Low-energy Test of Quantum Gravity via Angular Momentum Entanglement

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Bridging high and low energies in search of quantum gravity, Paris, 9 July 2025

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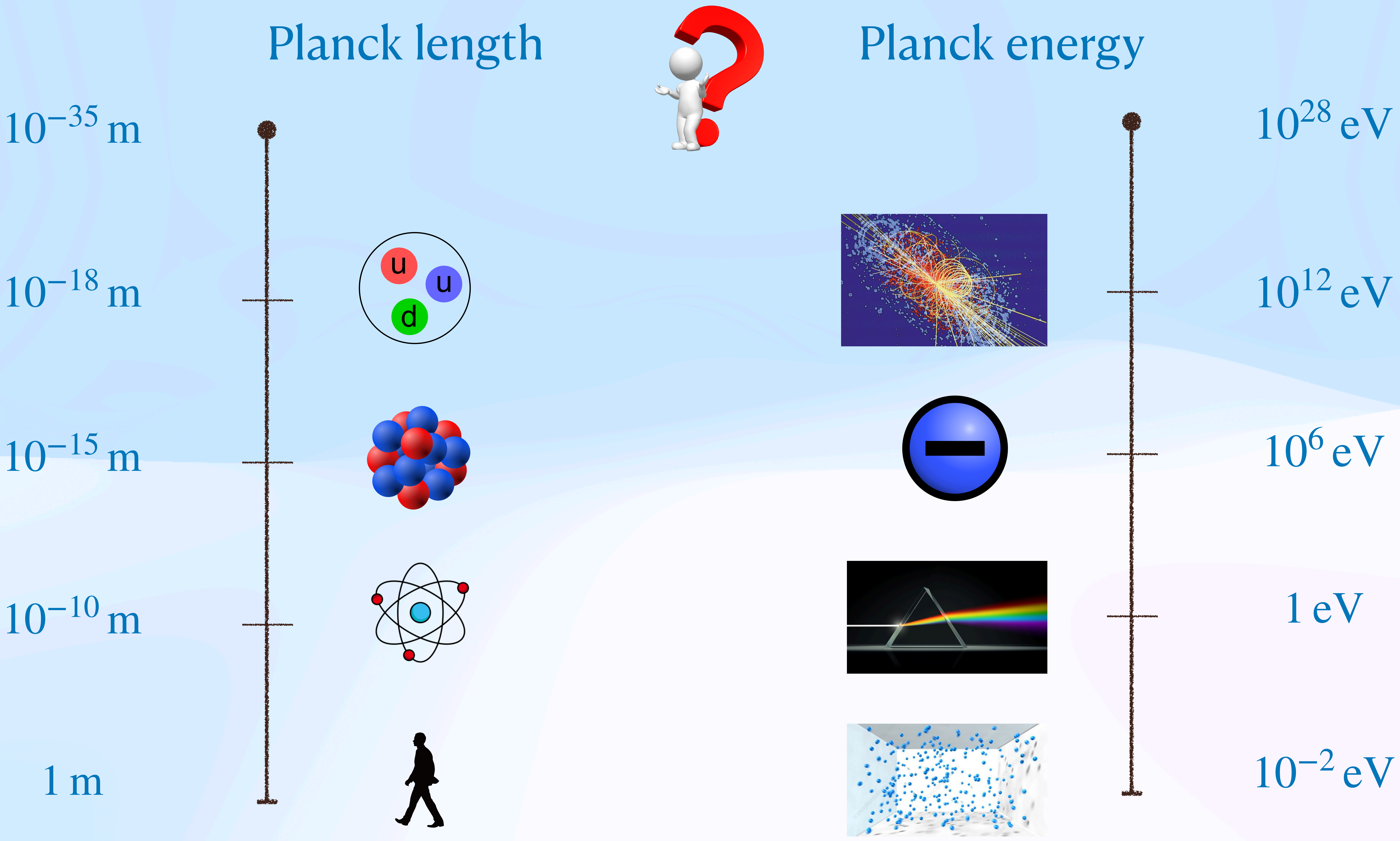
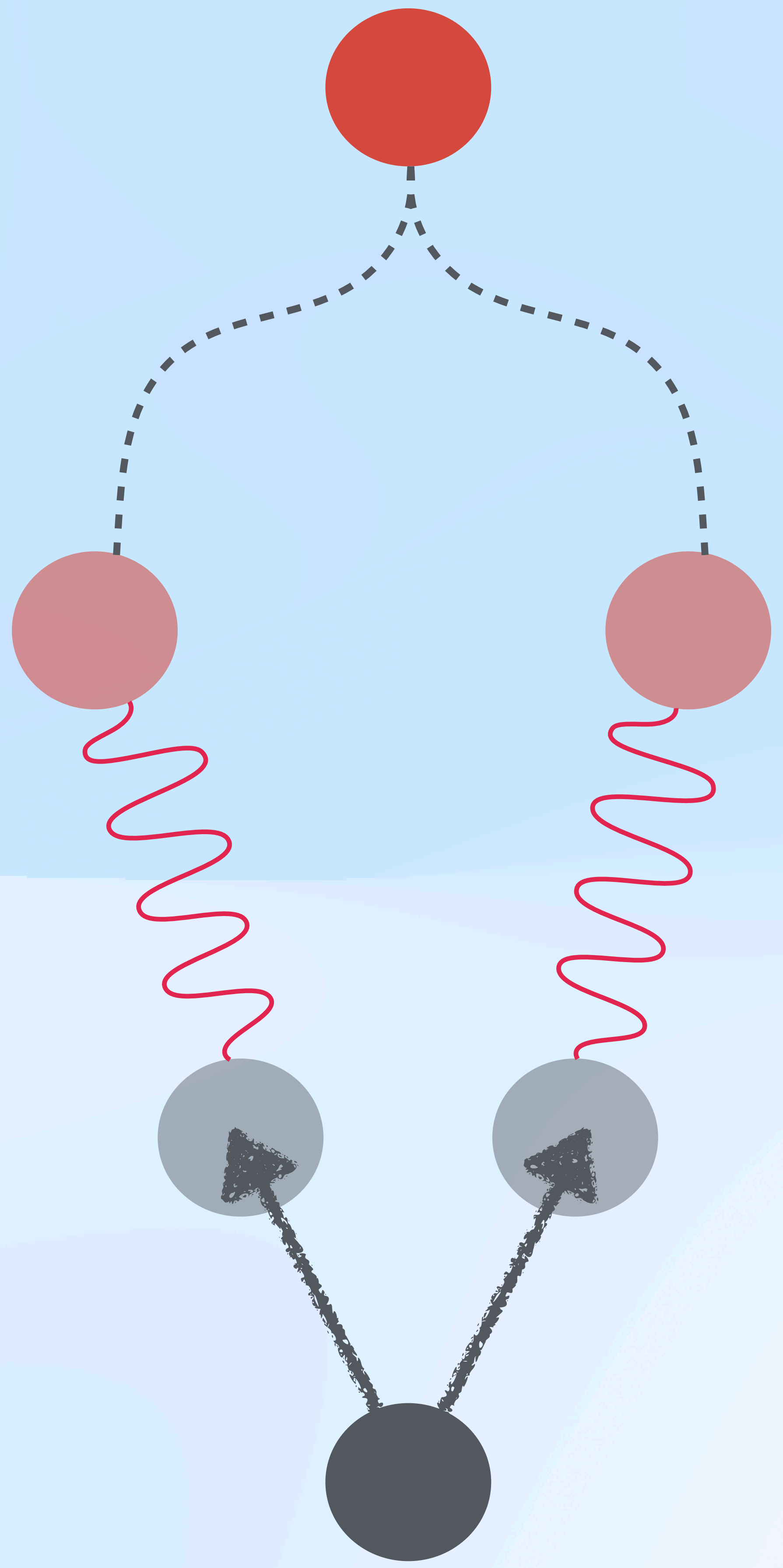
Let me share a secret you might not know...

We don't have a universally accepted theory of quantum gravity!

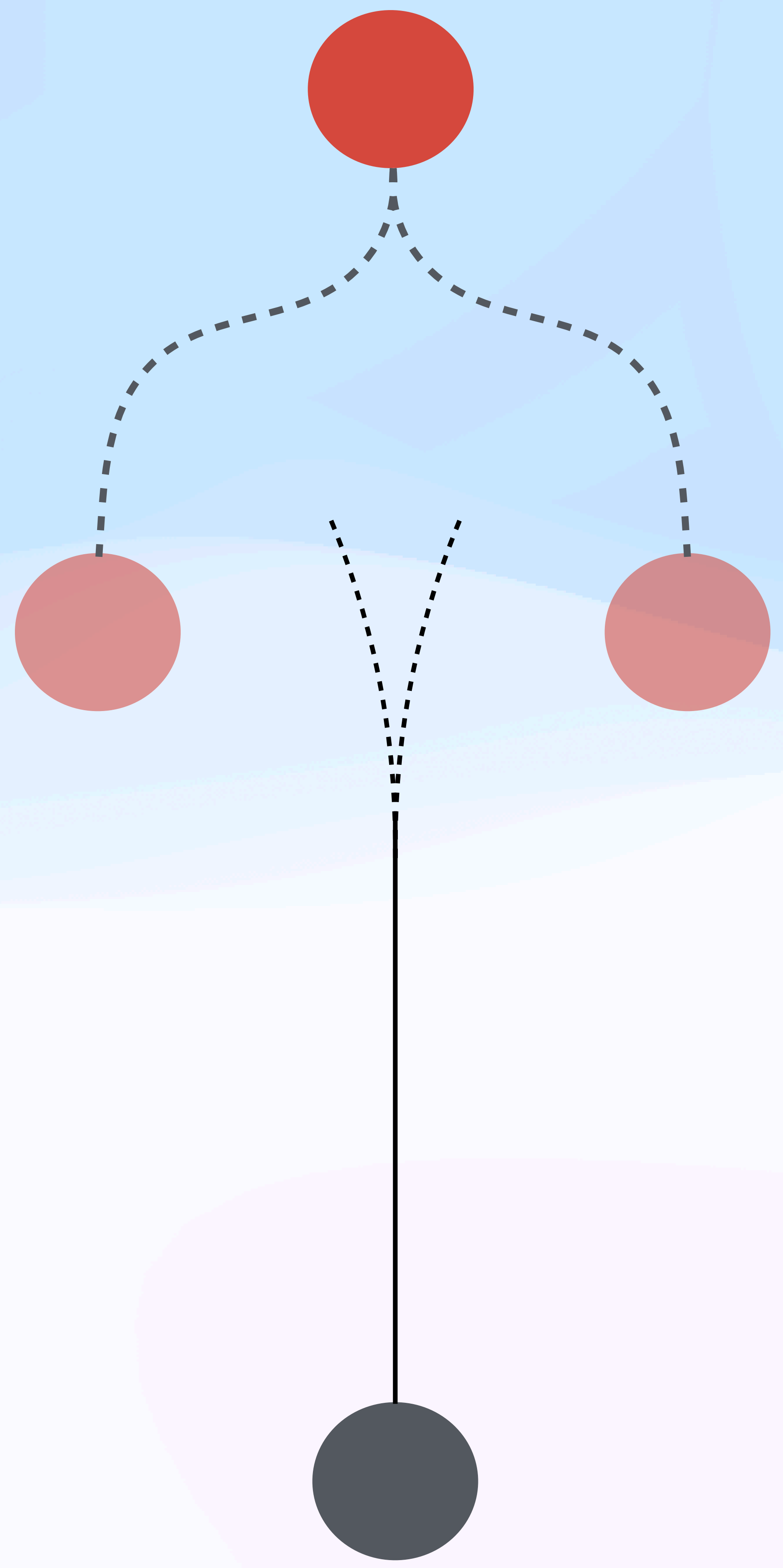
So far, it is still impossible to consistently and/or uniquely quantize general relativity or to gravitize quantum mechanics


Planck length
Planck energy
10^{-35} m
10^{-18} m
10^{-15} m
10^{-10} m
1 m
u
u
d
10^{28} eV
10^{12} eV
10^{6} eV
1 eV
10^{-2} eV

There might be hope to witness nonclassical aspects of gravity

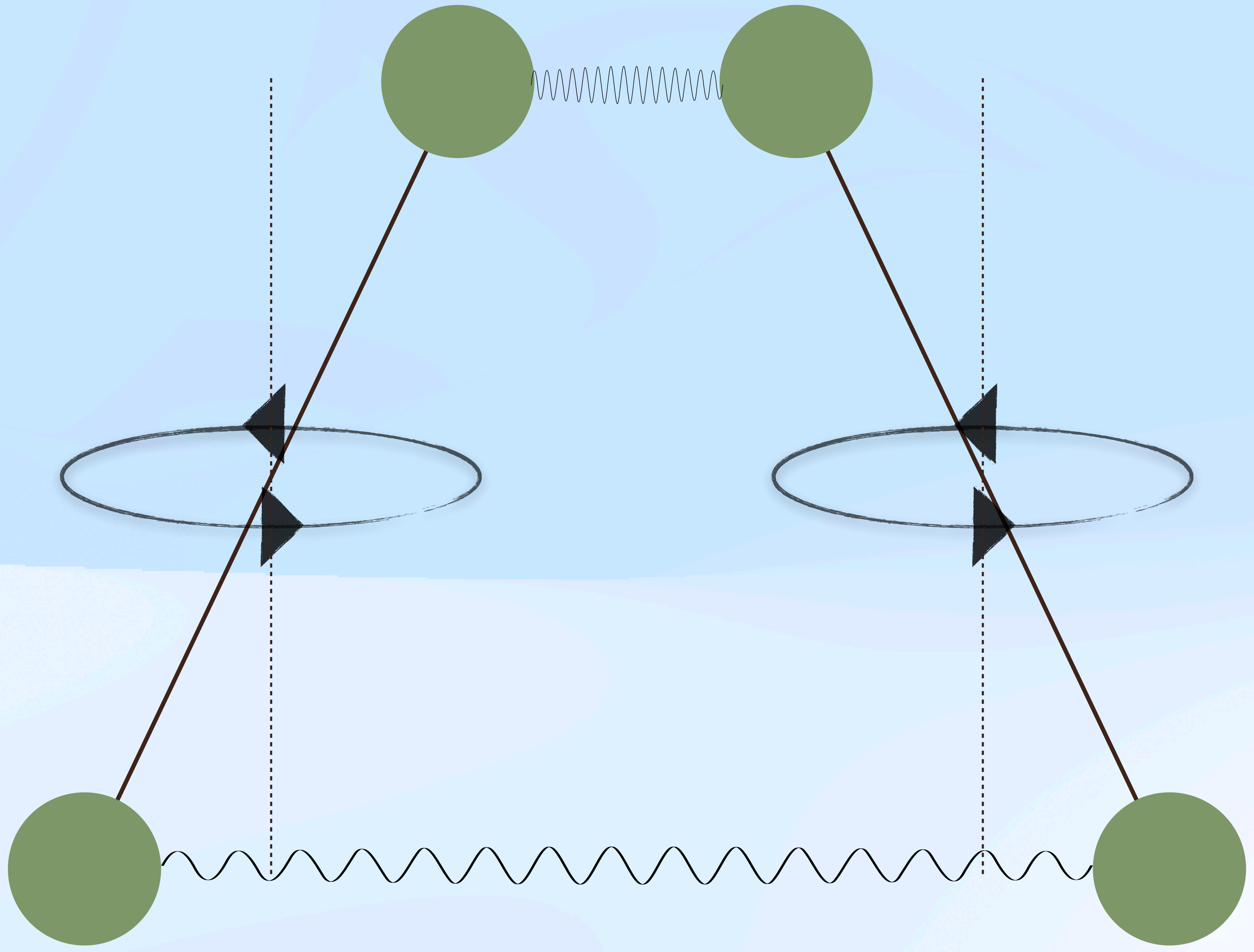


Feynman (1957)

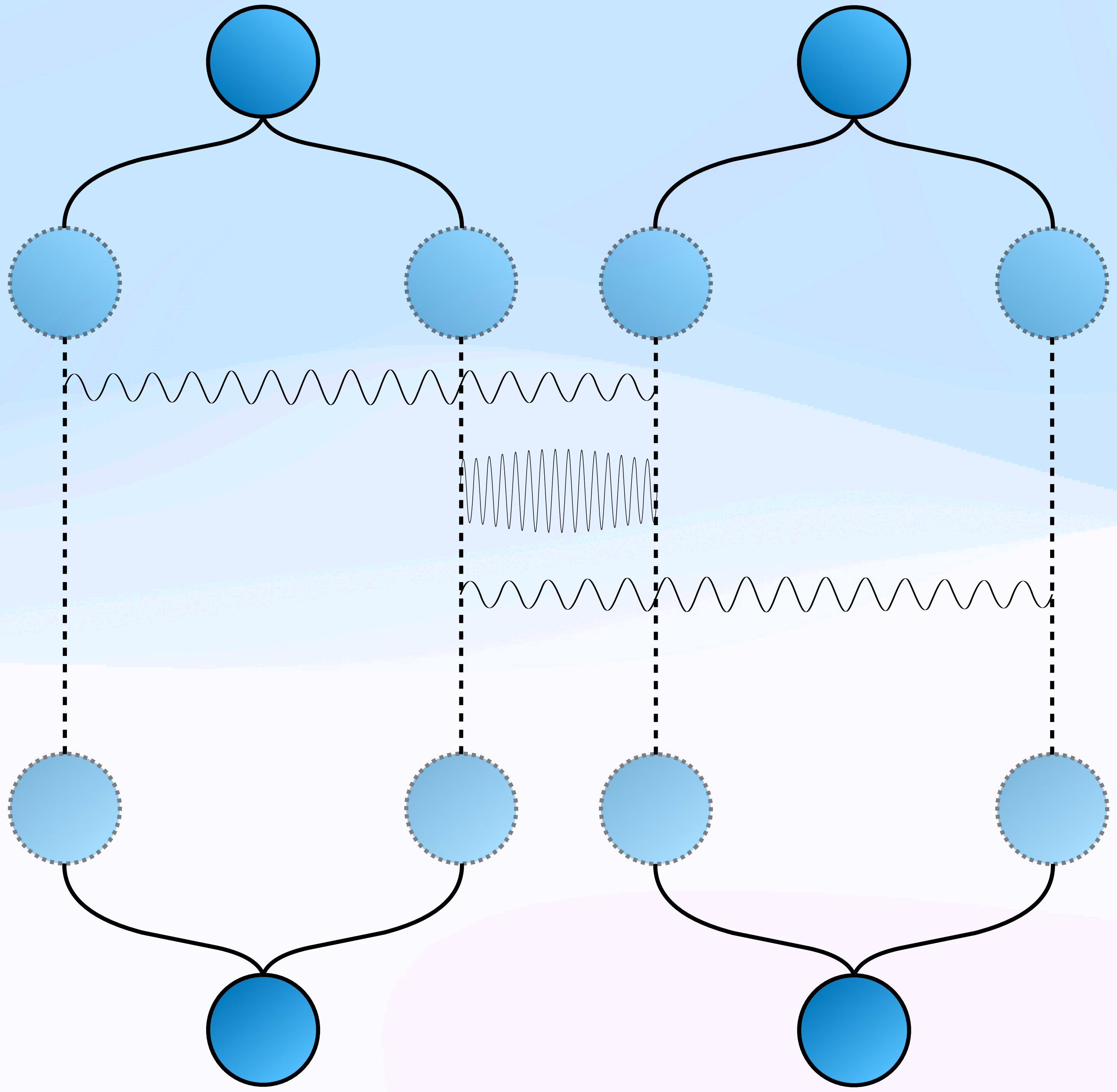


Lindner & Peres (2005)

More recent proposals revolve around the LOCC theorem



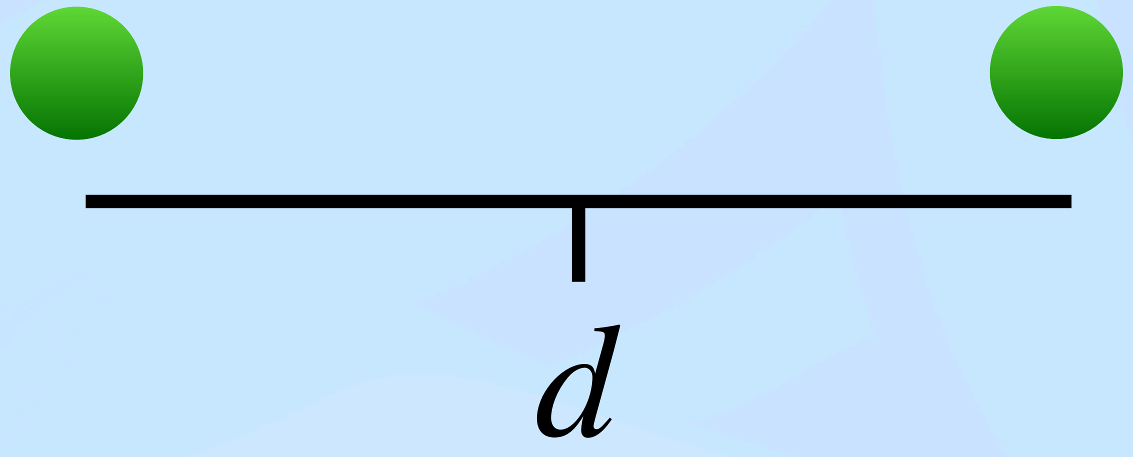
Kafri & Taylor (2013), Lami et al. (2024)



Bose et al. (2017), Marletto and Vedral (2017)

What do all these approaches have in common?

→ Good ol' Newton



In the two limits

$$\frac{d}{c} \ll t \qquad \text{(near-field)}$$

$$|\mathbf{v}| \ll c \qquad \text{(low velocity)}$$

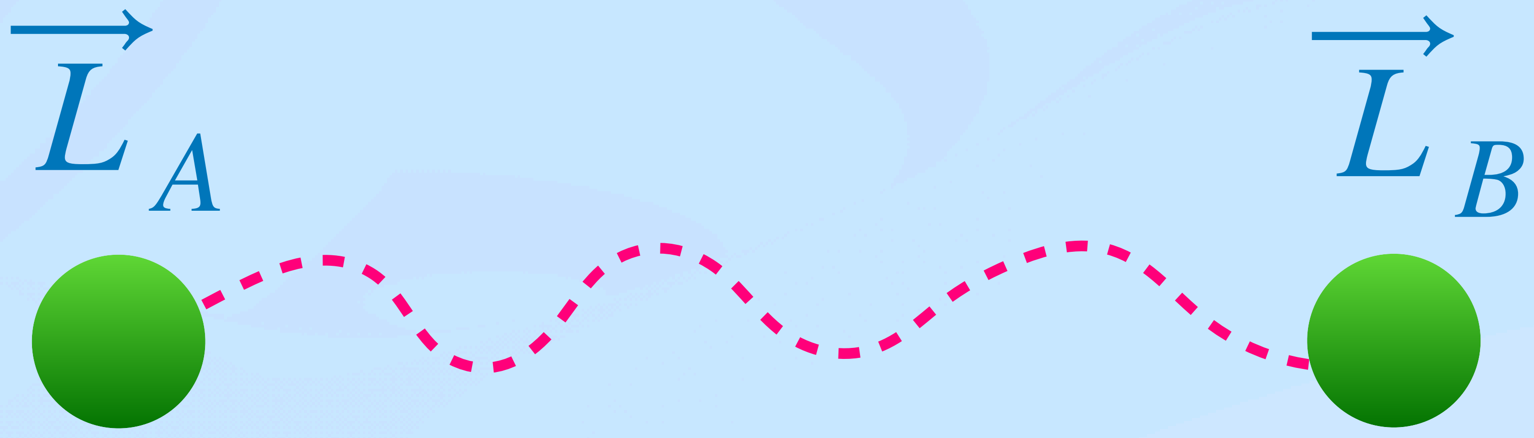
$$V(\mathbf{r}) \approx \frac{G m_A m_B}{|\mathbf{r}|}$$

Christodoulou et al. (2023)

→ Entanglement in spatial d.o.f.s

PROs	CONs
→ Low Hilbert space dimensionality (only two states available)	→ Difficulty in the realization of the initial state
→ Easy measurement scheme (at least in principle)	→ No direct general relativistic effect into play

We propose an alternative scheme with Post-Newtonian corrections



$\sim$ Newtonian $+$ Post-Newtonian

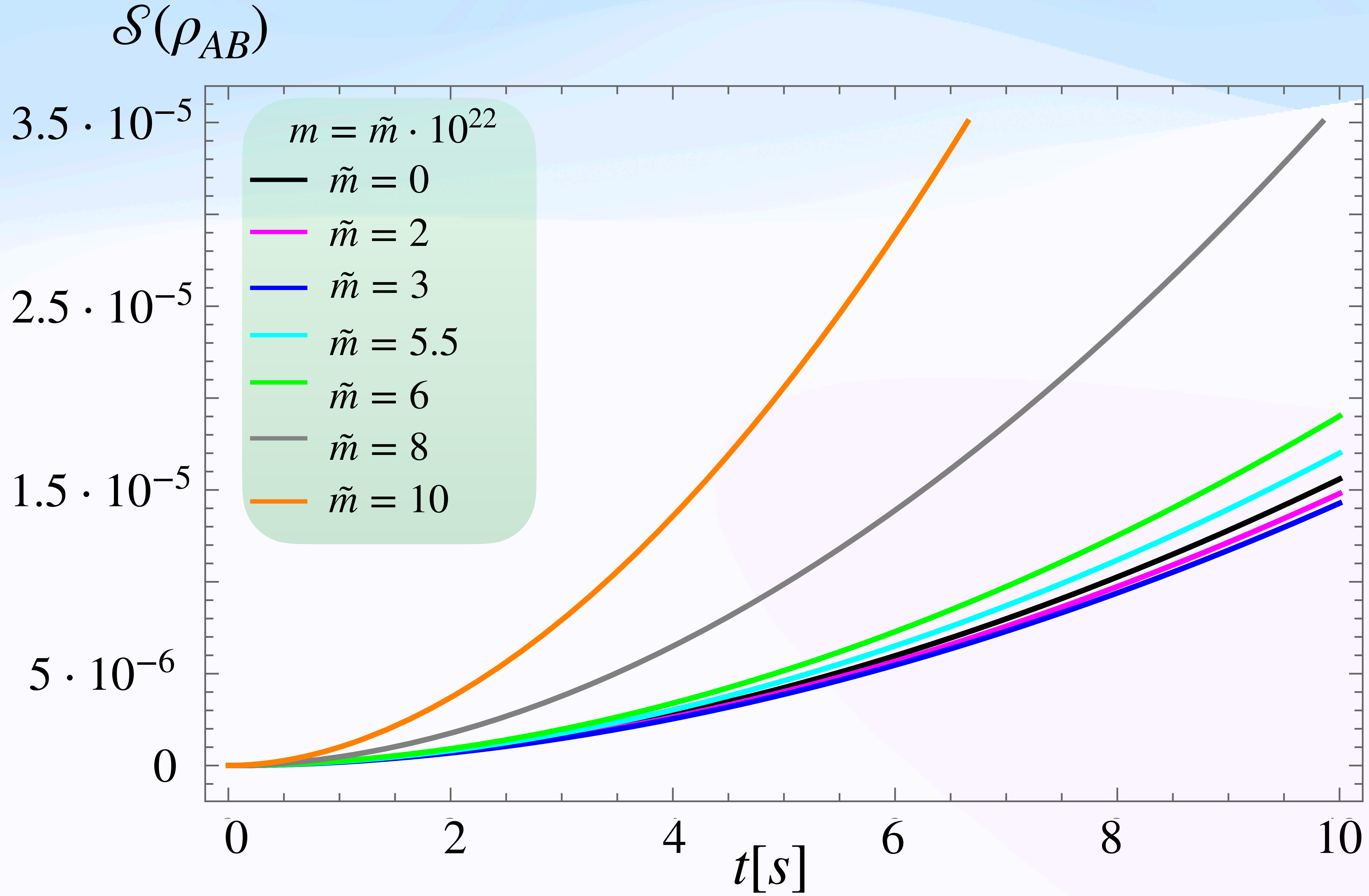
$$-\frac{G}{c^2 r^3}\left[\vec{L}_A \cdot \vec{L}_B - 3\left(\vec{L}_A \cdot \vec{e}_r\right)\left(\vec{L}_B \cdot \vec{e}_r\right)\right]$$

Fast rotating SiO_2 microspheres
$\omega \approx 10^7$ Hz, $R = 50\mu$m

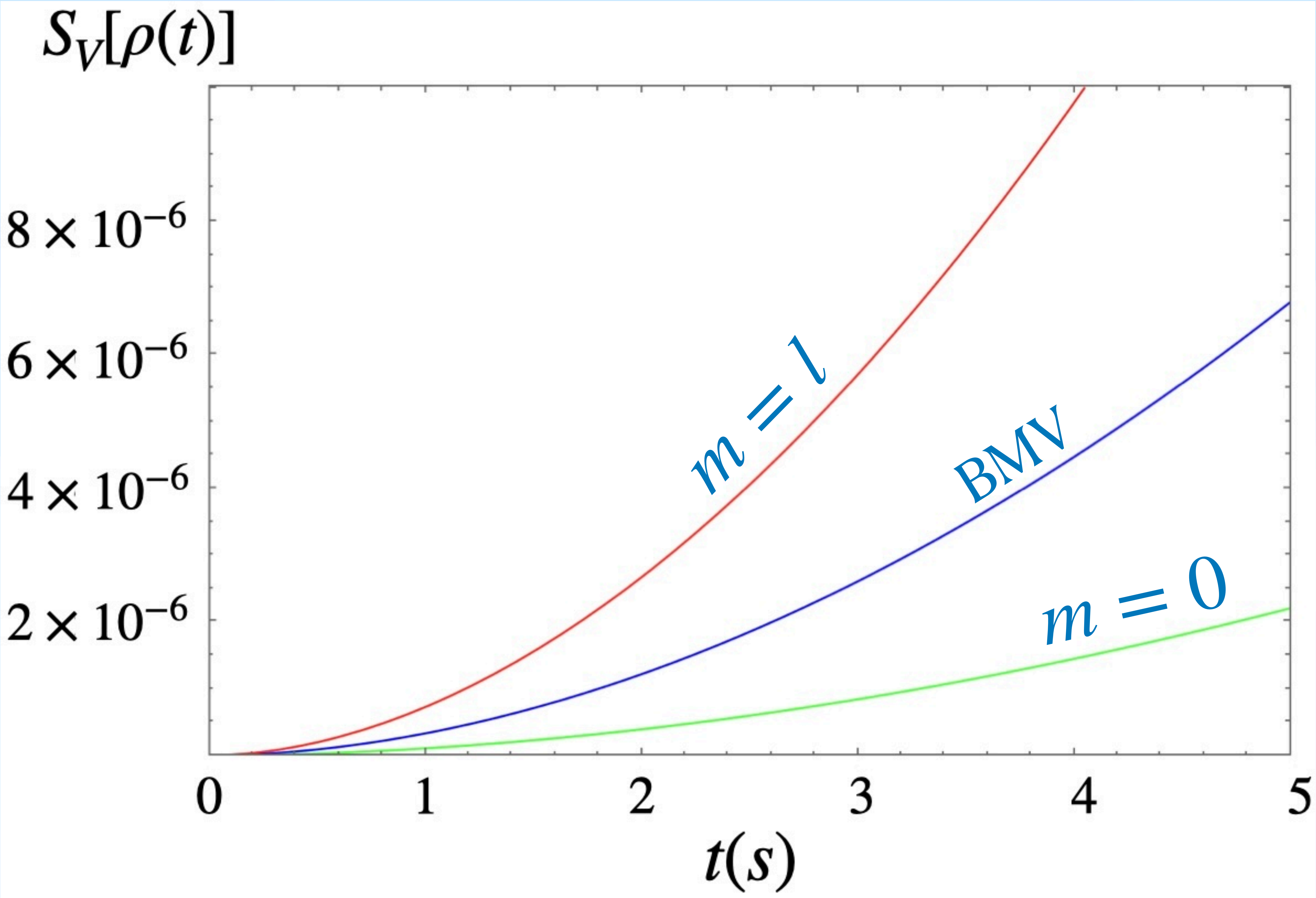
$$l = \frac{L}{\hbar} \approx 10^{23}$$

$$|\psi_{AB}(0)\rangle = \big(|l,m\rangle_A + |l,-m\rangle_A\big) \otimes \big(|l,m\rangle_B + |l,-m\rangle_B\big)$$

$$\boxed{\hat{H}_I = -\frac{G\hbar^2}{2c^2r^3}\left(\hat{L}_+^{(A)}\hat{L}_-^{(B)} + \hat{L}_-^{(A)}\hat{L}_+^{(B)} - 4\hat{L}_z^{(A)}\hat{L}_z^{(B)}\right)}$$



Isn’t the effect too small?



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But what are the differences with other QG tests?

PROs

- NO initial superpositions required
- Most of the usual decoherence channels do not apply here

CONs

- Difficult detection of angular momentum quanta
- Other decoherence channels might be troublesome

A protocol to measure angular momentum

A fast-spinning object tends to spontaneously magnetize in the direction of the rotation axis [Barnett (1915)]

$$\hat{H}_{c.o.m.} = \frac{\hat{p}^2}{2m} + \frac{|\chi_V| V \hat{B}^2}{2\mu_0} + \frac{|\chi_V| V}{2\gamma\mu_0 I}\left(\hat{\vec{B}} \cdot \hat{\vec{L}} + \hat{\vec{L}} \cdot \hat{\vec{B}}\right),$$

With a small magnetic gradient along z

$$\Delta^2 \hat{L}_z = \left(\frac{\gamma I B_0}{2\sin^2\left(\frac{\Omega t}{2}\right)}\right)^2 \left(\Delta^2 \hat{z}(t) + \Delta^2 \hat{z}(0)\right)$$

Angular momentum can be inferred from center of mass position!

Sources of decoherence

Magnetic dipole-dipole interaction

Looks just like our gravitational Hamiltonian!

$$H_{dip} = \frac{\mu_0 \gamma^2 \hbar^2}{4\pi r^3} \left[\vec{S}_A \cdot \vec{S}_B - 3 \left(\vec{S}_A \cdot \vec{e}_r \right) \left(\vec{S}_B \cdot \vec{e}_r \right) \right]$$

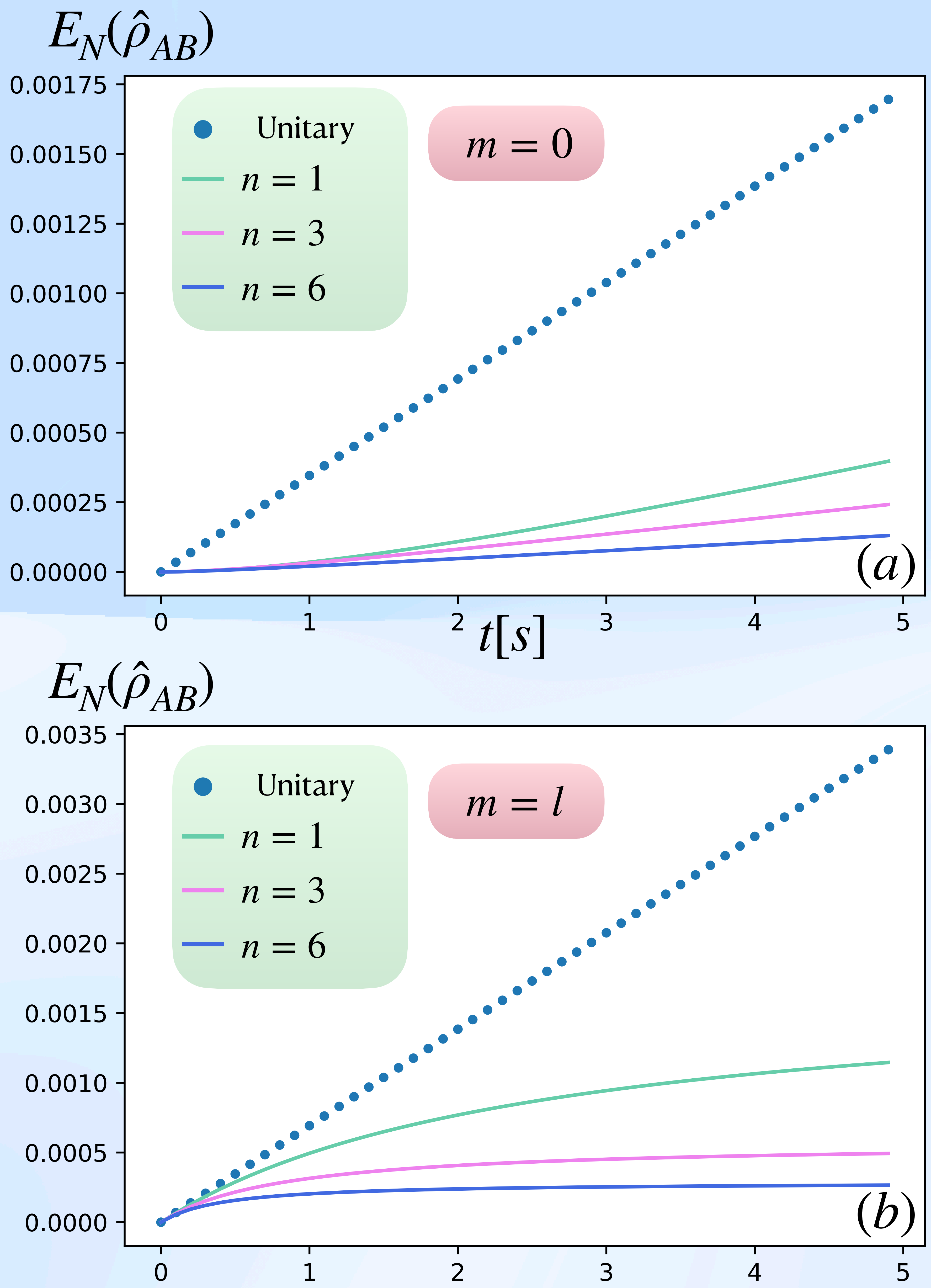
$\approx 10^9$ nuclear spins in a SiO_2 sphere of radius $R = 50\mu m$

$$V_M = \frac{\mu_0 \gamma^2 \hbar^2}{4\pi r^3} \times 10^{18} \approx \cdot 10^{-28} \times p^2 \text{ J}$$

$$V_G = \frac{G\hbar^2 l^2}{c^2 r^3} \approx 1.2 \cdot 10^{-38} \text{ J}$$

$$\frac{V_M}{V_G} \approx 10^{10} p^2$$

Decoherence due to one collision



The event can transfer up to n quanta to the m number

$T = 0.1$ K and P=10^{-16} Pa

Dramatic drop of entanglement!

Probability of collision must be $\ll 1$

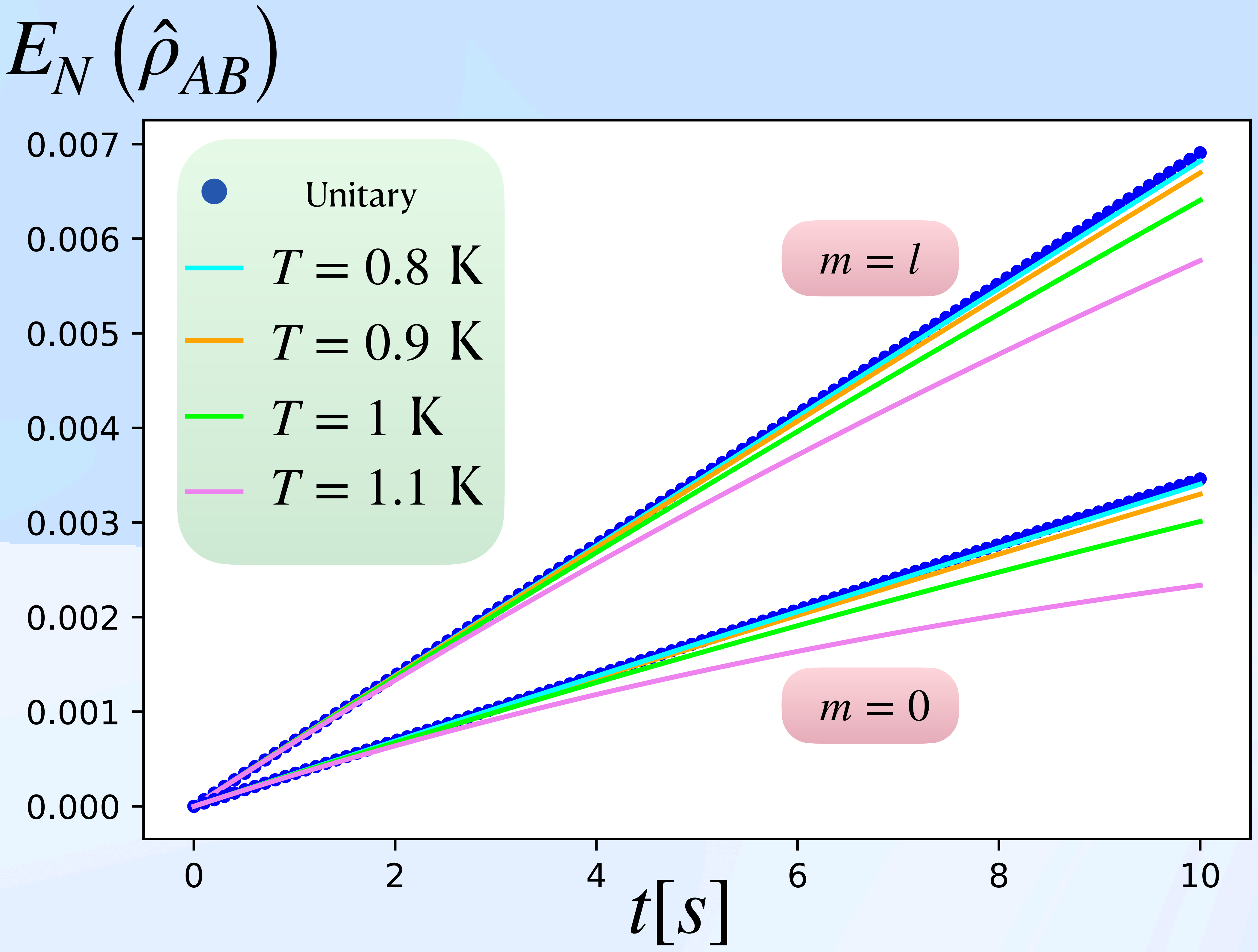
Sources of decoherence

- **Heating due to laser**

If we start rotating the spheres at $T_0 = 1\text{K}$, with a laser of 300nm, this leads to $T_f = 1.13\text{K}$ to achieve $\omega = 10^7\text{Hz}$

Is this temperature detrimental for the entanglement?

Decoherence due to thermal radiation



$$\frac{d}{dt}\hat{\rho}_S(t) = -\frac{i}{\hbar}\left[\hat{H}_I^{AB}, \hat{\rho}_S(t)\right] + \sum_{l\geq 0}\frac{\Delta_l^3\hbar^2}{6c^3I^3\epsilon_0}\left(1+N(\Delta_l)\right)\left[\hat{\vec{A}}^{AB}(\Delta_l)\cdot\hat{\rho}_S(t)\hat{\vec{A}}^{AB\dagger}(\Delta_l) - \frac{1}{2}\left\{\hat{\vec{A}}^{AB\dagger}(\Delta_l)\cdot\hat{\vec{A}}^{AB}(\Delta_l), \hat{\rho}_S(t)\right\}\right] + \sum_{l\geq 0}\frac{\Delta_l^3\hbar^2}{6c^3I^3\epsilon_0}N(\Delta_l)\left[\hat{\vec{A}}^{AB\dagger}(\Delta_l)\cdot\hat{\rho}_S(t)\hat{\vec{A}}^{AB}(\Delta_l) - \frac{1}{2}\left\{\hat{\vec{A}}^{AB}(\Delta_l)\cdot\hat{\vec{A}}^{AB\dagger}(\Delta_l), \hat{\rho}_S(t)\right\}\right],$$

With $\Delta_l = 2(l+1)$

$$\hat{A}_1^{AB} = \sum_{i=A,B}\sum_{m=-l}^{l} c_m^{(1)}\,|\,l,m\rangle_i\langle l+1, m+1\,|_i$$

$$\hat{A}_2^{AB} = \sum_{i=A,B}\sum_{m=-l}^{l} c_m^{(2)}\,|\,l,m\rangle_i\langle l+1, m-1\,|_i$$

$$\hat{A}_3^{AB} = \sum_{i=A,B}\sum_{m=-l}^{l} c_m^{(3)}\,|\,l,m\rangle_i\langle l+1, m\,|_i$$

Take-home message

- Many proposals for low-energy signatures of quantum gravity
- Angular momentum entanglement can be a promising alternative
- Effort in seeking alternative tests to the ones already available is required

Thanks for the attention!

Check the preprint here!