In this Letter, we report on a new experimental test of Bell’s inequality that, for the first time, uses distant astronomical sources to choose measurement settings. This is the first in a series of “cosmic Bell tests” that will use progressively more distant sources, ultimately pushing the measurement settings’ origin to greater and greater cosmological distances [1].

Background.—Scientists have struggled with the alleged incompatibility of quantum entanglement and our everyday intuitions about the physical world since the seminal paper by Einstein, Podolsky, and Rosen (EPR) in 1935 [2]. EPR concluded that the description of reality given by the quantum-mechanical wave function is incomplete because it is incompatible with the concepts of locality (no physical influences can travel faster than the speed of light in vacuum) and realism (objects possess complete sets of properties on their own, prior to measurement). A well-known “tool” to experimentally distinguish between the quantum predictions and local-realist alternatives of the sort envisaged by EPR is provided by the famous inequality derived by John Bell in 1964 [3]. Assuming locality and realism, Bell’s inequality limits the degree to which measurement outcomes on pairs of distant systems may be correlated, if the measurements of one system are carried out with only limited information about the other. By contrast, measurements on entangled particle pairs in the quantum singlet state, for example, are predicted to violate Bell’s inequality. Beginning with Ref. [4], essentially all significant experimental Bell tests to date have supported the quantum-mechanical predictions.

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However, the conclusions of any experiment are valid only
given certain assumptions, the violation of which leaves open
“loopholes,” whereby a local-realist description of nature
could still be compatible with the experimental results. (For
extensive reviews of Bell-test loopholes, see Refs. [5–7].)
For example, the locality loophole concerns whether any
information about one side’s measurement setting or meas-
urement outcome could have been communicated (at or
below the speed of light) to the other side prior to its
measurement. This loophole has been closed by space-like
separating measurement-setting choices on each side from
the other side’s measurement outcomes [8,9]. The fair-
sampling loophole [10] concerns whether the set of
entangled particles detected on both sides was representa-
tive of all emitted pairs rather than a biased subensemble, and
has recently been closed by ensuring a sufficient total fraction
of detected pairs [11–16]. Even more recently, several cutting-
edge experiments have demonstrated violations of Bell’s
inequality while closing both the locality and fair-sampling
loopholes simultaneously [17–21].

A third major loophole, known variously as the
freedom-of-choice, measurement-independence, or setting-
independence loophole [22–25], concerns the choice of
measurement settings. In particular, the derivation of Bell’s
inequality explicitly assumes that there is no statistical
Correlations. While locally correlated events at least several
hundred years ago, at locations seemingly unrelated to the
entangled-pair creation. Compared to previous experiments, this
pushes back by ∼16 orders of magnitude the most recent time
by which any local-realist influences could have engineered
the observed correlations.

The idea to address freedom of choice by using
distant astronomical sources to choose Bell-test measurement
settings was already discussed as far back as the 1976
Erice meeting organized by John Bell and Bernard
d’Espagnat [49]. While others have also briefly noted this
basic premise [38,50,51], this work is the first to implement
it experimentally, building on a detailed feasibility
study [1].

Experimental implementation.—Figure 1 shows our
three experimental sites across Vienna. A central entangled
photon source $S$ was located in a laboratory on the 4th floor
of the Institute for Quantum Optics and Quantum
Information (IQOQI) and the two observers, Alice ($A$)
and Bob ($B$), were situated on the 9th floor of the Austrian
National Bank (OENB) and on the 5th floor of the
University of Natural Resources and Life Sciences
(BOKU), respectively.

The entangled photon source is based on a Sagnac
interferometer [52,53] generating polarization-entangled
photon pairs in the maximally entangled singlet state
$|\Psi^{-}\rangle = (1/\sqrt{2})(|H_{A}V_{B}\rangle - |V_{A}H_{B}\rangle).$ Using single-mode
fibers, each entangled photon was guided to an entangled
photon transmitting telescope (Tx-EP) located at the roof-
top of IQOQI, which sent the photons via free-space
quantum channels to Alice and Bob, respectively.
Measurement stations for Alice and Bob each featured
an entangled photon receiving telescope (Rx-EP), a polar-
ization analyzer (POL), stellar photon receiving telescope
(Rx-SP), a setting reader (SR) and a control and data acquisition unit (CaDA). The entangled photons were collected with the Rx-EP and guided to the polarization analyzer where an electro-optical modulator (EOM) allowed for fast switching between complementary measurement bases. This was followed by a polarizing beam splitter with a single-photon avalanche diode (SPAD) detector in each output port.

The Rx-SPs collected stellar photons, which were guided by multimode fibers to setting readers, where dichroic mirrors with ≈700 nm cutoffs split them into “blue” and “red” arms, each fed to a SPAD. An FPGA board processed the SPAD signals to electronically implement the corresponding EOM measurement setting. Every detector click in a red or blue arm induced a measurement in the following linear polarization bases for Alice: 45°/135° (blue) and 0°/90° (red), and Bob: 22.5°/112.5° (blue) and −22.5°/67.5° (red), respectively. Finally, using a GPS-disciplined clock, all SPAD detections from the polarization analyzer and the setting reader were time stamped by the FPGA board and recorded by a computer.

We specifically use photon color to implement measurement settings under the assumption that the wavelength of the photon emitted from the star was determined at the time of emission and unaltered since. Astrophysical motivations for this assumption include the absence of any known mechanism that preferentially reradiates photons at a different wavelength along our line of sight; any such process would violate the conservation of energy and momentum. In addition, the effects of wavelength-dependent attenuation by the interstellar medium are negligible for Milky Way stars within a few thousand light years (1y) [54–56]. By contrast, significant attenuation from the Earth’s atmosphere (38%–45% loss) as well as from the experimental setup (59%–61% loss) is unavoidable (see the Supplemental Material [57]). Thus, our approach requires the assumption that this represents a fair sample of the celestial emissions.
Two other major effects must be considered to account for SPAD detections which do not represent stellar photons with correctly identified colors. First, local sources of noise, including sky glow, light pollution, and dark counts determine between 1% and 5% of the settings, as measured by looking at a dark patch of sky next to each star. Only a tenth of these are detector dark counts. In addition, due to imperfect dichroic mirrors, a certain fraction of detected stellar photons emitted far away at space-time events $A_k$ and $B_k$ (see Fig. 3). Ensuring locality limits valid settings to the shaded regions. Delays to implement each setting and an added safety buffer shorten the validity time windows actually used to the darker shaded regions.

![FIG. 2. (1 + 1)D space-time diagram for run 1, with the origin at the entangled pair creation (black dot) and a spatial projection axis chosen to minimize its distance to Alice and Bob. After a fiber delay (thick black line), entangled photons are sent via free-space channels (thin black lines) to be measured by Alice and Bob at events $A$ and $B$. Blue and red stars indicate example valid settings from measuring stellar photons emitted far away at space-time events $A_k$ and $B_k$ (see Fig. 3). Ensuring locality limits valid settings to the shaded regions. Delays to implement each setting and an added safety buffer shorten the validity time windows actually used to the darker shaded regions.](image)
cones of stellar emission events relevant hidden variables could lie within the past light stellar emission events from run 1. Events associated with errors less than 50% and Hipparcos [63,64] with parallax distances greater than 500 ly, distance receiving telescopes from the Hipparcos catalogue, and any small inaccuracies in timing or the distances between the experimental stations (see the Supplemental Material [57]).

In Fig. 2, stellar photons arriving parallel to the arrows in the blue and red shaded space-time regions (corresponding to the time intervals $t_{\text{valid}}$) provide valid basis settings, ensuring spacelike separation for all relevant events. The darker shading corresponds to regions actually used in run 1, with $t_{\text{used}}^A = 2 \mu s$ and $t_{\text{used}}^B = 5 \mu s$. In run 1, the fractions of time with valid settings for Alice and Bob were 24.9% and 40.6%, respectively, while in run 2 they were 22.0% and 44.6%, respectively. Duty cycles for each observer differ primarily due to different values of $t_{\text{used}}$ and different count rates for each star (see the Supplemental Material [57]).

We preselected candidate stars within the highly restrictive azimuth and altitude limits of the stellar photon receiving telescopes from the Hipparcos catalogue [63,64] with parallax distances greater than 500 ly, distance errors less than 50% and Hipparcos $H_p$ magnitude between 5 and 9. Combined with the geometric configuration of the sites, selection of these stars ensured sufficient setting validity times on both sides during each experimental run of 179 s. To ensure a sufficiently high signal-to-noise ratio, we chose $\sim 5$–6 magnitude stars (see the Supplemental Material [57]). Note that to avoid detector saturation, parts of the entrance aperture of the Rx-SPs had to be covered.

Figure 3 shows a $(2 + 1)$D space-time diagram for the stellar emission events from run 1. Events associated with relevant hidden variables could lie within the past light cones of stellar emission events $A_\star$ or $B_\star$, the most recent of which originated $604 \pm 35$ years ago, accounting for parallax distance errors arising primarily from the angular resolution limits of the Hipparcos mission [63,64].

which easily accounted for the delay of stellar photons due to the index of refraction of the atmosphere ($\tau_{\text{atm}} \approx 18$ ns) [62], and any small inaccuracies in timing or the distances between the experimental stations (see the Supplemental Material [57]).

Analysis and results.—We performed two cosmic Bell tests, each lasting 179 seconds. In runs 1 and 2, Alice and Bob’s settings were chosen with photons from Hipparcos stars in Table I. To analyze the data, we make the assumptions of fair sampling and fair coincidences [65]. Thus, all data can be postselected to include coincidence events between Alice’s and Bob’s measurement stations. We correct for GPS clock drift as in Ref. [66] and identify coincidences within a 2.5 ns time window.

We then analyze correlations between measurement outcomes $A, B \in \{ +1, -1 \}$ for particular setting choices $(a_i, b_j), i, j \in \{ 1, 2 \}$ using the Clauser-Horne-Shimony-Holt (CHSH) inequality [67]:

$$S \equiv |E_{11} + E_{12} + E_{21} - E_{22}| \leq 2,$$

where $E_{ij} = 2p(A = B|a_i, b_j) - 1$ and $p(A = B|a_i, b_j)$ is the probability that Alice and Bob measure the same outcome given joint settings $(a_i, b_j)$. While the local-realist bound is 2, the quantum bound is $2\sqrt{2}$, and the logical (algebraic) bound is 4. Our run 1 data yield $S_{\exp} = 2.425$, while for run 2, we observe $S_{\exp} = 2.502$. Both runs therefore violate the corresponding local-realist bound. See Fig. 4 and Table I.

Our analysis must further consider that some experimental trials will have “corrupt” settings triggered not by genuine stellar photons, but by atmospheric airglow, thermal dark counts, errant dichroic mirror reflections, or other noise in our detectors. Since these events originate very recently in the experiments’ past light cone, settings chosen with them are no better (and no worse) than settings chosen with conventional random number generators.

To constrain the fraction of experimental runs we can tolerate in which either or both sides were triggered by a corrupt event, we conservatively assume that any such events can produce maximal CHSH correlations ($S = 4$) [68], whereas settings triggered by correctly identified stellar photons are assumed to obey local realism.
An optimally efficient local hidden-variable model would only need to use individual corrupt photons on a single side to achieve $S = 4$, without needing to “waste” simultaneous corruptions or events in which changing the path of a stellar photon through the setting reader is unnecessary. We, therefore, use this maximally conservative model as our null hypothesis.

To calculate the statistical significance of our results, we account for background events and errant dichroic mirror reflections as well as differences in the measured total and noise rates for the red or blue dichroic ports on each side, which yield unequal (biased) frequencies for various combinations of detector settings $a_i b_j$. Moreover, whereas we assume fair sampling (for both entangled and stellar photon detections) and fair coincidences for entangled photons [65], we adopt the conservative assumption that the local hidden-variable model could retain memory of settings and outcomes of previous trials [69–71]. As detailed in the Supplemental Material [57], we find that the measured fractions of corrupt coincidences are sufficiently low that the probability that a local hidden-variable model could explain the observed violations of Bell’s inequality is $p \leq 1.78 \times 10^{-13}$ for experimental run 1, and $p \leq 3.96 \times 10^{-33}$ for run 2. These correspond to experimental violations of the CHSH bound by at least 7.31 and 11.93 standard deviations, respectively.

Conclusions.—For both runs, we assume fair sampling, close the locality loophole and, for the first time, explicitly constrain freedom of choice with astronomically chosen settings, relegating any local-realist models to have acted no more recently than 604 ± 35 and 577 ± 40 years ago, for runs 1 and 2, respectively. Therefore, any hidden-variable mechanism exploiting the freedom-of-choice loophole would need to have been enacted prior to Gutenberg’s invention of the printing press, which itself predates the publication of Newton’s Principia by two and a half centuries. While a Bell test like ours only constrains a local-realist mechanism to have acted no later than the most recent of the astronomical emission events, we note that any process that requires both emission events to have been influenced by the same common cause would be relegated to even earlier times, to when the past light cones from each emission event intersected 2409 ± 598 and 4040 ± 1363 years ago, for runs 1 and 2, respectively [72].

This work thus represents the first experiment to dramatically limit the space-time region in which hidden variables could be relevant, paving the way for future ground- and space-based tests with distant galaxies, quasars, patches of the cosmic microwave background (CMB), or other more exotic sources such as neutrinos and gravitational waves. Such tests could progressively push any viable hidden-variable models further back into deep cosmic history [1], billions of years in the case of quasars, back to the early universe in the case of the CMB, or even, in the case of primordial gravitational waves, further back to any period of inflation preceding the conventional big bang model [73–77].


[45] One may even consider retrocausal models in which the relevant hidden variable affects the measurement settings from the future [46,47]. The point is that the relevant hidden variable may be associated with spacetime regions far removed from the source of entangled particles.


[48] We note that it is only possible to fully close the locality and freedom-of-choice loopholes by making certain assumptions. If settings were fully determined at the beginning of the universe, they could always be known at the distant measurement locations or be correlated with the hidden variables.


