A COSMIC TEST OF QUANTUM
ENTANGLEMENT AND BELL’S INEQUALITY
Choosing Measurements with Light from High Redshift Quasars

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UCSD CASS Astrophysics Seminar
Let the Universe decide how to set up entanglement experiment!

**COSMIC BELL TEST WITH QUASARS**

**PHYSICAL REVIEW LETTERS 121, 080403 (2018)**

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

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3: Harvey Mudd
4: Max Planck MPQ
5: UCSD CASS
6: NASA JPL/Caltech

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COSMIC BELL TEST ON TV!

PREMIERING JAN 9 2019
The Shared Causal Pasts and Futures of Cosmological Events,

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

Cosmic Bell Test: Measurement Settings from Milky Way Stars,

Astronomical Random Numbers for Quantum Foundations Experiments,

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

Relaxed Bell Inequalities with Arbitrary Measurement Dependence for Each Observer,
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

Experiment feasible with existing technology!

z > 3.65 quasars bright enough

CMB an intriguing possibility
Pushed back local hidden variable explanations for entanglement to > 600 years ago, ~16 orders of magnitude better than previous tests.

Pushed this back to > 7.8 billion years ago! Excluded 96% of spacetime that could have causally influenced our experiment!
Describes an “Astronomical Random Number Generator”, built in Jason Gallicchio’s lab, used to turn cosmic photon colors into random numbers.


Relaxed Bell inequalities with arbitrary measurement dependence for each observer


Derives relaxed version of Bell’s inequality without the “freedom-of-choice” assumption. Shows local realistic models that can simulate quantum theory by quantitatively reducing freedom by only a minuscule amount.
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 $\rightarrow$ 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-realist” model

John S. Bell (1928-1990)

http://images.iop.org/objects/cer/cern/54/7/19/CCfac8_07_14.jpg
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

e.g. Can keep realism, locality. Relax Freedom.

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

**Angle Between Polarizers**

\( S \)

Optics symbols

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

John Clauser, LBNL, 1970s

Alain Aspect, Orsay, 1980s
Bell’s Inequality

The correlation function: $E(a,b) = \langle AB \rangle$

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

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.)

- **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
CLOSING THE LOCALLITY LOOPTHOLE

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 A,B 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 $\geq 83\%$

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

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

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

Bell explicitly assumed

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

equivalent to

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 the relaxed Bell inequality

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

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 \(|S| \to 2\sqrt{2}\).

Alice and Bob only must give up \(~14\%\) experimental freedom!

\((M_1=M_2=M\sim0.276, F=1-M/2\sim86.2\%, M/2\sim13.8\%)\)


FREEDOM OF CHOICE LOOPOHLE

\[ \lambda \quad \text{Hidden variables} \]

\[ a, b \quad \text{Joint measurement settings} \]

Freedom of choice assumption

\[ p(\lambda | a, b) = p(\lambda) \quad \text{Eq. (1)} \]

Relaxing freedom of choice: Mutual Information

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

\[ I(V) \text{ Bell Violation for Tsirelson bound} \]
\[ V = 2(\sqrt{2} - 1) \]

- \[ I_B(V) \] 0.247 bits
- \[ I_H(V) \] 0.172 bits
- \[ \tilde{I}_G(V) \] 0.046 bits

If we relax Eq. (1), only require
\[ I \approx 0.046 \sim 1/22 \text{ bit of correlation between hidden variables and joint settings to simulate QM} \]


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If detector settings depend on hidden variables $\lambda$ (e.g. from past events), experimental 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…
TOWARD A LOOPTHOLE FREE TEST

A. Locality Loophole
Hidden communication between parties

Closing Method?
Spacelike separated measurements, settings

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

High efficiency detectors

2 LOOPOHLES 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.
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 attempt to do so progressively…
Choosing Detector Settings

Albert

Source of Entangled Particles

Bohr

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

[Diagram showing a source of entangled particles connected to quantum random number generators labeled as Star A and Star B, with Albert Einstein and Niels Bohr depicted on the left and right respectively.]
CHOOSING DETECTOR SETTINGS

Albert

Source of Entangled Particles

Quantum Random Number Generator

Star A

Quantum Random Number Generator

Star B

Bohr

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

Albert

Source of Entangled Particles

Quantum Random Number Generator

* Quasar B

Quantum Random Number Generator

* Quasar A

Bohr

Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

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

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)

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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

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

Star Selection

Image Credit: Jason Gallicchio
OBSERVED BELL VIOLATION

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

Handsteiner, Friedman+2017

Fig. 4
Space-time diagram: stars

Handsteiner, Friedman+2017
Fig. 3

HIP (A*)
56127

604 ± 35 yr

1930 ± 605 yr

(B*) HIP
105259

604 ± 35 ly

1930 ± 605 ly

119°
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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• 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 $45^\circ$ 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 $A,B$
Prof. Anton Zeilinger
Cosmic Bell Test with Quasars

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

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![Table of data](Image)

Standard Deviations

FIG. 1, Rauch + 2018

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Mechanism must affect detector settings + measurement outcomes from within QA (blue), QB (red), past light cones (or their overlap), a region with only 4.0% of physical space-time volume within our past light cone.

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

4.2-m William Herschel Telescope (WHT)

Nordic Optical Telescope (NOT)

3.6-m Telescope Nazionale Galileo (TNG)

Entangled Particle Source
CHOOSING THE BEST QUASARS

Image Credit: Andrew Friedman (UCSD)
REMOTE ASSISTANCE

Image Credit: Andrew Friedman (UCSD)
NO PRESSURE!

Image Credit: Andrew Friedman (UCSD)
Nordic Optical Telescope (NOT)

Cosmic Bell Test
Entangled Particle Source
(Shipping Container)

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

 Cosmic Bell Test Shipping Container

Image Credit: Dominik Rauch (Vienna)

NEAR DISASTER!
NEAR DISASTER!

Image Credit: Dominik Rauch (Vienna)
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

Anton Zeilinger (Vienna)

Thomas Scheidl (Vienna)

Armin Hochrainer (Vienna)

Dominik Rauch (Vienna)

Image Credit: David Kaiser (MIT)
• 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 $9.3\sigma$ Bell inequality violation (p-value $\leq 7.4 \times 10^{-21}$) for quasar pair 1.

• Pushes back to $\cong 7.8$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!)
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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COSMIC BELL IN THE NEWS

Starlight test shows quantum world has been weird for 600 years

Cosmic test confirms quantum weirdness

Cosmic experiment is closing another Bell test loophole

600-year-old starlight bolsters Einstein’s “spooky action” theory
COSMIC BELL IN THE NEWS

SCIENTIFIC AMERICAN
Observations

Photons, Quasars and the Possibility of Free Will

Flexes of light from the edge of the cosmos help physicists advance the idea that the future is not predetermined

By Brian Roberston on November 22, 2020

Black Holes Bolster Case For Quantum Physics’ ‘Spooky Action’

Black holes bolster case for quantum physics’ ‘spooky action’

By Avi Rappaport, August 29, 2019 12:34 pm

The quest to test quantum entanglement

Quantum entanglement, dreamed of by Einstein, has passed increasingly stringent tests.

11/04/18 | By Laura Bettini

PHYS.ORG Nanotechnology Physics Earth Astronomy & Space

Physicists race to demystify Einstein’s ‘spooky’ science

Physicists race to demystify Einstein’s ‘spooky’ science

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

GIZMODO

Cosmic Bell test uses light from ancient quasars

Cosmic Bell test uses light from ancient quasars

21 Aug 2018 | Hannah Lewinson

MOTHERBOARD

Ancient Starlight Just Helped Confirm the Reality of Quantum Entanglement

Ancient Starlight Just Helped Confirm the Reality of Quantum Entanglement

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

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COSMIC BELL TEST ON TV!

EINSTEIN’S QUANTUM RIDDLE

Premiering Jan 9 2019
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BIG BELL TEST

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.

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

(Rauch+2018, Supplemental Material)
FUTURE COSMIC BELL TESTS

Conformal Diagram + Past Light Cones

$\alpha = 180.00 \text{ [deg]} \quad z_A = 1.00 \quad z_B = 1.00$

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

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

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

z > 3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation
SDSS quasars - photometric and spectroscopic redshifts

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

Ground based optical flux.
IR only usable from space
Local Sky noise!

Adapted from Fig. 3 (GFK14)
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>
</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>

Gallicchio, Friedman, & Kaiser 2014
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

Would be difficult to remove all pairwise causal overlap.

$z > 4.37 \ 120^\circ$: space
$z > 4.89 \ 105^\circ$: ground

But GHZ pilot test with stars or 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)
POSSIBLE OUTCOMES

Future 2-quasar/CMB 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 depends on which cosmic sources we look at. Maybe Bell’s limit is not violated for very distant sources.

Perhaps experimenter’s lack complete freedom!
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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