

Can the cosmos test quantum entanglement?

Albert Einstein hated the idea he called “spooky actions at a distance,” but astronomers now are hoping to illuminate some of these tricky quantum puzzles. **by Andrew Friedman**

Quantum mechanics remains our best physical theory of nature at the smallest scales, describing the bizarre world of subatomic particles like photons and electrons. It is arguably the most successful theory of modern science, predicting the behavior of light and matter with amazing precision and enabling transformative technologies like lasers, computer chips, and iPads. Unfortunately, despite nearly a century since physicists laid the foundation of quantum theory, we don't agree on its physical interpretation. While we know how to use quantum mechanics as a powerful practical tool, we still don't understand what it actually means.

Most researchers simply apply quantum theory without considering what the equations imply about reality. But maybe our embarrassingly poor grasp of quantum foundations represents an opportunity. In this view, science isn't just about making

predictions and building useful gadgets — it's about telling a story and explaining how the world works.

Perhaps a satisfying explanation of quantum reality consistently has eluded us because nature is subtly fooling us. Strange as it may sound, at the core of quantum mechanics lies an insidious possibility — a “loophole” — that might mean we lack complete freedom to set up our experiments. If the cosmos exploits this loophole, it might help explain some of the most perplexing aspects of quantum theory — but at the price of a conspiracy of cosmic proportions that could render the very concept of choice an illusion.

One path toward clarifying the quantum story is to leave the subatomic realm and instead look to the stars. By using connections between the quantum world and distant regions of the universe, we hope to illuminate some of the mysteries of quantum theory. To tell the cosmic story of how astronomy itself might help shore up quantum foundations, we must first explore “quantum entanglement.”

Inextricably entangled

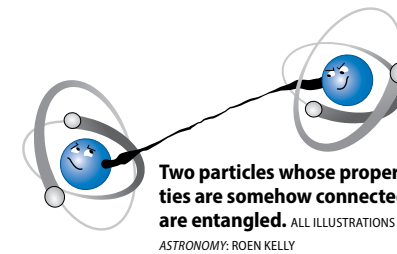
Entangled particles are connected in a way that transcends space and time. Measuring some property of one particle seems to

instantaneously “fix” the future measurement outcome for the other.

This happens even if they were too far apart for any known signals (those that travel at light-speed or less) to have been exchanged during the measurements. This feature of entanglement, which Albert Einstein famously called “spooky actions at a distance,” holds no matter how far apart the particles are in the portion of the universe that we can observe.

Particles can become entangled either by interacting or being created together. Physicists routinely create them in laboratories; to create an entangled pair of photons, the wavy particles that make up light, experimenters send single photons through a special crystal that yields two photons each time. Entangled pairs also occur frequently in nature.

How can such particles maintain coordination over vast distances and eons? No one really knows. Despite many experiments verifying that entanglement is real, scientists remain baffled of its true nature.



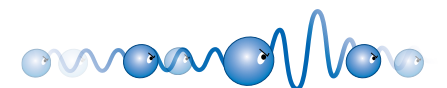
After two particles interact, they can become entangled — each one knows how the other acts no matter how far apart they are. Astronomers hope to use luminous distant galaxies called “quasars” to test this bizarre quantum mechanical behavior. ASTRONOMY: ROEN KELLY; ESA/NASA, THE HUBBLE HERITAGE TEAM (AURA/STScI/NASA), AND NASA/ESA/A. VAN DER WEL (MPIA, HEIDELBERG, GERMANY)/H. FERGUSON AND A. KOEKEMOER (STScI)/ THE CANDELS TEAM (BACKGROUND GALAXIES)

One way two photons can be entangled is with respect to the direction they vibrate, called “polarization.” Typically, the polarizations of entangled particles are aligned perpendicularly — one vertical and one horizontal. But which photon has which polarization?

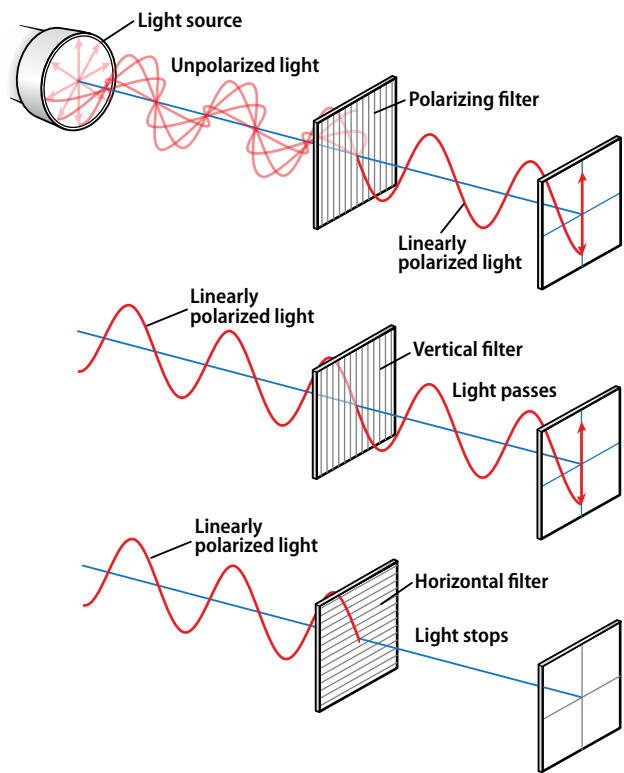
Quantum theory says we don't know because before we measure them, each photon is in an indefinite state with a 50-50 chance of us measuring either polarization. Only after we measure the first photon do it and its partner have fixed polarizations.

Imagine that we measure the first photon: vertical polarization. Its entangled partner then will display horizontal polarization. But if the photon detectors were sufficiently far apart, even signals traveling at the speed of light could not have been exchanged between measurements. So without any possible communication, how did the second photon manage to coordinate with the first and somehow know what to do? It is precisely this instantaneous, or so-called “non-local,” phenomenon that Einstein found so hair-raising. (And just to set things straight, because we can't know the

Any particle (photon, electron, or other) behaves both as a wave and a particle.



Light's preferred directions



Light's polarization is essentially the direction in which the radiation wiggles. In this illustration, light is linearly polarized. If a polarization filter is aligned (center) or misaligned (bottom) with light's polarization, radiation will either pass through or be absorbed, respectively. If a filter is misaligned at an intermediate angle (not shown), quantum theory predicts the probability that a vertically or horizontally polarized photon will pass or be absorbed. Before a measurement, however, two photons with entangled polarizations can each be in both "horizontal" and "vertical" states at the same time. ASTRONOMY: ROEN KELLY



When a polarizing filter (like polarized sunglass lenses) is in front of a polarized light source like a computer monitor, the screen brightens and dims, as seen through the lenses, based on how much the filter is aligned or misaligned with the average polarization of the photons. ANDREW FRIEDMAN

particles behave independently, which is what they would do if information can travel no faster than light-speed and these particles follow classical physics — and not quantum — rules. This is now known as "Bell's theorem." Quantum mechanics predicts correlation values greater than the maximum from Bell's theorem, and every published experimental test has strongly favored quantum theory. The usual conclusion is that quantum mechanics must be non-local, meaning that measuring properties of entangled particles can set the properties of their partners no matter where they are located in the universe.

According to Bell's theorem, given certain seemingly reasonable assumptions about the world, local causes can't explain the correlations seen in entanglement experiments. Furthermore, standard quantum theory seems to have no way to tell a consistent story about the actual states of the individual entangled particles before, during, and after the experiment — facts we can know only about the composite system of two particles. For those of us in the business of explanation, this seems quite unsatisfactory.

Is our theory of quantum mechanics complete, or is it missing key hidden information and therefore a fundamentally incomplete description of reality? This mystery formed the crux of the long-standing debate between Einstein and physicist Niels Bohr that began in the 1920s and still resounds among physicists and philosophers of science today. Einstein desperately wanted physics to be about reality and argued that quantum theory must be fundamentally incomplete, while Bohr declared that quantum mechanics was the whole story and it was meaningless to ask what was really going on in the quantum realm. Einstein's and Bohr's positions seemed fundamentally irreconcilable until Bell's theorem entered the fray in 1964.

Closing quantum loopholes

Like any theorem, Bell's proof requires certain assumptions. By altering any of them, one can introduce loopholes that could allow different explanations of entangled particle tests that would make

QUANTUM CONVERSATION

Hidden-variable theory: The idea that quantum mechanics is not complete and to make sense needs quantities that scientists can't measure (yet).

Locality: Immediate surroundings; signals that can travel at light-speed.

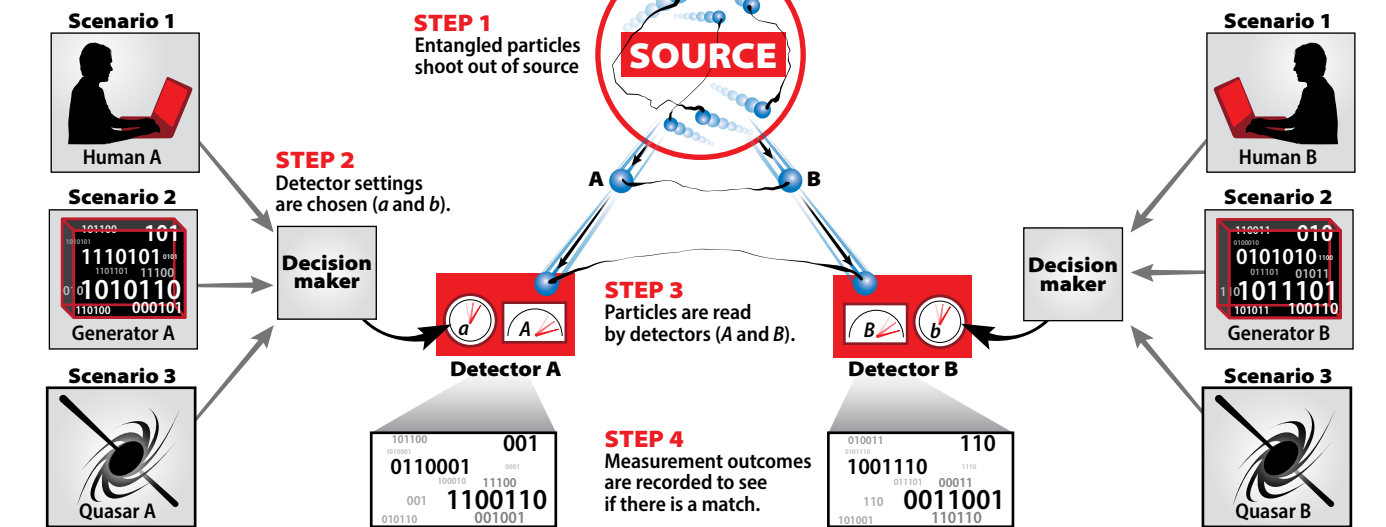
Photon: A particle of light; its energy depends on the type of

light (an X-ray photon has more energy than an infrared one).

Quantum entanglement: A phenomenon where two particles — no matter how far apart — are somehow linked and seem to know about each other.

Quantum theory: A scientific theory of matter and forces that governs the subatomic world.

Three Bell tests



To test Bell's theorem, entangled photons are sent from a source to two detectors. In a laboratory setup, (1) humans or (2) random-number generators can choose detector settings. A "cosmic Bell test" could use (3) quasars that are so distant from each other and Earth that nothing else in the past could have communicated with both of them since cosmic inflation to affect the experiment. ASTRONOMY: ROEN KELLY, AFTER GALLICCHIO, FRIEDMAN, AND KAISER 2014

sense without quantum mechanics — where the world is really local, and comprehensible, after all, just as in classical physics. We dub these quantum competitors "local hidden variable" theories to denote that information is missing from quantum theory. If such alternative theories are true, there might be a sensible story about the real, intrinsic, local properties of particles before, during, and after measurements.

Scientists who believe quantum theory is complete — and therefore doesn't require any local hidden variables — have gone to great lengths to test it by designing experiments that ensure the universe can't exploit certain loopholes. For example, to rule out a loophole that results from potential hidden communication between parts of the experiment — the so-called "locality" loophole — one can choose detector settings at the last instant while the entangled particles are still in flight. To close another loophole that could give biased results from inefficient detectors — the so-called "fair sampling" loophole — one can use extremely efficient new detectors.

While physicists have been performing locality and fair sampling experiments over the past four decades, they've only recently begun testing a third loophole. This is the so-called "setting independence" or "freedom of choice" loophole, which questions if the detector settings themselves were correlated with hidden information in their shared pasts. For example, if some hidden variables sent signals that influence the detectors before the measurement, then the experimenters might be unable to freely choose detector settings. This could constrain one's choices in a way that previous tests could not have ruled out, leaving a non-quantum explanation viable. We sometimes fancifully call this the "free will" loophole (see "Testing possible loopholes in Bell's theorem," on p. 32).

Recent theoretical work shows that only a minuscule amount of information

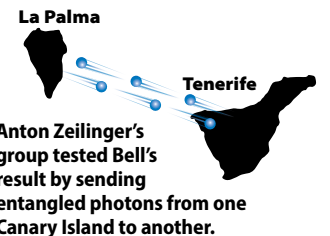
Humans assume we have freedom to set up Bell test experiments. But if the cosmos exploits the "free will" loophole, our choices might not be completely free.



shared between the detectors and any hidden variables could conspire to mimic quantum predictions. Even if the experimenters retain most of their freedom to choose detector settings, tiny constraints in their choices could explain entanglement experiments while preserving locality.

Anton Zeilinger of the Vienna Center for Quantum Science and Technology and his colleagues were the first to tackle this loophole in a 2008 experiment, which they published in 2010. They performed a groundbreaking Bell test by sending polarization-entangled photons an unprecedented 89 miles (144 kilometers) through open air between detectors at two observatories in the Canary Islands — one on La Palma and the other on Tenerife. The long distance gave the scientists enough time to use quantum random-number generators to rapidly change the orientations of the polarizing filters on the detectors at the last fraction of a second while the entangled photons were still in flight. This sophisticated setup did not close the fair sampling loophole, but it did close the locality loophole and narrowed the free will one, firmly ruling out any conspiratorial correlations set up during the experiment.

Because Zeilinger's study did not fully close the free will loophole, it left open the possibility of a conspiracy beginning a few milliseconds before the test. It takes only tens of milliseconds for light to cross Earth, so there is a chance that any terrestrial process we use to select detector settings could fall prey to this loophole. Furthermore, no experiment has closed all three major loopholes simultaneously. Now, my colleagues and I have proposed an experiment that we think can do so by relegating any conspiracy to the most distant epochs of cosmic history — all the way back to the universe's beginning 13.8 billion years ago.



Anton Zeilinger's group tested Bell's result by sending entangled photons from one Canary Island to another.

Cosmic light to the rescue

Jason Gallicchio of the University of Chicago, David Kaiser of the Massachusetts Institute of Technology in Cambridge, and I

first photon's outcome before we measure it, we can't use entanglement to transmit information faster than light.)

In modern laboratory setups, a source can send polarization-entangled photons to detectors dozens of miles away (although they could be on opposite ends of the cosmos). These detectors measure the photons' polarizations based on whether they pass through a special filter, similar to polarizing sunglass lenses. The detectors' settings are the orientation angles of the polarizing filters, such as 30° or 105°. When the detectors align, they always produce polarization measurements with opposite outcomes.

For varying angles of misalignment, quantum theory predicts how often we would measure the same or opposite result on each experimental run. Over many such runs, each detector measures what looks like a sequence of random outcomes. But when we compare the results, we see correlations that appear impossible to explain based on any shared history of the entangled particles. Quantum entanglement is an indisputable experimental fact, but we still cannot explain what it actually means! We do, however, have a few useful clues.

A hidden quantum reality?

Fifty years ago, physicist John S. Bell gave us perhaps the most helpful clue. He quantified the maximum amount that entangled particle measurements could be correlated assuming that both

TESTING POSSIBLE LOOPHOLES IN BELL'S THEOREM

LOOPHOLE NAMES	DEFINITION	HOW TO CLOSE LOOPHOLE	CLOSED FOR PHOTONS?*
"Locality" or "communication"	Potential hidden communication between parts of the experiment	Choose detector settings at last instant while entangled particles are still in flight	YES: A. Aspect, et al. 1982 G. Weihs, et al. 1998 T. Scheidl, et al. 2010
"Fair sampling" or "detection efficiency"	Biased results from inefficient detectors	Use newly developed, high-efficiency detectors	YES: M. Giustina, et al. 2013 B. G. Christensen, et al. 2013
"Setting independence" or "freedom of choice" or "free will"	Detector settings correlated with local hidden variables during experiment	Ensure no communication between detector-setting events and measurement outcomes	YES: T. Scheidl, et al. 2010
	Detector settings correlated with local hidden variables at any time in the past	Use causally disconnected cosmic sources (later than inflationary era) to choose detector settings	NOT YET: "Cosmic Bell," TBA

* Some loopholes have been closed for other systems besides photons. For example, the "fair sampling" loophole has been closed for atoms (M. A. Rowe, et al. 2001) and superconducting quantum bits (M. Ansmann, et al. 2009). No single experiment has closed all three loopholes simultaneously for photons or any other system. Physicists have discussed dozens of other loopholes, but these are the most prominent ones.

envision closing the free will loophole with the help of some of the oldest light in the universe. Our approach adds a new wrinkle to standard Bell tests by taking ourselves out of the equation and essentially letting the universe decide how to set the detectors on each run of the experiment.

In collaboration with the Zeilinger group, our test would first use a standard laboratory source to send entangled photons to two detectors 89 miles (144km) apart in the Canary Islands. Meanwhile, we would point telescopes on each island at astronomical sources on opposite sides of the sky and use the random arrival times of the photons from those objects to set the polarization angles of both detectors while the earthbound entangled photons are still en route. We would use real-time fluctuations in the signals from ancient objects such as quasars (active galaxies that lived billions of years ago) or patches of the cosmic microwave background (CMB, the Big Bang's residual light).

Our so-called "cosmic Bell test" would thus effectively turn the night sky into a special kind of random-number generator, where — most crucially — the astronomical signals are effectively guaranteed to be uncorrelated with one another and any past hidden variables, in principle. While laboratory photons are specifically prepared in an entangled state, the quasar's (or CMB's) photons are as *unentangled* as possible with each other or anything in their shared past — by design.

By picking pairs of quasars that are sufficiently distant from each other and Earth, we can be as sure as possible that no local hidden variables could have sent signals to both quasars in the finite amount of time since the Big Bang. The quasars themselves would have had no causal contact or mutual influence from anything else for essentially the entire history of the universe (see "Two Bell tests, and how they differ," on p. 33). Unentangled cosmic light from the night sky therefore can help disentangle some of the trickiest parts of quantum entanglement here on Earth.

How distant must these quasars be? Sources on opposite sides of the sky that emitted their light 12.1 billion years ago are now at

redshifts greater than 3.65; nothing else could have jointly communicated with both quasars in the past 13.8 billion years. We could incorporate these quasars in a cosmic Bell test from space — say, using the International Space Station and a distant satellite. For a ground-based experiment, we would need objects whose light was emitted 12.3 billion years ago (corresponding to a redshift of at least 4.13) to simultaneously observe both quasars above the horizon. Many such quasars exist that are bright enough to observe with 1- to 3-meter telescopes.

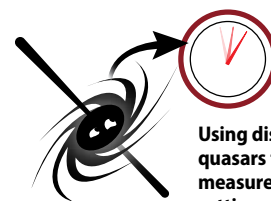
Loopholes all the way down?

Despite how careful our experiment will be to use distant light sources, even a cosmic Bell test is susceptible to another key loophole. It stems from a phase of hyperaccelerated expansion called inflation during the first instant of cosmic history. A recent

claimed observation of swirly polarization patterns in the CMB — thought to result from primordial gravitational waves produced during inflation — gives us even more confidence that inflation occurred. However, if the infant

cosmos underwent inflation, all events in our observable universe — including light emitted from distant quasar pairs — had a shared past during the inflationary epoch and thus could have communicated with one another in those first moments of cosmic history.

Because hidden variables during inflation could still exploit the free will loophole, this might seem to fundamentally undercut our argument. If inflation actually occurred, however, our proposed test is arguably the best anyone can do because it minimizes the amount of overlap that could have correlated the quasar photons. And if the cosmic Bell test reveals correlation values greater than Bell's theorem limits, as we expect and quantum theory predicts, we would still be closing the free will loophole as much as is physically possible in our universe. We could rest easy knowing that we had pushed any conspiracy all the way back to the very beginning of cosmic history, "implausifying" it as much as any experiment conceivably could.



Using distant quasars to choose measurement settings at the last second could close the "free will" loophole.

Entanglement on cosmic scales?

Could quantum entanglement yield observable effects on cosmological scales? Quantum mechanics doesn't mesh with our leading idea of the behavior of matter and gravity on scales as large as the entire universe — called Einstein's general relativity. Physicists are working hard to develop a new theory of "quantum gravity" to tie quantum mechanics and relativity together. In quantum gravity, the very concepts of space and time might not be fundamental properties, but instead might emerge from more basic concepts such as how *entangled* two regions are. In this view, highly entangled systems, each composed of many particles, could be extremely close together from the quantum gravity perspective, whereas in general relativity, large physical distances might appear to separate them.

One promising idea suggests that strongly entangled systems in quantum gravity might be like wormholes in general relativity — cosmic shortcuts that connect what appear to be very distant regions in space-time. Although wormholes are speculative, if astronomers find observational evidence for these structures, it also could suggest quantum entanglement on cosmic scales.

Another intriguing astronomical source of entanglement could come from cosmology. If inflation actually occurred, many regions of the cosmos could have become entangled through direct interaction in the universe's first fraction of a second before cosmic expansion accelerated them into causally separated parts of the universe. Astronomers have evidence in today's cosmos of a more gradual type of cosmic acceleration driven by dark energy — a mysterious substance with anti-gravitational properties. When we combine inflation and the current expansion, distant regions seem to be inaccessible to us forever. Both of these accelerations would push the regions beyond our "horizon" — both the distance out to which telescopes and other detectors can see as well as the farthest place we could ever reach, even if we could travel at the speed of light forever.

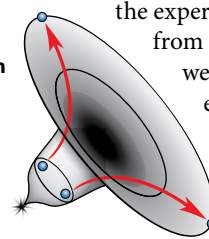
How could we test such cosmic entanglement, then, if we can't perform experiments on such causally inaccessible distant regions? Perhaps only if cosmic entanglement set up during inflation between local systems and distant ones were somehow frozen into the cosmos, immune to our meddling. This is a key open question at the frontier of quantum foundations and cosmology.

Cosmic bell in the real world?

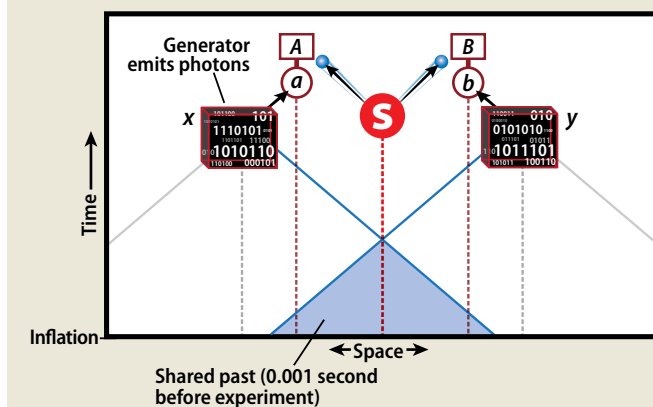
So what might a cosmic Bell experiment like ours reveal? While I would bet we would see correlations that violate Bell's result, as quantum theory predicts, no matter which cosmic sources we use, other outcomes are possible. That is the beauty of science. We can't be sure what we'll see until we actually perform the experiments!

For instance, if Bell's result is somehow not violated for any quasar pairs, or if the experiment displays a dependence on *which* quasars we use, then the role of inflation could turn from a bug into a feature. In such an unlikely scenario, the degree to which these objects shared pasts during inflation might relate to why the experiment shows deviations from quantum predictions. Thus, we could use a cosmic Bell experiment to test competing models of inflation, other theories of the early universe, and possibly even quantum gravity. Even if

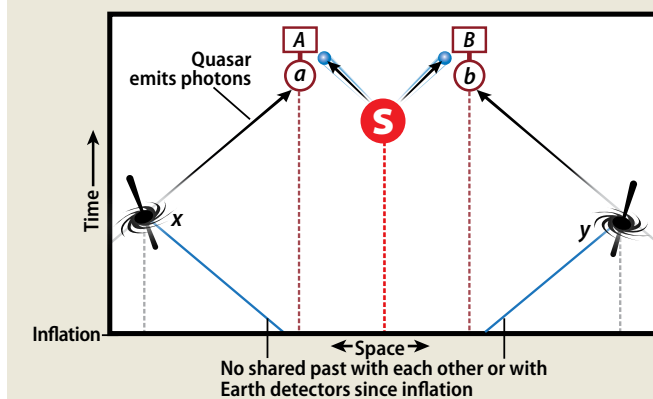
If the cosmos underwent inflation in the first fraction of a second, any pair of distant light sources could have communicated during inflation.



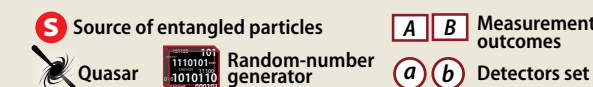
TWO BELL TESTS, AND HOW THEY DIFFER



Standard Bell test: Humans or quantum random-number generators choose detector settings. Events *x* and *y* have past light cones that intersect a few milliseconds before the experiment. Local hidden variables in the overlap region just before the experiment (blue) *could* exploit the "free will" loophole.



Cosmic Bell test: Causally disconnected cosmic sources choose detector settings. Past light cones of quasars *x* and *y* do not intersect over 13.8 billion years since inflation. No causal overlap between events *x* and *y* means that local hidden variables cannot exploit the "free will" loophole. Quasars *x* and *y* *did* share regions in the past (during inflation) — but those are below and outside the plots.



our cosmic Bell test yields the expected outcome, the experiment would still test quantum entanglement, non-locality, and further close the free will loophole — while increasing our confidence in quantum theory.

This seems to us like a clear win-win situation; either result will reveal important information about our universe. And while I wouldn't bet on seeing anything surprising, experiments that leverage the astronomical distances and timescales of cosmology to explore fundamental physics are exactly the types of tests that could reveal something even weirder than quantum mechanics. ☛