A COSMIC TEST OF QUANTUM ENTANGLEMENT
Choosing Experimental Bell Inequality Measurements with Light from High Redshift Quasars

Dr. Andrew Friedman
UC San Diego
Center for Astrophysics and Space Sciences
https://asfriedman.physics.ucsd.edu  asf@ucsd.edu
COSMIC BELL COLLABORATION
COSMIC BELL TEAM

Prof. David Kaiser
Dr. Andrew Friedman
Prof. Alan Guth
Prof. Brian Keating
Prof. Anton Zeilinger
Prof. Jason Gallicchio

Other Collaborators
Johannes Handsteiner
Dominik Rauch
Dr. Thomas Scheidl
Dr. Johannes Kofler
Dr. Hien Nguyen
Calvin Leung et al.

1: MIT Physics/CTP
2: Vienna IQOQI
3: Harvey Mudd
4: Max Planck MPQ
5: UCSD CASS
6: NASA JPL/Caltech

11/30/2018 San Diego State University, Physics and Astronomy Colloquium
FEYNMAN ON FREE WILL

“We have an illusion that we can do any experiment that we want. We all, however, come from the same universe, have evolved with it, and don't really have any `real' freedom. For we obey certain laws and have come from a certain past. Is it somehow that we are correlated to the experiments that we do, so that the apparent probabilities don't look like they ought to look if you assume they are random…”
– Richard Feynman 1982
OUTLINE

1. Entanglement Tests

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

3. Loopholes / Freedom-Of-Choice Loophole

4. Cosmic Bell Test with Milky Way Stars

5. Cosmic Bell Test with Quasars

6. Future Tests
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 (\(v\)).
Big question: Are non-quantum explanations for entanglement viable?
If yes, QM incomplete ⇒ Hidden variables
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BELL’S INEQUALITY ASSUMPTIONS

1. Realism
2. Locality
3. Freedom

1,2,3 → Bell’s Inequality

Upper limits on entangled particle measurement correlations in a “local-realistic” model
RELAXING BELL’S ASSUMPTIONS

1. Realism  2. Locality  3. Freedom

Experiments violate Bell’s inequality as predicted by quantum mechanics!

→ At least one of 1, 2, 3 are false!

But relaxing any assumption → LOOPHOLES

Alternative models could mimic quantum theory
**CORRELATIONS AT A DISTANCE**

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: \( |S_{\text{max}}| > 2 \)

\( \theta \)

11/30/2018  San Diego State University, Physics and Astronomy Colloquium
Bell's inequality

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

- **Bell's inequality:** \( |S| \leq 2 \)  
  Places limits on how correlated measurement outcomes can be in local realistic theories.

- It says nothing directly about quantum mechanics!

- Until you compare it to quantum theory as a benchmark

**Bell's Theorem**

No local-realist theory can reproduce the quantum predictions!

- e.g. QM prediction: \( |S_{\text{max}}| = 2\sqrt{2} \)
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LOOHOLES & WHY THEY MATTER

The standard interpretation of Bell tests — that “local realism” is incompatible with experiment — relies upon several assumptions.

So What?!

Quantum foundations!
Understanding reality at a deep level. If universe exploits loopholes, does not mean QM is “wrong”, but perhaps derived from a more fundamental underlying theory. Quantum gravity?

Quantum cryptography security
Tech applications! Hackers could exploit loopholes to undermine entanglement-based quantum information schemes
The standard interpretation of Bell tests — that “local realism” is incompatible with experiment — relies upon several assumptions.

Hidden communication between parties?

- Source emits entangled particles
- Select detector settings
- Measurement outcomes

\( A, B, S, a, b \)
The standard interpretation of Bell tests — that “local realism” is incompatible with experiment — relies upon several assumptions.

Space-like separate relevant pairs of events

measurement outcomes space like separated

detector setting choice a separated from measurement outcome B (and vice versa)

select detector settings while entangled particles are in flight
DETECTION EFFICIENCY LOOPHOLE

The standard interpretation of Bell tests — that “local realism” is incompatible with experiment — relies upon several assumptions.

Also called the “fair-sampling” loophole

No detectors are 100% efficient.

What if undetected photons skewed the statistics, faking Bell violation without genuine entanglement?

Closing loophole requires detector efficiencies $\geq 83\%$

TOWARD A LOOPOHLE 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

2 LOOPHOLES IN SAME TEST!

Locality & Detection

Hensen+2015 (Delft) (electrons)
Giustina+2015 (Vienna)
Shalm+2015 (NIST) (photons)
Rosenfeld+2017 (Germany) (atoms)
C. Freedom-of-Choice Loophole

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

Settings spacelike separated from EPR source

COSMIC BELL TESTS

Locality & Freedom (photons)

Handsteiner+2017 (Vienna)
Settings chosen with Milky Way Stars. Closed locality, constrained freedom-of-choice to ~600 years ago.

Locality & Freedom (photons)

Rauch+2018 (Canary Islands)
Settings from High Redshift Quasars. Closed locality, constrained freedom-of-choice to ~7.8 Billion years ago!

Locality & Detection & Freedom (photons)

Li+2018 (China)
Closed locality and detection, constrained freedom-of-choice to ~11 years ago.
LATEST EXPERIMENTS

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

B. Hensen¹,², H. Bernien¹,²†, A. E. Dréau¹,², A. Reiserer¹,², N. Kalb¹,², M. S. Blok¹,², J. Ruitenberg¹,², R. F. L. Vermeulen¹,², R. N. Schouten¹,², C. Abellán³, W. Amaya³, V. Pruneri³,⁴, M. W. Mitchell³,⁴, M. Markham³, D. J. Twitchen³, D. Elkouss¹, S. Wehner³, T. H. Taminiau¹,² & R. 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.
Closed both locality and detection loopholes for the first time *with photons*
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 Armin Hochrainer,1,3 Kevin Phelan,1 Fabian Steinlechner,1 Johannes Kofler,3 Jan-Åke Larsson,4 Carlos Abellán,5 Waldimar Amaya,5 Valerio Pruneri,5,6 Morgan W. Mitchell,5,6 Jörn Beyrer,7 Thomas Gerrits,8 Adriana E. Lita,8 Lynden K. Shalm,8 Sae Woo Nam,8 Thomas Scheidl,1,2 Rupert Ursin,1 Bernhard Wittmann,1,2 and Anton Zeilinger1,2,3

1Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, Vienna 1090, Austria
2Quantum Optics, Quantum Nanophysics and Quantum Information, Faculty of Physics, University of Vienna, Boltzmanngasse 5, Vienna 1090, Austria
3Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
4Institutionen för Systemteknik, Linköpings Universitet, 581 83 Linköping, Sweden
5ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain
6ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain
7Physikalisch-Technische Bundesanstalt, Abbestraße 1, 10587 Berlin, Germany

*Corresponding author. E-mail: m.giustina@iqm.wien.ac.at (M.G.)
HOFBURG PALACE, VIENNA
Significant-Loophole-Free Test of Bell’s Theorem with Entanglement

Marissa Giustina, 1,2,* Marijana A. M. Versteegh, 1,2 Sören Wengerowsky, 1,2 Johannes Hansch 1,2
Kevin Phelan, 1 Fabian Steinlechner, 1 Johannes Kofler, 1,3 Jan-Åke Larsson, 5 Carlos A. Ortiz, 6
Valerio Pruneri, 5,6 Morgan W. Mitchell, 5,6 Jörn Beyer, 1 Thomas Gerrits, 1 Adriana P. M. Spreeuw, 1
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1Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, Vienna 1090, Austria
2Quantum Optics, Quantum Nanophysics and Quantum Information, Faculty of Physics, University of Vienna, Boltzmanngasse 5, Vienna 1090, Austria
3Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
4Institut für Experimentalphysik 1, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
5University of Vienna, Faculty of Physics, Boltzmanngasse 5, 1090 Vienna, Austria
6Institut für Technische Optik, Technische Universität Graz, Steyrergasse 30, 8010 Graz, Austria
7ICFO – Institut de Ciencies Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain
8ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain
9INFN – National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO 80302, USA

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

• Closed “locality” and “detection” loopholes simultaneously
  Hensen+2015 (Delft), Giustina+2015 (Vienna), Shalm+2015 (NIST), Rosenfeld+2017 (Germany)

• None of these tests designed to fully address “freedom-of-choice” loophole

• Cosmic Bell tests will progressively attempt to do so
QM is most vulnerable to the “freedom-of-choice” loophole*: Are the detector settings correlated with the local hidden variable?

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

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

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

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)

locality assumption \[ p(A, B|a, b, \lambda) = p(A|a, \lambda)p(B|b, \lambda) \]

*Also known as the “measurement-independence” and “settings-independence” loophole.
If we do not assume $p(\lambda | a, b) = p(\lambda)$, then local-realist models would be compatible with

$$|S| \leq 2 + M_1 + M_2 + \min\{M_1, M_2\}$$

where

$$M_1 = \max\left\{ \int d\lambda |p(\lambda|x, y) - p(\lambda|x', y)|, \int d\lambda |p(\lambda|x, y') - p(\lambda|x', y')| \right\}$$

$$M_2 = \max\left\{ \int d\lambda |p(\lambda|x, y) - p(\lambda|x, y')|, \int d\lambda |p(\lambda|x', y) - p(\lambda|x', y')| \right\}$$

A minuscule amount of correlation between $\lambda$ and $a,b$ would suffice to mimic QM, with $|S| \to 2\sqrt{2}$.

**Mutual Information**

$$I = \sum_{\lambda,a,b} p(\lambda|a, b) p(a, b) \log_2 \frac{p(\lambda|a, b)}{p(\lambda)}$$

Only require $I = 0.046 \sim 1/22$ of a bit!

Friedman, Guth, Hall, Kaiser, Gallicchio, 1809.01307

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FREEDOM OF CHOICE LOOPHOLE

- Shrimp & Chicken Fajita $12.99
- Fajita Salsas (for One) $13.25
  A Combination of steak, chicken & shrimp.
- Fajita Salsas (for Two) $21.99
- Fajita Mixed $12.25
  Strips of steak & chicken.
- Fajita Mixed (for Two) $19.50
- Fajita Quesadilla $9.50
  2 flour tortillas grilled & stuffed with chicken or steak & cheese.
- Shrimp Fajitas $14.25
- Fajitas Steak or Chicken
  for One $11.99
  for Two $18.99
- Parillada Mexicana (for One) $13.99
  Pork tips, shrimp, chicken, chorizo & steak.
- Parillada Mexicana (for Two) $22.99

If detector settings depend on hidden variables $\lambda$ from past events, our choices might not be perfectly free!

Still have free will!

But limited freedom
ADDRESSING FREEDOM OF CHOICE

• If we don’t simply assume $p(\lambda|a, b) = p(\lambda)$, how might we address the “freedom-of-choice” assumption experimentally?

• Most recent experiments used QRNGs to select detector settings.

• Such devices produce output strings based on some physical process.

• According to QM, the outputs should be intrinsically random.

But the purported intrinsic randomness of QM is part of what is at stake in tests of Bell’s inequality…
CHOOSING DETECTOR SETTINGS

Source of Entangled Particles

Adapted from: Gallicchio, Friedman, & Kaiser 2014
CHOOSING DETECTOR SETTINGS

Source of Entangled Particles

Quantum Random Number Generator

Adapted from: Gallicchio, Friedman, & Kaiser 2014
Choosing Detector Settings

Source of Entangled Particles

Quantum Random Number Generator

Star A

Quantum Random Number Generator

Star B

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
Choosing Detector Settings

Source of Entangled Particles

Quasar B \rightarrow \text{Source of Entangled Particles} \rightarrow \text{Quantum Random Number Generator} \rightarrow \text{Quasar A}

Albert

Bohr

Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

Quantum Random Number Generator

Adapted from: Gallicchio, Friedman, & Kaiser 2014


**Source of Entangled Particles**

- **Quantum Random Number Generator**
  - *Quasar A*
  - *Quasar B*

**CMB Patch A**

**CMB Patch B**

*Choose settings with observations of CMB patches, etc…*

Relegates alternatives to Big Bang, era of early universe inflation!

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

Set $a, b$ by using astronomical sources as cosmic random number generators.

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6. Future Tests
**FIRST COSMIC BELL TEST (VIENNA)**

![Image of the paper](image)

**Alice:** Austrian National Bank

**Entangled Particles:** Institute for Quantum Optics and Quantum Information

**Bob:** University of Natural Resources and Life Sciences

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Handsteiner, Friedman+2017 (arXiv:1611.06985)

11/30/2018
San Diego State University, Physics and Astronomy Colloquium
VIENNA COSMIC BELL TEST

Johannes Handsteiner with 8-inch stellar photon telescope

Image Credit: Jason Gallicchio
VIENNA COSMIC BELL TEST

Entangled photon receiver and polarization analyzer

Image Credit: Jason Gallicchio
Cosmic Setting Generator

Red Arm

Guide Camera

Blue Arm

Credit: Jason Gallicchio, Amy Brown, Calvin Leung (HMC)

Light In
VIENNA COSMIC BELL TEST

Occupational Hazards

Image Credit: Jason Gallicchio
VIENNA COSMIC BELL TEST

Star Selection

Image Credit: Jason Gallicchio
OBSERVED BELL VIOLATION

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

Handsteiner, Friedman+2017

Fig. 4
SPACE-TIME DIAGRAM: STARS

Handsteiner, Friedman+2017
Fig. 3
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)
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COSMIC BELL DESIGN CONCEPT

**PHYSICAL REVIEW D** **88**, 044038 (2013)

*The shared causal pasts and futures of cosmological events*

Andrew S. Friedman,¹,* David I. Kaiser,¹,† and Jason Gallicchio²,‡


**Why use quasars? Brightest continuous cosmological sources.**

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

**PRL 112, 110405 (2014)**

**PHYSICAL REVIEW LETTERS**

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

Jason Gallicchio,¹,* Andrew S. Friedman,²,† and David I. Kaiser²,‡


**Experiment feasible with existing technology!**

z > 3.65 quasars bright enough

CMB an intriguing possibility
1+1D Spacetime Diagram

- Schematic cosmic Bell test space-time diagram (not to scale) in (dimensionless) conformal time $\eta$ vs. comoving distance $\chi$.

- In these coords, null geodesics on 45° diagonals.

- On each side, quasar emits light at events $x, y$

- Light received on Earth used to set detectors at events $a, b$

- Meanwhile, spacelike-separated from events $x, y$, and $a, b$, source $S$ emits entangled pairs, which are measured at events $A, B$

Adapted From FIG. 1 (Rauch+2018, Supplemental Material)
SDSS quasars - photometric and spectroscopic redshifts

Adapted from Fig. 3 (GFK14)

\[ z \approx 3.65 : F_{\text{Opt}} \approx 3 \times 10^4 \text{ photons s}^{-1} \text{ m}^{-2} \]
\[ z \approx 4.13 : F_{\text{Opt}} \approx 2 \times 10^4 \text{ photons s}^{-1} \text{ m}^{-2} \]

Ground based optical flux.

IR only usable from space

Local Sky noise!

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COSMIC BELL TEST WITH QUASARS

Roque de los Muchachos Observatory on Canary Island of La Palma
Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars

Dominik Rauch, Johannes Handsteiner, Armin Hochrainer, Jason Gallicchio, Andrew S. Friedman, Calvin Leung, Bo Liu, Lukas Bulla, Sebastian Ecker, Fabian Steinlechner, Rupert Ursin, Beili Hu, David Leon, Chris Benn, Adriano Ghedina, Massimo Cecconi, Alan H. Guth, David I. Kaiser, Thomas Scheidl, and Anton Zeilinger

# Cosmic Bell Test with Quasars


## Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars

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## Table of Data

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<th>ID</th>
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<th>$a_t$</th>
<th>$z$</th>
<th>$t_{lb}$ [Gyr]</th>
<th>$t_{valid}$ [$\mu$s]</th>
<th>$S_{exp}$</th>
<th>$p$ value</th>
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### Standard Deviations

**FIG. 1, Rauch + 2018**
Mechanism must affect detector settings + measurement outcomes from within $Q_A$ (blue), $Q_B$ (red), past light cones (or their overlap), a region with only 4.0% of physical space-time volume within our past light cone.

- Past light cone of pair 1 experiment (gray)
- Quasar emission events $Q_A$ (blue, 7.78 Gyr ago), $Q_B$ (red, 12.21 Gyr ago)
- Past light cones overlap 13.15 Gyr ago
- Big Bang 13.80 Gyr ago

Local-realist mechanism would need to have acted at least 7.78 Gyr ago.

Rules out 96% of space-time from causally influencing our experiment!

$$F_{\text{excl}} = 1 - \left( \frac{V_Q^{(4)}(\tau_A, \tau_B, \alpha)}{V_{\text{exp}}^{(4)}(\tau_0)} \right) = 0.960$$
COSMIC BELL TEST WITH QUASARS

William Herschel Telescope (WHT)

Nordic Optical Telescope (NOT)

Entangled Particle Source

Telescope Nazionale Galileo (TNG)

Image ©2018 DigitalGlobe (Google Earth)
Nordic Optical Telescope (NOT)

Cosmic Bell Test Entangled Particle Source (Shipping Container)

Image Credit: Dominik Rauch (Vienna)
Nordic Optical Telescope (NOT)

NEAR DISASTER!

Cosmic Bell Test Shipping Container

Image Credit: Dominik Rauch (Vienna)
NEAR DISASTER!

Image Credit: Dominik Rauch (Vienna)
NEAR DISASTER!

Image Credit: Dominik Rauch (Vienna)
Image Credit: Dominik Rauch (Vienna)

Cosmic Bell Test
Shipping Container

DISASTER AVERTED
Entangled photon source fixed, reinstalled in now secured shipping container control room.
ADVENTURES IN LA PALMA

Chris Benn, Head of Astronomy,
Isaac Newton Group of
Telescopes, La Palma

Thomas Scheidl
(Vienna)

Armin Hochrainer
(Vienna)

Dominik Rauch
(Vienna)

Anton Zeilinger
(Vienna)

Image Credit: David Kaiser (MIT)
**Cosmic Bell Test (Summary)**

- Free space Bell test with polarization-entangled photons
- Detector settings from real-time wavelength measurements of **high-z quasar photons**, light emitted billions of years ago
- Experiment simultaneously ensures **locality**
- Assumptions: 1) fair sampling for all detected photons, 2) quasar photon wavelengths had not been selectively altered or previewed between emission and detection
- Observed statistically significant **9.3σ Bell inequality violation** (p-value \( \leq 7.4 \times 10^{-21} \)) for quasar pair 1.
- **Pushes back to** \( \approx 7.8 \) Gyr ago most recent time when any local-realist influences could have exploited “freedom-of-choice” loophole to engineer observed Bell violation. *(Previous tests \( \sim 600 \) yr ago. 6 more orders of mag better!)*
- Excludes any such mechanism from 96% of the space-time volume of our experiment’s past light cone since Big Bang. *(Previous tests \( 10^{-5} \)%). *(~All vs. nothing!)*
Einstein was wrong: Why ‘normal’ physics can’t explain reality

The most ambitious experiment yet show that the quantum weirdness Einstein famously hated rules the road – not just here, but across the entire universe.

Physicists race to demystify Einstein’s ‘spooky’ science

August 27, 2018 by Cynthia Dillon, University of California - San Diego

Ancient Starlight Just Helped Confirm the Reality of Quantum Entanglement

“The real estate left over for the skeptics of quantum mechanics has shrunk considerably.”

Cosmic Bell test uses light from ancient quasars

The quest to test quantum entanglement

Quantum entanglement, doubt by Einstein, has passed increasingly stringent tests.
COSMIC BELL IN THE NEWS

San Diego State University, Physics and Astronomy Colloquium

http://web.mit.edu/asf/www/media_coverage.shtml

11/30/2018
COSMIC BELL IN THE NEWS

https://asfriedman.physics.ucsd.edu/media_coverage.shtml

Closing the ‘free will’ loophole
MIT researchers propose using distant quasars to test Bell’s theorem.

Cosmic Test For Quantum Physics' Last Major Loophole

Quasar Experiment May Shed Light on Quantum Physics and Free Will

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

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GAME OF TELEPHONE

MIT press release
Author read actual paper!
Interviewed scientists. Fact checked!
Read press release (maybe)
Read 2nd and 3rd round articles

https://asfriedman.physics.ucsd.edu/media_coverage.shtml
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Challenging local realism with human choices

The BIG Bell Test Collaboration


12 labs in 11 countries on 5 continents, plus $10^5$ “Bellster” volunteers who produced $10^8$ (quasi) random 0’s and 1’s
Progress in closing detection loophole in a cosmic Bell test

Closed locality and fair sampling, and constrained freedom-of-choice to ~11 years ago.

Li et al., 1808.07653
Past light cones from random number generators overlap milliseconds before test.

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.

2+1D Conformal Spacetime Diagram

La Palma cosmic Bell test didn’t completely remove causal overlap

11/30/2018  San Diego State University, Physics and Astronomy Colloquium
FUTURE COSMIC BELL TESTS

z > 3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation
NO SHARED CAUSAL PAST

$\alpha = 180.00 \text{ [deg]} \quad z_A = 3.62 \quad z_B = 3.62$

$z > 3.65$ for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation
NO SHARED CAUSAL PAST

Conical Diagram + Past Light Cones

\( \alpha = 180.00 \text{ [deg]} \quad z_A = 3.67 \quad z_B = 3.67 \)

\( z > 3.65 \) for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation
**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 Friedman+2013 for no shared causal past since the Big Bang at the end of

<table>
<thead>
<tr>
<th>Angular Separation</th>
<th>Redshift</th>
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<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>
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</tbody>
</table>

Gallicchio, Friedman, & Kaiser 2014;  Friedman+2019 in prep.
GHZ WITH QUASARS?

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

Will be difficult to remove all pairwise causal overlap in a ground based test.

But GHZ pilot test with stars and with brighter, moderate redshift quasars is technologically possible
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

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)

Balloon based test in Antarctica?
POSSIBLE OUTCOMES
Future 2-quasar Cosmic Bell tests with no causal overlap
3 CMB patch or 3-quasar GHZ test from ground, balloon, or space

Safe Bet
Bell or GHZ/Mermin inequalities always violated.
Strengthen evidence for quantum theory.

Rule out alternative theories, progressively close freedom-of-choice loophole as much as possible.

Longshot
Experimental results depend on which cosmic sources we look at. Maybe Bell’s limit is not violated for very distant sources.

Perhaps experimenter’s lack complete freedom!
COSMIC BELL PUBLICATIONS


Clauser, Horne, Shimony, & Holt 1969, PRL 23, 880
Greenberger+1990, American Journal of Physics, Volume 58, Issue 12, pp. 1131-1143
Hall 2011, Phys. Rev. A, vol. 84, 2, id. 022102
Mermin 1990, American Journal of Physics, Volume 58, Issue 8, pp. 731-734
Scheidl+2010, PNAS, 107, 46, p. 19708-19713