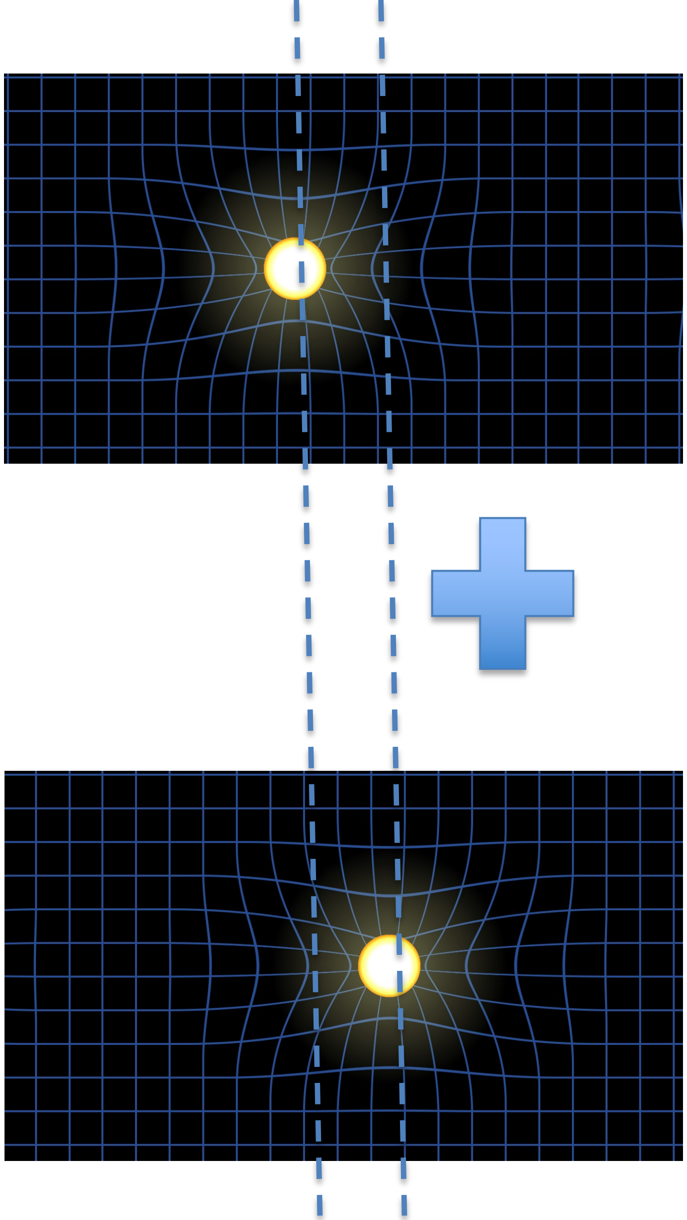
Ryan J. Marshman, Anupam Mazumdar, Gavin W. Morley, Peter F. Barker, Steven Hoekstra, Sougato Bose, **New J. Phys. 22, 083012 (2020).**

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



Meter Scale
Superposition in 1 second,
10^(-17) kg mass

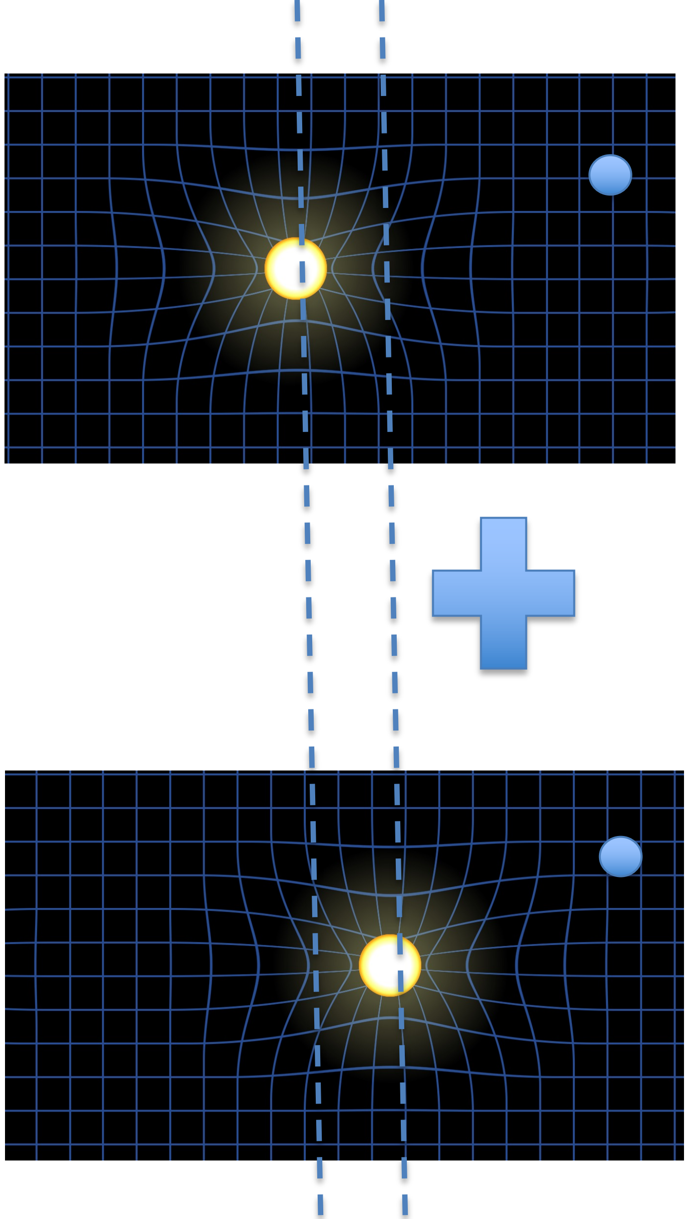


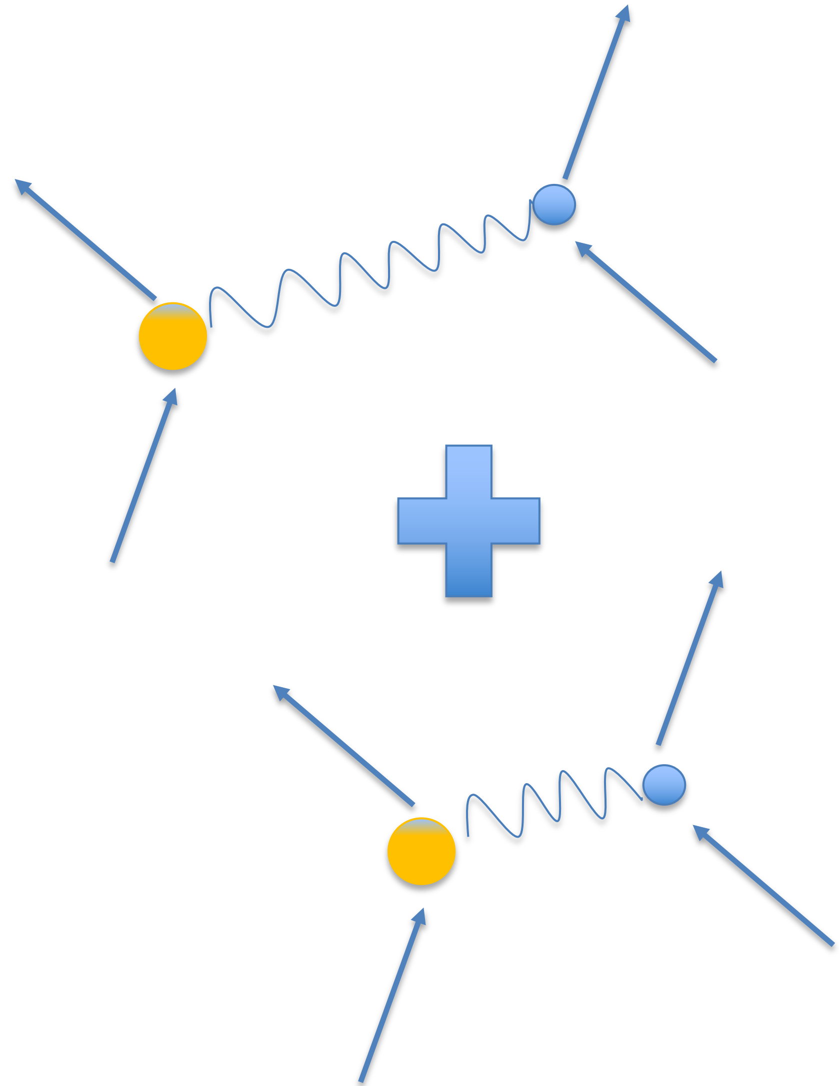


App 3: Is there a way to evidence a *quantum superposition* of different geometries?

One of the best ways of checking this is by entangling two masses, and evidencing that entanglement

- Need another mass to probe the gravity of the former.
- Need to show that quantum superpositon is still maintained in the two mass system (entanglement).



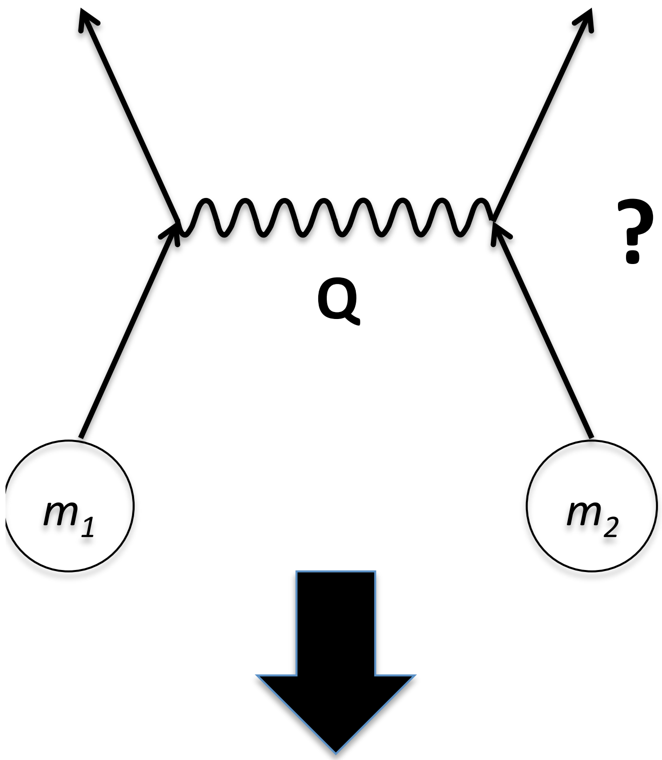


Quantum description
of this geometry in the weak field limit.

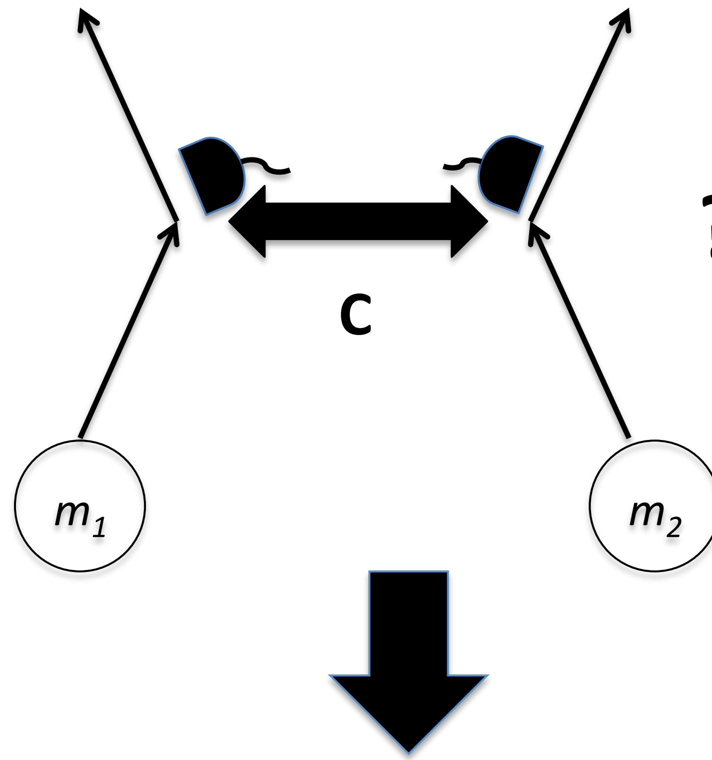
Thus equivalently, is gravitational force due to exchange of virtual quanta or not?

Is Gravity exactly like other forces in weak field limit? -- photons, W+/-, Z, gluons → **gravitons**

Or qualitatively different? **Is the Newtonian interaction actually quantum in origin?**



OR



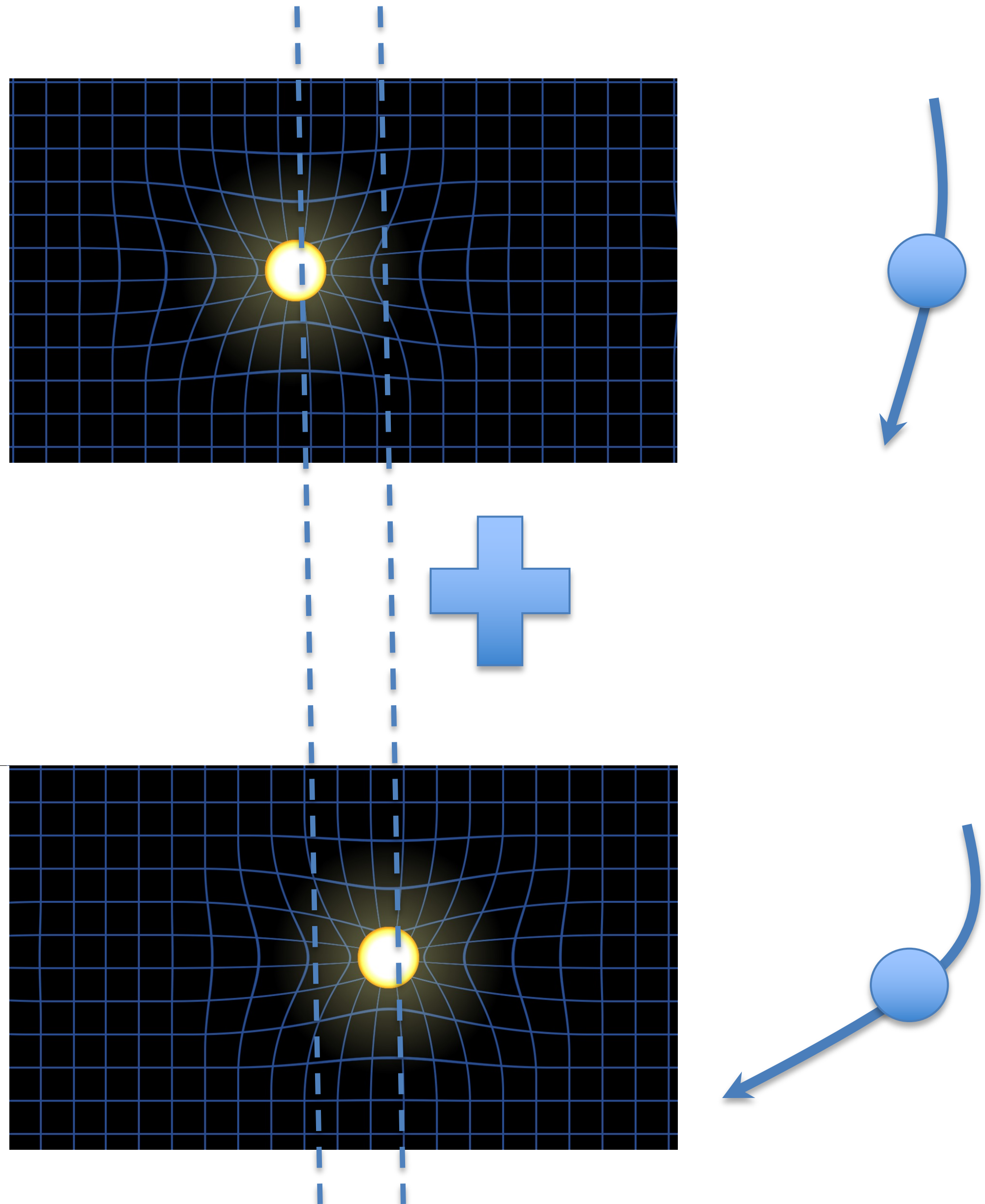
m_1 and m_2 can entangle

m_1 and m_2 ***cannot*** entangle

Verification: An IR prediction of literally any theory of quantum gravity

Falsification: *All* semiclassical gravity (QS+CG): e.g. Halliwell; Kafri-Taylor-Milburn; Oppenheim

A very poor way of generating this entanglement:



G is there, but no $\hbar$

10^{-16} ms^{-2}

An important open question is *whether* gravity is "quantum" (or *verify* that gravity is indeed quantum)

Want to use old QM? (very tough!)

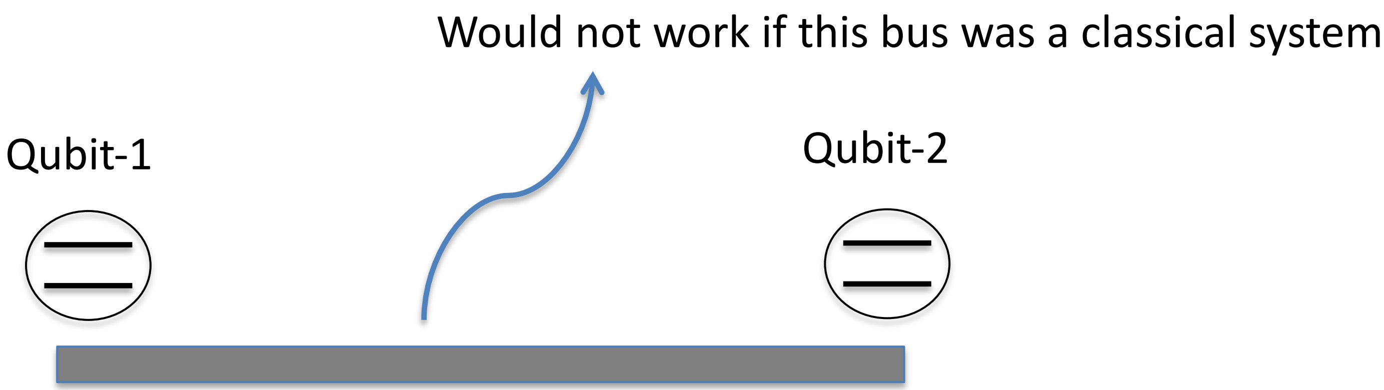
- **Energy quantization.** → **0.01 neV, 1 nK for 100 Hz GW**
- $O(\hbar)$ **corrections to variables and potentials.** → **10^{-34} times Newtonian for 10 micron distances**

But we are living post QI revolution, so use that, and exploit the Newtonian potential!

- ***Entanglement conveying ability is a nonclassical property*** **(the ability to convey entanglement between systems not *directly* interacting with each other).**

We can loosely will call *non-classicality* as quantum.

A Backdrop: Theory of virtual photon/phonon mediated quantum gates:



Efficient Scheme for Two-Atom Entanglement and Quantum Information Processing in Cavity QED

Shi-Biao Zheng[1,2,*] and Guang-Can Guo[1,†]

$[a, a^{\dagger}] = I$

$$H_i = g \sum_{j=1,2} (e^{-i\delta t} a^+ S_j^- + e^{i\delta t} a S_j^+)$$

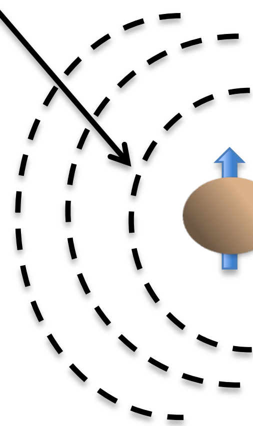
$$H = \lambda \Big[\sum_{j=1,2} (|e_j\rangle\langle e_j| a a^+ - |g_j\rangle\langle g_j| a^+ a) + (S_1^+ S_2^- + S_1^- S_2^+) \Big],$$

$$\lambda = g^2/\delta$$

1 Fact taken from nature (Other experiments) & 1 Definition:

It is a mediated interaction → Only local operations (LO) in nature

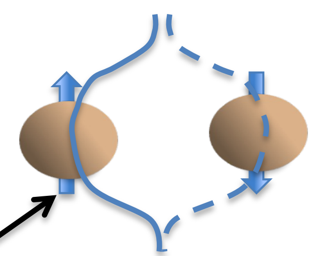
$$\kappa^2 h_{\mu\nu}(\vec{r},t)T^{\mu\nu}(\vec{r},t)$$

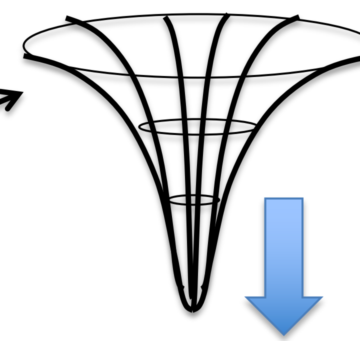


Relativity necessitates the *mediator*

Definition of Classical field

Fluctuations





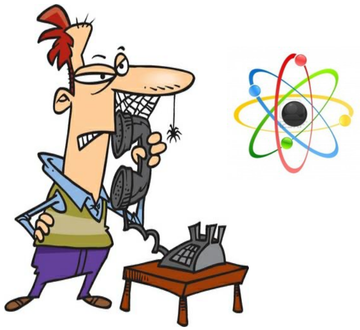
$$P_j,\{|j\rangle\langle j|, h^j_{\mu\nu}\}$$

Classical Communications (CC)

In a nutshell, *different potentials cannot be in superposition*

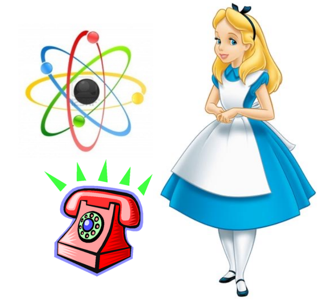
Marshman, Mazumdar, Bose, Phys. Rev. A 101, 052110 (2020).

LOCC *Cannot* Entangle (can be easily proved)

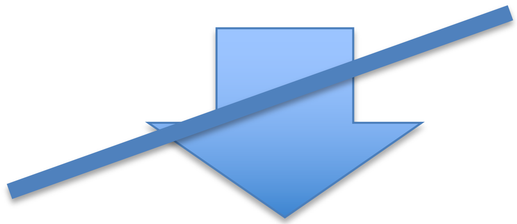


1. Unitary evolution
2. Measurements, Entangling , Tracing

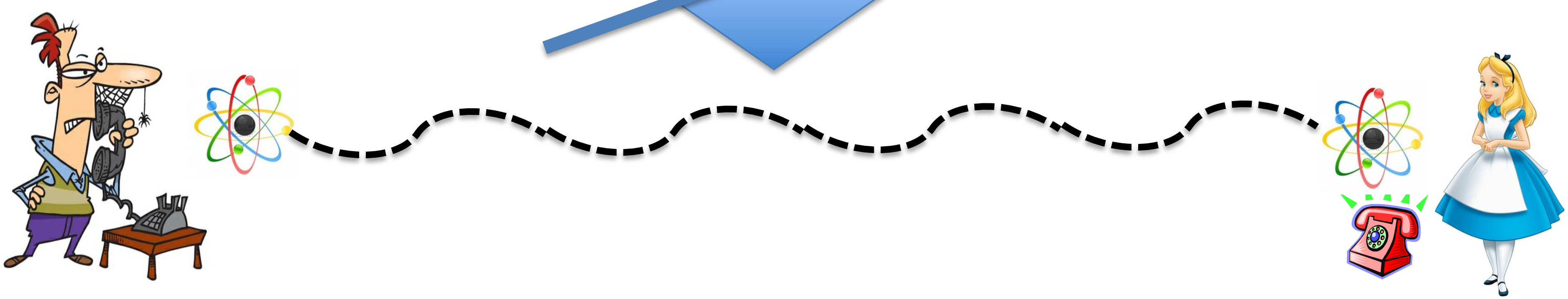
Informing the other party about the outcomes of measurements



Local Operations and Classical Communication (LOCC)



Not possible!

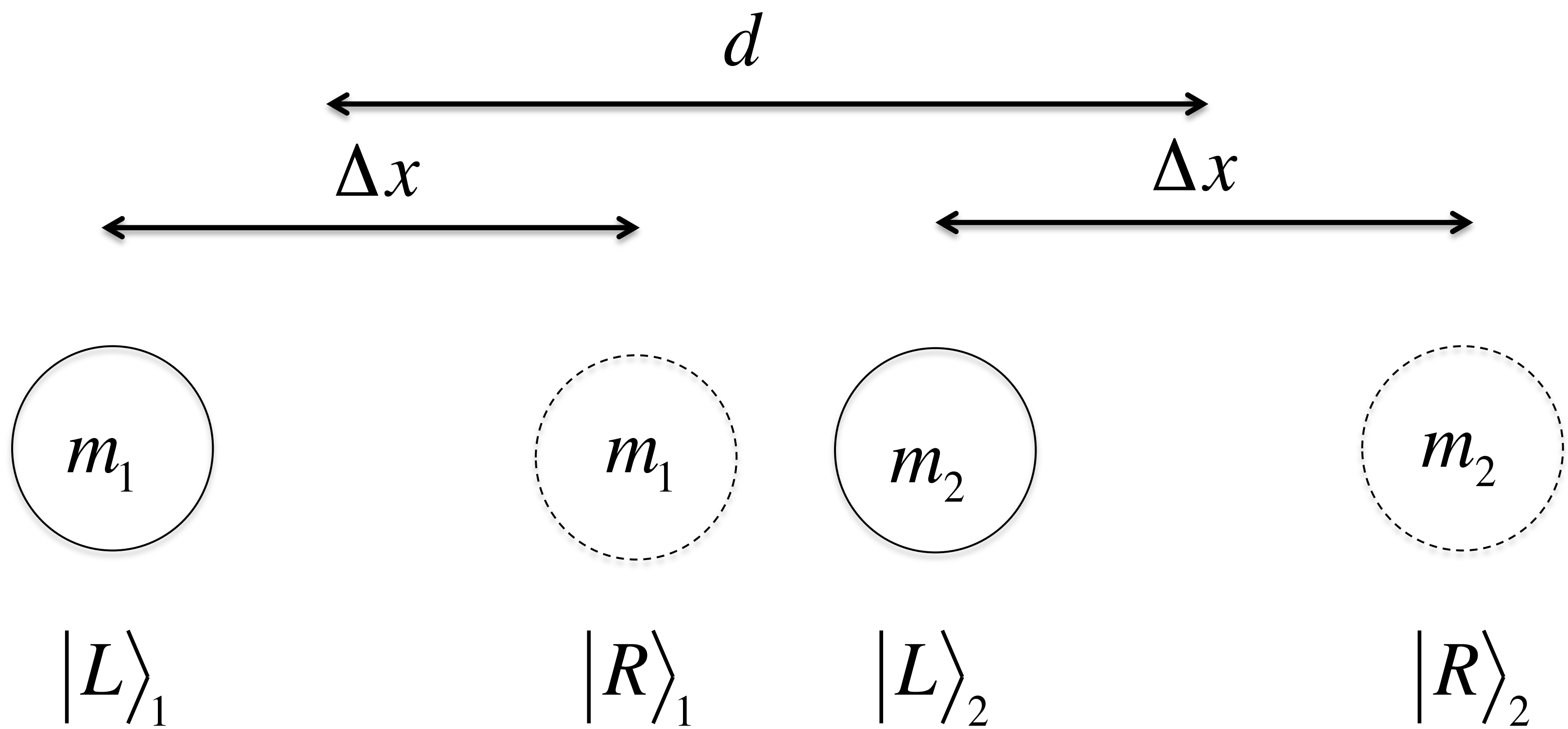


$$U_A \otimes U_B |\phi\rangle_A |\psi\rangle_B = |\phi'\rangle_A |\psi'\rangle_B$$

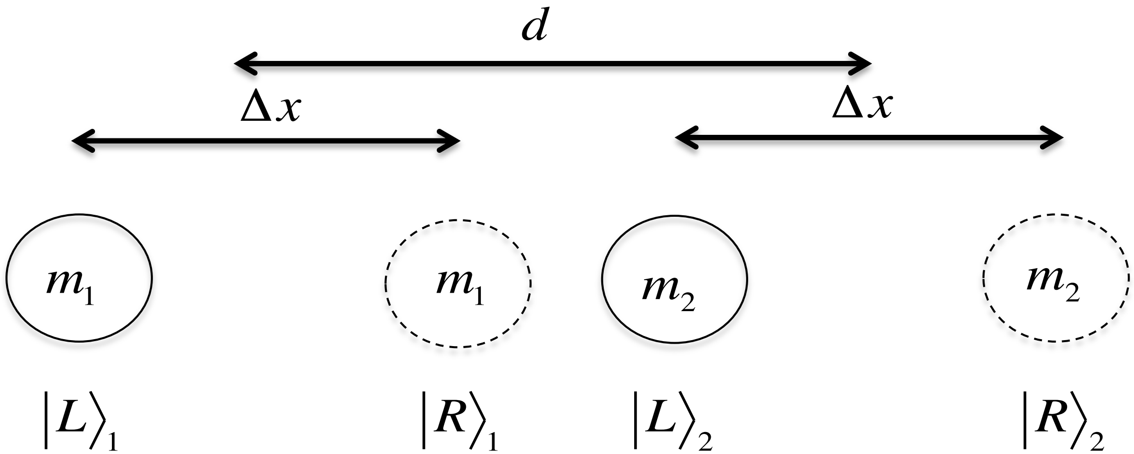
$$\sum_k P_k A_k \otimes B_k \left(\sum_i \Pi_i \rho_{iA} \otimes \rho_{iB}\right) A_k^+ \otimes B_k^+ \rightarrow \left(\sum_i P'_i \rho'_{iA} \otimes \rho'_{iB}\right)$$

Two gravitationally interacting matter-wave interferometers

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).



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



If they interact *only* through the gravitational force

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

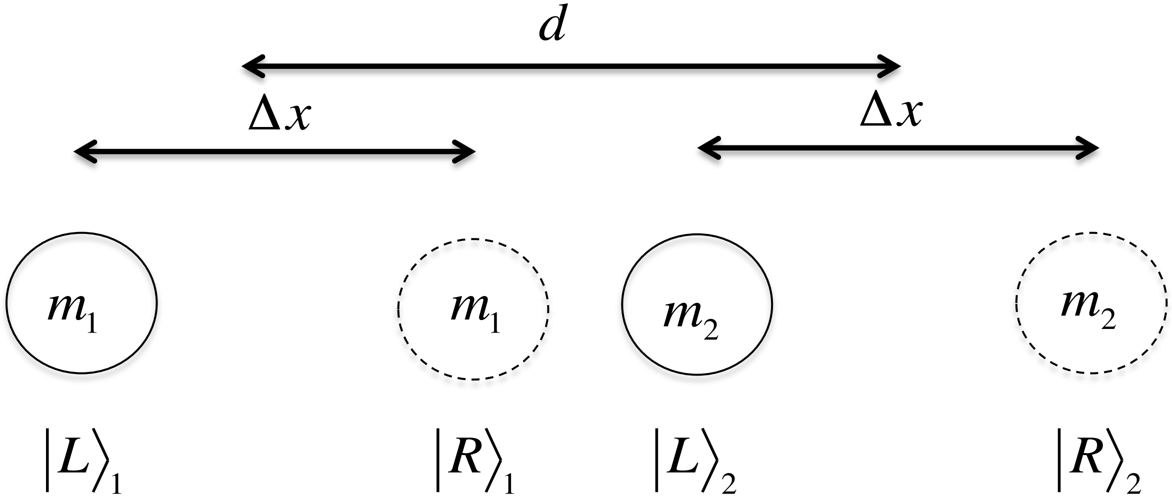
$$= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2)$$

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

where

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

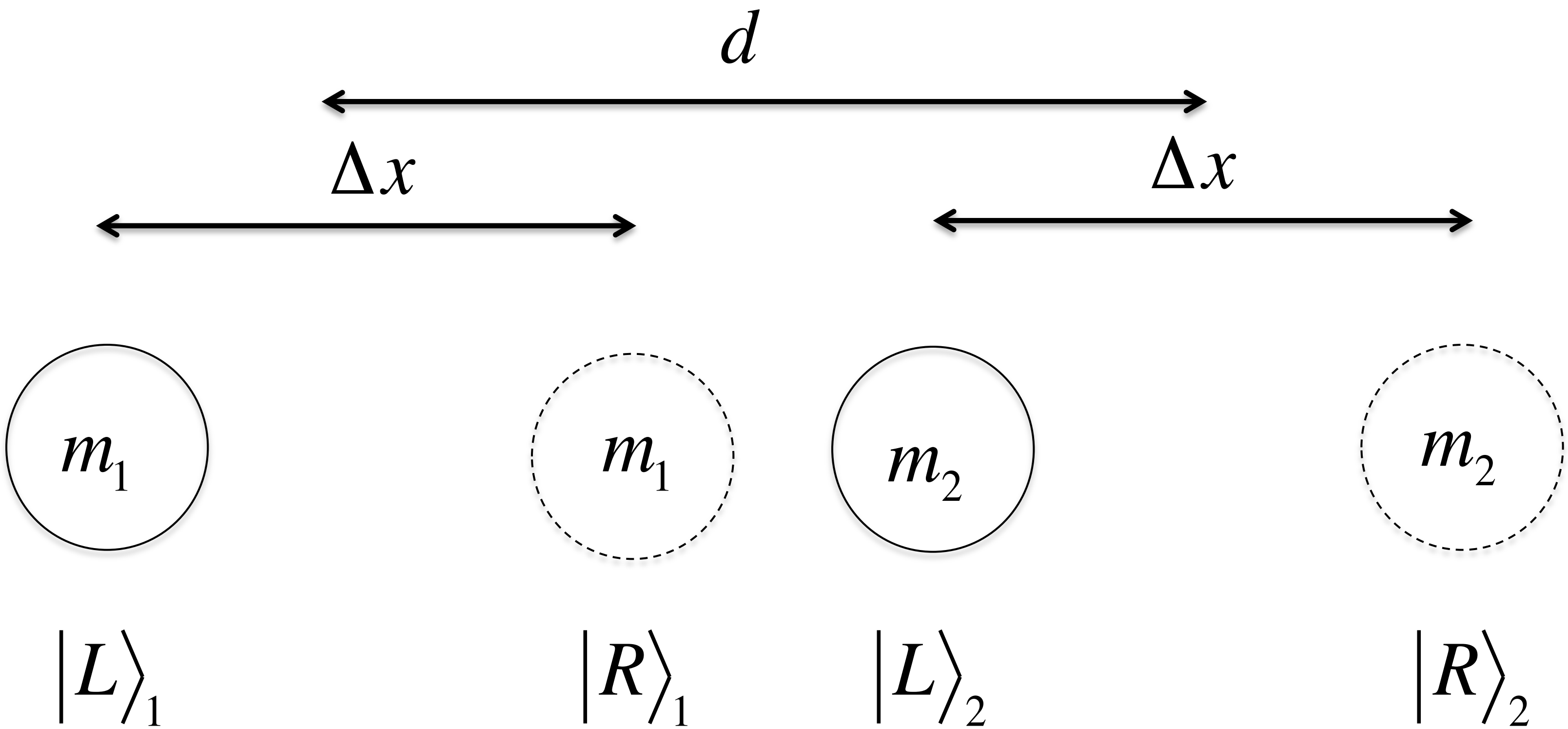
$$\phi_{LL} = \phi_{RR} \sim \frac{Gm_1m_2\tau}{\hbar d}$$



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

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

An important limit in order to see the full strength of the effect.

we have

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

Restrictions on *closest* appropach

$$U_{CASIMIR} \approx \frac{\hbar c}{d} \frac{R^6}{d^6}$$

$$\frac{U_{CASIMIR}}{U_{GRAVITY}} \approx \frac{m_p^2}{\rho^2 d^6}$$

If you need gravity to dominate by a factor of 10, you have to go to 200 microns

[But we will later discuss screening Casimir]

For

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

we have

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

Important limit to see the full strength

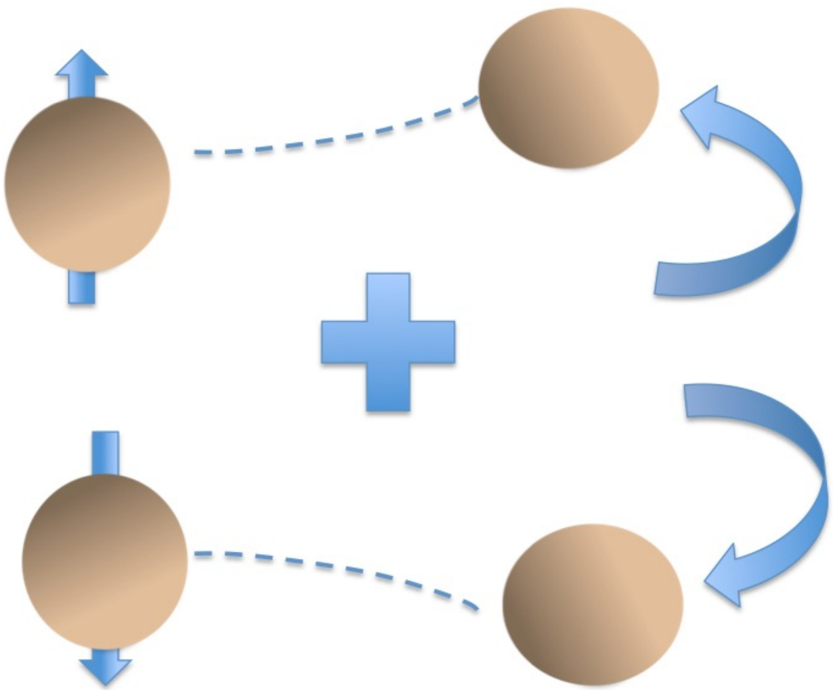
For mass ~ **10^(-14) kg (microspheres)**, separation at closest approach of the masses ~ 200 microns (to prevent Casimir interaction), **time ~ 1 seconds**, gives:
Scale of superposition ~ 100 microns, **Delta phi_{RL} ~ 1**

Planck's Constant fights Newton's Constant!
(Bose et. al. PRL 2017)

A little bit of History:

- Feynman Chapel Hill Conference 1957

" if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."



- Second mass will take long time to move (there is no amplification due to Planck's Constant)
- What aspect of the experiment?

Salecker: Semiclassical; Belinfante: Argue against semiclassicality; Feynman: Suggested the above expt; Bondi: How different from dice? Feynman: Amplitudes & bringing back to interfere. Louis Witten: What prevents this from becoming a pract. expt? Feynman: Noise in amplifying apparatus. Rosenfeld: Continued to argue.

Why *nothing lesser* than entangling similar masses make sense for testing the quantum nature of gravity

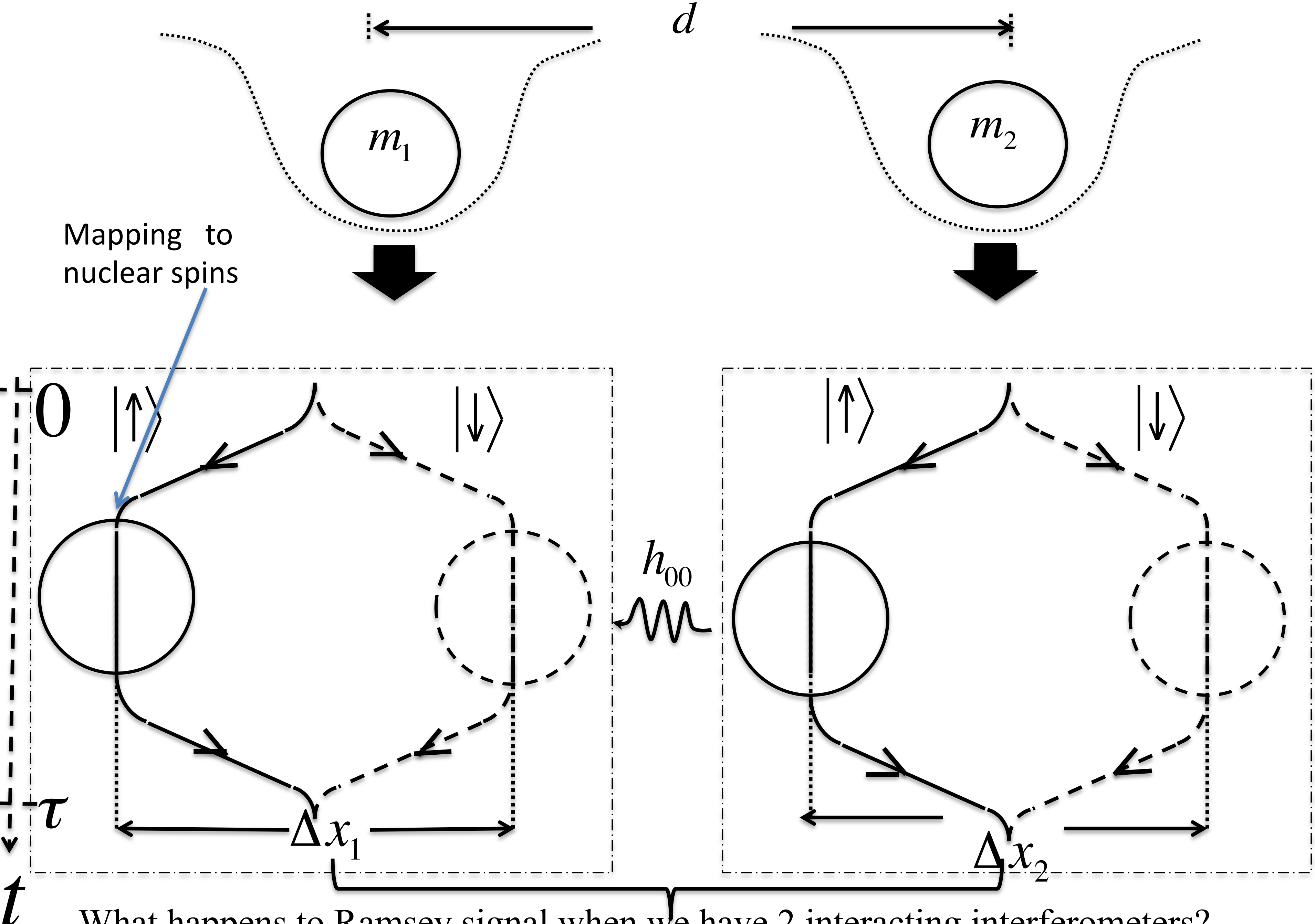
- Single mass interferometry – how do we know that gravity was involved at all at the end of the experiment?

- Detecting the gravity of the mass in superposition by the *deflection* of much smaller object, e.g., an atom: But how to know whether the gravitational field was a classical statistical mixture?

$$P_L \rightarrow |L\rangle\langle L|, h_{\mu\nu}(x - x_l),$$
$$P_R \rightarrow |R\rangle\langle R|, h_{\mu\nu}(x - x_R)$$

- While acceleration is same for all masses, the phases that entangle $\propto m_1 m_2$

  Use the largest mass interferometer you can make, and use two of them!



What happens to Ramsey signal when we have 2 interacting interferometers?

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*)

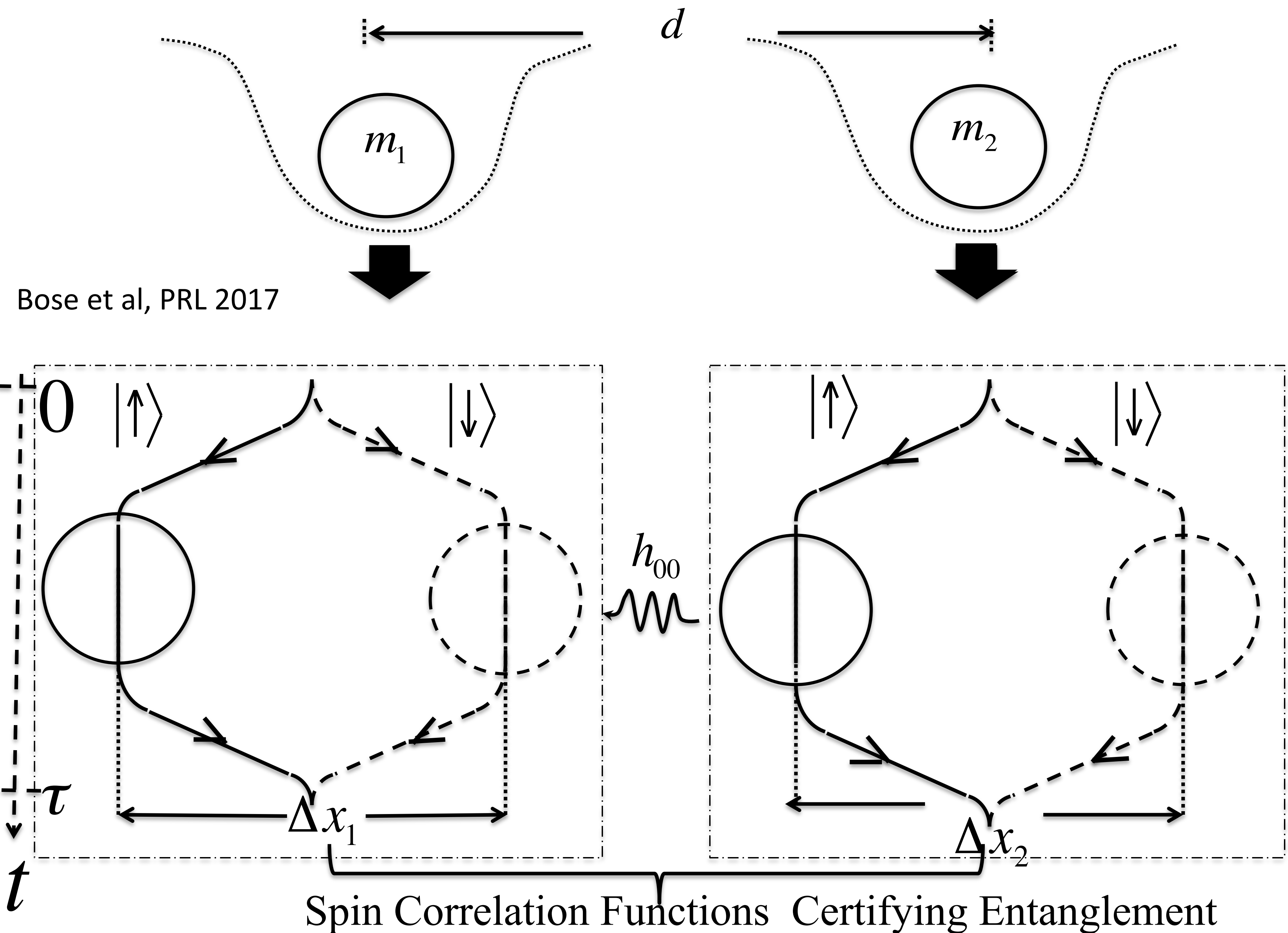
Step 3: SG recombination: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j,\ |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$

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:

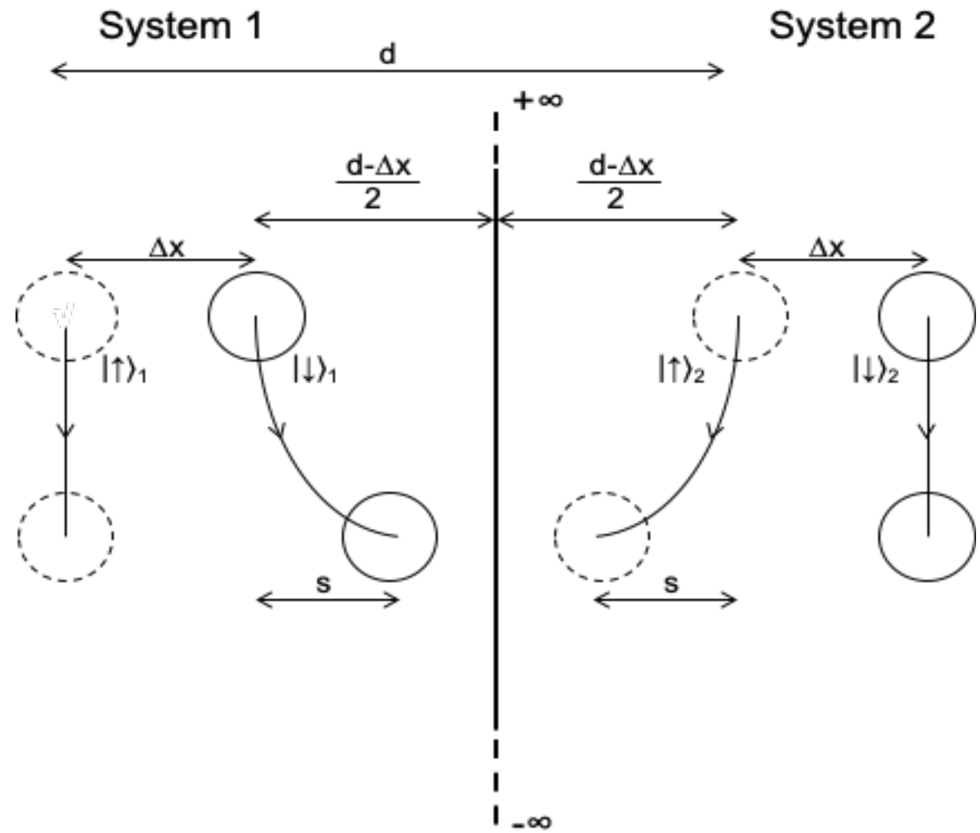
$$\mathcal{W} = \mathbb{I}\otimes\mathbb{I} - \sigma_x\otimes\sigma_x - \sigma_y\otimes\sigma_z - \sigma_x\otimes\sigma_z$$



d
m_1
m_2
Bose et al, PRL 2017
0
$|\uparrow\rangle$
$|\downarrow\rangle$
$|\uparrow\rangle$
$|\downarrow\rangle$
h_{00}
τ
Δx_1
Δx_2
t
Spin Correlation Functions Certifying Entanglement

Electromagnetic Screening

TW van de Kamp, RJ Marshman, S Bose, A Mazumdar, Physical Review A 102 (6), 0628074 (2020)



A good news is that with a Faraday Screen for Casimir, *and* demanding detecting only

$$\Phi_{eff} = \Delta\Phi_{LR} + \Delta\Phi_{RL} \sim 0.01$$

(10,000 measurements for good statistics)

we can get: $m \sim 10^{-15}\,kg,\ \Delta x \sim 10\,\mu m,\ \tau \sim 1\,s$

$$\Rightarrow \frac{\partial B}{\partial x} \sim 1000\ Tm^{-1}$$

$$\mathcal{W} = \mathbb{I} \otimes \mathbb{I} - \sigma_x \otimes \sigma_x - \sigma_y \otimes \sigma_z - \sigma_x \otimes \sigma_z$$

Full expression for an *open* system

$$\langle \mathcal{W} \rangle = 1 - e^{-\Gamma_{\mathrm{n}}/2 - \Gamma_{\mathrm{d}}/2} \left(\sin(\Delta\phi_{\uparrow\downarrow}) + \sin(\Delta\phi_{\downarrow\uparrow}) \right) + \frac{e^{-\Gamma_{\mathrm{d}}}}{2} \left(e^{-2\Gamma_{\mathrm{n}}} + \cos(\Delta\phi_{\downarrow\uparrow} - \Delta\phi_{\uparrow\downarrow}) \right),$$

$$\langle \mathcal{W} \rangle = \Gamma_{\mathrm{n}} + \Gamma_{\mathrm{d}} - \Phi_{\mathrm{eff}}$$

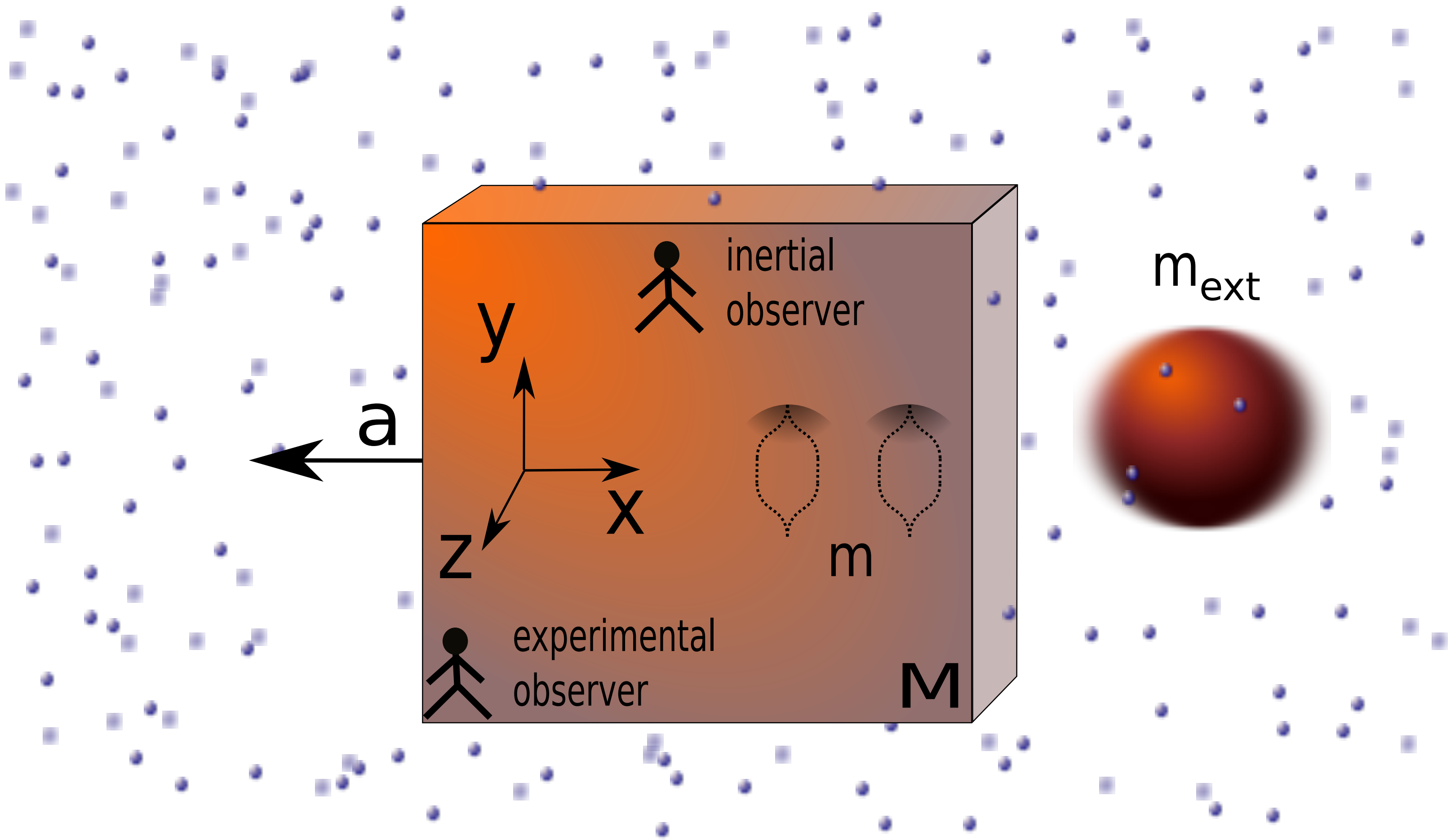
$$\Phi_{\mathrm{eff}} > \Gamma_{\mathrm{n}} + \Gamma_{\mathrm{d}} + \Gamma_s$$

Γ_{n}: Acceleration & Relative Acceleration Noise.

Γ_s: Systematic (fluctuations from apparatus)

Γ_{d}: Black-Body Radiation ($\propto R^3 T^6$) + Atom Scattering ($\propto R^2 P$)
(laboratory, T~1 K, P ~ 5×10^{-16} Pa, nano-object internal T ~ 150 mK)
Bose et al PRL 2017; van de Kamp et al PRA 2020

The experiment in a freely falling laboratory to cancel gravitational acceleration noise



What noise is left?

$$L = \frac{1}{2}mv^2 - max - \frac{1}{2}m\omega_{\rm gg}^2 x^2$$

Non-inertial jitter

$$\omega_{\rm gg}^2 = R_{0101}c^2$$

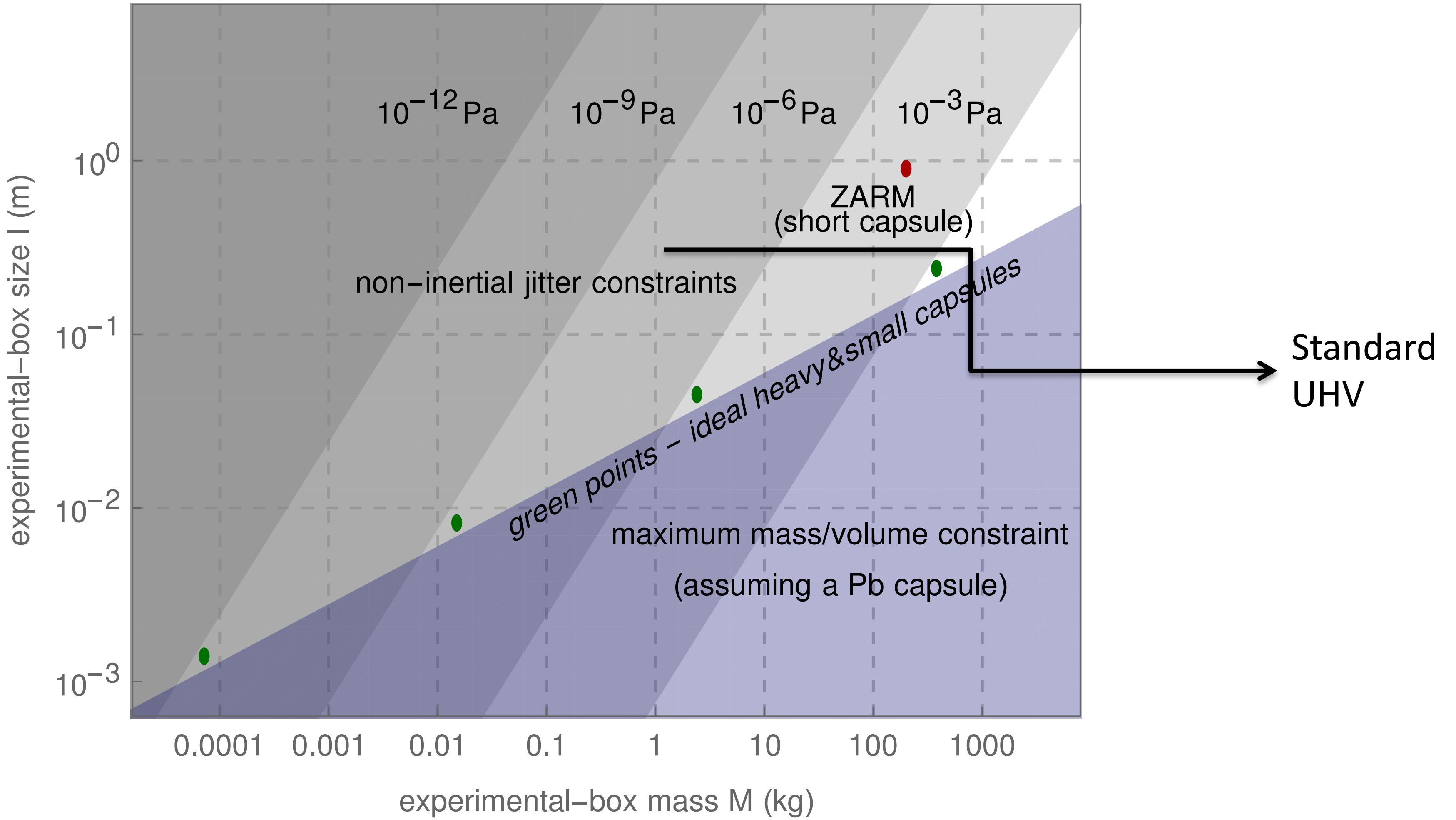
Curvature due to external masses

$$\gamma = \frac{pl^2}{M}(1+\frac{\pi}{8})\left(\frac{32m_g}{\pi k_b T}\right)^{1/2}$$

$$\Gamma_{\text{jitter}} = \frac{16\gamma k_B T f_{\text{m}}^2}{\hbar^2 M}\left[\frac{23}{15}t_a^5 + t_a^4 t_e\right]$$

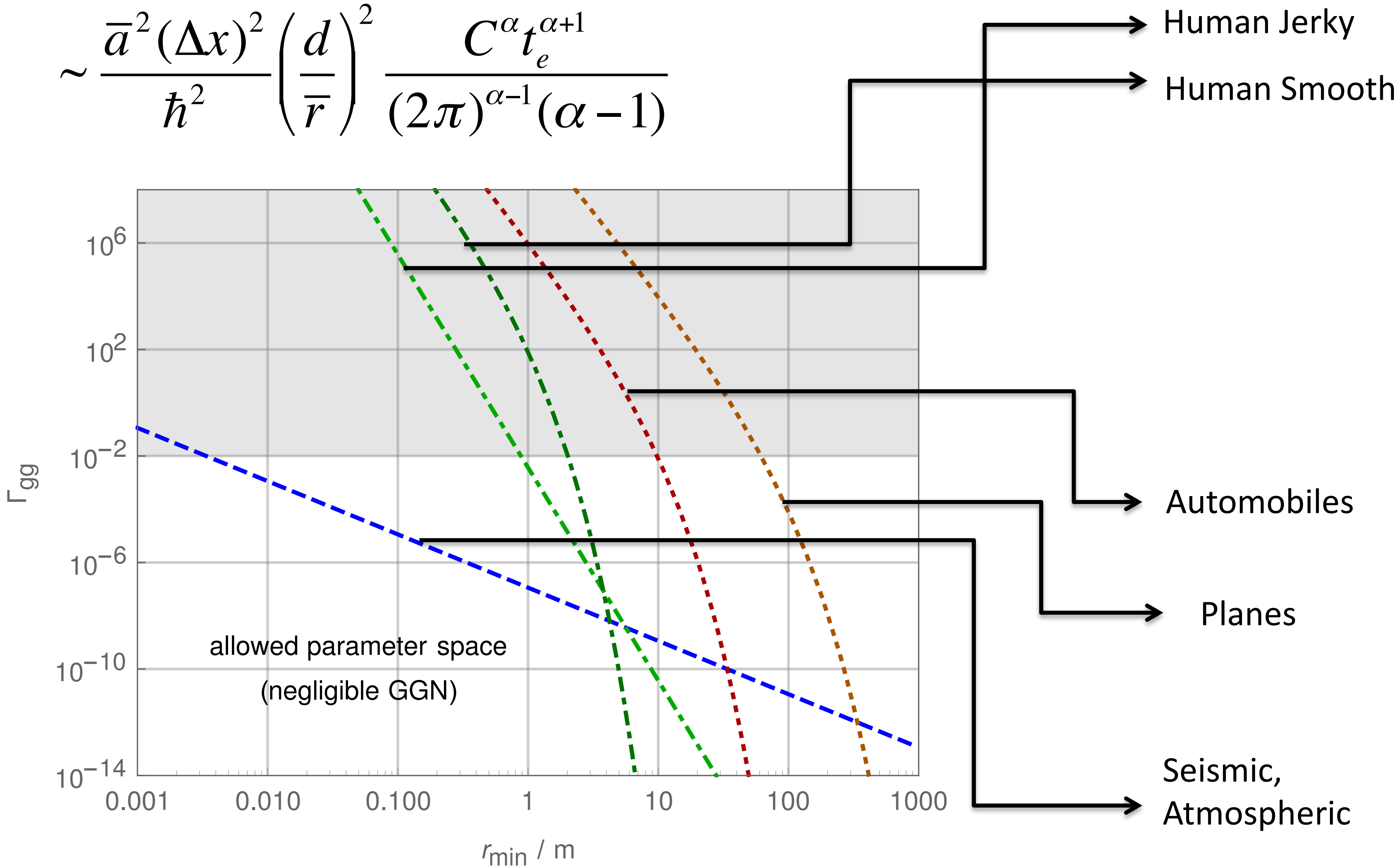
[LISA related literature;
Cavalleri et al PRL 2009]

Smaller *p, l*, Larger *M, under T=300 K*



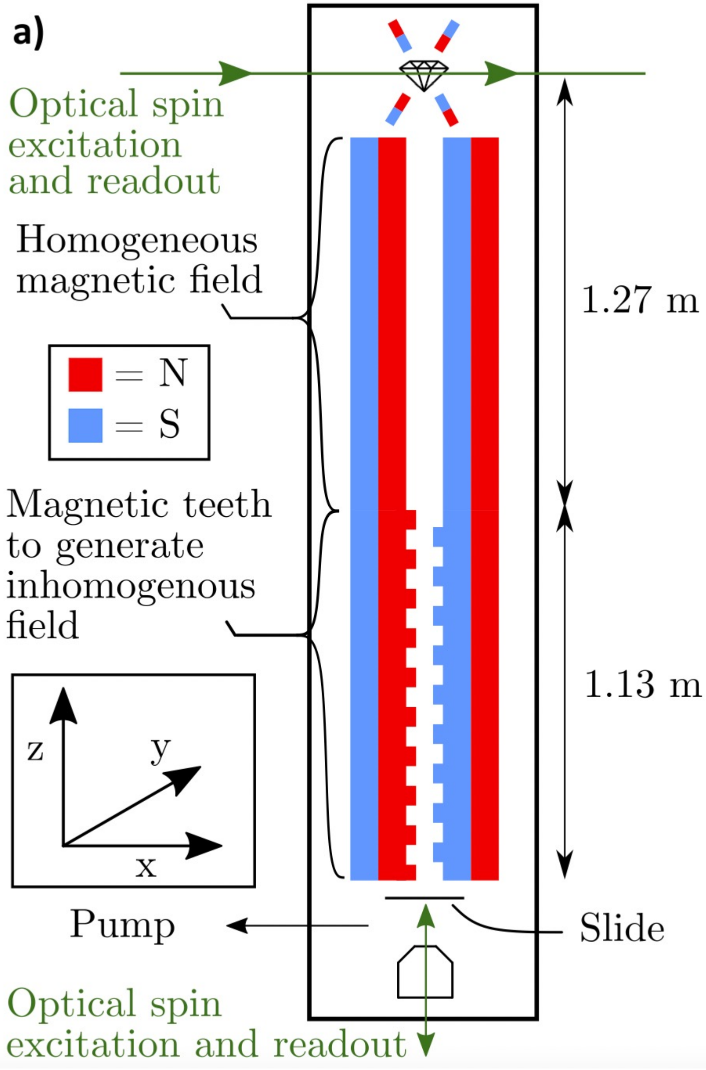
$$\Gamma_{\mathrm{gg}} \approx \frac{\bar{a}^2 f_{\mathrm{m}}^2 t_a^4}{\hbar^2}\left(\frac{d}{\bar{r}}\right)^2 \left[\frac{C^\alpha (t_a+t_e)^2 t_{\mathrm{exp}}^{\alpha-1}}{(2\pi)^{\alpha-1}(\alpha-1)}\right]$$

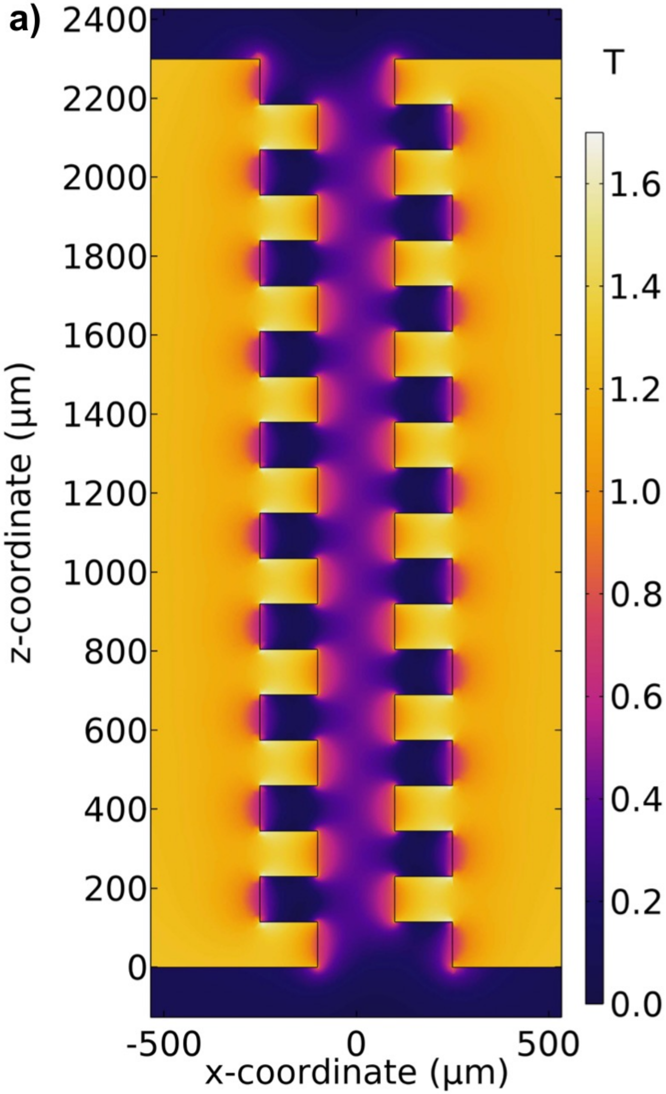
$$\sim \frac{\bar{a}^2 (\Delta x)^2}{\hbar^2}\left(\frac{d}{\bar{r}}\right)^2 \frac{C^\alpha t_e^{\alpha+1}}{(2\pi)^{\alpha-1}(\alpha-1)}$$



Including spin dynamical decoupling

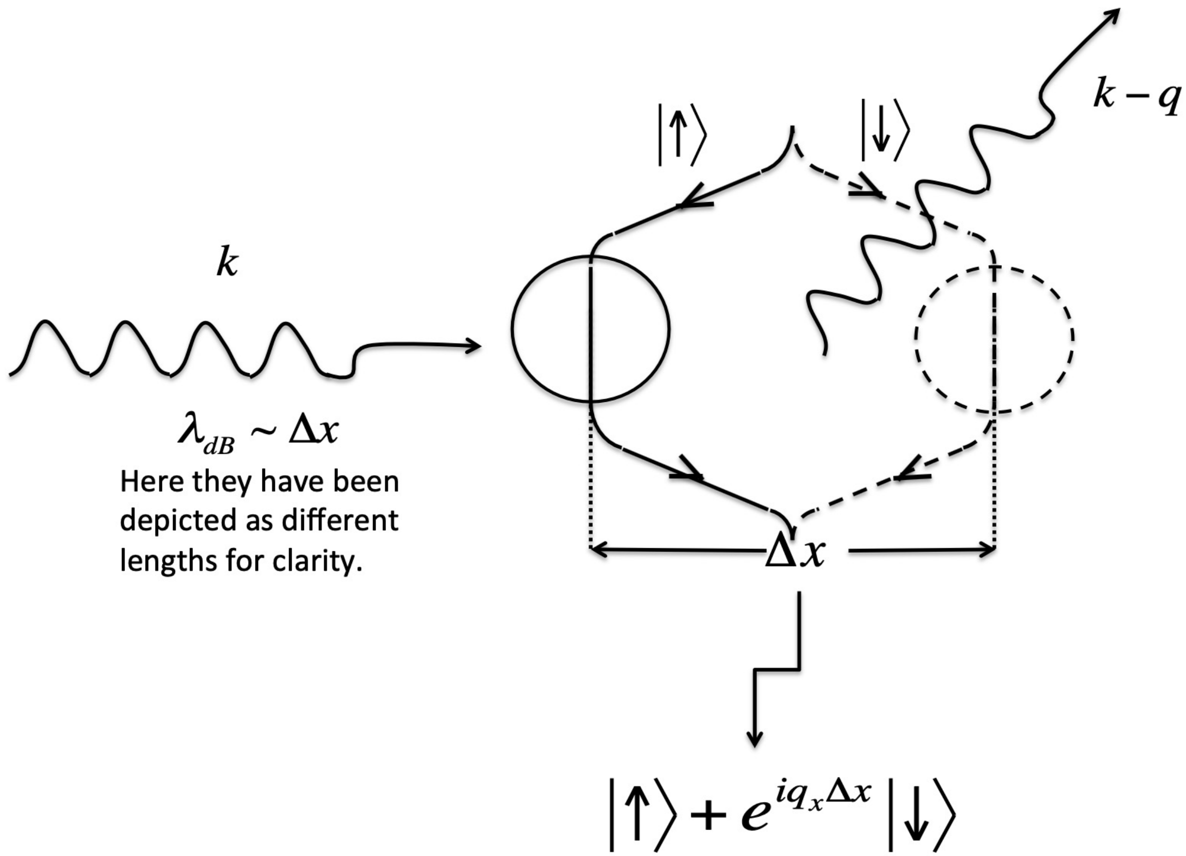
Wood et al PRR 2022





Possibility of neutrino detection?

Kilian, Toros, Deppisch, Saakyan, Bose, arXiv:2204.13095 (to appear PRR)



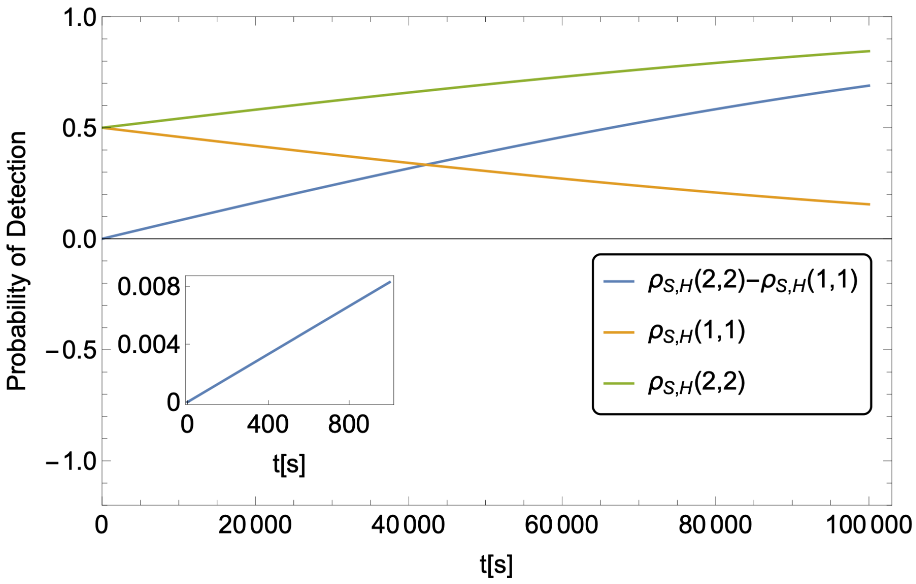
$$\frac{d\rho_S}{dt} = -\frac{i}{\hbar}[H_S, \rho_S] - \Big\{ \int_0^\infty d\tau \sum_{\alpha\beta} C_{\alpha\beta}(-\tau) \times [S_\alpha S_\beta(-\tau)\rho_S - S_\beta(-\tau)\rho_S S_\alpha] + \text{H.c.} \Big\}$$

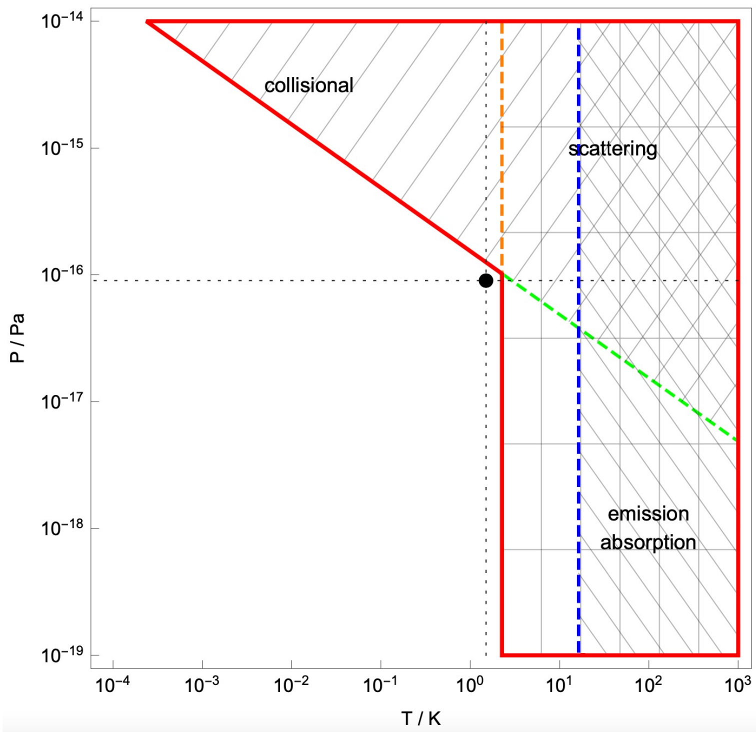
$$\hat{H}_{n,\nu} = \int d\mu_\nu \frac{\mathcal{M}_{p_i,p_f}}{2m_{\text{nucl}}} |p_f\rangle\langle p_i| \otimes e^{i(p_i - p_f)\hat{x}} \mathbb{I}$$

G_F	$1.1664 \cdot 10^{-11}[\text{MeV}^{-2}]$
u	$931.5[\text{MeV} \cdot \text{c}^{-2}]$
m_{nucl} [49]	$(Z+N)u - 0.00054858Z \cdot u +$ $(14.4381Z^{2.39} + 1.55468 \cdot 10^{-6} Z^{5.35})10^{-6}$
Flux	$1.7 \cdot 10^{13}[\text{s} \cdot \text{cm}^{-2}]$
Δx	$10^{-14}[\text{m}]$
S(E)	$\frac{1}{\sigma_E\sqrt{2\pi}} e^{-(E-E_0)^2/(2\sigma_E^2)}$
σ_E	$0.75[\text{MeV}]$
E_0	$2.6[\text{MeV}]$

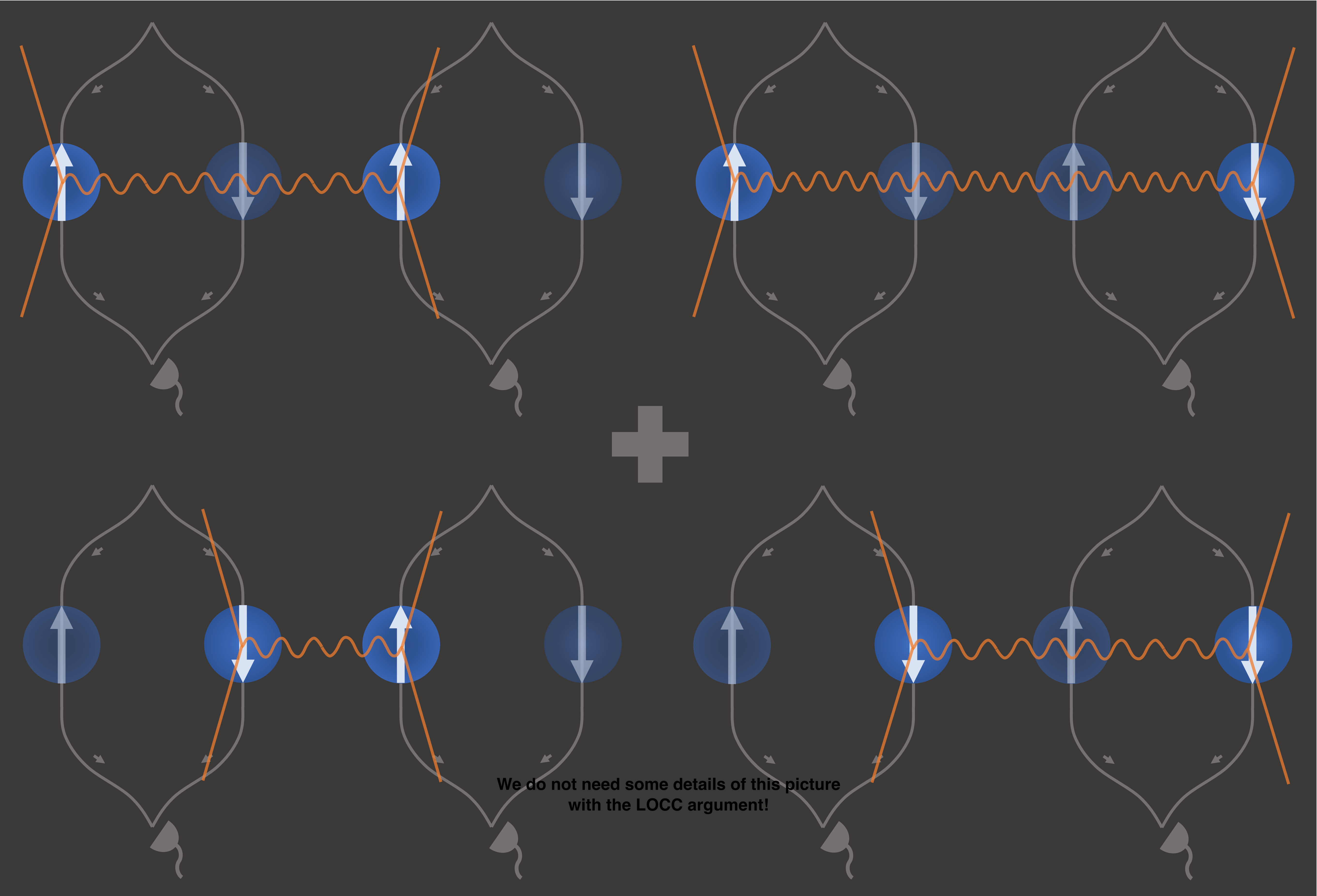
$$\frac{d\rho_S}{dt} = -\frac{2F_1 \cdot N_{\text{Atoms}}}{64\pi^2 m_{\text{nucl}}^2} \int dES(E) \int d\Omega |\mathcal{M}(\Omega)|^2$$

$$\{-e^{i(\Delta(E,\Omega))\hat{x}} \rho_S e^{-i(\Delta(E,\Omega))\hat{x}} + \rho_S + c.c.\}.$$





Kilian, Toros, Deppisch, Saakyan, Bose, arXiv:2204.13095 (to appear PRR)


We do not need some details of this picture
with the LOCC argument!

Some of our papers

- **Large mass superpositions:**

M. Scala et al, Phys. Rev. Lett. 111, 180403 (2013). C. Wan et al., Phys. Rev. Lett. 117, 143003 (2016); Marshman et al. PRR 2021, Wood et al. arXiv 2021, Zhou et al. PRR 2022 (to appear), Zhou et al. arXiv:2210.05869.

- **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).

- **Assumptions spelt out, covariant treatment, role of virtual gravitons:**

R. Marshman, A. Mazumdar, S. Bose, Physical Review A 101 (5), 052110.

- **Casimir screening**

TW van de Kamp, RJ Marshman, S Bose, A Mazumdar, Physical Review A 102 (6), 0628074 (2020)

- **GGN and Jitter Noise Mitigation**

M Toroš, TW van de Kamp, RJ Marshman, MS Kim, A Mazumdar, S Bose

Phys. Rev. Research 3, 023178 (2021).

- **Nonclassicalities using a free mass as a qubit:**

Bin Yi, Urbasi Sinha, Dipankar Home, Anupam Mazumdar, Sougato Bose, arXiv:2106.11906

- **Experiment (Ron Folman's group): Y Margalit et. al.,Science advances 7 (22), eabg2879 (2021).**
- **Neutrino Detection: Kilian, Toros, Deppisch, Saakyan, Bose, arXiv:2204.13095**

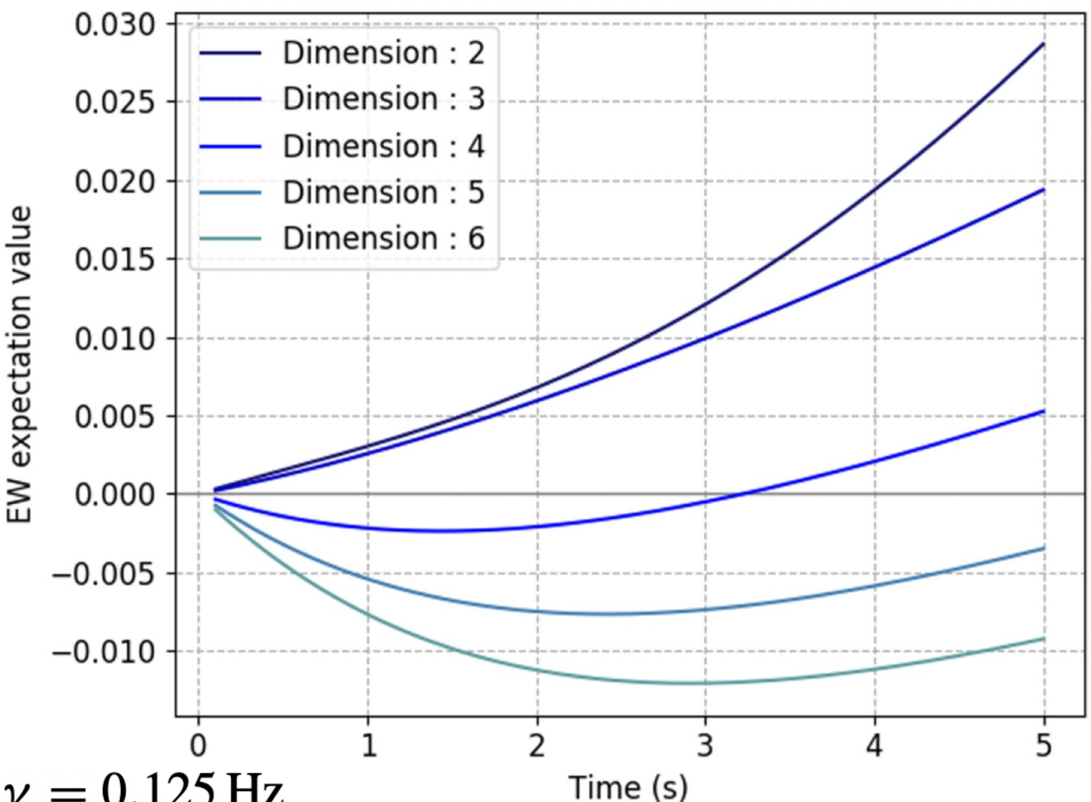
Qudits in Gravity Induced Entanglement

$$|\psi(t=\tau)\rangle = \frac{1}{D}\sum_{p=0}^{D-1}\left(|p\rangle \otimes \sum_{q=0}^{D-1} e^{i\phi_{pq}}|q\rangle\right)$$

$$\phi_{pq} \sim \frac{Gm_1 m_2 \tau}{\hbar C_{pq}}$$

J. Tilly, R. J. Marshman, A. Mazumdar, S. Bose, Phys. Rev. A **104**, 052416 (2021).

Gravitational Entanglement Witness in terms of Qudit Operators



$\gamma = 0.125\,\mathrm{Hz}$

$$\mathcal{W}_{\mathrm{PPT}} = |\lambda_-\rangle\langle\lambda_-|^T$$

$$= \sum_i^{\mathcal{D}} \sum_j^{\mathcal{D}} c_{ij} \lambda_i^{(1)} \otimes \lambda_j^{(2)}$$

Interactions appear as operator valued energy shifts of the system due to source-gravity interaction, with gr $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ to vacuum

$$\hat{H}_{\rm int} = -\frac{1}{2}\int d\boldsymbol{r}\,\hat{h}^{\mu\nu}(\boldsymbol{r})\hat{T}_{\mu\nu}(\boldsymbol{r})$$

Gravity vacuum

Source+Field States

Gravity vacuum

$$\Delta\hat{H}_g \equiv \int d\boldsymbol{k}\,\frac{\langle 0|\hat{H}_{\rm int}|\boldsymbol{k}\rangle\langle\boldsymbol{k}|\hat{H}_{\rm int}|0\rangle}{E_0 - E_{\boldsymbol{k}}}$$

Gravitational Entanglement between Moving Masses (in the limit of adiabatic "switching on" of interactions)

Effectively lowering harmonic trap frequencies

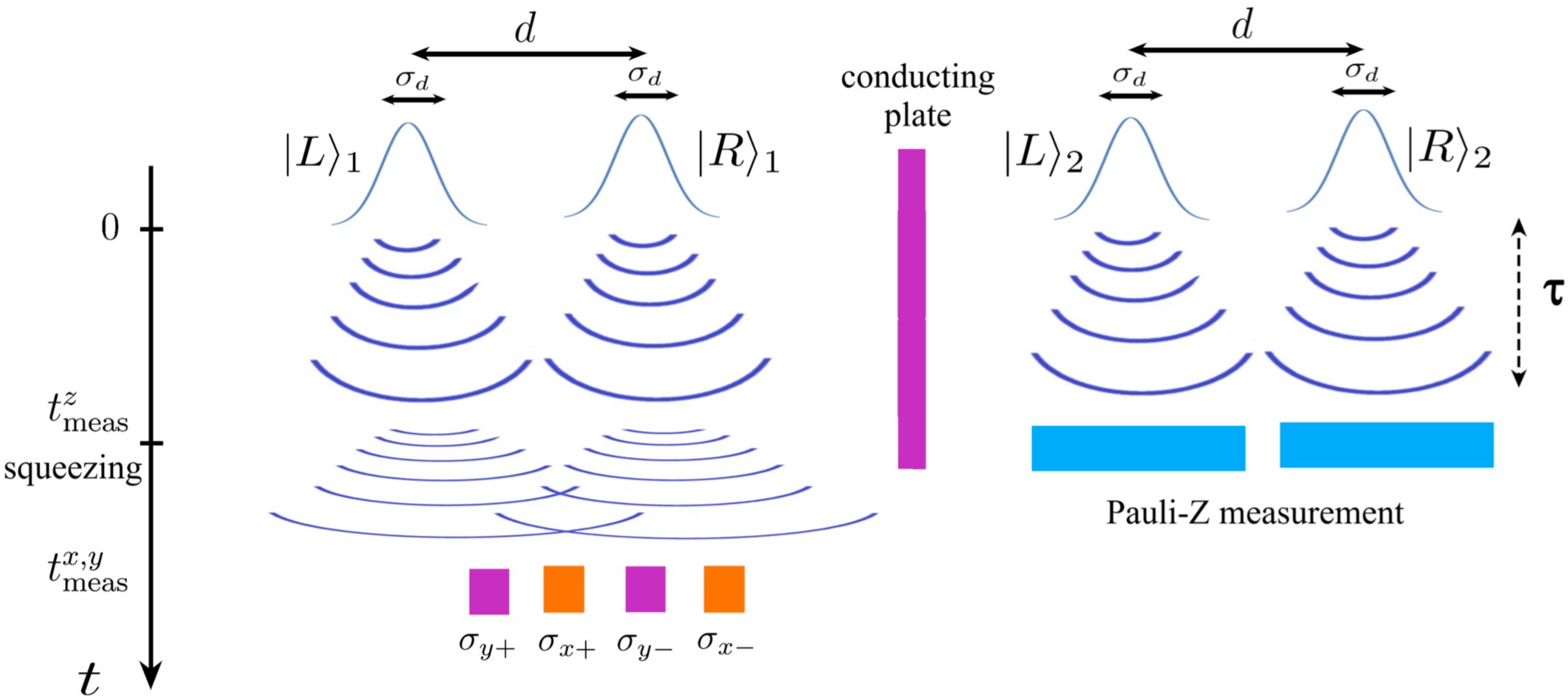
$$\Delta \hat{H}_g = -\frac{Gm^2}{|\hat{x}_A - \hat{x}_B|} \rightarrow C = \frac{\sqrt{2}Gm}{d^3\omega_{\mathrm{m}}^2}$$

$$-\frac{G(3\hat{p}_A^2 - 8\hat{p}_A\hat{p}_B + 3\hat{p}_B^2)}{2c^2|\hat{x}_A - \hat{x}_B|} \rightarrow C = \frac{2\sqrt{2}Gm}{c^2 d}$$

$$-\frac{G(5\hat{p}_A^4 - 18\hat{p}_A^2\hat{p}_B^2 + 5\hat{p}_B^4)}{8c^4m^2|\hat{x}_A - \hat{x}_B|} \rightarrow C = \frac{9\sqrt{2}G\hbar\omega_{\mathrm{m}}}{16c^4 d}$$

Sougato Bose, Anupam Mazumdar, Martine Schut, and Marko Toroš, Phys. Rev. D 105, 106028 (2022).

A new tool: A free mass as a Qubit



Bin Yi, Urbasi Sinha, Dipankar Home, Anupam Mazumdar, Sougato Bose, arXiv:2106.11906;
Bin Yi, Urbasi Sinha, Dipankar Home, Anupam Mazumdar, Sougato Bose, arXiv (Nov, 2022).