Quantum correlations in long-baseline quantum optics

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DLR

Gravitational effects in the quantum regime

- Experimentally investigating the gravitational field *sourced* by a delocalized quantum superposition is still extremely challenging.

- But substantial progress in measuring gravitational effects on delocalized quantum superpositions (as *test* particles):
  - matter-wave interferometry
  - quantum-clock interferometry

- What about relativistic particles (photons)?

  Starting to explore aspects of quantum field theory (QFT) in curved spacetime.

Matter-wave interferometry

Effect of gravity on delocalized quantum superpositions

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

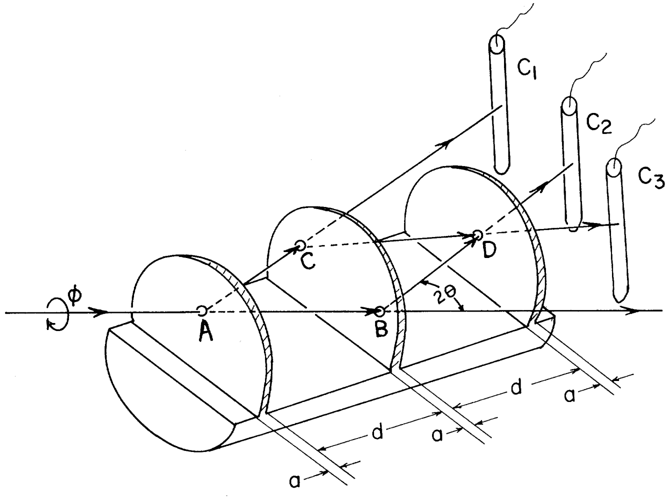
and

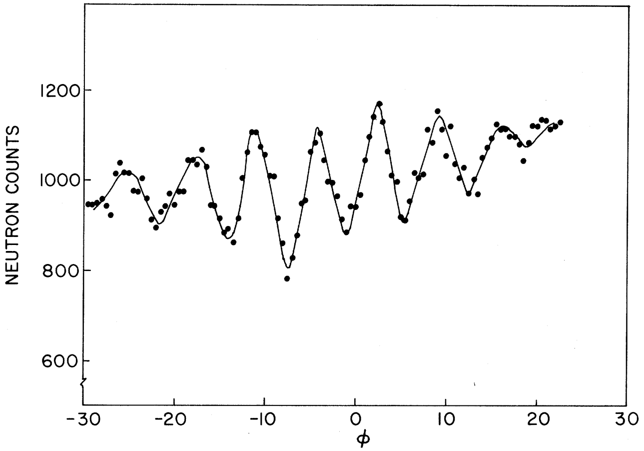
S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

- Matter-wave interferometry with freely falling neutrons.
- Sensitive to Earth's approximately uniform gravitational field.
- Measures relative acceleration between freely falling neutrons and planes of Si crystal.

Effect of gravity on delocalized quantum superpositions





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Albert Roura, Institute of Quantum Technologies, 08.07.2025

Spacetime curvature and proper-time difference

INSIGHTS | PERSPECTIVES

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Quantum probe of space-time curvature

An atom interferometer measures the quantum phase due to gravitational time dilation

By **Albert Roura**

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RESEARCH

PHYSICS

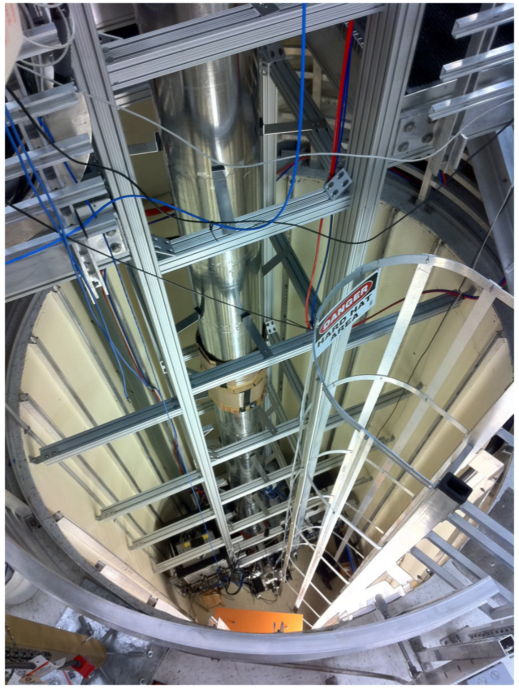
Observation of a gravitational Aharonov-Bohm effect

Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

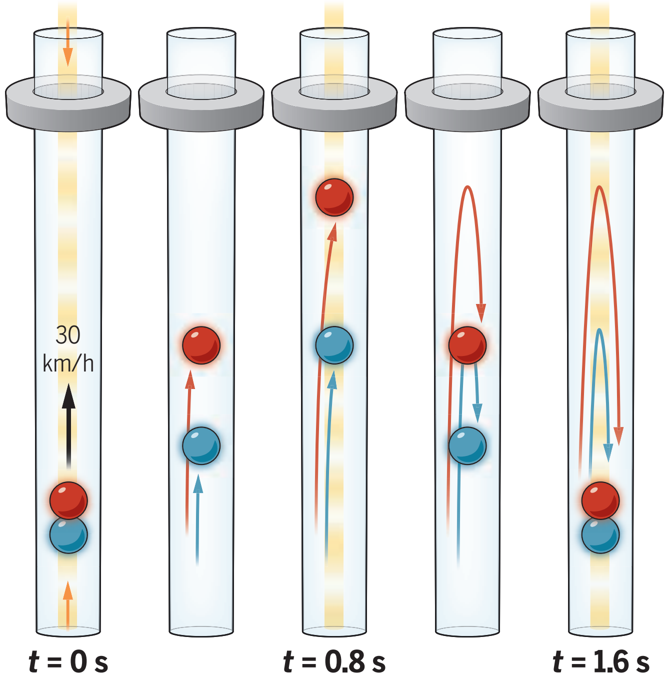
Overstreet *et al.*, *Science* **375**, 226–229 (2022) 14 January 2022

- Effect of *spacetime curvature* on a delocalized quantum superposition.
- *Proper-time time difference* between the two interferometer arms.
- Gravitational analog of the scalar Aharonov-Bohm effect.

Spacetime curvature and proper-time difference



Stanford (USA)



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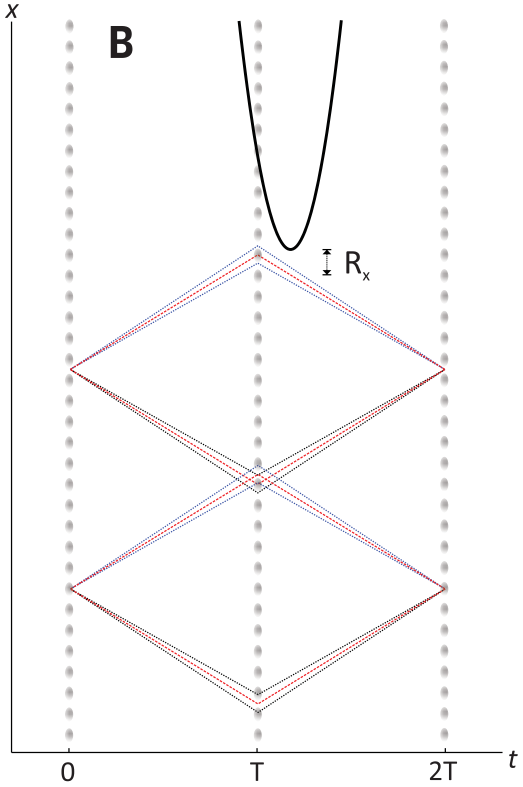

freely falling frame

Spacetime curvature and proper-time difference

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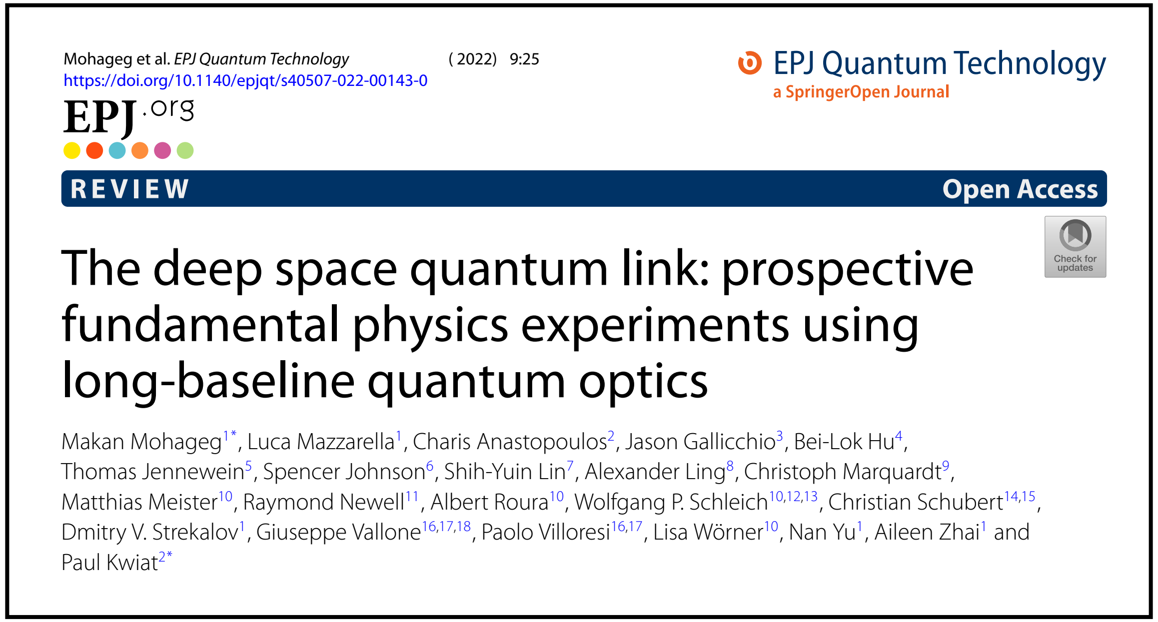
- Interpretation in terms of spacetime curvature and proper-time time difference within the framework of general relativity.
- BUT alternative description in terms of *non-relativistic* quantum mechanics plus *Newtonian gravity* also possible.

Long-baseline quantum optics

Interferometry with quantum states of light

- Compared to state-of-the-art matter-wave interferometers, optical interferometers with quantum states of light offer the following appealing features:
  - Use of *relativistic* particles → quantum field theory
  - *Multiparticle entanglement* including external degrees of freedom.
  - *Multiparticle interference* with no classical analog.
  - Long baselines and large arm separations (up to hundreds of kilometers or more) → greater sensitivity to *spacetime curvature* effects.

Long-baseline quantum optics experiments


Mohageg et al. *EPJ Quantum Technology* (2022) 9:25
https://doi.org/10.1140/epjqt/s40507-022-00143-0

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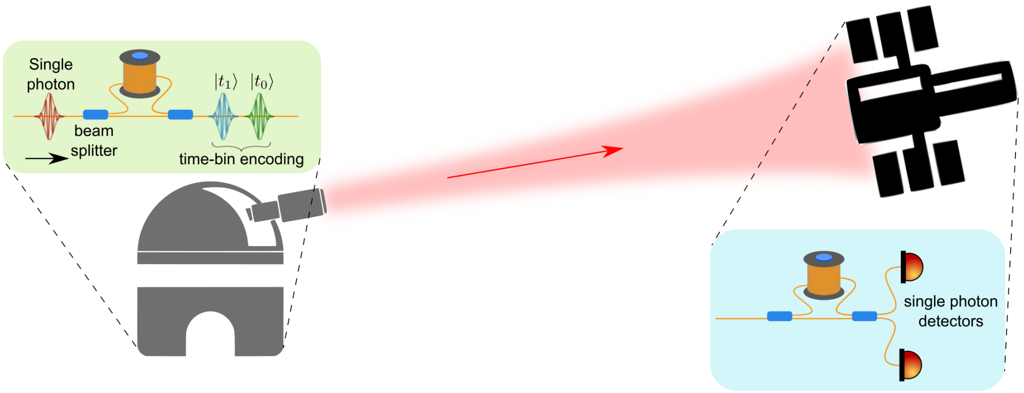
The deep space quantum link: prospective fundamental physics experiments using long-baseline quantum optics

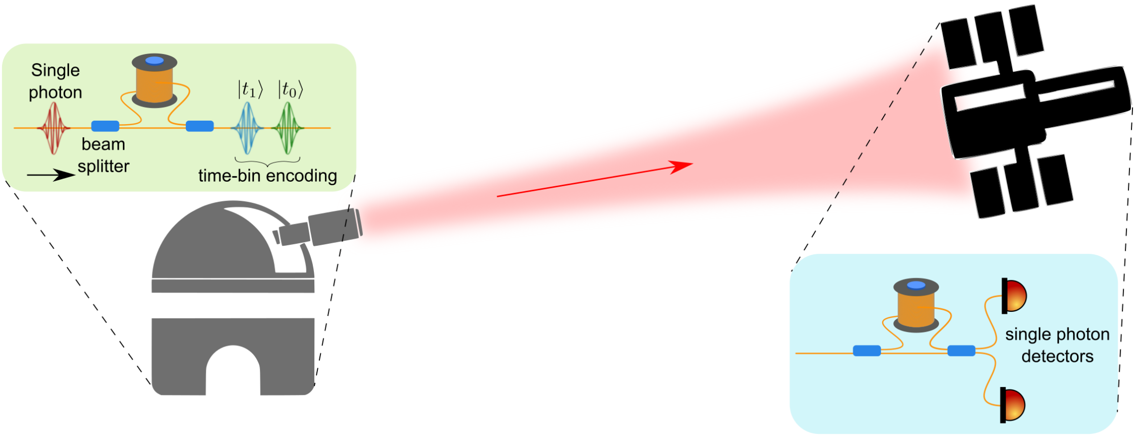
Makan Mohageg[1*], Luca Mazzarella[1], Charis Anastopoulos[2], Jason Gallicchio[3], Bei-Lok Hu[4], Thomas Jennewein[5], Spencer Johnson[6], Shih-Yuin Lin[7], Alexander Ling[8], Christoph Marquardt[9], Matthias Meister[10], Raymond Newell[11], Albert Roura[10], Wolfgang P. Schleich[10,12,13], Christian Schubert[14,15], Dmitry V. Strekalov[1], Giuseppe Vallone[16,17,18], Paolo Villoresi[16,17], Lisa Wörner[10], Nan Yu[1], Aileen Zhai[1] and Paul Kwiat[2*]

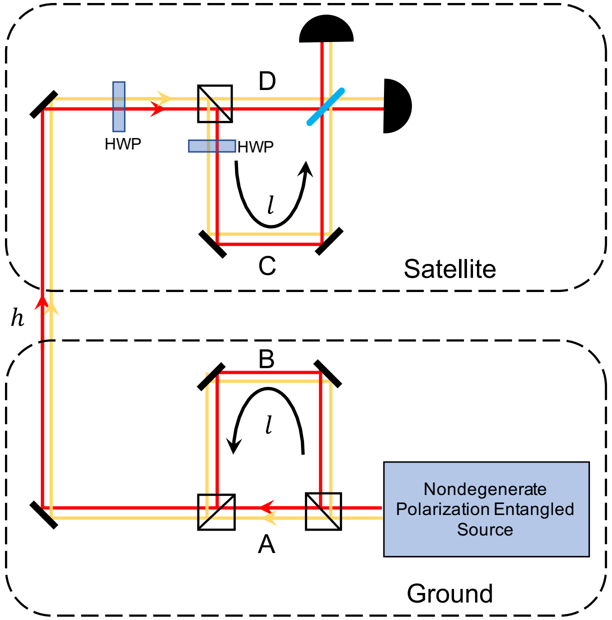


- Comprehensive study by the Science Definition Team for a NASA mission concept.
- Recognized with a *NASA Group Achievement Award*.

(i) Gravitational-redshift measurement

- Delay lines with equal proper length in different gravitational potentials ⟶ gravitational time dilation
  - interesting version involving *two-photon interference* and frequency-entangled photon pairs
  - huge loses ⟶ focus here on *single-photon* states





$$|\Psi_0\rangle = \frac{1}{\sqrt{2}}\Big(|\omega_1, H\rangle\,|\omega_2, V\rangle - |\omega_1, V\rangle\,|\omega_2, H\rangle\Big)$$

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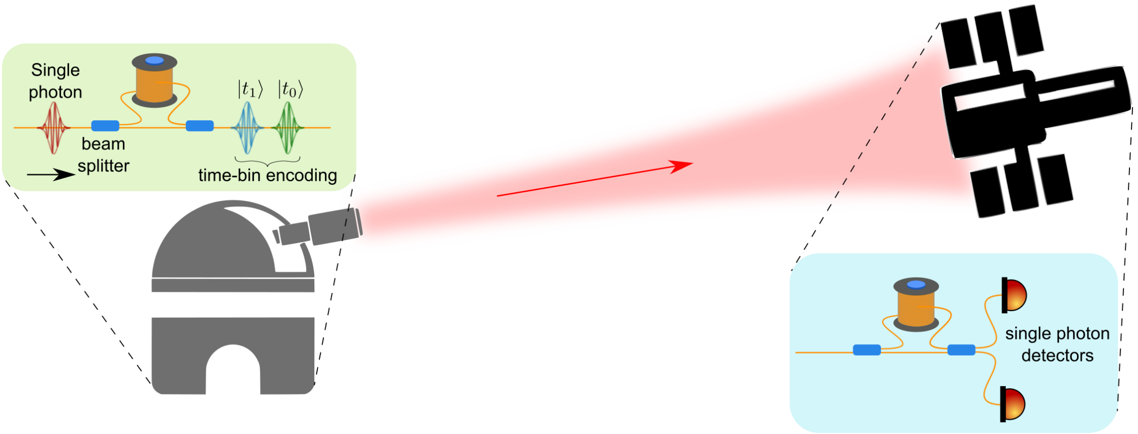
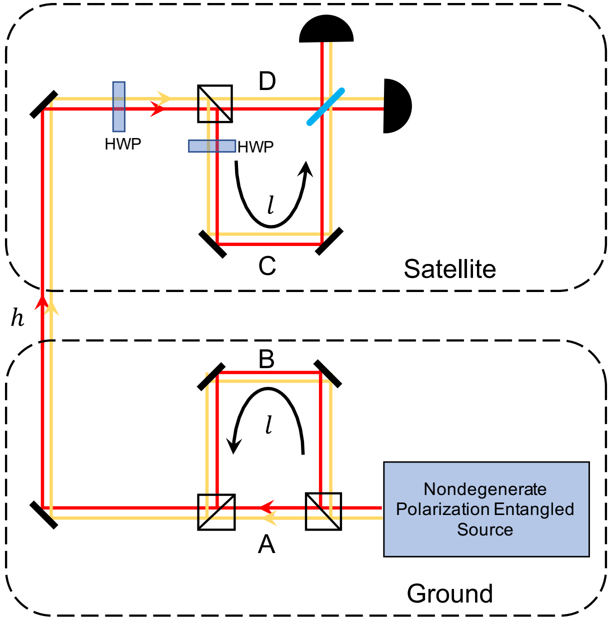
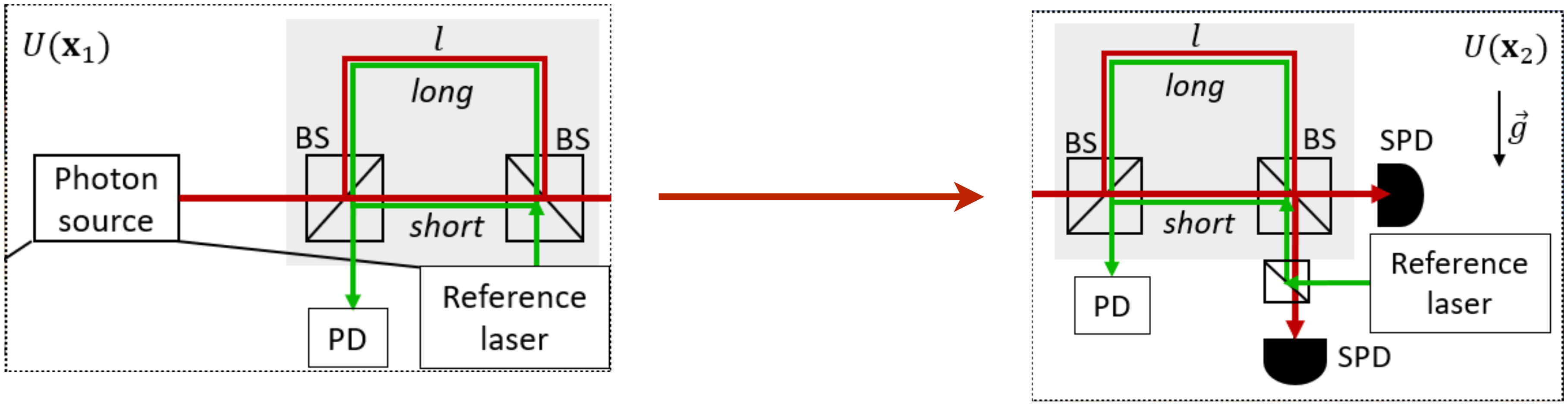




$$|\Psi_0\rangle = \frac{1}{\sqrt{2}}\Big(|\omega_1, H\rangle + |\omega_1, V\rangle\Big)$$

- The two delay lines need to be calibrated and stabilized with identical frequency references.
- Gravitational redshift over Earth-Moon baseline → calibration at 10^{-10} level or better.
- Linear Doppler shift needs to be post-corrected with laser-ranging measurement (smaller, slowly varying and much more stable than for LEO spacecraft)



Collaboration with Paul Kwiat, Makan Mohageg, Alex Lohrmann and Spencer Johnson

(ii) Long-baseline Bell tests

- Well beyond previous Bell tests: much longer baselines, much larger variations of gravitational potential, spacetime curvature effects (test of QFT in curved spacetime)

- Main challenge: beam divergence for such long baselines ⟶ very small number of detected photons
  - use large aperture telescopes + adaptive optics
  - entangled photon-pair source with very high emission rate is needed

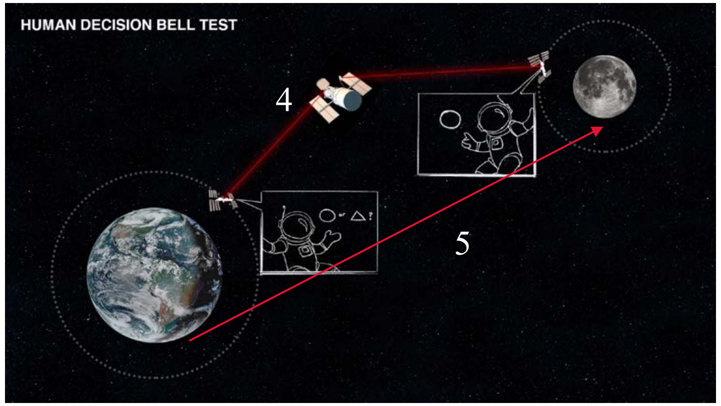
- Optimal encoding still to be determined (e.g. polarization vs. time bins).
  Could use of continuous (e.g. entangled squeezed states) rather than discrete variables be advantageous?

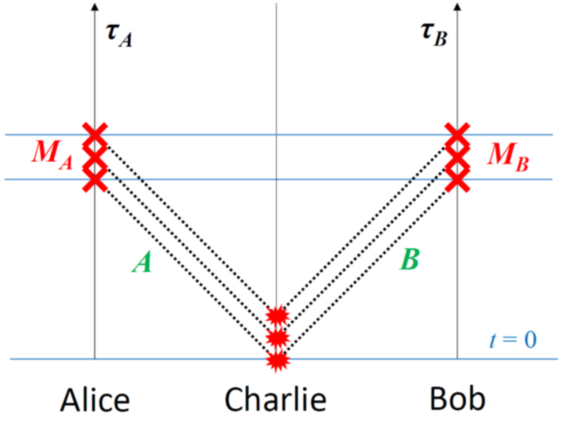
- Micius satellite: demonstrated entanglement distribution & passive quantum teleportation over 10^3 km.

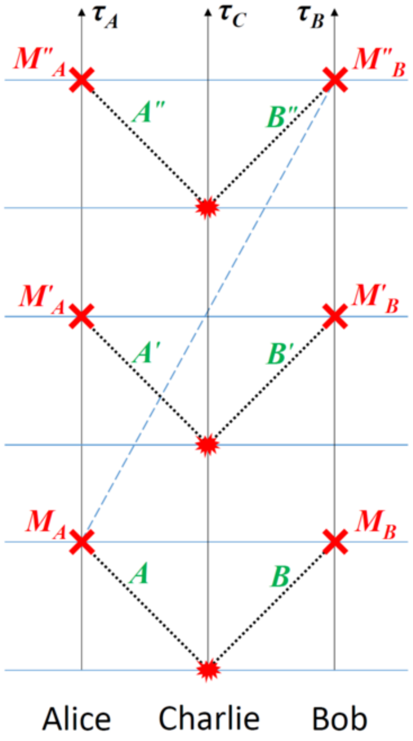
(iii) Long-baseline Bell test with quantum memories

- Possibility of closing the “memory loophole”.
- Possibility of performing human-decision Bell tests.
- *Quantum memories* could be used instead of extra spacecraft

  → storage time feasible, but major requirement on *multiplexing*.







Conclusions

- Quantum optics experiments over long baselines (Earth–Moon) → opportunity to explore the interplay between quantum mechanics and gravitation with relativistic particles in an unprecedented regime.

- Key experiments identified:
  - gravitational-redshift measurement with quantum states of light
  - long-baseline Bell tests (+ quantum memories) & quantum teleportation

- Main challenges for practical implementation:
  - *huge losses* due to beam divergence → small number of detected photons (vs. dark counts)
  - source of entangled photon pairs with *high emission rate* is needed
  - major requirements on *multiplexing* in experiments with quantum memories

Thank you for your attention.

Relativistic Quantum Information
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