Decoherence effects in non-classicality tests of gravity

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Outlook

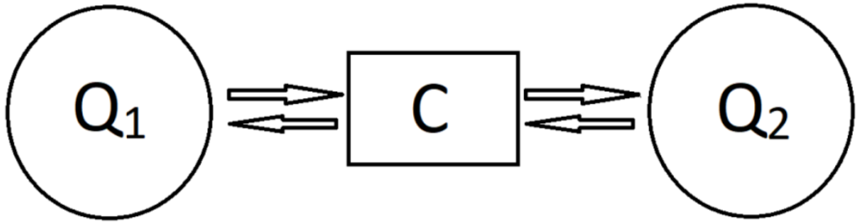
- Revealing non-classicality of gravity via entanglement
- Some experimental proposals
- Environmental decoherence
- Effects of the CSL model

Revealing non-classicality via entanglement

Can we look at potential quantum features of gravity at low-energy scales?

Let’s consider one of the ‘‘most quantum’’ aspects: *entanglement*

Question: *can gravity induce entanglement between two masses?*



Bose *et al.* [1], Marletto and Vedral [2]: **only if its mediator is ‘‘non-classical’’**

[1] S. Bose *et al.*, *Phys. Rev. Lett.* **119**, 240401 (2017).
[2] C. Marletto, V. Vedral, *Phys. Rev. Lett.* **119**, 240402 (2017).

Revealing non-classicality via entanglement

Different arguments:

1. Bose *et al.* [1] → LOCC theorem
2. Marletto, Vedral [2] → Mediator must have 2+ non-commuting observables
3. Marletto, Vedral [3] → Notion of non-classicality from Constructor Theory

"Fewer quantum assumptions"

Same conclusion:

If the gravitational interaction is mediated and is capable of generating entanglement between 2 masses, then its mediator must be *non-classical*

[1] S. Bose *et al.*, *Phys. Rev. Lett.* **119**, 240401 (2017).
[2] C. Marletto, V. Vedral, *Phys. Rev. Lett.* **119**, 240402 (2017).
[3] C. Marletto, V. Vedral, *Phys. Rev. D* **102**, 086012 (2020).

Observing gravitationally-induced entanglement

How do we test if gravity is capable of entangling two masses?

Bose *et al.* [1], Marletto and Vedral [2]:

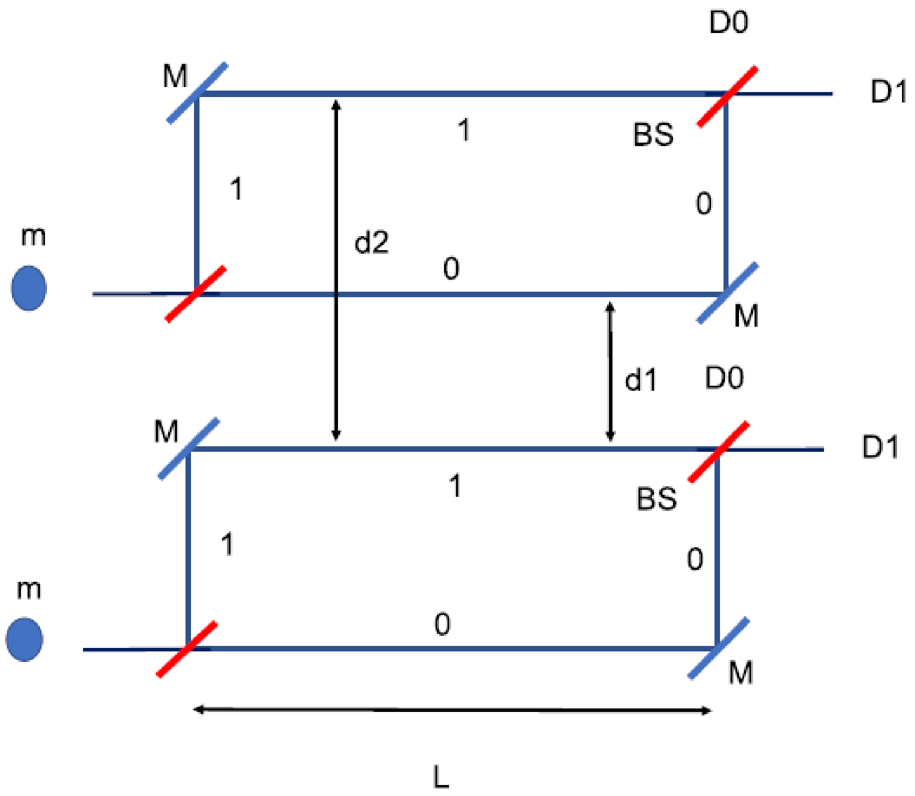


Image from [2]

This setup should be a hard test for gravity!
We can make a model assuming:

1. Gravity obeys the superposition principle (''branchwise interaction'')
2. Newtonian-like potential

The state of the system before the second beam-splitter would be:

$$\frac{1}{2}\left(e^{i\phi_2}\left|0\right\rangle\left|0\right\rangle + \left|0\right\rangle\left|1\right\rangle + e^{i\phi_1}\left|1\right\rangle\left|0\right\rangle + e^{i\phi_2}\left|1\right\rangle\left|1\right\rangle\right)$$

with $\phi_i = \dfrac{Gm^2\Delta t}{\hbar d_i}$ → <u>ENTANGLED!</u>

[1] S. Bose *et al.*, *Phys. Rev. Lett.* **119**, 240401 (2017).
[2] C. Marletto, V. Vedral, *Phys. Rev. Lett.* **119**, 240402 (2017).

Observing gravitationally-induced entanglement

What are the scales involved?

We want $\phi = \dfrac{Gm^2\Delta t}{\hbar d} \approx 1$

Proposed values [1]: $m \approx 10^{-14}$ kg, $d \approx 10^{-4}$ m and $\Delta t \approx 1$ s

Promising experimental setups:

1. Bose *et al.* [1]
2. Krisnanda *et al. [4]*

[1] S. Bose *et al.*, *Phys. Rev. Lett.* **119**, 240401 (2017).
[4] Krisnanda *et al.*, *npj Quantum Inf.* **6**, 12 (2020).

Experimental setups

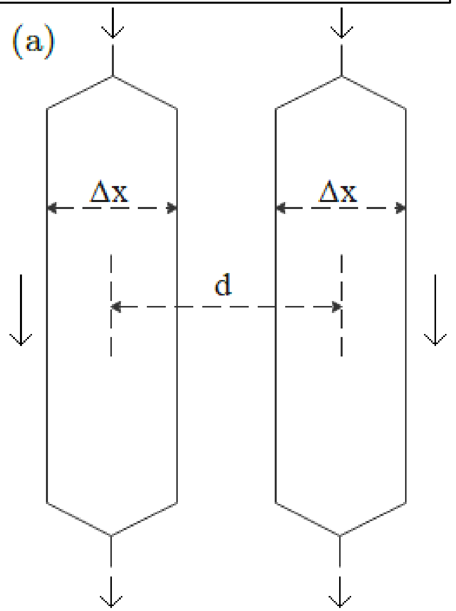
Spin Entanglement Witness for Quantum Gravity

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]

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto[1] and V. Vedral[1,2]

Setup based on Stern-Gerlach interferometry

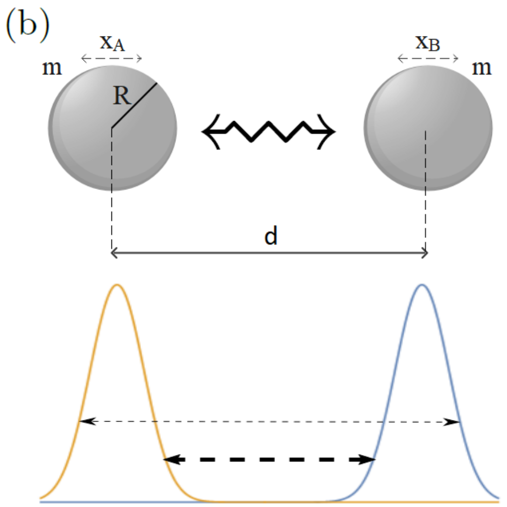


Proposal	m [kg]	R [m]	d [m]	Δx [m]	ω_0 [Hz]
Bose	10^{-14}	10^{-6}	4.5×10^{-4}	2.5×10^{-4}	/

Observable quantum entanglement due to gravity

Tanjung Krisnanda[1*], Guo Yao Tham[1], Mauro Paternostro[2] and Tomasz Paterek[1,3,4*]

Model: two masses trapped in 1D harmonic potentials and cooled down close to ground state.



Two cases:

1. Masses trapped
2. Masses released and in free-fall

$\Delta x << d$ limit of the Bose *et al.* setup

Proposal	m [kg]	R [m]	d [m]	Δx [m]	ω_0 [Hz]
Krisnanda	10^{-7}	10^{-4}	3×10^{-4}	/	10^5

[1] S. Bose *et al.*, *Phys. Rev. Lett.* **119**, 240401 (2017).
[4] Krisnanda *et al.*, *npj Quantum Inf.* **6**, 12 (2020).

Experimental challenges

Main experimental challenges:

- Initial state preparation
- Cooling
- Creating superposition
- Control
- Measuring entanglement
- Time of flight
- Excluding other types of interactions between the masses
- Noise
- ……..
- Maintaining superposition → **limiting decoherence**

Environmental decoherence

How does decoherence affect the non-classicality tests of gravity based on entanglement?

➢SR, Carlesso, Bassi, Vedral, Marletto, *New J. Phys.* **23**, 043040 (2021) (extending work from [5,6,7], see also[8])

We consider decoherence due to:

1. Residual air molecules
2. Thermal photons (scattering, absorption, emission)
3. Continuous Spontaneous Localization (CSL) model

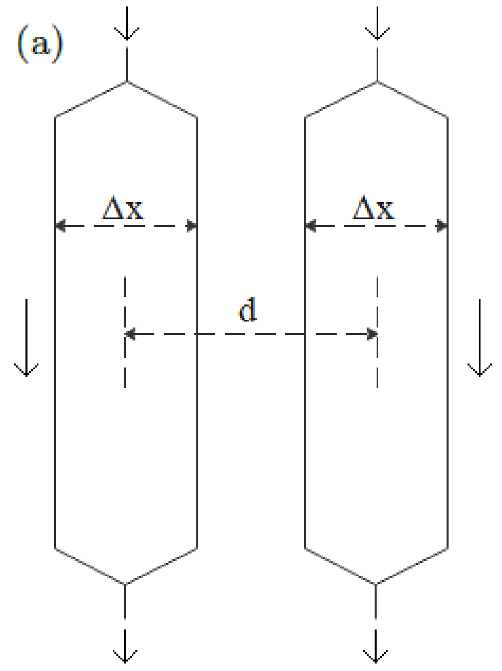
Decoherence master equation: $\frac{d\rho\left(\boldsymbol{x},\boldsymbol{x}',t\right)}{dt} = -\frac{i}{\hbar}\left\langle \boldsymbol{x}\left|\left[\hat{H},\hat{\rho}(t)\right]\right|\boldsymbol{x}'\right\rangle - \Gamma(|\boldsymbol{x}-\boldsymbol{x}'|)\rho(\boldsymbol{x},\boldsymbol{x}',t), \quad \Gamma\left(\Delta x\right) = \Gamma_0\left(1-\exp\left[-\frac{\Delta x^2}{4a^2}\right]\right)$

[5] H.C. Nguyen and F. Bernards, *Eur. Phys. J. D* **74,** 69 (2020). [7] T.W. van de Kamp T W *et al.*, *Phys. Rev. A* **102,** 062807 (2020).
[6] H. Chevalier *et al.*, Phys. Rev A **102**, 022428 (2020). [8] D. Miki *et al.*, *Phys. Rev. D* **103,** 026017 (2021).

Decoherence effects – Bose *et al.*

Let us model the setup assuming:

- Particles in position eigenstates
- No deviation from parallel trajectories
- Hamiltonian: $H_{\mathrm{BM-g}} = \begin{pmatrix} U_0 & 0 & 0 & 0 \\ 0 & U_- & 0 & 0 \\ 0 & 0 & U_+ & 0 \\ 0 & 0 & 0 & U_0 \end{pmatrix}, \quad U_0 = G\frac{m^2}{d}, \quad U_\pm = G\frac{m^2}{d \mp \Delta x}$



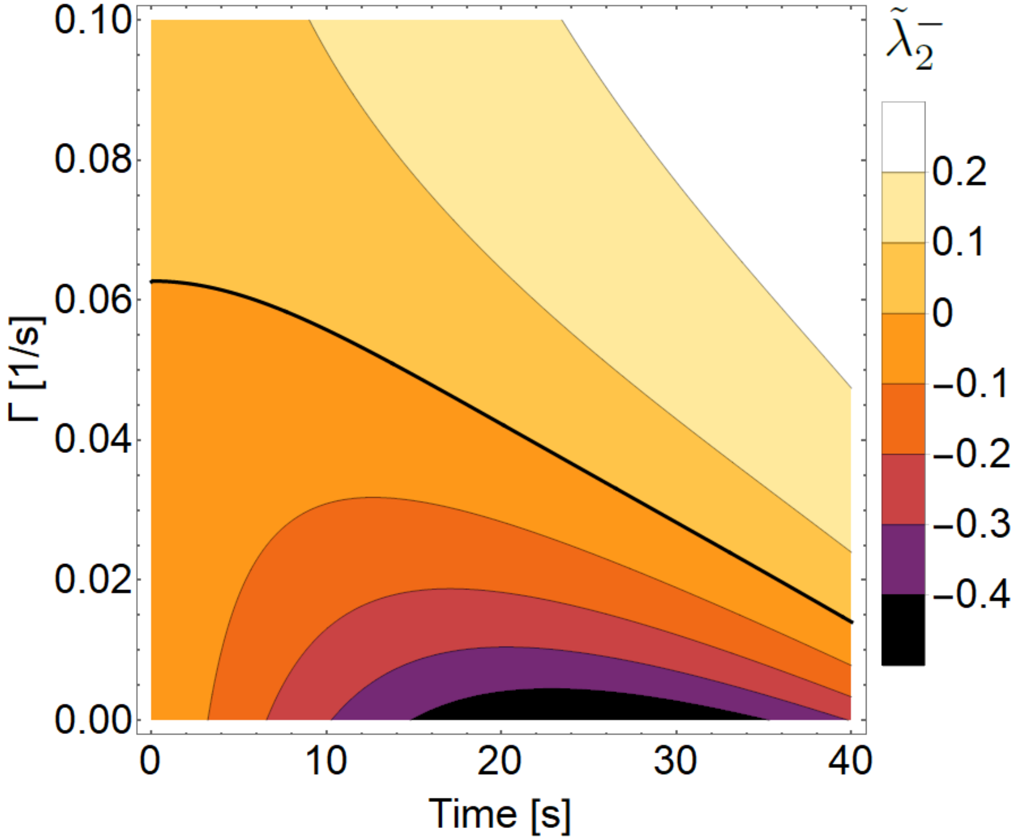
Check entanglement using the eigenvalues of PT density matrix.

<u>Entanglement only if:</u> $\Gamma < \frac{1}{\tau_G} = \frac{Gm^2}{\hbar d((\frac{d}{\Delta x})^2 - 1)}$ or, equivalently, $\boxed{\tau_C > \tau_G}$

where $\tau_C \equiv \frac{1}{\Gamma}$ and $\boxed{\tau_G = \frac{\hbar d\left[\left(\frac{d}{\Delta x}\right)^2 - 1\right]}{Gm^2}}$

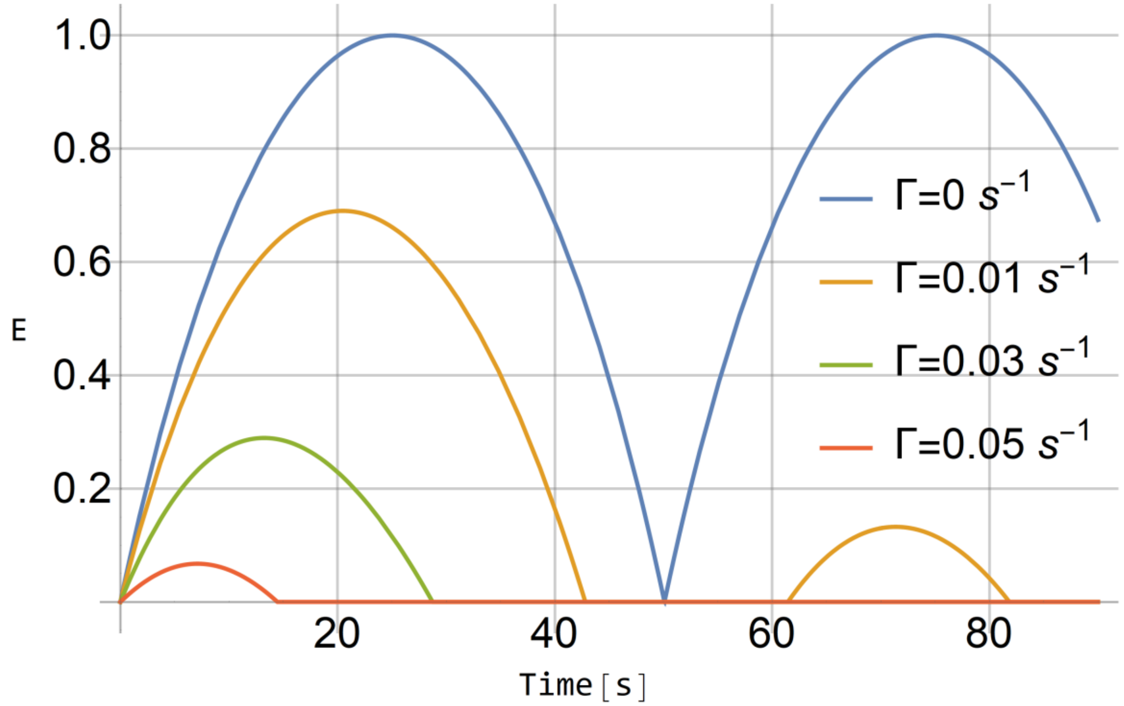
Decoherence effects – Bose *et al.*

Minimum eigenvalue of PT density matrix



Logarithmic negativity: $E = \log_2 ||\tilde{\rho}||_1$

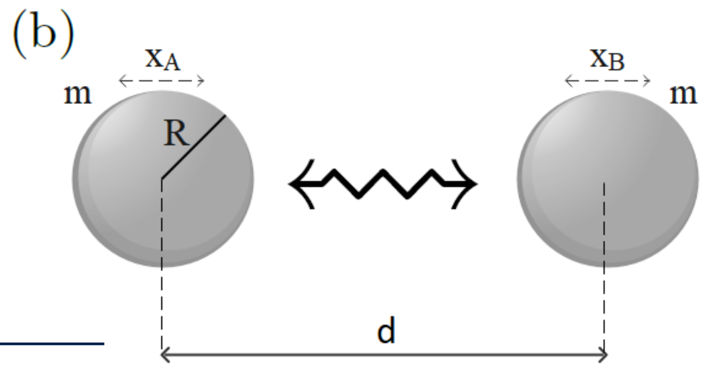
$$E_{\text{BM-dec}} = \max\left\{0, \log_2\left[e^{-\Gamma t}\left(\cosh\Gamma t + \left|\sin\frac{t}{\tau_G}\right|\right)\right]\right\}$$



Decoherence effects – Krisnanda *et al.*

Model:

- Potential → $\hat{H}_{\text{K-g}} = -\frac{Gm^2}{d}\left(1 + \frac{(\hat{x}_A - \hat{x}_B)}{d} + \frac{(\hat{x}_A - \hat{x}_B)^2}{d^2}\right)$
- Initial state: ground state of the harmonic potentials
- Particles in free-fall



We study the system using the Heisenberg-Langevin equation:

$$\frac{dx(t)}{dt} = \frac{i}{\hbar}[H_S, x(t)] \; ,$$
$$\frac{dp(t)}{dt} = \frac{i}{\hbar}[H_S, p(t)] - \gamma p(t) + \xi(t) \, ,$$

Check entanglement using the symplectic eigenvalues of PT covariance matrix

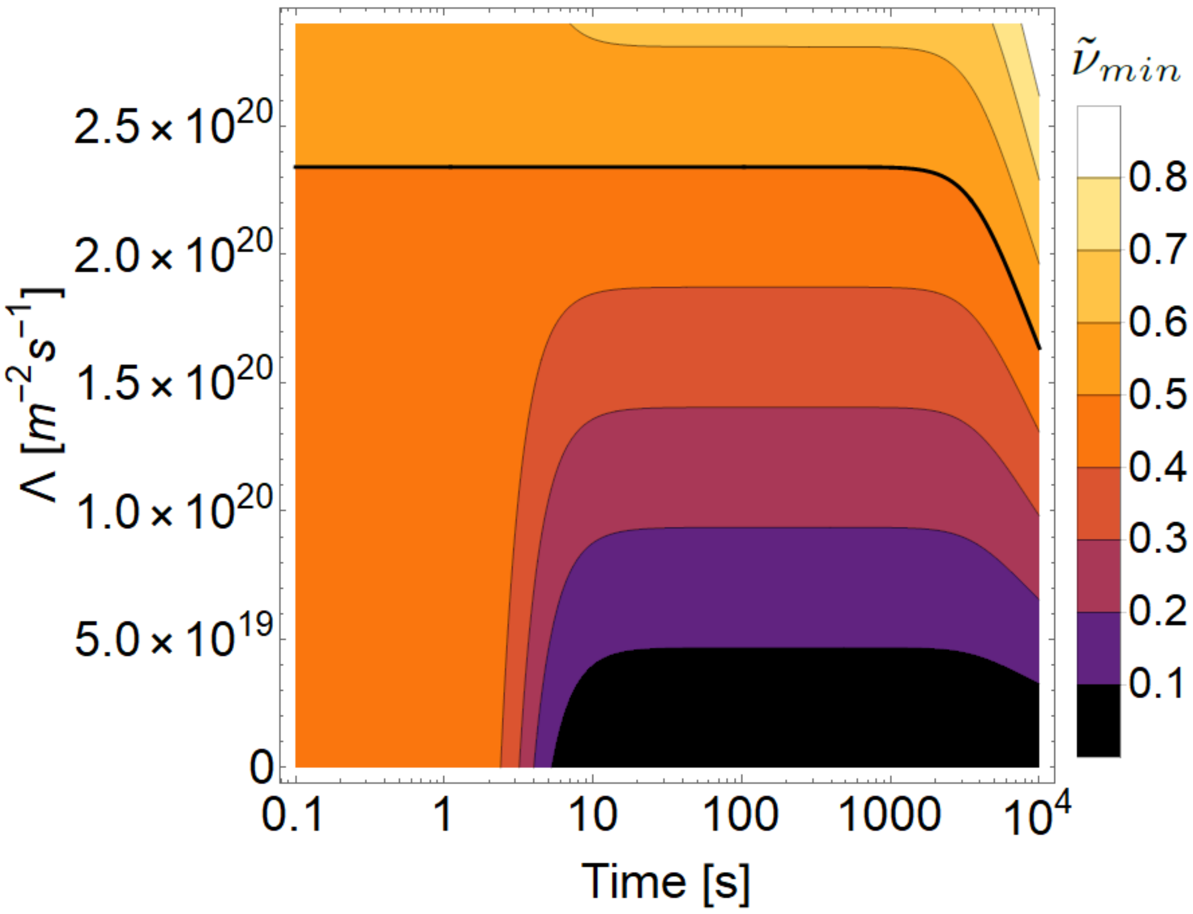
Minimum condition to have entanglement: $\boxed{\Lambda < \frac{Gm^2}{\hbar d^3},}$ where $\Lambda = \frac{\Gamma_0}{4a^2}$

This is the $\Delta x << d$ limit of the condition $\boxed{\tau_C > \tau_G}$

$$\Gamma(\Delta x) = \Gamma_0\left(1 - \exp\left[-\frac{\Delta x^2}{4a^2}\right]\right)$$
$$\tau_G = \frac{\hbar d\left[\left(\frac{d}{\Delta x}\right)^2 - 1\right]}{Gm^2}$$

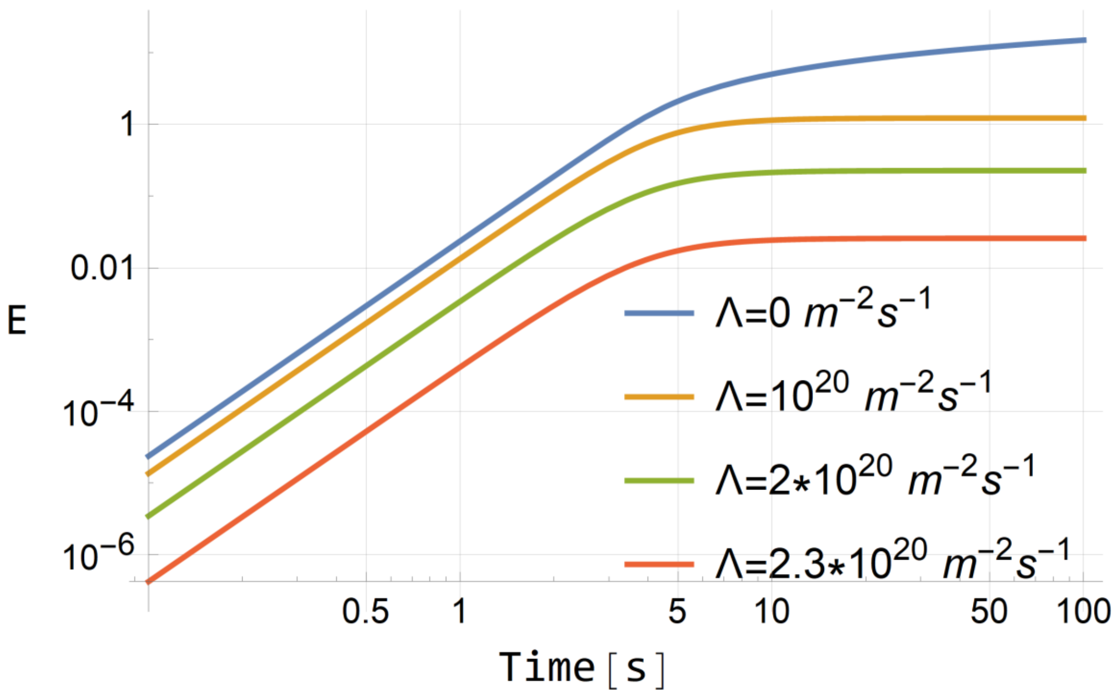
Decoherence effects – Krisnanda *et al.*

Minimum eigenvalue of PT covariance matrix



Logarithmic negativity

$$E_{\text{K-dec}} = -\log_2(2\tilde{\nu}_{\min})$$



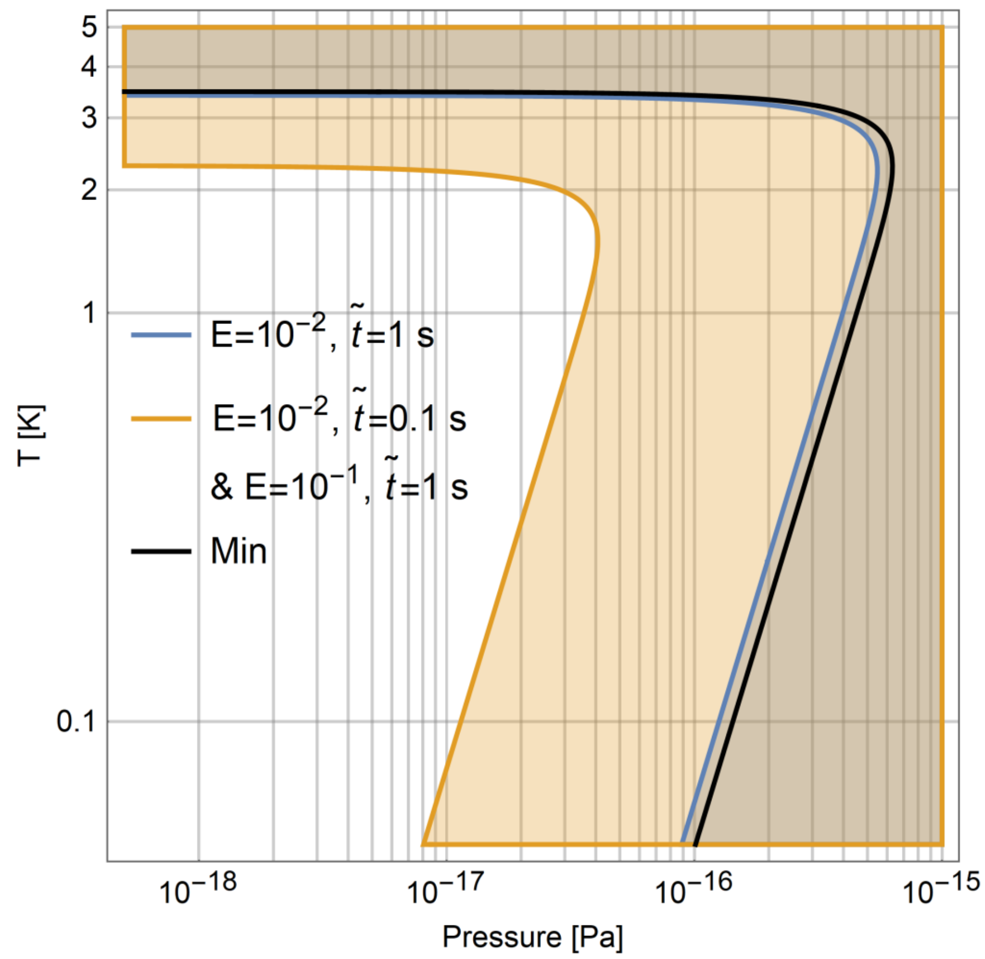
Experimental conditions

$T_i = T$

$m_{\text{air}} \sim 6.6 \times 10^{-27}\,\text{kg}$

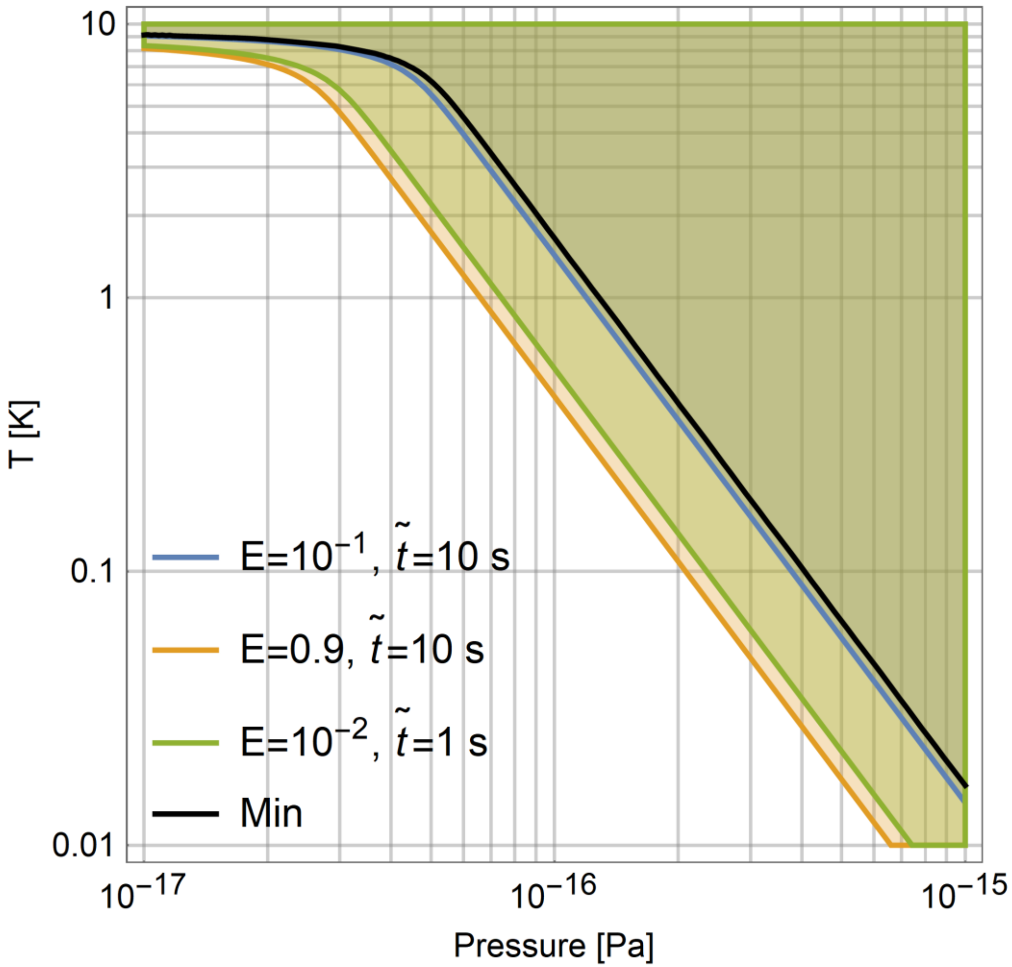
Bose *et al.*

$\epsilon = 5.7 + i \times 10^{-4}$



Krisnanda *et al.*

$\epsilon = 0.6 + i \times 2.5$



Experimental conditions

Proposal	T [K]	P [Pa]	E	t [s]	h [m]
BM	1	10^{-16}	10^{-2}	0.15	0.1
	1	10^{-16}	10^{-1}	1.5	11
	1	10^{-15}	no generation	/	/
	10^{-2}	10^{-15}	no generation	/	/
Krisnanda	1	10^{-16}	10^{-2}	1.1	6.2
	1	10^{-16}	10^{-1}	2.9	42
	1	10^{-15}	no generation	/	/
	10^{-2}	10^{-15}	10^{-2}	1.2	7.6

Characteristic time of the experiment

In both setups we have the following requirement on the coherence times:

$$\boxed{\tau_C > \tau_G}$$

where $$\tau_G = \frac{\hbar d \left[\left(\frac{d}{\Delta x} \right)^2 - 1 \right]}{G m^2}$$

Also, $\frac{\pi}{2}\tau_G$ is the time for MAX entanglement in free Bose setup (timescale of the experiment)

We want to minimize this ''characteristic'' time of the experiment. How?

- Increase mass
- $\Delta x \to d$

But we have a limit on the minimum separation s_{min} between the 2 closest branches:

$$\tau_G = \frac{\hbar \left(s_{min} + \Delta x \right) \left[\left(\frac{s_{min} + \Delta x}{\Delta x} \right)^2 - 1 \right]}{G m^2} \xrightarrow[\Delta x \gg s_{min}]{} \frac{2 \hbar s_{min}}{G m^2}$$

Only m (or R) available

$a \ll \Delta x$
$\tau_G \propto \frac{1}{R^6}$
$\tau_{air} \propto \frac{T^{1/2}}{R^2 P}$
$\tau_{sc} \propto \frac{1}{R^6 T^7}$
$\tau_{ab} \propto \frac{1}{R^3 T^4}$
$\tau_{em} \propto \frac{1}{R^3 T_i^4}$

Effects of the CSL model

Model has 2 parameters:

1. ''Collapse frequency'': λ
2. ''Collapse radius'': r_C

Estimates: $r_{\mathrm{C}} = 10^{-7}\,\mathrm{m}, \quad \text{and} \quad \lambda = (10^{-17} \div 10^{-9})\,\mathrm{s}^{-1}$

We can account for the effects of the CSL model in the following way:

1. Bose *et al.* → decoherence master equation $\frac{d\rho\left(\boldsymbol{x},\boldsymbol{x}',t\right)}{dt} = -\frac{i}{\hbar}\left\langle \boldsymbol{x}\left|\left[\hat{H},\hat{\rho}(t)\right]\right|\boldsymbol{x}'\right\rangle - \Gamma(|\boldsymbol{x}-\boldsymbol{x}'|)\rho(\boldsymbol{x},\boldsymbol{x}',t),$

   with $\Gamma_0^{\mathrm{CSL}} = \lambda\frac{6m^2r_{\mathrm{C}}^4}{m_0^2R^4}\left[1-\frac{2r_{\mathrm{C}}^2}{R^2}+e^{-\frac{R^2}{r_{\mathrm{C}}^2}}\left(1+\frac{2r_{\mathrm{C}}^2}{R^2}\right)\right]$ and $a = r_C$

2. Krisnanda *et al.* → $\frac{\mathrm{d}\hat{p}_j(t)}{\mathrm{d}t} = \frac{i}{\hbar}\left[\hat{p}_j(t),\hat{H}\right] + \xi^{\mathrm{CSL}}(t)$

<u>Any proposed value of the CSL parameters would prevent the creation of entanglement in the two setups (by at least 6/7 orders of magnitude:</u> $\lambda \leq 10^{-24}\mathrm{s}^{-1}$)

Conclusions

- Environmental decoherence is a serious challenge for the setups considered

- For both setups, we need coherence times $\tau_C > \tau_G$ to have entanglement

where $\tau_G = \frac{\hbar d \left[\left(\frac{d}{\Delta x} \right)^2 - 1 \right]}{G m^2}$ or $\tau_G \approx \frac{2 \hbar s_{min}}{G m^2}$

- Any other decohering mechanism with same master equation would have the same bound on the coherence time

- The experimental conditions are for both setups roughly around $p = 10^{-16}$ Pa, $T = 1$ K

- Any proposed value of CSL model would prevent entanglement generation (by at least 6/7 orders of magnitude)

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