Beable-guided quantum theories and other generalisations of quantum theory

Adrian Kent

Centre for Quantum Information and Foundations, DAMTP,
University of Cambridge

and

Perimeter Institute for Theoretical Physics

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"Beyond Boundary Conditions: General Cosmological theories "
(A.K. in Proceedings of COSMO97 (1997), arxiv: 0905.0632)

"Beable-Guided Quantum Theories: Generalising Quantum Probability Laws"
(A.K., Phys Rev A 87 022105 (2013))

Some motivations for intrinsic decoherence models and other generalisations of quantum theory:

1. A combination of theoretical curiosity and the desire to test quantum theory as well as possible (and prove Weinberg wrong in as many ways as possible)

"[I]t is very difficult to find any logically consistent generalization of quantum mechanics."
(Steven Weinberg, in Testing Quantum Mechanics, Annals of Physics (1989))

2. The incompatibility of quantum theory and general relativity and a hunch that neither is completely correct and (to some degree) quantum theory needs to be

3. Belief that the quantum reality problem -- or, if you prefer, our inability to explain the appearance of a quasiclassical world from within quantum theory -- implies that even non-relativistic quantum theory is necessarily either incomplete or not completely correct.

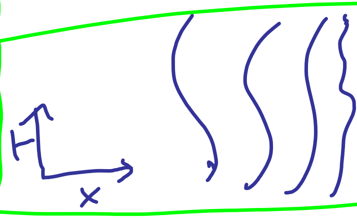
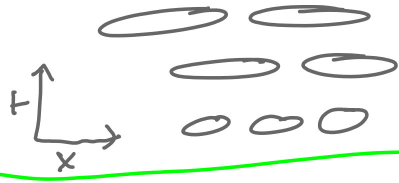
Beables for Quantum Theory

Those (like me) who take the third motivation very seriously are interested in models or theories that say, in a mathematically precise way, what quantum probabilities are probabilities **of** -- i.e. in what John Bell called **beable theories**.

Beable theories give a precise mathematical definition of (i) a sample space (defining possible configurations in space and time of the "beables" -- which could be trajectories or pointlike events or spatially and temporally extended histories or configurations of some auxiliary field or something else) and (ii) a probability distribution on that sample space.

On this view, given the initial conditions and Hamiltonian, quantum theory tells us the possible configurations of beables and their probabilities. Reality is described by one randomly chosen beable configuration from this distribution. The quasiclassical world we experience is described in terms of the beables, and the part-deterministic part-probabilistic laws it
follows must be derivable from the beable probability distribution.

Examples of beable theories

Theory	(Possible choice of) Beables	
De Broglie-Bohm theory Valentini's generalised deB-B	Particle trajectories Particle trajectories	
Consistent histories with some (alas undiscovered) quasiclassical set selection rule	Histories of events from the selected quasiclassical set	
Discrete GRW collapse model	Space and time coordinates of the collapses	

Double Ontologies and Veiled Ontologies -- Worries for Friends of the Beable

"Pay no attention to that man behind the curtain"
(from *The Wizard of Oz*, quoted by Dowker and Henson, J Stat Phys 115 (2004), re the role of the wave function in the Bell collapse model ontology)

"Inert, uninfluential, a simple passenger in the voyage of life, it is allowed to remain on board, but not to touch the helm or handle the rigging."
(from *Are We Automata?* (1879) -- but William James would have said this of beables in an alternate chronology.)

"Pilot wave theories are parallel-universe theories in a state of chronic denial."
(David Deutsch, from *Comment on Lockwood* (1996))

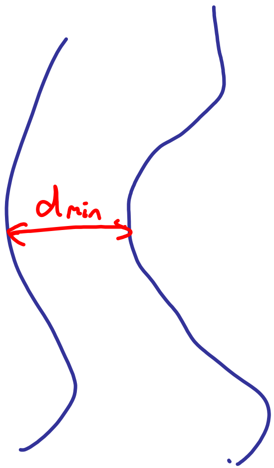
Beable-Guided Quantum Theories

A standard version of quantum theory with beables is defined by:
* a theory T of the quantum initial state ψ_0 and Hamiltonian H.
* a set B of possible beable configurations
* a probability measure $\mu_T(B)$ defined (using a relatively simple algorithm) by T on the set B.

There is no logical constraint that requires the probability measure on B to be given by simple rules from ψ_0 and H alone. We can perfectly consistently define theories in which the measure also depends directly on the beable configurations.
For example (although even this is not the most general possibility) we could allow probability distributions on B of the form $c\,\mu_T(B)\,w(B)$, where w is a weight function on the beable configurations.

Although this is a simple point, if you take it seriously it radically changes your view of the range of possible generalizations of quantum theory, and indeed on what could count as a theoretical explanation of observed data.

Simple examples



Just to illustrate: a non-relativistic de Broglie-Bohm model of two particles could be modified by a weight function $w(B) = \exp(-(d_{min}/a))^2$

This enhances the probability of pairs of trajectories that come close to one another at some point in time, and suppresses those that always stay distant.

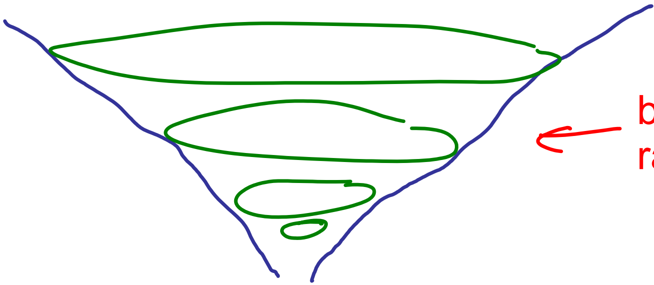
You can play similar games with collapse centres in GRW models, or any other beable theory that interests you.

In principle any weight function that produces a normalisable probability distribution could be used. Lorentz or generally covariant theories require Lorentz or generally covariant weight functions -- but it is not hard to find many possible examples (some might say too many!).

Possibly more physically interesting applications...

...arise if one thinks of larger-scale quasiclassical properties or features of the space-time manifold as determined by the beables, and considers the scope for effective

For example, assuming a quantum theory of gravity, one could -- if one wished -- imagine a weight function that ensures that the universe attains any given sizes, or has any given degrees of inhomegeneity, at a given list of cosmological times -- even though these features would be unlikely given the initial state and Hamiltonian.



beable-weight enforced rate of expansion

Would allowing such general theories mean the end of science?

Not at all. It's true you can formally write down a "theory" of this type that fits any data, but no one will or should take it seriously as an explanation of nature unless it is either simpler or more theoretically compelling than any alternative (and preferably both).

Cosmological BGQT with relatively simple weight functions could be useful foils against which to test the success of standard theories.

They could, even, in principle, actually turn out to be simpler and more compelling than any standard alternative. There seems no evidence for this at present, but the possibility seems worth keeping in mind.

"Causal Quantum Theory and the Collapse Locality Loophole",
A.K.,
Phys. Rev. A 72 012107 (2005)

Theoretical proposal:
a consistent version
of collapse quantum theory
that is locally causal

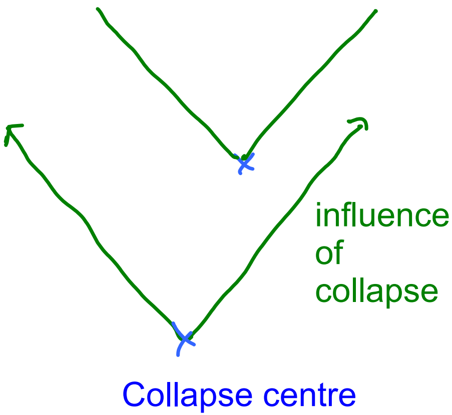
"A Proposed Test of the Local Causality of Spacetime",
A.K.,
In "*Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle: Essays in Honour of Abner Shimony*",
(Springer, 2009), pp. 369-378

Extension of Bell's
definition of
local causality to
gravitational field and
proposal for experimental
tests

"Spacelike separation in a Bell test assuming gravitationally induced collapse"
D. Salart, A. Baas, J. van Houwelingen, N. Gisin and H. Zbinden,
Phys. Rev. Lett. 100 220404 (2008)

Beautiful experiment that begins
to explore these possibilities

Causal quantum theory



Causal quantum theory is a non-standard variant of quantum theory with very strange features but no evident logical inconsistency, inspired by GRWP collapse models.

Collapse events are localized and affect physics (i.e. alter the probability of future collapse events) only within their future light cone.

Causal quantum theory predicts

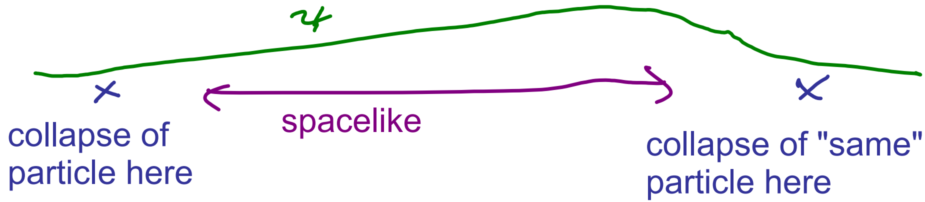
1) local correlations in suitably large scale Bell experiments with suitably fast macroscopic amplification of measurement results.

How large scale? How fast? How macroscopic? Depends which collapse model we use [GRWP ? Diosi? Penrose? ...]

I will focus here on the possibility of refuting causal quantum theory via this prediction.

But note that causal quantum theory has other strange features too:

e.g. 2) apparently inconsistent collapse events for wave functions with macroscopic spread



but never actually logically inconsistent - although extraordinarily unlikely according to standard collapse theories, and with weird implications.

Maybe some definitive test could be found using this or other predictions? It's an open question.

Testing the Non-locality of the Gravitational Field

I'll argue that:

1) If we have a probabilistic (maybe only approximate) theory describing a gravitational metric) it makes sense to ask whether the metric has non-local correlations.

2) The answer isn't directly deducible from standard Bell experiments...

3) ...but the question can in in principle be resolved by non-standard Bell experiments...

4) and we now have some relevant (though not yet decisive) data!

Local Causality for Metric Theories

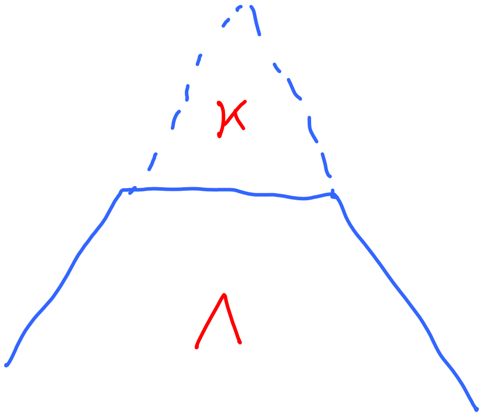
We suppose some theory which assigns probabilities to (complete or incomplete) space-times in such a way that suitable quantities of the form $\mathrm{Prob}\,(K \mid \Lambda\,,\, R(K,\Lambda))$ can be defined.

that space-time contains a region isometric to K

given that space-time contains a region isometric to Λ

and where the relevant regions are required to be related in some way we code as $R(K,\Lambda)$.

(Thanks to Dowker; cf also Henson, Rideout-Sorkin)



We are particularly interested in conditional probabilities $P(K|\Lambda)$ for events in a small region K conditioned on events in its past Λ.

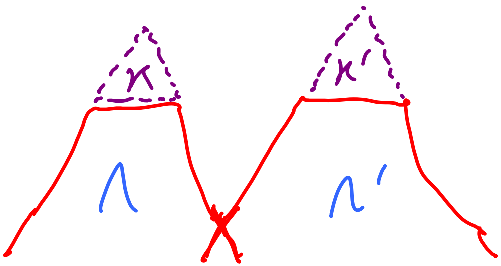
Technically, Λ is a past region: all timelike curves through points in Λ are contained in Λ.

K is its domain of dependence: all timelike past curves through points in K intersect Λ.

In particular, we want the following quantities to be defined:

$\mathrm{Prob}(K \mid \Lambda \perp \Lambda')$ = probability that the domain of dependence of Λ is isometric to K, given that $\Lambda \cup \Lambda'$ forms part of spacetime and that Λ, Λ' have space-like separated domains of dependence and are past regions.

$\mathrm{Prob}(K \mid \Lambda \perp \Lambda' ; K')$ = ditto, given also that domain of dependence of Λ' is isometric to K'



The theory is locally causal if these two quantities are always well -defined and equal. Note that this is a purely geometric criterion.

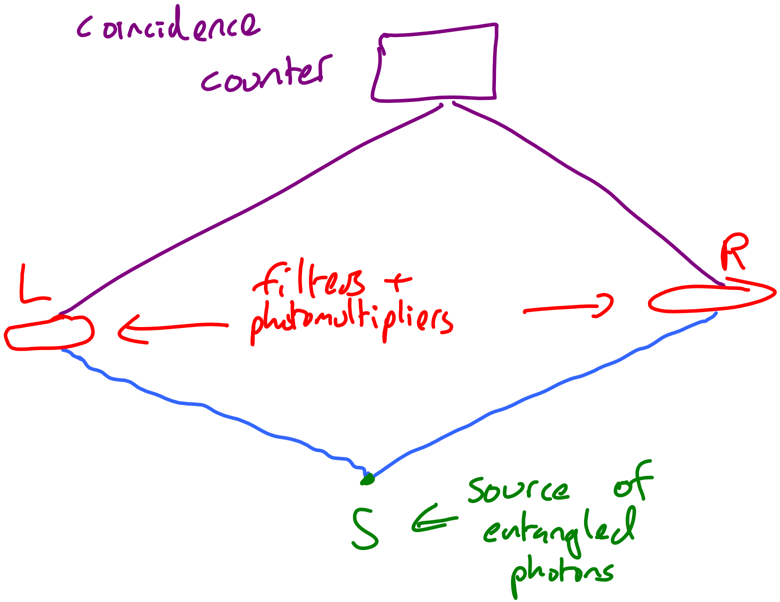
General relativity clearly is locally causal, in this sense, since it's deterministic and causal:

$$\mathrm{Prob}(\kappa \mid \Lambda) = \mathrm{Prob}(\kappa \mid \Lambda \cup \Lambda') = \mathrm{Prob}(\kappa \mid \Lambda \cup \Lambda' ; \kappa').$$

As Bell famously showed, quantum theory isn't locally causal in the usual sense (which the above definition generalizes from Minkowski space-time).

One might be tempted to assume that any Bell experiment testing quantum local causality also tests gravitational local causality. But a little thought shows, interestingly, this isn't necessarily true ...

Schematic standard Bell experiment

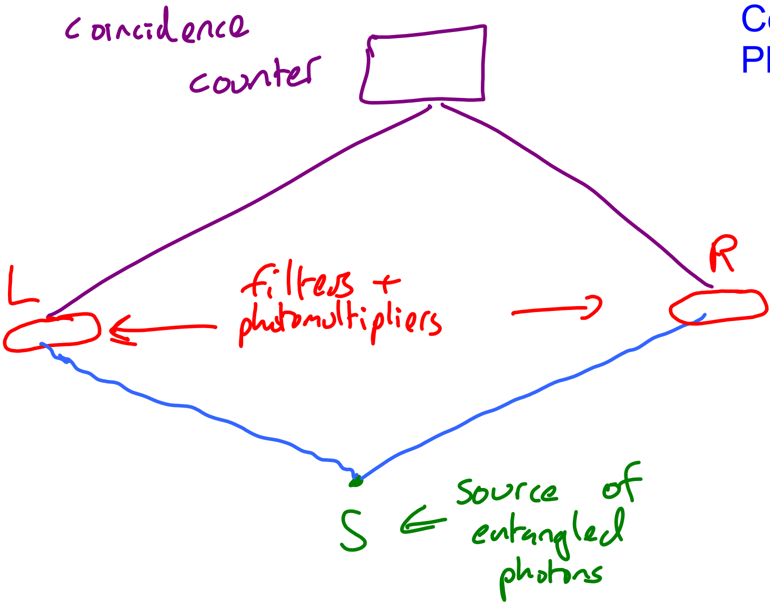


The photon detections on L and R produce only tiny currents, with no detectable gravitational effect, perhaps even in principle -and so no test of gravitational nonlocality.

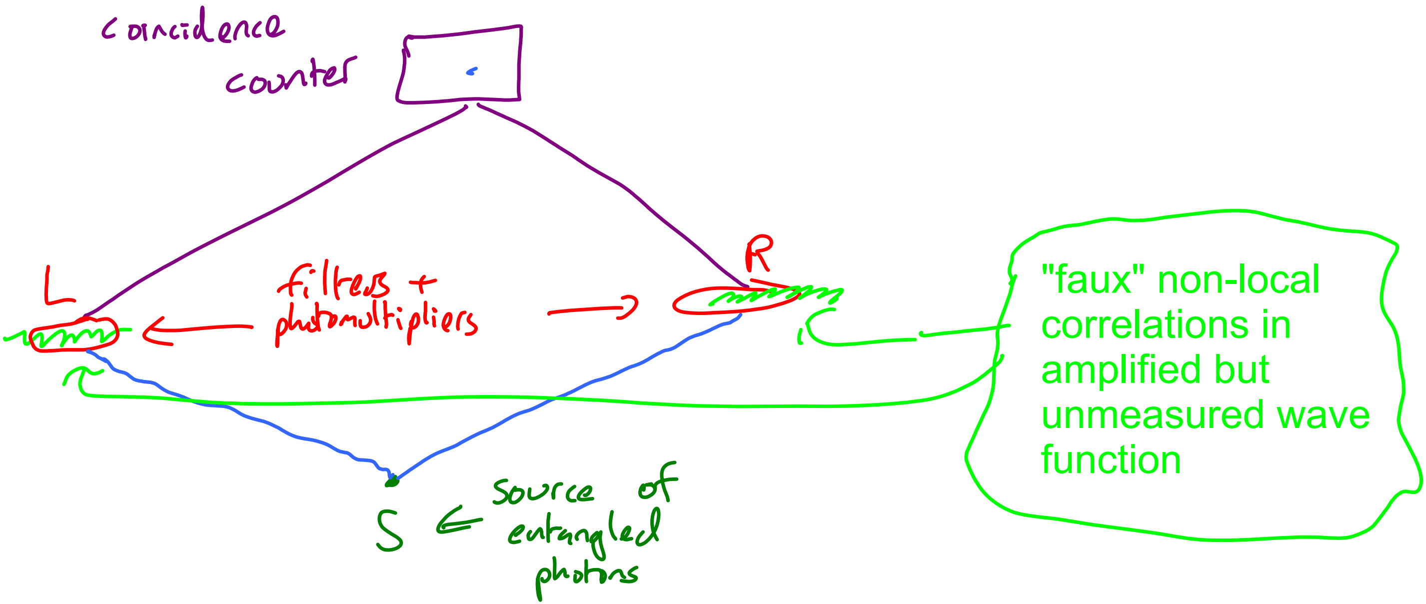
In fact, if we take the view that quantum theory involves a transition from potential (wave function) to actual (measurements) at some uncertain scale, standard Bell experiments don't **necessarily** even establish quantum nonlocalily

The collapse locality loophole

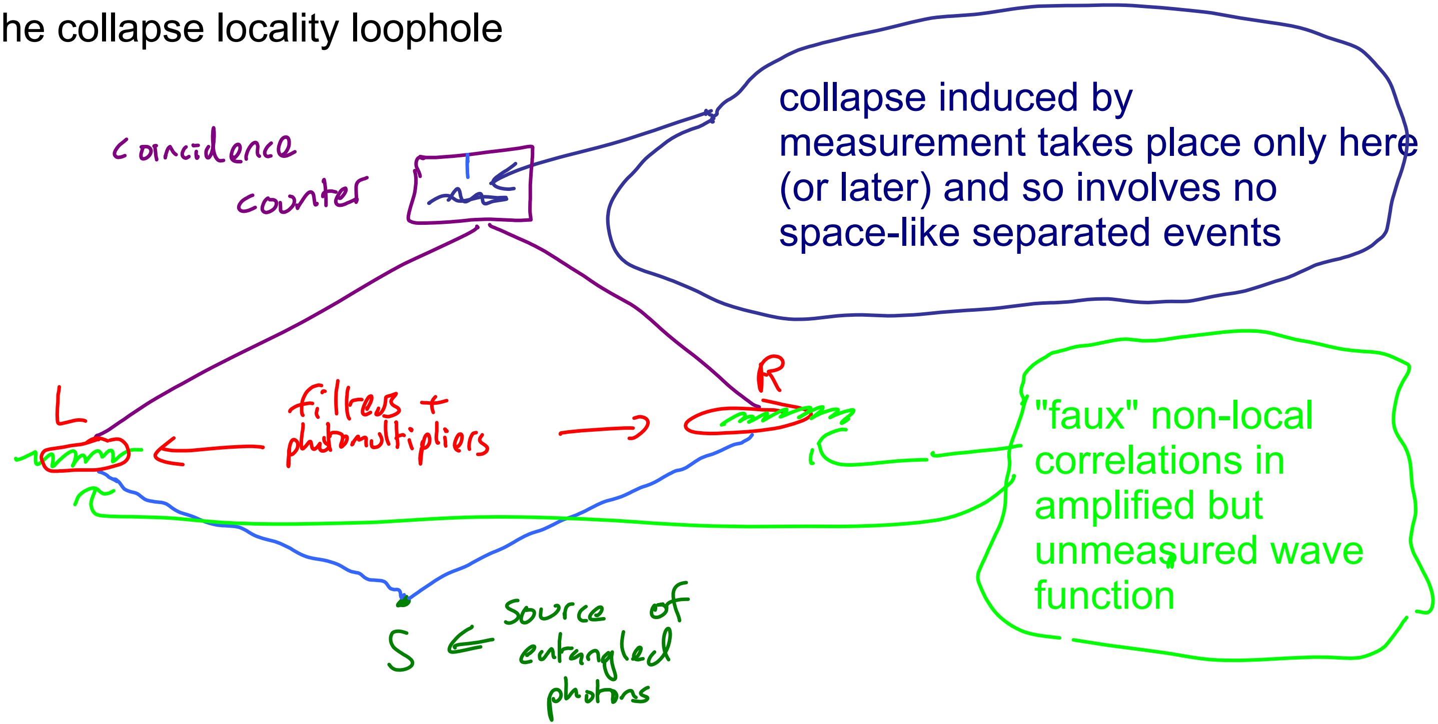
Causal Quantum Theory and the Collapse Locality Loophole, A.K., Phys. Rev. A 72, 012107 (2005)



The collapse locality loophole



The collapse locality loophole



Noteworthy motivations (which don't apply to most Bell experiment loopholes)

1) Testing the collapse locality loophole tests quantum theory against another consistent theory -- Causal quantum theory -- not just against an ad hoc hypothesis. One can make sense of quantum theory plus local causality - although it has some unfamiliar properties - without running into contradictions.

2) One might reasonably hope that hybrid classical gravity + quantum matter theories are easier to define and make sense of if locally causal. Dynamical laws with non-local correlations seem exceptionally hard to define. (Of course, there may not be any sensible hybrid theory. But it's a hypothesis worth excluding - we don't have quantum gravity at the moment.)

One can thus think of tests of gravitational nonlocality
both as attempts to verify directly a property of the gravitational field,
and as attempts to close the collapse locality loophole in Bell
experiments (*)

(*) We assume here that if outcomes on two wings correspond to
gravitational fields that can in principle (ideally, in practice)
be distinguished within time t, a wave function collapse must
take place before the end of that interval.

Motivational disclaimer:

I definitely don't see any compelling or even strong objection to quantum non-locality (as usually understood), nor any compelling reason why the gravitational field can't be non local (in the sense given above).

But the questions are of such fundamental interest, and our understanding of quantum gravity in particular is so hazy, that it seems only sensible to try to test and verify our intuitions beyond reasonable doubt.

And our intuitions just conceivably might be wrong. We tend to assign a rather higher Bayesian weight to scientific consensus opinion than history suggests we should.

The Geneva experiment

(Phys. Rev. Lett. **100**, 220404 (2008))

Space-like Separation in a Bell Test assuming Gravitationally Induced Collapses

D. Salart, A. Baas, J.A.W. van Houwelingen, N. Gisin, and H. Zbinden

Group of Applied Physics, University of Geneva, 20, Rue de l'Ecole de Médecine, CH-1211 Geneva 4, Switzerland

March 17, 2008

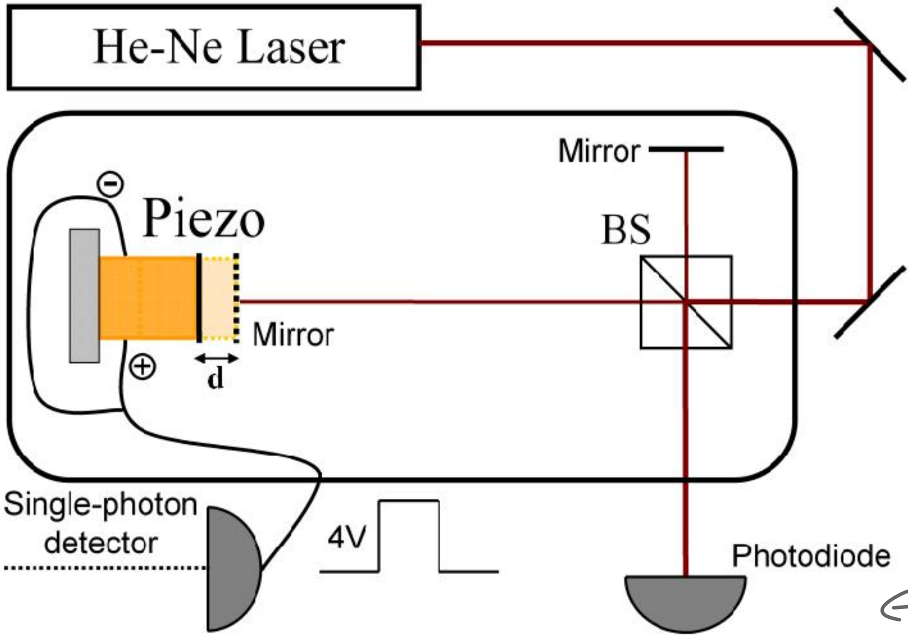
We report on a Bell experiment with space-like separation assuming that the measurement time is related to gravity-induced state reduction. Two energy-time entangled photons are sent through optical fibers and directed into unbalanced interferometers at two receiving stations separated by 18 km. At each station, the detection of a photon triggers the displacement of a macroscopic mass. The timing ensures space-like separation from the moment a photon enters its interferometer until the mass has moved. 2-photon interference fringes with a visibility of up to 90.5% are obtained, leading to a violation of Bell inequality.

When is a quantum measurement finished? Quantum theory has no definite answer to this seemingly innocent question and this leads to the quantum measurement problem. Various interpretations of quantum physics suggest opposite views. Some state that a quantum measurement is over as soon as the result is secured in a

Hence, according to Eq. 1, a typical measurement in quantum optics is finished once the alternative results would have led to displacements of a sufficiently massive object. This view differs stridently from the one adopted in practice by most quantum opticians. Indeed, the common view in this community is that a quantum measure-

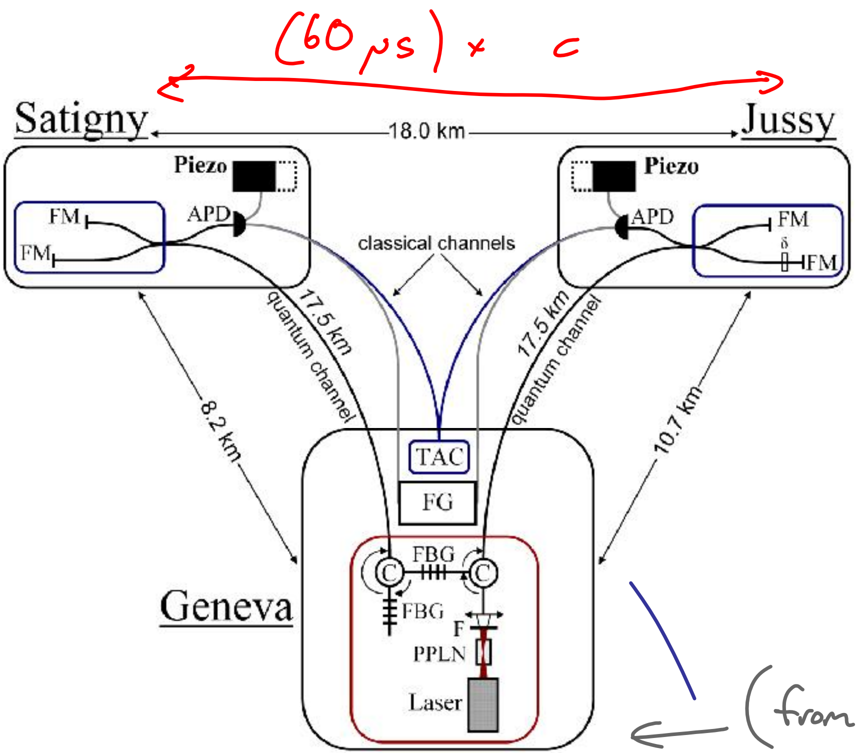
Key experimental ideas

1 Piezo crystal responds very fast to pulse from photodetector



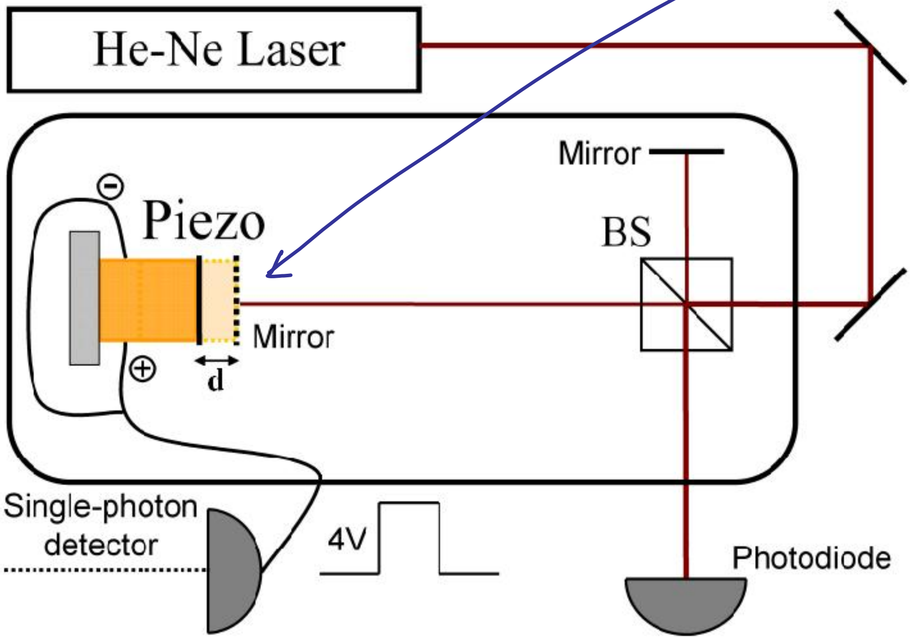
2 attached mirror allows deformation of crystal to be measured very precisely and fast via interferometry

(from Salart et al., op. cit.)



Combining two such piezo-enhanced measuring apparatuses in a long distance Bell experiment allows Bell-correlated deformations of piezo-crystals
to be confirmed in spacelike separated regions.

(from Salart et al., op. cit.)



Time from photons entering detector to mirror displacing is

$\boxed{\leq 6.1\,\mu s}$

for a displacement of

$\boxed{\geq 12.6\,nm}$

with mirror of mass

$\boxed{2\,mg}$

Time from photons entering detector to mirror displacing is

$\boxed{\lesssim 6.1\,\mu s}$

for a displacement of

$\boxed{\gtrsim 12.6\,nm}$

with a mirror of mass

$\boxed{2\,mg}$

$\Longrightarrow$

Whether and how quickly a superposition of the relevant gravitational fields collapses is model-dependent. But at least a couple of well known (albeit arguably ad hoc and incomplete) models, due to Penrose and Diosi, predict

$$\tau_{collapse} \approx \frac{3\hbar V}{2\pi G m^2 d^2} \approx 1\,\mu s$$

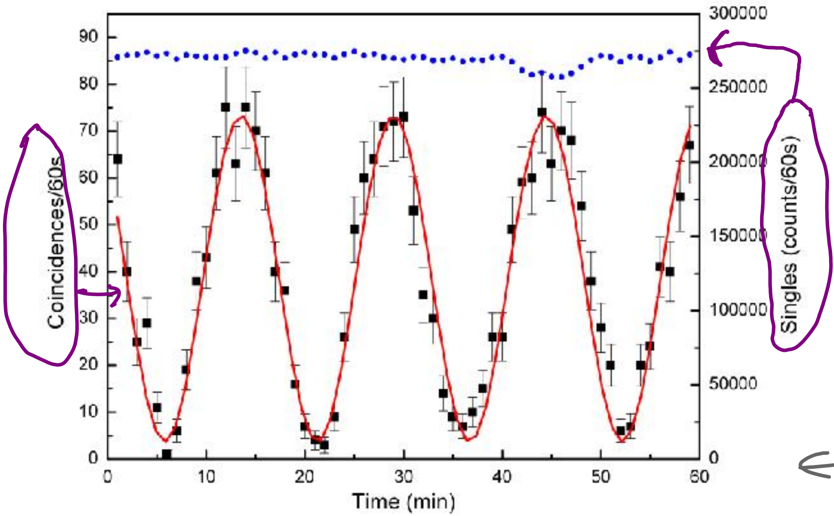
mirror volume

mirror mass

displacement

making the total time from entering the detector until collapse $\Delta\tau \lesssim 7.1\,\mu s, \ll 60\,\mu s$

So, at least according to Penrose-Diosi intuitions about gravitational collapse, we have - for the first time - a rigorous test of Bell correlations for space like collapse events.



(from Salart et al., op. cit.)

While this is a beautifully designed first test of gravitational nonlocality, it falls short of the ideal in various ways:

1) The Penrose-Diosi collapse criterion is somewhat ad hoc.
and moreover
2) it seems hard to produce a truly compelling criterion from theory alone

Ideally, then, we would like to arrange for Bell experiment outcomes to correspond to distinct gravitational fields which we can directly distinguish by Cavendish experiments or other direct measurements, within space-like separated regions.

This may have to wait for long-distance (space-based?) controlled distribution of entanglement.

Some interesting open questions on this last topic:

Are there good cosmological observational tests of gravitational nonlocality? Should we already have seen something anomalous if the gravitational field were (against all our expectations) locally causal?

Are there other more compelling criteria for gravity-induced collapse than those of Penrose and Diosi?

How fast can we create and directly distinguish outcome-dependent gravitational fields? (Triggered springs? Explosions? Electromagnetic propulsion? ..)

Is there a natural locally causal hybrid classical-quantum gravity theory?