A COSMIC BELL TEST WITH MEASUREMENT SETTINGS FROM MILKY WAY STARS

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3/8/17
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Quantum Physics Tells Us Our Fate Is Not Written In The Stars

Cosmic experiment is closing another Bell test loophole

Extra Dimensions A new experiment combines nanoscale measurements and interstellar distances to demonstrate quantum nonlocality.

Andrew Grant

Cosmic test confirms quantum weirdness

Distant stars as source of randomness constrains loophole in entanglement experiments

BY EMILY CONOVER 7:00AM, DECEMBER 5, 2016

Starlight test shows quantum world has been weird for 600 years
Cosmic test backs 'quantum spookiness'

Physicists harness starlight to support the case for entanglement.

Elizabeth Gibney

02 February 2017

600-year-old starlight bolsters Einstein's "spooky action" theory

By CALLA COFIELD SPACE.COM February 13, 2017, 1:00 PM

The Universe Is as Spooky as Einstein Thought

In a brilliant new experiment, physicists have confirmed one of the most mysterious laws of the cosmos.

Natalie Wolchover | Feb 10, 2017 | Science
**GAME OF TELEPHONE**

**MIT News**
ON CAMPUS AND AROUND THE WORLD

Stars align in test supporting “spooky action at a distance”
Physicists address loophole in tests of Bell’s inequality, using 600-year-old starlight.

Jennifer Chu | MIT News Office
February 6, 2017

**MIT press release**
**Author read actual paper!**
**Interviewed scientists. Fact checked!**

Read press release (maybe)
Read 2nd and 3rd round articles
OUTLINE

1. Entanglement Tests

2. Bell’s Inequality vs. Bell’s Theorem

3. Bell’s Theorem Loopholes

4. Freedom-Of-Choice Loophole

5. Cosmic Bell Test with Milky Way Stars

6. Future Cosmic Bell Tests with Quasars, CMB
Beginning in the 1930s, the great architects of quantum theory struggled to understand the notion of “entanglement.”
State does not factorize: no way to describe behavior of particle 1 ($u$) without referring to behavior of particle 2 ($v$).

\[ |\psi\rangle = \frac{1}{\sqrt{2}} \left( |u_1\rangle |v_2\rangle + |u_2\rangle |v_1\rangle \right) \]
Big question: Are non-quantum explanations for entanglement viable?

If yes, QM incomplete → Hidden variables
Choosing Detector Settings

Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

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Choosing Detector Settings

Choose settings with observations of causally disconnected cosmic sources

Relegates alternatives to billions of years ago or even back to inflation era!

Adapted from: Gallicchio, Friedman, & Kaiser 2014
Let the Universe decide how to set up experiment!

Use stars or quasars as cosmic random number generators

Past light cones from random number generators overlap milliseconds before test. Past light cones from quasars don’t overlap since big bang, 13.8 billion years ago.

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PHOTON POLARIZATION CORRELATION

Quantum Predictions

\[ \cos^2(\Delta \theta) \]

…or alternative models with Bell’s theorem loopholes

\( p(\text{Measurement Outcomes Agree}) \)

\( \Delta \theta: \text{Angle between polarizers} \)

3/8/17

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BELL’S INEQUALITY ASSUMPTIONS

1. Determinism (Realism)
   Can predict future (or past) of some state from initial conditions using dynamical laws. (External reality exists. Particles have definite and complete properties, whether or not they are observed)

2. Locality
   If distant systems no longer interact, nothing done to system 1 can affect system 2 faster than c.

3. Fair Sampling
   Probability of detector click uncorrelated w/ hidden variables, measurement outcomes.

4. Freedom-of-Choice / Free Will
   Detector settings choices independent of hidden variables in past light cones that could influence measurement outcomes. Observers can choose settings “freely and randomly”.

Einstein, Podolsky, & Rosen (EPR) 1935; Bell 1964; Clauser, Horne, Shimony, & Holt (CHSH) 1969; Hall 2015
**CHSH CORRELATIONS**

Clauser, Horne, Shimony, & Holt (CHSH) 1969

correlation function: $E(a,b) = \langle A B \rangle$

$$S = E(a, b) + E(a', b) + E(a, b') - E(a', b')$$

$a, b$: Settings

Outcomes $A, B: (-1,+1)$
**CHSH Correlations**

Clauser, Horne, Shimony, & Holt (CHSH) 1969

Correlation function: $E(a,b) = \langle A \, B \rangle$

$$S = E(a, b) + E(a', b) + E(a, b') - E(a', b')$$

Bell: if

$$P(A, B|a, b) = \int d\lambda P(\lambda)P(A|a, \lambda)P(B|b, \lambda)$$

then $|S| \leq 2$. 

$a, b$: Settings

$A, B$: (-1, +1)

$\lambda$: Hidden Variables
CHSH CORRELATIONS
Clauser, Horne, Shimony, & Holt (CHSH) 1969

Correlation function: \( E(a, b) = \langle A B \rangle \)

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\]

then \( |S| \leq 2 \).

(Locality: \( A \) does not depend on \( B \) or \( b \), and vice versa.)
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Clauser, Horne, Shimony, & Holt (CHSH) 1969

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**CHSH CORRELATIONS**

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S = E(a, b) + E(a', b) + E(a, b') - E(a', b')
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Bell: if

\[
P(A, B|a, b) = \int d\lambda P(\lambda)P(A|a, \lambda)P(B|b, \lambda)
\]

then \(| S | \leq 2.\)

(Locality: \( A \) does not depend on \( B \) or \( b \), and vice versa.)

**Freedom:** \( P(\lambda|a, b) = P(\lambda) \)

**Outcomes**

\( a, b: \) Settings  \( A, B: (-1,+1) \)

\( \lambda: \) Hidden Variables

\( QM \)

\( \text{Local Realism} \)

3/8/17

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**CHSH CORRELATIONS**

Clauser, Horne, Shimony, & Holt (CHSH) 1969

Correlation function: \( E(a, b) = \langle A, B \rangle \)

\[
S = E(a, b) + E(a', b) + E(a, b') - E(a', b')
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Bell: if

\[
P(A, B | a, b) = \int d\lambda P(\lambda)P(A | a, \lambda)P(B | b, \lambda)
\]

then \( |S| \leq 2 \).

QM prediction: \( S_{\text{max}} = 2\sqrt{2} \)
**CHSH Correlations**
Clauser, Horne, Shimony, & Holt (CHSH) 1969

Correlation function: $E(a,b) = \langle A B \rangle$

$$S = E(a,b) + E(a',b) + E(a,b') - E(a',b')$$

Bell: if $P(A,B|a,b) = \int d\lambda P(\lambda) P(A|a,\lambda) P(B|b,\lambda)$

then $|S| \leq 2$. (Locality: $A$ does not depend on $B$ or $b$, and vice versa.)

QM prediction: $S_{\text{max}} = 2\sqrt{2}$

Dozens of experiments: $S_{\text{max}} > 2$
**BELL’S INEQUALITY VS. THEOREM**

1. Determinism/Realism  
2. Locality  
3. Fair Sampling  
4. Freedom

1,2,3,4 → **Bell’s Inequality (CHSH form)**

\[ S = E(a, b) + E(a', b) + E(a, b') - E(a', b') \]

\[ | S | \leq 2. \]

**QM Prediction (Singlet State):**  
\[ S_{\text{max}} = 2 \sqrt{2} > 2 \]

**Bell’s Theorem**

No local-realistic hidden variable theory can reproduce the quantum predictions!

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Einstein, Podolsky, & Rosen (EPR) 1935; Bell 1964; Clauser, Horne, Shimony, & Holt (CHSH) 1969
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BELL’S THEOREM LOOPHOLES

1. Determinism/Realism  
2. Locality  
3. Fair Sampling  
4. Freedom

What Do Real Experiments Actually Tell Us?

$S > 2 \rightarrow$ At least one of 1, 2, 3, 4 are false!

**Usual Story:** (1, 2, or both false, 3, 4 true)  
“Local realist” HV theories ruled out

**Another Story:** (1, 2 true but 3 or 4 false)  
Keep deterministic local-realism, but relax fair sampling or freedom

Fully or partially relax any assumption:  
Non-quantum alternatives still viable, can simulate quantum predictions!

Einstein, Podolsky, & Rosen (EPR) 1935; Bell 1964; Clauser, Horne, Shimony, & Holt (CHSH) 1969
LOOHOLES AND WHY THEY MATTER

Quantum foundations!

If universe exploits loopholes, does not mean QM is “wrong”, but that perhaps there is a more fundamental underlying theory. Quantum gravity?

Quantum cryptography security

Hackers can exploit loopholes to undermine quantum information schemes
TOWARD A LOOPHOLE FREE TEST

A. Locality Loophole
Hidden communication between parties

B. Detection Loophole
Measured sub-sample not representative
for atoms: Rowe+2001, superconducting qubits:
Ansmann+2009, photons: Giustina+2013, Christensen+2013

C. Freedom-of-Choice Loophole
Settings correlated with hidden variables
partially for photons: Scheidl+2010

Closing Method?
Spacelike separated measurements, settings
High efficiency detectors
Settings spacelike separated from EPR source
TOWARD A LOOPHOLE FREE TEST

A. Locality Loophole
*Hidden communication between parties*

B. Detection Loophole
*Measured sub-sample not representative*
for atoms: Rowe+2001, superconducting qubits:
Ansmann+2009, photons: Giustina+2013, Christensen+2013

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*Settings correlated with hidden variables*
partially for photons: Scheidl+2010

2 LOOPHOLES IN SAME TEST!
Locality & Detection (electrons) Hensen+2015 (Delft)
Locality & Detection (photons) Giustina+2015 (Vienna)
Shalm+2015 (NIST)
LATEST EXPERIMENTS

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen¹,², H. Bertien³,²†, A. E. Dréau¹,², A. Reiserer¹,², A. Kalb¹,², M. S. Blok¹,², J. Ruitenberg¹,², R. F. L. Vermuelen¹,², R. N. Schouten¹,², C. Abellán³, W. Amaya³, V. Frunieri³,⁴, M. W. Mitchell³,⁴, M. Markham⁵, D. J. Twitchen⁵, D. Elkouss¹, S. Wehner¹, T. H. Taminiau¹,² & T. Hanson¹,²

The New York Times

Sorry, Einstein. Quantum Study Suggests ‘Spooky Action’ Is Real.

By JOHN MARKOFF OCT. 21, 2015

First experiment to close both the locality and detection loopholes.
Significant-Loophole-Free Test of Bell’s Theorem with Entangled Photons

Marissa Giustina,1,2† Marijn A. M. Versteegh,1,2† Sören Wengerowsky,1,2† Johannes Handsteiner,1,2 Annin Hochrainer,1,2 Kevin Phelan,1 Fabian Steinlechner,1 Johannes Kofler,3 Jan-Åke Larsson,4 Carlos Abellán,5 Waldimar Amaya,3 Valerio Pruneri,5,6 Morgan W. Mitchell,5,6 Jörn Beyre,1 Thomas Gerrits,8 Adriana E. Lita,7 Lynden K. Shalm,3
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14Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario, Canada
(Rceived 10 November 2015; published 16 December 2015)

Strong Loophole-Free Test of Local Realism

Lynden K. Shalm,1,† Evan Meyer-Scott,2 Bradley G. Christensen,2 Peter Bierhorst,1 Michael A. Wayne,3,‡ Martin J. Stevens,1 Thomas Gerrits,1 Scott Glancy,1 Deny R. Hame1, Michael S. Allman,1 Kevin J. Coakley,1 Shellee D. Dyer,1 Carson Hodge,1 Adriana E. Lita1 Varun B. Verma,1 Camila Lambrem,1 Edward Tortonci,1 Alan L. Migdall,4,5 Yanbao Zhang,2 Daniel R. Kim,5 William H. Farr,1 Francesco Masielli,7 Matthew D. Shaw,7 Jeffrey A. Stern,7 Carolos Abellán,8 Waldimar Amaya,3 Valerio Pruneri,5,6 Thomas Jennewein2,10 Morgan W. Mitchell,5,6 Paul G. Kwiat,3 Joshua C. Bienfang,4,6 Richard P. Mirin,1 Emanuel Knill,1 and Sae Woo Nam1,†

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(Received 11 November 2015; published 16 December 2015)
Significant-Loophole-Free Test of Bell’s Theorem with Entangled Photons

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Received 10 November 2015; published 16 December 2015
Significant-Loophole-Free Test of Bell’s Theorem with Entanglement

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(Received 10 November 2015; published 16 December 2015)
RECENT ENTANGLEMENT TESTS

Three recent entanglement experiments have closed the “locality” and “detection” loopholes simultaneously

Hensen+2015 (Delft), Giustina+2015 (Vienna), Shalm+2015 (NIST)

These are amazing experiments!

Still very far from definitive “loophole free” experiment

None of these tests were designed to fully address the “freedom-of-choice” or “free will” loophole

Cosmic Bell tests will progressively attempt to do so
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**FREEDOM-OF-CHOICE LOOPHOLE**

Freedom assumption

\[ P(a, b|\lambda) = P(a, b) \]  
Eq. 1

Are experimental choices for detector settings really “free and random”? 

Relax Eq. 1 →

Only a *tiny* correlation between settings and HVs in past light cone can reproduce quantum predictions!

Hall 2010, Barret & Gisin 2011, Hall 2011
QM is most vulnerable to the **freedom-of-choice loophole***: Are the detector settings correlated with the local hidden variables?

*Also known as “measurement-independence” and “setting independence” loophole.

\[
P(A, B|a, b) = \int d\lambda \, P(A, B|a, b, \lambda)P(\lambda|a, b)
\]
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\]

\[
P(\lambda|a, b) = P(\lambda)
\]

Bell explicitly assumed
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P(\lambda|a, b) = P(\lambda)
\]

equivalent to

\[
P(a, b|\lambda) = P(a, b), \quad P(a, b, \lambda) = P(a, b)P(\lambda)
\]
FREEDOM-OF-CHOICE LOOPTHOLE

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equivalent to

\[
P(a, b|\lambda) = P(a, b), \quad P(a, b, \lambda) = P(a, b)P(\lambda)
\]

Bell: “It has been assumed that the settings of instruments are in some sense free variables — say at the whim of the experimenters — or in any case not determined in the overlap of the backward light cones.” (1976)
**MUTUAL INFORMATION**

\[ M(a, b : \lambda) = H(a, b) + H(\lambda) - H(a, b, \lambda) \]

a, b measurement settings

H is the Shannon Entropy.

For a, b independent of \( \lambda \), last term is by definition sum of first two. \( M = 0 \).

For a, b determined completely by \( \lambda \), all 4 of these are equal and \( M \) is at a maximum.
RELAXING FREEDOM

• LHV model can mimic QM singlet (CHSH scenario) with ~1/15 (~1/22) bits of mutual information between settings & HVs (Hall 2011, Friedman+2017b in prep.)

• Freedom = most fragile loophole quantitatively.
Communication models relaxing locality need ≥ 1 bit (e.g. Toner & Bacon 2001, Hall 2010, 2011)

• Deterministic local HV theory (e.g. Brans 1986)

Quantitative models! Relaxing Freedom does not imply “superdeterministic cosmic conspiracy”
FREEDOM-OF-CHOICE LOOPHOLE

QM is most vulnerable to the freedom-of-choice loophole*: Are the detector settings correlated with the local hidden variable?

Bell’s original assumption \(P(a, b|\lambda) = P(a, b)\)

was debated among Bell, Clauser, Horne, and Shimony in “Epistemological Letters,” 1976-77.
FREEDOM-OF-CHOICE LOOPHOLE

QM is most vulnerable to the freedom-of-choice loophole*: Are the detector settings correlated with the local hidden variables?

Bell’s original assumption

\[ P(a, b|\lambda) = P(a, b) \]

was debated among Bell, Clauser, Horne, and Shimony in “Epistemological Letters,” 1976-77.

The formalism makes no distinction about where or when the relevant \( \lambda \) is created or acts. \( P(a, b|\lambda) \neq P(a, b) \) is a statement about the shared causal past.

Recent attention from Michael J. W. Hall, Nicolas Gisin, et al.
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Cosmic Bell Test: Measurement Settings from Milky Way Stars

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Bell’s theorem states that some predictions of quantum mechanics cannot be reproduced by a local-realist theory. That conflict is expressed by Bell’s inequality, which is usually derived under the assumption that there are no statistical correlations between the choices of measurement settings and anything else that can causally affect the measurement outcomes. In previous experiments, this “freedom of choice” was addressed by ensuring that selection of measurement settings via conventional “quantum random number generators” was spacelike separated from the entangled particle creation. This, however, left open the possibility that an unknown cause affected both the setting choices and measurement outcomes as recently as mere microseconds before each experimental trial. Here we report on a new experimental test of Bell’s inequality that, for the first time, uses distant astronomical sources as “cosmic setting generators.” In our tests with polarization-entangled photons, measurement settings were chosen using real-time observations of Milky Way stars while simultaneously ensuring locality. Assuming fair sampling for all detected photons, and that each stellar photon’s color was set at emission, we observe statistically significant $\geq 7.31\sigma$ and $\geq 11.93\sigma$ violations of Bell’s inequality with estimated $p$ values of $\leq 1.8 \times 10^{-13}$ and $\leq 4.0 \times 10^{-33}$, respectively, thereby pushing back by $\sim 600$ years the most recent time by which any local-realist influences could have engineered the observed Bell violation.
Cosmic Bell Test Schematic

Alice - OENB
- CRx
- QRx
- POL
- CSR
- CaDA
- FPGA
- GPS Clock

Source - IQOQI
- QTx

Bob - BOKU
- CRx
- CSR
- GPS Clock
- FPGA
- CaDA

B = 1150 m
A = 560 m

Telescope, dichroic mirror, polarizing beam splitter, electro optical modulator, single photon detector, ppKTP crystal, optical fiber, half-waveplate, electrical wire
Cosmic Bell Test: Measurement Settings from

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VIENNA COSMIC BELL TEST

Entangled photon receiver and polarization analyzer
VIENNA COSMIC BELL TEST

Occupational Hazards
VIENNA COSMIC BELL TEST

Star selection
GOOGLE MAPS IS THE BEST!

Entangled Photon Source (IQOQI, S)

1. University of Natural Resources and Life Sciences (BOKU, Bob)

2. Austrian National Bank (OENB, Alice)

HIP56127

HIP80620

HIP105259 & HIP2876

Spatial axis

563m

1150m

3/8/17

UCSD Center for Astrophysics & Space Sciences
CAUSAL ALIGNMENT

Locality Loophole
Space-like separate these events:
measurement outcomes from each other
measurement outcome 1 from detector setting 2
(and vice versa)

Locality Loophole+ Causal Alignment
Must space-like separate new pairs of events

Also need causal wavefront from star/quasar 1 to hit telescope 1 before telescope 2 or EPR source (and vice versa)

If final conditions are not met for either side at any time, can’t use the data and also claim to have closed locality loophole.
How long are settings valid on each side with fresh random #?

\[
\begin{align*}
\tau^A_{\text{valid}}(t) &= \frac{1}{c} \hat{n}_{S_A}(t) \cdot (\vec{r}_A - \vec{m}_B) + \frac{n}{c} \left[ |\vec{m}_A - \vec{s}| - |\vec{m}_B - \vec{s}| \right] - \frac{\eta_A}{c} |\vec{r}_A - \vec{m}_A| \\
\tau^B_{\text{valid}}(t) &= \frac{1}{c} \hat{n}_{S_B}(t) \cdot (\vec{r}_B - \vec{m}_A) + \frac{n}{c} \left[ |\vec{m}_B - \vec{s}| - |\vec{m}_A - \vec{s}| \right] - \frac{\eta_B}{c} |\vec{r}_B - \vec{m}_B|
\end{align*}
\]

If either \( \tau^k_{\text{valid}}(t) < 0 \), \((k=A,B)\) configuration out of “causal alignment”

\( \hat{n}_{S_k}(t) \) Unit vectors from Earth center to cosmic source

Spatial 3-vectors \( \vec{r}_k \) Telescopes \( \vec{s} \) EPR source \( \vec{m}_k \) measurements

Refractive index \( n \) Air \( \eta_k \) Fiber from telescope to EPR detector

Processing Delays Optics, FPGA board, Pockell Cell switching...

\[
\tau^k_{\text{used}} = \min_t \left\{ \tau^k_{\text{valid}}(t) \right\} - \tau^k_{\text{buffer}} - \tau_{\text{set}}
\]

Handsteiner, Friedman+2017 (SM) Friedman+2017 in prep.
Space-time diagram: run 1

Handsteiner, Friedman+2017

Fig. 2
Google Maps is the best!

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OBSERVED BELL VIOLATION

\[ S \equiv \left| E_{11} + E_{12} + E_{21} - E_{22} \right| \]

Handsteiner, Friedman+2017
Fig. 4
DATA ANALYSIS

“Noise Loophole”

Need triggers by genuine cosmic photons, not local “noise” photons: atmospheric airglow, thermal dark counts, errant dichroic mirror reflections.

Conservatively allow $S=4$ for any background events, $S<2$ for cosmic photons. Accounts for bias in red/blue ports.

Observed sufficient signal-to-noise from cosmic sources.

Highly significant Bell violation still observed:

Run 1: 7.31 sigma, Run 2: 11.93 sigma

See Handsteiner, Friedman+2017 (Supplemental Material)
**SPACE-TIME DIAGRAM: STARS**

![Space-time diagram of stars with labels and measurements.]

- **HIP (A\_\star) 56127**: 604 ± 35 yr
- **(B\_\star) HIP 105259**: 1930 ± 605 yr
- **Distance**: 604 ± 35 ly, 1930 ± 605 ly
- **Angle**: 119°

*Handsteiner, Friedman+2017, Fig. 3*
SPACETIME DIAGRAMS: RUNS 1, 2

Run 1

\[ t_A = 604 \pm 35 \text{ yrs} \]
\[ t_{AB} = 2409 \pm 598 \text{ yrs} \]

\( t_A \)  Lookback time to emission of light from nearest star (A)

\( t_{AB} \)  Lookback time to when past light cones intersect

Run 2

\[ t_A = 577 \pm 40 \text{ yrs} \]
\[ t_{AB} = 4040 \pm 1363 \text{ yrs} \]

Handsteiner, Friedman+2017 (SM Fig. 2)
OUTLINE

1. Entanglement Tests

2. Bell’s Inequality vs. Bell’s Theorem

3. Bell’s Theorem Loopholes

4. Freedom-Of-Choice Loophole

5. Cosmic Bell Test with Milky Way Stars

6. Future Cosmic Bell Tests with Quasars, CMB
Testing Bell’s Inequality with Cosmic Photons: Closing the Setting-Independence Loophole

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(Received 25 October 2013; published 18 March 2014)

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, with settings determined by quantum random number generators, only a small amount of correlation between detector settings and local hidden variables, established less than a millisecond before each experiment, would suffice to mimic the predictions of quantum mechanics. By setting the detectors using pairs of quasars or patches of the cosmic microwave background, observed violations of Bell’s inequality would require any such coordination to have existed for billions of years—an improvement of 20 orders of magnitude.

DOI: 10.1103/PhysRevLett.112.110405
PACS numbers: 03.65.Ud, 42.50.Xa, 98.54.Aj, 98.70.Vc

Experiment feasible with existing technology!

$z > 3.65$ quasars bright enough
CMB an intriguing possibility

We derive criteria for whether two cosmological events can have a shared causal past or a shared causal future, assuming a Friedmann-Lemaître-Robertson-Walker (FLRW) universe with best-fit cosmological parameters from the Planck satellite. We further derive criteria for whether either cosmic event could have been in past causal contact with our own worldline since the time of the hot “big bang,” which we take to be the end of early-universe inflation. We find that pairs of objects such as quasars on opposite sides of the sky with redshifts $z \geq 3.65$ have no shared causal past with each other or with our past worldline. More complicated constraints apply if the objects are at different redshifts from each other or appear at some relative angle less than $180^\circ$, as seen from Earth. We present examples of observed quasar pairs that satisfy all, some, or none of the criteria for past causal independence. Given dark energy and the recent accelerated expansion, our observable Universe has a finite conformal lifetime, and hence a cosmic event horizon at current redshift $z = 1.87$. We thus constrain whether pairs of cosmic events can signal each other’s worldlines before the end of time. Lastly, we generalize the criteria for shared past and future causal domains for FLRW universes with nonzero spatial curvature.

Why use quasars? Brightest continuous cosmological sources.

$z > 3.65$ quasars at 180 deg have no shared causal past since inflation

LC INTERSECTION @BIG BANG

Comoving Distance $R_{\kappa}$ [Glyr] ($\kappa = 180$ Degrees, $z_A = 98.90$, $z_B = 0.33$)

Animation 1 (F13a supplementary material)

http://web.mit.edu/asf/www/01_conformal_movie.shtml
http://web.mit.edu/asf/www/01_conformal_movie.shtml
http://web.mit.edu/asf/www/01_conformal_movie.shtml
SDSS quasars - photometric and spectroscopic redshifts

Ground based optical flux.

IR only usable from space

Local Sky noise!

Adapted from Fig. 3 (GFK13)

\[ z \approx 3.65 : F_{\text{Opt}} \sim 3 \times 10^4 \text{ photons s}^{-1} \text{ m}^{-2} \]

\[ z \approx 4.13 : F_{\text{Opt}} \sim 2 \times 10^4 \text{ photons s}^{-1} \text{ m}^{-2} \]
WHICH QUASARS TO USE?

\[ M \equiv \frac{T}{\Delta t} P_2 P_E \]

**CANYON ISLANDS**

Each dot represents a pair of quasars, each with \( z \geq 4.13 \), jointly viewable from Canaries on a given night, with \( \alpha \leq 130^\circ \)

Past LC intersection during inflation

**Friedman+2017 in prep.**
**2 OR MORE COSMIC SOURCES**

2 (EPR) or 3 or more (GHZ) entangled particles

Greenberger, Horne, Zeilinger 1989; Greenberger+1990; Mermin 1990

*Each cosmic source pair in set of N=2, 3 (or > 3) satisfies pairwise constraints from F13a*

<table>
<thead>
<tr>
<th>Angular Separation</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Way Space</td>
<td>180°</td>
</tr>
<tr>
<td>2-Way Ground</td>
<td>130°</td>
</tr>
<tr>
<td>3-Way Space</td>
<td>120°</td>
</tr>
<tr>
<td>3-Way Ground</td>
<td>105°</td>
</tr>
</tbody>
</table>

GFK13; Friedman+2017f in prep.
**GHZ WITH CMB?**

3+ particles, Bell’s theorem without inequalities
QM, Local realism give opposite answers to yes/no questions

Greenberger, Horne, Zeilinger 1989; Greenberger+1990; Mermin 1990

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Balloon based test in Antarctica?

Easy! Pick 3 CMB patches, each separated by 2.3°

Hard! Local noise dominates from ground (GFK14)

Noise loophole limits better than 2-particle Bell test (Hall 2011)
What if Bell test correlations depended on causal overlap? Causal origin for entanglement via free will loophole?

Size of purple region. Comoving spacetime 4-volume (use physical coordinates)

Fig. 2 (F13a) Friedman+2017 in prep.
**Expected:**
Bell inequality always violated, for any $z$ and $\alpha$. That would rule out (or constrain) local hidden-variables theories as much as physically possible in our universe.

**Unexpected:**
Bell inequality *not* violated for certain cosmic source pairs?!

**Strangest:**
Degree of Bell violation depends on the distances to cosmic sources, or the extent of overlap of their past lightcones.

Implications for inflation? Quantum gravity?
**COSMIC BELL PUBLICATIONS**

*Cosmic Bell Test: Measurement Settings from Milky Way Stars*,

*Testing Bell's Inequality with Cosmic Photons: Closing the Setting-Independence Loophole*,

*The Shared Causal Pasts and Futures of Cosmological Events*,

*Can the Cosmos Test Quantum Entanglement?*,

*The Universe Made Me Do It? Testing “Free Will” With Distant Quasars*,
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