# DETECTING HIGH FREQUENCY NONLINEAR QUANTUM PHENOMENA USING WEAK MEASUREMENTS

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# AGENDA

Nonlinear Quickly Oscillating Pure States

Weak Measurements

Detecting Quick Oscillations

Possible Experiments

Concluding Remarks

# QUICKLY OSCILLATING PURE STATES

- Black hole information paradox – a pure state can collapse into a black hole and end up as a mixed state as the result of Hawking radiation
- This is an important issue because it implies nonunitarity of quantum evolution
- But there is also a thermodynamical issue – an isolated system at thermal equilibrium can't increase its entropy
- If Hawking radiation is fundamentally not a mixed state, but a pure state which for all practical purposes behaves as a mixed state, the thermodynamical issue is resolved at least

# QUICKLY OSCILLATING PURE STATES

- Pure states are vastly different from mixed states. How can they be effectively the same?
- Due to the imperfection of quantum measurements – every time measuring device has a finite resolution
- The exact moment at which a measurement occurs can't be precisely controlled
- Experimentally observed results correspond to averaging the measurement results over the time interval of the resolution of the time measuring device

[Mertens, Wesseling, van Wezel, 2024]

# QUICKLY OSCILLATING PURE STATES

- Hawking radiation is not the only process under which a pure state can become a mixed state – this also occurs under nonselective quantum measurement
- It has recently been shown that objective quantum collapse of a wavefunction can be obtained under nonunitary, nonlinear, stochastic quantum evolution
- This motivated us to consider a general mixed state under the same lens

# QUICKLY OSCILLATING PURE STATES

- Nonunitary – a pure state can become effectively mixed
- Stochastic – quick oscillations and averaging over time can simulate stochastic behavior
- Nonlinear – the “same” quantum state can evolve in multiple distinct ways*

* In quantum mechanics we usually assume that all states differing only by a complex factor are identical. If evolution is not homogenous, this is no longer the case; different factors lead to different evolutions.

# QUICKLY OSCILLATING PURE STATES

- Let us choose a state of the following form:

$$|\psi\rangle = A_1 e^{i\varphi_1(t)} |\psi_1\rangle + A_2 e^{i\varphi_2(t)} |\psi_2\rangle + ... + A_n e^{i\varphi_n(t)} |\psi_n\rangle$$

- Written in the projector form, the state is:

$$\Pi_\psi = \sum_i |A_i|^2 |\psi_i\rangle \langle\psi_i| + \sum_{i \neq j} A_i^* A_j e^{i(\varphi_j(t) - \varphi_i(t))} |\psi_j\rangle \langle\psi_i|$$

- When we say a state is quickly oscillating, we mean that it is of the former form, that all coefficients are approximately constant in the measurement time interval, and that all the phase differences quickly change in time

# QUICKLY OSCILLATING PURE STATES

- If we average the projector over the measurement time interval, we obtain a mixed state:

$$\rho_\psi = \sum_i |A_i|^2 \, |\psi_i\rangle \langle\psi_i|$$

- States are (usually) not directly observed in quantum mechanics. Instead, we observe:

  - Expectation value;
  - Transition probabilities;
  - Higher moments of probability distribution

# QUICKLY OSCILLATING PURE STATES

- Expectation value for a quickly oscillating state is:

$$\langle\hat{O}\rangle = Tr\left[\Pi_\psi \hat{O}\right] = \sum_i |A_i|^2 \langle\psi_i|\hat{O}|\psi_i\rangle + \sum_{i\neq j} A_i^* A_j e^{i(\varphi_j(t)-\varphi_i(t))} \langle\psi_i|\hat{O}|\psi_j\rangle$$

- After averaging it over the time resolution interval, the result is the same as for the corresponding mixed state

$$\langle\hat{O}\rangle_t \equiv \frac{1}{\Delta t}\int_0^{\Delta t} \langle\psi(t)|\hat{O}|\psi(t)\rangle\, \mathrm{d}t = \langle\hat{O}\rangle \equiv Tr\left[\rho_\psi \hat{O}\right] = \sum_i |A_i|^2 \langle\psi_i|\hat{O}|\psi_i\rangle$$

- The transition probability from state $\widehat{\Pi}_\psi$ into some state $\widehat{\Pi}_a$ is the expectation value of the projector $\widehat{\Pi}_a$ in the state $\widehat{\Pi}_\psi$, and as such

$$\langle Tr\left[\Pi_\psi \Pi_a\right]\rangle_t = Tr\left[\rho_\psi \Pi_a\right]$$

# QUICKLY OSCILLATING PURE STATES

- One can also consider time correlations:

$$C_1 = \langle\psi(t)|\,\hat{O}(\tau_1)...\hat{O}(\tau_N)\,|\psi(t)\rangle = Tr\left[\mathit{\Pi}_\psi\hat{O}(\tau_1)...\hat{O}(\tau_N)\right]$$

- The moments in time at which the observables are taken cannot be chosen exactly due to the finite resolution of the time measurement device. As such, we average over both $t$ and $\tau_i$

- Since the operator product does not depend on time *t*, and due to the linearity of the trace, one obtains:

$$\langle C_1\rangle_t = Tr\left[\rho_\psi\hat{O}(\tau_1)...\hat{O}(\tau_N)\right]$$

# QUICKLY OSCILLATING PURE STATES

- One can also evaluate the product of means at different moments of time:

$$C_2 = \langle\psi(t+\tau_1)|\,\hat{O}\,|\psi(t+\tau_1)\rangle \dots \langle\psi(t+\tau_N)|\,\hat{O}\,|\psi(t+\tau_N)\rangle$$

- We need to average over both $t$ and $\tau_i$ as before. Each mean depends only on a single time $\tau_i$, and when averaging over it, time $t$ is treated as a constant phase. As such:

$$\langle\psi(t+\tau_i)|\,\hat{O}\,|\psi(t+\tau_i)\rangle_{\tau_i} = Tr\left[\rho_\psi \hat{O}\right]$$

- This analysis also applies for the special case where all parameters $\tau_i$ are equal to zero, which corresponds to the higher moments of probability distribution
- Due to the finite resolution of the time measuring device, one cannot be certain that they are correlating simultaneous experimental results, and not results in slightly different moments of time

# QUICKLY OSCILLATING PURE STATES

- One can substitute all projectors onto states of quickly oscillating phases with corresponding mixed states and omit averaging over time. No realistic measurement result will be modified in this way
- The quickly oscillating state and the mixed state are fully equivalent for observable quantities
- The question whether the state is fundamentally pure and quickly oscillating, or mixed without rapid time dependence, appears to be metaphysical for all practical purposes
- We will show that this is not the case if one considers weak measurements on postselected systems

[Aharonov, Bergmann, Lebowitz, 1964]

# WEAK MEASUREMENTS

- In addition to absolute probabilities, there are also conditional probabilities
- Conditional probabilities in quantum mechanics correspond to postselected systems
- At some initial time, a selective measurement is performed, and only the elements of the ensemble that satisfy the preselection condition contribute to the measurement result
- After the measurement, another selective measurement is performed, and the measurement results corresponding to the elements of the ensemble which do not satisfy the postselection condition are discarded

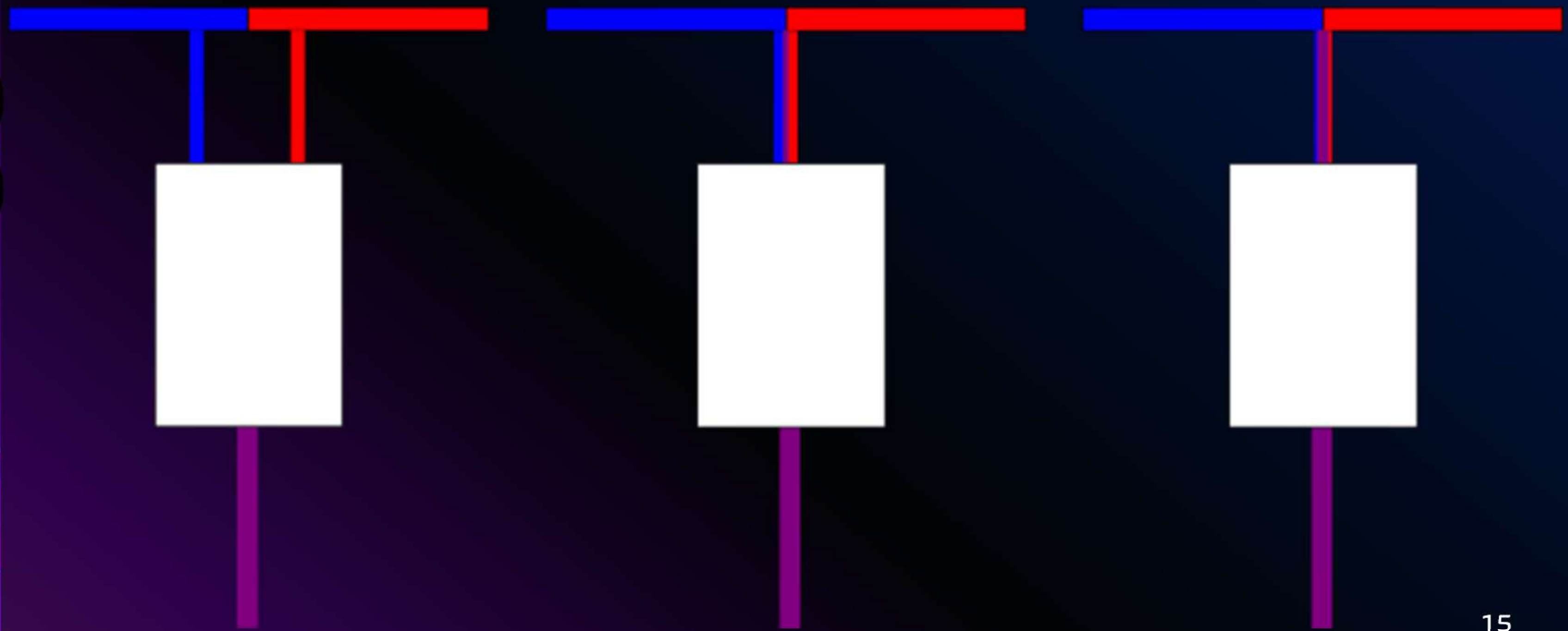
[Aharonov, Vaidman, 1990]

# WEAK MEASUREMENTS

- When one wants to determine what is the expectation value of a given observable, one usually strongly couples it with the quantum system and performs a strong measurement
- The entire probability distribution for all eigenvalues of the observable is obtained, and the quantum state collapses in the act of measurement
- There is a way to measure expectation values directly without collapsing the state: weakly couple the observable to the quantum system
- The measurement device is not capable of determining what are individual measurement results of the given observable for each member of the ensemble, however the mean value can be observed
- This type of measurement can be called weak non-postselected measurement

[Aharonov, Vaidman, 1990]

# WEAK MEASUREMENTS



[Jordan, Martínez-Rincón, Howell, 2014]
[Lundeen, Sutherland, Patel, Stewart, Bamber, 2011]
[Kocsis, Braverman, Ravets, Stevens, Mirin, Shalm, Steinberg, 2011]

# WEAK MEASUREMENTS

- When the experimental setup used to obtain weak non-postselected measurements is used under a postselection condition, one obtains so-called weak values of (postselected) weak measurements
- Usually, using the term “weak measurement” implies that postselection has been performed
- Experimentally, weak measurements have been applied in many different practical problems: to amplify the measurement signal, to directly measure the wavefunction, to measure “trajectories” in the double-slit experiment and many more
- As will be shown, weak measurements can be used to distinguish quickly oscillating pure states from mixed states as well

# WEAK MEASUREMENTS

- Unlike in non-postselected case, weak measurements in postselected systems do not simply give an expectation value.
- Weak values are complex numbers. The real part of a weak value is directly observable as the position of the pointer of the measurement device, and the imaginary part corresponds to the momentum of the pointer.
- Since the pointer can be a macroscopic object, the uncertainty principle can be ignored

[Aharonov, Vaidman, 1990]

# WEAK MEASUREMENTS

- The weak value of an observable $\hat{O}$ in a quantum system described by the preselected and postselected states $|\psi_1\rangle$ and $|\psi_2\rangle$ respectively, is given by:

$$O_w = \frac{\langle \Psi_1 | \hat{O} | \Psi_2 \rangle}{\langle \Psi_1 | \Psi_2 \rangle}$$

- We can rewrite the expression using the statistical operators:

$$O_w = \frac{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{O} \hat{\Pi}_2\right]}{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{\Pi}_2\right]}$$

- The proof is simple:

$$\frac{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{O} \hat{\Pi}_2\right]}{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{\Pi}_2\right]} = \frac{\mathrm{Tr}\left[|\Psi_1\rangle\langle\Psi_1|\hat{O}|\Psi_2\rangle\langle\Psi_2|\right]}{\mathrm{Tr}\left[|\Psi_1\rangle\langle\Psi_1|\Psi_2\rangle\langle\Psi_2|\right]} = \frac{\langle\Psi_1|\hat{O}|\Psi_2\rangle\langle\Psi_2|\Psi_1\rangle}{\langle\Psi_1|\Psi_2\rangle\langle\Psi_2|\Psi_1\rangle}$$

# WEAK MEASUREMENTS

- If the postselected state is chosen to be identical to the preselected state, postselection has no effect and the weak value reduces to the expectation value:

$$O_w = \frac{\langle \Psi_1 | \hat{\mathrm{O}} | \Psi_1 \rangle}{\langle \Psi_1 | \Psi_1 \rangle} = \langle \hat{O} \rangle$$

- If the weak value is weighted by the probability of the postselection condition being satisfied, and summed over all possible results of the postselection measurement, it once again becomes the expectation value:

$$\sum_i |\langle \Psi_1 | \Psi_i \rangle|^2 \frac{\langle \Psi_1 | \hat{\mathrm{O}} | \Psi_i \rangle}{\langle \Psi_1 | \Psi_i \rangle} = \sum_i \langle \Psi_1 | \hat{\mathrm{O}} | \Psi_i \rangle \langle \Psi_i | \Psi_1 \rangle = \langle \hat{O} \rangle$$

# WEAK MEASUREMENTS

- If the phase of the first state quickly oscillates in time, the observable weak value needs to be time-averaged. As such, the measurement result directly corresponds to:

$$\langle O_w \rangle_t \equiv \frac{1}{T} \int_0^T O_w dt = \langle \frac{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{O} \hat{\Pi}_2\right]}{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{\Pi}_2\right]} \rangle_t$$

- If the preselected and postselected states are mixed, they can be written as:

$$\rho_1 = \sum_i p_i \hat{\Pi}_i, \quad \rho_2 = \sum_j q_j \hat{\Pi}_j$$

- Preselecting into the mixed state $\rho_1$ can be done by utilizing different preselection criteria for different members of the ensemble: $p_i$ is the ratio of the members of the ensemble that are preselected in the pure state $\Pi_i$ . Similar interpretation applies for postselection.

# WEAK MEASUREMENTS

- Thus, a weak measurement with mixed states can be considered as a combination of weak measurements with pure states
- The probability of a random member of the ensemble corresponding to the pure states $\Pi_i$ and $\Pi_i$ is $p_i q_j$
- Not all members of the ensemble satisfy the postselection criterion
- The former probability needs to be multiplied by the probability that the postselection is satisfied, which is the transition probability from the initial pure state to the final pure state, and normalized by the total probability of postselection occurring:

$$O_w = \sum_{i,j} \frac{p_i q_j \mathrm{Tr}\left[\hat{\Pi}_i \hat{\Pi}_j\right]}{\sum_{k,l} p_k q_l \mathrm{Tr}\left[\hat{\Pi}_k \hat{\Pi}_l\right]} \frac{\mathrm{Tr}\left[\hat{\Pi}_i \hat{\mathrm{O}} \hat{\Pi}_j\right]}{\mathrm{Tr}\left[\hat{\Pi}_i \hat{\Pi}_j\right]} = \frac{\mathrm{Tr}\left[\hat{\rho}_1 \hat{\mathrm{O}} \hat{\rho}_2\right]}{\mathrm{Tr}[\hat{\rho}_1 \hat{\rho}_2]}$$

# WEAK MEASUREMENTS

- It is interesting to observe the case where the preselected state is either mixed or quickly oscillating, while the postselected state is pure

- If the preselected state is quickly oscillating, the observed weak value is:

$$\langle O_w \rangle_t = \langle \frac{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{\mathrm{O}} \hat{\Pi}_2\right]}{\mathrm{Tr}\left[\hat{\Pi}_1 \hat{\Pi}_2\right]} \rangle_t$$

- If it is mixed though, the weak value is:

$$O_w = \frac{\mathrm{Tr}\left[\hat{\rho}_1 \hat{\mathrm{O}} \hat{\Pi}_2\right]}{\mathrm{Tr}\left[\hat{\rho}_1 \hat{\Pi}_2\right]} = \frac{\langle \mathrm{Tr}\left[\hat{\Pi}_1 \hat{\mathrm{O}} \hat{\Pi}_2\right] \rangle_{\mathrm{t}}}{\langle \mathrm{Tr}\left[\hat{\Pi}_1 \hat{\Pi}_2\right] \rangle_t}$$

- Here we make an important observation: if the state is fundamentally quickly oscillating and pure, the value of the weak measurement will differ from the case when the state is fundamentally mixed. The question regarding the nature of the state is no longer metaphysical, it becomes experimentally testable.

# DETECTING QUICK OSCILLATIONS

- Let us start with two-state vector systems:

$$|\psi_1\rangle = N_1(|+\rangle + Ae^{i\varphi}|-\rangle), \quad |\psi_2\rangle = N_2(|+\rangle + Be^{i\chi}|-\rangle)$$

- The coefficients *A* and *B* are taken to be strictly positive. The negative signs can be absorbed into the phases. The coefficients $N_i$ are normalization factors

- The weak value becomes:

$$O_w = \frac{\langle +|\hat{O}|+\rangle + Be^{i\chi}\langle +|\hat{O}|-\rangle + Ae^{-i\varphi}\langle -|\hat{O}|+\rangle + ABe^{i(\chi-\varphi)}\langle -|\hat{O}|-\rangle}{1+ABe^{i(\chi-\varphi)}}$$

# DETECTING QUICK OSCILLATIONS

- With a proper choice of the measured observable, the expression can simplify significantly. For example, let us pick the polarization observable:

$$\hat{O} = |+\rangle\langle+| - |-\rangle\langle-| \equiv \hat{S}$$

- Its weak value is given by the expression:

$$S_w = \frac{1 - ABe^{i(\chi-\varphi)}}{1 + ABe^{i(\chi-\varphi)}}$$

- The real part of this weak value is:

$$Re\left[S_w\right] = \frac{\frac{1-A^2B^2}{2AB}}{\frac{1+A^2B^2}{2AB} + \cos(\chi-\varphi)}$$

# DETECTING QUICK OSCILLATIONS

- To explicitly evaluate the time average, we will assume that the phase difference depends linearly on time, with a very high frequency:

$$\chi - \varphi = \omega t + \phi, \quad \phi = const$$

- Since the weak value is a periodic function, the average over a time interval much larger than the period of oscillations is equal to the average over a single period:

$$\langle Re\left[S_w\right]\rangle_t = \frac{1}{T}\int_0^T Re\left[S_w\right] dt$$

- Using the following known integral we can evaluate the average:

$$\int_0^{2\pi} \frac{dx}{a+\cos x} = \frac{2\pi}{\sqrt{a^2-1}}, \quad a > 1$$

$$\langle Re\left[S_w\right]\rangle_t = \mathrm{sgn}\left[1 - A^2 B^2\right]$$

# DETECTING QUICK OSCILLATIONS

- The imaginary part of the weak value is given by the expression:

$$Im\left[S_w\right] = -\frac{2AB\sin(\chi-\varphi)}{1+A^2B^2+2AB\cos(\chi-\varphi)}$$

- The time averaged imaginary part of the weak value becomes zero, since we are averaging an odd function over its period

- It is important to note that these results do not depend on the frequency of oscillations, as long as the oscillation period is much shorter that the duration of the measurement

- In principle, this includes even the frequencies at Planck scale

# DETECTING QUICK OSCILLATIONS

- Now we will consider the weak value of the same observable when the quickly oscillating pure state is substituted by the corresponding mixed state:

$$\rho_1 = N_1^2(|+\rangle\langle+| + A^2 |-\rangle\langle-|)$$

$$\Pi_2 = |\psi_2\rangle\langle\psi_2| = N_2^2(|+\rangle\langle+| + B^2 |-\rangle\langle-| + Be^{ix} |-\rangle\langle+| + Be^{-ix} |+\rangle\langle-|)$$

- The weak value is now:

$$S_w = \frac{1-A^2B^2}{1+A^2B^2}$$

- This weak value can take on any value in the range [-1,1], depending on the choice of *A* and *B*, and is not limited to +1, -1 and 0 like in the quickly oscillating pure state case

- Weak measurements can be used to distinguish whether states are quickly oscillating and pure, or mixed

# DETECTING QUICK OSCILLATIONS

- The previous analysis can easily be repeated in the case of countably many dimensions. Now, the quickly oscillating pure state is:

$$|\psi_1\rangle = \sum_j \widetilde{A}_j e^{i\varphi_j} |j\rangle$$

- The corresponding mixed state is:

$$\rho_1 = \sum_j \left|\widetilde{A}_j\right|^2 |j\rangle \langle j|$$

- We choose two basis vectors $|a\rangle$ and $|b\rangle$, and measure the observable:

$$\hat{O} = |a\rangle \langle a| - |b\rangle \langle b|$$

# DETECTING QUICK OSCILLATIONS

- We can rewrite the states as:

$$|\psi_1\rangle = N_1(|a\rangle + Ae^{i\varphi}|b\rangle + \sum_{j\neq a,b} A_j e^{i\varphi_j}|j\rangle)$$

$$\rho_1 = |N_1|^2 (|a\rangle\langle a| + A^2|b\rangle\langle b| + \sum_{j\neq a,b} A_j^2 |j\rangle\langle j|)$$

- For the postselected state we choose:

$$|\psi_2\rangle = N_2(|a\rangle + Be^{i\chi}|b\rangle)$$

- It is easy to see that the results from the two-dimensional case are obtained once more

# DETECTING QUICK OSCILLATIONS

- In the case of a continuous basis, the analysis requires more finesse
- A quickly oscillating state is taken to be of the following form:

$$|\psi_1\rangle = \int_{-\infty}^{+\infty} A(x)e^{i\varphi(x,t)}\,|x\rangle\,dx$$

$$\Pi_1 = |\psi_1\rangle\langle\psi_1| = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} A(x)A(y)e^{i[\varphi(x,t)-\varphi(y,t)]}\,|x\rangle\langle y|\,dxdy$$

- We will assume that $A(x)$ and $\varphi(x,t)$ are smooth
- As before, we will absorb the negative sign into the phase, making the phase a piecewise continuous function

# DETECTING QUICK OSCILLATIONS

- If we take *x* and *y* to be arbitrarily close, the oscillations will stop being fast at some point
- Time averaging of this quickly oscillating state will never give the exact mixed state
- Just like for time, there is a finite resolution of realistic measurement
- There exists a $\Delta x$ such that for all practical purposes, $x$ and $x + \Delta x$ are experimentally indistinguishable

# DETECTING QUICK OSCILLATIONS

- The projector averages out over time into a matrix experimentally indistinguishable from the mixed state:

$$\rho_1 = \int_{-\infty}^{+\infty} A^2(x) \left| x \right\rangle \left\langle x \right| dx$$

- For simplicity, we can assume:

$$\varphi(x,t) = -\omega(x)t + \varphi(x)$$

- For the averaging to hold, the following relationship must be true for all *x*:

$$|\omega'(x)| \gg \frac{2\pi}{\Delta x \Delta t}$$

- $\Delta t$ and $\Delta x$ are the cutting-edge experimental resolutions of time and the observable with a continuous spectrum chosen as the basis, respectively

# DETECTING QUICK OSCILLATIONS

- Due to the finite resolution of the observable *X*, the effective mixed state might occur even at a fixed moment of time, due to averaging over *x*
- This will happen if $\varphi(x)$ is a quickly oscillating function in *x*
- Otherwise, we will assume that $\varphi(x)$ is slowly changing with *x*
- As before, we proceed with choosing the appropriate observable and the postselected state

# DETECTING QUICK OSCILLATIONS

- For the observable, we will pick:

$$\hat{O} = \int_{a-\Delta a}^{a} |x\rangle \langle x| \, dx - \int_{a}^{a+\Delta a} |x\rangle \langle x| \, dx$$

- For the postselected state we will take:

$$|\psi_2\rangle = \int_{a-\Delta a}^{a} B(x)e^{i\chi(x)} |x\rangle \, dx + \int_{a}^{a+\Delta a} B(x)e^{i\chi(x)} |x\rangle \, dx$$

- For the weak value we obtain:

$$O_w = \frac{\int_{a-\Delta a}^{a} A(x)B(x)e^{i[\chi(x)-\varphi(x,t)]}dx - \int_{a}^{a+\Delta a} A(x)B(x)e^{i[\chi(x)-\varphi(x,t)]}dx}{\int_{a-\Delta a}^{a} A(x)B(x)e^{i[\chi(x)-\varphi(x,t)]}dx + \int_{a}^{a+\Delta a} A(x)B(x)e^{i[\chi(x)-\varphi(x,t)]}dx}$$

# DETECTING QUICK OSCILLATIONS

- In what follows we will assume that the quickly changing phase is:

$$\varphi(x,t) = -\Omega x t + \Phi x$$

- The amplitude of the quickly oscillating state $A(x)$ cannot be controlled
- It can be measured without postselection since $A^2(x)$ is the probability of finding the effectively mixed state in state $|x\rangle$. It's a known parameter
- For the postselected state, we will choose:

$$B(x) = \frac{NC_1}{A(x)}, \quad a - \Delta a < x < a, \qquad B(x) = \frac{NC_2}{A(x)}, \quad a < x < a + \Delta a$$

# DETECTING QUICK OSCILLATIONS

- The parameters $C_1$ and $C_2$ are positive constants
- Now we can evaluate the weak value:

$$O_w = \frac{C_1 + C_2 - C_1 e^{-i(\Omega \Delta a t - \Phi \Delta a)} - C_2 e^{i(\Omega \Delta a t - \Phi \Delta a)}}{C_1 - C_2 - C_1 e^{-i(\Omega \Delta a t - \Phi \Delta a)} + C_2 e^{i(\Omega \Delta a t - \Phi \Delta a)}}$$

- It's simple to show this is equivalent to:

$$O_w = \frac{1 - \frac{C_2}{C_1} e^{i(\Omega \Delta a t - \Phi \Delta a)}}{1 + \frac{C_2}{C_1} e^{i(\Omega \Delta a t - \Phi \Delta a)}}$$

- This has the same form as the weak value in the two-state case and as such, the time average is the same:

$$\langle O_w \rangle_t = \mathrm{sgn}[1 - \frac{C_2^2}{C_1^2}]$$

# DETECTING QUICK OSCILLATIONS

- In the case that the initial state is mixed, the weak value becomes:

$$O_w = \frac{\int_{a-\Delta a}^{a} A^2(x)B^2(x)dx - \int_{a}^{a+\Delta a} A^2(x)B^2(x)dx}{\int_{a-\Delta a}^{a} A^2(x)B^2(x)dx + \int_{a}^{a+\Delta a} A^2(x)B^2(x)dx}$$

- After applying the postselection condition, the expression evaluates to:

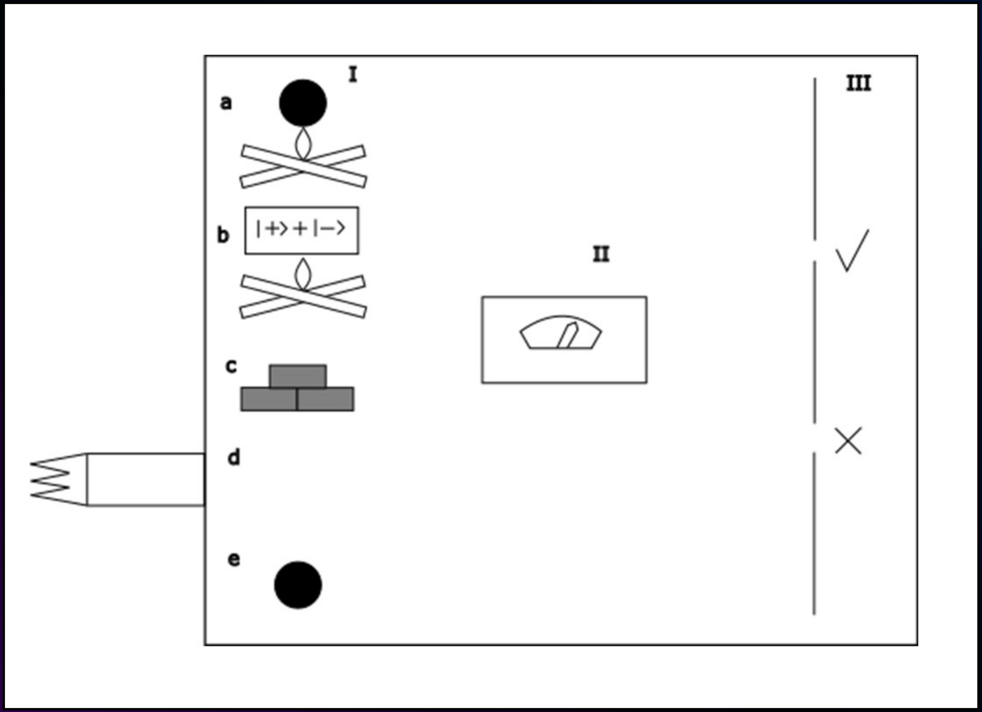
$$O_w = \frac{1 - \frac{C_2^2}{C_1^2}}{1 + \frac{C_2^2}{C_1^2}}$$

- As such, weak measurements can be used to test the nature of effectively mixed states even in the continuous case.

# POSSIBLE EXPERIMENTS

- We have explained how to preselect a system in a mixed quantum state: use different preselection criteria on different members of the ensemble
- This is not the approach we suggest in potential experiments
- We should not be preselecting the states ourselves. Instead, we introduce a source of states which should be mixed according to theory
- These can be experimentally feasible, like a radiating black body, a quantum state prepared long time ago likely to have faced decoherence, or electrons in some material
- We can also consider thought experiments involving Unruh radiation or Hawking radiation

# POSSIBLE EXPERIMENTS



# CONCLUDING REMARKS

- We do not claim that the quick oscillations exist, nor do we suggest that the quick oscillations occur at Planckian frequencies
- However, if mixed states are fundamentally pure states oscillating at Planckian frequencies, tabletop weak measurements would be able to observe the effect
- As such, we have shown that there exist possible Planck scale phenomena which are observable by weak measurements in postselected systems, while invisible under strong nonpostselected measurements

# CONCLUDING REMARKS

- It has been argued that weak measurements are equivalent to a set of nonpostselected strong measurements
- As such, weak measurements would contain no new information relative to nonpostselected measurements
- There are measurements which are impossible for all practical purposes
- A feasible weak measurement might be equivalent to a set of strong measurements on nonpostselected systems, but such that some of those equivalent measurements are not possible for all practical purposes
- Thus, in practice, weak measurements may lead to new information

# CONCLUDING REMARKS

- The question if states are fundamentally mixed, or they are pure but with relative phases quickly oscillating is not metaphysical
- This is relevant for considerations of the black hole information paradox
- We suggest there is merit in further, more rigorous study of weak measurements in the framework of Quantum Field Theory, as other applications of weak measurements could be found
- A possible extension of presented work would be to study if weak measurements can be used to test different models of objective quantum collapse which depend on stochastic perturbations.

# THANK YOU
# FOR YOUR ATTENTION