Title: Models and Tests of Quantum Theory and Gravity

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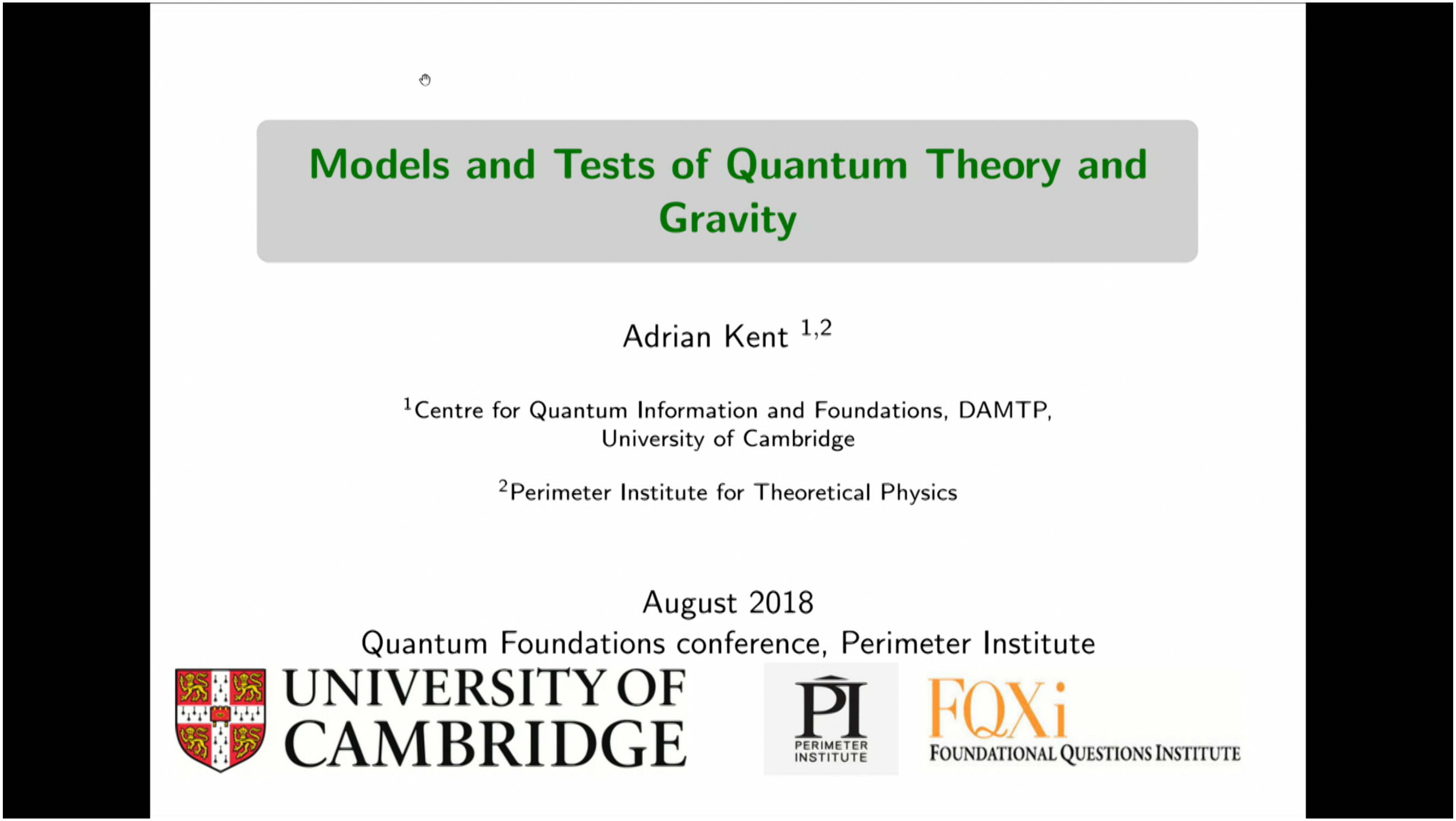
Abstract: Models that have some but not all features of standard quantum theory can be valuable in several ways, as Bell, Ghirardi-Rimini-Weber-Pearle, Hardy, Spekkens and many others have shown. One is to illuminate quantum theory and shed light on possible reaxiomatisations or reformulations. Another is to suggest experiments that might confirm some untested aspect of quantum theory or point the way to a new theory. I discuss here some models that combine quantum theory and gravity and experimental tests.



Models and Tests of Quantum Theory and Gravity

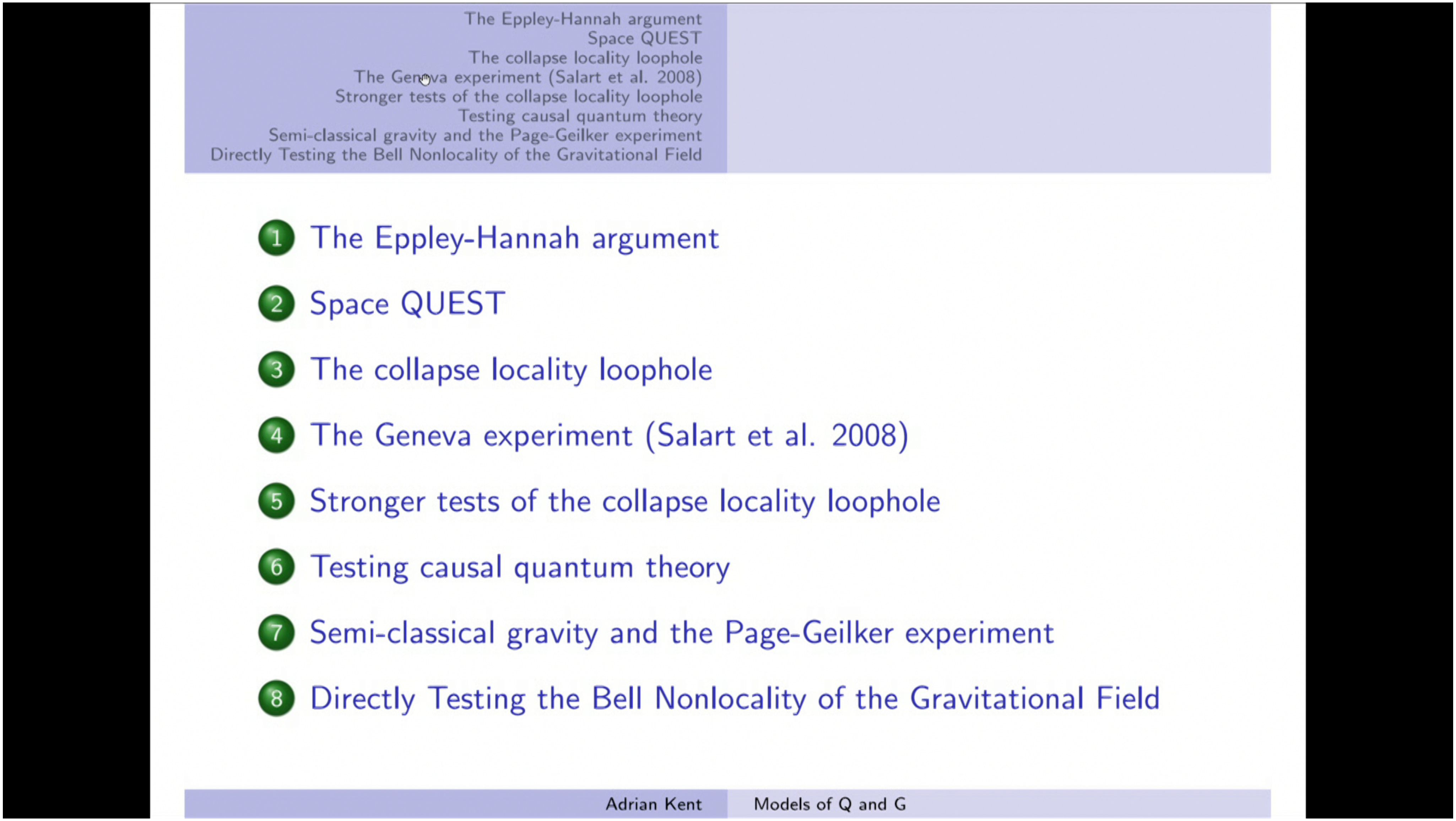
Adrian Kent [1,2]

[1] Centre for Quantum Information and Foundations, DAMTP,
University of Cambridge

[2] Perimeter Institute for Theoretical Physics

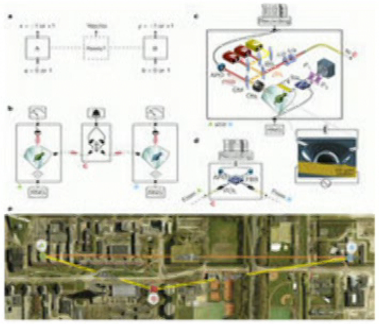
August 2018
Quantum Foundations conference, Perimeter Institute


CAUTION

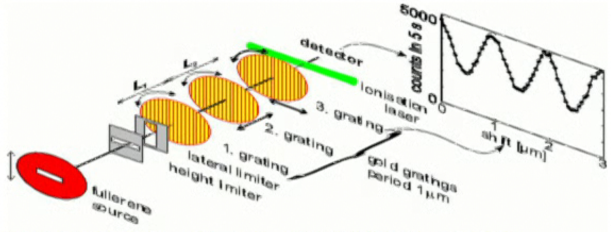


1. The Eppley-Hannah argument
2. Space QUEST
3. The collapse locality loophole
4. The Geneva experiment (Salart et al. 2008)
5. Stronger tests of the collapse locality loophole
6. Testing causal quantum theory
7. Semi-classical gravity and the Page-Geilker experiment
8. Directly Testing the Bell Nonlocality of the Gravitational Field

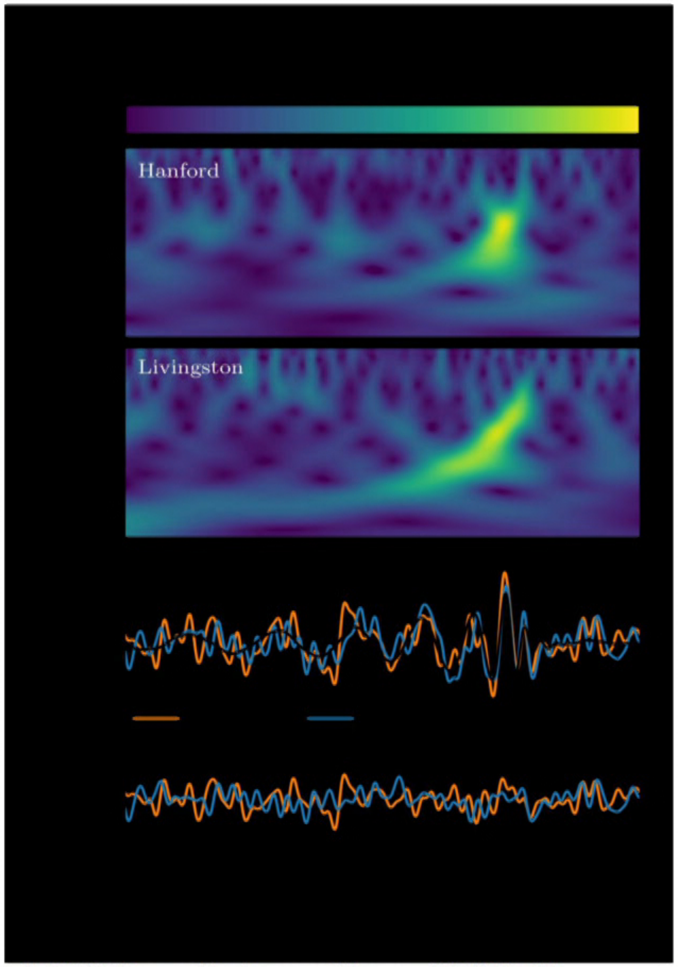
Quantum theory and general relativity continue their Mexican standoff.



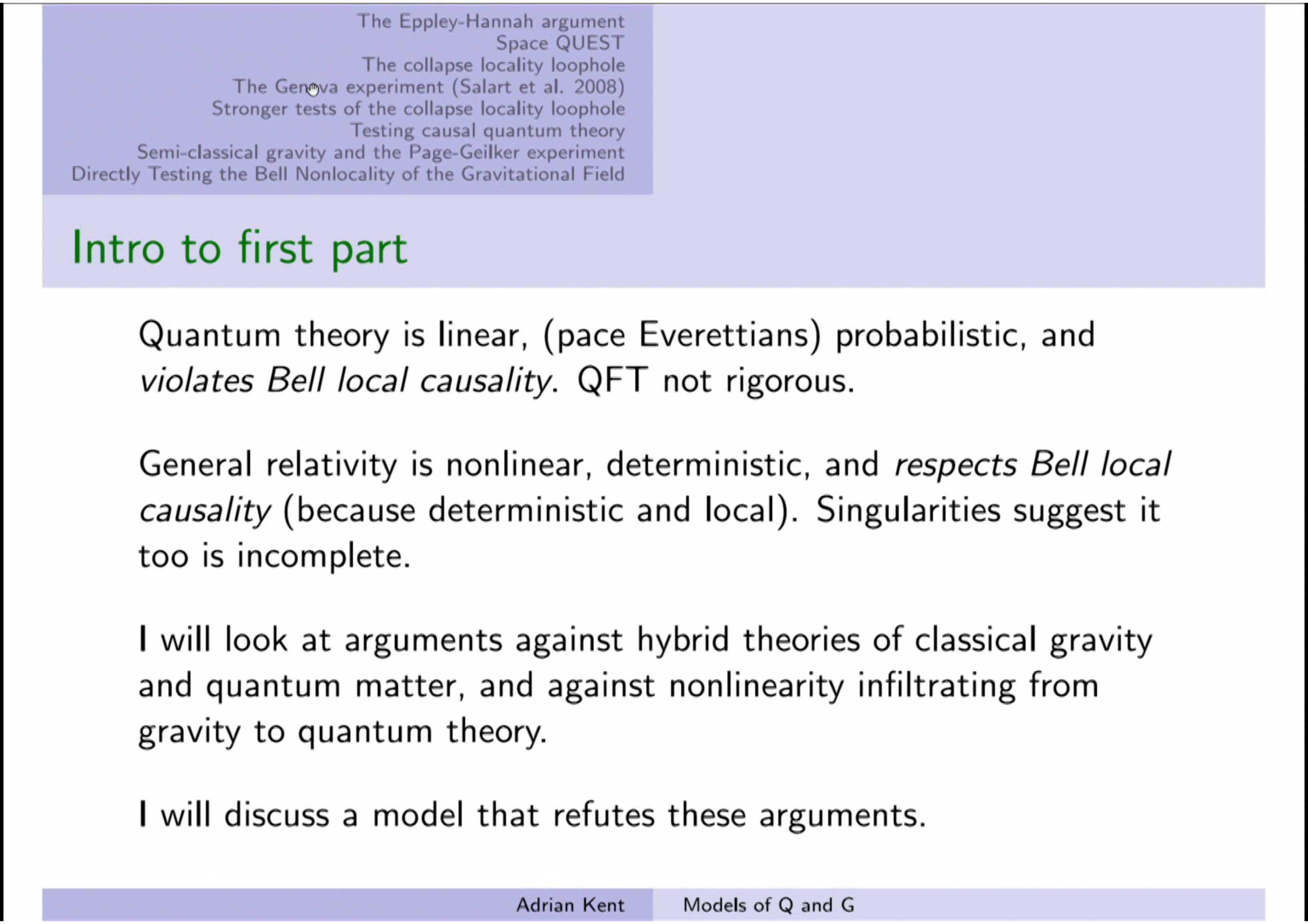
Hensen et al. (2015) "Loophole-free" Bell violation



Brezger et al. (2002) and ongoing: Demonstrations of mesoscopic interference



LIGO collaboration (2017): detection of gravitational waves



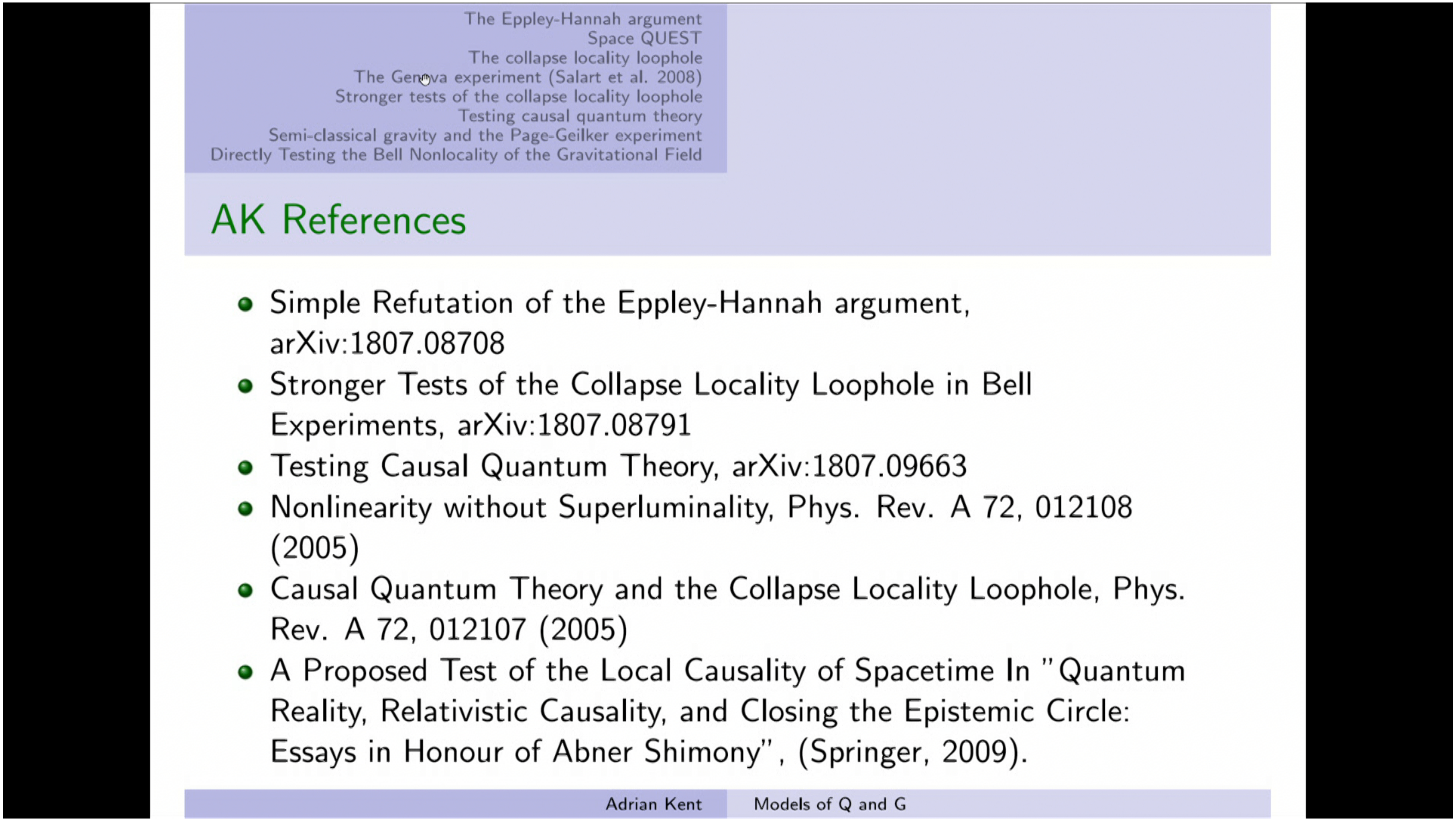
Intro to first part

Quantum theory is linear, (pace Everettians) probabilistic, and *violates Bell local causality*. QFT not rigorous.

General relativity is nonlinear, deterministic, and *respects Bell local causality* (because deterministic and local). Singularities suggest it too is incomplete.

I will look at arguments against hybrid theories of classical gravity and quantum matter, and against nonlinearity infiltrating from gravity to quantum theory.

I will discuss a model that refutes these arguments.



AK References

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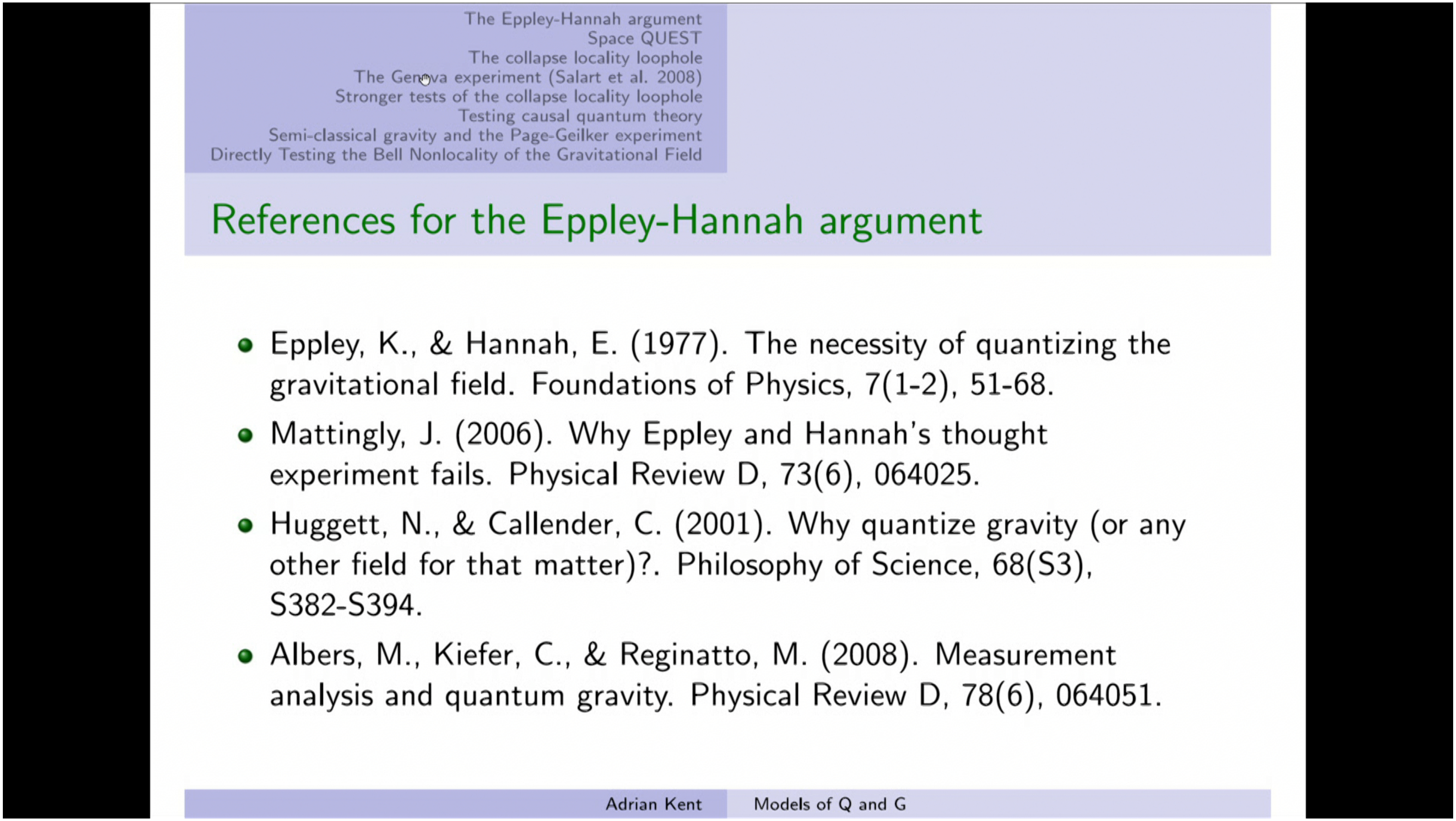
- Stronger Tests of the Collapse Locality Loophole in Bell Experiments, arXiv:1807.08791
- Testing Causal Quantum Theory, arXiv:1807.09663
- Nonlinearity without Superluminality, Phys. Rev. A 72, 012108 (2005)
- Causal Quantum Theory and the Collapse Locality Loophole, Phys. Rev. A 72, 012107 (2005)
- A Proposed Test of the Local Causality of Spacetime In "Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle: Essays in Honour of Abner Shimony", (Springer, 2009).



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- Eppley, K., & Hannah, E. (1977). The necessity of quantizing the gravitational field. Foundations of Physics, 7(1-2), 51-68.
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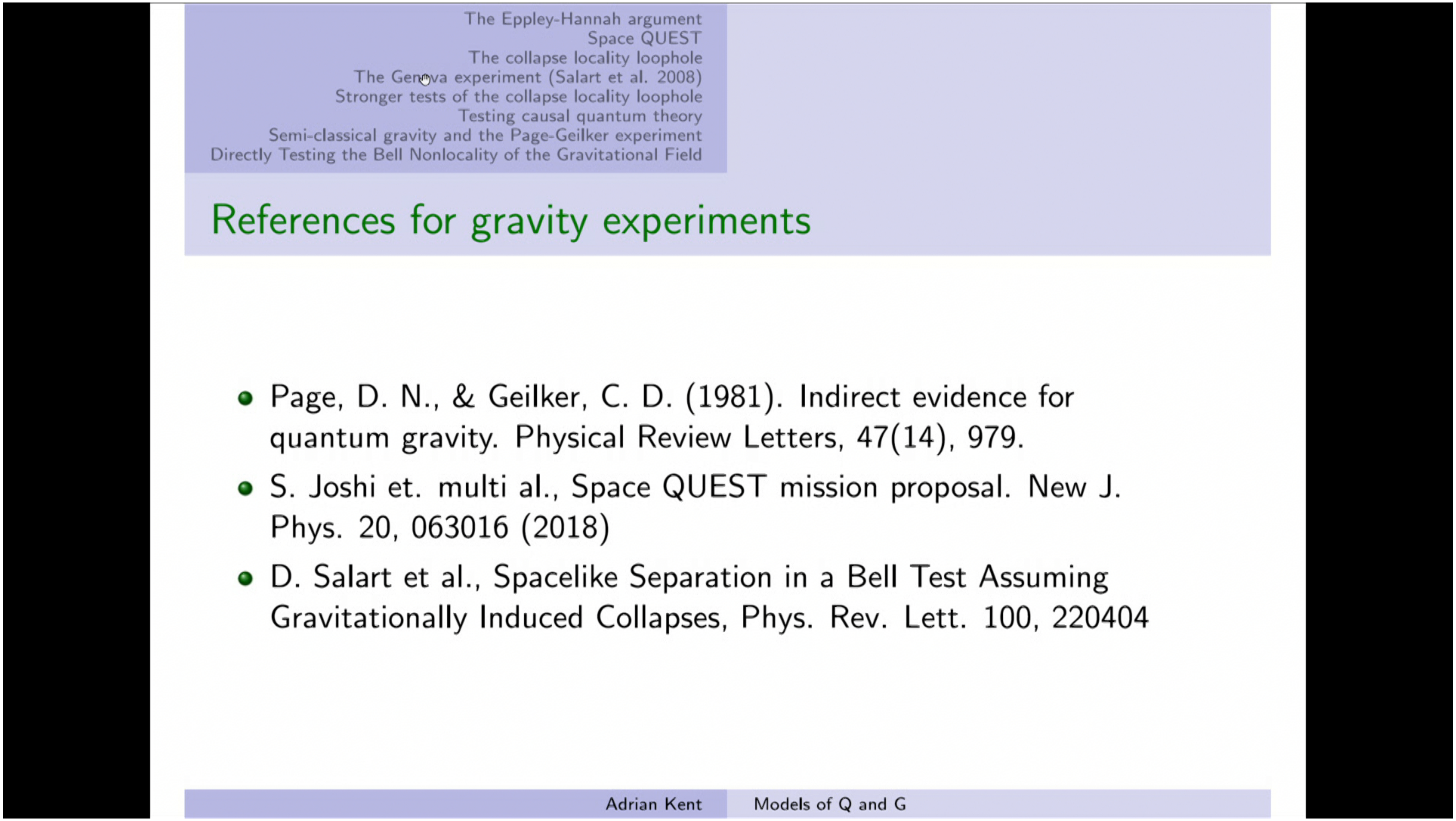
- Huggett, N., & Callender, C. (2001). Why quantize gravity (or any other field for that matter)?. Philosophy of Science, 68(S3), S382-S394.
- Albers, M., Kiefer, C., & Reginatto, M. (2008). Measurement analysis and quantum gravity. Physical Review D, 78(6), 064051.



References for gravity experiments

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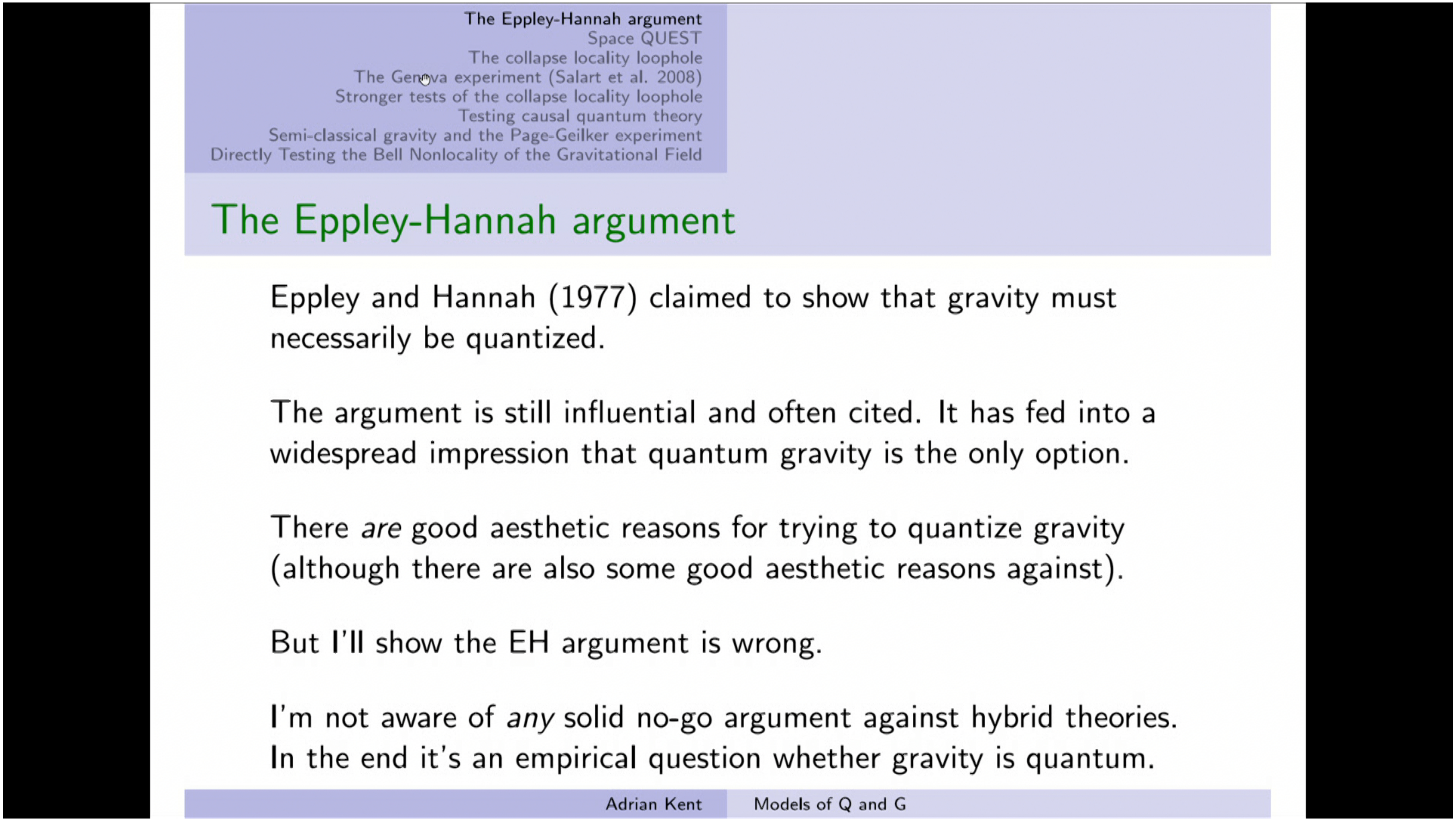


The Eppley-Hannah argument

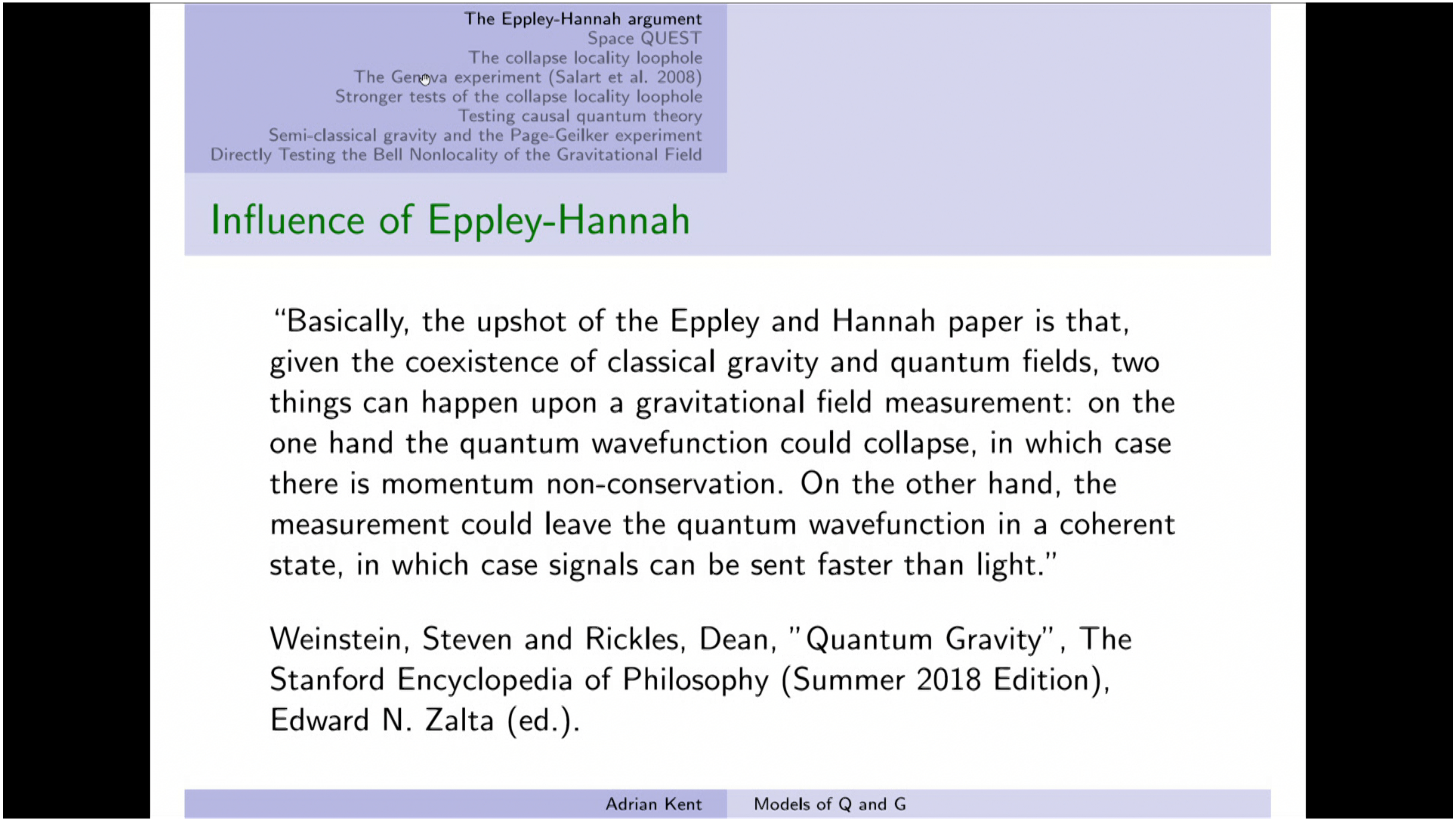
Eppley and Hannah (1977) claimed to show that gravity must necessarily be quantized.

The argument is still influential and often cited. It has fed into a widespread impression that quantum gravity is the only option.

There *are* good aesthetic reasons for trying to quantize gravity (although there are also some good aesthetic reasons against).

But I'll show the EH argument is wrong.

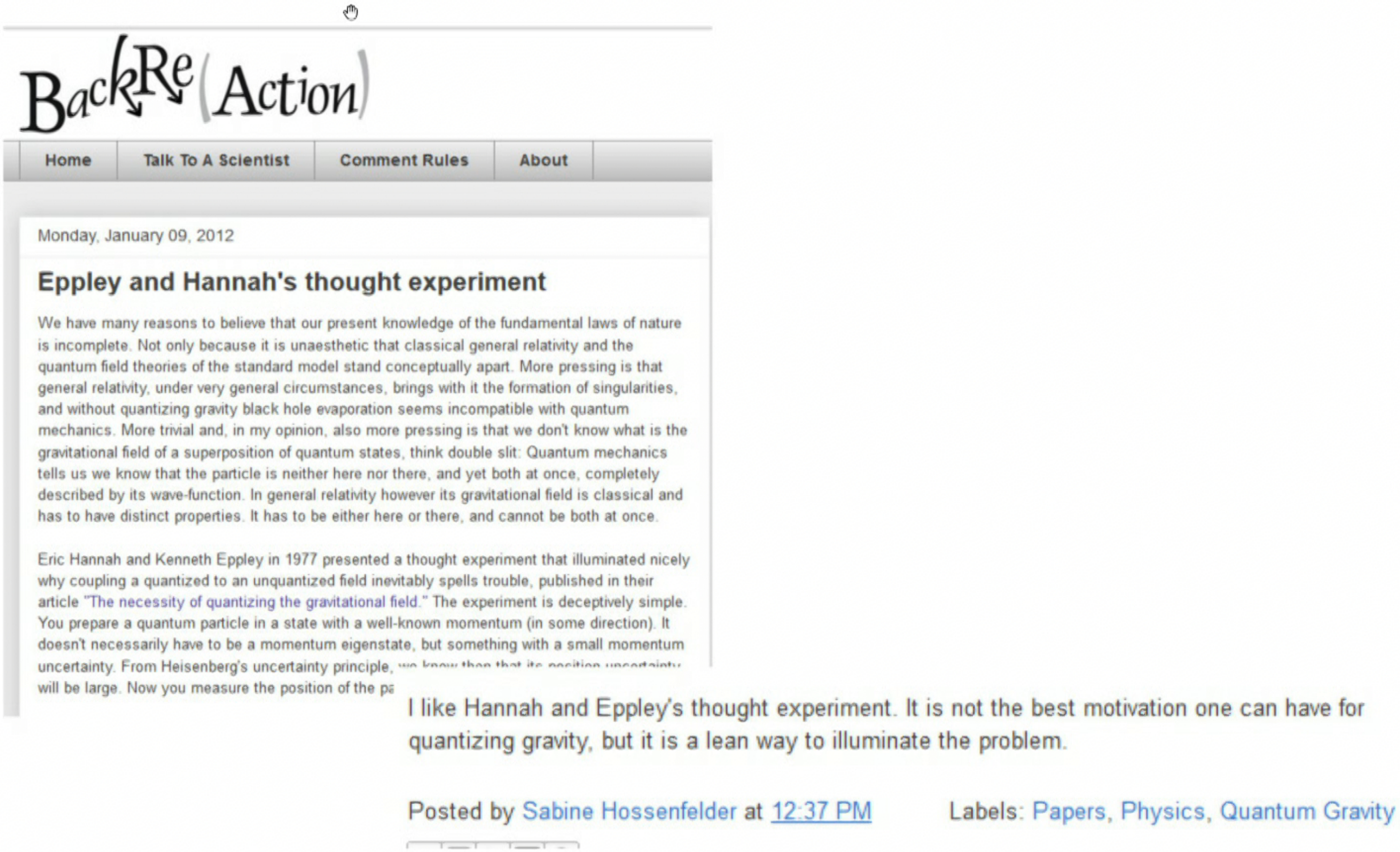
I'm not aware of *any* solid no-go argument against hybrid theories. In the end it's an empirical question whether gravity is quantum.



Influence of Eppley-Hannah

"Basically, the upshot of the Eppley and Hannah paper is that, given the coexistence of classical gravity and quantum fields, two things can happen upon a gravitational field measurement: on the one hand the quantum wavefunction could collapse, in which case there is momentum non-conservation. On the other hand, the measurement could leave the quantum wavefunction in a coherent state, in which case signals can be sent faster than light."

Weinstein, Steven and Rickles, Dean, "Quantum Gravity", The Stanford Encyclopedia of Philosophy (Summer 2018 Edition), Edward N. Zalta (ed.).



Monday, January 09, 2012

Eppley and Hannah's thought experiment

We have many reasons to believe that our present knowledge of the fundamental laws of nature is incomplete. Not only because it is unaesthetic that classical general relativity and the quantum field theories of the standard model stand conceptually apart. More pressing is that general relativity, under very general circumstances, brings with it the formation of singularities, and without quantizing gravity black hole evaporation seems incompatible with quantum mechanics. More trivial and, in my opinion, also more pressing is that we don't know what is the gravitational field of a superposition of quantum states, think double slit: Quantum mechanics tells us we know that the particle is neither here nor there, and yet both at once, completely described by its wave-function. In general relativity however its gravitational field is classical and has to have distinct properties. It has to be either here or there, and cannot be both at once.

Eric Hannah and Kenneth Eppley in 1977 presented a thought experiment that illuminated nicely why coupling a quantized to an unquantized field inevitably spells trouble, published in their article "The necessity of quantizing the gravitational field." The experiment is deceptively simple. You prepare a quantum particle in a state with a well-known momentum (in some direction). It doesn't necessarily have to be a momentum eigenstate, but something with a small momentum uncertainty. From Heisenberg's uncertainty principle, we know then that its position uncertainty will be large. Now you measure the position of the pa

I like Hannah and Eppley's thought experiment. It is not the best motivation one can have for quantizing gravity, but it is a lean way to illuminate the problem.

Posted by Sabine Hossenfelder at 12:37 PM Labels: Papers, Physics, Quantum Gravity

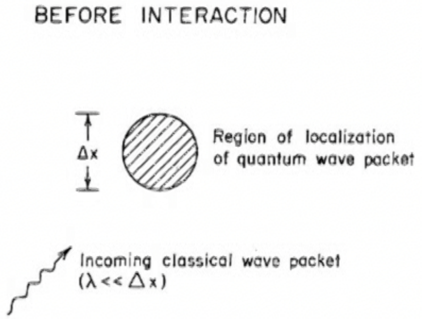


Fig. 1a. A quantum particle is prepared in a state of highly defined momentum and poorly defined position. Gravitational wave packets localized to a region $\lambda \ll \Delta x$ are directed at the region of localization.

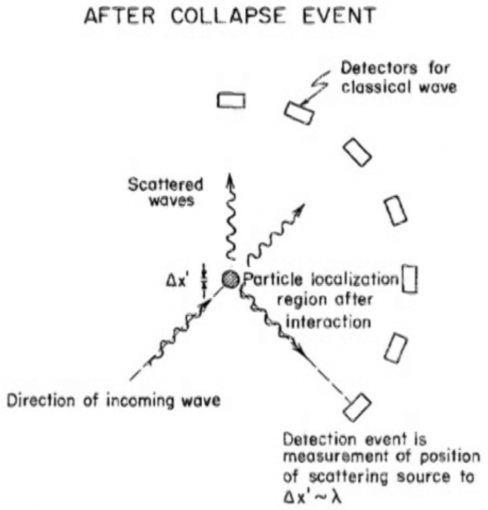


Fig. 1b. If the interaction results in wave function collapse, the particle is now localized to a region of size λ, which is determined by observation of the scattered waves and the known trajectory of the incoming wave packet. Since there was negligible momentum perturbation, both position and momentum of the particle are now highly defined.

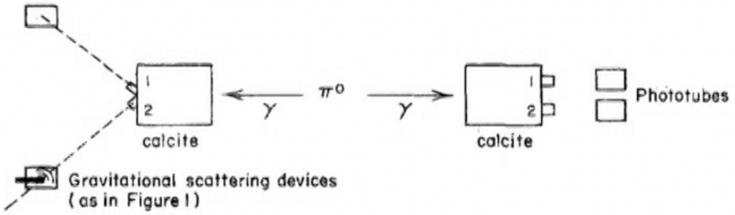
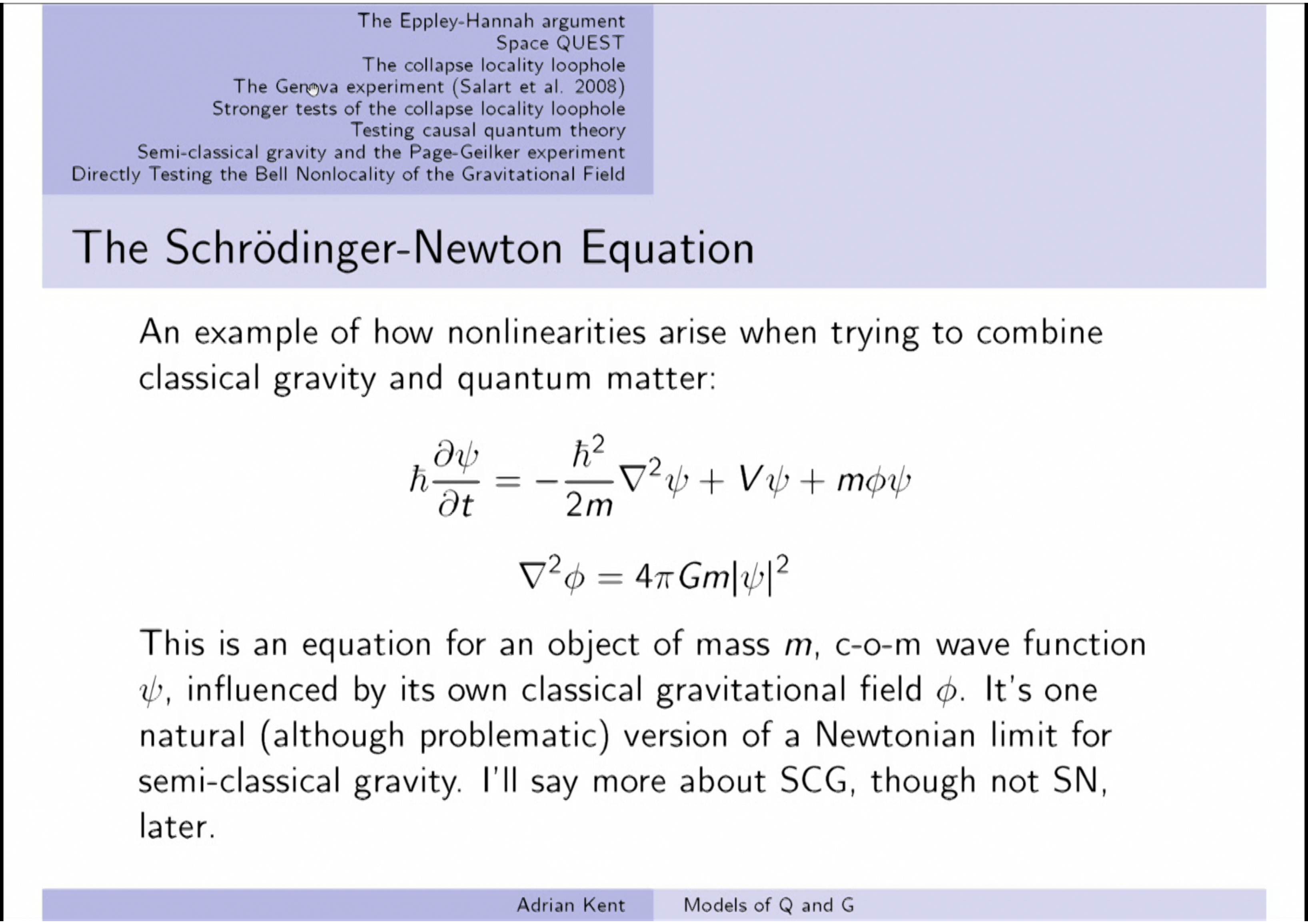


Fig. 2. Apparatus for sending signals faster than c if gravitational wave packets do not collapse the wave function. Case I. When no measurement is made on photon 1, scattered gravitational waves will be observed along both possible paths for photon 2. Case II. When photon 1 is measured to be in a definite channel, scattered gravitational waves will be observed only along the opposite channel for photon 2.



The Schrödinger-Newton Equation

An example of how nonlinearities arise when trying to combine classical gravity and quantum matter:

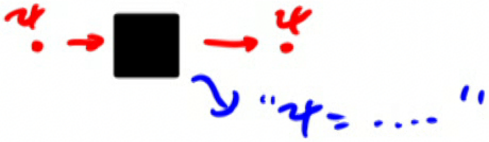
$$\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi + m\phi\psi$$

$$\nabla^2 \phi = 4\pi G m |\psi|^2$$

This is an equation for an object of mass m, c-o-m wave function ψ, influenced by its own classical gravitational field ϕ. It's one natural (although problematic) version of a Newtonian limit for semi-classical gravity. I'll say more about SCG, though not SN, later.

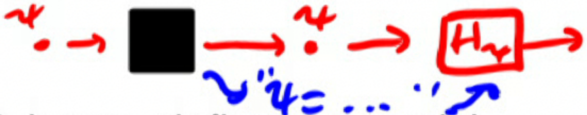
A Quantum State Readout Device Model

Consider quantum theory supplemented by small hypothetical black boxes that give a classical description of the quantum state within the box to specified precision.

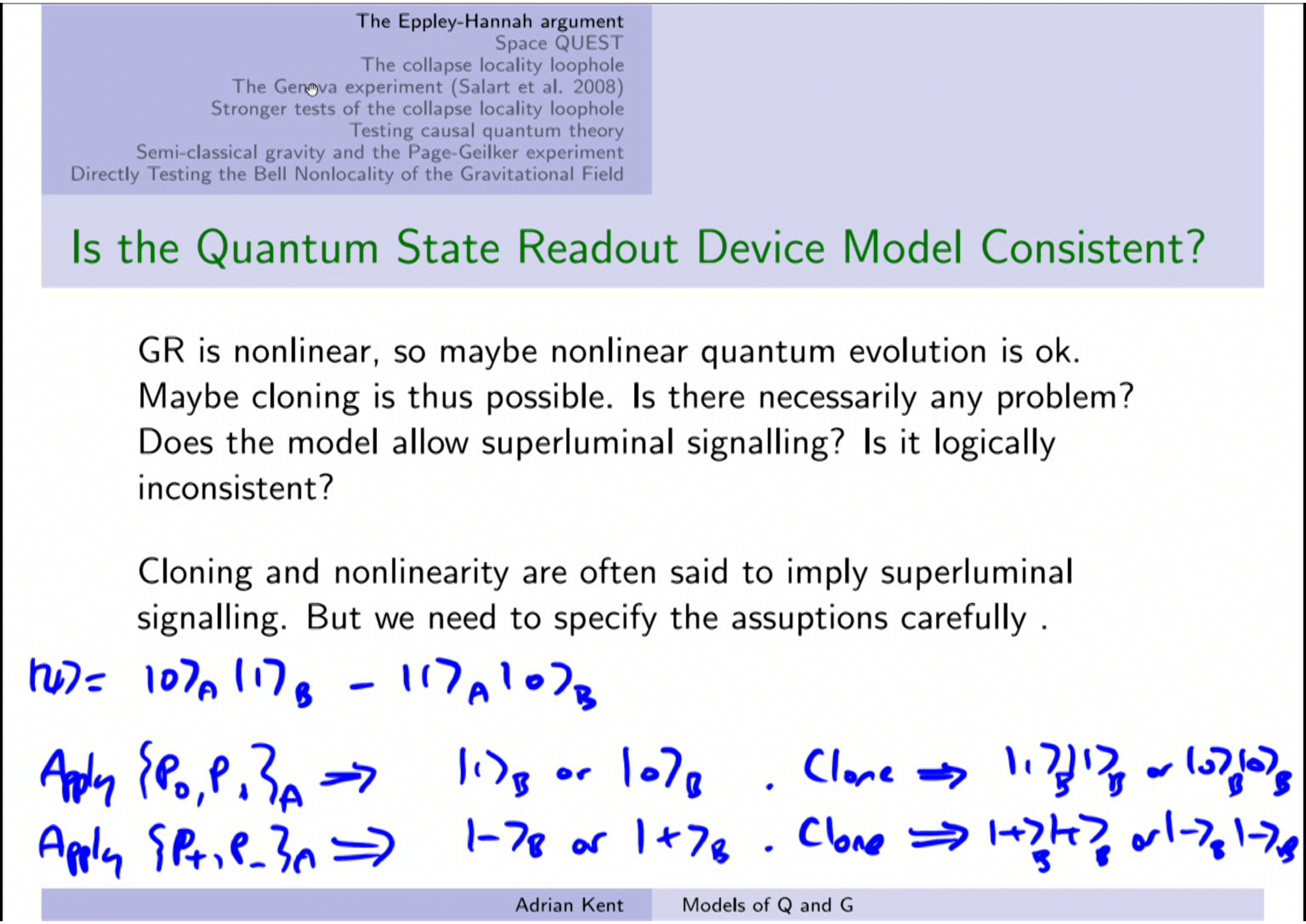


The black boxes allow cloning of pure states.

They allow nonlinear evolution of quantum states, since we can read out the state and then apply a Hamiltonian that depends on the readout.



Maybe helpful to think of these as like PR boxes, defining a model that goes beyond quantum theory and has interesting properties.



Is the Quantum State Readout Device Model Consistent?

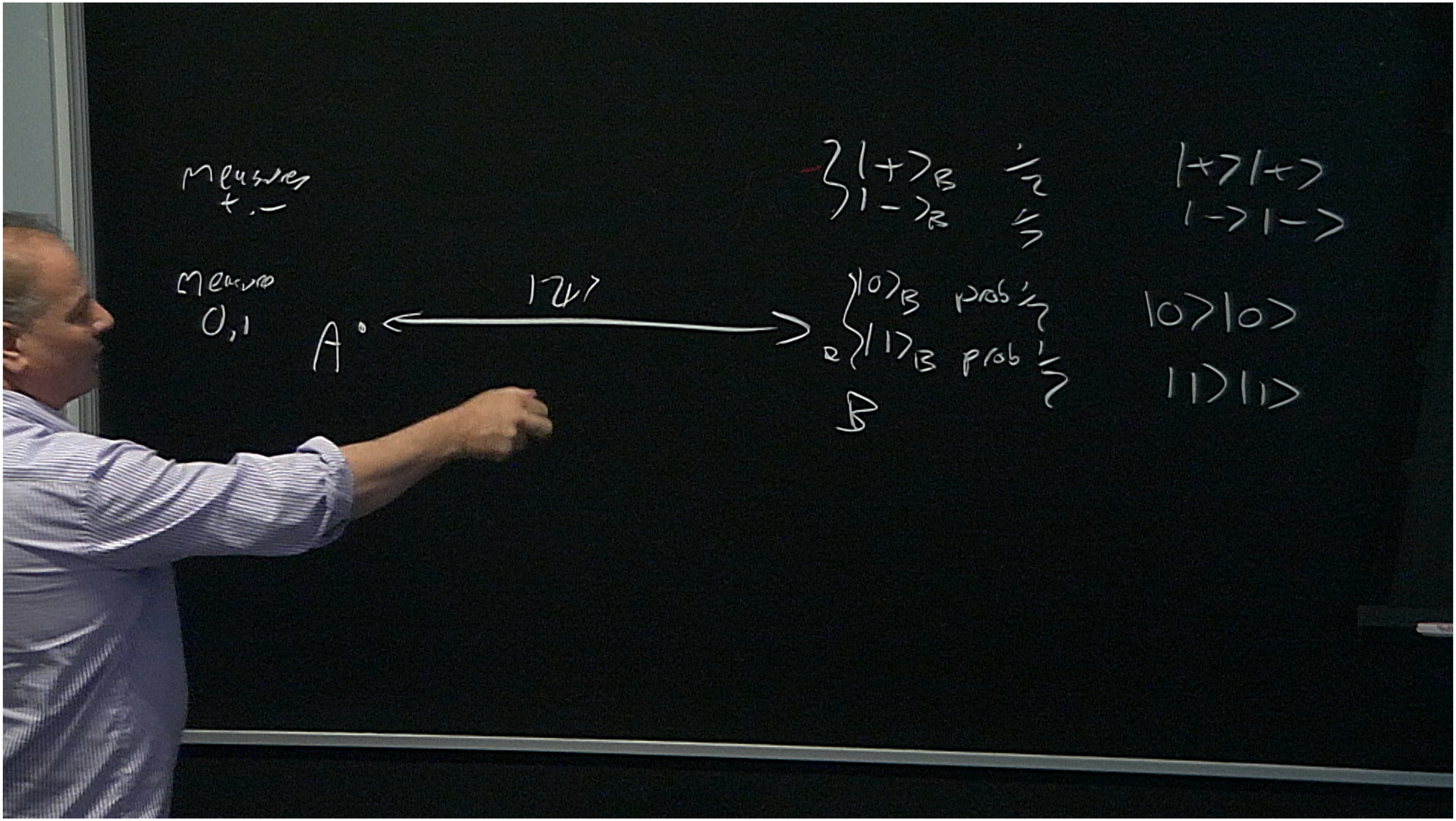
GR is nonlinear, so maybe nonlinear quantum evolution is ok. Maybe cloning is thus possible. Is there necessarily any problem? Does the model allow superluminal signalling? Is it logically inconsistent?

Cloning and nonlinearity are often said to imply superluminal signalling. But we need to specify the assuptions carefully .

$|\psi\rangle = |0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B$

Apply $\{P_0, P_1\}_A \Rightarrow$ $|1\rangle_B$ or $|0\rangle_B$. Clone $\Rightarrow$ $|1\rangle_B |1\rangle_B$ or $|0\rangle_B |0\rangle_B$

Apply $\{P_+, P_-\}_A \Rightarrow$ $|-\rangle_B$ or $|+\rangle_B$. Clone $\Rightarrow$ $|+\rangle_B |+\rangle_B$ or $|-\rangle_B |-\rangle_B$



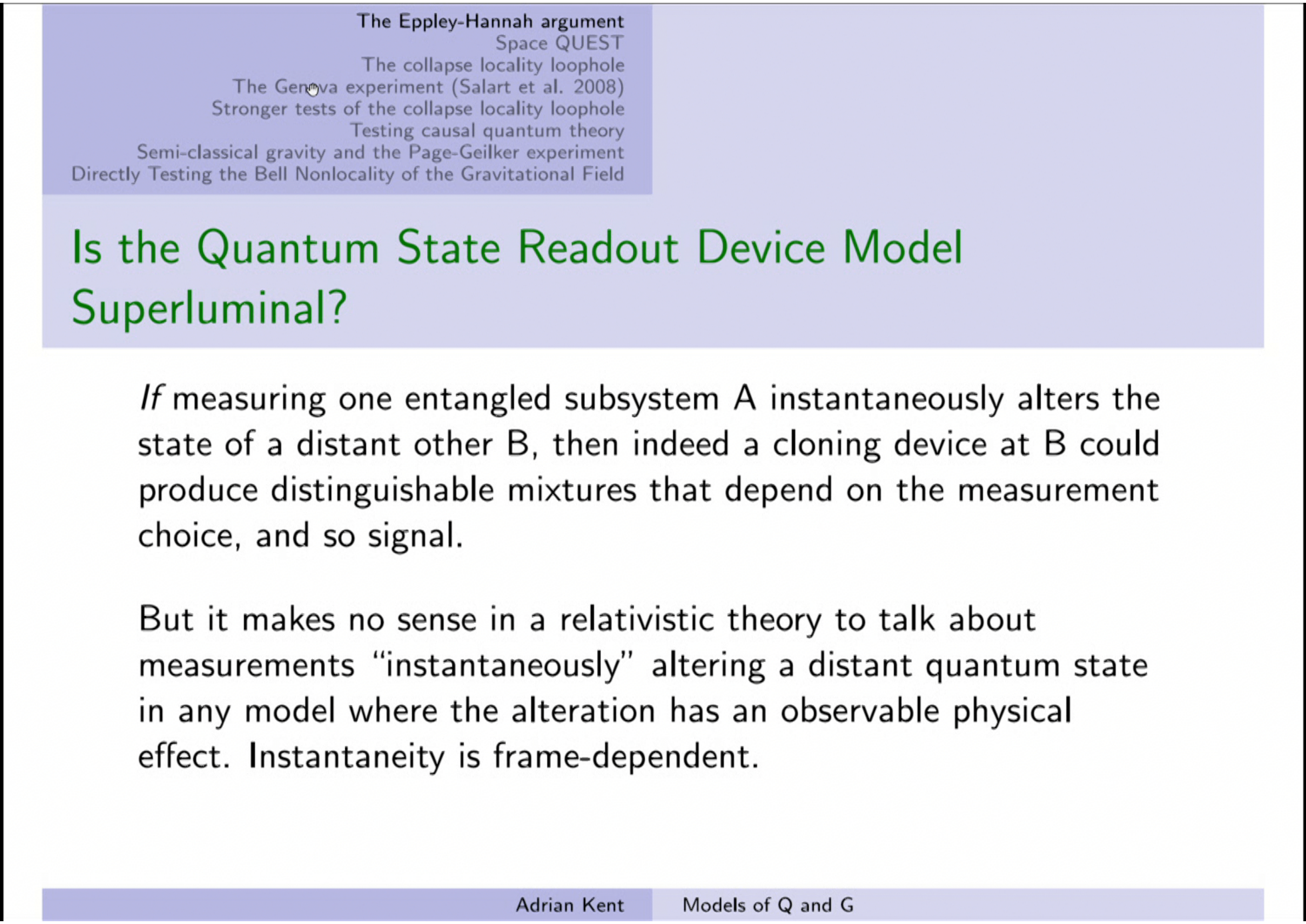
Measures $+,-$

Measure $0,1$

$$A \longleftrightarrow^{|\Psi\rangle} B$$

$$\left\{\begin{array}{ll} |+\rangle_B & \frac{1}{2} \\ |-\rangle_B & \frac{1}{2} \end{array}\right. \qquad \begin{array}{l} |+\rangle|+\rangle \\ |-\rangle|-\rangle \end{array}$$

$$\left\{\begin{array}{ll} |0\rangle_B & \text{prob } \frac{1}{2} \\ |1\rangle_B & \text{prob } \frac{1}{2} \end{array}\right. \qquad \begin{array}{l} |0\rangle|0\rangle \\ |1\rangle|1\rangle \end{array}$$



Is the Quantum State Readout Device Model Superluminal?

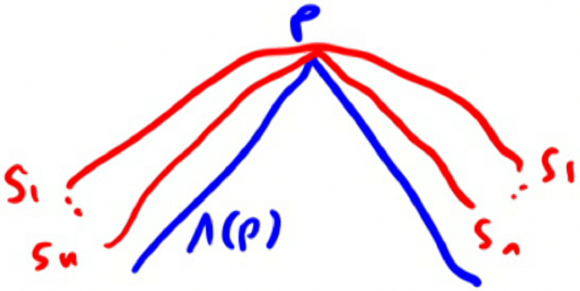
If measuring one entangled subsystem A instantaneously alters the state of a distant other B, then indeed a cloning device at B could produce distinguishable mixtures that depend on the measurement choice, and so signal.

But it makes no sense in a relativistic theory to talk about measurements “instantaneously” altering a distant quantum state in any model where the alteration has an observable physical effect. Instantaneity is frame-dependent.

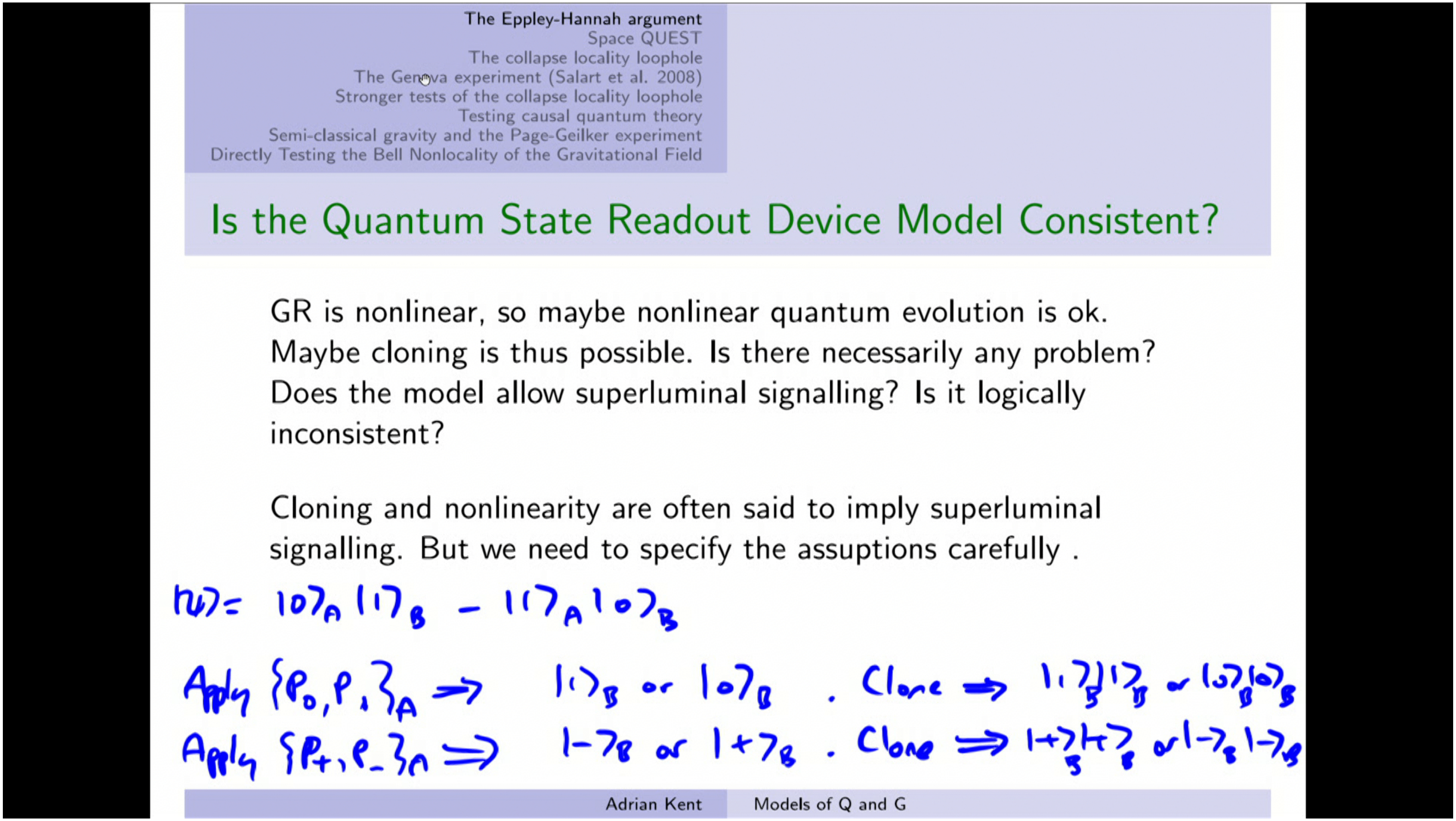
Is the Quantum State Readout Device Model Superluminal?

It *does* make sense, though, to allow physical effects to propagate at light speed.

If our read out devices read out the *local quantum state*, we have no superluminality.



$$\rho_p = \lim_{n \to \infty} \mathrm{Tr}_{S_n \sim \{p\}} \left(|\psi\rangle_{S_n} \langle\psi| \right)$$



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Apply $\{P_+, P_-\}_A \Rightarrow$ $|-\rangle_B$ or $|+\rangle_B$. Clone $\Rightarrow$ $|+\rangle_B |+\rangle_B$ or $|-\rangle_B |-\rangle_B$

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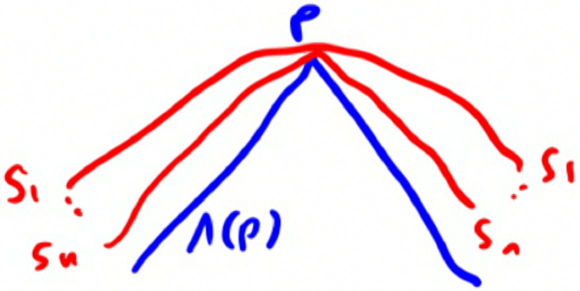
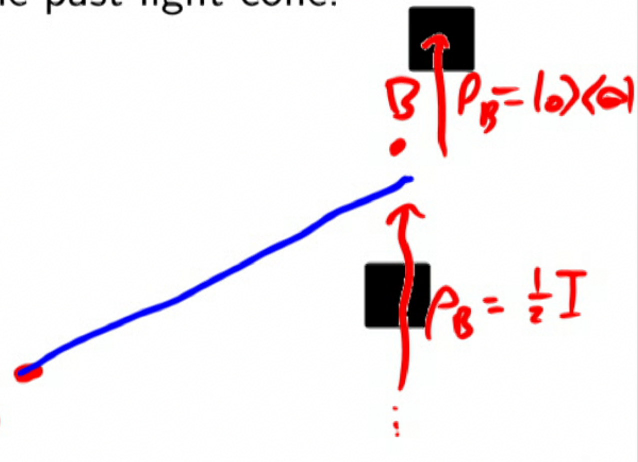


$$\rho_P = \lim_{n\to\infty} \mathrm{Tr}_{S_n \sim \{P\}} \left(|\psi\rangle_{S_n}\langle\psi| \right)$$

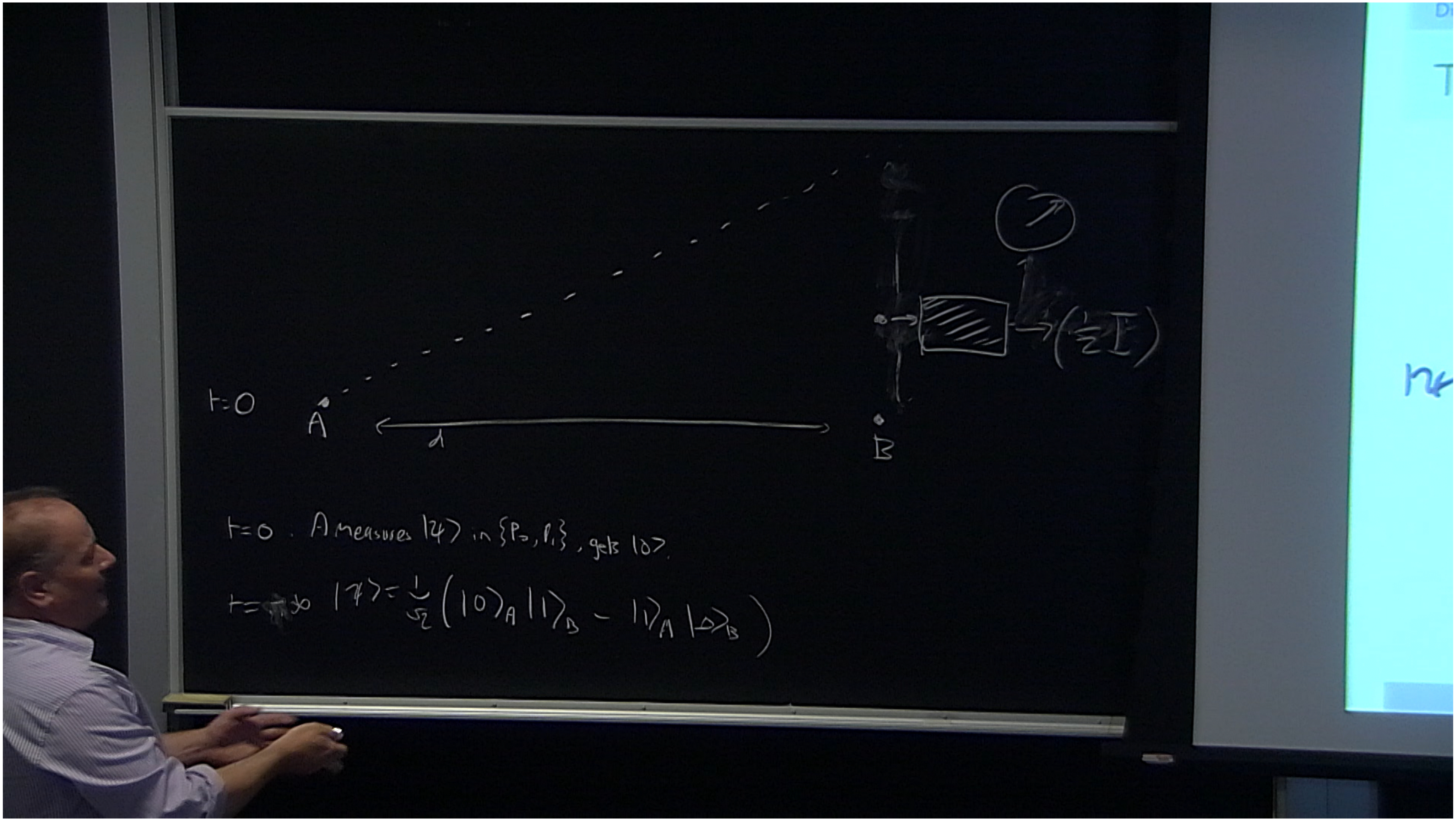
The local quantum state

In any theory with localized collapses, we may define the *local quantum state* at a space-time point as the local density matrix obtained by evolving the initial quantum state, taking account of (only) those collapses that took place in the past light cone:

$$|\psi\rangle = |0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B .$$



A measures, obtains outcome $|1\rangle$



$t=0$. A measures $|\psi\rangle$ in $\{P_0, P_1\}$, gets $|0\rangle$.

$t=-\infty$ $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B\right)$

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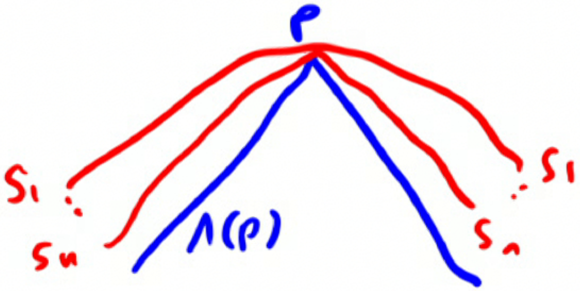

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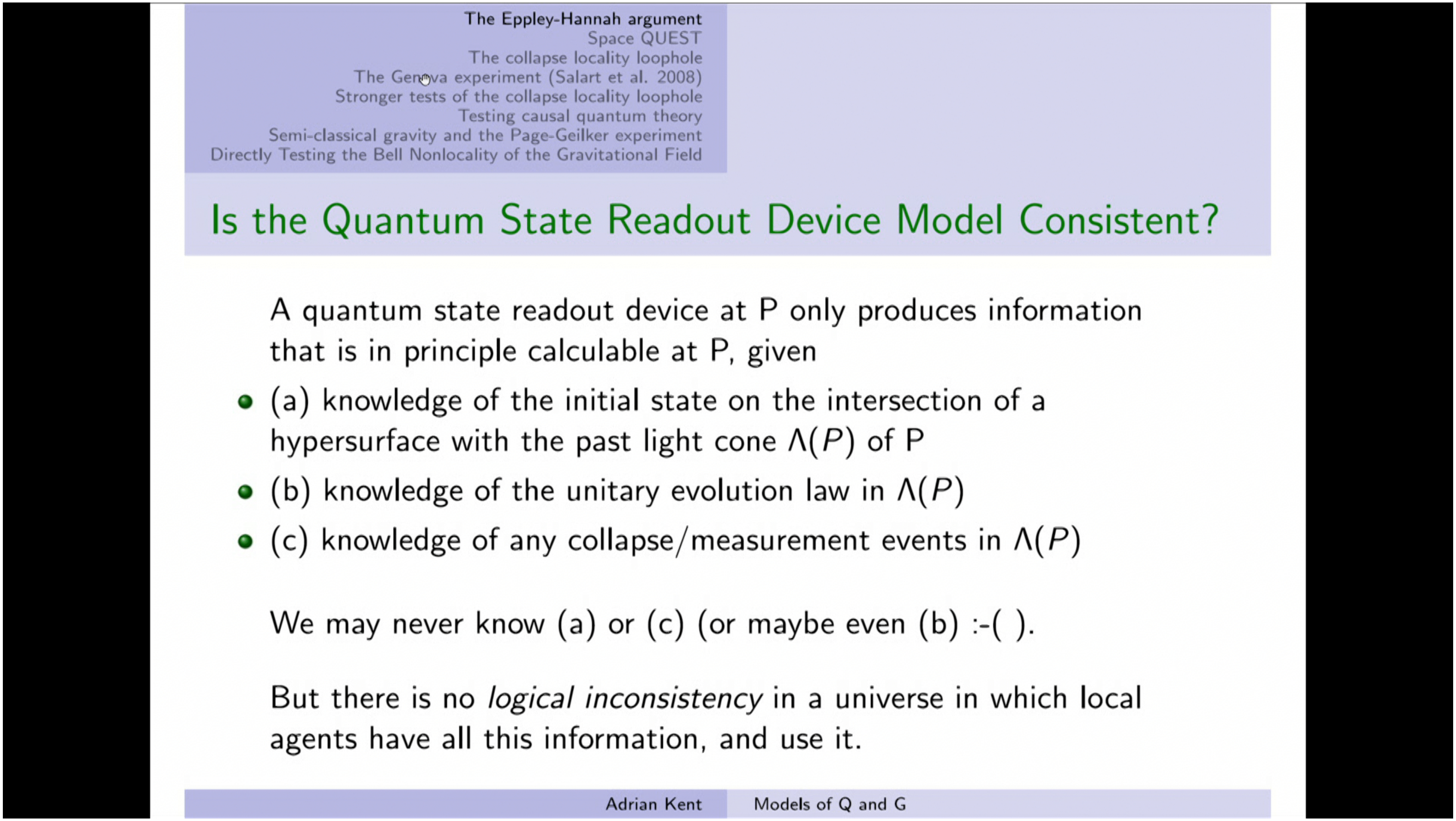


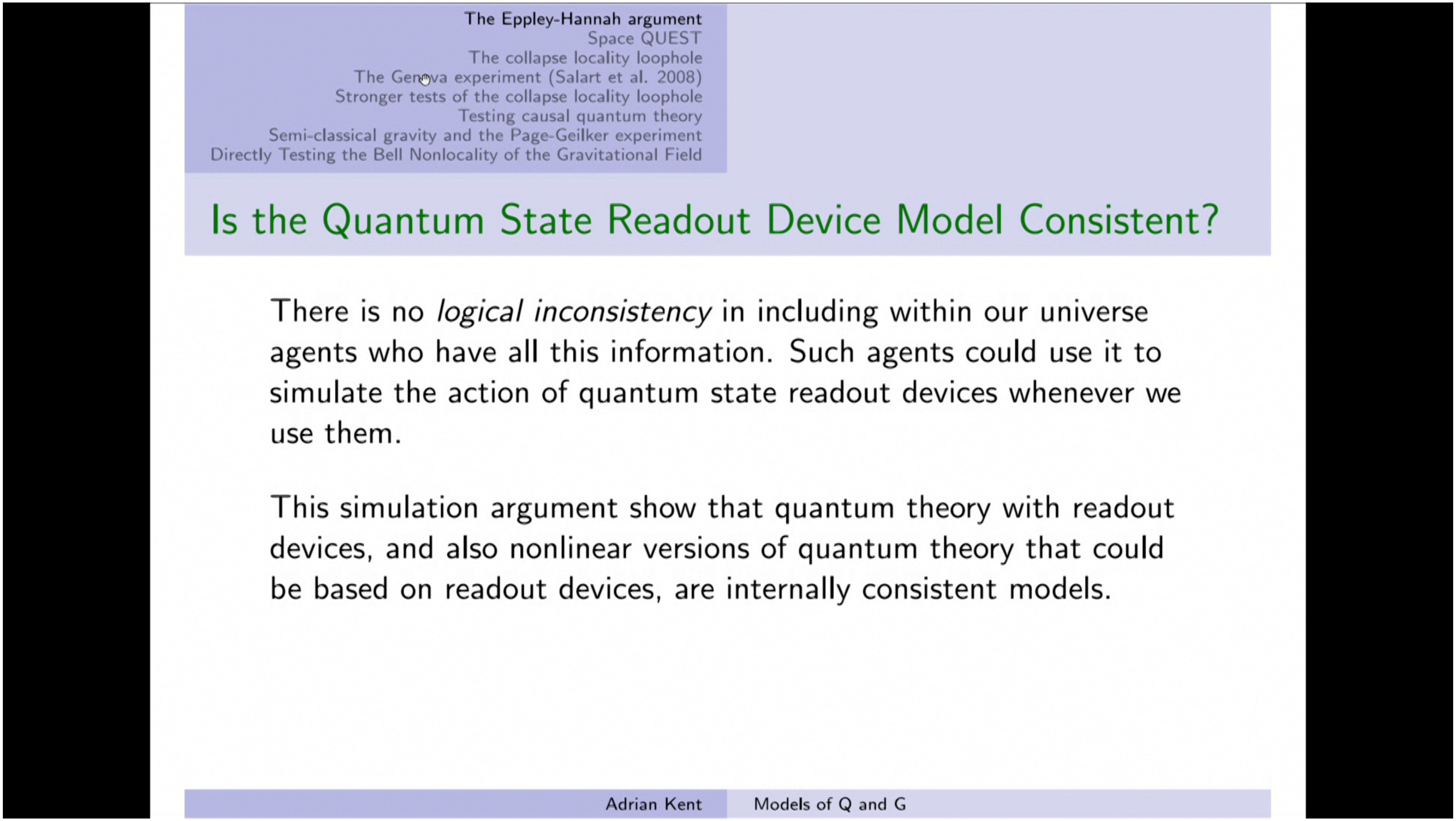
Is the Quantum State Readout Device Model Consistent?

A quantum state readout device at P only produces information that is in principle calculable at P, given

- (a) knowledge of the initial state on the intersection of a hypersurface with the past light cone $\Lambda(P)$ of P
- (b) knowledge of the unitary evolution law in $\Lambda(P)$
- (c) knowledge of any collapse/measurement events in $\Lambda(P)$

We may never know (a) or (c) (or maybe even (b) :-( ).

But there is no *logical inconsistency* in a universe in which local agents have all this information, and use it.



Is the Quantum State Readout Device Model Consistent?

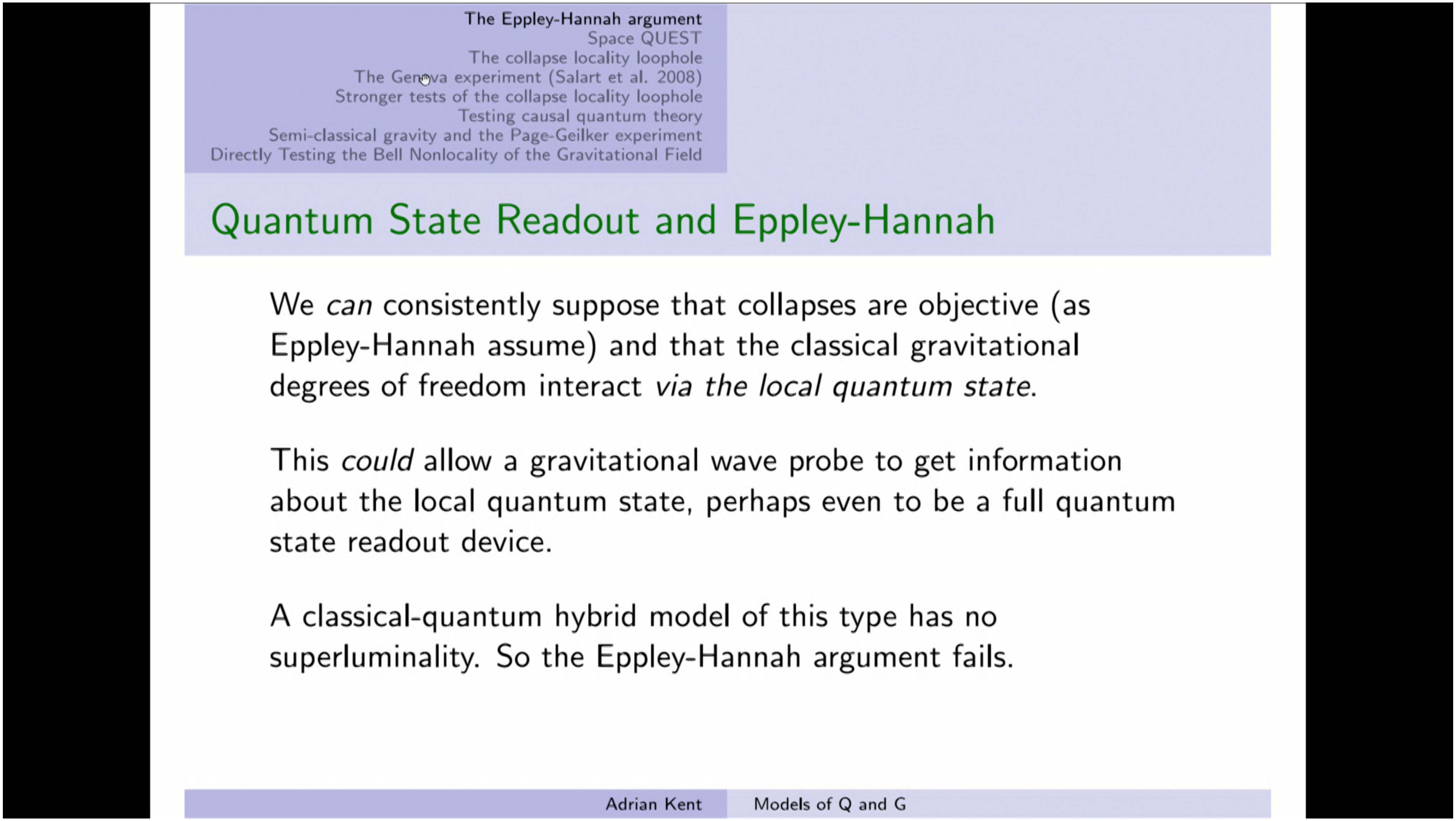
There is no *logical inconsistency* in including within our universe agents who have all this information. Such agents could use it to simulate the action of quantum state readout devices whenever we use them.

This simulation argument show that quantum theory with readout devices, and also nonlinear versions of quantum theory that could be based on readout devices, are internally consistent models.

Quantum State Readout and Eppley-Hannah

The fundamental problem (there are others) with Eppley-Hannah's discussion is that their model of relativistic classical-quantum interaction is *incoherent*.

We already noted it makes no sense in a relativistic theory to talk about measurements "instantaneously" altering a distant quantum state in any model where the alteration has an observable physical effect. Instantaneity is frame-dependent.



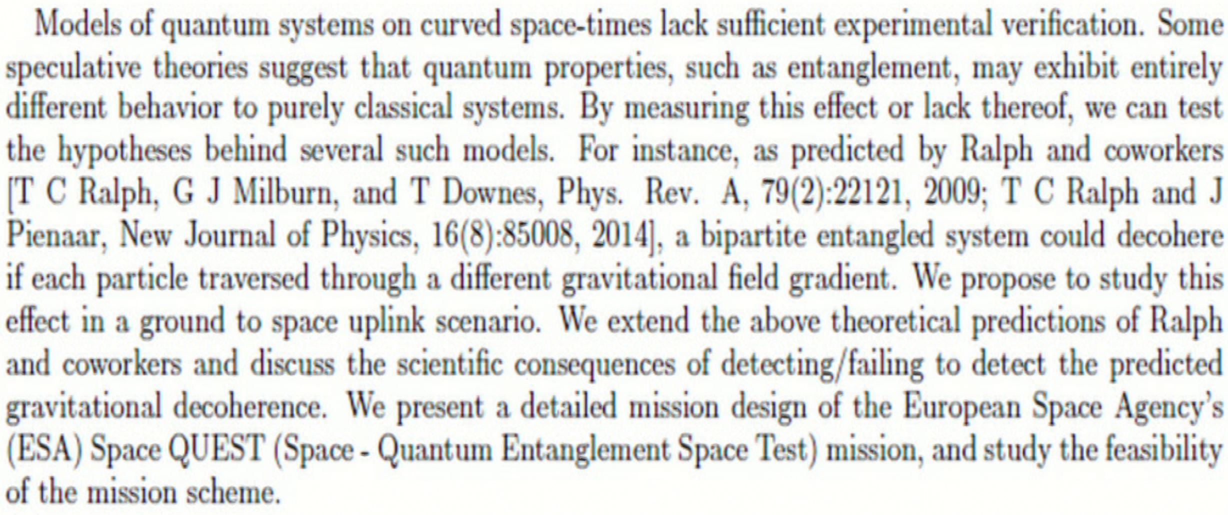
Quantum State Readout and Eppley-Hannah

We *can* consistently suppose that collapses are objective (as Eppley-Hannah assume) and that the classical gravitational degrees of freedom interact *via the local quantum state*.

This *could* allow a gravitational wave probe to get information about the local quantum state, perhaps even to be a full quantum state readout device.

A classical-quantum hybrid model of this type has no superluminality. So the Eppley-Hannah argument fails.

The Space QUEST proposal



Models of quantum systems on curved space-times lack sufficient experimental verification. Some speculative theories suggest that quantum properties, such as entanglement, may exhibit entirely different behavior to purely classical systems. By measuring this effect or lack thereof, we can test the hypotheses behind several such models. For instance, as predicted by Ralph and coworkers [T C Ralph, G J Milburn, and T Downes, Phys. Rev. A, 79(2):22121, 2009; T C Ralph and J Pienaar, New Journal of Physics, 16(8):85008, 2014], a bipartite entangled system could decohere if each particle traversed through a different gravitational field gradient. We propose to study this effect in a ground to space uplink scenario. We extend the above theoretical predictions of Ralph and coworkers and discuss the scientific consequences of detecting/failing to detect the predicted gravitational decoherence. We present a detailed mission design of the European Space Agency's (ESA) Space QUEST (Space - Quantum Entanglement Space Test) mission, and study the feasibility of the mission scheme.

Space QUEST mission proposal: Experimentally testing decoherence due to gravity

Siddarth Koduru Joshi,[1] Jacques Pienaar,[1] Timothy C. Ralph,[2] Luigi Cacciapuoti,[3] Will McCutcheon,[4] John Rarity,[4] Dirk Giggenbach,[5] Jin Gyu Lim,[6] Vadim Makarov,[7] Ivette Fuentes,[1] Thomas Scheidl,[1] Erik Beckert,[8] Mohamed Bourennane,[9] David Edward Bruschi,[10] Adan Cabello,[11] Jose Capmany,[12] Alberto Carrasco-Casado,[13] Eleni Diamanti,[14] Miloslav Dušek,[15] Dominique Elser,[16] Angelo Gulinatti,[17] Robert H. Hadfield,[18] Thomas Jennewein,[7] Rainer Kaltenbaek,[19] Michael A. Krainak,[20] Hoi-Kwong Lo,[21] Christoph Marquardt,[16] Gerard Milburn,[22] Momtchil Peev,[23] Andreas Poppe,[24] Valerio Pruneri,[25] Renato Renner,[26] Christophe Salomon,[27] Johannes Skaar,[28] Nikolaos Solomos,[29] Mario Stipčević,[30] Juan P. Torres,[31] Morio Toyoshima,[13] Paolo Villoresi,[32] Ian Walmsley,[33] Gregor Weihs,[34] Harald Weinfurter,[35] Anton Zeilinger,[1] Marek Żukowski,[36] and Rupert Ursin[1]
(Space QUEST topical team)

New J. Phys. 20, 063016 (2018)
arXiv:1703.08036

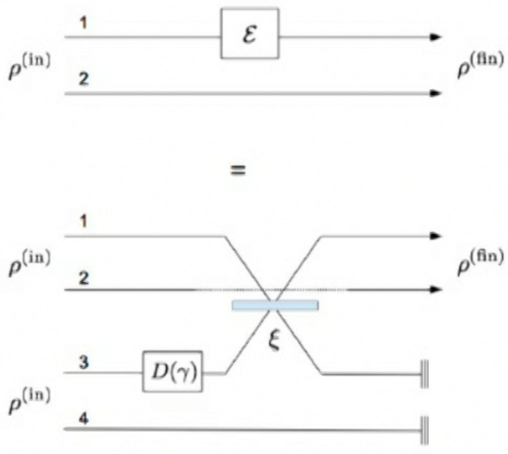


FIG. 1: The event operator formalism can be understood as a nonlinear map $\mathcal{E}$ acting on the mode 1 as it travels through curved space-time. This map is equivalent to a displacement followed by a beamsplitter as depicted in the lower diagram. It is nonlinear because ξ, γ depend on the initial state, and because the initial state has to be "copied" to modes 3, 4, which violates the no-cloning theorem. In this diagram, there are two copies of the state $\rho^{(\mathrm{in})}$; one acts on the modes 1, 2 and the other acts on the modes 3, 4.

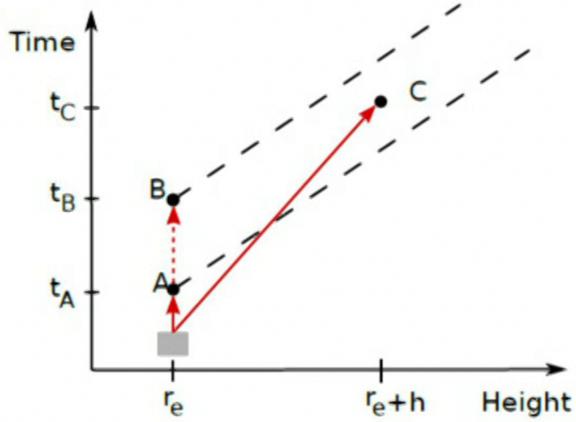
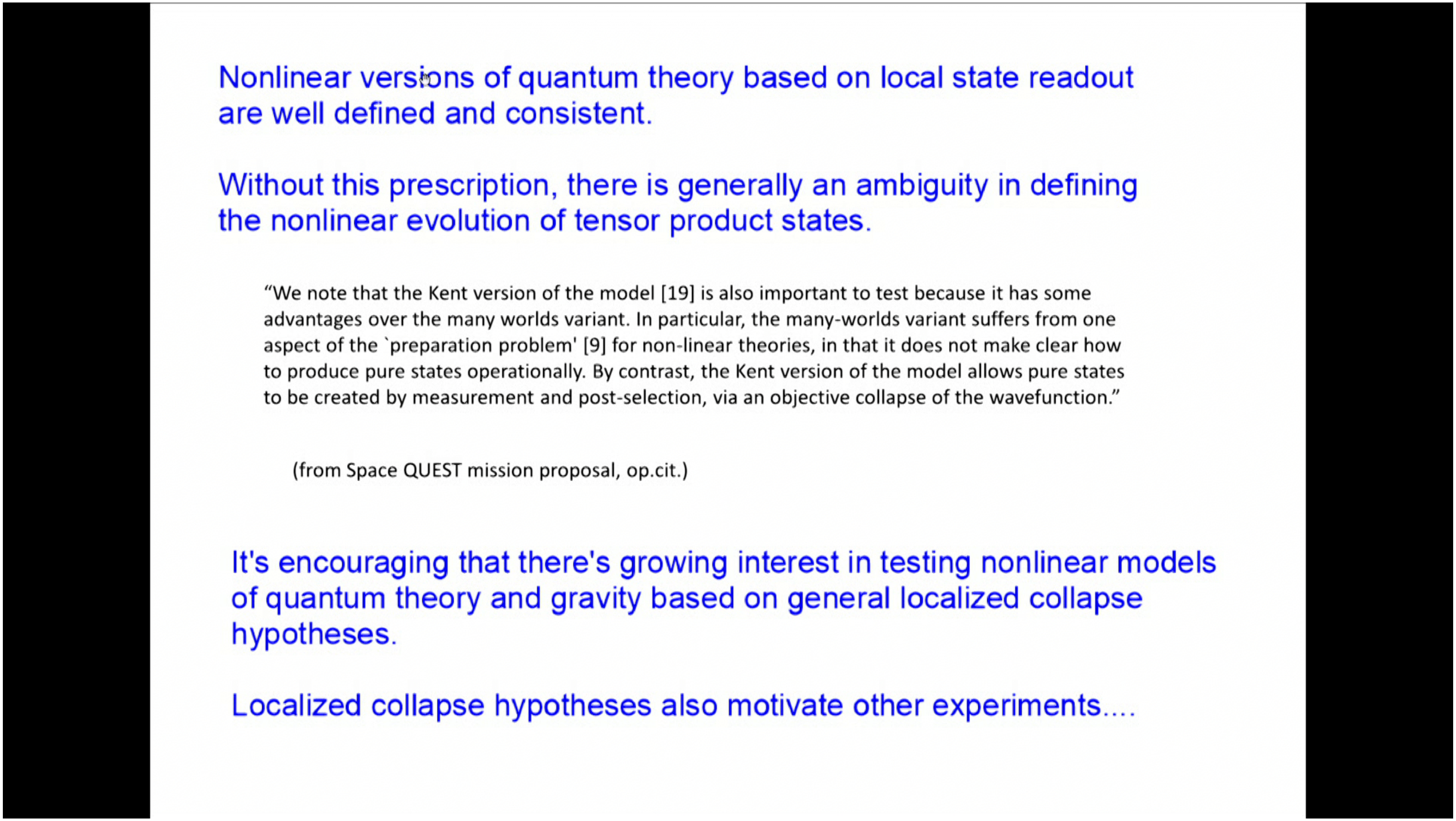


FIG. 2: A space-time diagram showing the causal relationship between the detectors. The source (gray box) produces two photons, one of which is delayed on the ground and detected at time t_A or t_B (events A and B) while the other (mode 1) is sent to space and detected at time t_C (event C). The dotted lines indicate the path that would be taken by light traveling in a vacuum. As a result, the detection event A is in the causal past of C, while event B is causally separated from C. If the event operator model is modified to take into account the proposal of Kent [18, 19], then only photons detected at events B and C will experience gravitational decoherence.



Nonlinear versions of quantum theory based on local state readout are well defined and consistent.

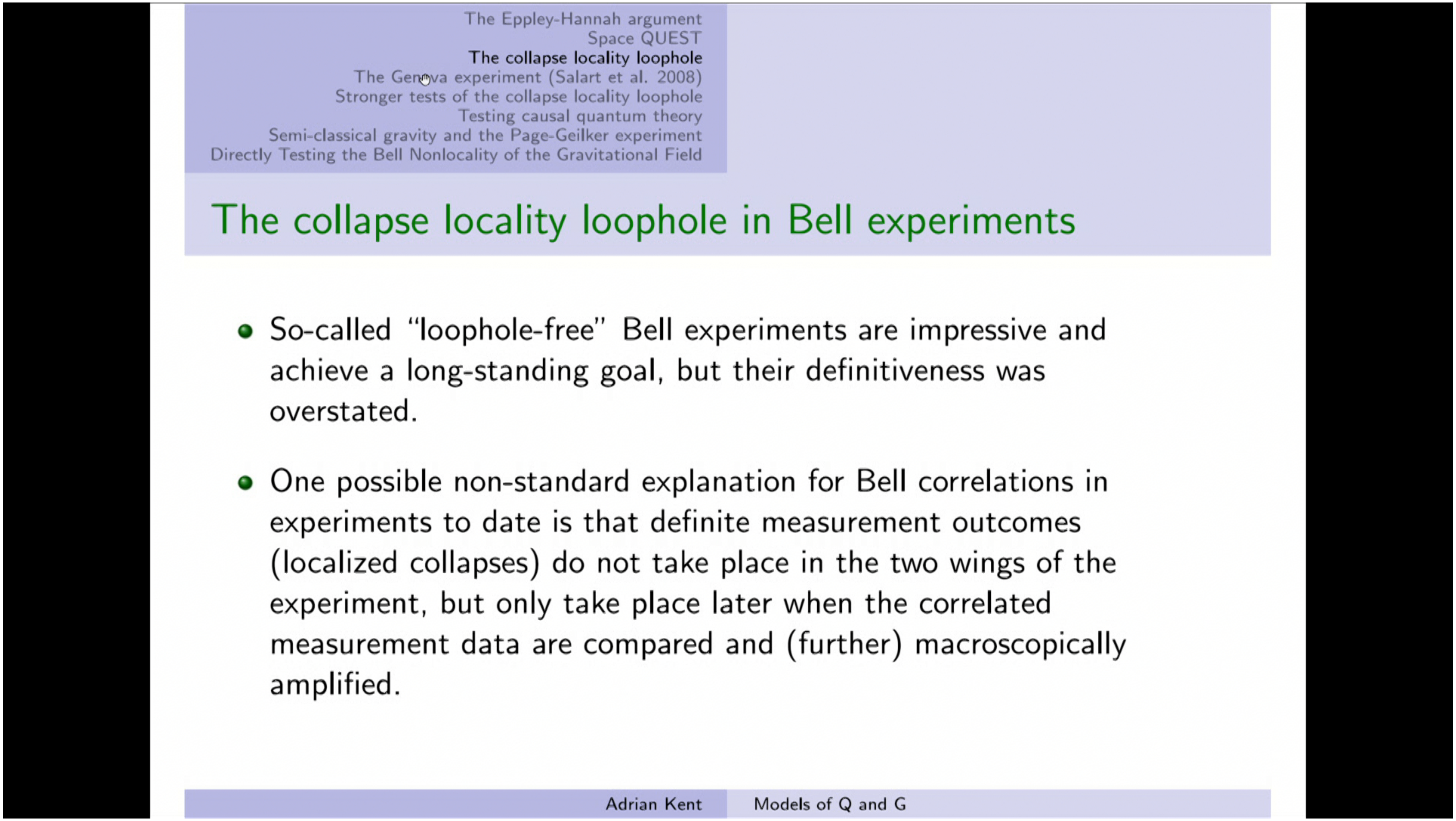
Without this prescription, there is generally an ambiguity in defining the nonlinear evolution of tensor product states.

> “We note that the Kent version of the model [19] is also important to test because it has some advantages over the many worlds variant. In particular, the many-worlds variant suffers from one aspect of the `preparation problem' [9] for non-linear theories, in that it does not make clear how to produce pure states operationally. By contrast, the Kent version of the model allows pure states to be created by measurement and post-selection, via an objective collapse of the wavefunction.”

(from Space QUEST mission proposal, op.cit.)

It's encouraging that there's growing interest in testing nonlinear models of quantum theory and gravity based on general localized collapse hypotheses.

Localized collapse hypotheses also motivate other experiments....



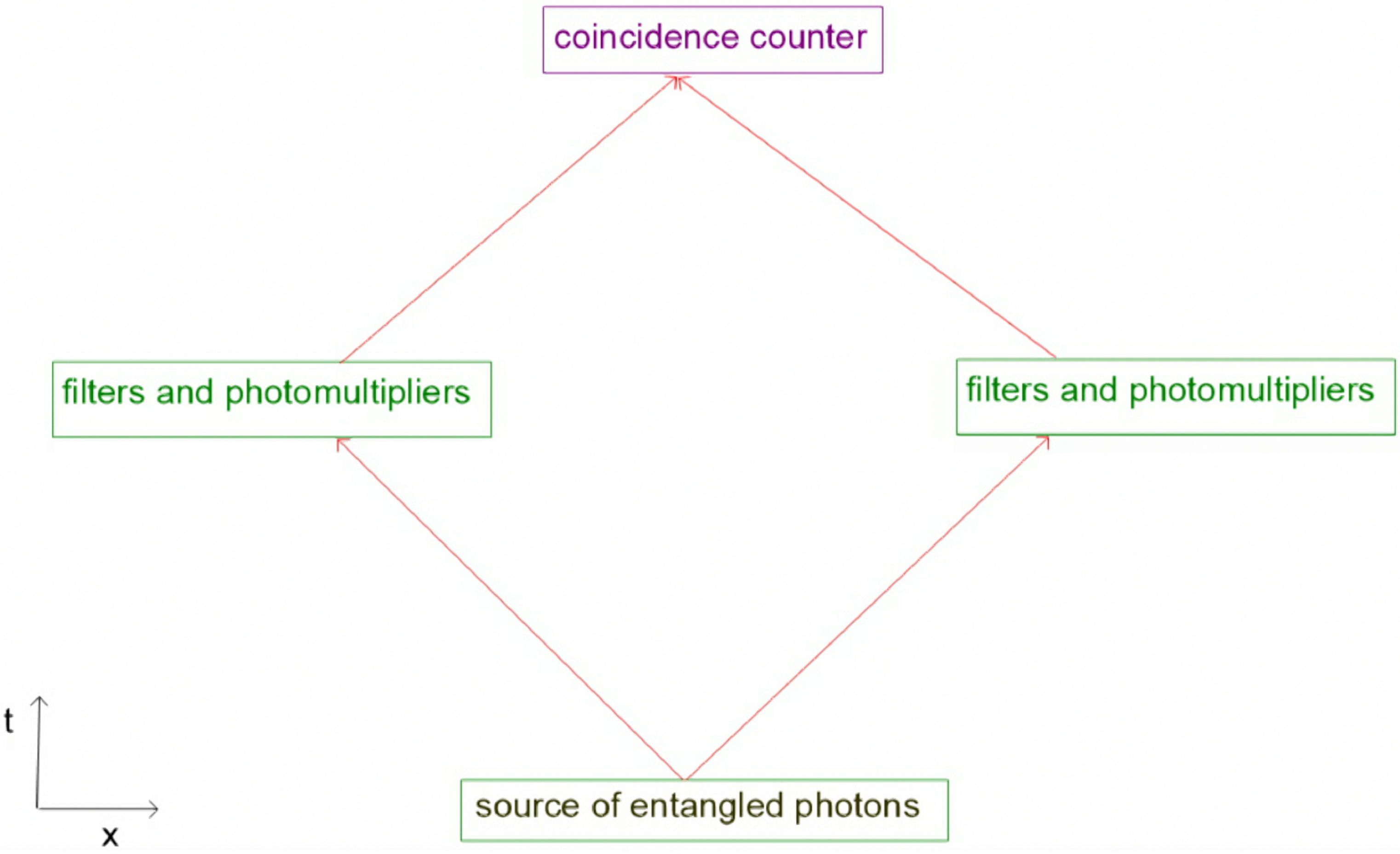
The collapse locality loophole in Bell experiments

- So-called "loophole-free" Bell experiments are impressive and achieve a long-standing goal, but their definitiveness was overstated.
- One possible non-standard explanation for Bell correlations in experiments to date is that definite measurement outcomes (localized collapses) do not take place in the two wings of the experiment, but only take place later when the correlated measurement data are compared and (further) macroscopically amplified.

The collapse locality loophole in Bell experiments

- The loophole plausibly or definitely applies for most well known localized collapse hypotheses (Wigner, gravitationally induced collapse, GRWP spontaneous localization).
- Standard Bell experiments don't produce outcome signals that involve macroscopic superpositions, or are consciously observed until (generally long) after they are brought together and checked for correlation.

The collapse locality loophole (AK Phys. Rev. A 72, 012107 (2005)



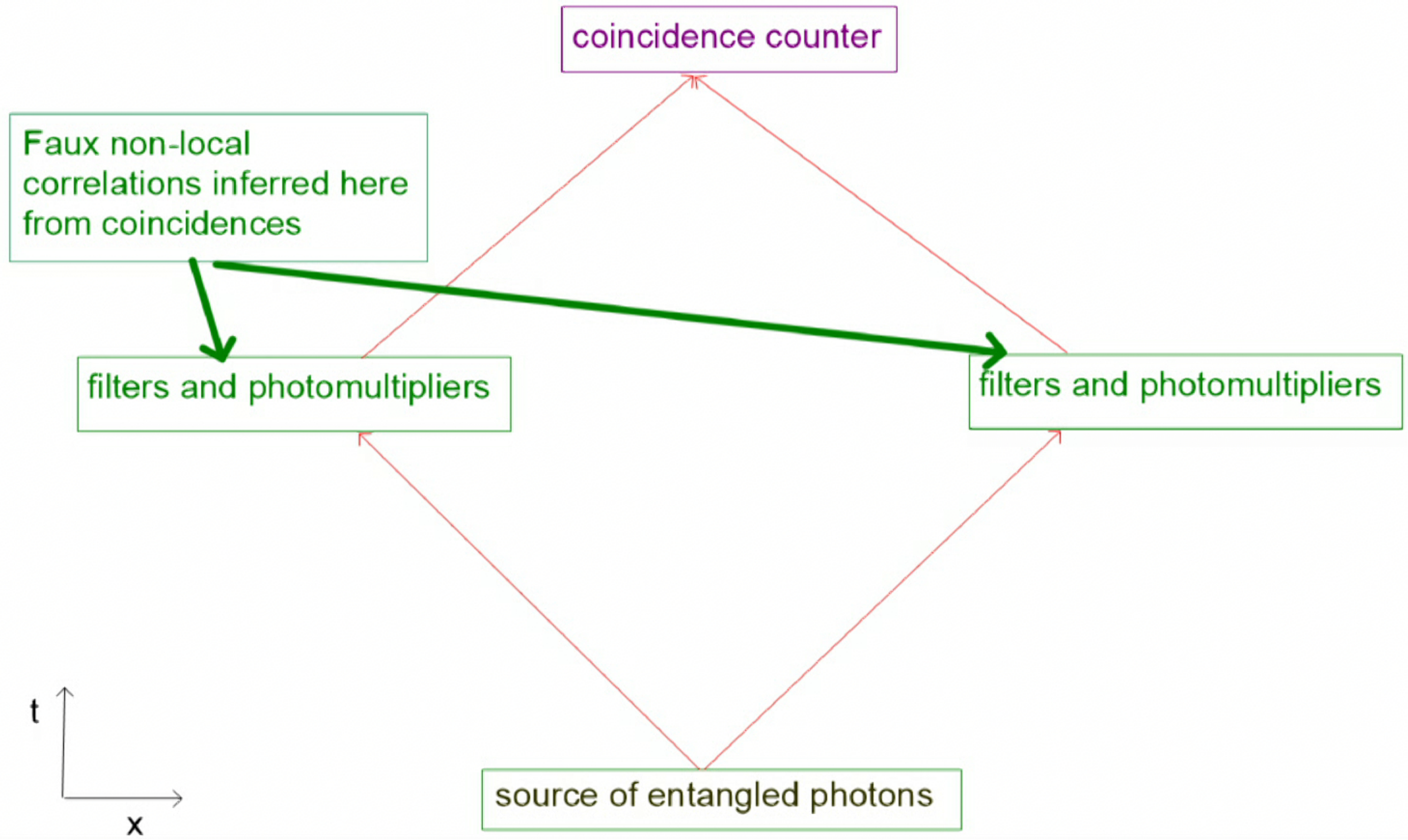
coincidence counter

filters and photomultipliers

filters and photomultipliers

source of entangled photons

The collapse locality loophole (AK Phys. Rev. A 72, 012107 (2005)



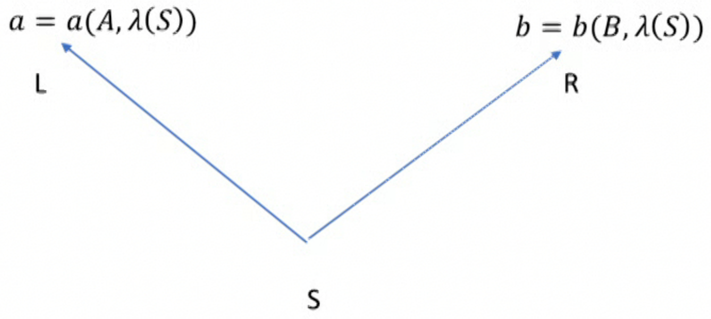
coincidence counter

Faux non-local correlations inferred here from coincidences

filters and photomultipliers

filters and photomultipliers

source of entangled photons



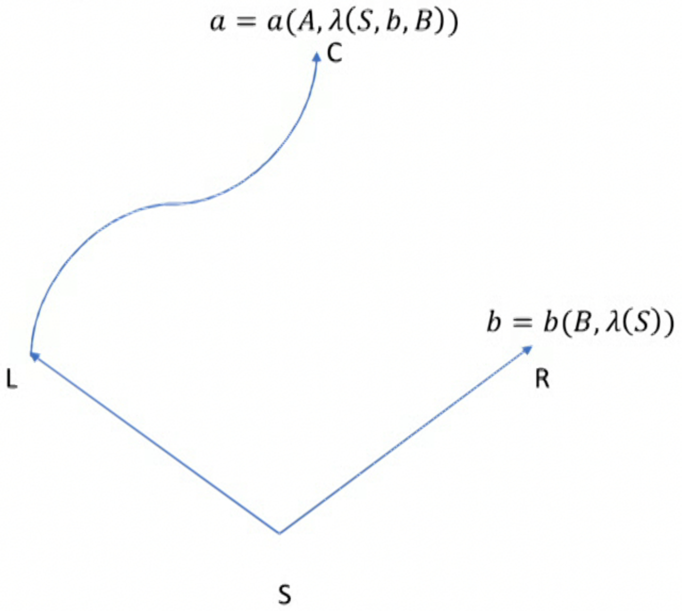
$a = a(A, \lambda(S))$

$b = b(B, \lambda(S))$

L

R

S

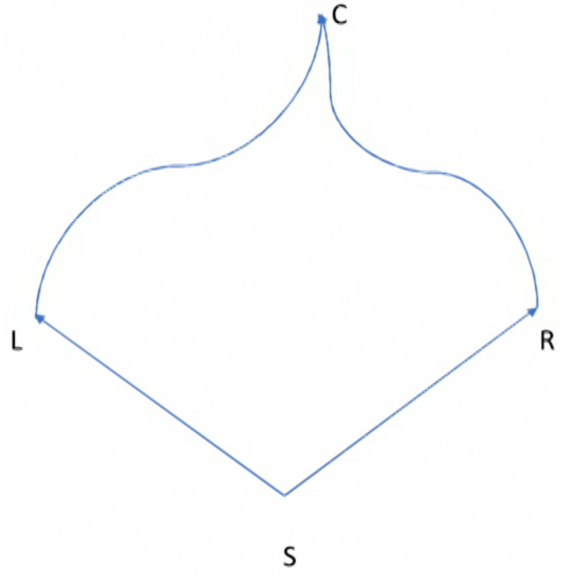


$$a = a(A, \lambda(S, b, B))$$

$$b = b(B, \lambda(S))$$

A Bell experiment in which the collapse locality loophole allows records of outcomes, apparently from one wing, to depend on measurement settings and outcomes in the other wing.

$a = a(A, B, \lambda(S)),\ b = b(A, B, \lambda(S))$



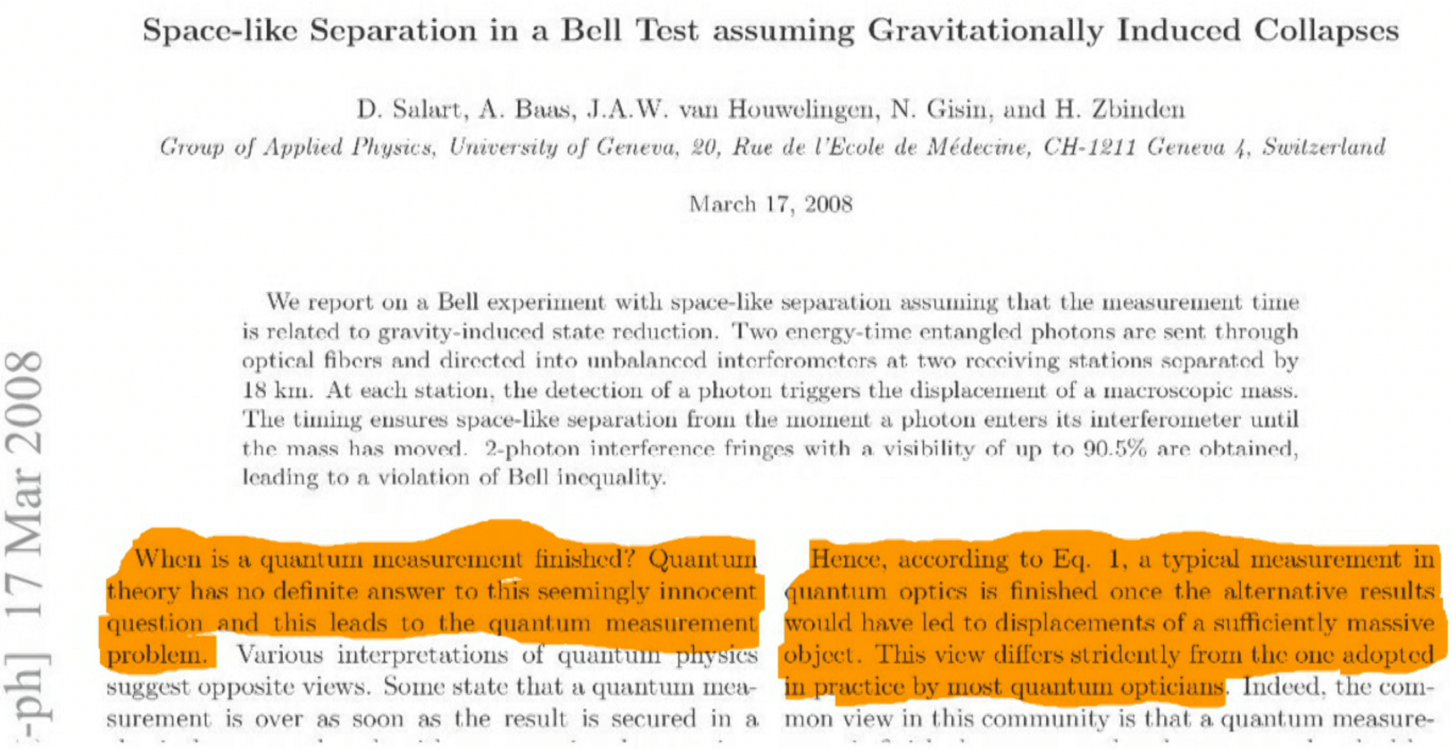
Another application of the collapse locality loophole.

Here the records of outcomes, apparently from both wings, are actually generated together at point C.

The recorded measurement outcomes for each wing may depend on both measurement settings.

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

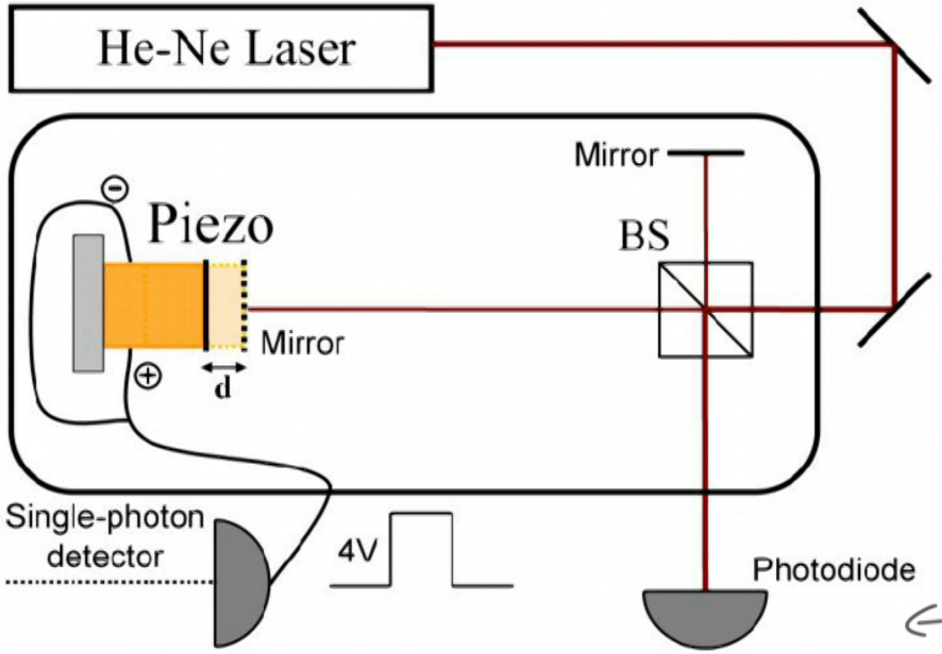
We report on a Bell experiment with space-like separation assuming that the measurement time is related to gravity-induced state reduction. Two energy-time entangled photons are sent through optical fibers and directed into unbalanced interferometers at two receiving stations separated by 18 km. At each 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-

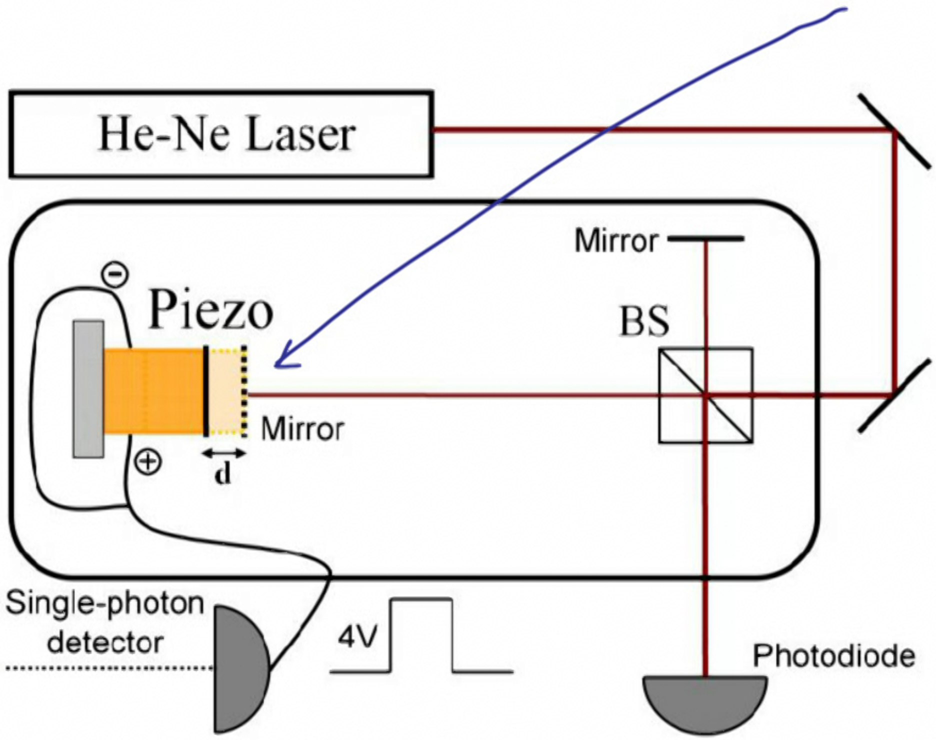
Key experimental ideas

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.)



Time from photons entering detector to mirror displacing is

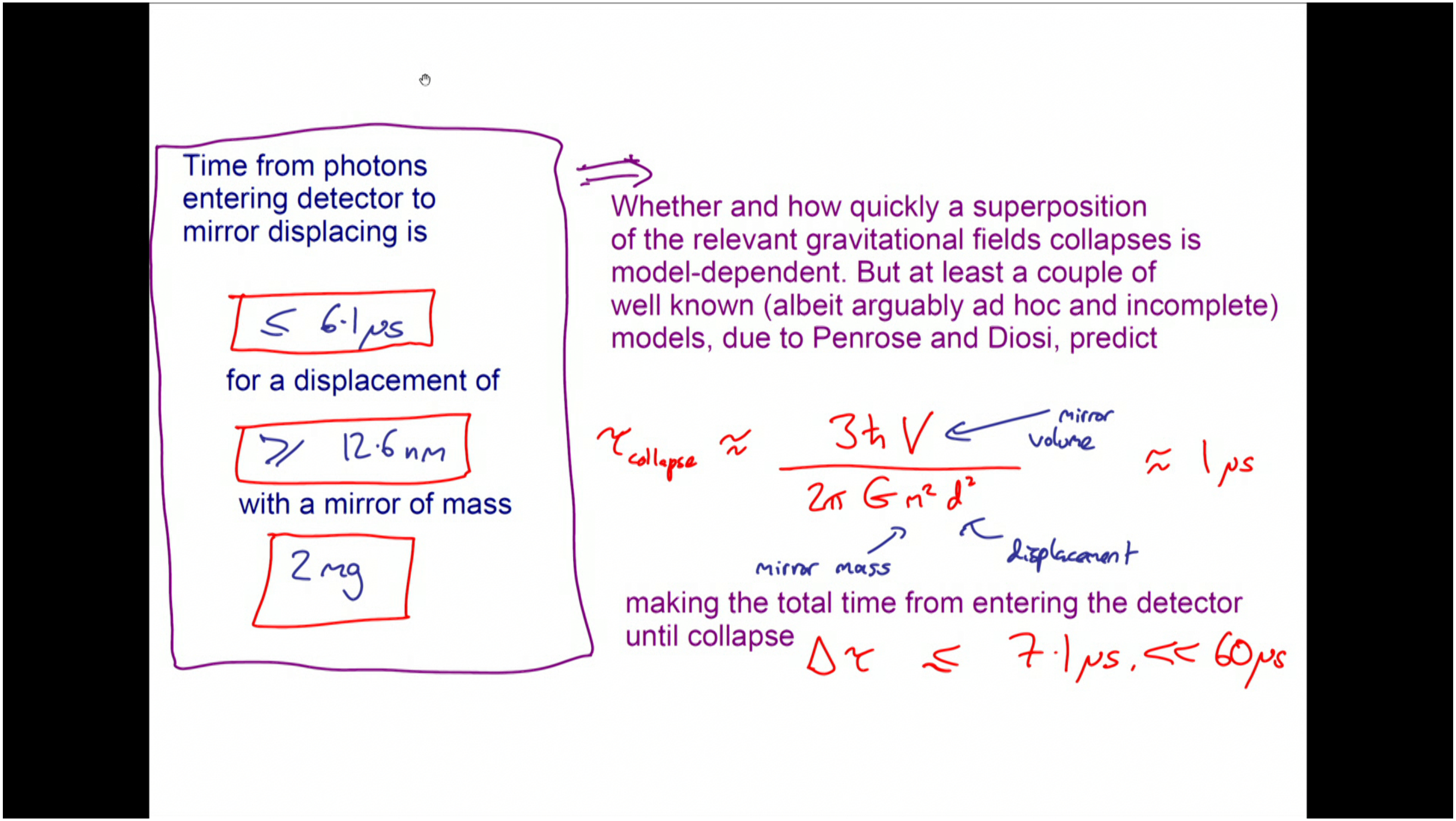
$\boxed{\leq 6.1\,\mu s}$

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

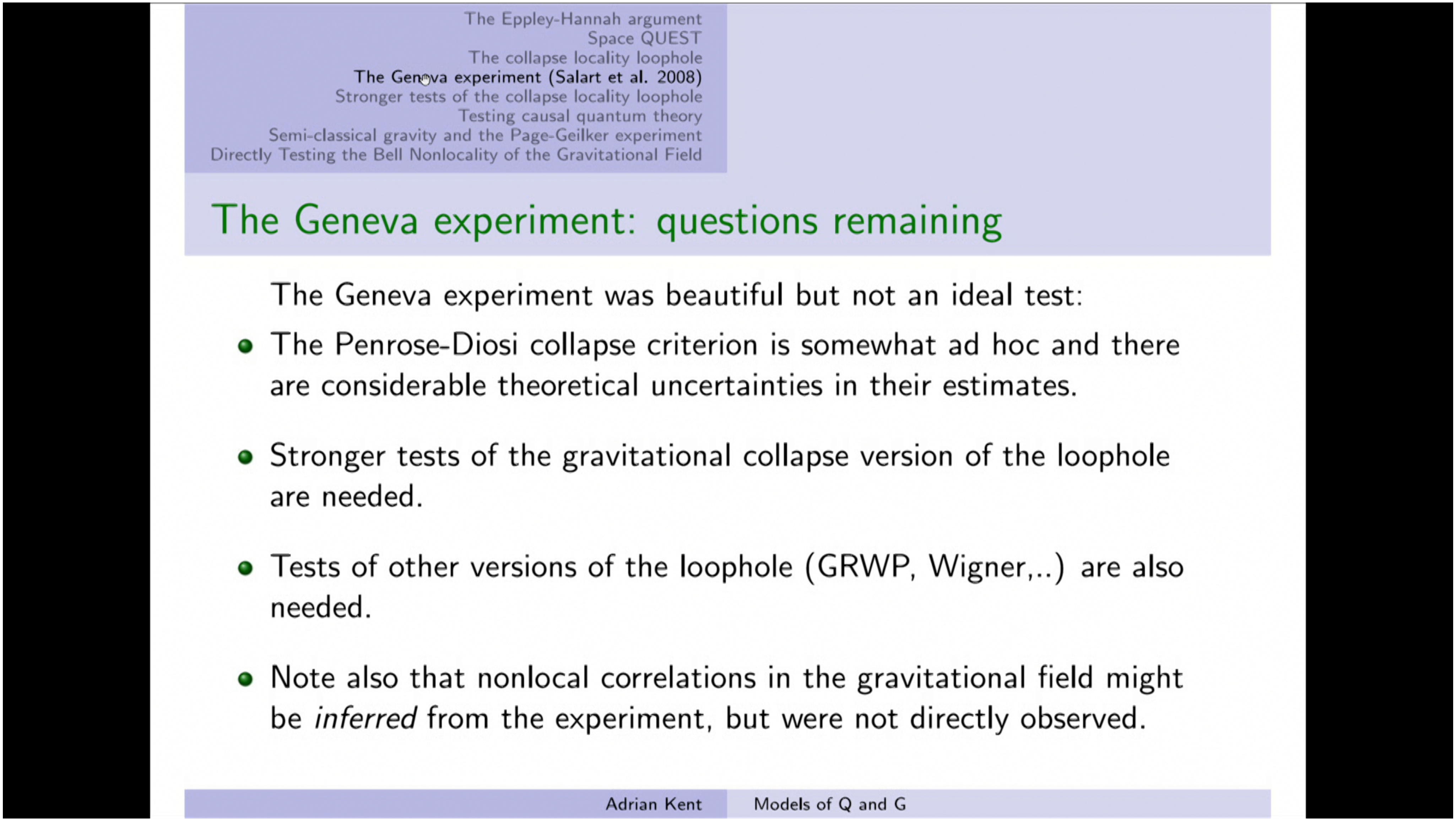
$$\tau_{collapse} \approx \frac{3\hbar V}{2\pi G m^2 d^2} \approx 1\,\mu s$$

mirror volume

mirror mass

displacement

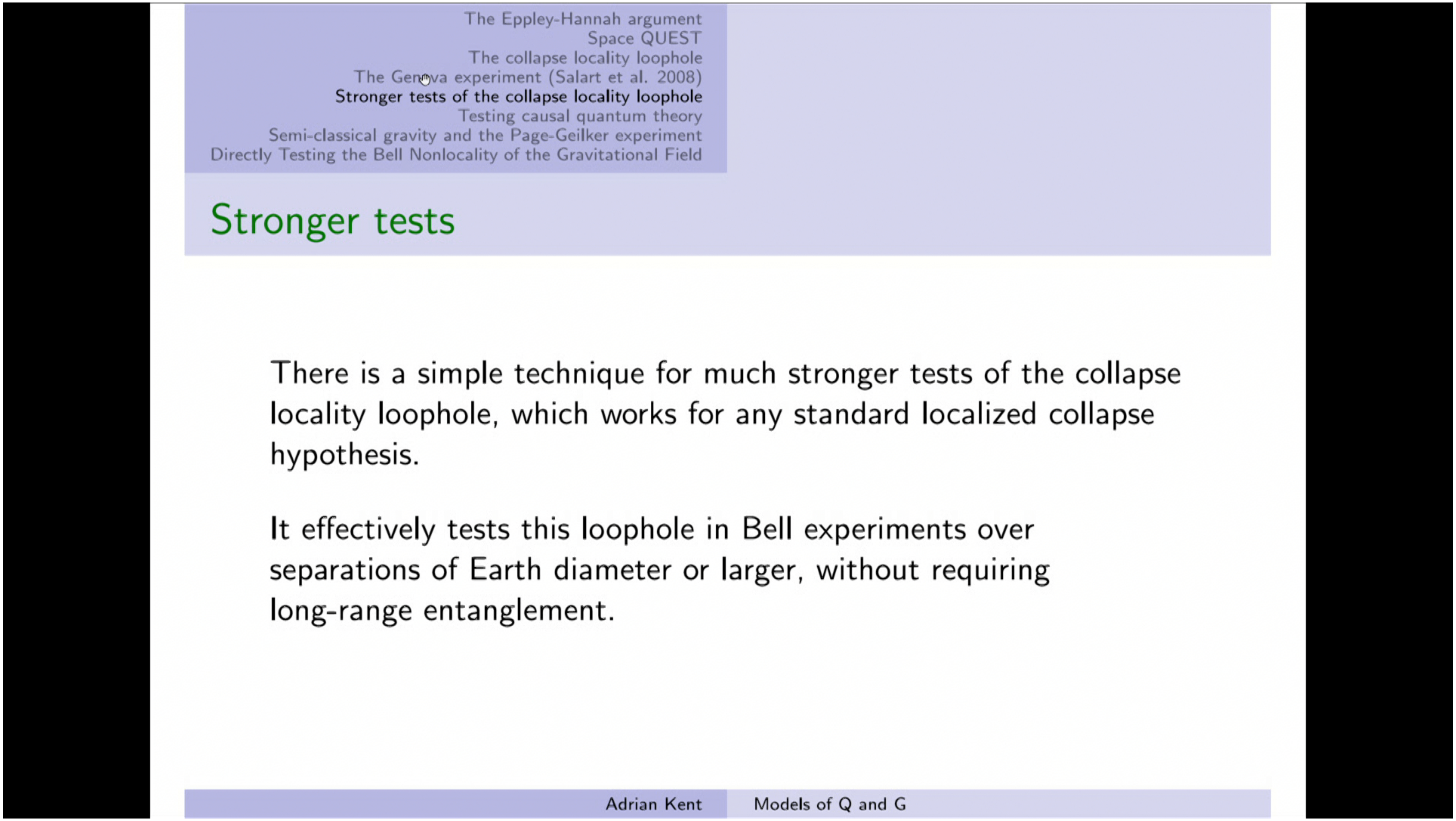
making the total time from entering the detector until collapse $\Delta\tau \lesssim 7.1\,\mu s, \ll 60\,\mu s$



The Geneva experiment: questions remaining

The Geneva experiment was beautiful but not an ideal test:

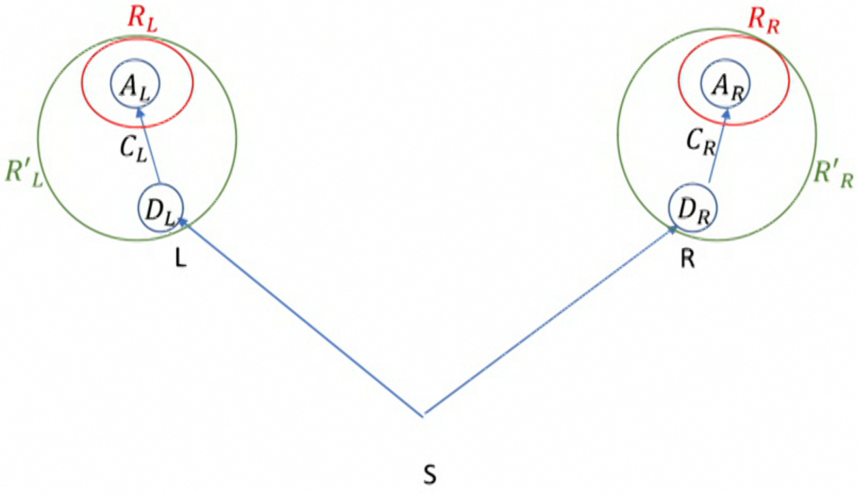
- The Penrose-Diosi collapse criterion is somewhat ad hoc and there are considerable theoretical uncertainties in their estimates.
- Stronger tests of the gravitational collapse version of the loophole are needed.
- Tests of other versions of the loophole (GRWP, Wigner,..) are also needed.
- Note also that nonlocal correlations in the gravitational field might be *inferred* from the experiment, but were not directly observed.



Stronger tests

There is a simple technique for much stronger tests of the collapse locality loophole, which works for any standard localized collapse hypothesis.

It effectively tests this loophole in Bell experiments over separations of Earth diameter or larger, without requiring long-range entanglement.



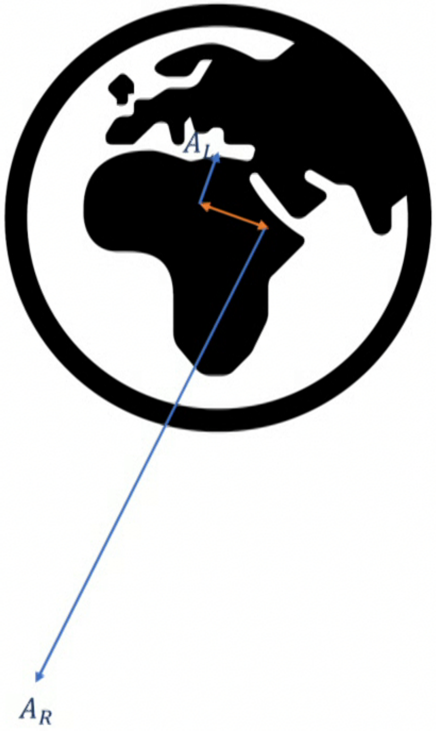
Schematic description of an experiment designed to close some version of the collapse locality loophole.

The detector readings are communicated via channels to apparatus which, in an appropriate sense, amplify them to ensure that collapses are induced. The regions R_L and R_R are space-like separated.

It may seem that the regions R' on each wing need to be spacelike separated, as in the Salart et al. experiment.
But actually, if the local collapse hypothesis implies no collapse before A, then only the regions R on each wing need be spacelike separated.

A long range terrestrial experiment designed to test the collapse locality loophole.

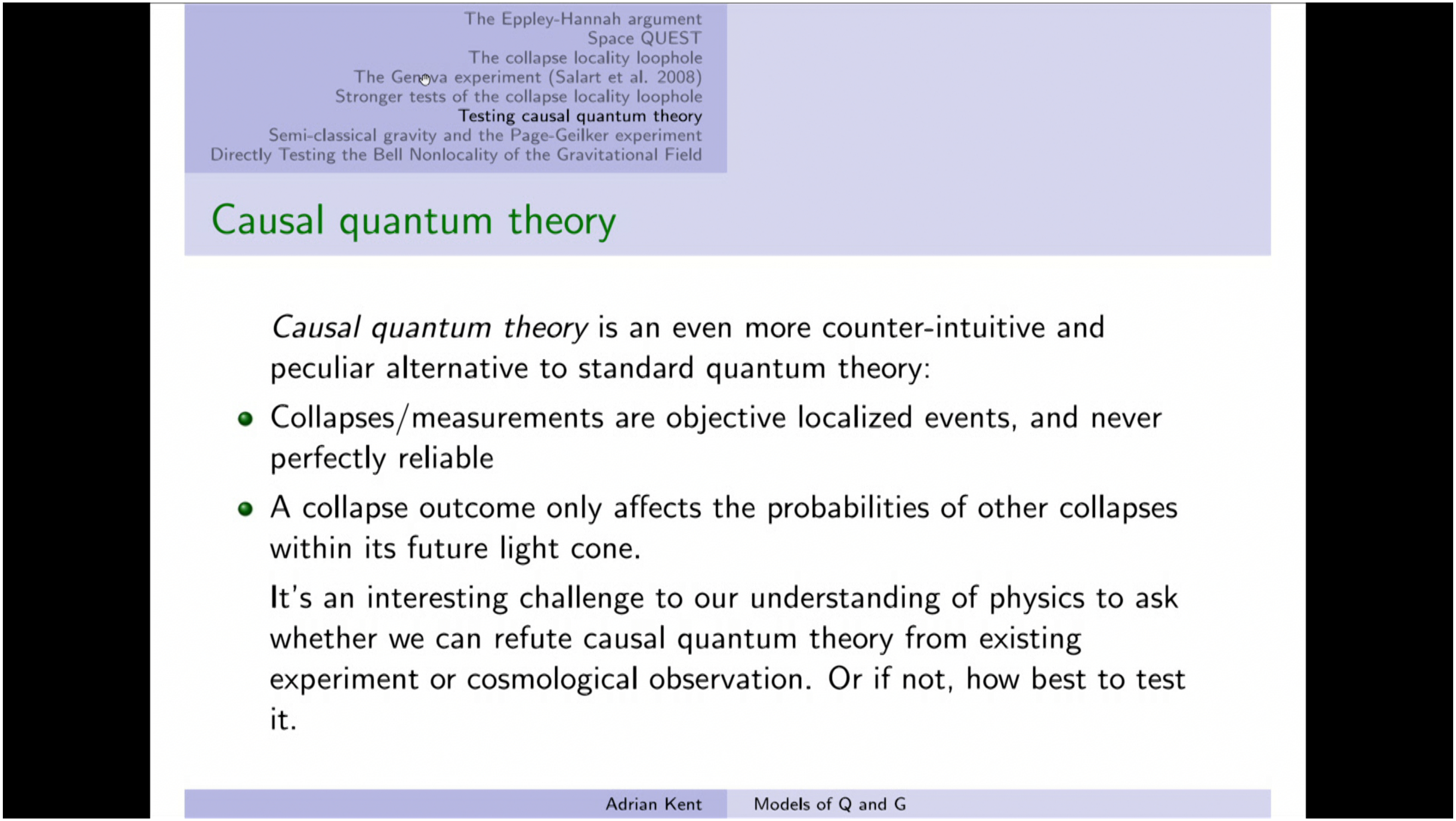
The detector readings from wings of a short range Bell experiment are communicated to amplifying apparatus at antipodal points. By introducing delays if necessary, they are input into the apparatus nearly simultaneously in rest frame, so as to maximize the collapse time for which space-like separated collapses would ensure.



A partly space-based version of the previous experiment.

One signal is sent to an apparatus on a space-based laboratory, while the other goes to an apparatus on a ground station.

To test the Wigner version of the collapse locality loophole, the apparatus may include human observers.



Causal quantum theory

Causal quantum theory is an even more counter-intuitive and peculiar alternative to standard quantum theory:

- Collapses/measurements are objective localized events, and never perfectly reliable
- A collapse outcome only affects the probabilities of other collapses within its future light cone.

It's an interesting challenge to our understanding of physics to ask whether we can refute causal quantum theory from existing experiment or cosmological observation. Or if not, how best to test it.