

Title: A proposed Test of the Local Casuality of Spacetime

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Abstract: A theory governing the metric and matter fields in spacetime is {\it locally causal} if the probability distribution for the fields in any region is determined solely by physical data in its past, i.e. it is independent of events at space-like separated points. This is the case according to general relativity, and it is natural to hypothesise that it should also hold true in any theory in which the fundamental description of space-time is classical and geometric --- for instance, some hypothetical theory which stochastically couples a classical spacetime geometry to a quantum field theory of matter. On the other hand, a quantum theory of gravity should allow the creation of spacetimes which macroscopically violate local causality.

I describe a feasible experiment to test the local causality of spacetime, and hence to test whether gravity is better described, in this respect, by general relativity or by quantum theory. The experiment will either identify a definite limit to the domain of validity of quantum theory or else produce significant evidence for the hypothesis that gravity is described by a quantum theory.

causality of spacetime  
A. Kent

(Centre for Quantum Computation,  
DAMTP, University of Cambridge)

talk @ Shimony-fest @ PI

1015.21.07.2006

I want to argue that it's both meaningful and interesting, theoretically, to ask whether the gravitational field is locally causal (using a definition generalising Bell's). I also want to discuss experimental tests, including a beautiful recent proposal of Eisin et al., that can address and <sup>eventually?</sup> definitively resolve the question.

(A.K. quant-ph/0507045; also 0204104)

Issues of the local causality of spacetime

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## Some working assumptions

① We just don't understand how to unify quantum theory and gravity; we don't even know whether any of the currently fashionable programmes are on the right track. That doesn't stop us from having strong hunches about how things must work, but it makes it important to verify them if there's room for a sliver of doubt.

② The measurement problem makes it reasonable to suppose that quantum theory is augmented by some mathematical account of "localised beables" or "real events" — possibly associated with localised collapses of the wave function.

③ At least at mesoscopic scales, gravity is described by a spacetime metric  $g_{\mu\nu}$ , whose geodesics determine trajectories for test masses. Moreover, the metric is a real quantity, in the sense of ② above: either it is a fundamental beable or it's effectively determined by them.

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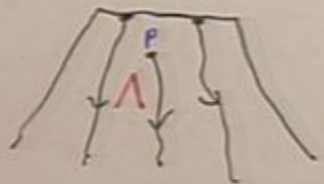
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## Local usability for Spacetime Metrics

(This is a modified version of a definition suggested to me by Fay Dowker, to whom many thanks.)

Preliminaries: ① A past region in spacetime is a region containing its own causal past:



all timelike geodesics to the past of points  $p$  in  $\Lambda$  lie in  $\Lambda$ .

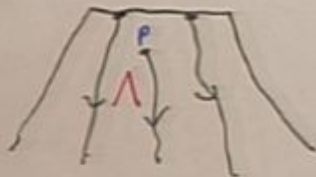
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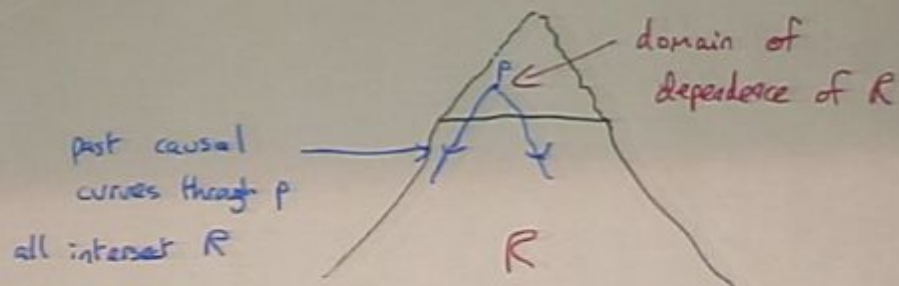
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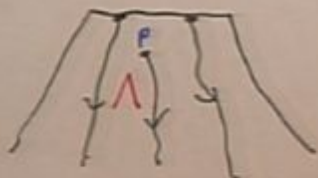
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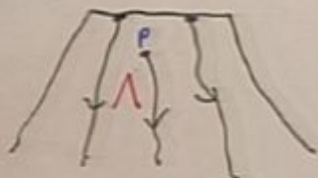
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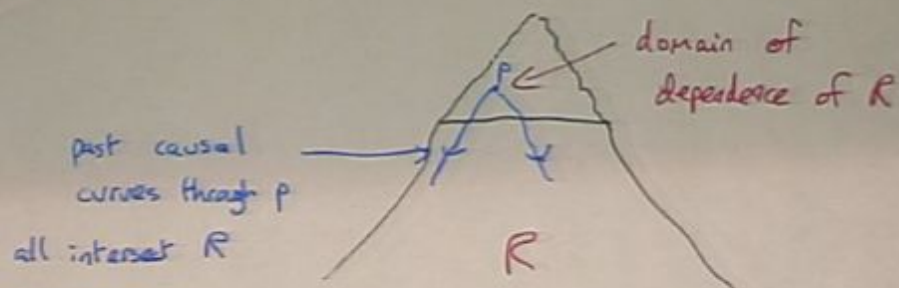
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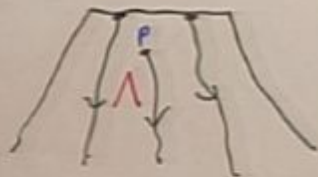




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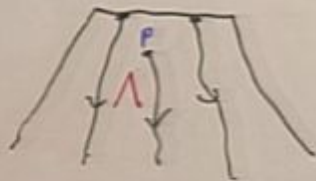
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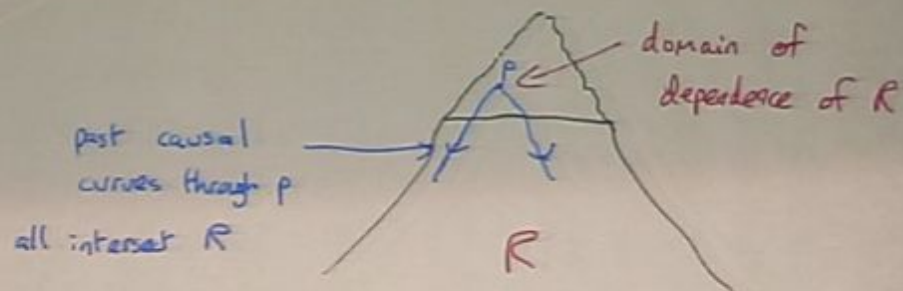
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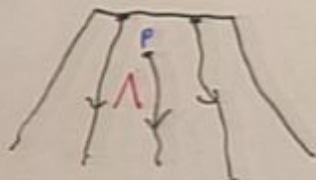
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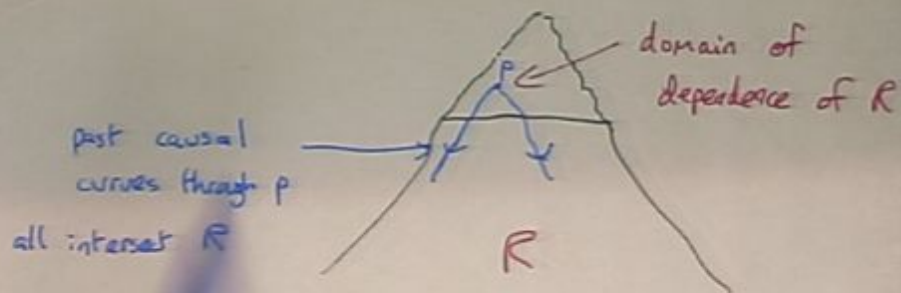
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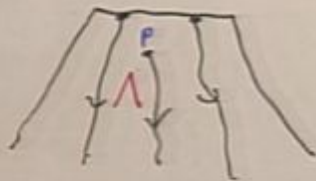
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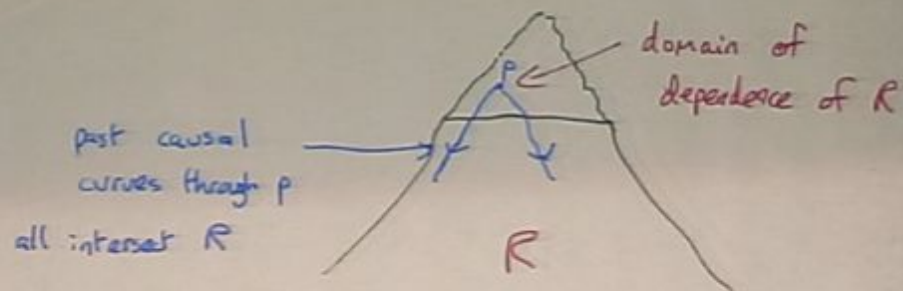
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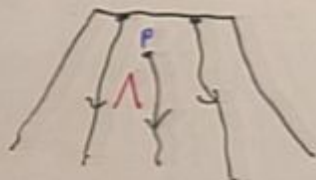
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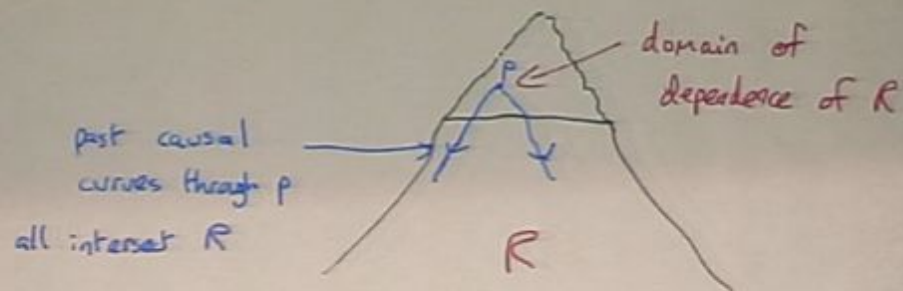
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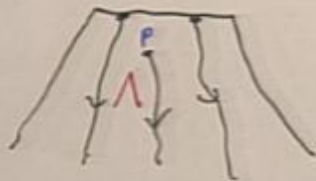
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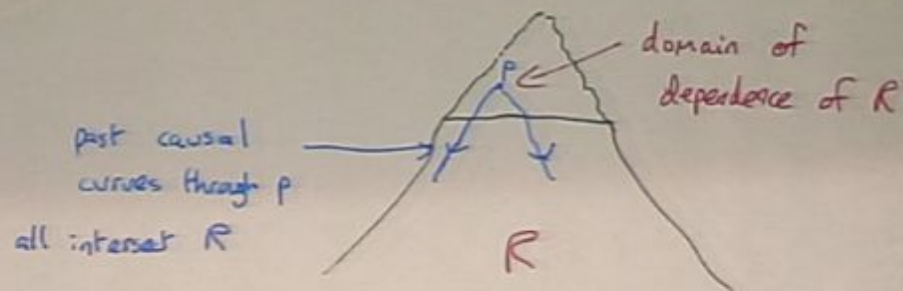
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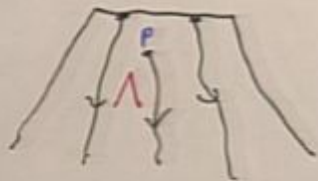
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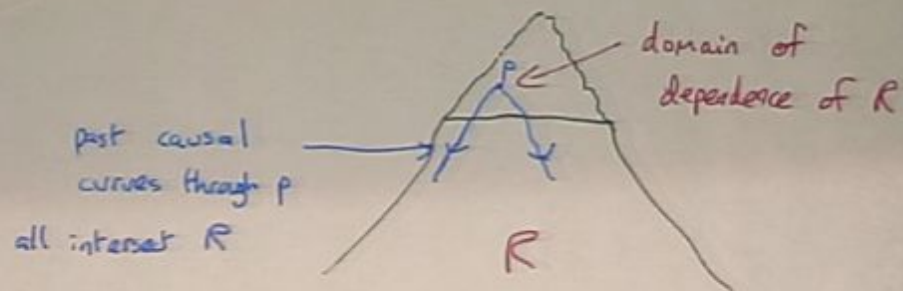
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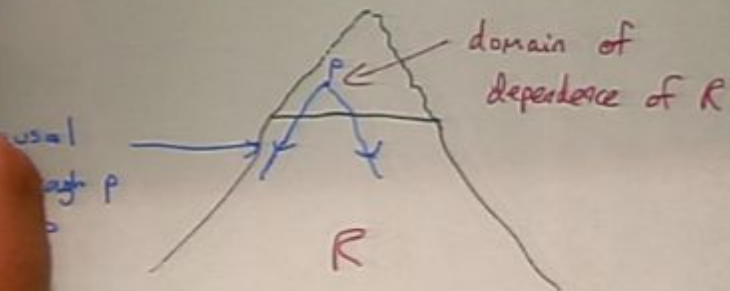
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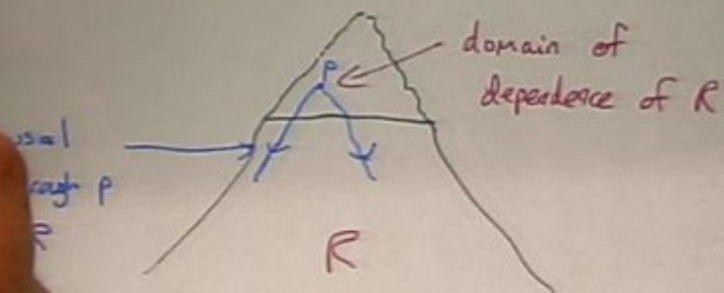
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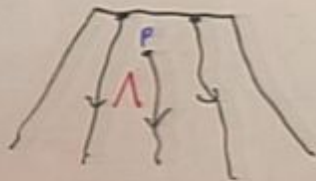
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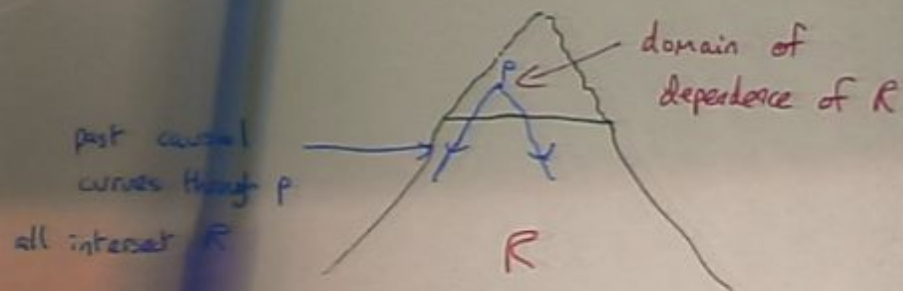
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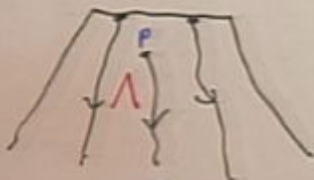
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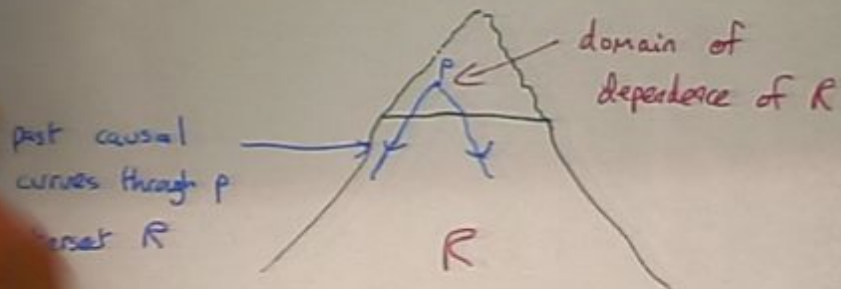
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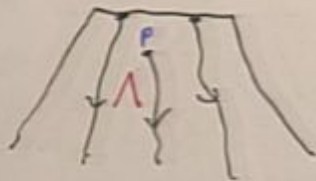
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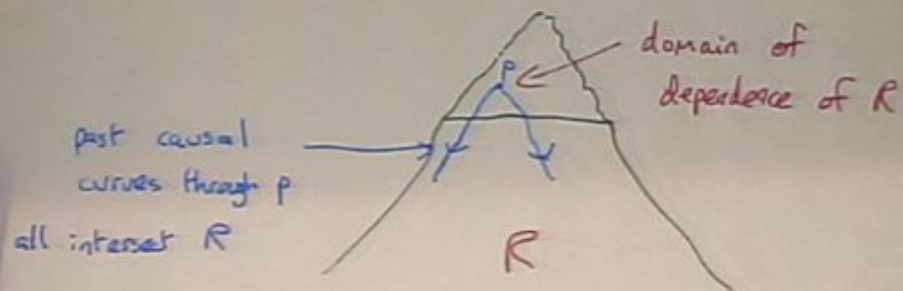
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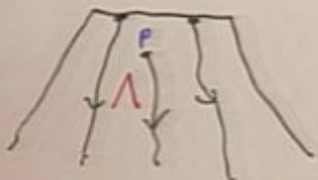
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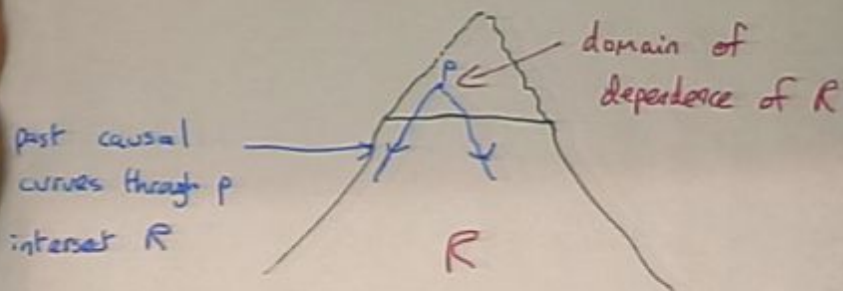
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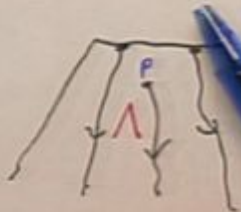
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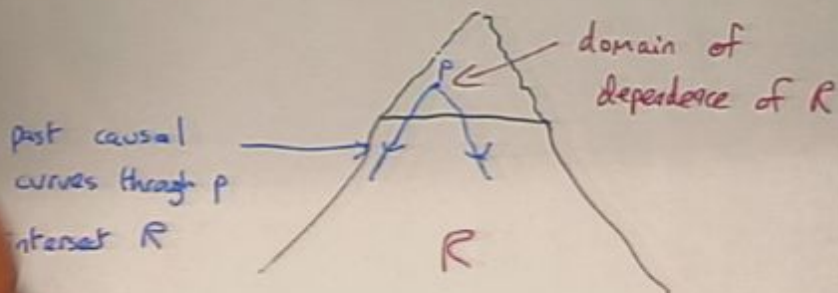
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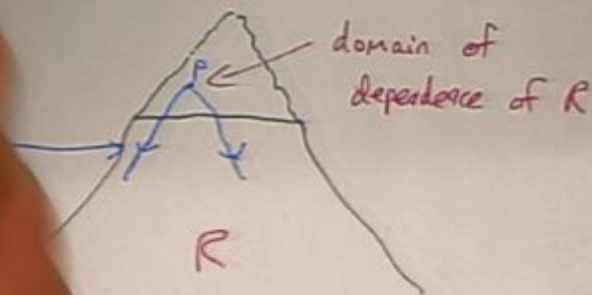
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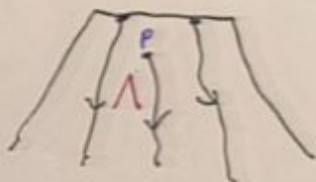
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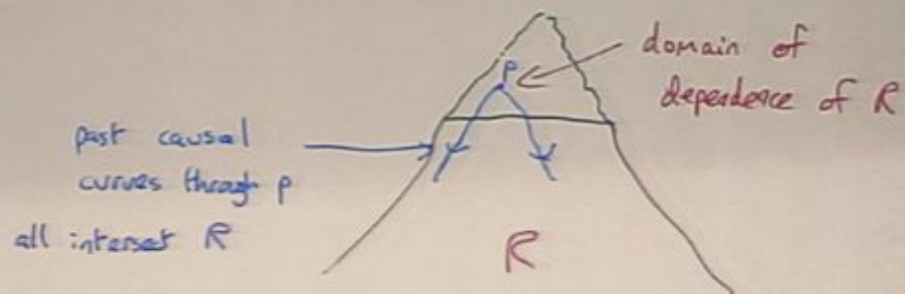
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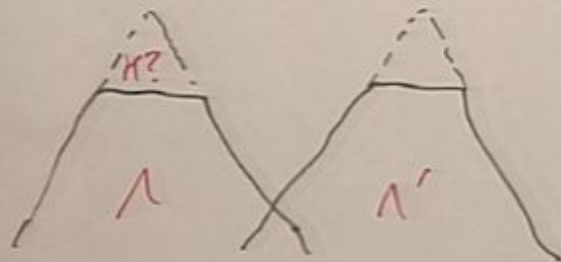


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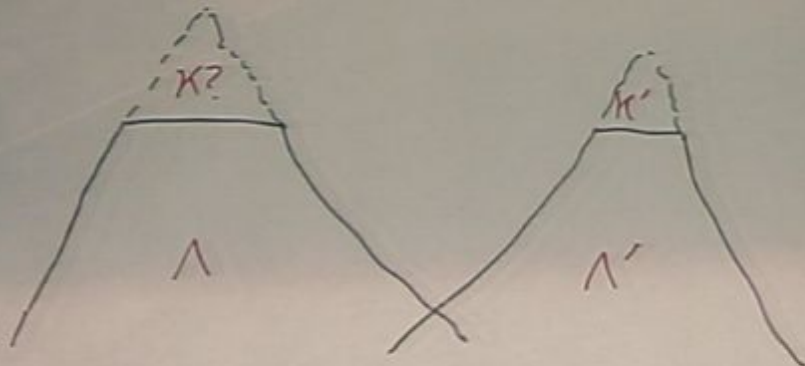
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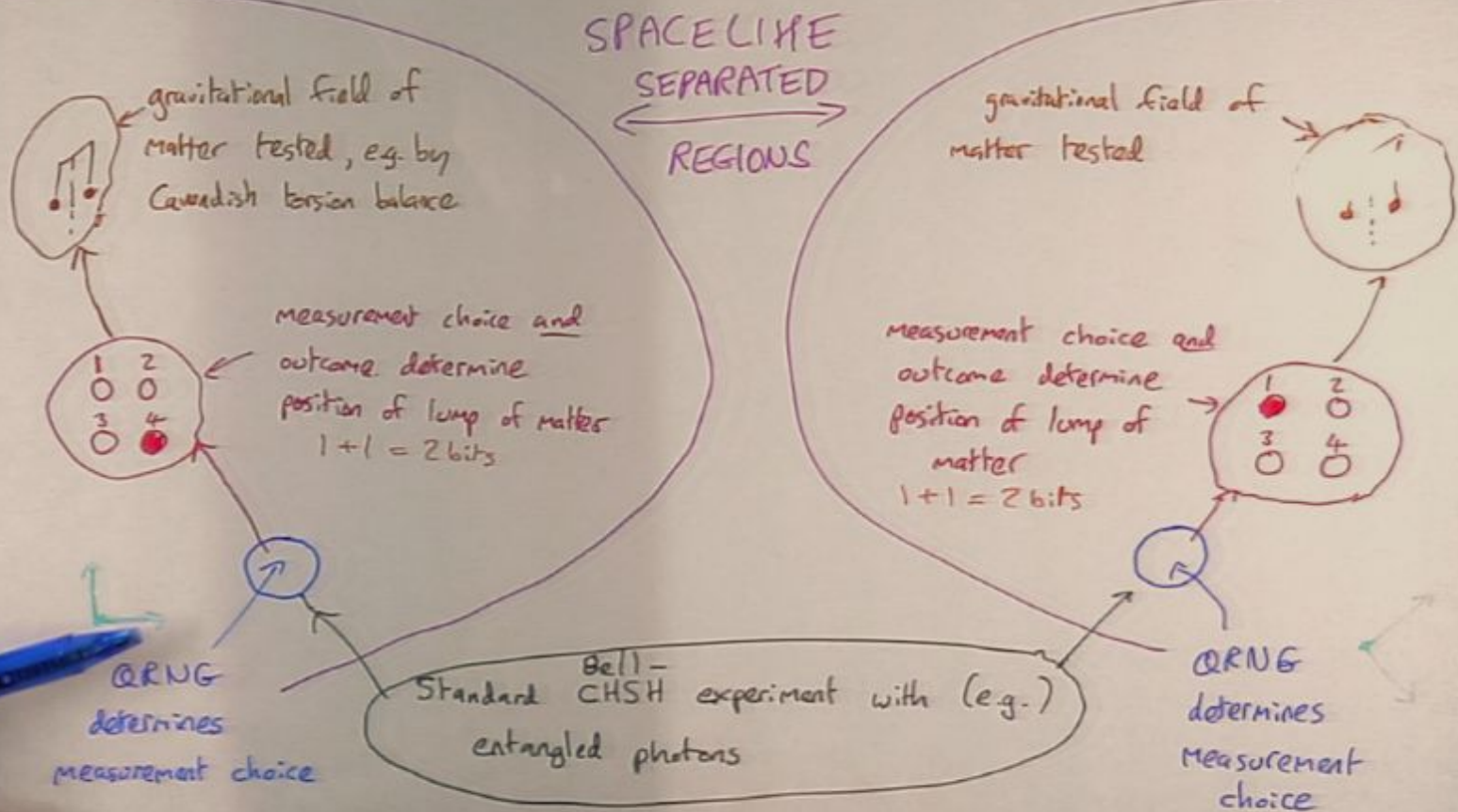


Define  $\text{Prob}(K | \Lambda \perp \Lambda'; K')$  to be the probability that the domain of dependence of  $\Lambda$  will be isometric to  $K$ , given the above and given that the domain of dependence of  $\Lambda'$  is isometric to  $K'$ :

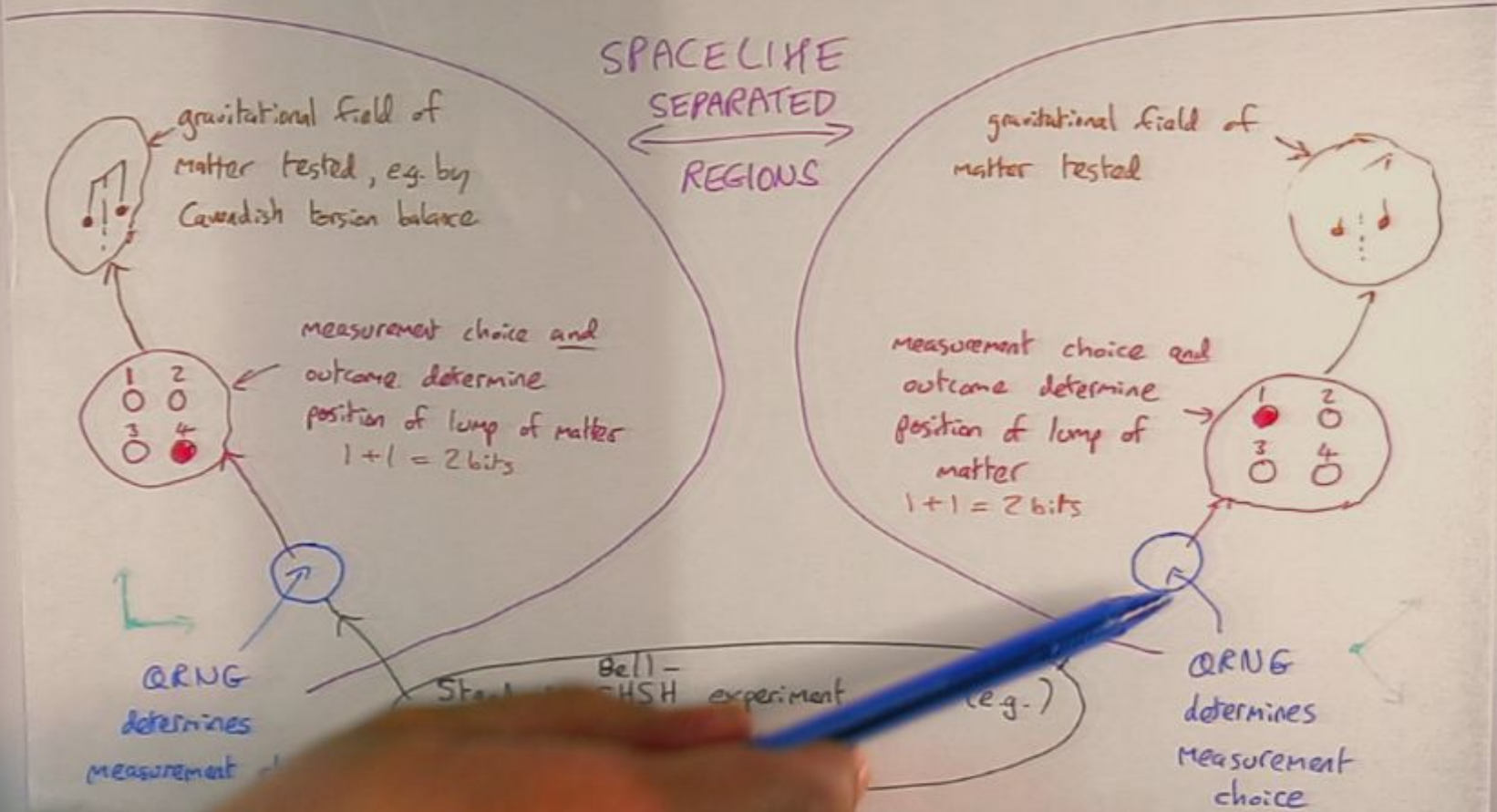


A stochastic metric theory is locally causal if these

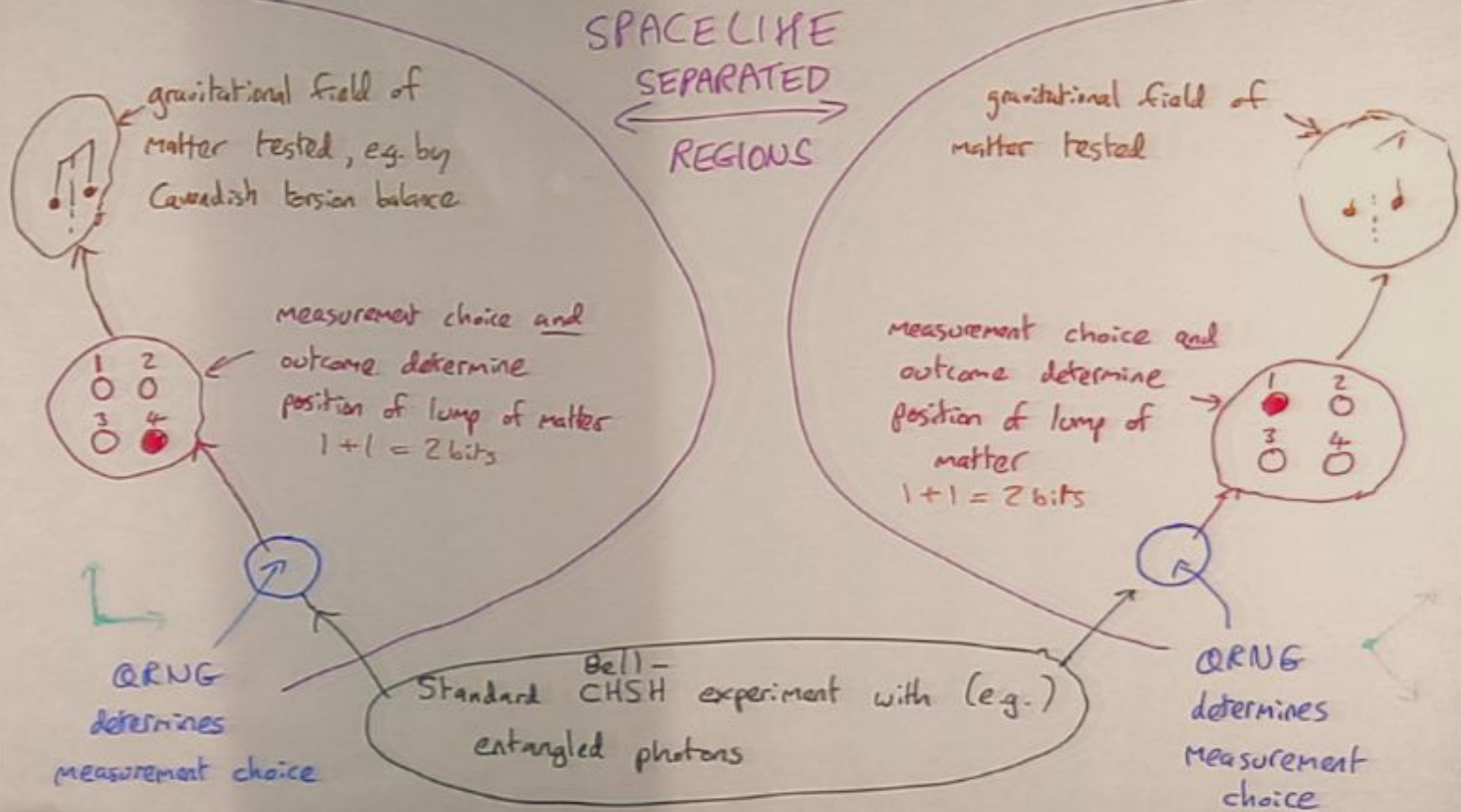
Testing the local causality of spacetime: ideal experiment



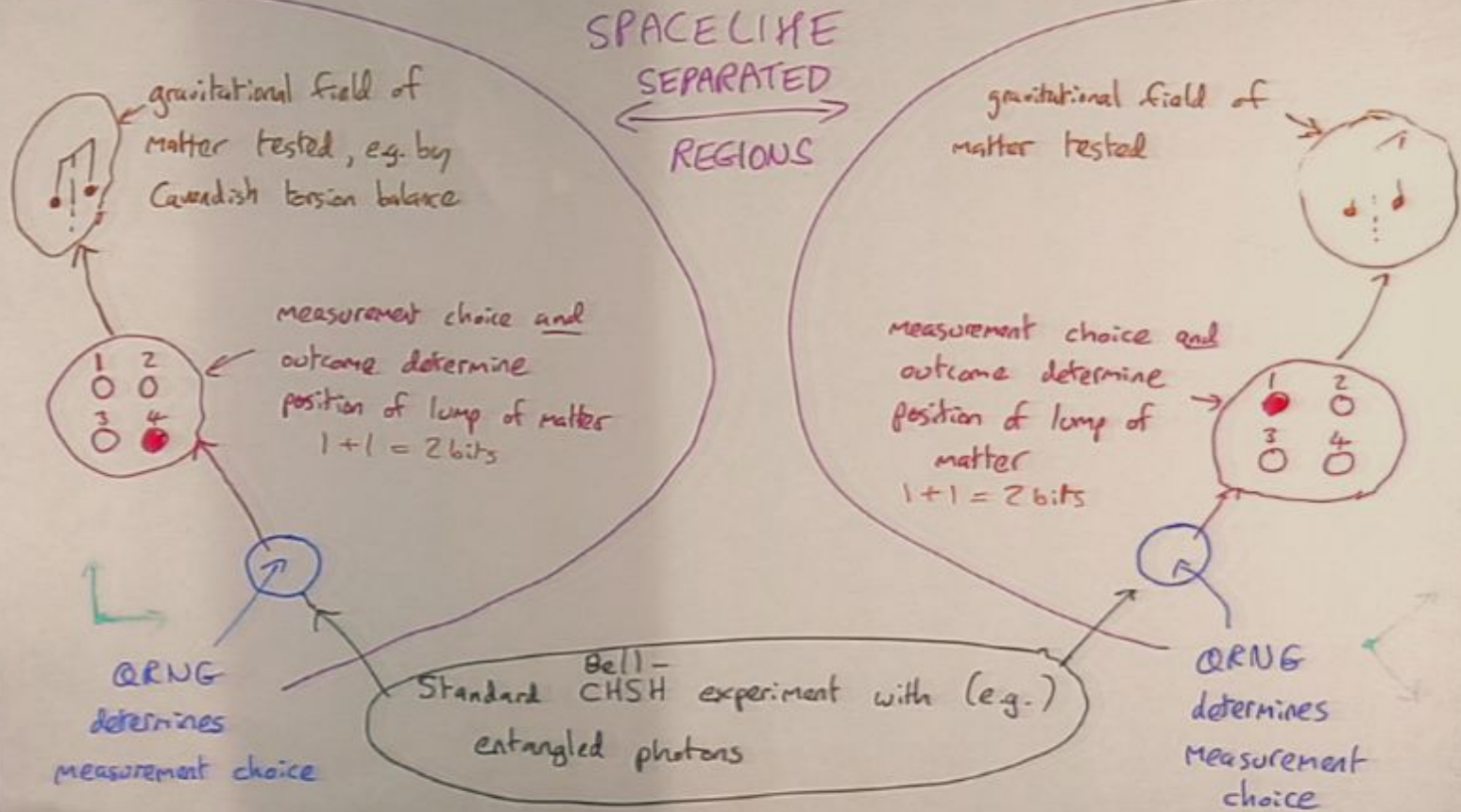
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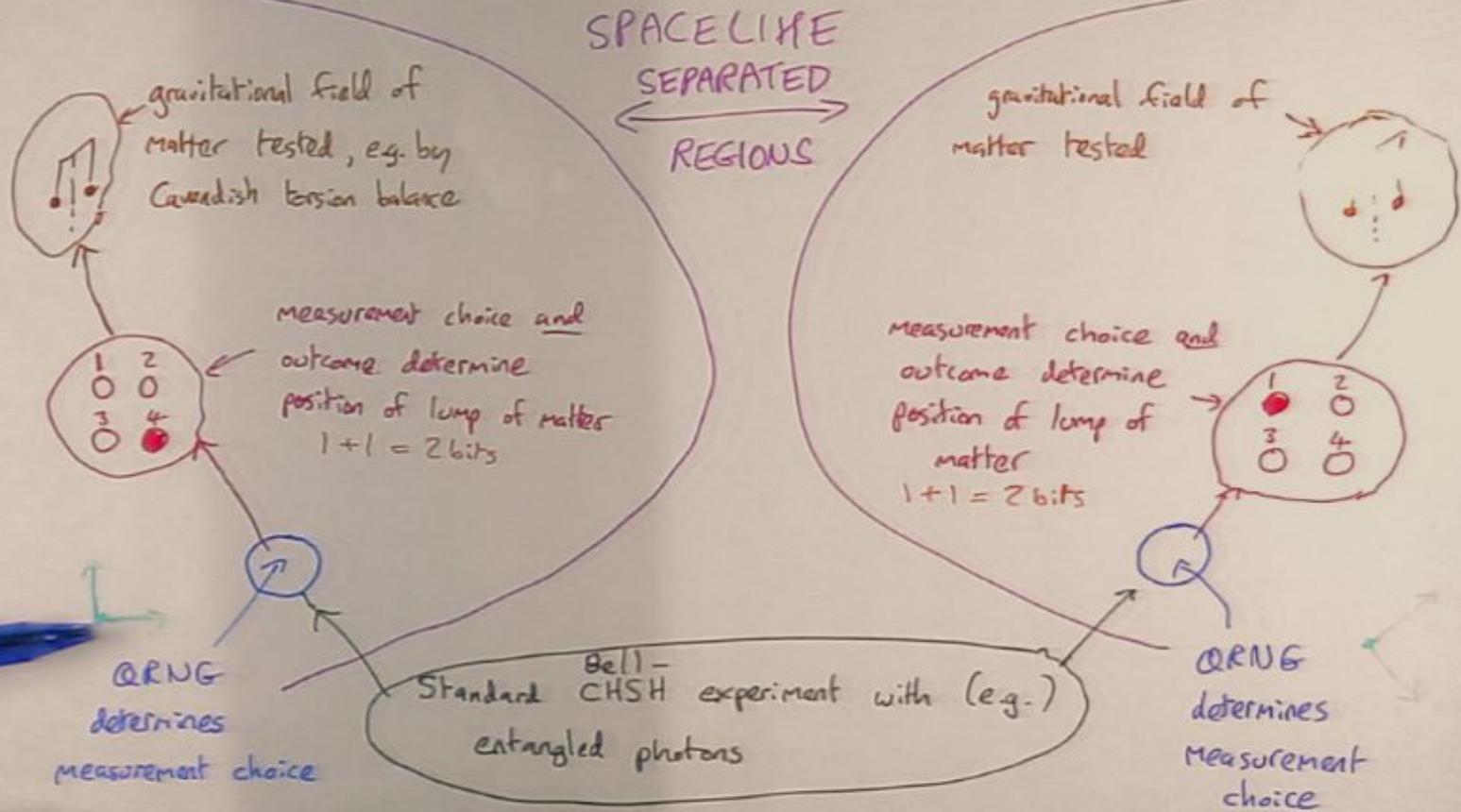


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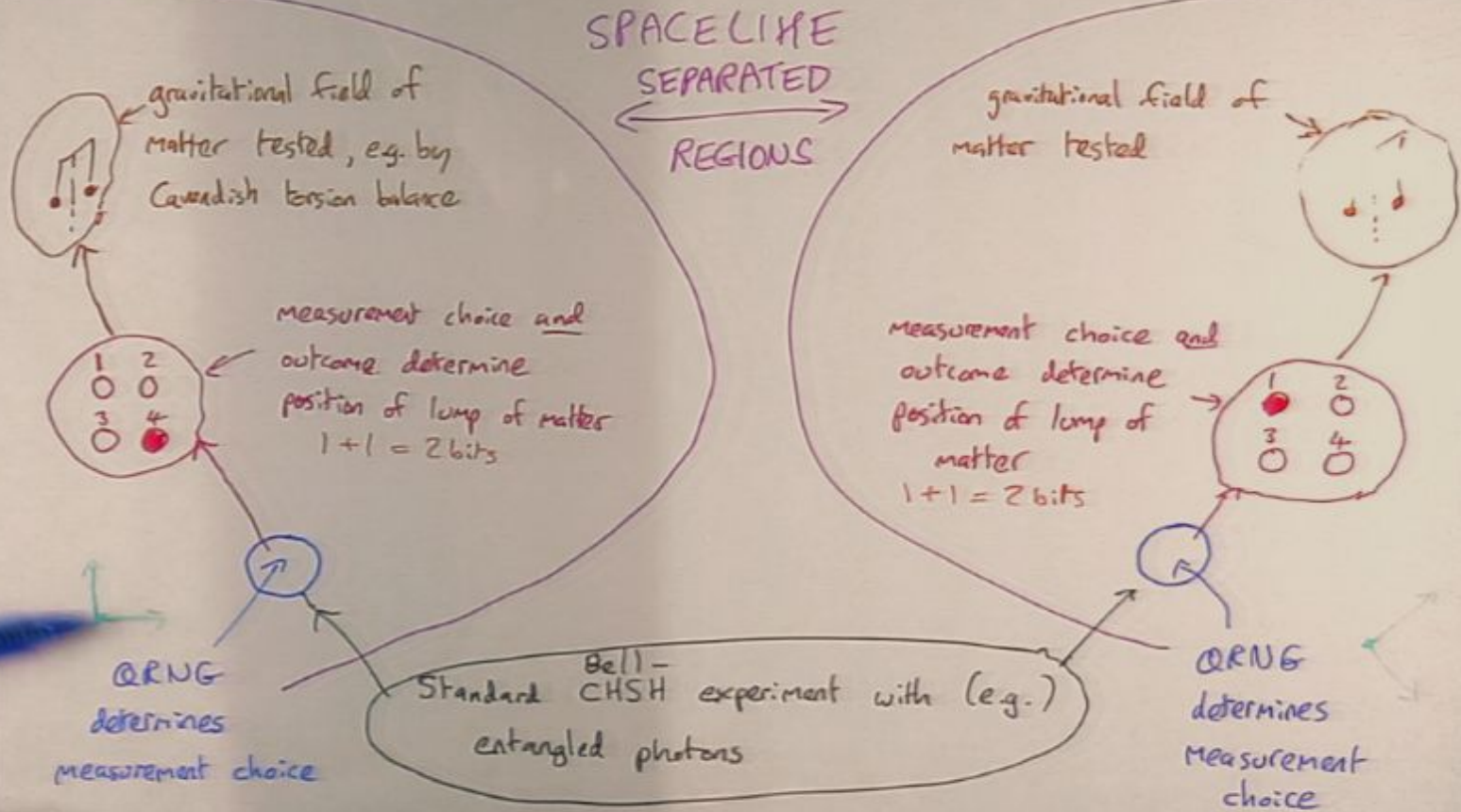




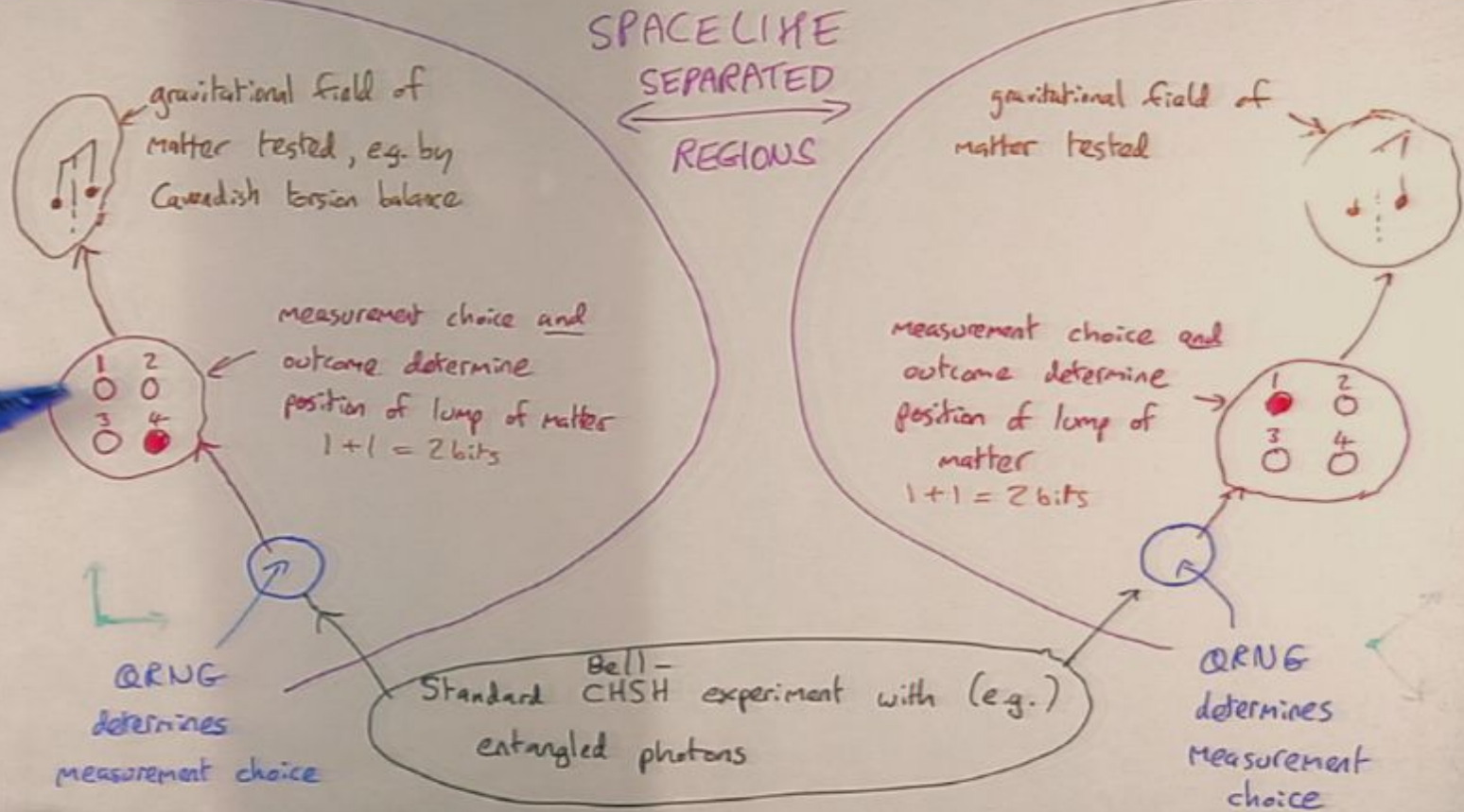
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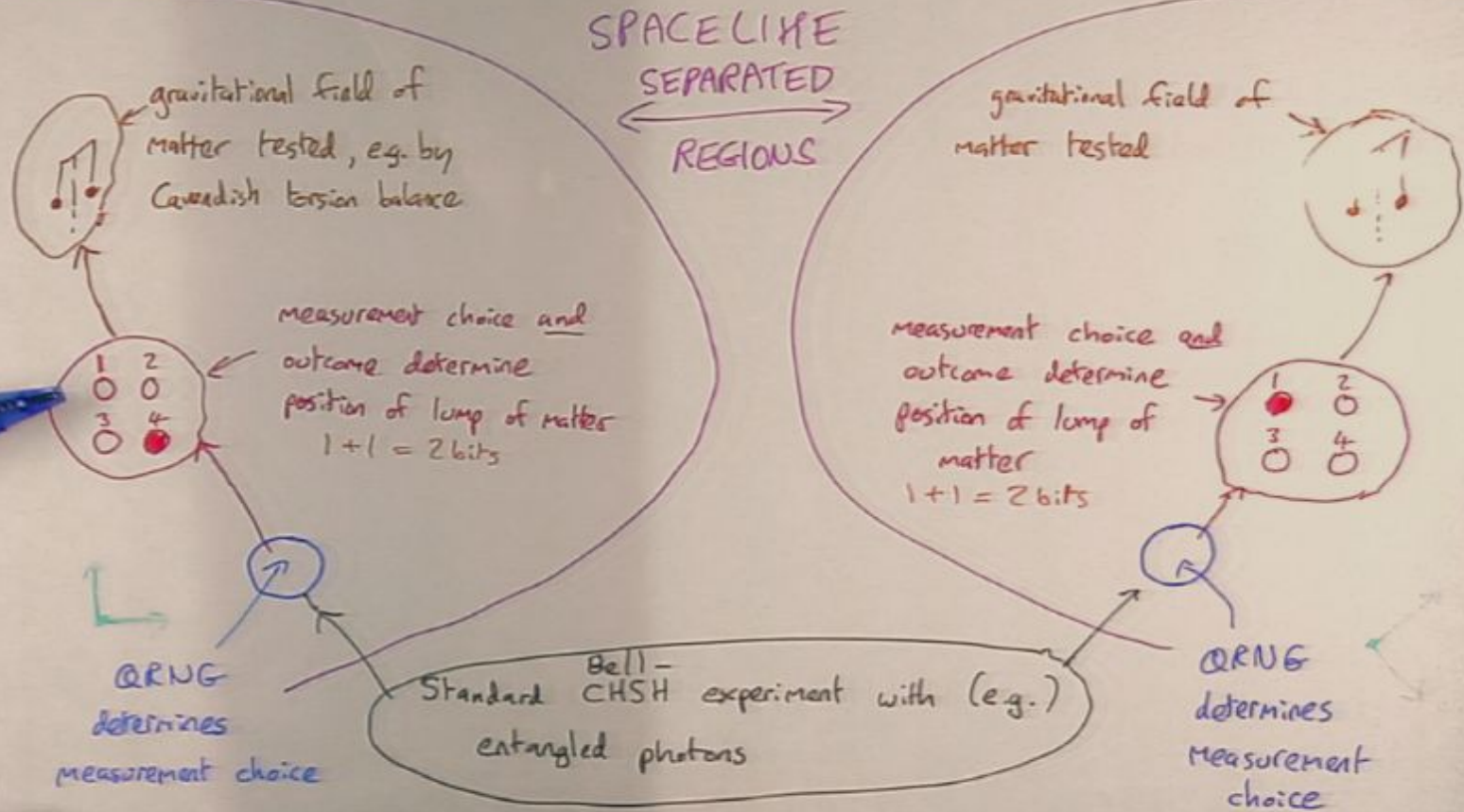
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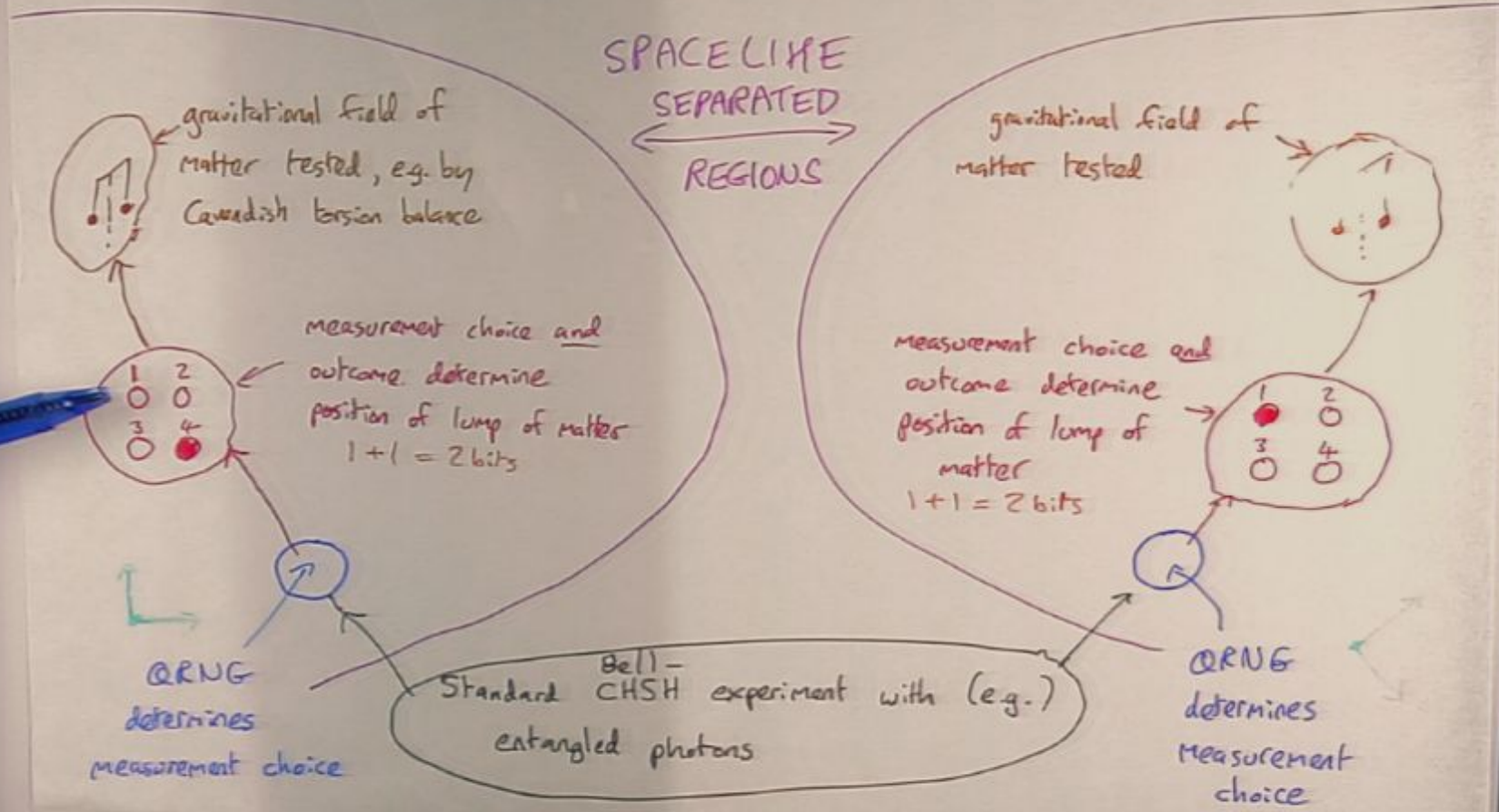
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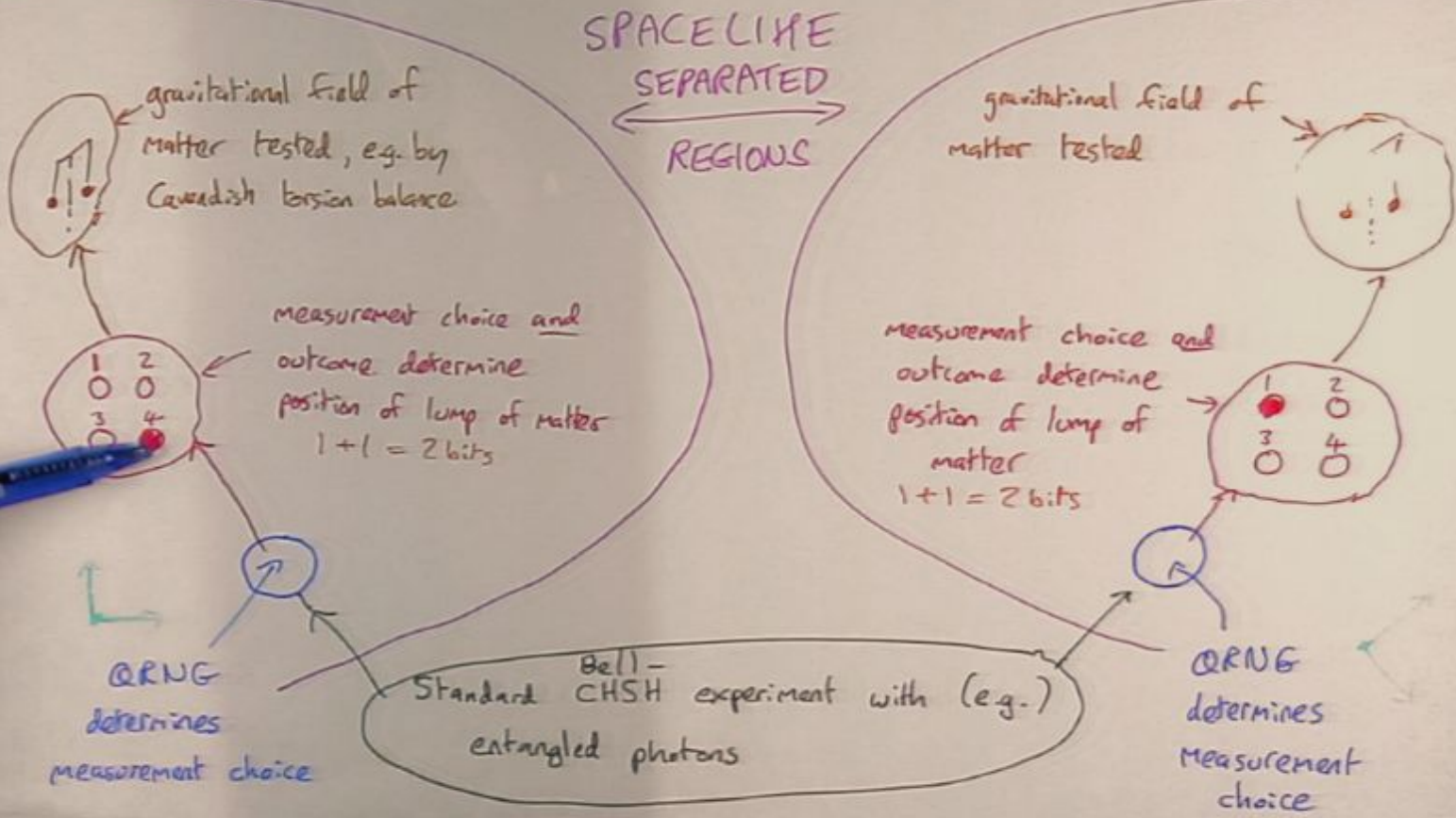
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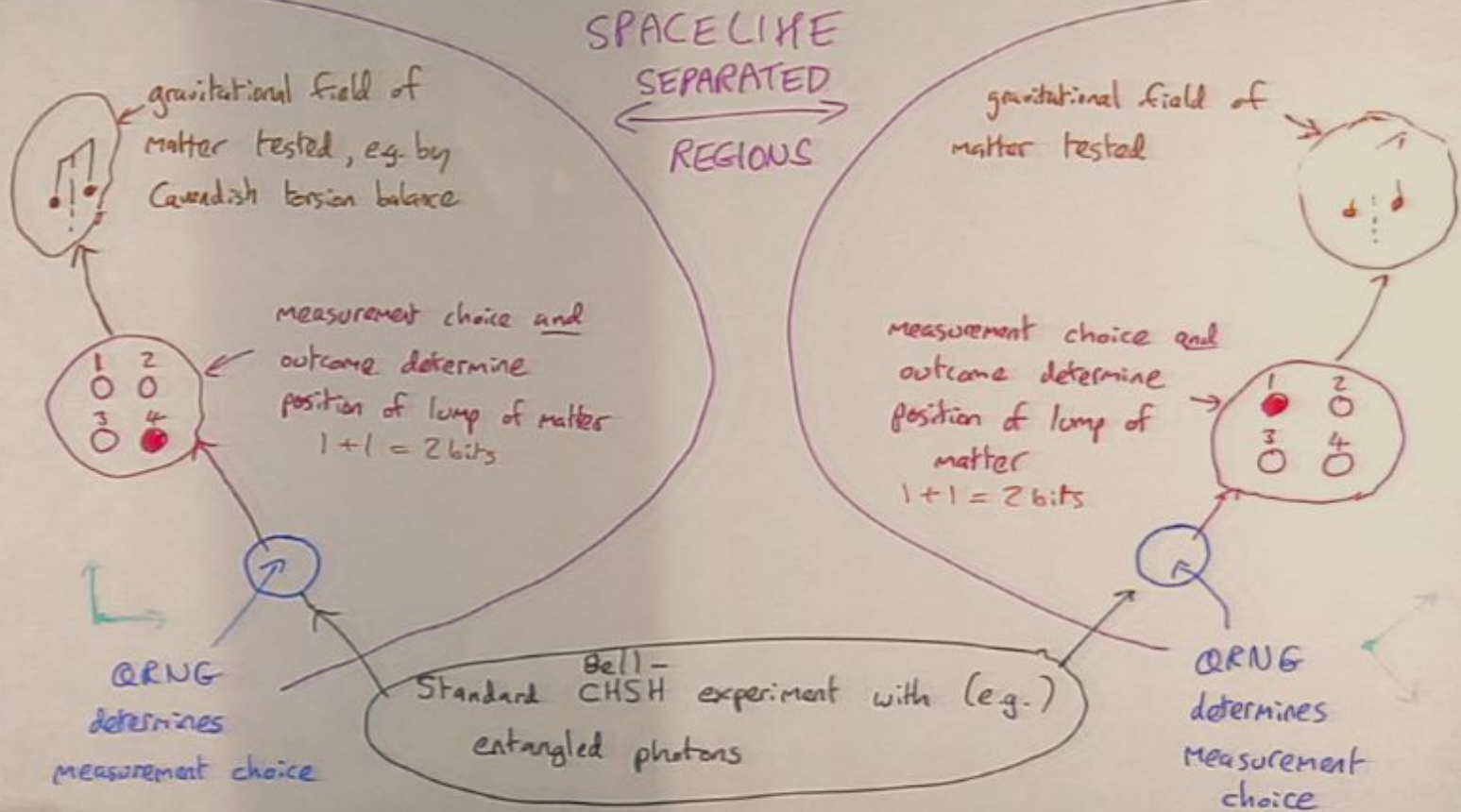
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Testing the local causality of spacetime: ideal experiment



What would happen in the ideal experiment?

Standard intuition (I think): The Bell-CHSH experiment produces nonlocal relations. These are faithfully translated to the distributions of matter lumps on each wing, and hence to the corresponding measured gravitational fields.

IF SD, we have direct experimental evidence for the gravitational field violating local causality (contradicting the geometric intuition inspired by general relativity).

A logically possible alternative: When we couple a Bell-CHSH experiment to gravitational fields as described, we find that the nonlocal correlations predicted by q.m. are NOT observed.

IF SD - obviously it would be a huge surprise - we would have evidence that the gravitational field respects local causality, in accord with general relativistic intuition but in dramatic contradiction with quantum theory.

(There are even stranger logical possibilities - for example the matter lumps' positions could be nonlocally correlated but the associated gravitational fields could not be: this would mean violating Newtonian gravity until a signal could reach from one wing to the other. But I'll neglect these here.)



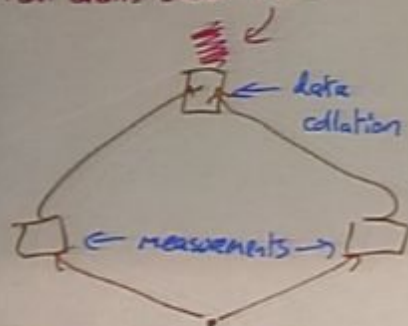
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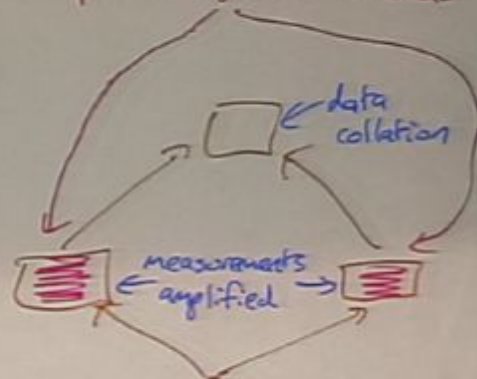
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earliest relevant  
real events occur here



APPARENT BUT FAUX  
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spacelike separated real events



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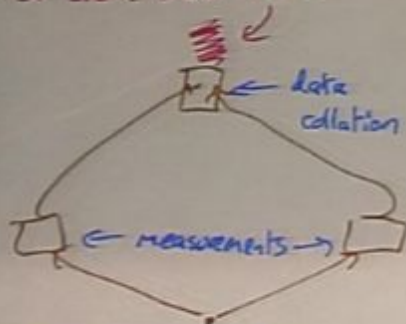
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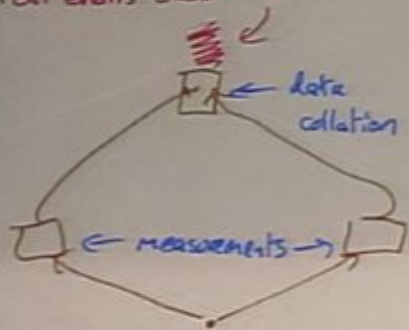
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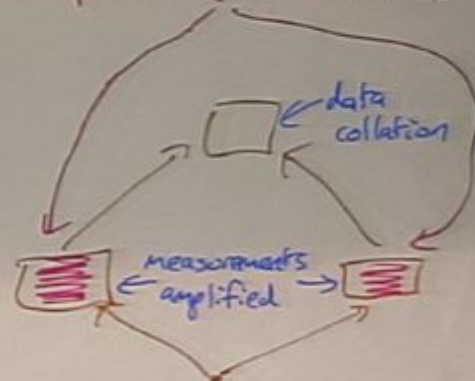
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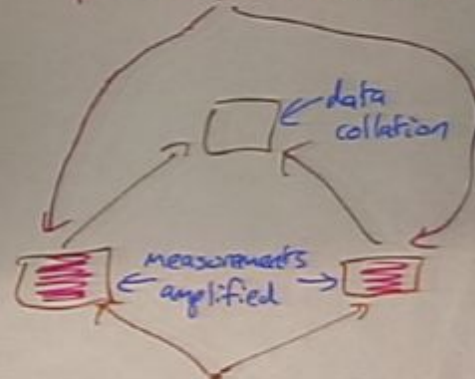
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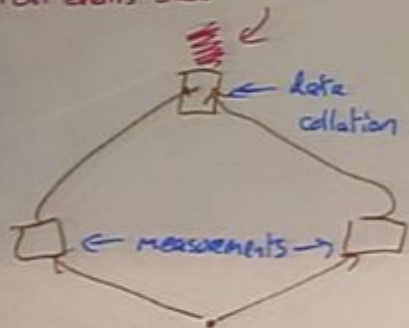
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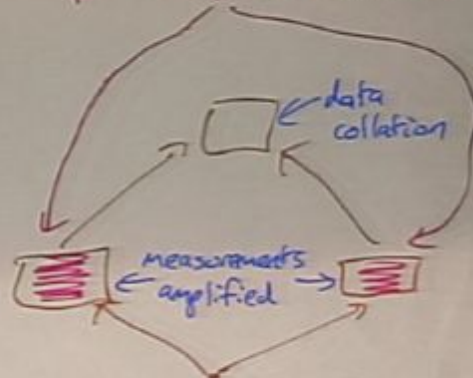
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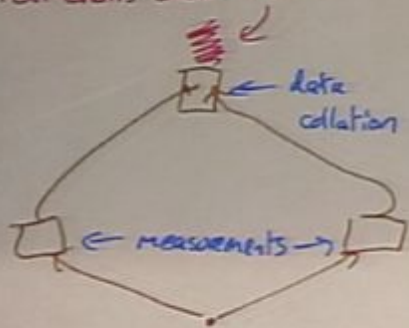
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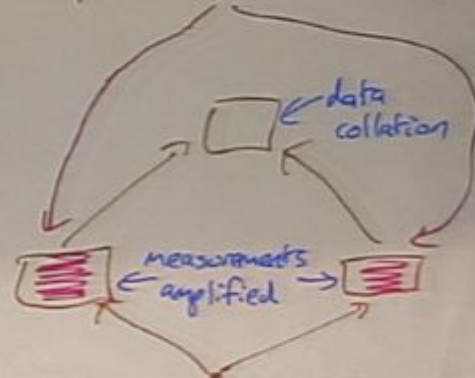
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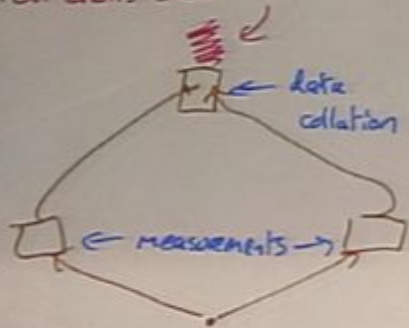
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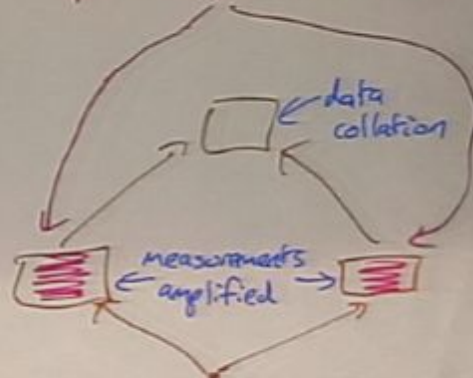
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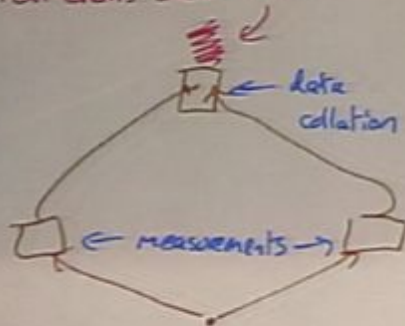
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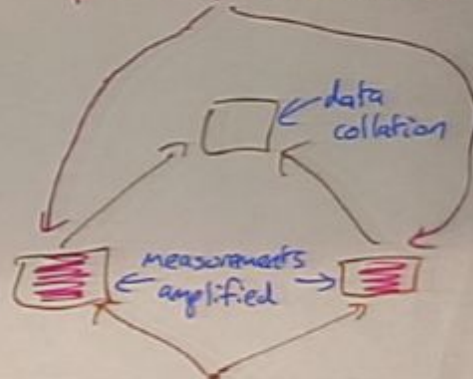
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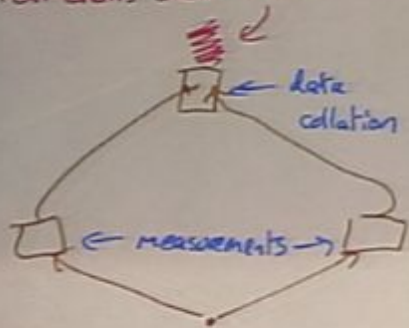


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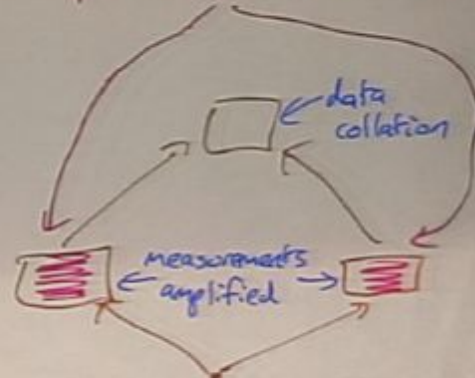
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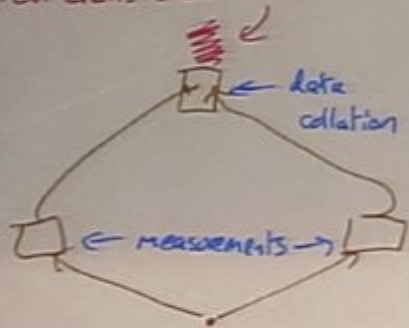
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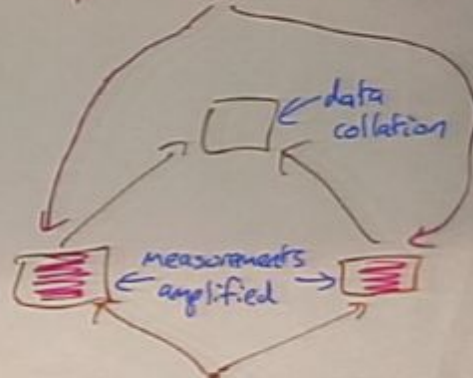
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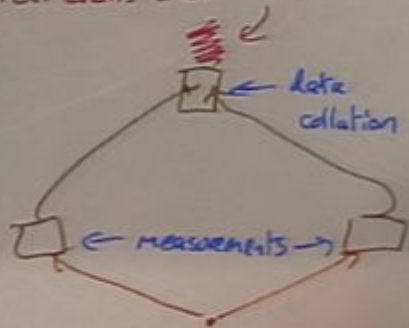
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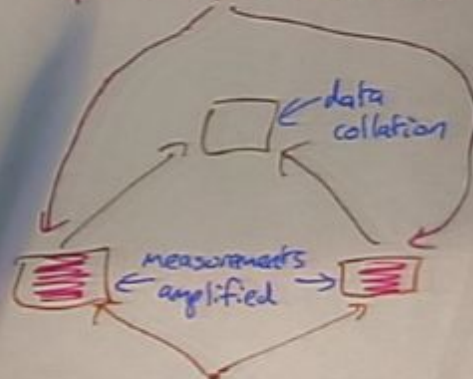
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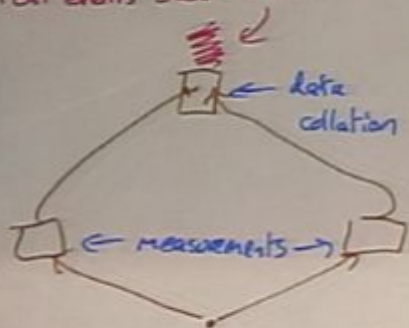
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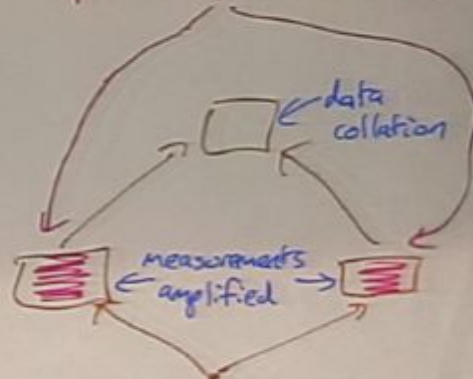
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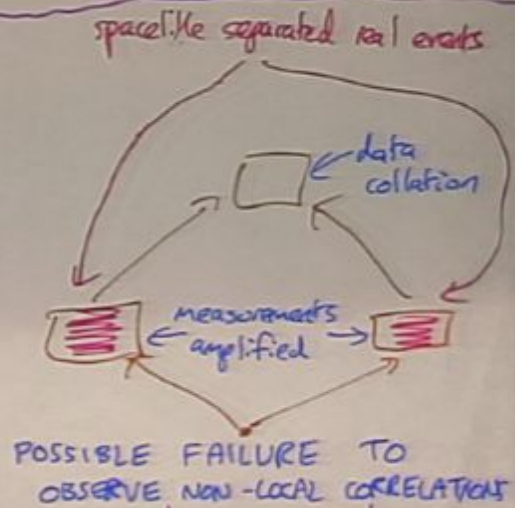
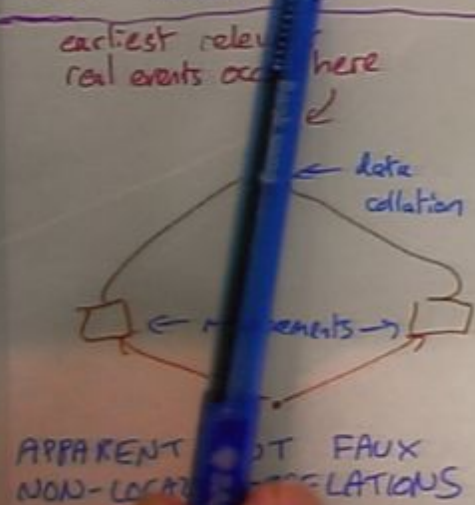


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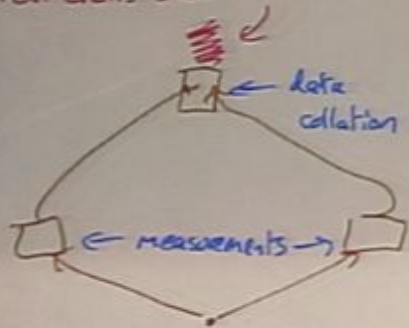


## Is the experiment worth doing?

"Logically possible" doesn't really cut much ice as a motivation: lots of silly hypotheses are logically possible. What, if anything, makes this proposal better motivated? I would offer two reasons (but maybe there are others).

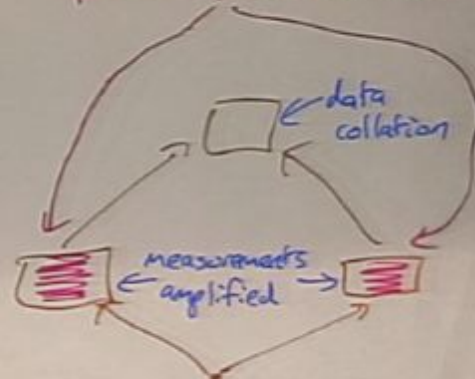
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earliest relevant  
real events occur here



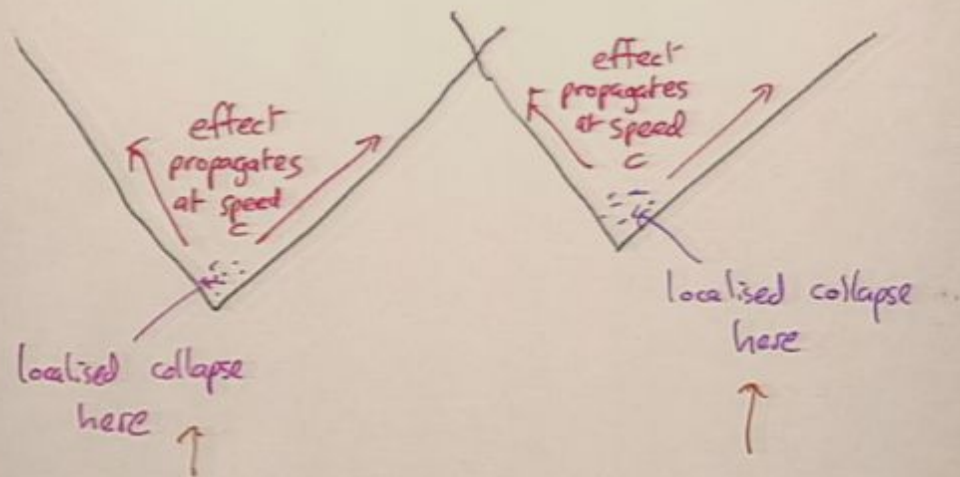
APPARENT BUT FAUX  
NON-LOCAL CORRELATIONS

spacelike separated real events



POSSIBLE FAILURE TO  
OBSERVE NON-LOCAL CORRELATIONS

Possibility (2) : the "collapse locality loophole" in Bell experiments to date



Spacelike separated collapse events (e.g. suitably amplified measurements) do not influence one another and  $\therefore$  do not display non-local correlations

Assuming some model of localised collapse, can define a consistent (if weird) alternative to standard quantum theory which has this property and which agrees with quantum theory for Bell experiments in which the collapses are not spacelike separated.

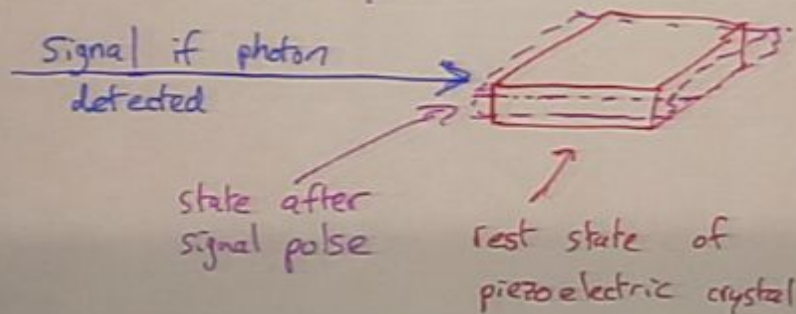
(cf A.H. Phys. Rev A 72 012107 (2005))  
(q-ph/0204104)

Is (some interesting version of) the experiment feasible?

The ideal version may be difficult: even a 100nm separation in the "all" experiment allows only  $3 \times 10^{-6}$  sec to create and measure macroscopically distinct gravitational fields.

However, Gisin et al. have a beautiful idea for a simpler version, which quickly creates (but doesn't directly measure) distinct gravitational fields

(ON EACH WING)



..... corresponding to two possible states of a piezoelectric crystal.

This hopefully should allow tests of the essential idea, for at least some plausible intuitions about gravity-related collapse.



## Summary

- \* There is a  $\mathbb{R}$ -defined notion of local causality for metric space-time theories, extending Bell's definition for theories of events in Minkowski space.
- \* In principle it is an open question whether gravity is described by a locally causal theory or not (though the standard intuition suggests not). And there is at least a sliver of motivation for considering the possibility that gravity is locally causal.
- \* The question can be resolved by experiment, and some interesting (if not definitive) experiments in this direction appear presently feasible.