Title: Quantum Models of CTCs and a space-based experiment

Speakers: Tim Ralph

Collection: Indefinite Causal Structure

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Abstract: I will discuss various models of how quantum systems might interact with Closed Time-like Curves and some of the curious effects that can arise. I will then use this to motivate a speculative gravitational decoherence model and describe a recent space-based experiment which made the first test of such models.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

QUANTUM MODELS OF CTCS AND A SPACE BASED EXPERIMENT

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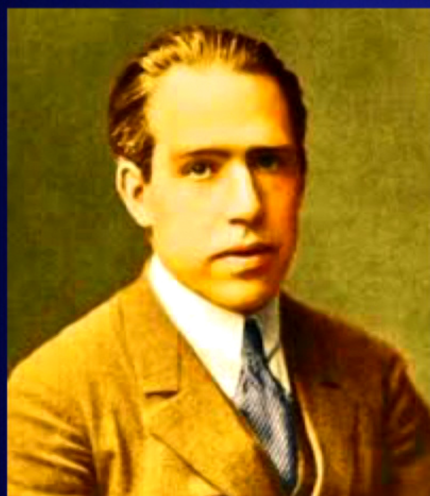
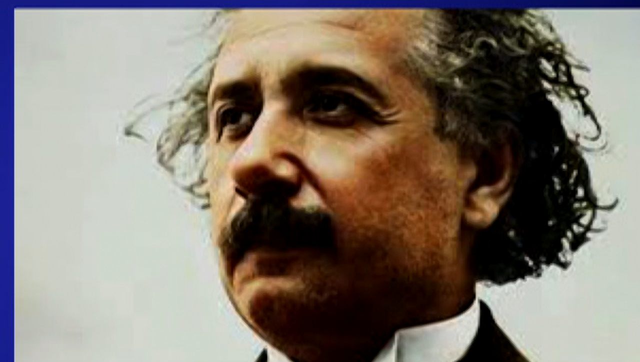
CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY

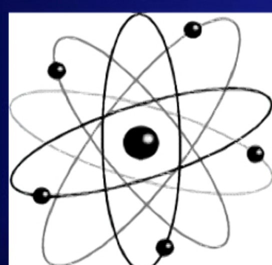
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

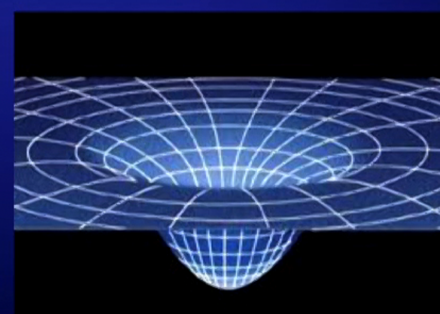
$Q|O\rangle Q|I\rangle$ Quantum Optics Quantum Information Theory Group

Quantum Mechanics and General Relativity are incompatible at a fundamental level

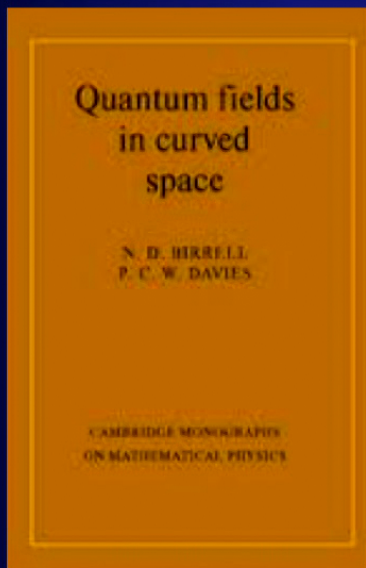


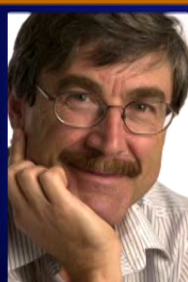






Standard approach to combining quantum mechanics and general relativity



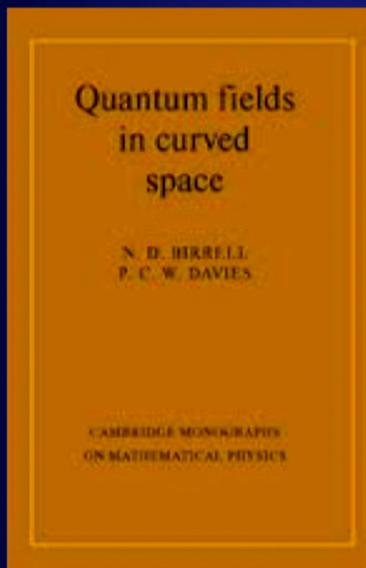


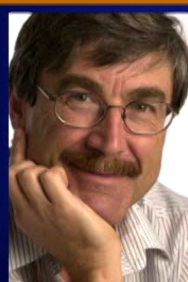
* Quantizes fields on a classical back-ground metric.

* Analogous to semi-classical quantum optics.

but….

Standard approach to combining quantum mechanics and general relativity



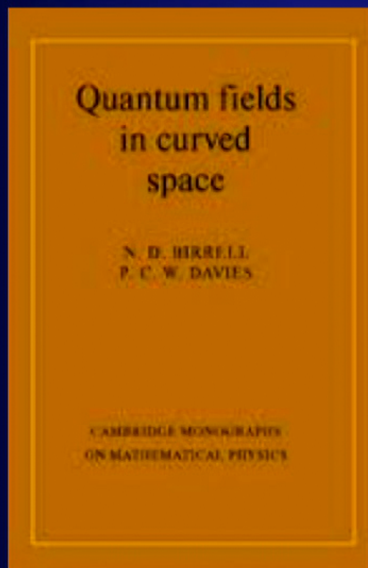


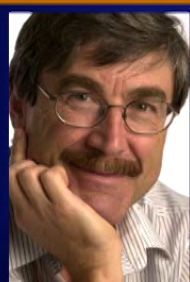
* Analogy with QO breaks
  because it is not known
  if the metric can be quantized.

* Calculations can be difficult
  so untested approximations
  and assumptions are needed,

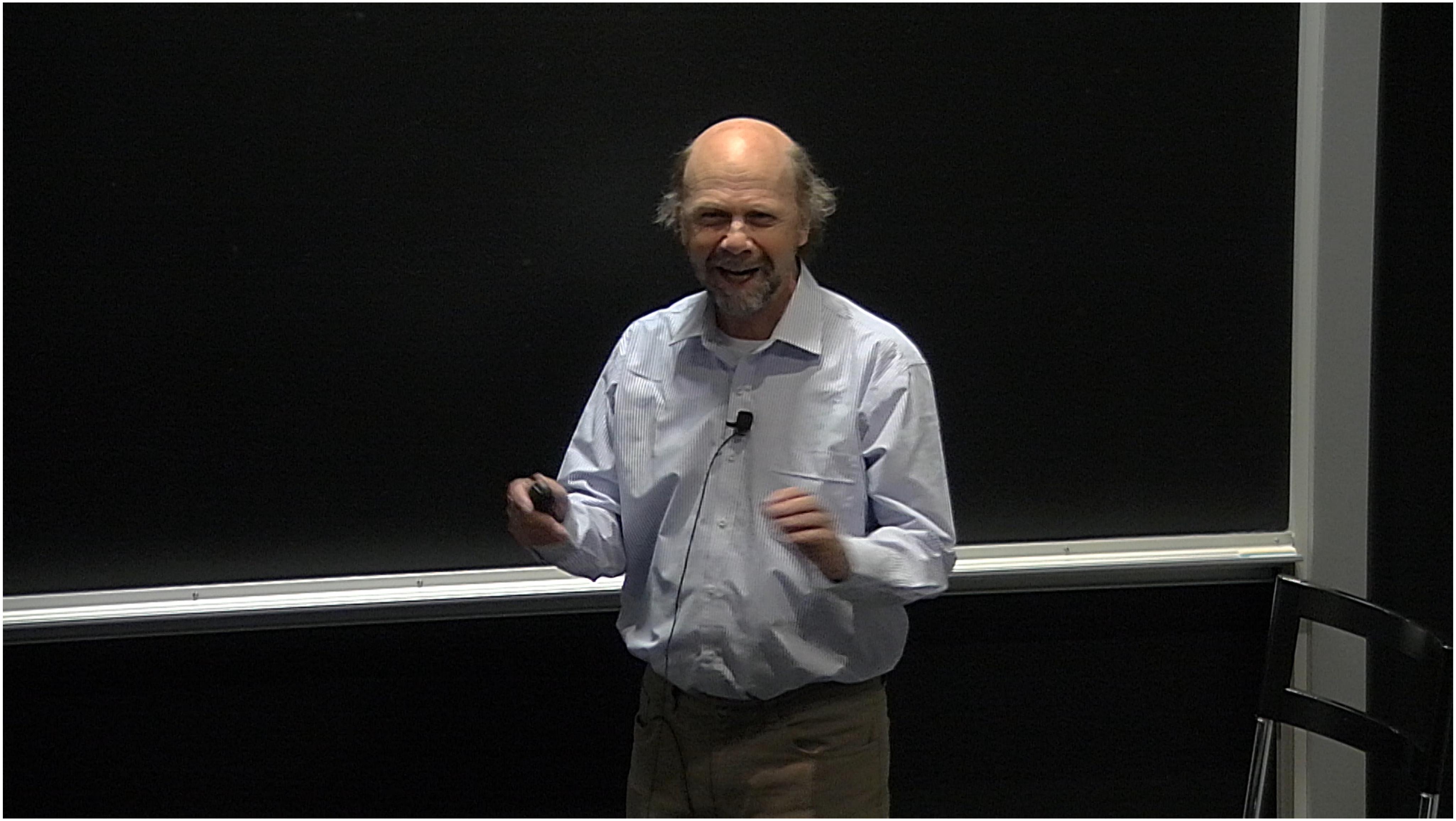
and….

Standard approach to combining quantum mechanics and general relativity





* **There have been virtually no experimental tests!**



Reconciling quantum mechanics and general relativity:

* Widely believed that General Relativity
must change on the microscopic scale
to be consistent with Quantum Mechanics

but…

* Maybe Quantum Mechanics must also
change on the macroscopic scale to be
consistent with General Relativity

Problems with non-hyperbolic spacetimes:

* CTCs can lead to paradoxes in classical mechanics

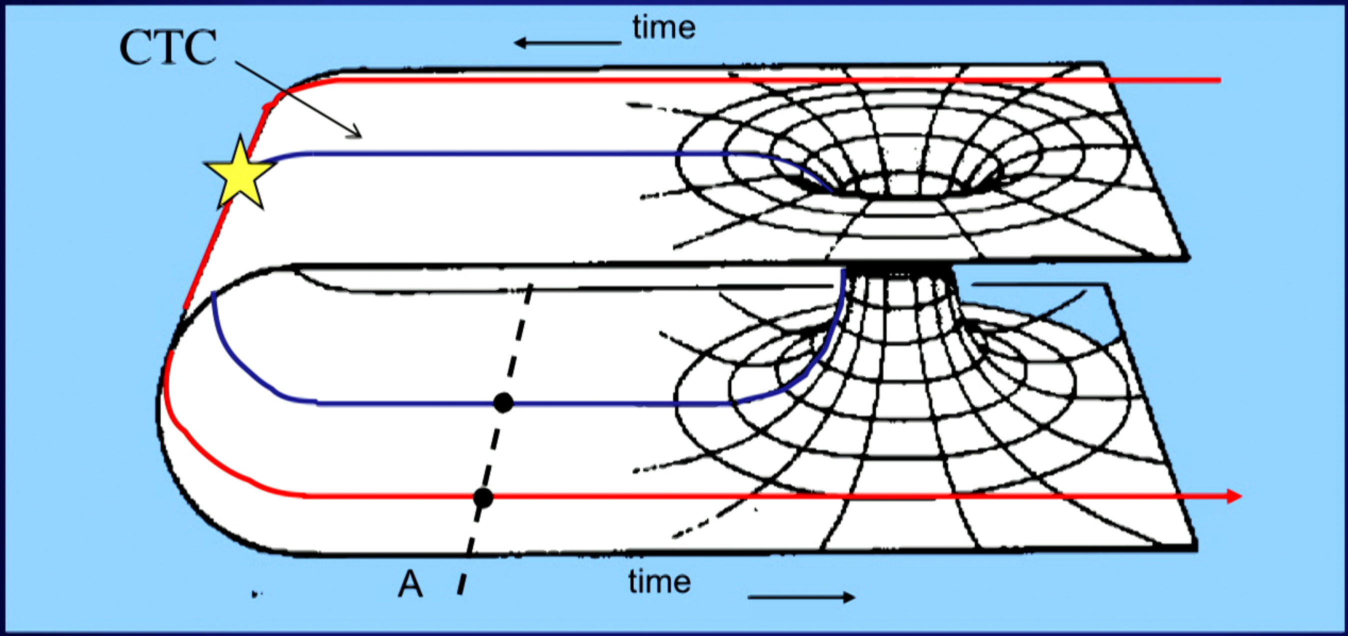
and

* Quantum field theory is inconsistent with CTCs

Intriguingly it is possible to resolve both issues via a modification to quantum field theory

GR allows non-hyperbolic spacetime geometry

Time-like Wormhole



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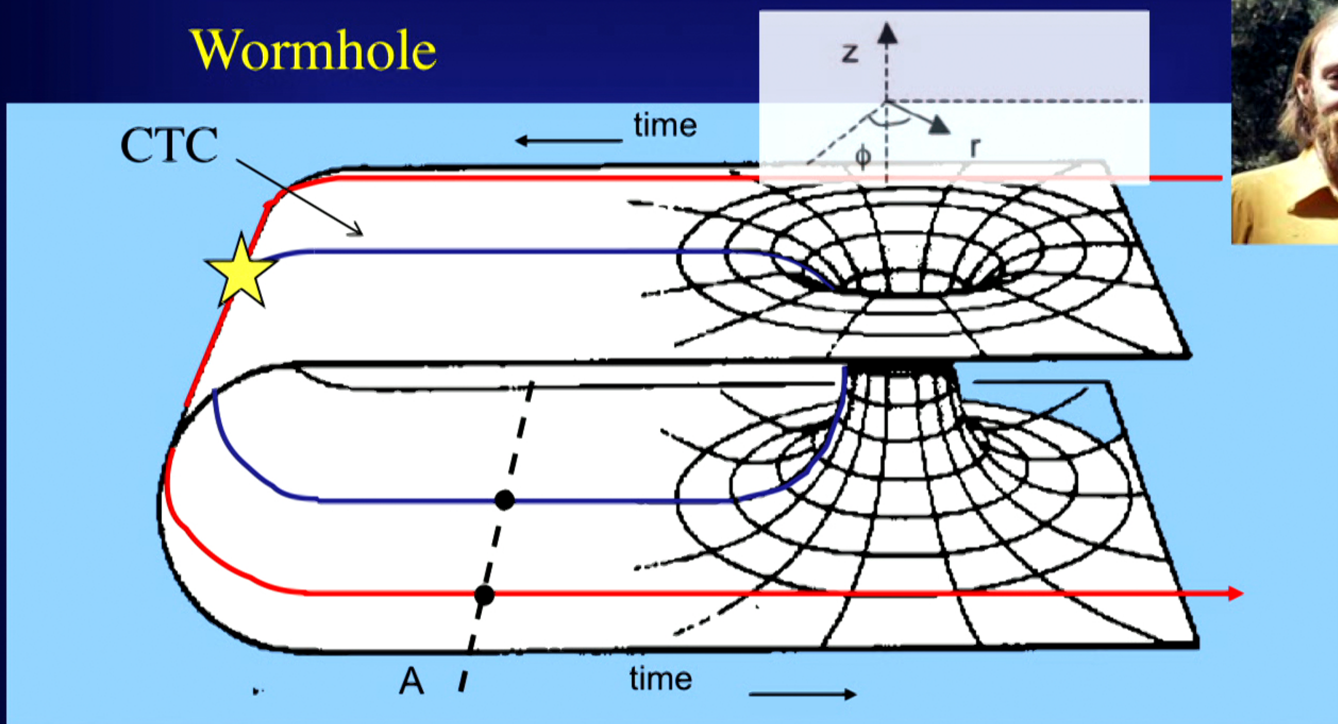
Wormhole



$$ds^2 = -\exp(2\Phi)\,dt^2 + dr^2 \frac{1}{1 - b(r)/r} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2).$$

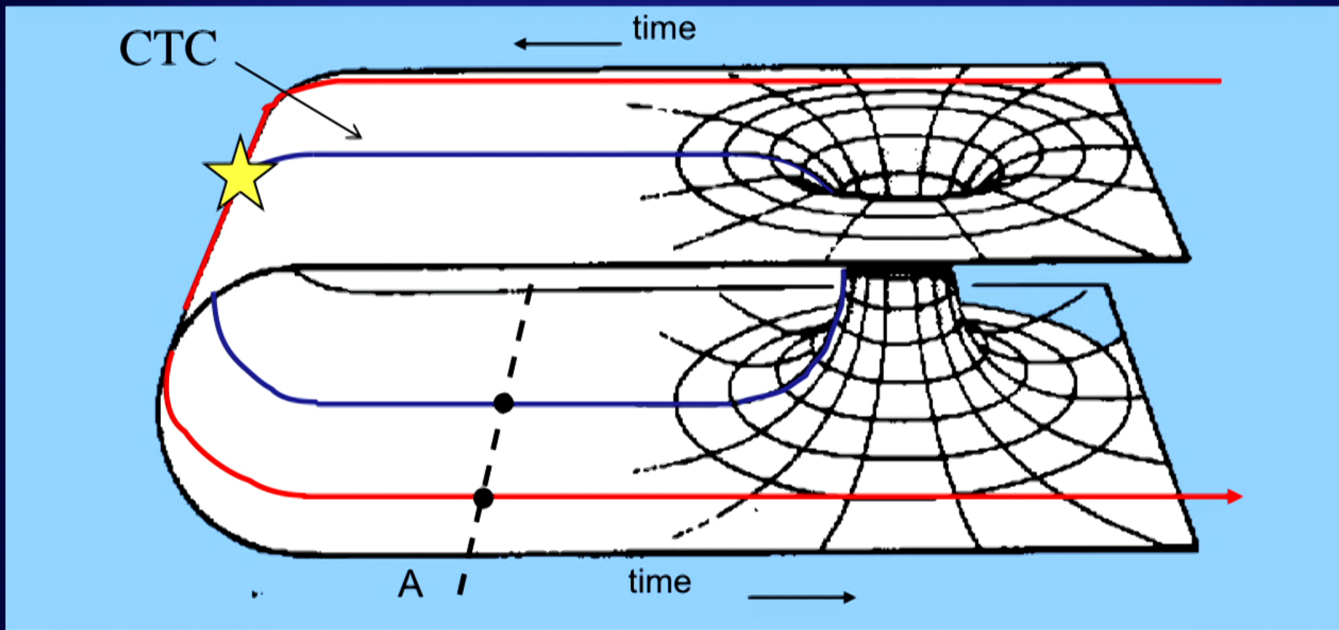
$\Phi(r) = 0$ $\qquad$ $b(r) = 0$ for $r > b_0 + a_0$

$b(r) = b_0(1 - (r - b_0)/a_0)^2$ for $b_0 < r < b_0 + a_0$

$\tau \simeq \pi a_0/v \gtrsim (a_0/b_0)^{1/2}$ s

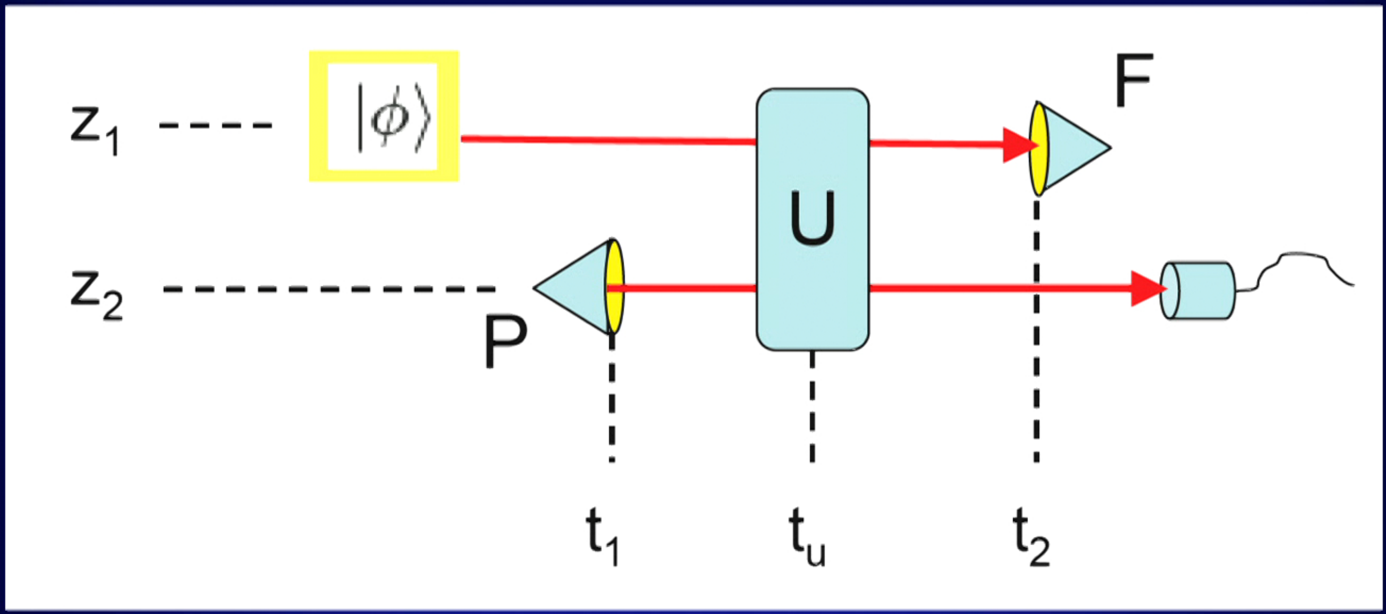
GR allows non-hyperbolic spacetime geometry

Time-like Wormhole



What happens if we place quantum fields on this type of background?

Quantum Mechanics on a Closed Timelike Curve



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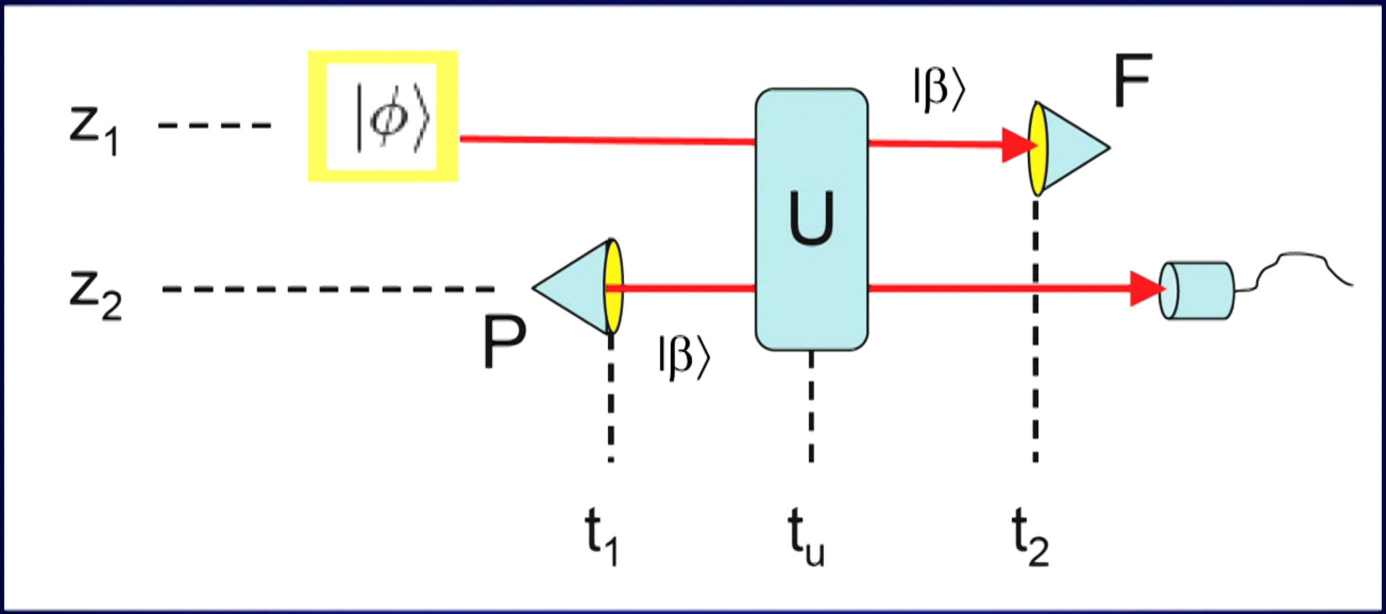
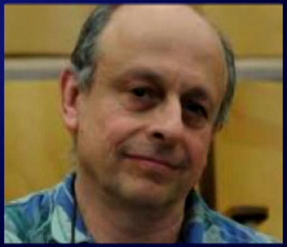
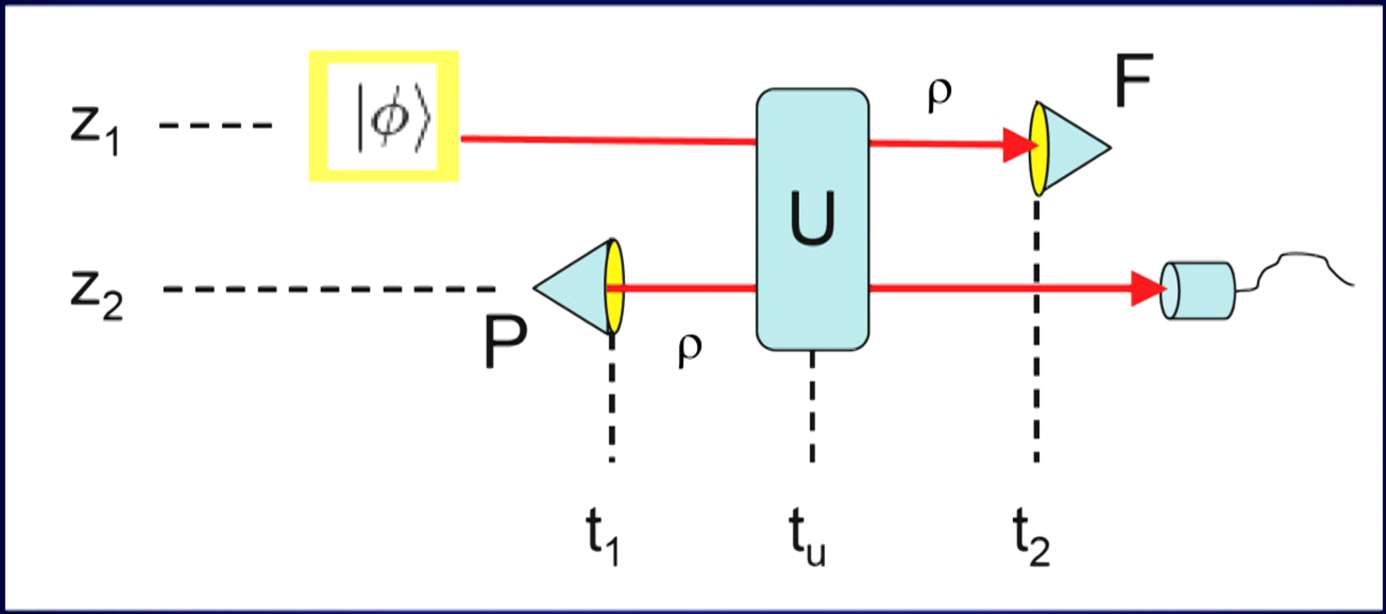


(i) Path integral approach (P-CTC) – match individual trajectories.

(i) H.D.Politzer, Phys.Rev.D, **49**, 3981 (1994)



Quantum Mechanics on a Closed Timelike Curve

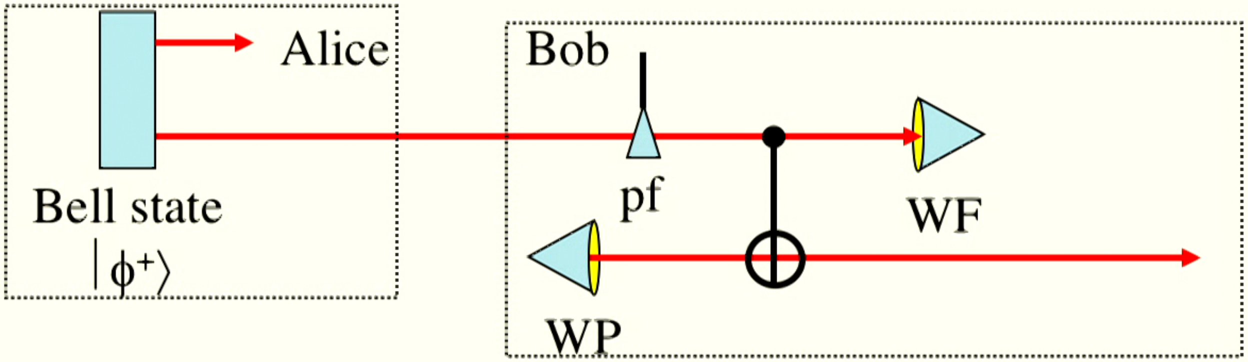


(i) Path integral approach (P-CTC) – match individual trajectories.

(ii) Deutsch approach – match reduced density operators.

(i) H.D.Politzer, Phys.Rev.D, **49**, 3981 (1994)
(ii) D.Deutsch, Phys.Rev.D, **44**, 3197 (1991)

P-CTC Radio to the Past



T.C.Ralph, arXiv:1107.4675

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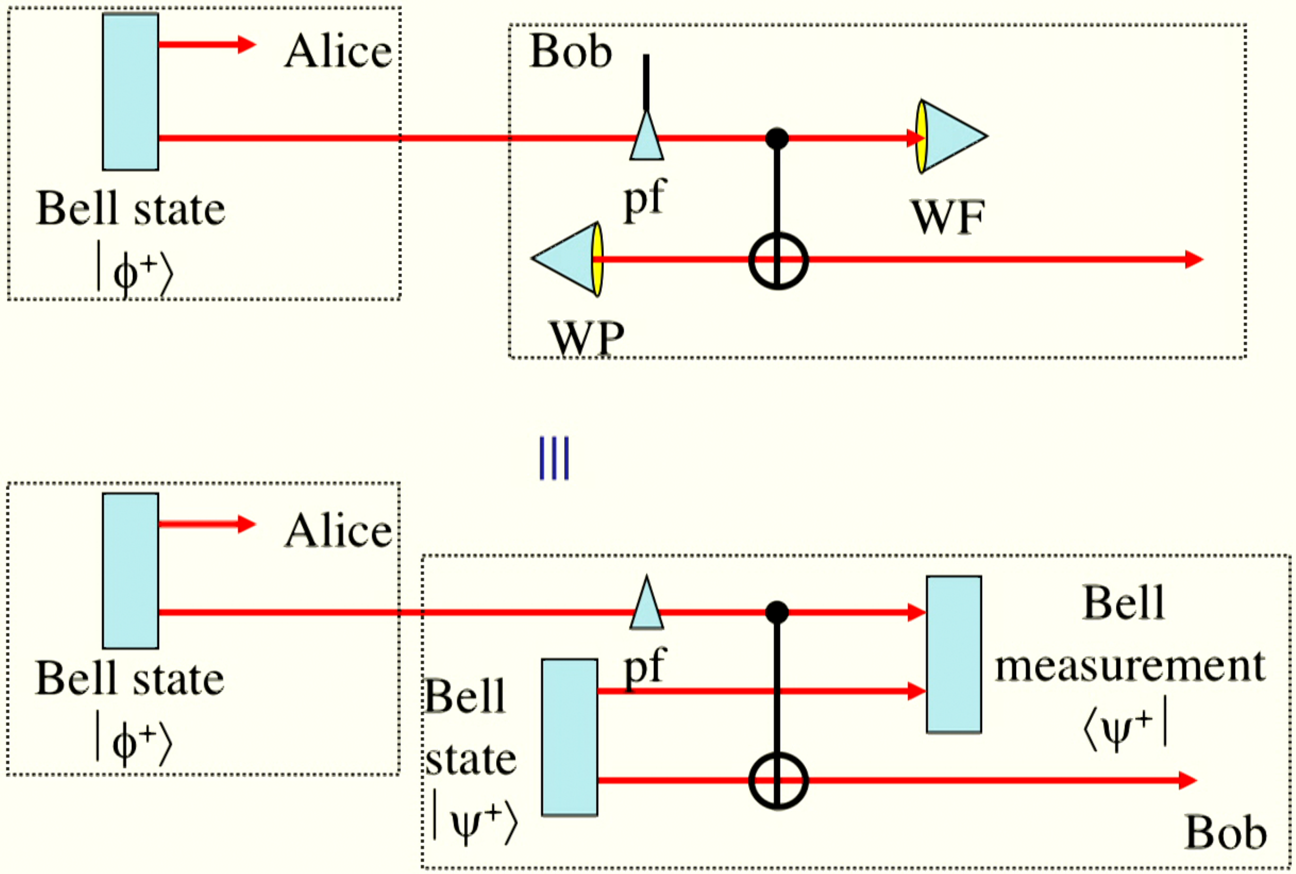

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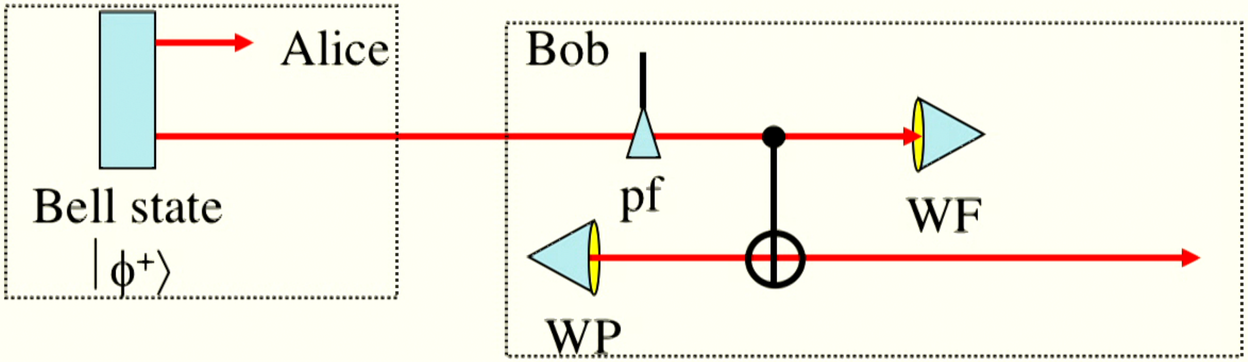
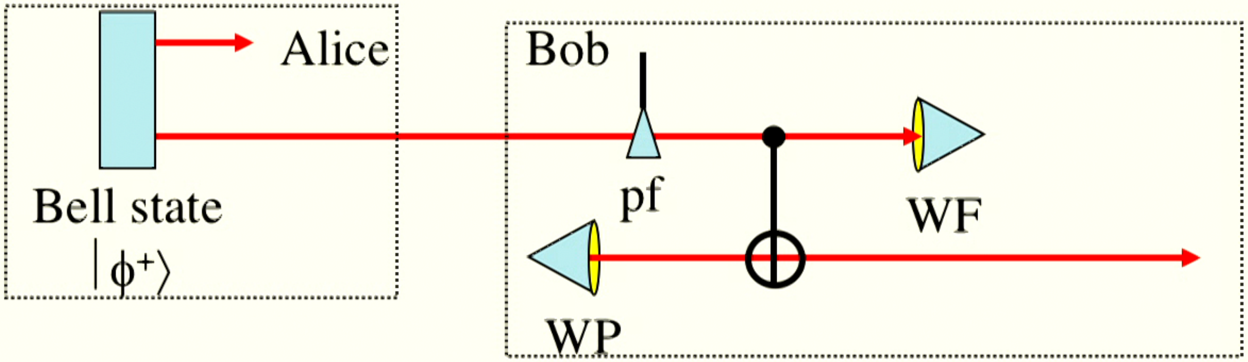


$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)_A|0\rangle_B$$

T.C.Ralph, arXiv:1107.4675



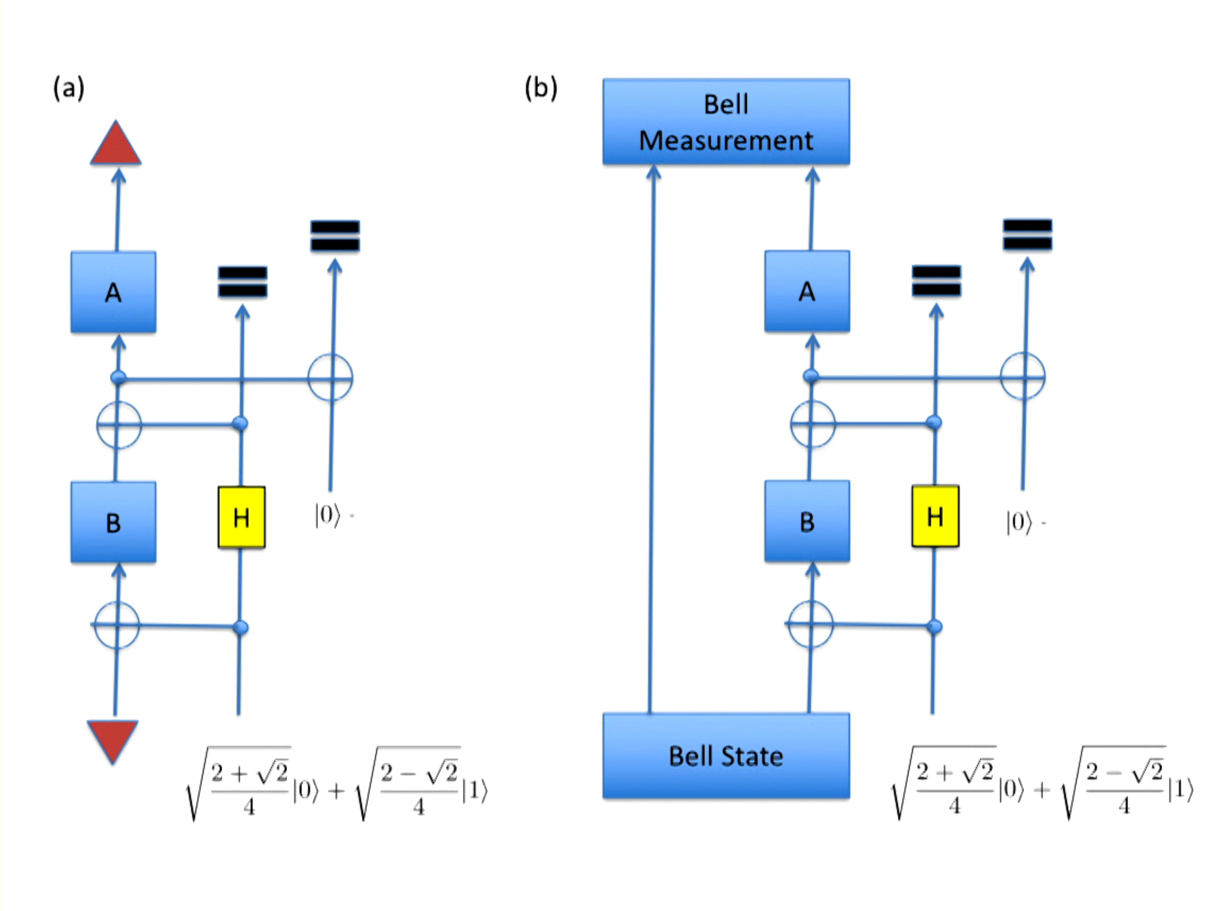
P-CTC

$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)_A |0\rangle_B$$

D-CTC

$$\frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|)_A \bigotimes \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|)_B$$

P-CTC as a component in indefinite causal circuits



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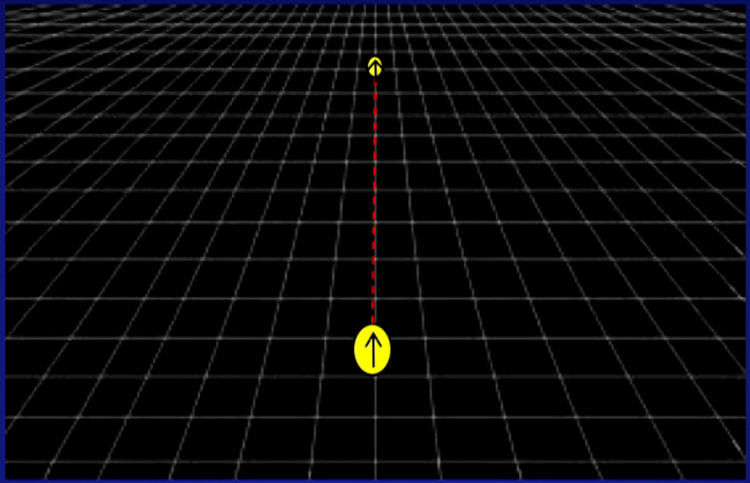
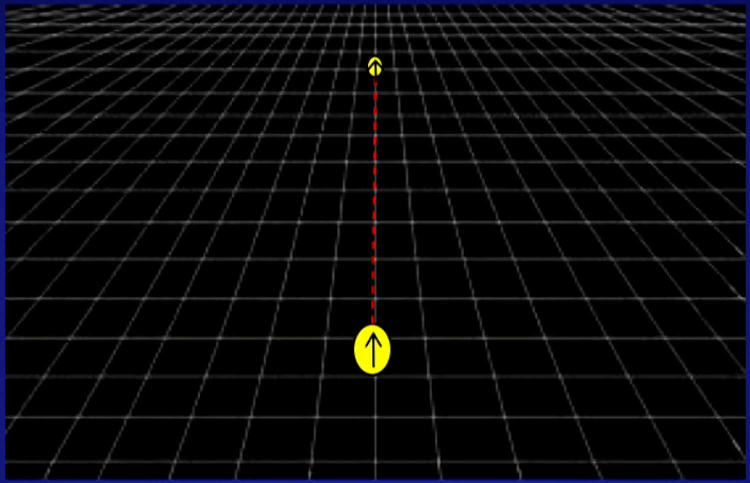
Example: range of entanglement

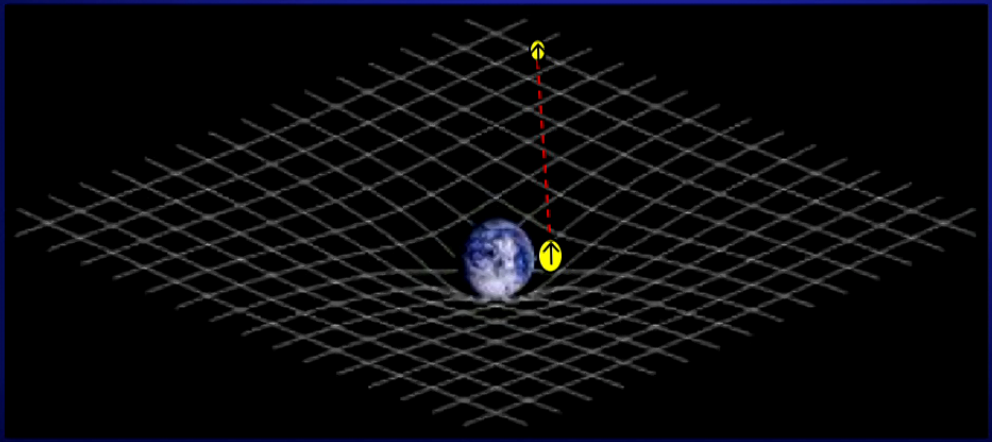


infinite range of entanglement in special relativity

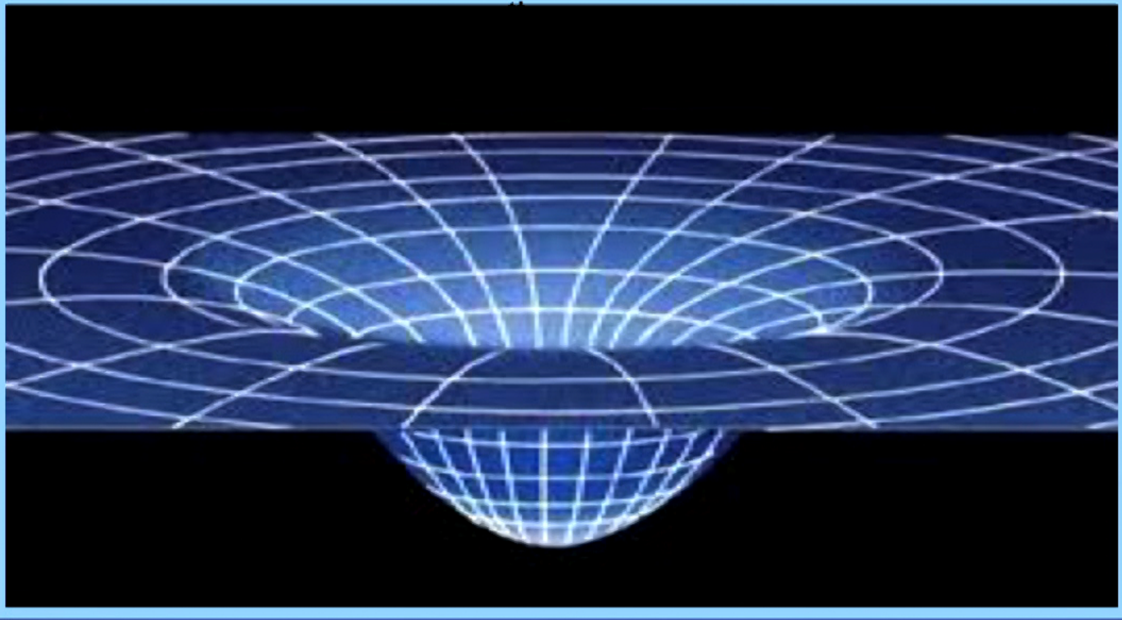
Example: range of entanglement



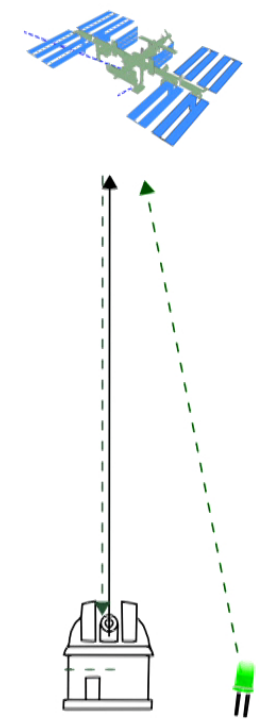
infinite range of entanglement in special relativity



should we expect the same in general relativity?



Can we probe this experimentally?



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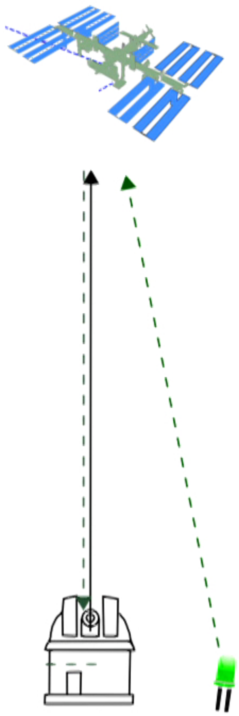
$$t = r_2 - r_1 + 2M \ln \frac{r_2}{r_1}$$



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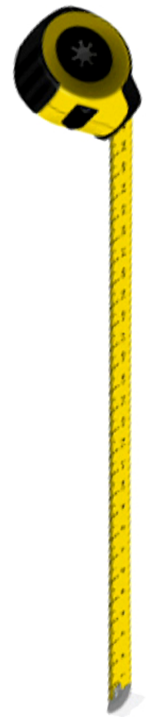
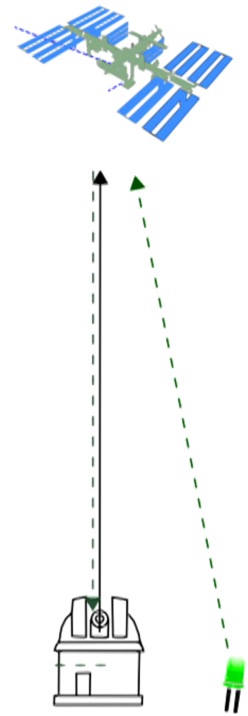




$$h = r_2 - r_1 + M \ln \frac{r_2}{r_1}$$

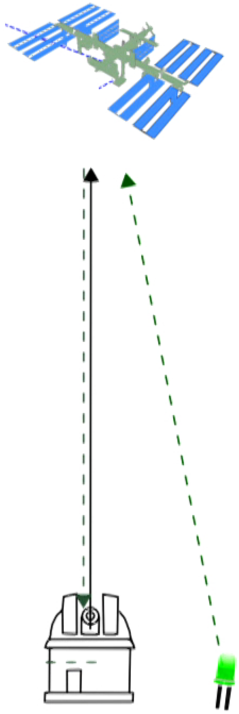
Can we probe this experimentally?

$$t = r_2 - r_1 + 2M \ln \frac{r_2}{r_1}$$

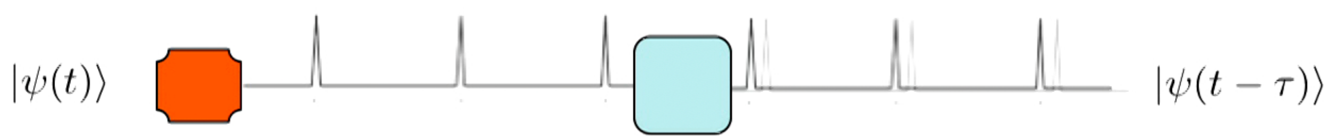
$$h = r_2 - r_1 + M \ln \frac{r_2}{r_1}$$

$$\Delta_t = M \ln \frac{r_2}{r_1} \approx \frac{Mh}{r_e} = 0.0002$$

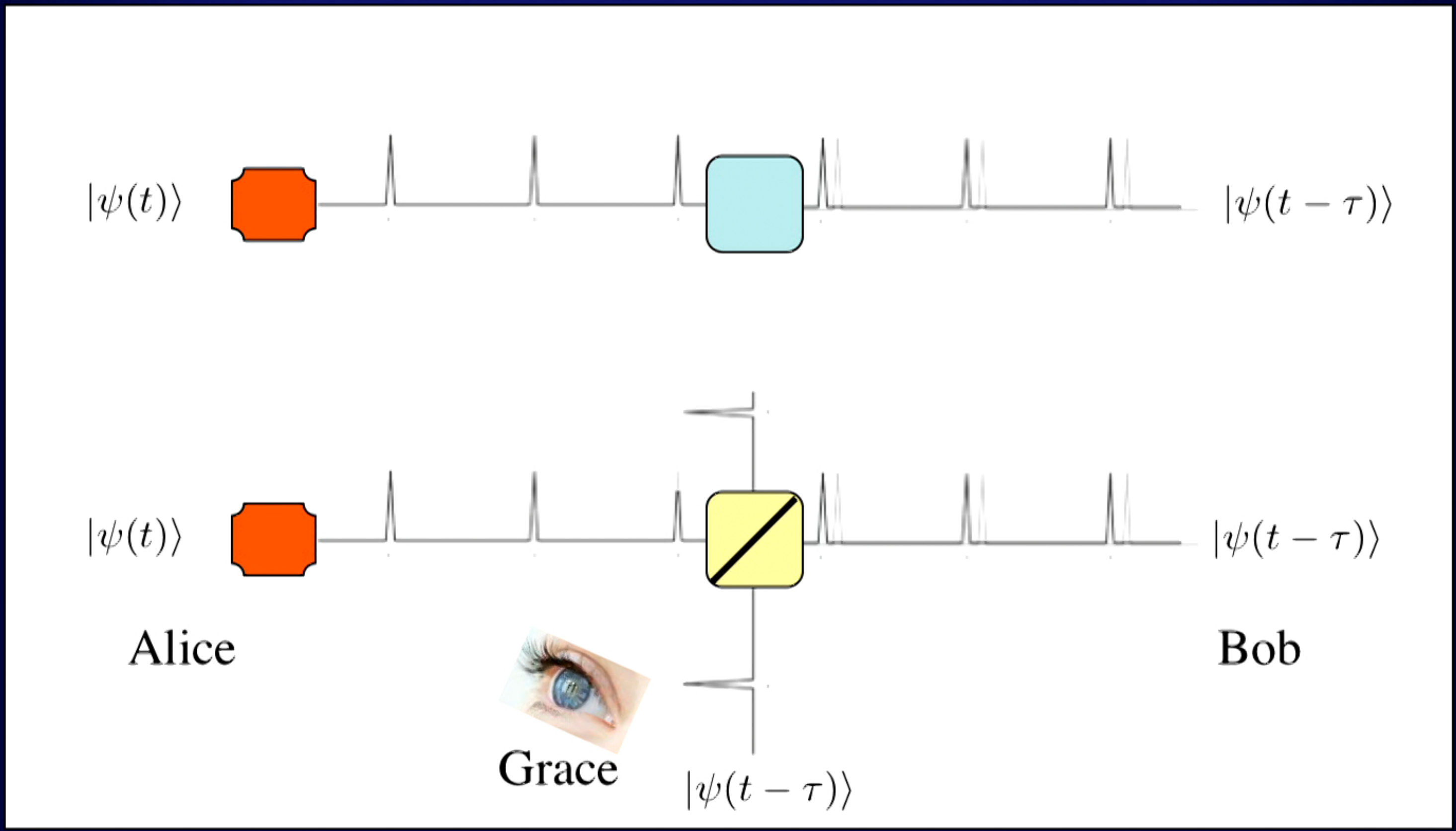
$$1ps = 0.0003$$



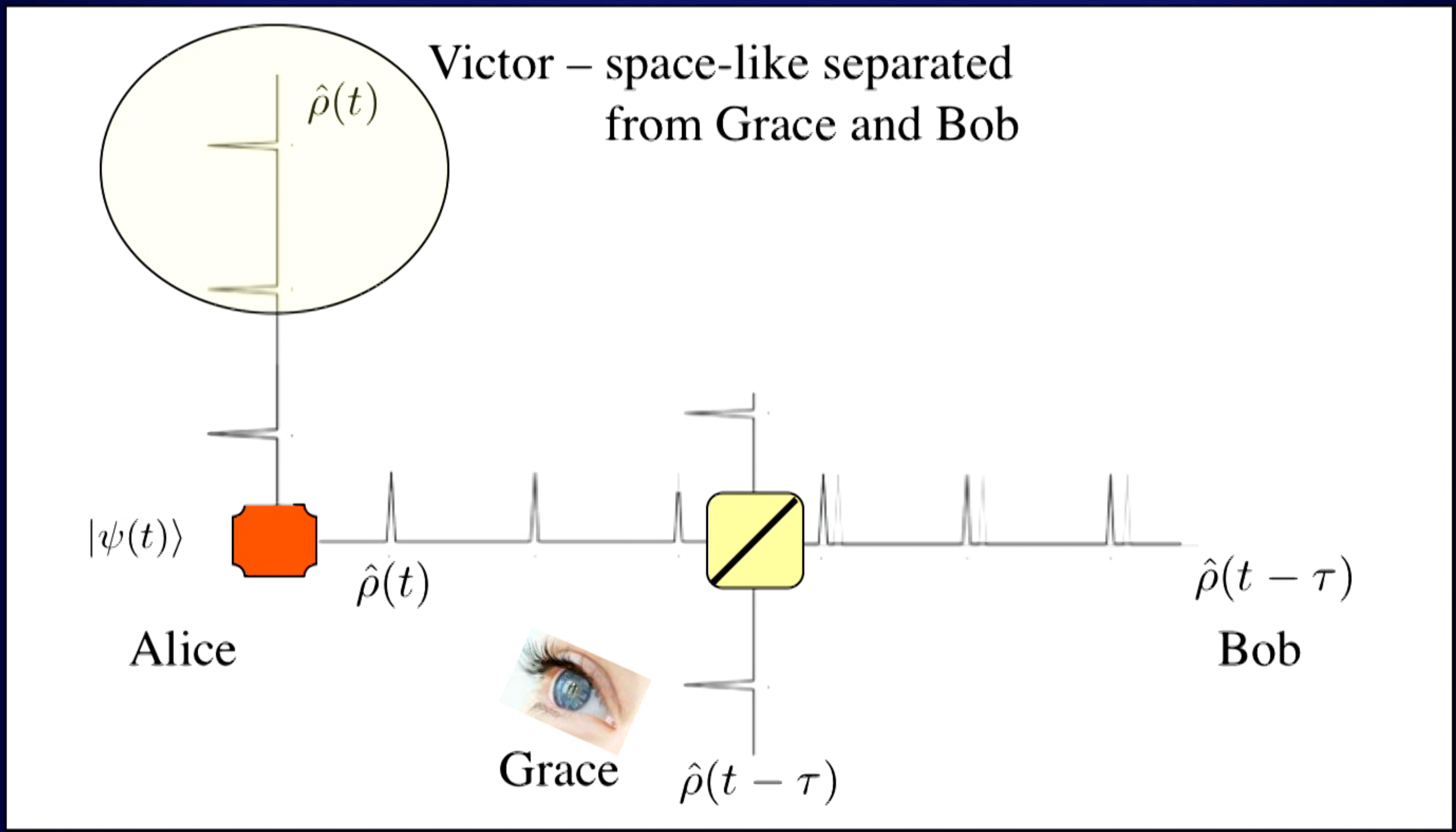
What does the standard approach say?



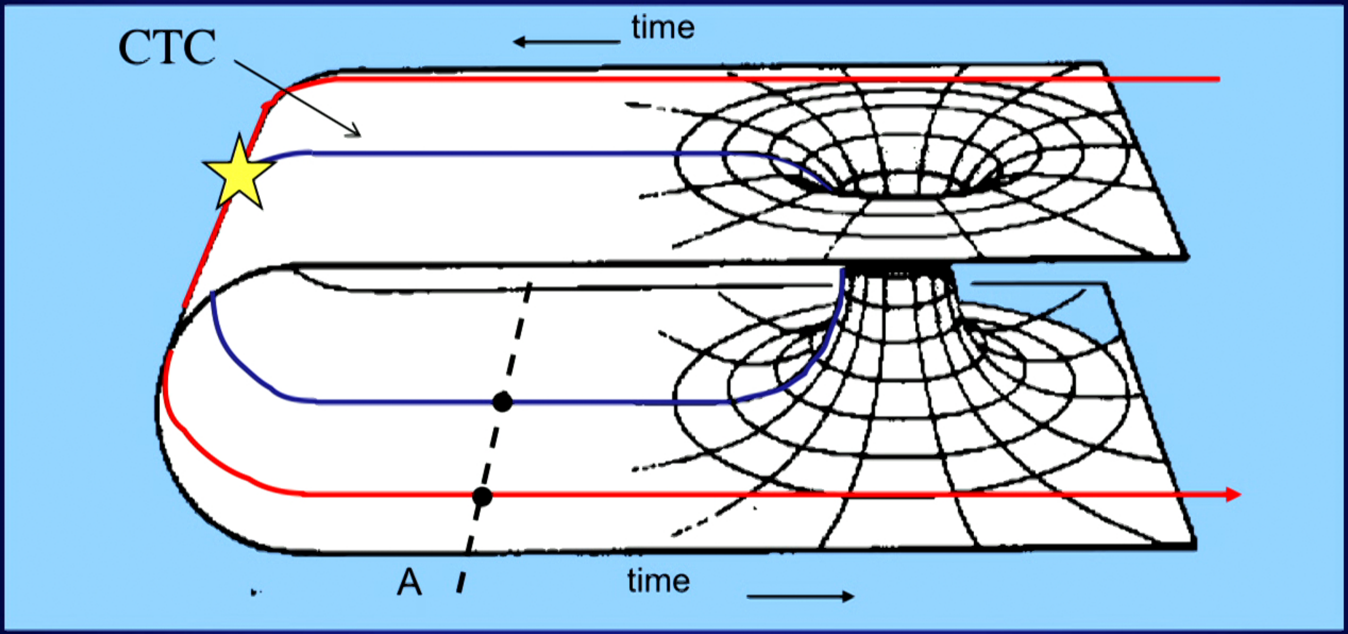
How else could it be?



How could we tell the difference?

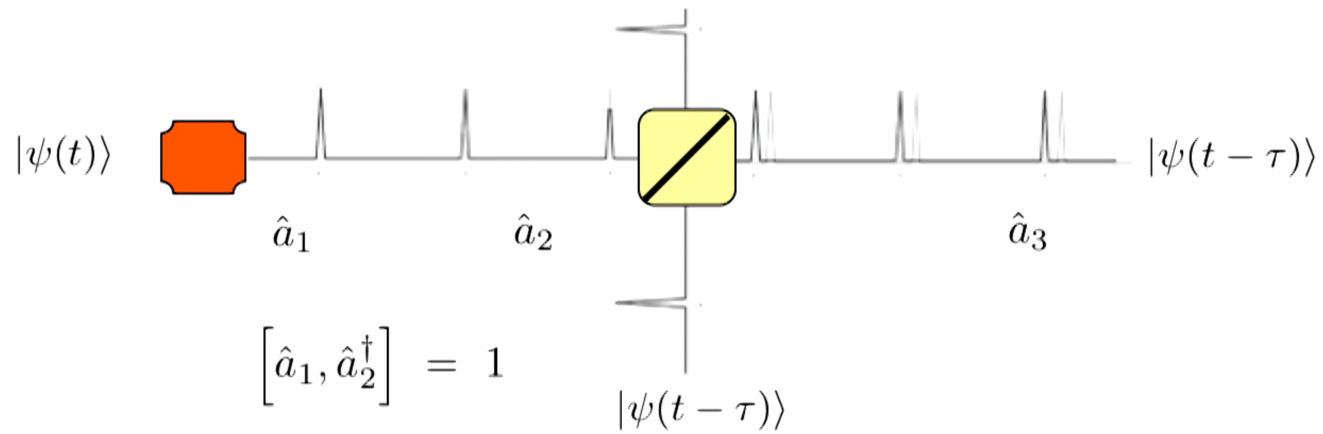


Time-like Wormhole



In terms of mode operators Deutsch's theory implies the commutator decays as a function of proper time along the geodesic

Schrödinger versus Heisenberg Picture



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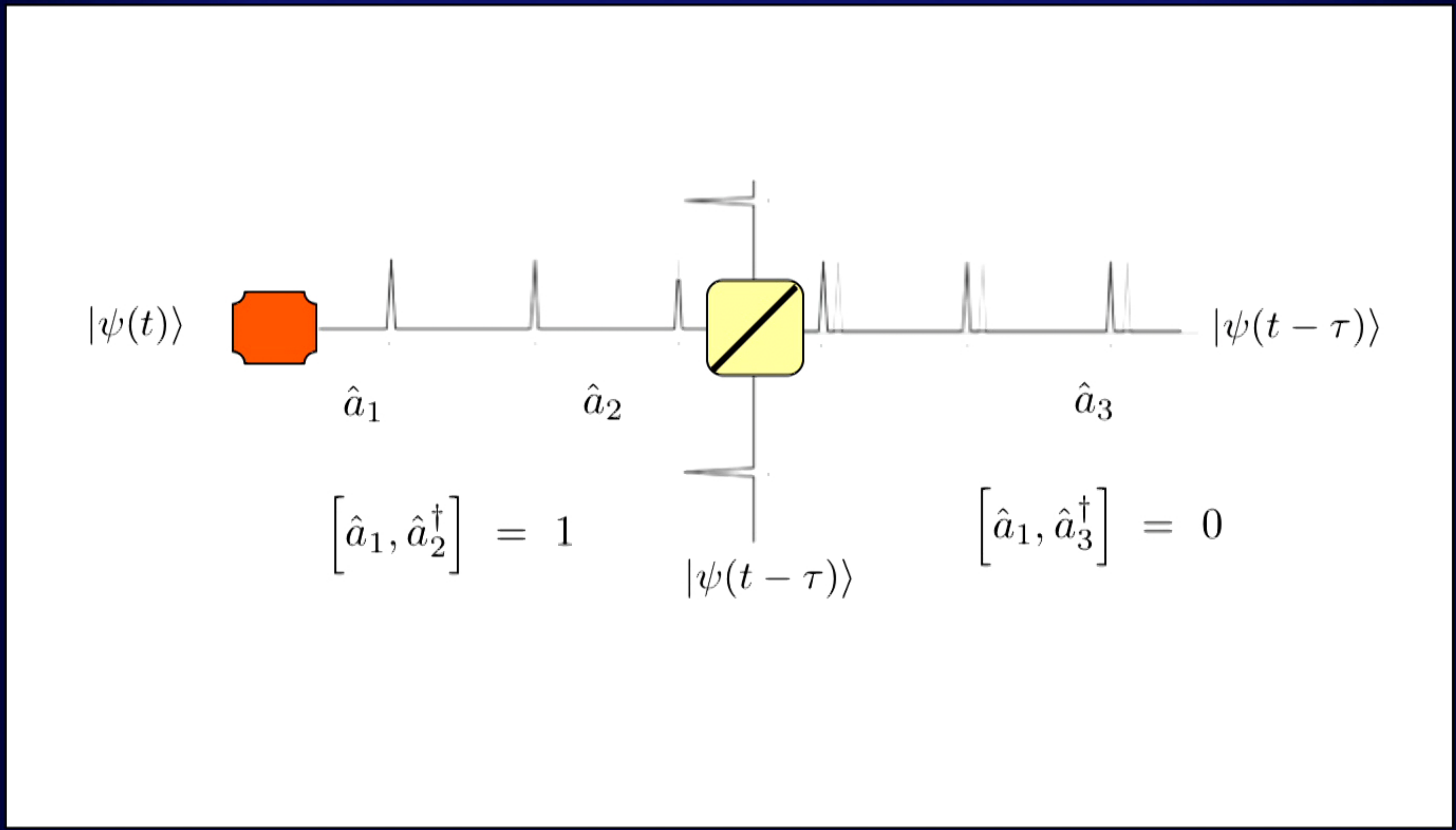

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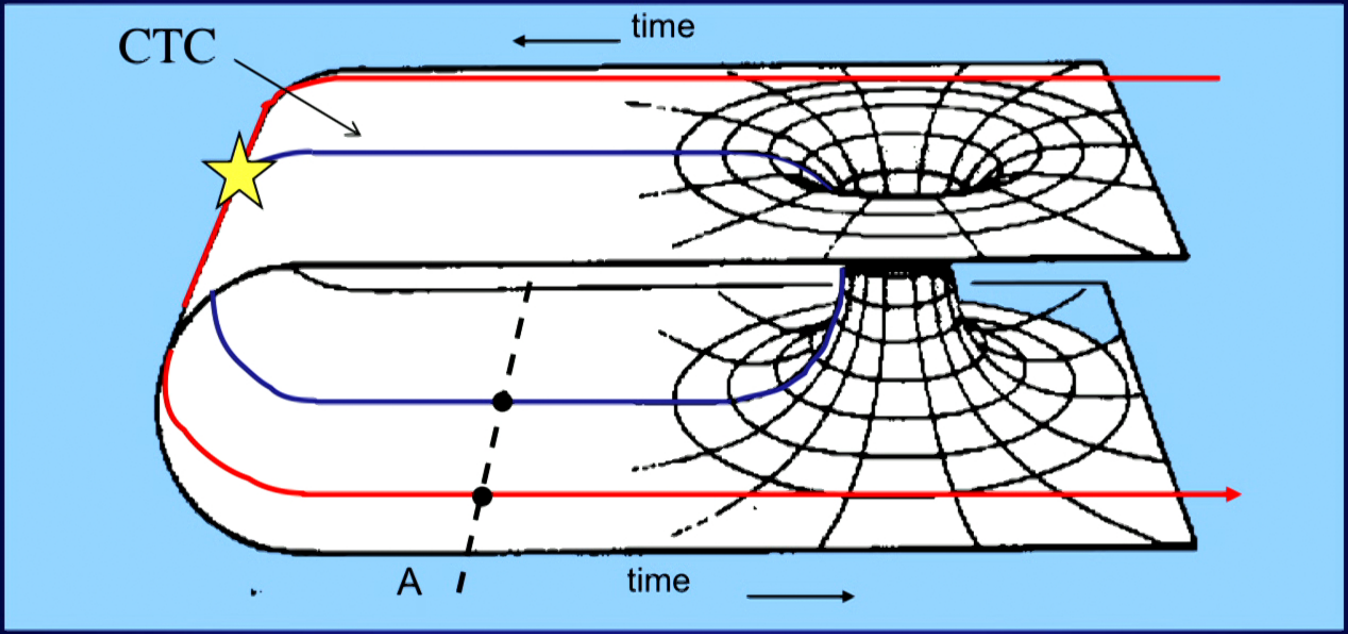

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* **T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. 79, 022121 (2009)**
  - quantum optical event operator

$$\hat{a}(t,x) = \int dk g(k) e^{ik(x-t)}\, \hat{a}_k.$$

* T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. 79, 022121 (2009)

- quantum optical event operator

$$\hat{a}(t,x) = \int dk g(k) e^{ik(x-t)} \int d\Omega J(\Omega) e^{i\Omega(t_d - \tau)} \hat{a}_{k,\Omega}$$

$$\tau = \int_t^{t_d} ds$$

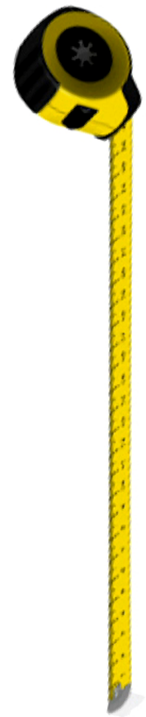
* **T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. 79, 022121 (2009)**
  - quantum optical event operator

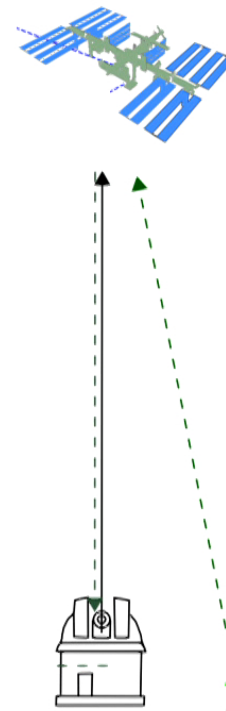
* J.L.Pienaar, C.R.Myers, and T.C.Ralph, Phys Rev A **84**, 062316 (2011)
  - event operators reproduce the Deutsch solution

* S. Joshi, et al, New Journal of Physics **20**, 063016 (2018).
  - experimental proposal

Can we probe this experimentally?

$$t = r_2 - r_1 + 2M \ln \frac{r_2}{r_1}$$



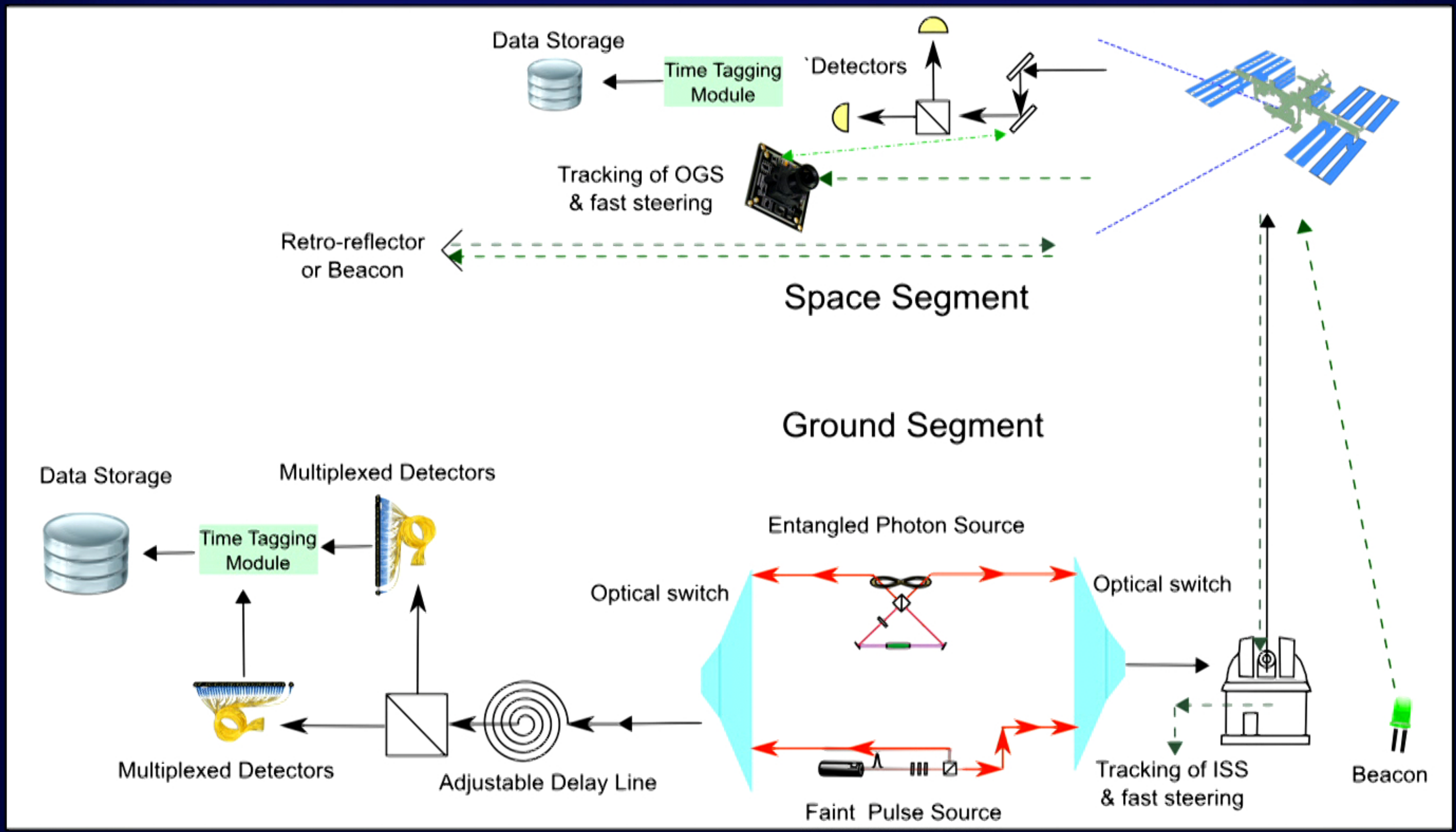


$$h = r_2 - r_1 + M \ln \frac{r_2}{r_1}$$

$$\Delta_t = M \ln \frac{r_2}{r_1} \approx \frac{Mh}{r_e} = 0.0002$$

$$1ps = 0.0003$$

Experimental proposal



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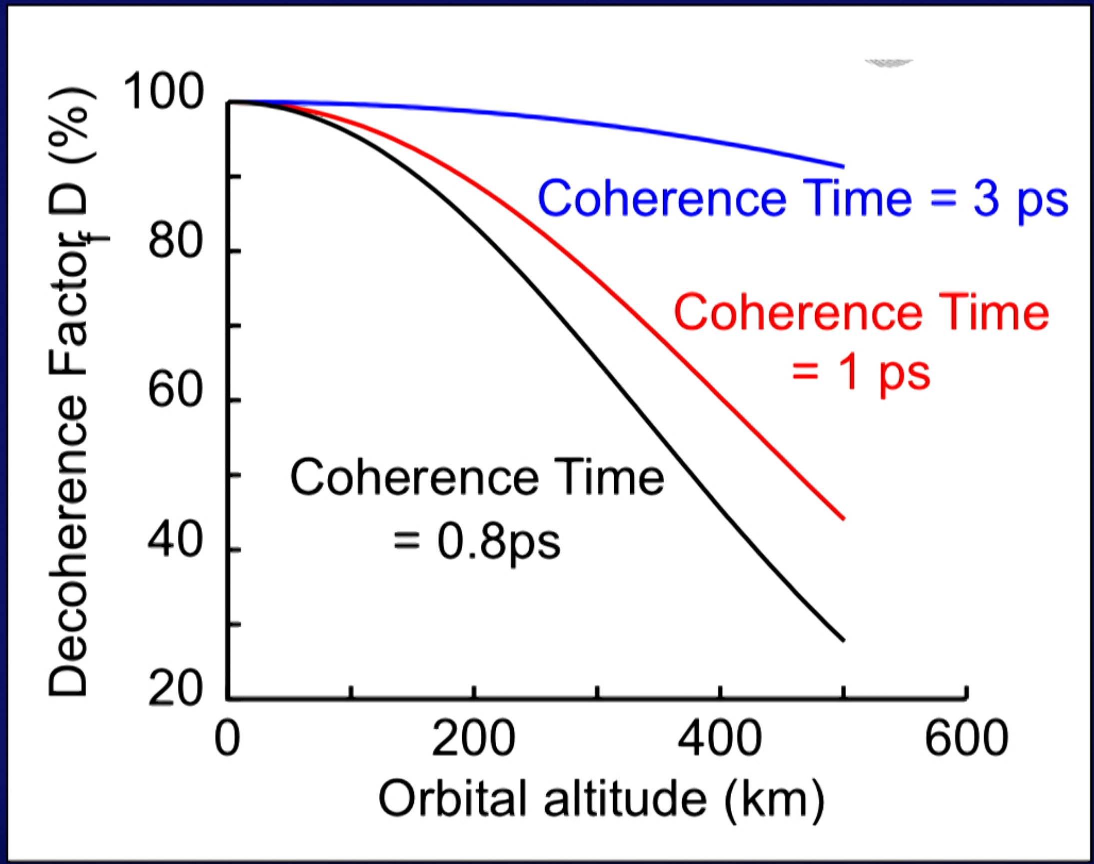


S. Joshi, et al, New Journal of Physics **20**, 063016 (2018).

Micius quantum satellite

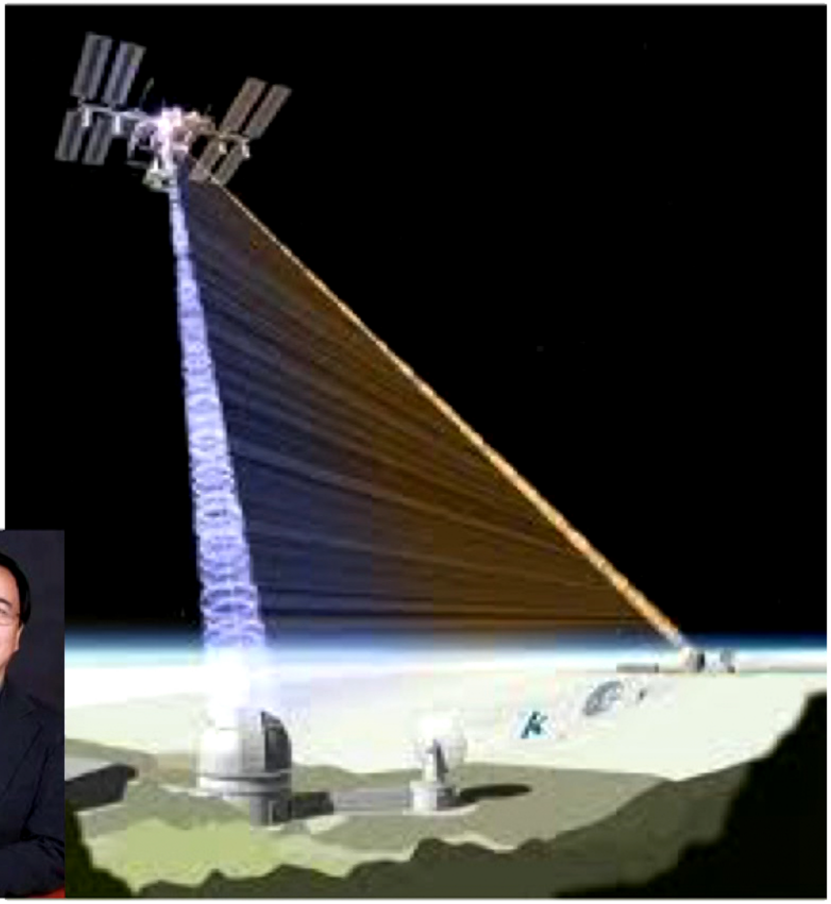
Global Quantum Comm:

Distribute entanglement from space to the ground enabling secure communication over long distance

Also used to distribute entanglement from ground to space (teleportation)

Orbit height ~ 500km

Jian-Wei Pan
University of Science and Technology of China
Hefei, China



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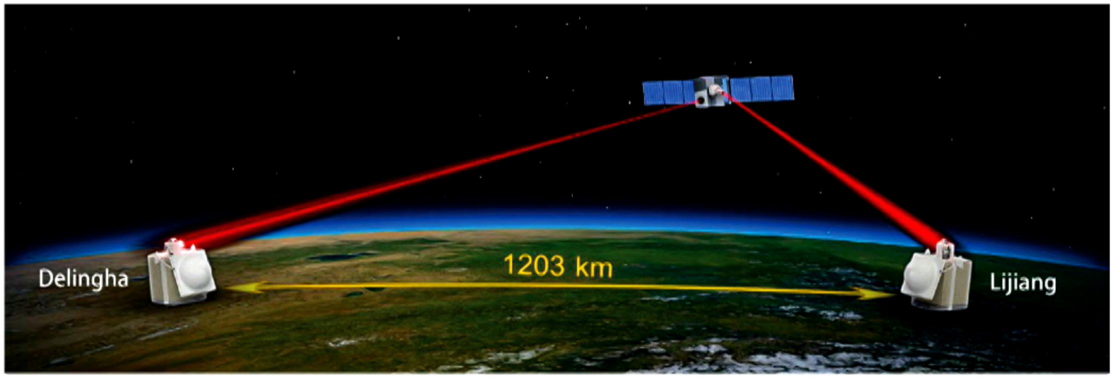

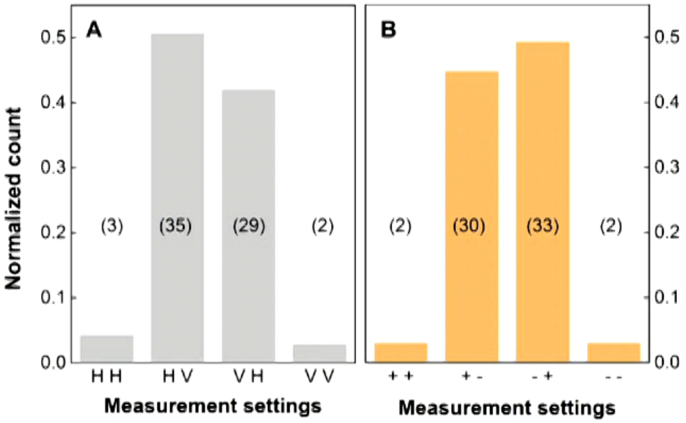

classical correlations

$S \leq 2$

observed

$S = 2.37 \pm 0.09$

Juan Yin, et al,
Science 356, 1140 (2017)

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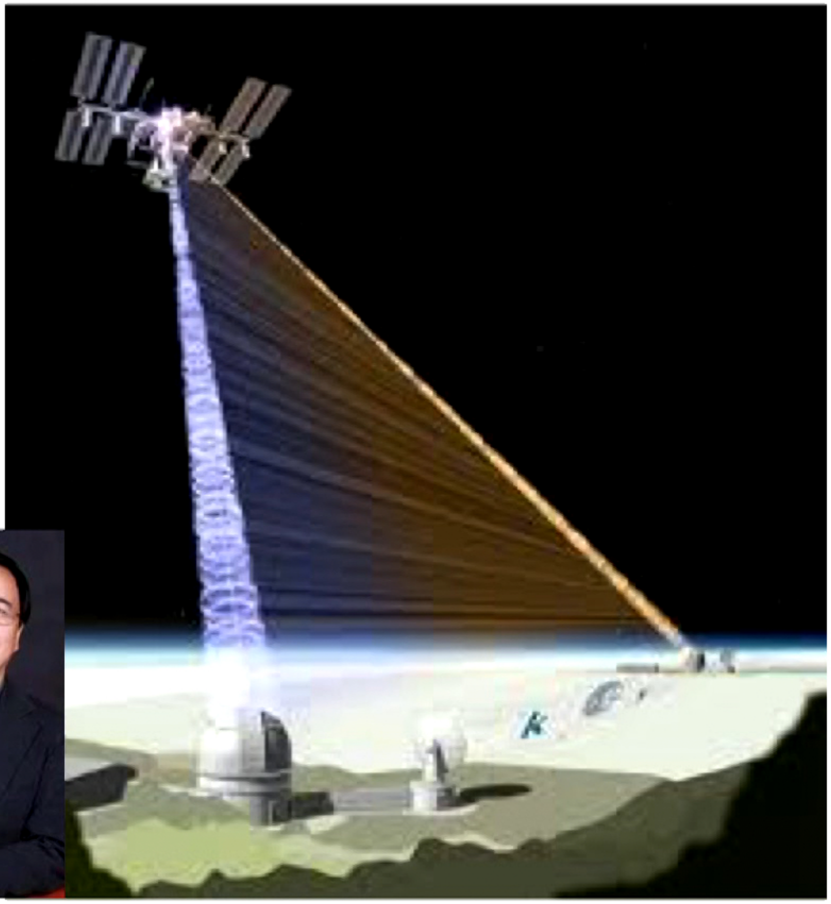


Decoherence experiment

RESEARCH

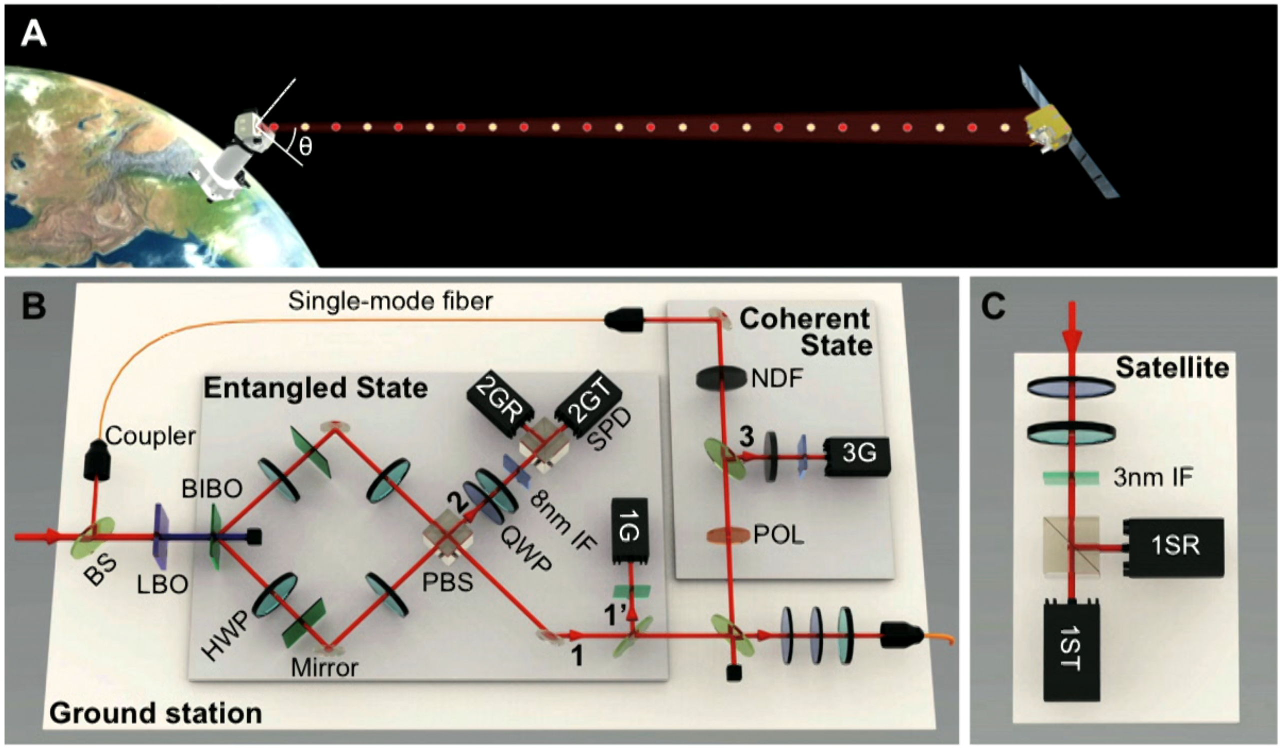
QUANTUM PHYSICS

Satellite testing of a gravitationally induced quantum decoherence model

Ping Xu[1,2]*, Yiqiu Ma[3]*, Ji-Gang Ren[1,2]*, Hai-Lin Yong[1,2], Timothy C. Ralph[4], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Xuan Han[1,2], Hui-Nan Wu[1,2], Wei-Yang Wang[1,2], Feng-Zhi Li[1,2], Meng Yang[1,2], Feng-Li Lin[5], Li Li[1,2], Nai-Le Liu[1,2], Yu-Ao Chen[1,2], Chao-Yang Lu[1,2], Yanbei Chen[3], Jingyun Fan[1,2]†, Cheng-Zhi Peng[1,2]†, Jian-Wei Pan[1,2]†

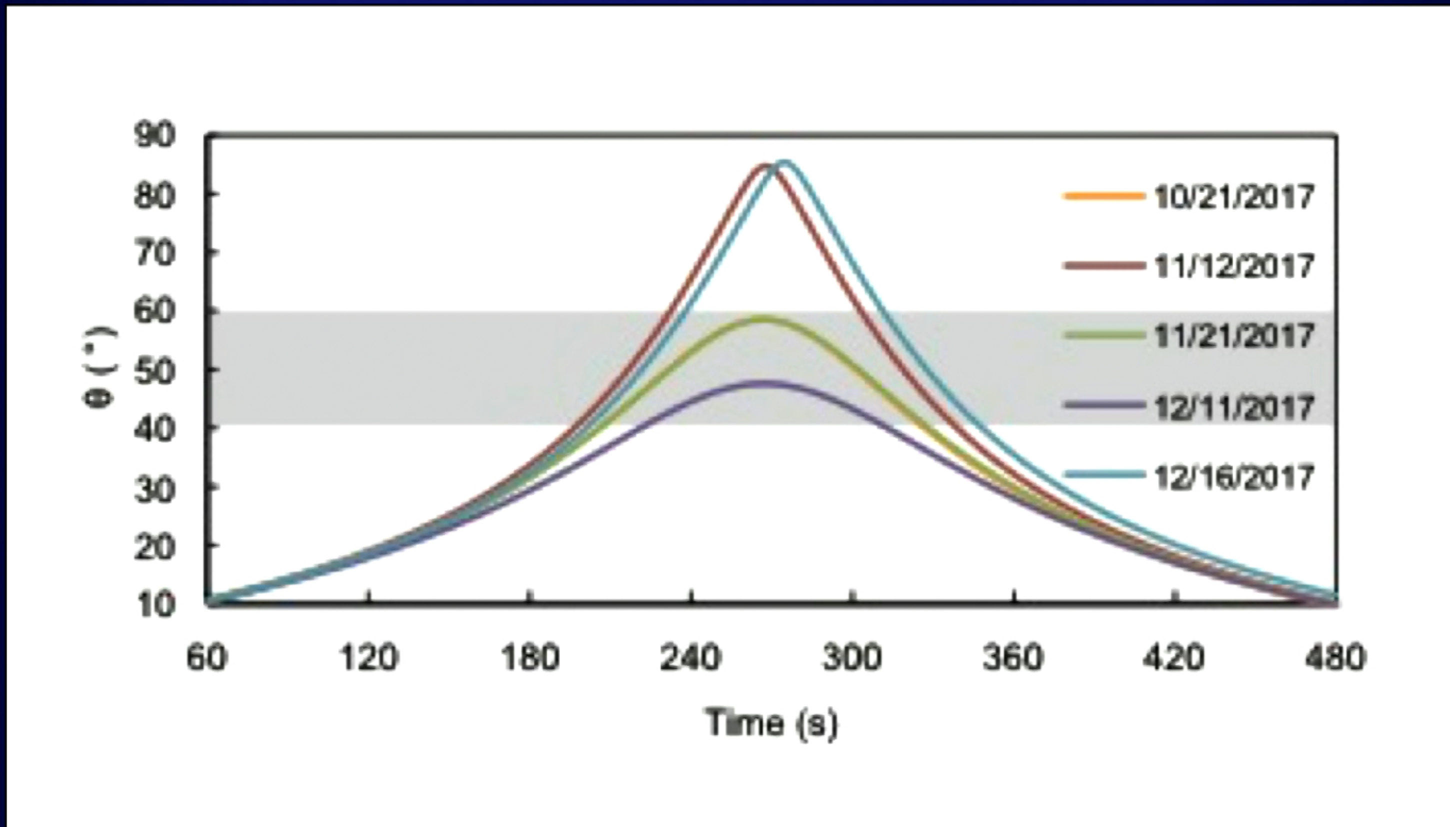
Xu *et al.*, *Science* **366**, 132–135 (2019)   4 October 2019

Decoherence experiment



0.2 ps pulse length   Orbit height ~ 500km

Decoherence experiment



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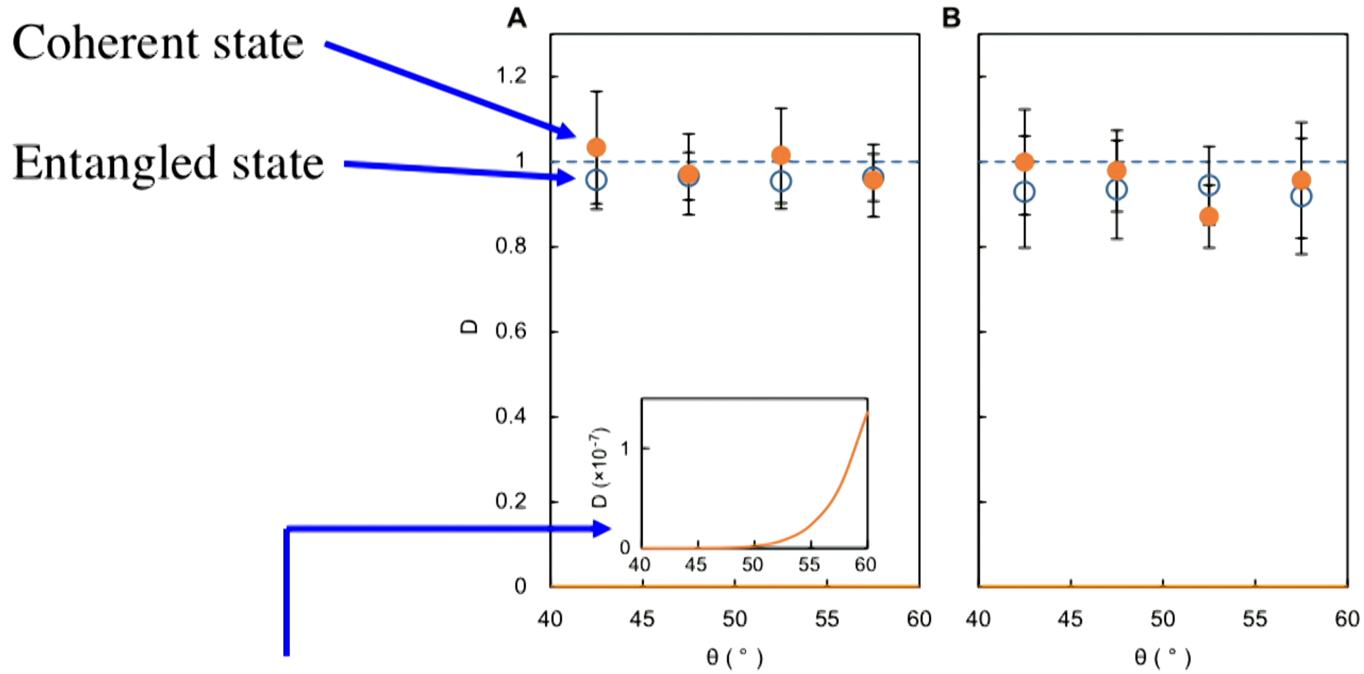
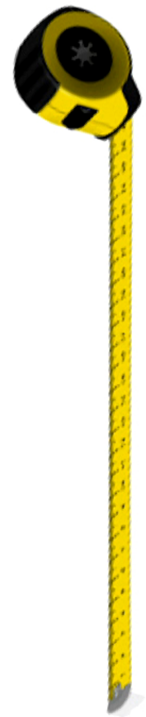
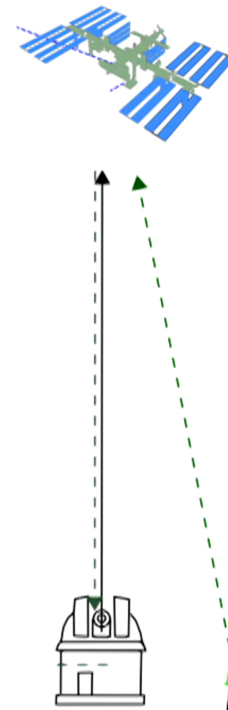


$$\Delta_t \approx \int_{r_e}^{r_e+h} \frac{M}{r}(1+\frac{2M}{r}+\frac{r_e^2\tan^2(90-\theta)}{r^2})^{1/2}dr$$

Can we probe this experimentally?

$$t = r_2 - r_1 + 2M \ln \frac{r_2}{r_1}$$





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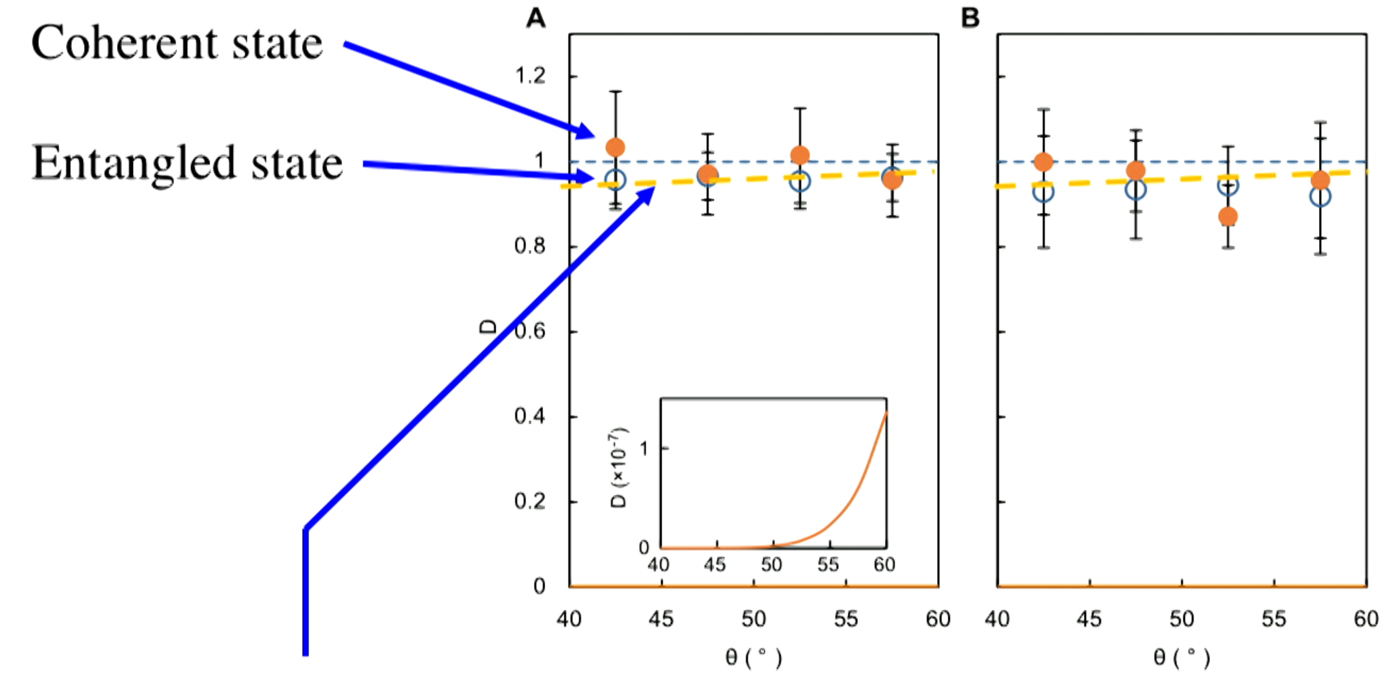
$$1ps = 0.0003$$

Decoherence experiment



$$\Delta_t = \int_{r_e}^{r_e+h} \left(\frac{M}{r} - \frac{M}{r_e+h}\right)\left(1+\frac{2M}{r}+\frac{r_e^2\tan^2(90-\theta)}{r^2}\right)^{1/2} dr$$

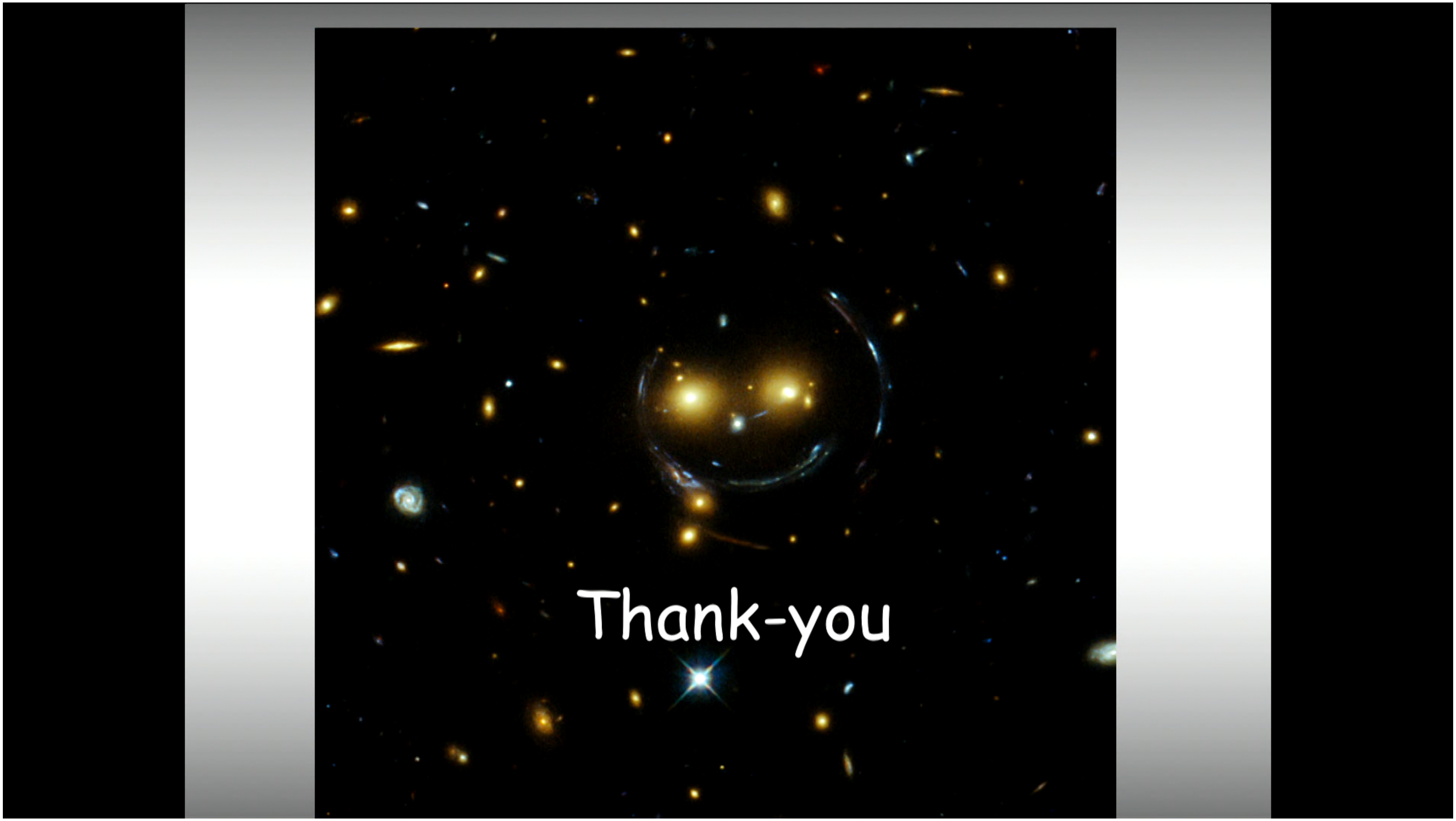
Conclusions

* There are good reasons to test quantum field theory on a curved background

* Considering space-times when indefinite causal orders can motivate such tests.

* First satellite based test of gravitational decoherence shows no effect to first order

* Such tests are key technology drivers


Thank-you