We propose a practical scheme to use photons from causally disconnected cosmic sources to set the detectors in an experimental test of Bell’s inequality. In current experiments, detector settings are determined by local quantum random number generators. In such experiments, only a small amount of correlation between detector settings and some local hidden variables, established less than a millisecond before each experimental run, would suffice to mimic the predictions of quantum mechanics. By setting the detectors using cosmic sources instead, observed violations of Bell’s inequality in our proposed “Cosmic Bell” experiment would require any such coordination to have been in place for billions of years rather than milliseconds — an improvement of 20 orders of magnitude. Quasar pairs can be used as real-time triggers to establish detector settings using existing technology. For quasars on opposite sides of the sky with redshifts $z > 3.65$, there is no event after the hot big bang 13.8 billion years ago (following any period of inflation) that lies in the past light cones of both quasars. Alternatively, detector settings could be set by observing patches of the Cosmic Microwave Background (CMB, $z \approx 1089$). For CMB patches with angular separations $> 2.3^\circ$, the events determining the detector settings would have no shared causal past since the hot big bang. In the case of the CMB, noise from the receiver and atmosphere make it difficult to rule out local influences on causal grounds alone, but a specially designed balloon-based system using state-of-the-art detectors is a realistic near-term possibility.

To date, every published experimental test of Bell’s inequality has yielded results compatible with the predictions of quantum mechanics. In light of this robust experimental evidence, Bell’s theorem implies that one or more eminently reasonable assumptions about the nature of the world must be abandoned or revised [1, 2]. These include locality [3–6], fair sampling of inefficient detectors [7–11], and detector settings-independence (sometimes called freedom-of-choice or free will) [12–19]. While Bell tests are usually interpreted as evidence for abandoning the specific assumption of locality to explain the experimental results, relaxing the other assumptions leads to loopholes that could salvage a local realist view where quantum mechanics is incomplete and there are local hidden variables describing its missing degrees of freedom.

Compared to the locality and detector-efficiency loopholes, settings-independence has received far less scrutiny, though arguably the standard interpretation of Bell tests is most vulnerable to the settings-independence loophole. Recent calculations have demonstrated that if the settings-independence assumption were false, then rival models could reproduce the predictions of quantum mechanics if the detector settings shared even a small correlation with some local hidden variables [16–18]. For example, singlet state correlations in the common two-setting, two-outcome Bell test with entangled photons could be reproduced by a local model that allows as little as 1/22 of a bit of mutual information to be shared between the detectors’ polarizer orientations and the hidden variables [15]. This means that a local explanation of observed violations of Bell’s inequality could be maintained if only one out of every 22 seemingly “free choice” binary detector settings were determined by some prior “conspiracy,” established within the shared past light cones of the detectors and the source of entangled particles.

Performing a loophole-free Bell test and decisively closing the settings-independence-loophole remains an important goal not just in the arena of fundamental physics, but in the burgeoning field of quantum information science [10–12]. If hidden variable models of any sort are viable, upcoming quantum encryption schemes could be broken by a sophisticated future eavesdropper that learns to measure the previously “hidden” variables [17].

Our proposed “Cosmic Bell” experiment, illustrated in Fig. 1 seeks to close this loophole in a more definitive way than any experiment performed to date, using causally disconnected cosmic sources to set the detectors while the entangled pair is in flight. By using cosmic

![FIG. 1. Schematic of proposed experiment where cosmic sources determine the detector settings in an otherwise standard Bell-type experiment.](image-url)
mic sources that are farther and farther away, we may put quantitative bounds on the distances and timescales over which any such hidden-variable “conspiracy” must act. If violations of Bell’s inequality are still observed with all other loopholes closed, a local realist explanation would require that the correlations were put in place billions of years ago. Existing state-of-the-art experiments, in contrast, have used quantum random number generators (QRNGs) to set the detectors (e.g. [5, 15], see [20] for review). The settings-independence loophole in such scenarios requires hidden-variable correlations to have been established merely milliseconds before each detector’s measurement, rather than billions of years earlier. Our “Cosmic Bell” experiment would thereby yield an improvement of 20 orders of magnitude in constraining the crucial settings-independence loophole.

Fig. 2 shows a conformal diagram of our setup. Distant quasars emit light at events $x$ and $y$. If those emission events satisfy the conditions on redshift and angular separation (as viewed from Earth) as detailed in [21], then given best-fit ΛCDM cosmological parameters from the Planck satellite [22], the past light cones from events $x$ and $y$ share no overlap with each other or with the worldline of the Earth since the time of the hot big bang. Event $y'$ lies within the past light cones of $y$ and $S$ and can influence both.

emits a pair of entangled particles toward detectors 1 and 2. Finally, at measurement events $M_1$ and $M_2$, detectors 1 and 2 each register one of two possible outcomes.

The same basic protocol could be extended to test quantum entanglement in a three-particle GHZ state [23, 26]. In that case a triplet of quasars, each satisfying pairwise constraints on redshift and relative angle to preserve causal independence between each other and the Earth’s worldline, could be used to determine detector settings. In general, local hidden-variable explanations for the results of GHZ experiments require far greater violation of the settings-independence assumption than do tests of two-particle states. For example, in a typical three-particle GHZ test that measures only one of two orthogonal spin (or polarization) bases for each entangled particle, 0.415 bits rather than $1/22 \approx 0.045$ bits are required to mimic the quantum expectations [18].

For experiments with either two-particle or three-particle entangled states, sufficiently distant quasars may be used to push any suspected coordination between detectors to times earlier than the hot big bang. However, if the source $S$ could somehow tailor its emissions based on partial information about detector settings, causality alone would only require that local hidden variables establish some coordination with events that occurred before the quasars’ emission. For example, there could exist an event $y'$ within the past light cones of $y$ and $S$. If that event determined the properties of the quasar emission at event $y$, which in turn determined the setting of detector 2, then causality alone would not prevent $S$ from exploiting information from $y'$ to predict the setting of detector 2. Even in such a “smart source” scenario, however, use of distant quasars pushes the setting-influencing event $y'$ deep into cosmic history, and hence would require any such information from $y'$ to be preserved over cosmological distances and times and to be identifiable as pertinent by the source amid all the other data within the past light cone of $S$.

While preparing this Letter, we discovered that others have briefly mentioned the basic premise of using cosmic sources to determine detector settings [15, 27, 28]. However, we believe we are the first to develop a realistic protocol for such an experiment which computes appropriate causal conditions [21] and quantifies basic detector requirements for real candidate sources in our universe.

Quasars — Quasars are the brightest continuous astronomical sources at cosmological distances and have been observed out to high redshifts (ULAS J1120+0461, $z = 7.085$ [29]), farther than the most distant supernova (SN 1994I, $z = 2.357$ [30]). While some gamma-ray bursts (GRBs) are more distant (GRB 090429B, $z \sim 9.4$ [31]), and early-time GRB optical/IR afterglows can be brighter than comparable redshift quasars [32], GRBs are transient sources and difficult to use for our purposes.

Two quasars on opposite sides of the sky with redshifts $z > 3.65$ have been causally disconnected from each
FIG. 3. Optical ugriz-band [23] photon flux per unit area from quasars in the Sloan Digital Sky Survey (SDSS) up to Data Release 9 [34]. Measured photometric brightness in each band was multiplied by the appropriate conversion factor to get an approximate photon rate, then all bands were summed. Though this is a biased sample, the optical flux of known $z > 3.65$ quasars yields candidate sources and sets the scale for telescope size, distance between the entangled particle source and detectors, and quasar photon coincidence rate.

other and from the worldline of the Earth since the hot big bang. For separations of less than $180^\circ$ — as required for earthbound observations due to atmospheric extinction and noise — pairs of quasars must be correspondingly farther away to guarantee past causal independence. A feasible ground-based test of 2-particle entanglement could be done for $130^\circ$ separations, with each quasar satisfying $z > 4.13$. Similarly, a 3-particle GHZ state could be tested from space if each quasar pair in the triplet were separated by $120^\circ$ and had $z > 4.37$, or from the ground with $110^\circ$ separations and $z > 4.69$ [21]. Most quasars emit most strongly in the rest-frame UV, around the 121.6 nm Ly-α hydrogen line. Redshifts of interest move this into the visible and near-IR region, with the most useful photons for a ground-based test in the optical due to increased near-IR sky noise. As shown in Fig. 3, recent surveys like SDSS include substantial optical photon flux from quasars at such redshifts.

To turn quasar light into a bitstream, we can use the arrival time, wavelength, or polarization. Since accurate timing is already needed to record the entangled particles’ arrival, identical time-stamp electronics would be used to record the quasar photons’ arrival. The detector setting can be switched based on whether the quasar photon arrived on an even or odd microsecond. A more sophisticated scheme can get more bits of entropy by whitening the exponential distribution of arrival times at the cost of added latency [35, 36].

For a given flux per unit area of photons from a quasar, $F$, the rate of photons arriving at a telescope per second is $r = F \pi (d/2)^2$, where $d$ is the telescope diameter. Within some time interval $\Delta t$, and for a detector efficiency of $\eta$, the average number of photons detected is $\mu = \eta r \Delta t$. Assuming Poisson statistics, the probability that exactly $n$ photons are detected within $\Delta t$ is $P_\mu(n) = \mu^n e^{-\mu}/n!$. Hence the probability of detecting one or more quasars photons within that period is $P_\mu(n > 0) = 1 - P_\mu(0) = 1 - e^{-\eta r \Delta t}$. The probability that both detectors register at least one photon from their respective quasars within $\Delta t$ is

$$P_{12} = \left[1 - e^{-\eta r_1 \Delta t}\right] \left[1 - e^{-\eta r_2 \Delta t}\right].$$

If the baselines $L_i$ between the source of entangled particles and the detectors are sufficiently long, we may ensure that the time required to register the quasar photons (and adjust the detector settings) is shorter than the entangled particles’ flight time. For a symmetric arrangement, $L_1 = L_2 = L$, we therefore take $\Delta t \approx L/c$. For realistic values of $d_1 = d_2 = 1$ m, $\eta = 0.50$, $L = 50$ km, and $F_1 = F_2 \approx 2 \times 10^4$ s$^{-1}$ m$^{-2}$ at $z \approx 4.13$ (see Fig. 3), we find $P_{12} = 0.53$. During about half the experimental runs, both detector settings would be determined by quasar photon observations. For a ground-based, three-particle GHZ test, with optical flux reduced by a factor of $\sim 2$ from $z \sim 4.13$ to $z \sim 4.69$ and thus $F_1 = F_2 \approx 10^4$ s$^{-1}$ m$^{-2}$, the baselines could be increased by a factor of $\sim 2$ to $L \sim 100$ km to yield $P_{12} = 0.39$. Locality-preserving Bell tests with $L \sim 144$ km have already been achieved with entangled photons [15]. With coincidence rates for both setups of $> 10^3$ Hz, which would not be limited by achievable entangled photon pair production rates of $> 10^7$ Hz [16], we could achieve $> 10^6$ triggered experimental runs for pairs or triplets jointly observable at low enough airmass for only 15 minutes. Runs in which any or all detectors were not triggered by quasars would serve as useful controls.

The required detector technology also exists. Superconducting transition edge sensors (TES) have been used to detect entangled photons in Bell tests that close the detector-efficiency loophole [10, 11]. These sensors offer a combination of photon number resolution and high detection efficiency of up to $\eta = 95\%$ at 1,550 nm, while being virtually free of dark counts [37]. Others have reported efficiencies larger than $97\%$ at 820 nm with jitters of 78 ns when operated between 40 and 75 mK [38], which would provide adequate timing resolution for a two-particle Bell test with $L \sim 26$ km and $\Delta t \sim 86$ $\mu$s. Avalanche photo diodes (APDs) have reduced efficiencies $\eta \sim 50\%$, but offer much better timing resolution (tens of picoseconds) [38] and have already been used for nanosecond optical astronomy [39]. The experimental duty cycle and total number of runs can also be increased by selecting an observing site where the brightest pairs and triplets are well above the horizon for much of the year. Reducing the telescope area by a factor of 2 would reduce the double coincidence rate by 4, and the triple GHZ coincidence by 8, assuming the quasar signal to noise ratio was still acceptable. Similarly for decreasing the baseline, given sufficiently short detector timescales.
To rule out local hidden-variable explanations for experimental results, the detector-setting photons must be of genuine cosmic origin. Hence we must also close the “noise loophole”: photons of more local origin, such as from airglow, light pollution, zodiacal light, and scattered starlight, must be minimized by exposing the detector to as small an angular area on the sky as possible. This background, along with dark counts from the detector, must be estimated by pointing at a dark patch of sky near the quasar. For a two-particle Bell test, this local noise must be kept below 1/22 ~ 0.045 of the signal rate to beat the Hall limit [18]. The brightest quasars in the SDSS catalog with \( z > 3.65 \) come close, but only exceed this limit on dark nights with good seeing, mostly in the \( r \) and \( i \)-bands (623 and 764 nm). A space experiment could take full advantage of the factor of \( \sim 2 - 4 \) in quasar photon flux by including the near-IR \( YJHK \) bands, while avoiding sky noise from near-IR airglow that would be prohibitive in any ground-based test. Noise constraints are an order of magnitude weaker for a 3-particle GHZ test, which only requires background not to exceed 0.415 of the signal rate [18].

Not only should the photons be of cosmic origin; they should not be altered significantly as they travel through the intergalactic medium, our atmosphere, telescopes, or photodetectors. At the very least, we must assume that all distant photons are affected identically by such media in a way that varies on slow time-scales, like refraction through slowly-varying gas. Indeed, away from the plane of the Milky Way, space is transparent. In gamma ray bursts and supernovae, all the photons arrive at nearly the same time: they are ‘prompt’ or ‘ballistic,’ rather than delayed by some interaction [10]. More generally, ignoring effects of intervening media is comparable to the assumption made in current Bell experiments, that fiber optics do not significantly alter the properties of entangled photons.

**Cosmic Microwave Background** — The CMB has many appealing features for setting detectors in a causally independent way. CMB patches separated by only 2.3° share no causal overlap after the hot big bang [21], so both receivers can look almost straight up through very little atmosphere. There is no need to wait for the brief window during the Earth’s rotation when selected quasars are observable through low enough airmass by the telescopes. The bitstream-creating fluctuations themselves would arise from the Poisson photon noise from incoming cosmic radiation. Unfortunately, local sources often swamp the instantaneous CMB signal. The CMB is 2.7 K, and from the ground, the atmosphere, galactic emission, foregrounds, local electromagnetic interference, ground-pickup, and detector noise temperature are often effectively hotter than this. See Fig. 4.

Incoherent bolometers currently have better noise properties than coherent detectors at 80-300 GHz. Here, galactic emission is low compared to the CMB, but atmospheric emission dominates in any ground-based experiment. Moreover, bolometers operate on thermal timescales of milliseconds, making them problematic to rapidly determine detector settings in a small-baseline experiment. Maximizing the instantaneous CMB signal to noise requires atmospheric conditions achievable only from high altitude balloon experiments or satellites (see Fig 4), which must be at least hundreds of kilometers away from the source of entangled particles, each staring at a patch of sky away from the source. The CMB measurements must then be transmitted down to the detectors or the entangled photons must be transmitted up. Relevant ground to space entanglement proposals using the International Space Station have already been suggested [41]. Avoiding light-cone overlap would result in strict latency and positioning requirements.

For the TES bolometers currently on the South Pole Telescope, the useful Poisson photon fluctuations (including both CMB and the 20-30\( \times \) greater atmospheric loading) are similar in magnitude to the local phonon noise from thermal impedance and Johnson noise from the electrical current [45]. The *Planck* satellite’s spider web bolometers [46] (also used on the *Archeops* balloon experiment [47]) are also nearly photon-noise limited, even with no atmospheric loading. Current CMB experiments have no reason to optimize their detectors beyond the photon noise limit, and they typically use single-mode optics. This photon noise is actually our detector-setting signal, and a multi-mode Winston cone could increase it relative to the intrinsic detector noise [43]. Careful optics and detector design could beat the Hall limit of less than 1/22 bits of influence from local sources. The three-particle GHZ setup is appealing for the CMB because this...
requirement is an order of magnitude less strict. And finding three causally-disconnected spots on the CMB is easy compared to finding three bright quasars that meet the angle and redshift requirements.

Conclusions — Until recently, most discussions of Bell tests simply assumed experimenters were able to choose their settings freely. While seemingly quite reasonable, 

locality itself seemed equally reasonable before Bell’s theoretical work [1] and the first Bell tests [2,3] began to challenge it empirically. Recent work [15,16] demonstrates how vulnerable the standard interpretation of Bell tests is to the settings-independence loophole. Our proposed “Cosmic Bell” experiment is a realizable test that uses the causal structure of space-time to improve the limits on possible correlation between settings and local hidden variables by 20 orders of magnitude, forcing any “conspiracy” to have been enacted billions of years ago rather than milliseconds before a given measurement.

If such an experiment were to be performed, closing all other loopholes, several outcomes are possible. Most likely the Bell inequalities would be violated for every combination of redshifts and angular separations of cosmic sources, regardless of whether the sources’ past light cones shared any overlap since the hot big bang. Such results would be in keeping with the predictions of quantum mechanics. In that case, the experiment would have succeeded in closing what is arguably the most crucial outstanding loophole in tests of Bell’s inequality. All local hidden-variable theories would be constrained as much as is physically possible in our universe, except perhaps for super-deterministic cosmic conspiracies, which themselves may not be falsifiable [18]. The inference that Bell tests imply that the universe is truly non-local would then be on as firm a ground as possible.

An intriguing possibility would be if the degree to which the Bell inequalities were violated showed a statistically significant dependence on the extent to which the past light cones of the cosmic sources overlapped, or how long ago the overlap occurred. Nearby astronomical sources can probe large, recent overlap; even by triggering on nearby stars in the galaxy, we could push any conspiracy back 13 orders of magnitude in time, before recorded human history. Quasars can probe intermediate Hubble-scale overlaps going all the way back to the hot big bang. And the CMB can push this overlap many e-foldings back into any inflationary period. If experimental systematics could not explain such results, and if other experiments confirmed them, at least two explanations would need to be considered. Perhaps some local hidden-variable theory really were viable; and perhaps the requisite correlations could be traced to an era of early-universe inflation. In such a scenario, cosmic inflation would be responsible for establishing the correlations observed in the CMB, as well as correlations between later events like quasar emissions on opposite sides of the observable universe. Such a result would certainly be unexpected, though it would open up the possibility of testing both our most fundamental understanding of non-locality in quantum mechanics, as well as probing various models of inflation.

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