量子引力低能效应的理论预期

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引力相关的量子效应

1. Direct quantum gravity effects

$$l_p = \sqrt{G\hbar / c^3} \approx 1.6 \times 10^{-33} cm \qquad E_p = \sqrt{\hbar c^5 / G} \approx 1.2 \times 10^{19} GeV$$

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2. Quantum gravity phenomenology

$$E^2 = m^2c^4 + p^2c^2 + (l_p p)^n p^2c^2 \qquad \Delta x \Delta p \geq \frac{\hbar}{2}(1 + l_p^2 \Delta p^2)$$

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4. Quantum simulation without gravity

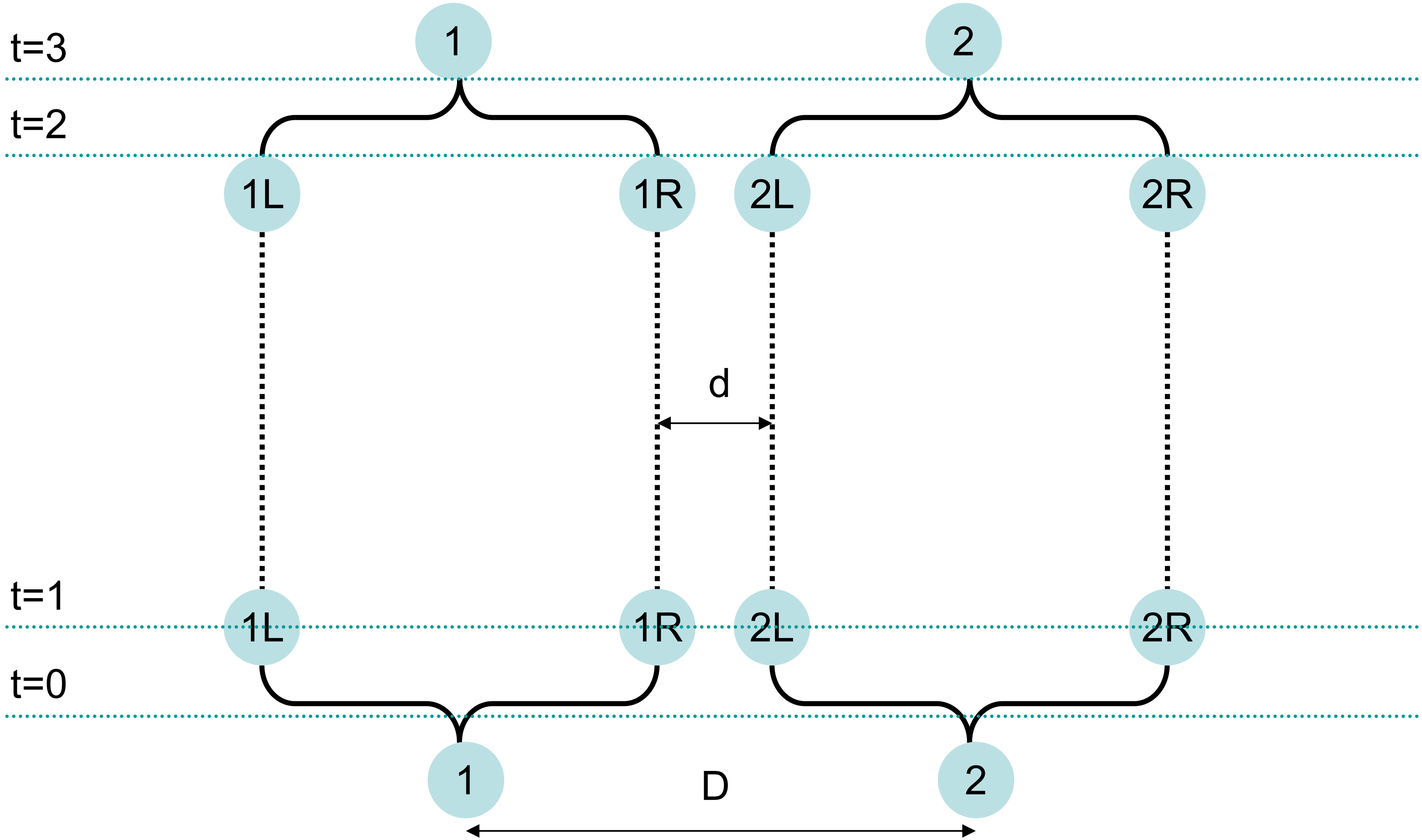
Review of QGEM

Matter-Wave system

Bose, et.al., Phys.Rev.Lett. 119 (2017)240401

Marletto and Vedral, Phys.Rev.Lett. 119 (2017) 240402

Two Stern-Gerlach devices



$d \ll D$

Review of QGEM

- 引力若是量子的，将引起相位差：

$$|\psi_{t=0}\rangle = \frac{1}{2}\left(|\psi_1^L\rangle + |\psi_1^R\rangle\right) \otimes \left(|\psi_2^L\rangle + |\psi_2^R\rangle\right) \otimes |g\rangle$$

$$= \frac{1}{2}\left(|LL\rangle + |RR\rangle + |LR\rangle + |RL\rangle\right) \otimes |g\rangle$$

$$|\psi_{t=1}\rangle = \frac{1}{2}\left(|LL\rangle \otimes |g_{d_{LL}}\rangle + |RR\rangle \otimes |g_{d_{RR}}\rangle + |LR\rangle \otimes |g_{d_{LR}}\rangle + |RL\rangle \otimes |g_{d_{RL}}\rangle\right)$$

$$|LL\rangle \to e^{i\phi_{LL}} |LL\rangle \qquad \phi_{ij} = \frac{Gm^2 \Delta t}{\hbar d_{ij}} \qquad \phi_{LL} = \phi_{LR} = \phi_{RR} \neq \phi_{RL} \qquad d \quad R$$

$$|\psi_{t=2}\rangle = \frac{1}{2}\left(|LL\rangle \otimes |g_{d_{LL}}\rangle + |RR\rangle \otimes |g_{d_{RR}}\rangle + |LR\rangle \otimes |g_{d_{LR}}\rangle + e^{i\frac{Gm^2 t}{\hbar d}} |RL\rangle \otimes |g_{d_{RL}}\rangle\right)$$

$$|\psi_{t=3}\rangle = \frac{1}{2}\left(|LL\rangle + |RR\rangle + |LR\rangle - |RL\rangle\right) \otimes |g\rangle$$

$$\neq |1\rangle \otimes |2\rangle$$

最大纠缠态!

$$m \sim 10^{-11} g, d \sim 10^{-4} cm, t \sim 1s \to \phi \sim \pi$$

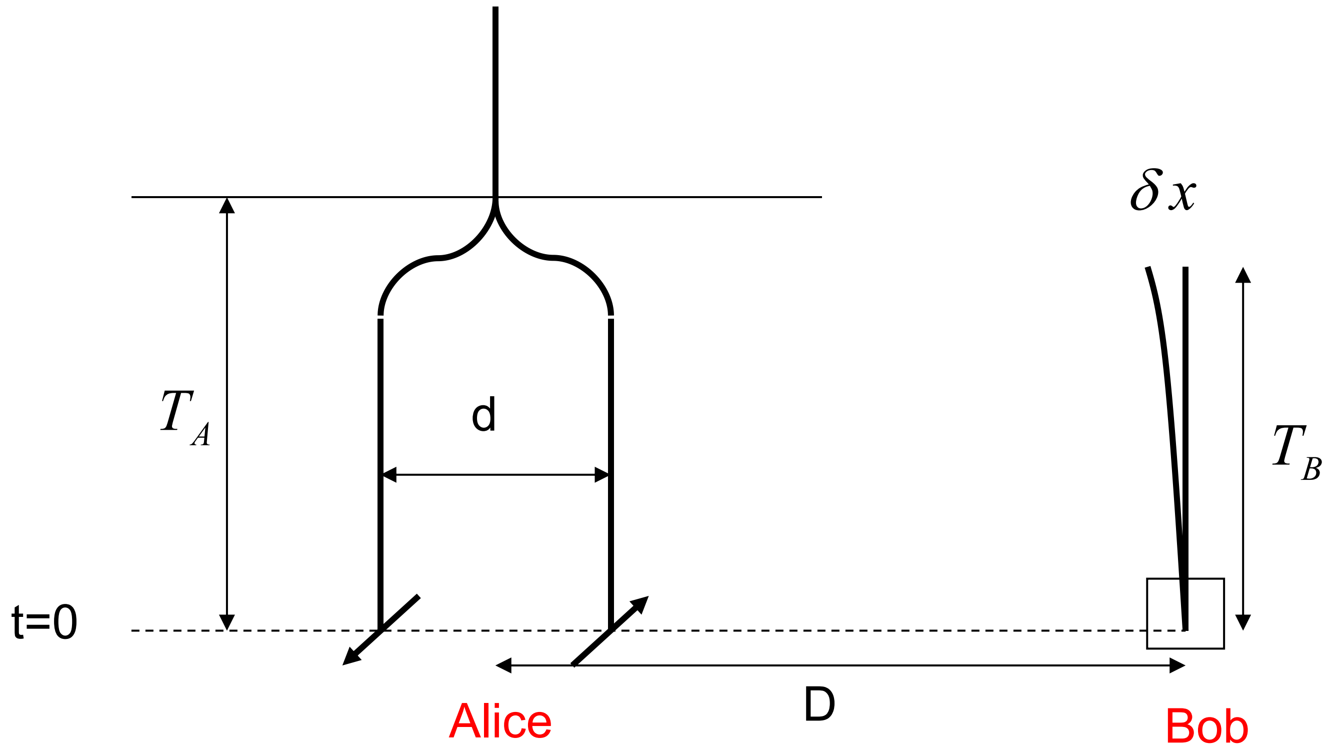
Theoretical investigation on superposition of massive objects

The Setup

Mari, et.al., Sci.Rep.6(2016)22777

Belenchia,Wald, et.al., PRD98(2018)12,126009

Belenchia,Wald, et.al., IJMPD28(2019)14,1943001

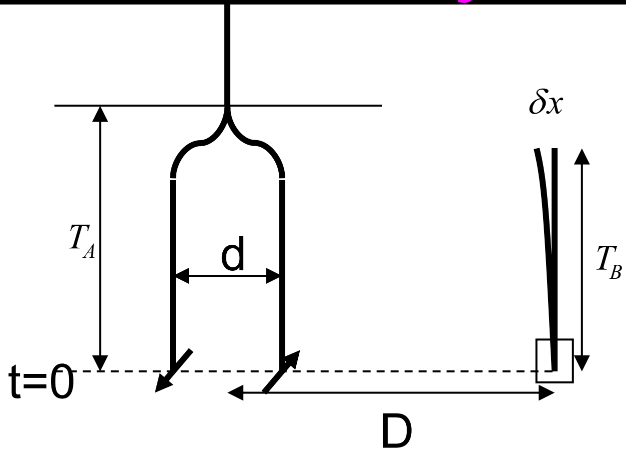


$D \quad d$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L_A\rangle|\downarrow\rangle_A + |R_A\rangle|\uparrow\rangle_A\right) \otimes |\varphi_0\rangle_B$$

Theoretical investigation on superposition of massive objects

I. Apparent paradox



$$T_B < D \qquad T_A < D$$

T_B : δx **Which path?**

T_A : **Recombine the superposition without emitting radiation**

Theoretical investigation on superposition of massive objects

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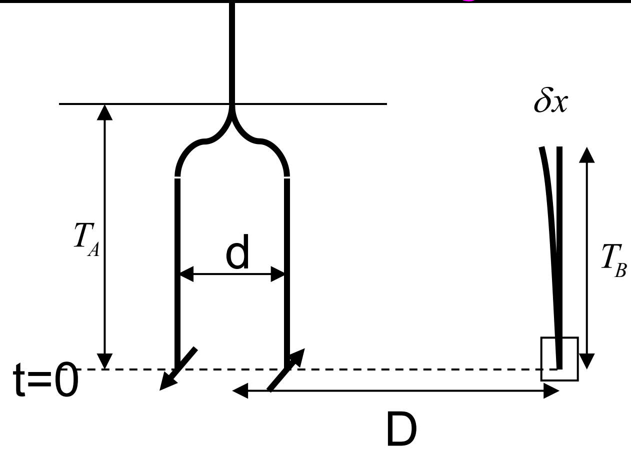

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(1) If complementarity holds.

Alice tests the coherence of state and know whether or not open the trap

Violation of causality

Theoretical investigation on superposition of massive objects

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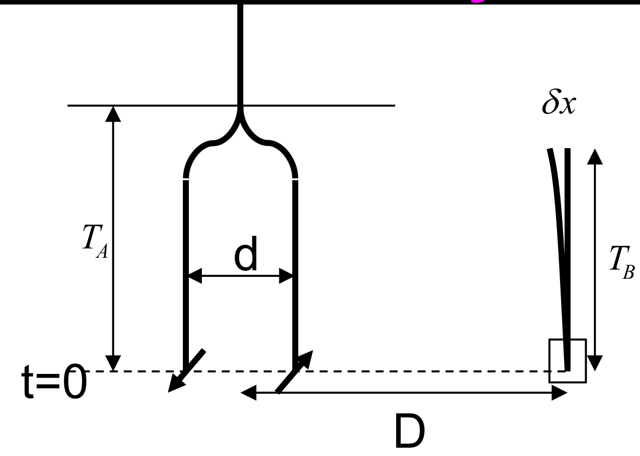

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Violation of causality

(2) If causality holds.

Alice maintains the coherence **Bob acquired which path**

Violation of complementarity

Theoretical investigation on superposition of massive objects

II. EM Version

Before open the trap

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L_A\rangle|\downarrow\rangle_A|\alpha_L\rangle_F + |R_A\rangle|\uparrow\rangle_A|\alpha_R\rangle_F\right)\otimes|\varphi_0\rangle_B$$

$$\left|\langle\alpha_L|\alpha_R\rangle_F\right| \quad 1$$

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(1) Vacuum fluctuations of electric field $c = 1$

$$\Delta E \sim \frac{1}{R^2} \qquad m\ddot{x} = Eq$$

The displacement of the position of a classical free particle over the time scale R

$$\Delta x \sim \frac{q}{m}\Delta E \Delta t^2 \sim \frac{q}{m}\frac{1}{R^2}R^2 \sim \frac{q}{m}$$

Limit Bob's ability to entangle his particle with Alice.

Theoretical investigation on superposition of massive objects

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Limit Bob's ability to entangle his particle with Alice.

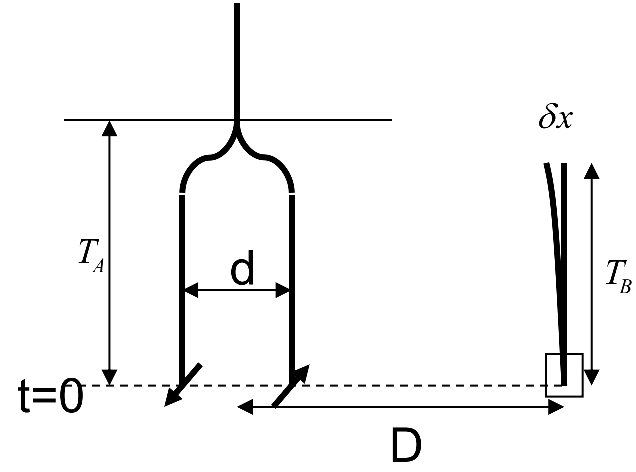
To significant entanglement it is necessary to have

$$\delta x > \frac{q_B}{m_B}$$

Theoretical investigation on superposition of massive objects

(2) EM radiation

Dipole moment $$D_A = q_A d$$



(i) $$E \sim \frac{D_A}{D^3}$$

$$\delta x \sim \frac{q_B E}{m_B} T_B^2 \sim \frac{q_B}{m_B} \frac{D_A}{D^3} T_B^2$$

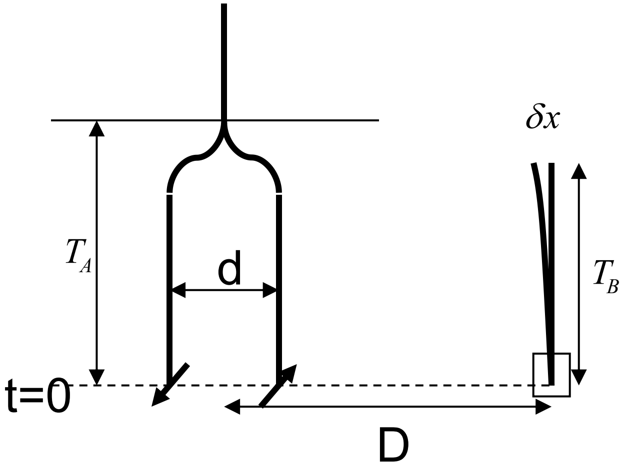
Bob will be able to obtain significant "which path" information iff

$$\frac{D_A}{D^3} T_B^2 > 1$$

Theoretical investigation on superposition of massive objects

(2) EM radiation

Dipole moment $$D_A = q_A d$$



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(ii) The amount of entangling radiation emitted by Alice's particle

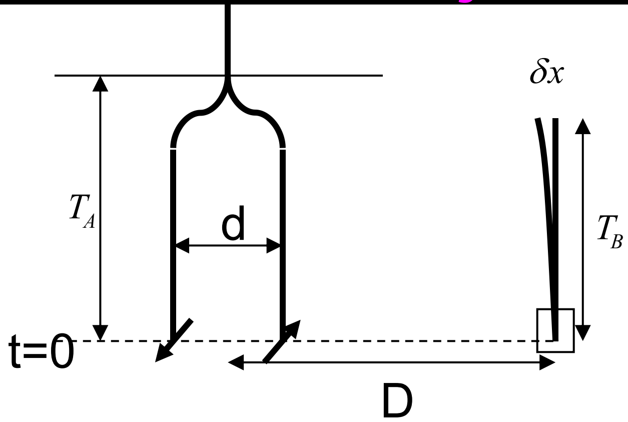
$$\varepsilon \sim \left(\frac{D_A}{T_A^2} \right)^2 T_A$$

Photon's frequency $$\frac{1}{T_A} \quad \Rightarrow N \sim \left(\frac{D_A}{T_A} \right)^2$$

Alice can avoid emitting entangling radiation iff $$D_A < T_A$$

Theoretical investigation on superposition of massive objects

1. Main case of interest $T_B < D, \quad T_A < D$



(a) $D_A < T_A$

Alice can close her superposition without radiation

$$D_A < T_A < D$$

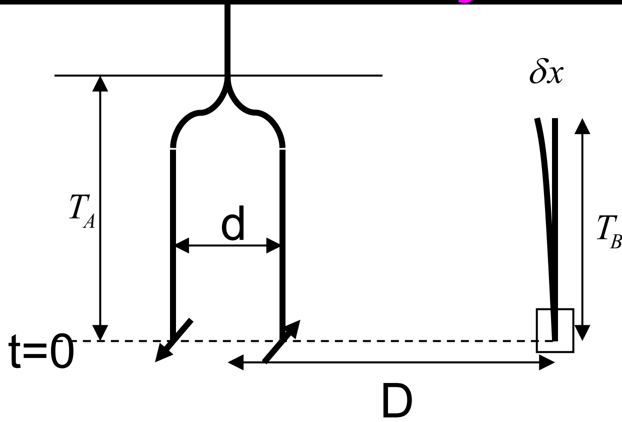
Bob is unable to acquire "which path" information in time $T_B < D$

$$\frac{D_A}{D^3} T_B^2 = \frac{D_A}{D} \frac{T_B^2}{D^2} < 1$$

Alice recohere particle, Bob can do nothing to stop her

Theoretical investigation on superposition of massive objects

1. Main case of interest $T_B < D, \quad T_A < D$



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Bob is unable to acquire "which path" information in time $T_B < D$

$$\frac{D_A}{D^3} T_B^2 = \frac{D_A}{D} \frac{T_B^2}{D^2} < 1$$

Alice recohere particle, Bob can do nothing to stop her

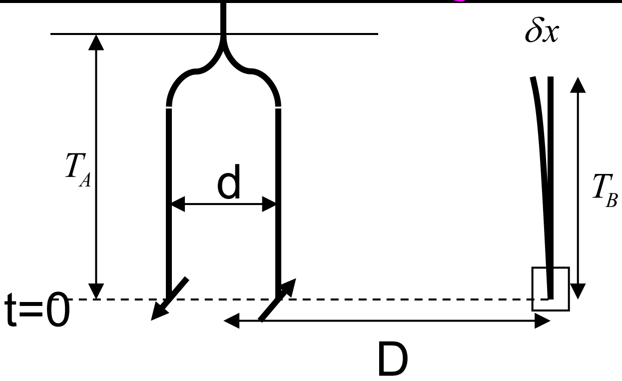
(b) $D_A > T_A$

Alice's particle will necessarily emit entangling radiation, recoherence experiment fails

Bob's particle can obtain "which path" information.

Theoretical investigation on superposition of massive objects

Summary



If no vacuum fluctuation

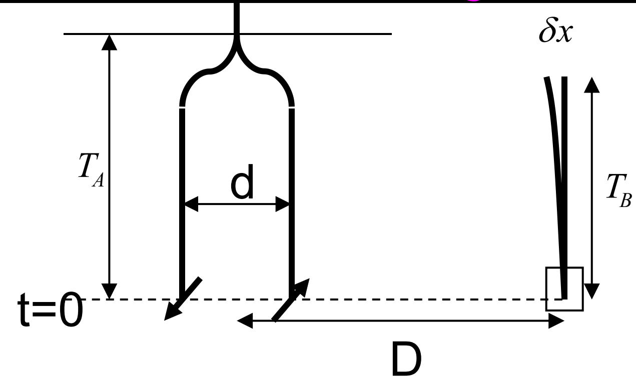
(a) $D_A < D$

Bob would obtain "which-path" information in time $T_B < D$

- **If he influences Alice's state** $\longrightarrow$ **Violation of causality**
- **If he doesn't** $\longrightarrow$ **Violation of comlementarity**

Theoretical investigation on superposition of massive objects

Summary



If no vacuum fluctuation

(a) $D_A < D$

Bob would obtain "which-path" information in time $T_B < D$

If he influences Alice's state $\rightarrow$ **Violation of causality**

If he doesn't $\rightarrow$ **Violation of comlementarity**

If no quantized radiation

(b) $D_A > D$

Alice would be able to recohere her particle in $T_A < D$

But Bob can obtain "which path" information in $T_B < D$

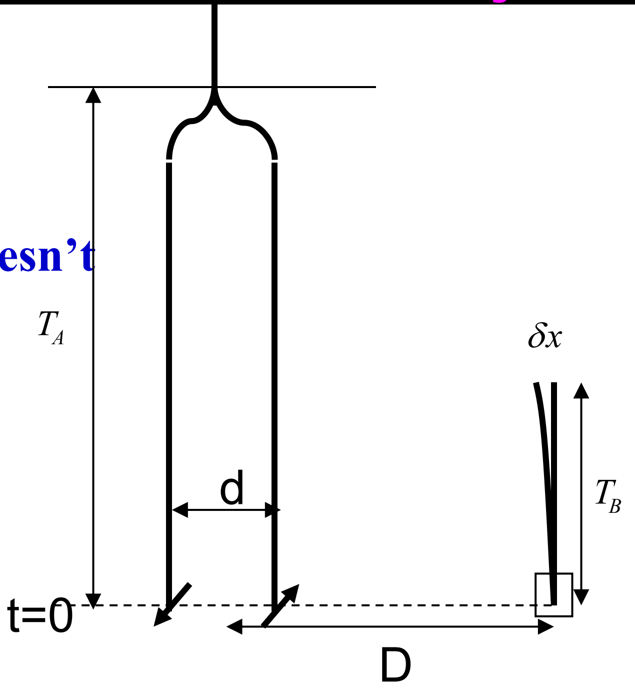
$\rightarrow$ **Violation of causality or complementarity**

Theoretical investigation on superposition of massive objects

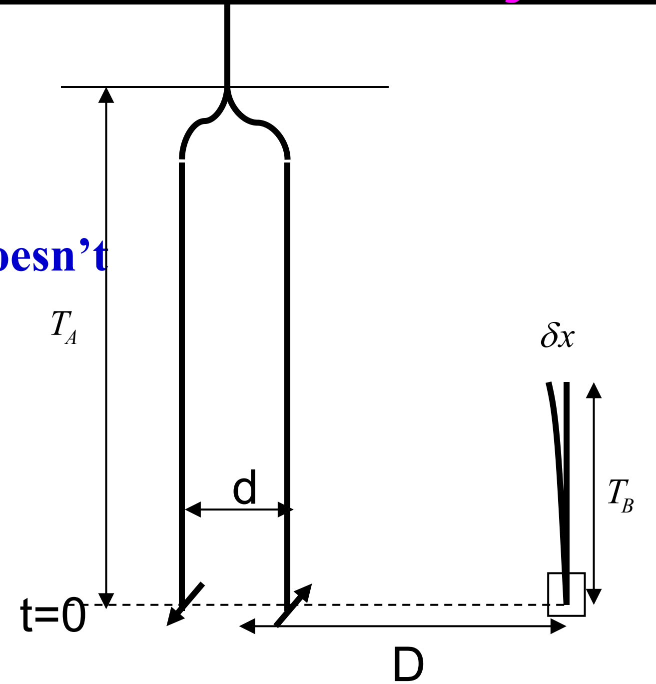
(II) $T_A > D_A > D$ **No radiation**

Bob could obtain "which path" information if release
Bob could not obtain "which path" information if he doesn't

No causality issue



Theoretical investigation on superposition of massive objects



(II) $T_A > D_A > D$ **No radiation**

Bob could obtain "which path" information if release
Bob could not obtain "which path" information if he doesn't

No causality issue

(III) $T_A \quad D_A > D$

No radiation

Bob can acquire "which path" information

Alice's particle must be entangled with Bob's at the end of process.

How can Bob's particle become entangled with Alice's?

$$t < T_A \qquad \left|x = L, \uparrow\right\rangle_A \left|\phi_L\right\rangle_F \left|R\right\rangle_B + \left|x = R, \downarrow\right\rangle_A \left|\phi_R\right\rangle_F \left|L\right\rangle_B$$

$$t > T_A \qquad \left|x = 0\right\rangle_A \left|\phi_0\right\rangle_F \otimes \left(\left|\uparrow\right\rangle_A \left|R\right\rangle_B + \left|\downarrow\right\rangle_A \left|L\right\rangle_B\right)$$

Summary and outlooks

- QGEM provides a strategy to test the nature of gravity, quantum or classical.
- Current theoretical investigation supports that the gravity should be quantum.
- Could we propose more Gedanken experiments at low energy level to signalize the quantum nature of gravity?

Thanks !