Quantum Superposition of Massive Objects and the Quantization of Gravity

Alessio Belenchia

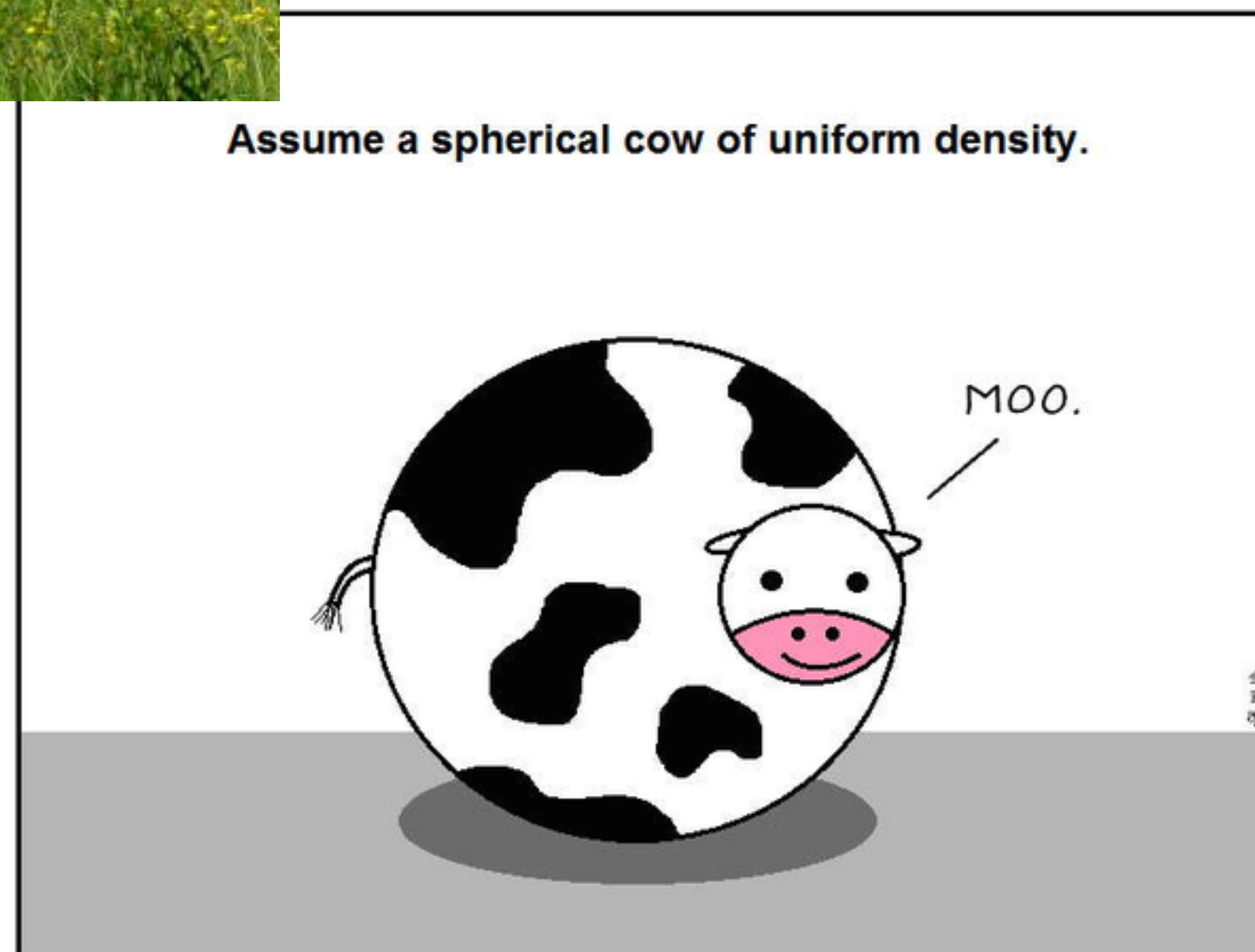
Queen's University Belfast

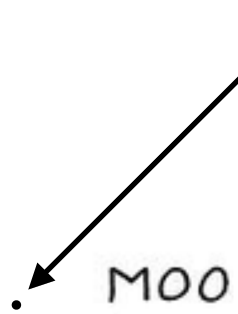
Primordial black holes, de Sitter space and quantum tests of gravity

DESY

Hamburg, 12 February 2019

In collaboration with: R. M. Wald (Chicago), F. Giacomini, E. Castro, C. Brukner and M. Aspelmeyer (Vienna)


Assume a spherical cow of uniform density.
MOO.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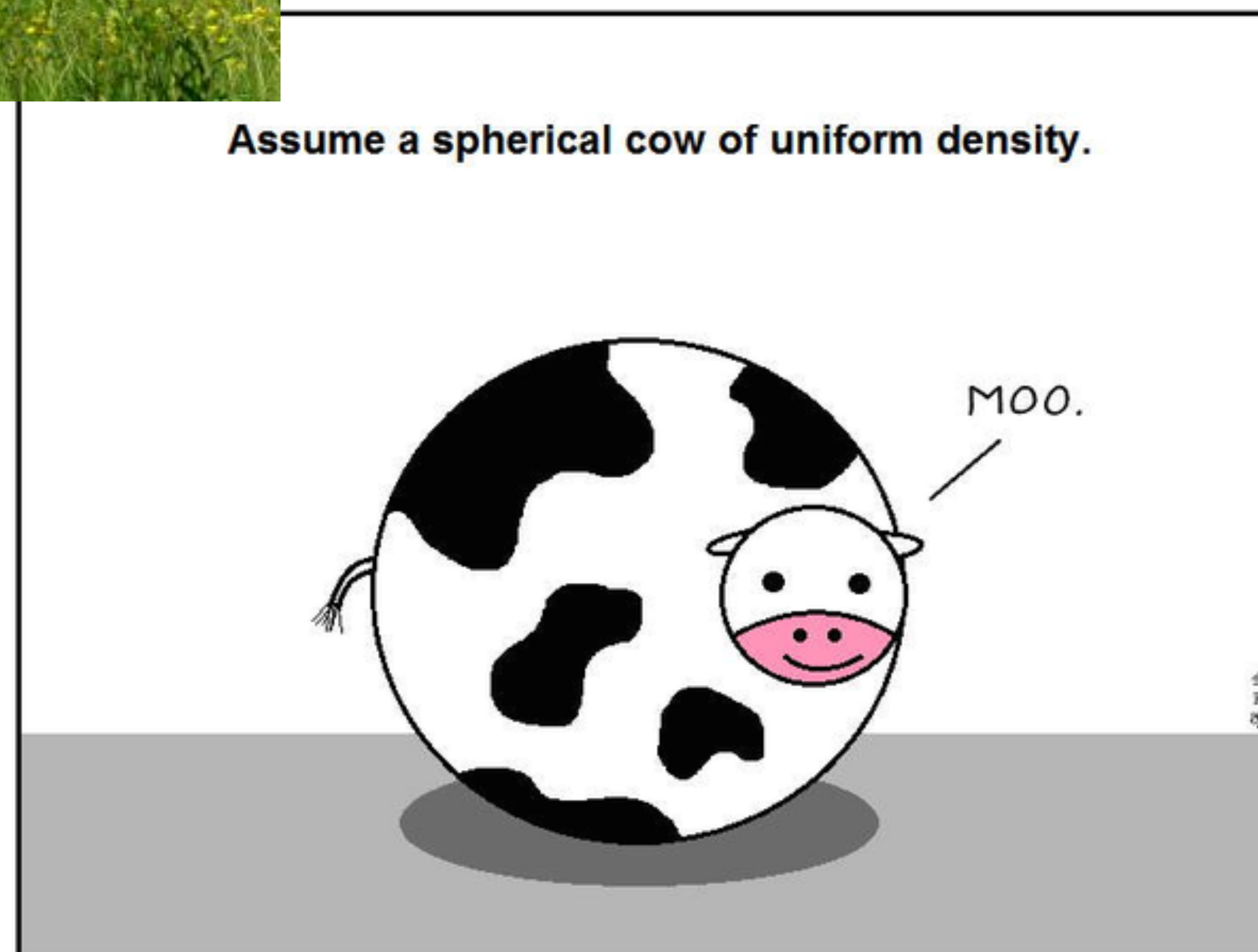
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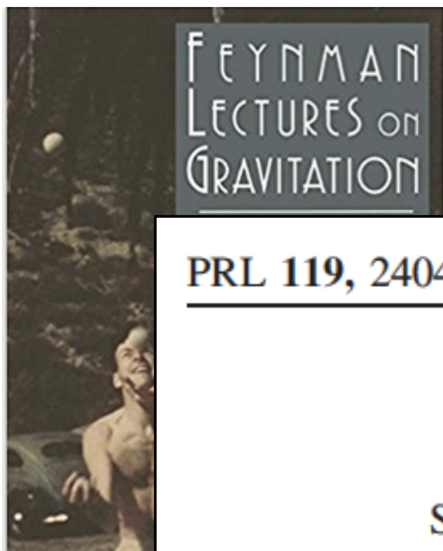
A simple question*

Is gravity quantum as the other fundamental forces?



On Gravity's Role in Quantum State Reduction

Roger Penrose[1,2]

PHYSICAL REVIEW A, VOLUME 63, 022101

Hybrid classical-quantum dynamics

Asher Peres* and Daniel R. Terno†

VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

PRL 119, 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

Department of Physics, William Jew

...avitational

D Kafri[1], J M Taylor[1] and G J Milburn[2,3]

Probing a gravitational cat state

C Anastopoulos[1,3] and B L Hu[2]

Is Gravity Quantum?

M. Bahrami,[1,2] A. Bassi,[1,2] S. McMillen,[3] M. Paternostro,[3] and H. Ulbricht[4]

When Cavendish meets Feynman: A quantum torsion balance for testing the quantumness of gravity

Matteo Carlesso,[1,2,*] Mauro Paternostro,[3,4] Hendrik Ulbricht,[5] and A

Two-slit diffraction with highly charged particles: Niels Bohr's consistency argument that the electromagnetic field must be quantized

Gordon Baym[1] and Tomoki Ozawa

Superposition of Massive Objects and Quantumness of Gravity

Q1: Can we argue that gravity ought to be quantum?

A1: Yes if we assume known physics to hold

Q2: How general is the argument?

A2: In order to avoid inconsistencies with known physics gravity must be quantum……however the last word is left to experiments

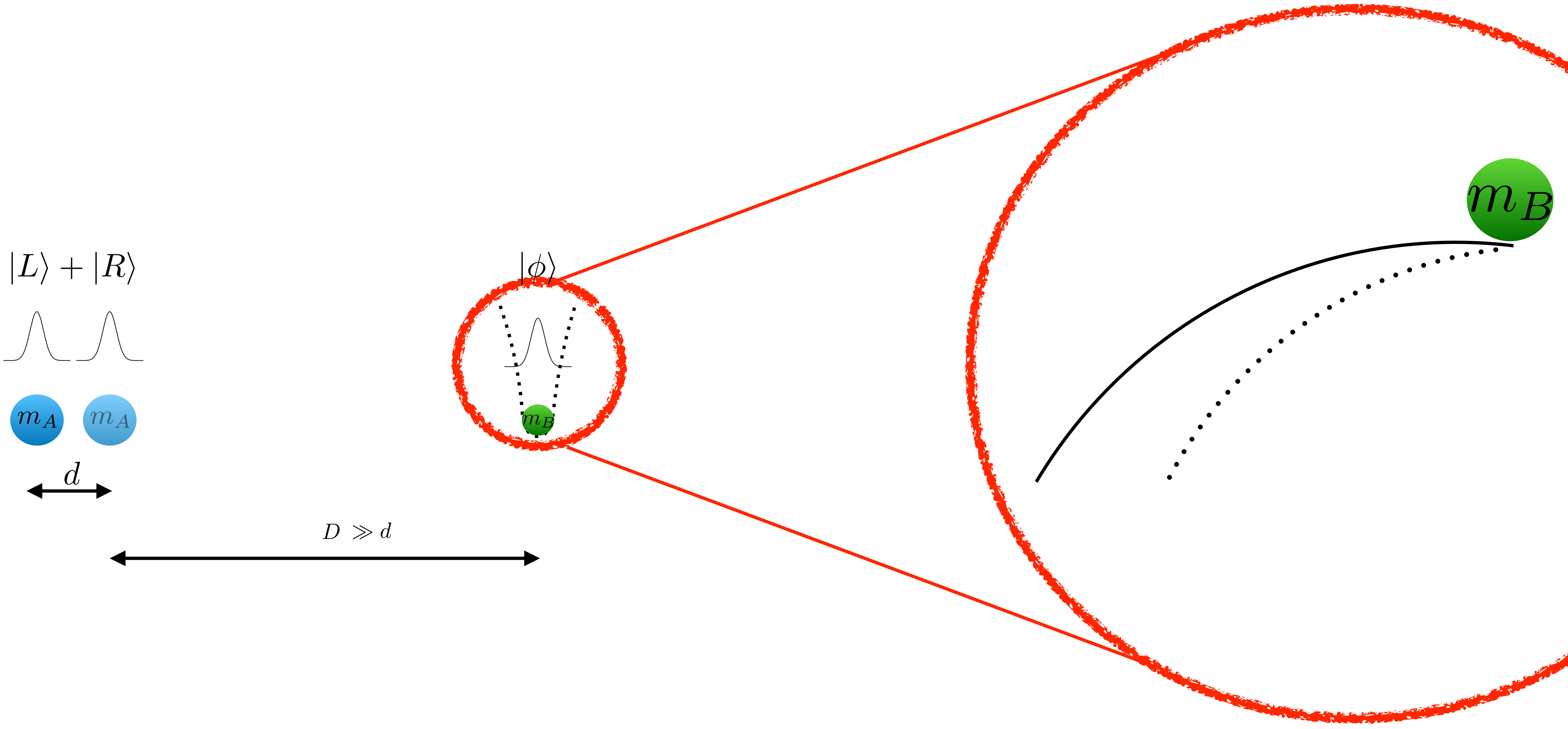
Take at home message:

A consistent picture for entanglement of massive objects through gravity necessarily requires (linearized) gravity to be quantum

Quantum superposition of Massive Objects and the Quantization of Gravity
AB, R. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner and M. Aspelmeyer
ArXiv: 1807.07015

1.A Gedankenexperiment

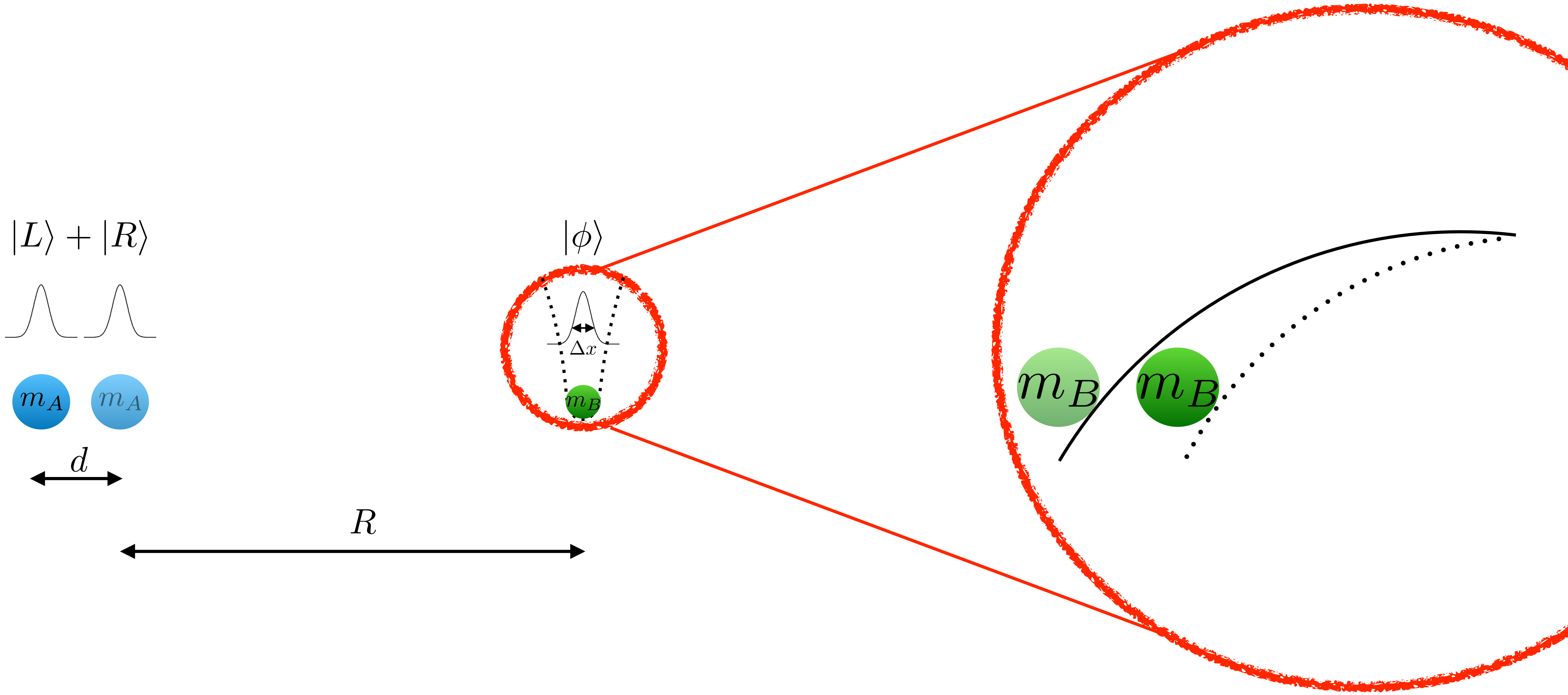
A gedankenexperiment:



$$(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle) \otimes |\phi_B\rangle$$

De Palma, Giovannetti, Mari; Scientific Reports 6, 22777 (2016)

A gedankenexperiment:

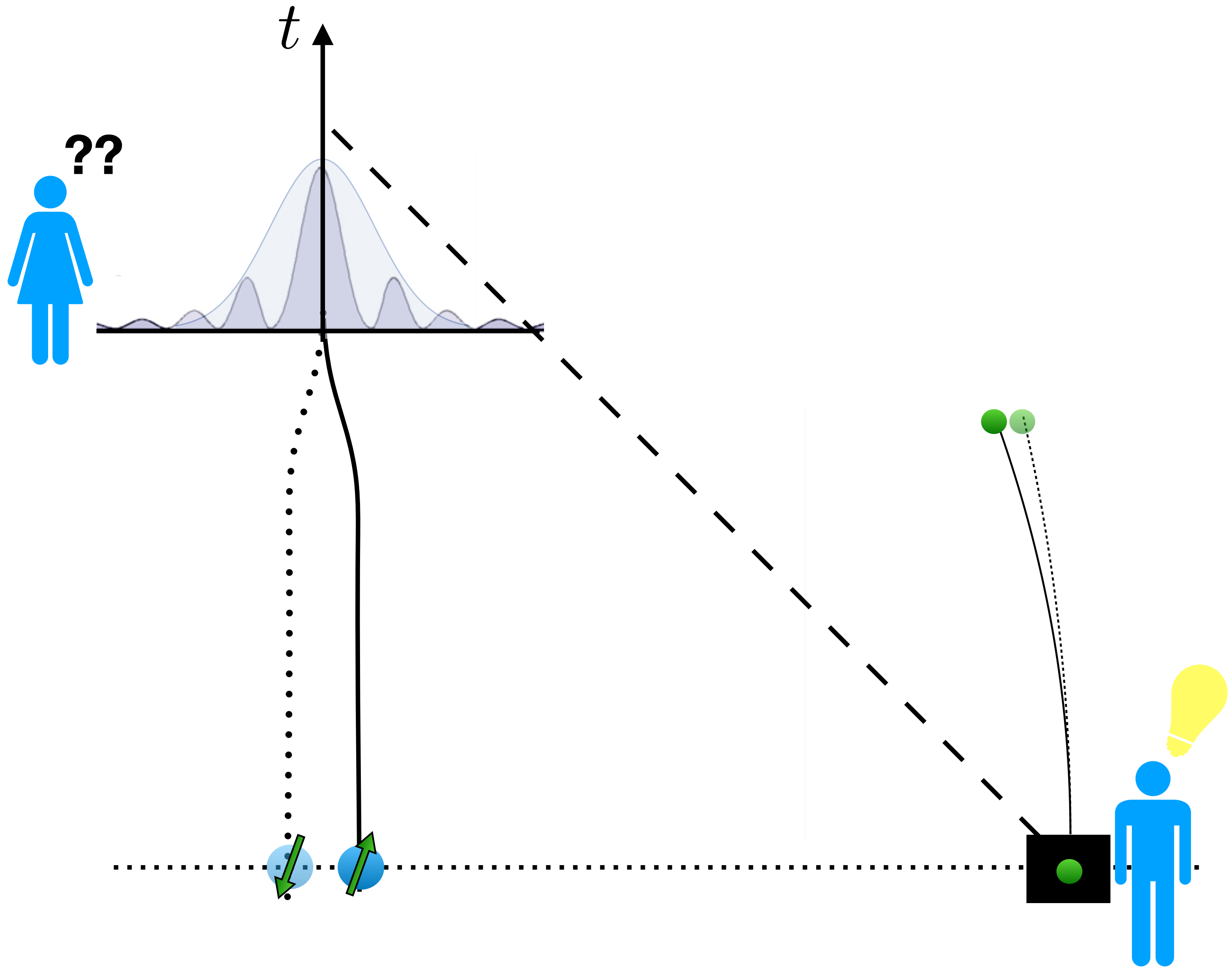


$$(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle) \otimes |\phi_B\rangle \rightarrow |L\rangle|\uparrow\rangle|\phi_B^L\rangle + |R\rangle|\downarrow\rangle|\phi_B^R\rangle$$

De Palma, Giovannetti, Mari; Scientific Reports 6, 22777 (2016)

- Up until now we have used Schrödinger eq. evolution with a Newton/Coulomb potential
- Implicit assumption: the gravitational/Coulomb potential can entangle the two particles
- “Weaker” assumption: Bob acquires “which-path” information on Alice

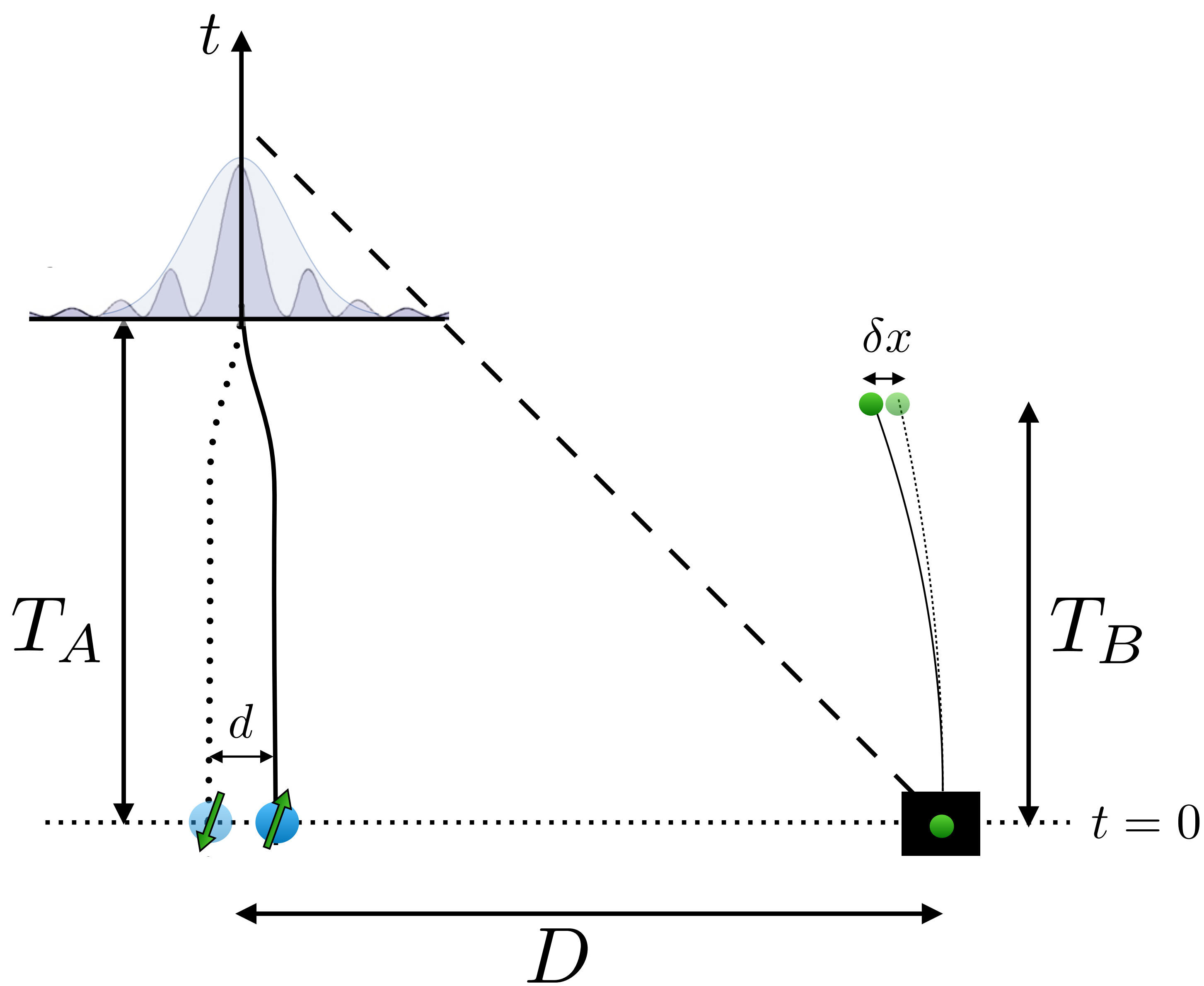
Guess What Game:



- **Up until now we have used Schrödinger eq. evolution with a Newton/Coulomb potential**
- **Implicit assumption: the gravitational/Coulomb potential can entangle the two particles**
- **"Weaker" assumption: Bob acquires "which-path" information on Alice**

Guess What Game:

$$T_A, T_B < D$$



Causality:

If the two particles get entangled, Alice can discover what Bob did in a time less than the light-crossing time

Complementarity:

If we assume a priori that causality has to be respected , we find ourself in trouble with complementarity of quantum mechanics

2. EM case revisited

Quantum Vacuum Fluctuations

Limit* on charge localization due to fluctuations of the Electric field: $\Delta x \sim q/m$

In order to acquire significant which-path information

$$\boxed{\delta x_B > q_B/m_B}$$

*more stringent than Compton length localization only for q>1

Quantum Vacuum Fluctuations

Limit* on charge localization due to fluctuations of the Electric field: $\Delta x \sim q/m$

In order to acquire significant which-path information

$$\boxed{\delta x_B > q_B/m_B}$$

Quantized E.M. radiation

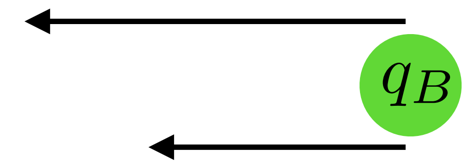
Effective (or fictitious) electric dipole moment of Alice superposition $\mathcal{D}_A = q_A d$

When Alice perform the interferometric experiment the dipole will reduced to zero in time T_A and radiation is emitted by the accelerated trajectory(ies)

*more stringent than Compton length localization only for q>1

Quantum Vacuum Fluctuations $\boxed{\delta x_B > q_B/m_B}$

$$F_1 = q_B E_1 = k\frac{q_A q_B}{D^2}$$



$$F_2 = q_B E_2 = k\frac{q_A q_B}{(D+d)^2}$$

$$\delta x \sim \frac{q_B}{m_B}\frac{\mathcal{D}_A}{D^3}T_B^2$$

$$\frac{\mathcal{D}_A}{D^3}T_B^2 > 1^{*}$$

* reintroducing some constant we would have $\mathcal{D}_A T_B^2/D^3 > 1/c^2$

Quantized E.M. radiation

(Estimate of the) energy radiated by Alice fictitious dipole

$$\mathcal{E} \sim \left(\frac{\mathcal{D}_A}{T_A^2}\right)^2 T_A$$

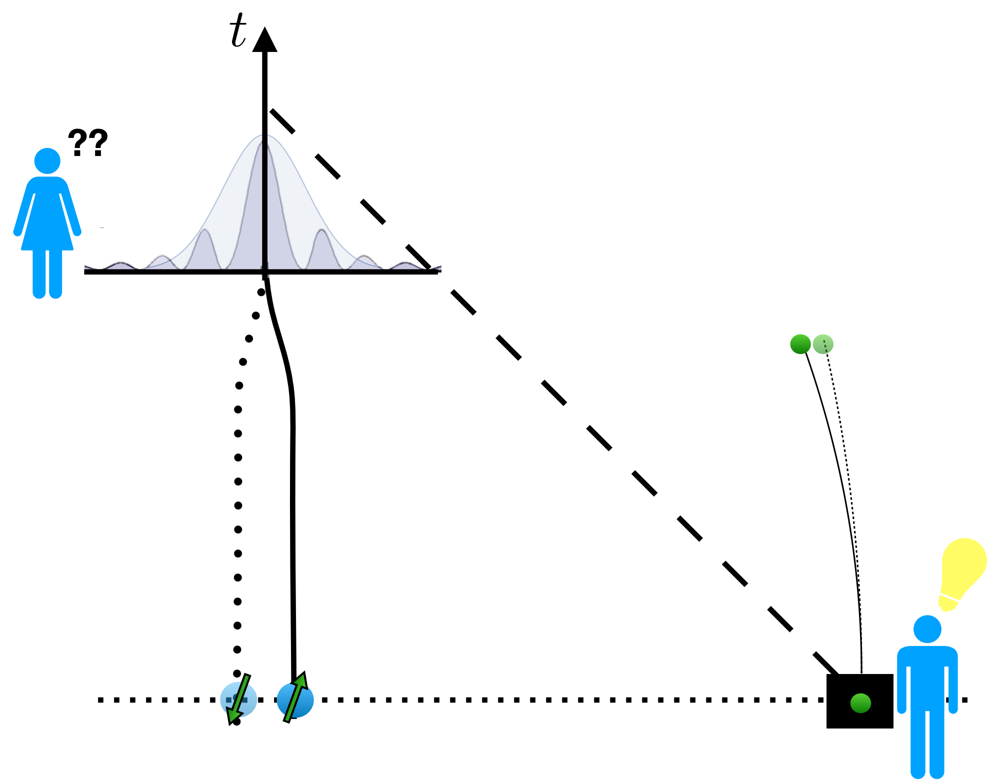
The degree of decoherence due to radiation can be estimated by requiring that no photon with characteristic frequency $1/T_A$ is emitted by the fictitious dipole *

$$\mathcal{D}_A < T_A$$

* A more detailed treatment can be obtained by looking at the overlap of the coherent states produced by the classical currents corresponding to the paths in the interferometer. This has been extensively studied and leads to the same result.

RESOLUTION OF THE "APPARENT" PARADOXES

$$T_A, T_B < D$$



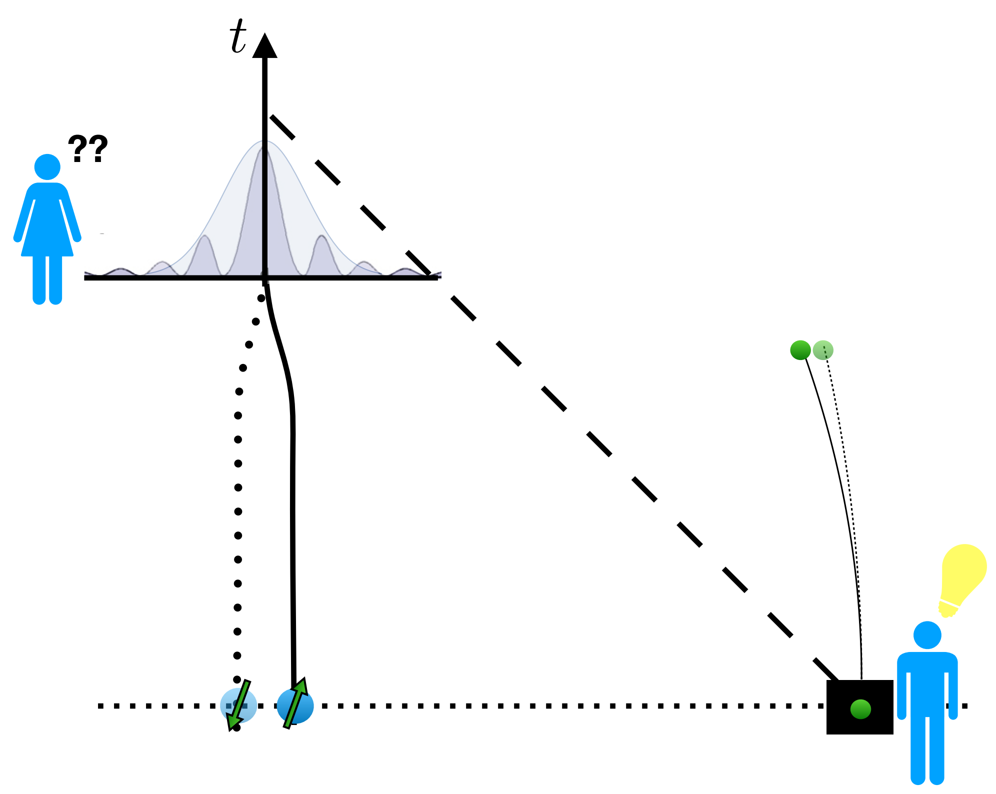
If $\mathcal{D}_A < T_A$ No entangling radiation from Alice

$$+$$

$$\frac{\mathcal{D}_A}{D^3} T_B^2 < 1$$ i.e. no which-path info for Bob

RESOLUTION OF THE "APPARENT" PARADOXES

$T_A, T_B < D$

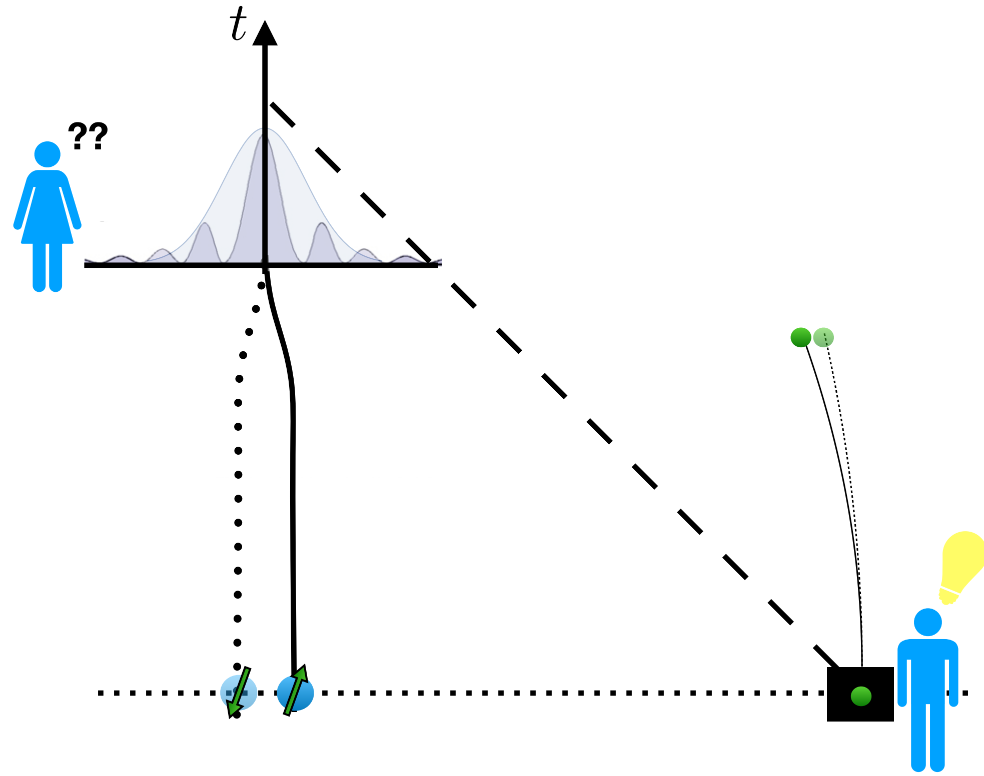


If $\mathcal{D}_A > T_A$

Alice gets decohered by radiation

Bob in this case can be able to acquire which-path information without any contradiction with complementarity

RESOLUTION OF THE “APPARENT” PARADOXES $T_A, T_B < D$



3. Gravitational case

Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

*more stringent than Compton length localization only for m>1

Quantum Vacuum Fluctuations

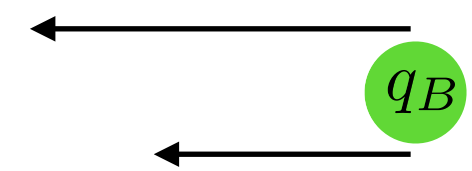
Limit* on charge localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\delta x_B > \ell_P$$

$$\delta x \sim G \frac{\mathcal{D}_A^{\text{grav.}}}{D^3} T_B^2$$

$$F_1 = G\frac{m_A m_B}{D^2}$$



$$F_2 = G\frac{m_A m_B}{(D+d)^2}$$

*more stringent than Compton length localization only for q>1

Quantum Vacuum Fluctuations

Limit* on charge localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

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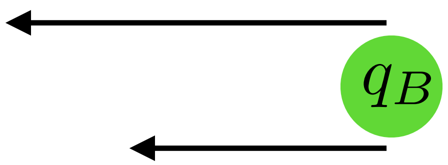

$$F_2 = G\frac{m_A m_B}{(D+d)^2}$$

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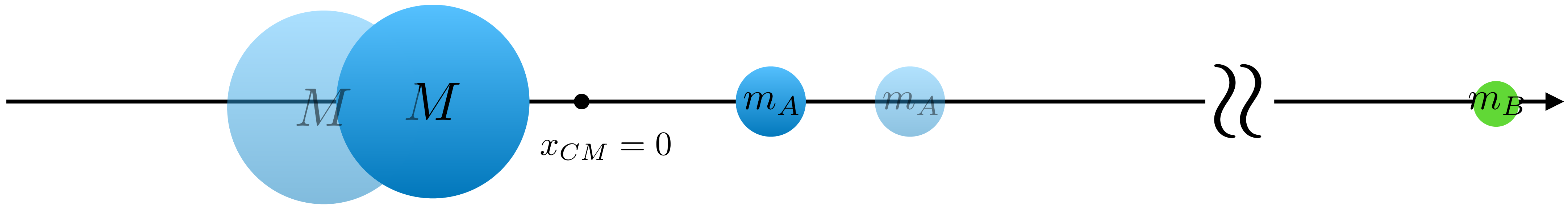
Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

Conservation of the center of mass:



$$\mathcal{D}_A^{\text{grav.}} = 0$$

*more stringent than Compton length localization only for q>1

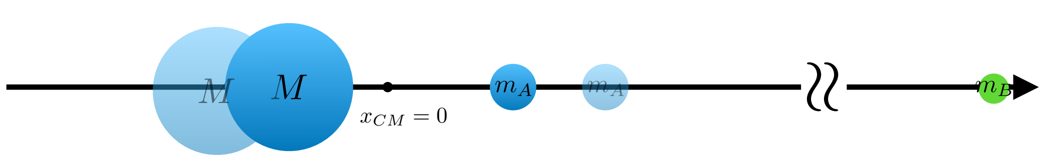
Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

$$\delta x_B \sim \frac{\mathcal{Q}_A^{(n)}}{D^{n+2}} T_B^2 > 1$$



*more stringent than Compton length localization only for q>1

Quantized gravitational radiation

(Estimate of the) energy radiated by Alice fictitious n-pole

$$\mathcal{E} \sim \left(\frac{\mathcal{Q}_A^{(n)}}{T_A^{n+1}} \right)^2 T_A$$

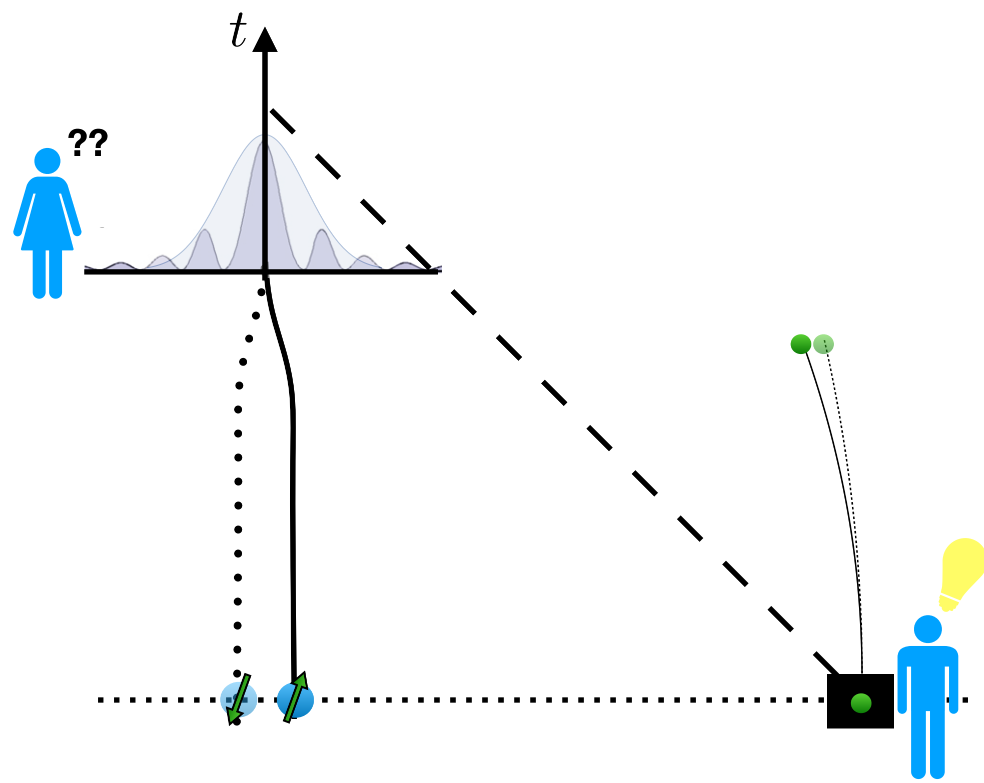
The degree of decoherence due to radiation can be estimated by requiring that no graviton with characteristic frequency $1/T_A$ is emitted by the fictitious n-pole *

$$\mathcal{Q}_A^{(n)} < T_A^n$$

* A more detailed treatment can be obtained by looking at the overlap of the coherent states produced by the classical currents corresponding to the paths in the interferometer. This leads to the same result.

RESOLUTION OF THE "APPARENT" PARADOXES

$$T_A, T_B < D$$



If $\mathcal{Q}_A^{(n)} < T_A^n$ No entangling radiation from Alice

$$+$$

$$\frac{\mathcal{Q}_A^{(n)}}{D^{n+2}} T_B^2 < 1$$ i.e. no which-path info for Bob

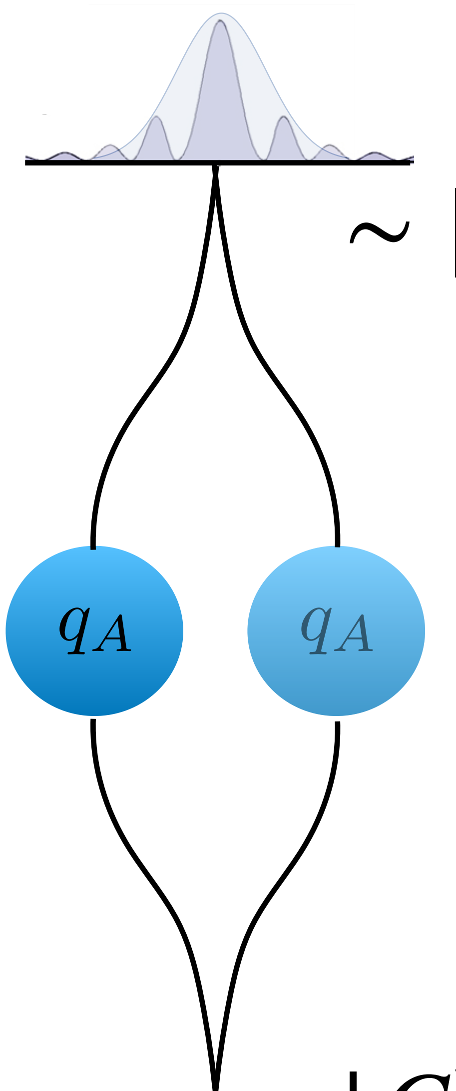
Further Thoughts

How information is encoded in gauge fields?

How can we formally account for superposition of different spacetimes?

False loss of coherence

$$\mathscr{D}_A < T_A$$



$$\sim |C\rangle \otimes (|\uparrow\rangle + |\downarrow\rangle) \otimes |\Omega\rangle$$

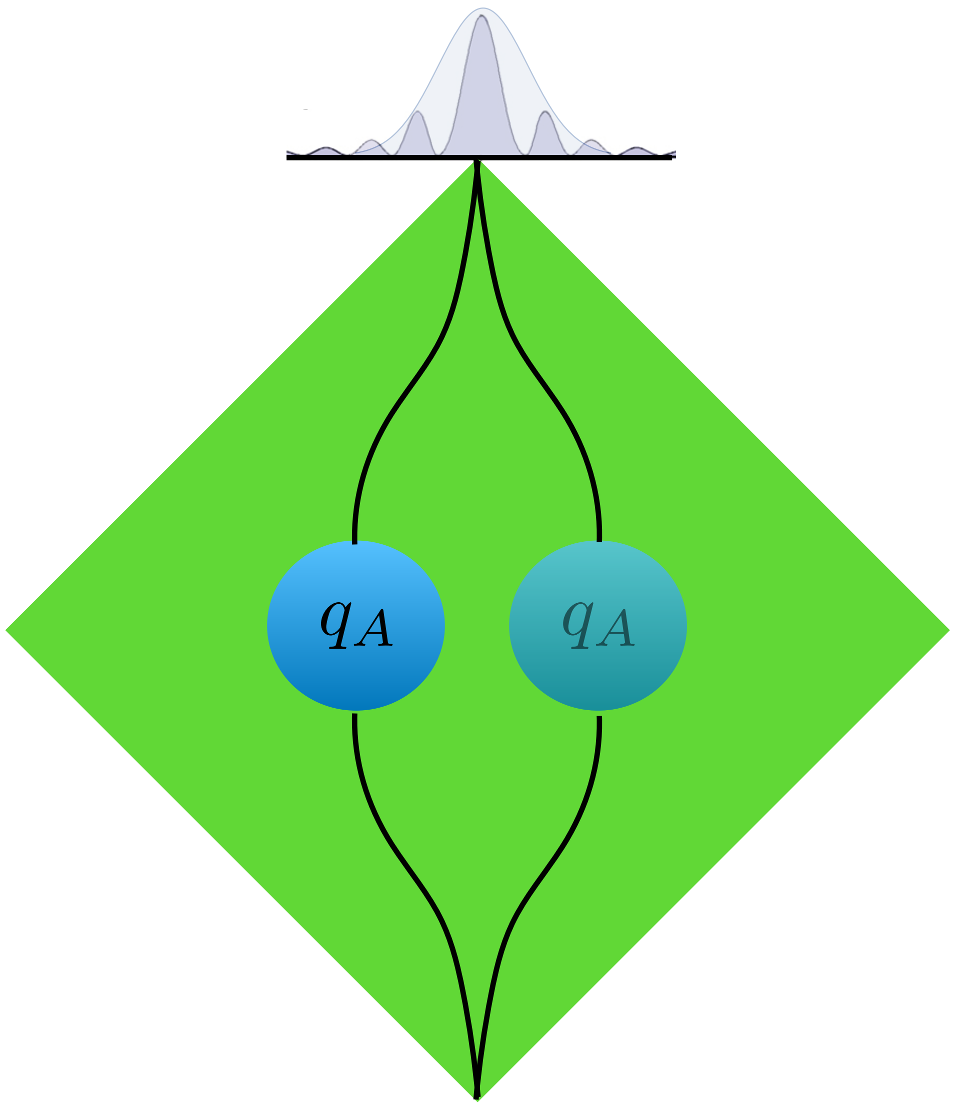
$$\sim |L\rangle |\uparrow\rangle |\alpha_L\rangle + |R\rangle |\downarrow\rangle |\alpha_R\rangle$$

$$|C\rangle \otimes (|\uparrow\rangle + |\downarrow\rangle) \otimes |\Omega\rangle$$

W. G. Unruh, *in Relativistic quantum measurement and decoherence pp. 125{140. Springer, 2000.*

False loss of coherence

$$\mathscr{D}_A < T_A$$



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Conclusions

- **Gedankenexperiment shows inconsistencies if dynamical d.o.f.s are neglected**
- **Inconsistencies are resolved if: vacuum fluctuations + quantized radiation**

Limit Bob’s ability to acquire which-path info

Decohere Alice superposition via entanglement with radiation

- **Gedankenexperiment shows inconsistencies if dynamical d.o.f.s are neglected**
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Limit Bob's ability to acquire which-path info

Decohere Alice superposition via entanglement with radiation

By treating the (linearized) gravitational field [or the e.m. field] as a quantum field a consistent analysis of the gedankenexperiment is obtained

рахмат
danke
謝謝
ngiyabonga
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
gracias
хвала
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
thank you
asante
manana
bedankt
hvala
köszönöm
bayarlalaa
gràçie
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dankon
akun
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mochchakkeram
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chokrane
dziękuję
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gratias ago
gràcies
sulpáy
go raibh maith agat
sobodi
dēkuji
taiku
obrigado
sagolun
sukriya
kop khun krap
arigatô
takk
dakujem
trugarez
mèsi
didi madloba
najis tuke
ありがとう
tanemirt
grazie
terima kasih
rahmet
shukriya
mercé
мерси
kam sah hamnida
rahmat
diolch
dhanyavadagalu
তোমাকে ধন্যবাদ
감사합니다
xièxie
ευχαριστώ
merci

While this result is satisfactory from a theoretical point of view, a more practical question is, at what distance and on what time scale a point charge in a superposition of two different locations (such as an electron during an interference experiment) would be decohered by the corresponding dipole field. Classically, the retarded Coulomb field on the forward light cone would contain complete information about the path of the charge. However, since interference between different electron paths has been observed over distances of the order of millimeters (Nicklaus and Hasselbach 1993; see also Hasselbach's contribution to this conference), one has to conclude that quantum Coulomb fields contribute to decoherence by their monopole component only.[1]

This consequence, which appears surprising from a classical point of view, may be readily understood in terms of quantized fields, since photons with infinite wave length (representing static Coulomb fields) cannot 'see' position at all (even though their number may diverge). Static dipole (or higher) moments do not possess any far-fields, which are defined to decrease with $1/r^2$ only. Therefore, only the 'topological' Gauß constraint $\partial_\mu F^{\mu 0} = 4\pi j^0$ remains of the Coulomb field in QED. This requires that the *observed* (retarded) Coulomb field has to be completely described by transversal photons, corresponding to the vector potential $\boldsymbol{A}$, with $\text{div}\boldsymbol{A} = 0$ in the Coulomb gauge, and in states obeying the Gauß constraint. According to this picture, only the 'positions' of electric field lines — not their total number or flux — represent dynamical variables that have to be quantized. In this sense, charge decoherence has been regarded as *kinematical*, although it may as well be interpreted as being dynamically *caused* in the usual way by the retarded Coulomb field of the (conserved) charge in its past. However, the absence of a dynamical Coulomb field, which may also eliminate the need to renormalize the mass of a charged particle, is incompatible with the concept of a Hilbert space spanned by direct products of *local* states.

averaged over a spacetime region of (space and time) dimension R—recall that we have set $c = 1$—the magnitude of the vacuum fluctuations of the electric field will be of order[4] [35]

$$\Delta E \sim 1/R^2 \,. \tag{2}$$

When averaged over a worldline for a timescale R, the electric field will randomly fluctuate by this magnitude. The classical motion of a free, nonrelativistic particle of charge q and mass m will be influenced by this electric field according to Newton's second law, $m\ddot{x} = qE$. Integrating this equation, we find that the vacuum fluctuations of the electromagnetic field will displace the position of a classical free particle over the timescale R by the amount

$$\Delta x \sim q/m \tag{3}$$

independently of R. Thus, as a consequence of vacuum fluctuations, a classical free particle cannot be localized to better than its *charge-radius*[5] q/m. We assume that the same must be true for a quantum free particle. Note that the charge-radius localization limit is more stringent than the localization limit given by the Compton wavelength, $1/m$, only when[6] $q > 1$. However, it should be possible to evade the Compton wavelength localization limit by using relativistic bodies, whereas the charge radius localization limit is a fundamental limit arising from the quantum nature of the electromagnetic field.

[4] Here, $\Delta E = \sqrt{\langle [E(f)]^2 \rangle}$, where $E(f)$ is the electric field smeared with a smooth function f with support in a region of size R that is nearly constant in this region and normalized so that $\int f = 1$. Eq. (2) follows from the fact that the two-point correlation function of the vector potential behaves as $1/\sigma$ —where σ denotes the squared geodesic distance between the points—and the electric field is constructed from one derivative of the vector potential.

On account of the absence of background structure in general relativity, the ``location'' of a particle is not a well defined concept. The best one can do is consider the relative location of two bodies.

Consider two bodies separated by a distance R. When averaged over a spacetime region of (space and time) dimension R, the magnitude of the vacuum fluctuations of the Riemann curvature tensor should be of order **

$$\Delta \mathcal{R} \sim l_P / R^3$$

Integration of the geodesic deviation equation over time R then yields the result that the two bodies should fluctuate in their relative position by an amount

$$\Delta x \sim l_P$$

independently of R (and independently of the mass or other properties of the body). This leads to the conclusion that localization of any body cannot be achieved to better than a Planck length - a conclusion that has been previously reached by many authors

***This follows from the fact that the correlation function of the linearized metric diverges as l_P^2/σ, where σ denotes the squared geodesic distance between the points. Since the linearized Riemann tensor is constructed from two derivatives of the metric, the correlation function of the linearized Riemann tensor diverges as l_P^2/σ^3*