



Probing the
Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?

Probing the Quantum nature of Gravity

Prajwal Hassan Puttasiddappa

Your passion for (AMO-)physics: What are you curious about?
University of Heidelberg

April 27, 2021



What is the discussion about?

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Mechanics

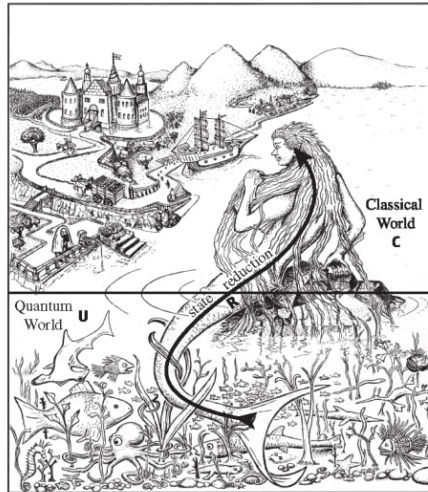
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What we will see,
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[Fashion, Faith, and Fantasy in the New Physics of the Universe; Roger Penrose (2016)]¹





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- Gravity in local scales is well tested and well understood
QT is well tested but **not** well understood?
- Gravity stands out among other forces
QT has problems with formalism and/or measurement
- l_P where we realise quantized gravity.
 M_P is massive enough to expect breakdown of QT -behave gravitationally
- **Are these problems related?**
Why should we be sure about their influence on each other?
- Lets first see some theoretical motivations and flaws and then look into the few experimental directions to test the above questions.



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Quantum
Mechanics

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Penrose Collapse

Entangled Diamonds

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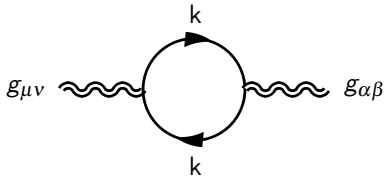
What we will see,
what we will
know?

- 1 Quantizing Gravity
 - Detect a Graviton?
- 2 Gravitizing Quantum Mechanics
 - Stochastic Collapse
 - Penrose Collapse
 - Entangled Diamonds
- 3 Summary
- 4 What we will see, what we will know?



Quantizing Gravity

- Begin with a notion that 'quantum' is fundamental theory.
- EH action way too simple? $S = \int_x \sqrt{-g} R$
Pure gravity is renormalizable in 1 loop
With matter it is not renormalisable. [G.t'Hooft, M.Veltman (1974)]².
- 1 loop matter correction: No counter terms in the EH action. [J.Donoghue (1997)]³



- The non-renormalizability concerns the UV-behaviour of the theory and **does not lead to any new prediction**.
- We can already see quantum correction for Newton Potential etc in an effective theory.



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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

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what we will
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Where is the Problem?

- Quantum field theory of Gravity : local field operators.
- Small distances or large momenta : divergences show up in calculations of integrals in momentum space.

We may not make have a theory in the most fundamental level.

But

- Effective Field Theory of Gravity
- Extra dimensions, Emergent Gravity, String Theory
- Lower dimensions: $(2+1)$ D Gravity, (Canonical) Loop Quantum Gravity



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Puttasiddappa

Quantizing
Gravity

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Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
know?

- We shall **not** dive in detail into various ways we could try to quantize gravity **rather** treat it as Effective Field Theory
- EFT: Quantum theory of General Relativity at low energy. Any deviation detected then we need to look for UV completion.

If there is a quantum aspect of gravitation then,

- Single Graviton
- Excite an electron in Hydrogen atom. [Rothman, Boughn(2006)]⁴
- Entanglement

Dyson conjectured, detecting a single graviton is **not realistic**. [Dyson(2013)]⁵



Can we detect a Graviton?

- Sensitivity of LIGO : Detects if more than $3 \cdot 10^{37}$ gravitons.



Mirrors of LIGO

- We already use quantum mechanics to detect the gravitons!
- Electron excitation in H -atom by a graviton: Cross-sections
(graviton - electron) - 10^{-65} sq.cm
(p-p at 7 TeV) - 10^{-25} sq.cm
(Higgs - 10^{-38} sq.cm)



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Quantizing
Gravity

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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?



Fundamental Problems with QM

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Quantizing
Gravity

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Quantum
Mechanics

Stochastic Collapse

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Entangled Diamonds

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- Superposition principle breaks down for macroscopic objects.
- QM is a **two step process**: Unitary evolution - State reduction
- QM gives us **probability connections**: 2 step measurements
- Formalism Problems
- Gravity might not be quantized but they might play a role in wave function collapse.

"My own point of view is that as soon as a 'significant' amount of space time curvature is introduced, the rules of quantum linear superposition must fail"

-R. Penrose



Gravitizing Quantum Mechanics

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Gravity

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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
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- Semi-Classical : Classical gravity coupled to quantum matter

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} \langle \psi | \hat{T}_{\mu\nu} | \psi \rangle \longrightarrow \nabla^2 \Phi_N = 4\pi G_N \langle \psi | \hat{\rho}_{\mu\nu} | \psi \rangle$$

- Schrodinger-Newton Equation

$$i\partial_t |\psi\rangle = (H_M + \underbrace{H_N}_{\text{Gravitational Potential}}) |\psi\rangle$$

Gravitational Potential

$$H_N = G \int_{\vec{r}} \frac{m_1 m_2 |\psi_1(t, r) \psi_2(t', r')|}{|\vec{r}' - \vec{r}|}$$

- Non-linear equation: Matter fields $|\psi\rangle$ determine the Newtonian potential and potential determines the evolution of $|\psi\rangle$.
- Stochastic Collapse and Penrose Collapse



Stochastic Collapse

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of Gravity

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Quantizing
Gravity

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Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?

- Gravity is considered as a stochastic **noise** background.
- Replace $H_N \rightarrow H_S$ given by stochastic variable $\Phi(r, t)$ which is, independent of $|\psi\rangle$. Its statistical correlation function is defined as,

$$\langle \Phi_N(t_1, r) \Phi_N(t_2, r') \rangle = G_N \frac{\delta(t_1 - t_2)}{|\vec{r} - \vec{r}'|}$$

- for a local mass distribution $M(r)$, SN equation for stochastic variable $\psi(t)$ is

$$i\partial_t \psi(t) = \left[H_M + \int_r \Phi_N M(r) \right] \psi(t)$$



Stochastic Collapse: Gravitational Decoherence

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Quantizing
Gravity

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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse
Entangled Diamonds

Summary

What we will see,
what we will
know?

- In terms of density matrix it reads,

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H_M, \rho(t)] - \underbrace{\frac{G}{2\hbar} \int_{\vec{r}\vec{r}'} \frac{[M(\vec{r})[M(\vec{r}'), \rho(t)]]}{|\vec{r} - \vec{r}'|}}_{\text{Non-Unitary, Off-diagonal Damping Lindbladian}}$$

Non-Unitary, Off-diagonal Damping Lindbladian

- This is the evolution equation from $((t_1, r) \rightarrow (t_2, r'))$ in the noisy background. To know the influence of damping term we will go to coordinates x and y to see the correlations of configurations of $M(r)$.
- **Decoherence time (τ):** $M(r|x)$ being the corresponding mass distribution at x , we can define,

$$[\tau(x, y)]^{-1} = \Gamma = \frac{G}{2\hbar} \int_{\vec{r}\vec{r}'} \frac{[M(\vec{r}|x) - M(\vec{r}|y)][M(\vec{r}'|x) - M(\vec{r}'|y)]}{|\vec{r} - \vec{r}'|}$$



Stochastic Collapse: Spatial Superposition

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Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

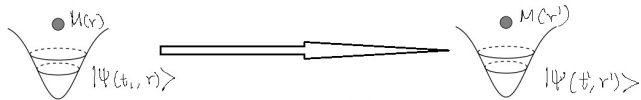
Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?





Stochastic Collapse: Superposition

Probing the
Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

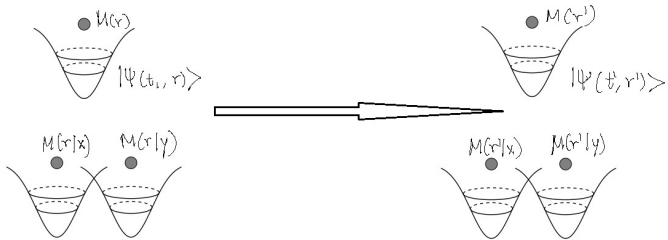
Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse
Entangled Diamonds

Summary

What we will see,
what we will
know?





Stochastic Collapse: Gravitational Decoherence

Probing the
Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
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- We had,

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H_M, \rho(t)] - \Gamma\rho$$

- Decoherence implies decay of the **off-diagonal density matrix elements**.

$$\rho_{xy}(t) = \langle x | \rho | y \rangle = \rho_{xy}(0)e^{-\Gamma t}$$

- The integral above will diverge for a point particle.
- $\tau = \Gamma^{-1}$ is the time taken by a wave function of a massive object in spatial superposition to collapse.
- We can define a length scale $R_D = \hbar^2/Gm^3$ from coefficients of SN equation.
- This is a critical parameter within which the system acts like coherent particle and beyond which there is decoherence.
- R_D for a proton would be 10^6 !



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Gravity

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Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

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what we will
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Wait a minute

- Massive object in superposition? Can we really see it?
- Example: We have seen 10^5 Rb atoms ($m \sim 10^{-25}\text{kg}$) spatial superposition at $\Delta x \sim 0.5\text{m}$ collapse, for 1sec



Superposition: Observations

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Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

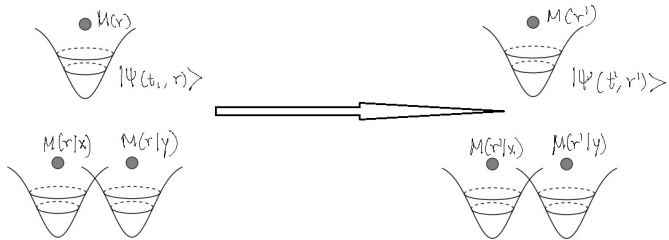
Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?





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Probing the
Quantum nature
of Gravity

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Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

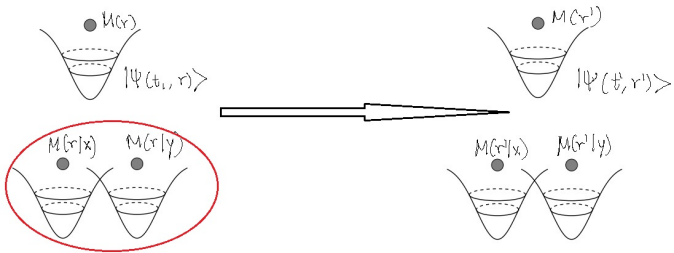
Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse
Entangled Diamonds

Summary

What we will see,
what we will
know?





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Probing the
Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

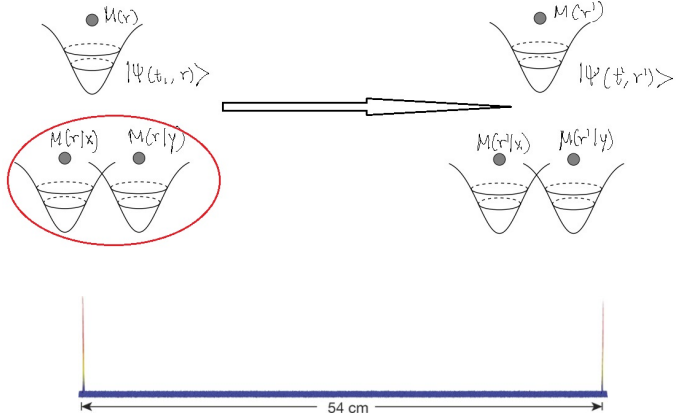
Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

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what we will
know?



[Kasevich et.al (2015)]



Interference: Observations

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Quantum nature
of Gravity

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Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

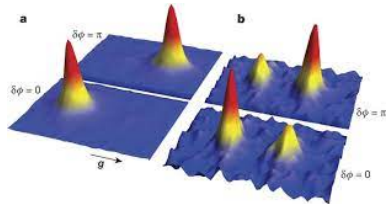
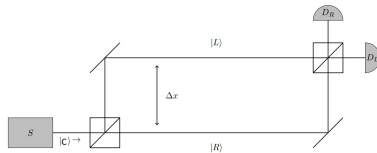
Penrose Collapse

Entangled Diamonds

Summary

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what we will
know?

$$|C\rangle = |L\rangle + |R\rangle$$



[Kasevich et.al (2015)]⁶



Problems

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Quantum nature
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Quantizing
Gravity

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Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

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what we will
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Experimental

- Neutral masses, Low internal temperature: No Casimir only Gravity.
- Cannot distinguish the source of collapse

We may not make predictions in the most fundamental level.

Stochastic Collapse

- Normalisation problems (generic to semi-classical SN)
- Mass distribution dependence: only by varying the mass distribution we get many predictions of the theory.
- The nature of noise or the source is not explained.
- Unrealistic predictions: For simple matter distribution, $\tau = \Gamma^{-1} \sim \frac{\hbar R_D}{G_N m^2}$ for Rb atoms, would be 10^9 seconds!



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Quantum nature
of Gravity

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Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?



Penrose Collapse

Probing the
Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
know?

- Lets start with stationary states (ignoring gravity), ψ_L, ψ_R with corresponding space-time associated

$$|\Psi\rangle = a_L |\psi_L; g_{\mu\nu}^L\rangle + a_R |\psi_R; g_{\mu\nu}^R\rangle$$

- Stationarity implies associated killing vectors (timelike)
- Schrodinger time-evolution operator $\partial/\partial t$ acting on such a stationary state,

$$i\hbar \frac{\partial}{\partial t} |\Psi\rangle = E |\Psi\rangle$$

- But matter distributions associated with the two states are different, in the presence of a background gravitational field $\psi_L g_{\mu\nu}^L \neq \psi_R g_{\mu\nu}^R$.



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Quantum nature
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Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse
Entangled Diamonds

Summary

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- Assume approximate isometry between $g_{\mu\nu}^L \rightarrow g_{\mu\nu}^R$. That means they are equal upto an error term.
- This corresponds to slight difference in Schrodinger operator \implies **uncertainty in Energy**.
- In weak field limit,

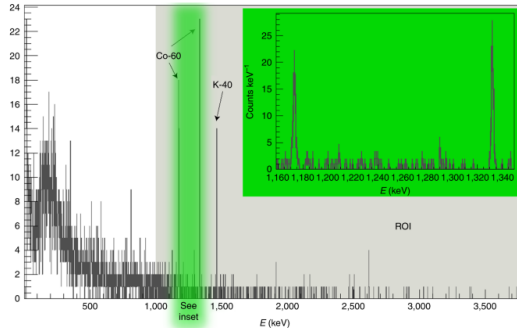
$$\Delta E_{LR} = 4\pi G_N \int_{r,r'} \frac{\Delta M_{LR}(r) \Delta M_{LR}(r')}{|\vec{r} - \vec{r}'|}$$

- This is the energy uncertainty which is associated with Decoherence/Collapse time $\Delta t_{LR} = \frac{\hbar}{\Delta E_{LR}}$

$$\tau^{-1} = [\Delta t_{LR}]^{-1} = \Gamma \sim \frac{G_N m^2}{\hbar R_P}$$



Penrose Collapse



[Donadi et.al(2020)]⁷



Penrose Collapse

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Quantum nature
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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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- Is Brownian-like diffusion an unavoidable consequence of gravity-induced collapse of wave-function of charged massive objects?
- Energy range: $10 - 10^5 \text{ keV}$
Wavelength: $10^{-5} - 0.1 \text{ nm}$
- 62 days, Germanium Detector (375 c.c), 3100m water equivalent shield.
- R_P
 - Penrose : size of nucleus wave function $0.05 \cdot 10^{-10} \text{ m}$
 - Experiment bound: $> 0.54 \cdot 10^{-10} \text{ m}$



Discussion

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Quantum nature
of Gravity

Prajwal Hassan
Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?



Quantum Gravity mediated Entanglement

Probing the
Quantum nature
of Gravity

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Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
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Consider 2 masses in two mass interferometers with a spin
Center of mass state of the masses

$$|C\rangle_j = |L\rangle_j + |R\rangle_j \quad ; j \in \{1, 2\}$$

spin-1/2 dof as markers, $|L/R\rangle \rightarrow |\uparrow / \downarrow\rangle$

$$|C\rangle_j = |\uparrow\rangle_j + |\downarrow\rangle_j$$

state at $t = 0$, split them using a magnetic field

$$|\psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 + |\downarrow\rangle_1) \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + |\downarrow\rangle_2)$$

Hold the superposition till $t = \tau$, refocus using Unitary transformation

$$|\psi(t=\tau)\rangle_{12} = \frac{1}{2} \left[|\uparrow\rangle_1 (|\uparrow\rangle_2 + e^{i\phi} |\downarrow\rangle_2) + |\downarrow\rangle_2 (e^{i\bar{\phi}} |\uparrow\rangle_1 + |\downarrow\rangle_1) \right]$$

Not Product States; ENTANGLED STATES



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Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

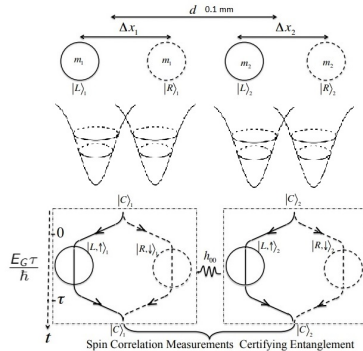
Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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what we will
know?



- M_P is accessible mass scale.
Work with mesoscopic test masses $\sim 10^{-14}$ kg
- Send it through beam splitter and then recombine: state evolution from $(t = 0) \rightarrow (t = \tau)$ under mutual gravitational interaction
- Entanglement \implies impart phases to components of superposition \rightarrow only from graviton [Bose et al (2017)]⁸



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Quantum nature
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Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
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- The differential phases $\phi = \frac{Gm^2\tau}{(d+\Delta x)\hbar}$ and $\bar{\phi} = \frac{Gm^2\tau}{(d-\Delta x)\hbar}$.
- $\phi + \bar{\phi} = 2n\pi$ for $n = 0$, the equation is separable - coherence : not entangled
- Other wise we cannot factorise them - decoherence : entangled.
 $\phi + \bar{\phi} \in [0, \pi]$ so, the condition to have entanglement is

$\phi + \bar{\phi} \sim \mathcal{O}(1)$
- To see it explicitly we can use any tool : Check the Entropy or Just see the violation of Bell inequality.
- If the states turned out to be entangled, **then gravitational field has some quantum behaviour.**



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Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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know?

- **Quantizing Gravity:** Theoretically quest to treat gravity equally like other fundamental forces. Local tests are **not feasible**, may have cosmological implications.



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Quantum nature
of Gravity

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Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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- **Gravitizing Quantum Theory:** Try to solve the wave function **collapse problem**. The **non-linearity** in SN equations pose many problems. Two models:
 - 1 **Stochastic Collapse:** Gravitational noise in quantum experiments.
Significant noise for large mass distribution radius
Unreal decoherence time
Theory depends on mass distribution
No explanation on noise (nature and source)



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 - 1 **Stochastic Collapse:** Gravitational noise in quantum experiments.
 - 2 **Penrose Collapse:** The massive particle in spatial superposition curve the spacetime.
Time evolution of such systems \rightarrow energy uncertainty \rightarrow decoherence time.
Collapse \rightarrow radiation \rightarrow test



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Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

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 - 1 **Stochastic Collapse:** Gravitational noise in quantum experiments.
 - 2 **Penrose Collapse:** The massive particle in spatial superposition curve the spacetime.
 - 3 **Entangled Diamonds:** To see if gravity has any quantum nature at all. Does it interact with the quantum world.



What we will see, what we may know?

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Quantum nature
of Gravity

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Puttasiddappa

Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

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what we will
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- First direct detection of quantum nature of gravitational interactions.
- Gravity can be viewed as an effective quantum field theory, may not be UV complete, but perfectly capable of making predictions for tabletop experiments.
- More enthusiasm in Table top experiments - gravitational waves etc!
- Scope for new theoretical models (Emergent gravity etc), study of existing models, theoretical tests.
Still the problem of 'interpretation' remains.
- Better control of non-gravitational decoherence: helps Quantum Computing etc.



THANK YOU (Discussions)

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Detect a Graviton?

Gravitizing
Quantum
Mechanics

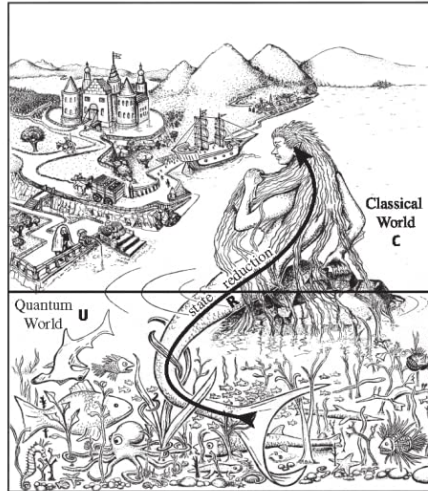
Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

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what we will
know?





Appendix

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Quantum nature
of Gravity

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Quantizing
Gravity

Detect a Graviton?

Gravitizing
Quantum
Mechanics

Stochastic Collapse

Penrose Collapse

Entangled Diamonds

Summary

What we will see,
what we will
know?

The two masses are interacting only through gravity. The overall phase factor should be multiplied for completeness $e^{i\varphi}$

$$\varphi = \frac{E_G \tau}{\hbar} = \frac{G_N m^2 \tau}{d \hbar} \approx 60 \left(\frac{m}{1\text{ng}} \right) \left(\frac{\tau}{1\text{s}} \right) \left(\frac{1\text{mm}}{d} \right)$$

The condition to see Entanglement is,

$$\mathcal{W} = | \langle \sigma_x^1 \sigma_z^2 \rangle - \langle \sigma_y^1 \sigma_z^2 \rangle | \geq 1$$



Reference

Probing the
Quantum nature
of Gravity

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