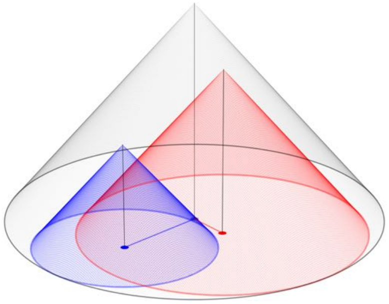
A COSMIC TEST OF QUANTUM ENTANGLEMENT

Choosing Experimental Bell Inequality Measurements with Light from High Redshift Quasars

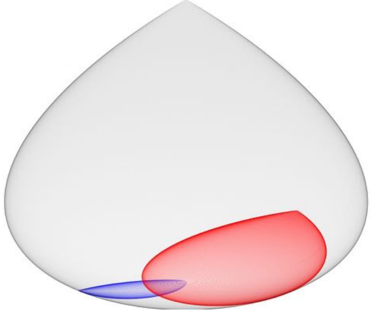


Dr. Andrew Friedman

UC San Diego

Center for Astrophysics and Space Sciences

https://asfriedman.physics.ucsd.edu   asf@ucsd.edu



UCSD CASS Massachusetts Institute of Technology IQI Vienna MPQ HARVEY MUDD COLLEGE NASA JPL NSF

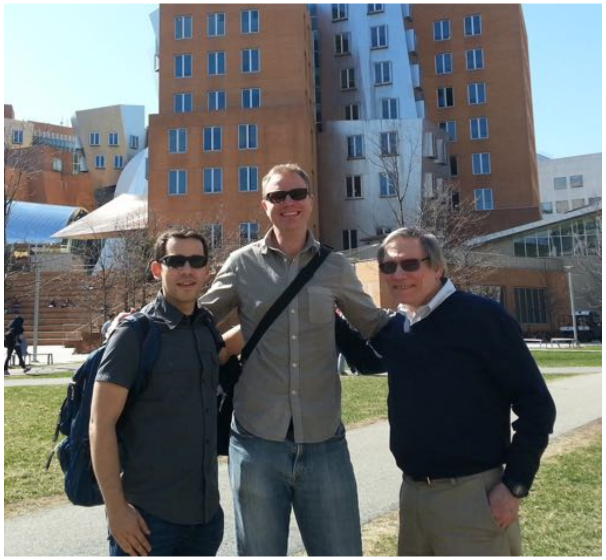
11/30/2018   San Diego State University, Physics and Astronomy Colloquium

COSMIC BELL COLLABORATION

NSF

ÖAW
Austrian Academy of Sciences

MPQ



COSMIC BELL TEAM

Prof. David Kaiser [1]

Dr. Andrew Friedman [1,5]

Prof. Alan Guth [1]

Prof. Brian Keating [5]

Prof. Anton Zeilinger [2]

Prof. Jason Gallicchio [3]

Other Collaborators

Johannes Handsteiner [2],
Dominik Rauch [2],
Dr. Thomas Scheidl [2],
Dr. Johannes Kofler [4],
Dr. Hien Nguyen [6],
Calvin Leung [3]
et al.

Massachusetts Institute of Technology

IQOQI Vienna

MPQ

UCSD

NASA JPL

HARVEY MUDD COLLEGE

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

NSF

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

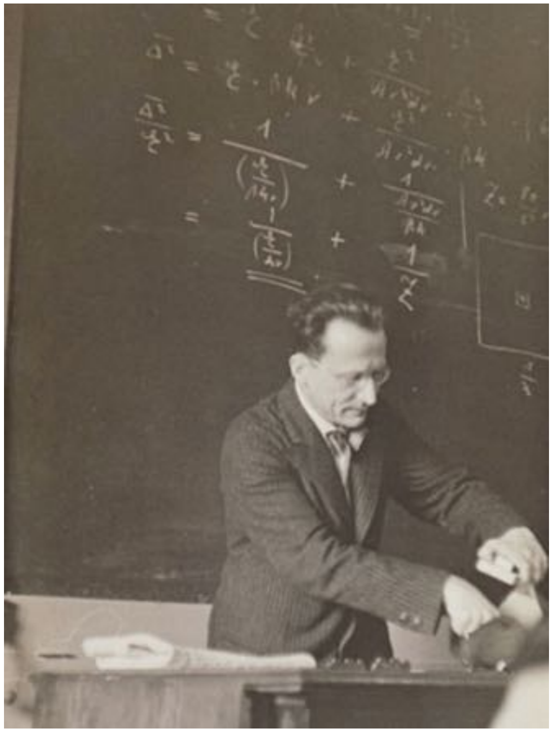
OUTLINE

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

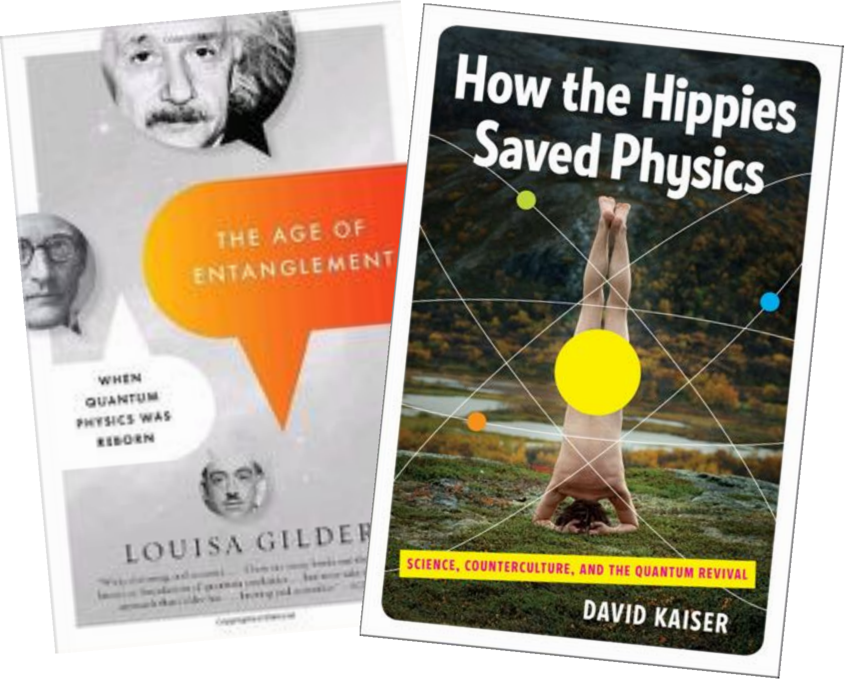
QUANTUM ENTANGLEMENT

Beginning in the 1930s, the great architects of quantum theory struggled to understand the notion of “entanglement.”

Niels Bohr and Albert Einstein

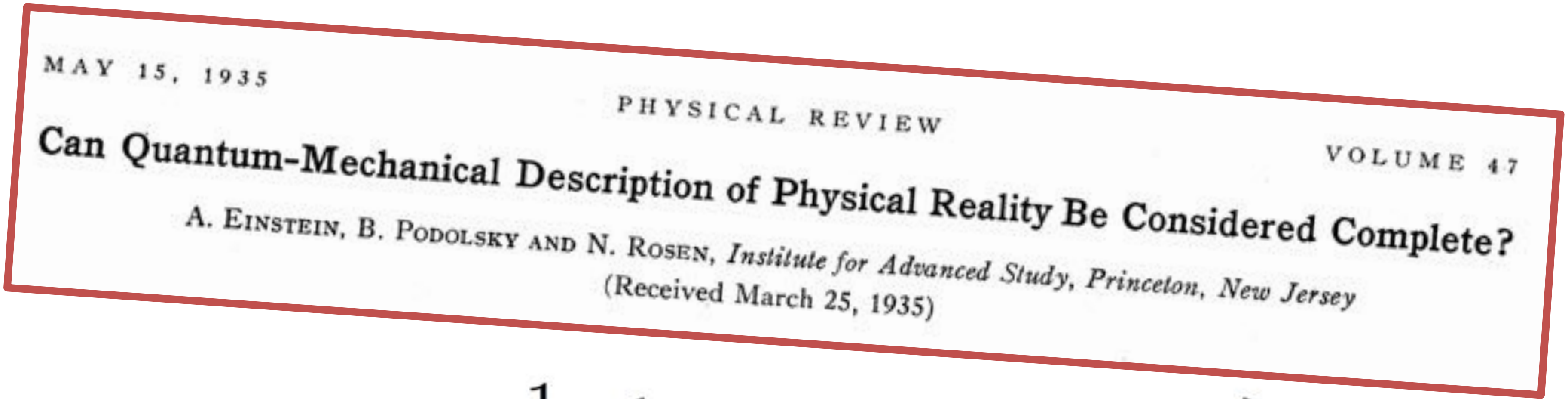


Erwin Schrödinger



EPR PARADOX

E P R



MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

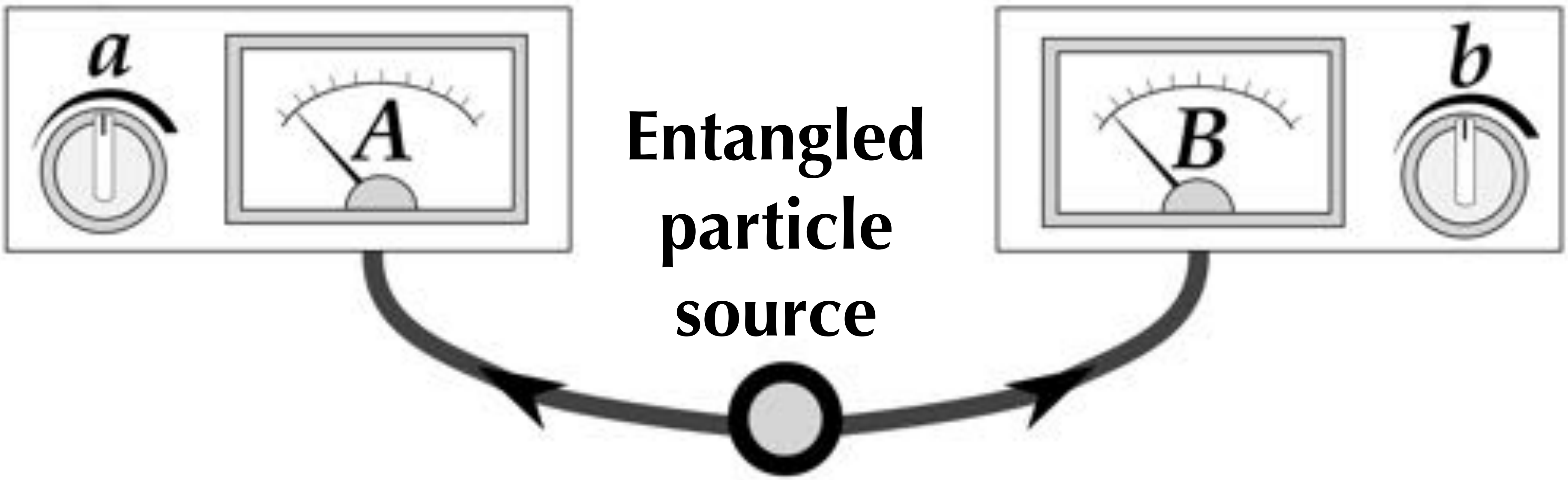
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big\{|u_1\rangle|v_2\rangle + |u_2\rangle|v_1\rangle\Big\}$$

State does not factorize: no way to describe behavior of particle 1 (u) without referring to behavior of particle 2 (v).

BELL TESTS



a, b : Settings

A, B : Outcomes

Big question: Are non-quantum explanations for entanglement viable?

If yes, QM incomplete → *Hidden variables*

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

BELL'S INEQUALITY ASSUMPTIONS

1. Realism
2. Locality
3. Freedom

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

John S. Bell (1928-1990)

1,2,3 → Bell's Inequality

Upper limits on entangled particle measurement correlations in a **"local-realist"** 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!**

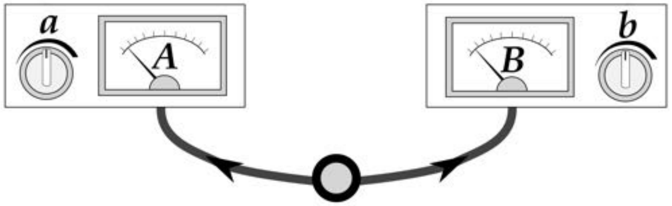
But relaxing any assumption → ***LOOPHOLES***

Alternative models could mimic quantum theory

CORRELATIONS AT A DISTANCE

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

$$\boxed{S = E(a,b) + E(a',b) + E(a,b') - E(a',b')}$$



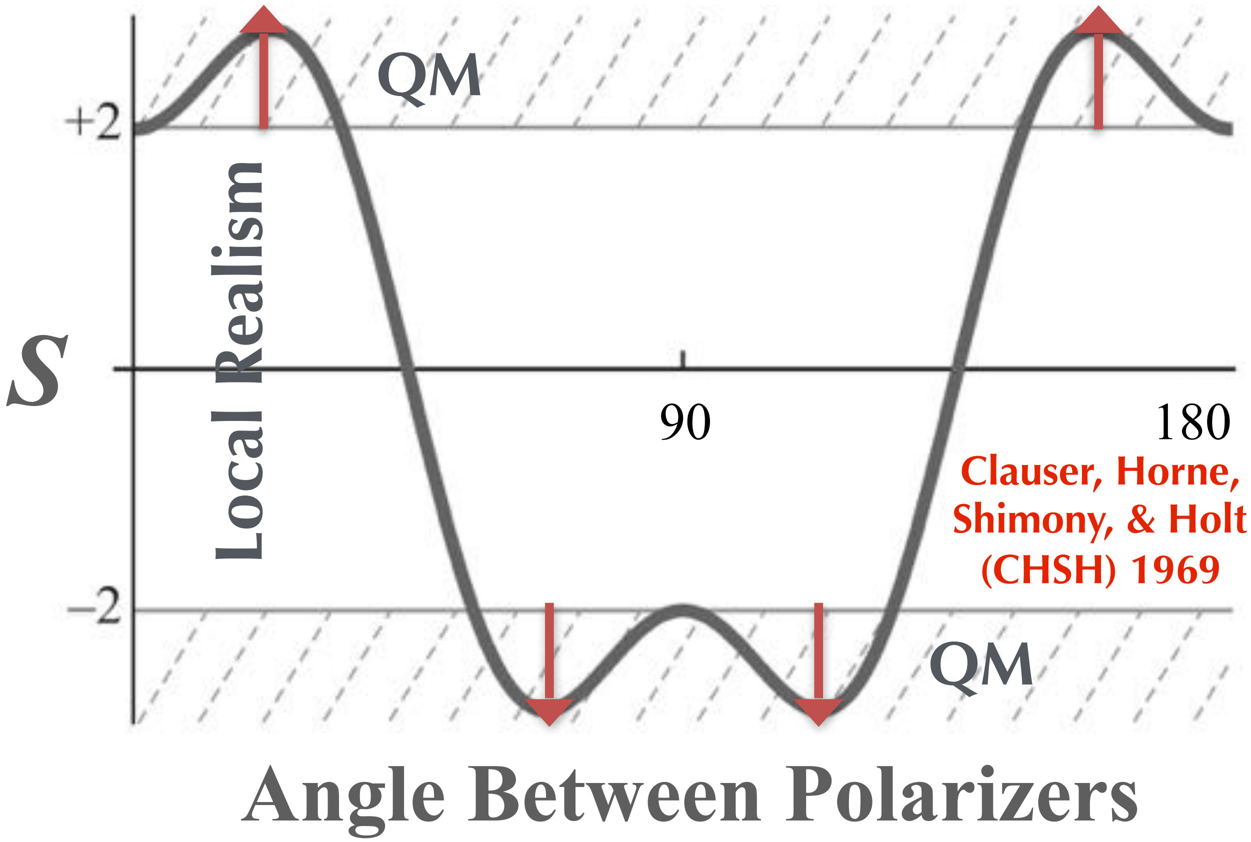
Bell: if $p(A,B|a,b) = \int d\lambda\, p(\lambda)\, \underbrace{p(A|a,\lambda)}\, p(B|b,\lambda)$

then $\boxed{|\,S\,| \leq 2.}$

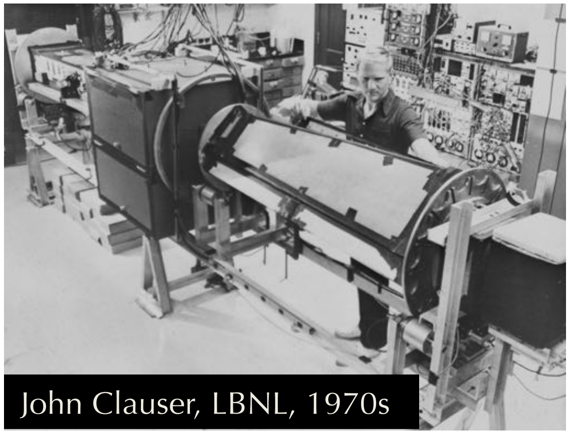
Locality: A does not depend on b or B, and vice versa.)

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

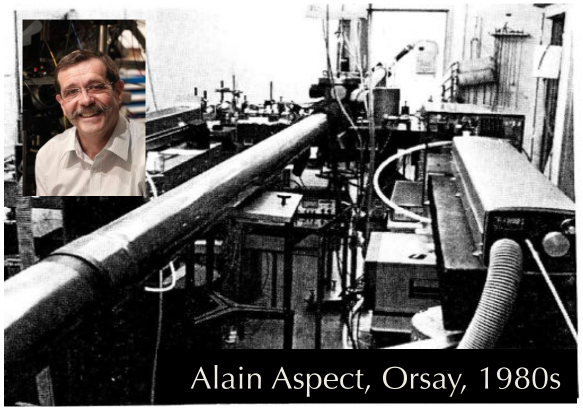
Dozens of experiments: $|S_{max}| > 2$



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



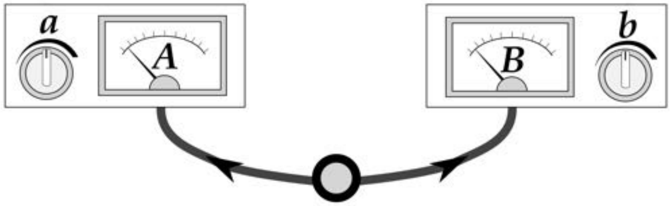
John Clauser, LBNL, 1970s



Alain Aspect, Orsay, 1980s

BELL'S INEQUALITY

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



$$\boxed{S = E(a,b) + E(a',b) + E(a,b') - E(a',b')}$$

Bell: if $p(A,B|a,b) = \int d\lambda\, p(\lambda)\, \underbrace{p(A|a,\lambda)}\, p(B|b,\lambda)$

then $\boxed{|\,S\,| \leq 2.}$ 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:** $|S_{max}| = 2\sqrt{2}$

OUTLINE

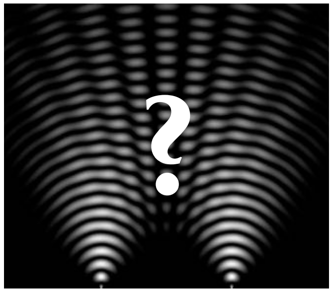
1. Entanglement Tests
2. Bell’s Inequality vs. Bell’s Theorem
3. Loopholes / Freedom-Of-Choice Loophole
4. Cosmic Bell Test with Milky Way Stars
5. Cosmic Bell Test with Quasars
6. Future Tests

LOOPHOLES & 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?

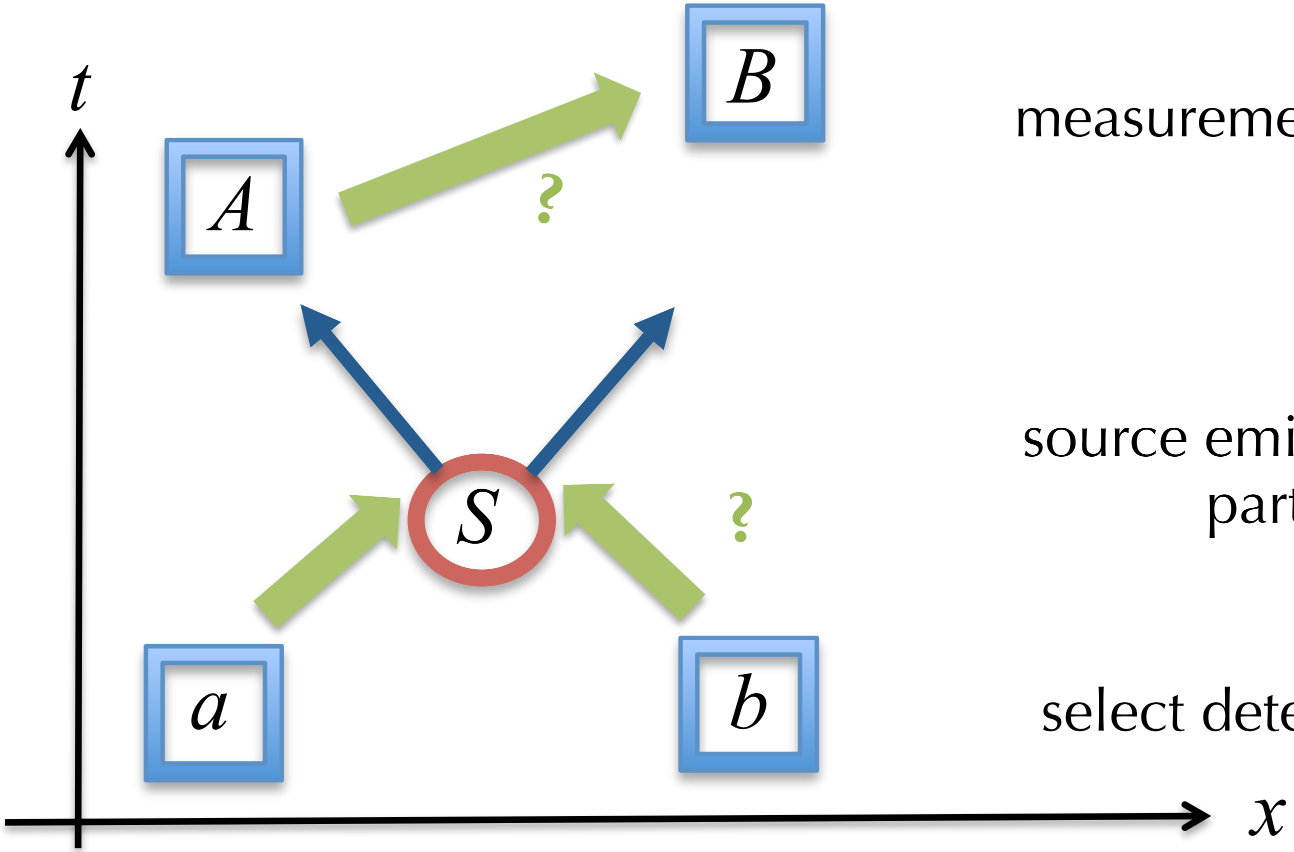
Quantum cryptography security

Tech applications! Hackers could exploit loopholes to undermine entanglement-based quantum information schemes

LOCALITY LOOPHOLE

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

Hidden communication between parties?



measurement outcomes

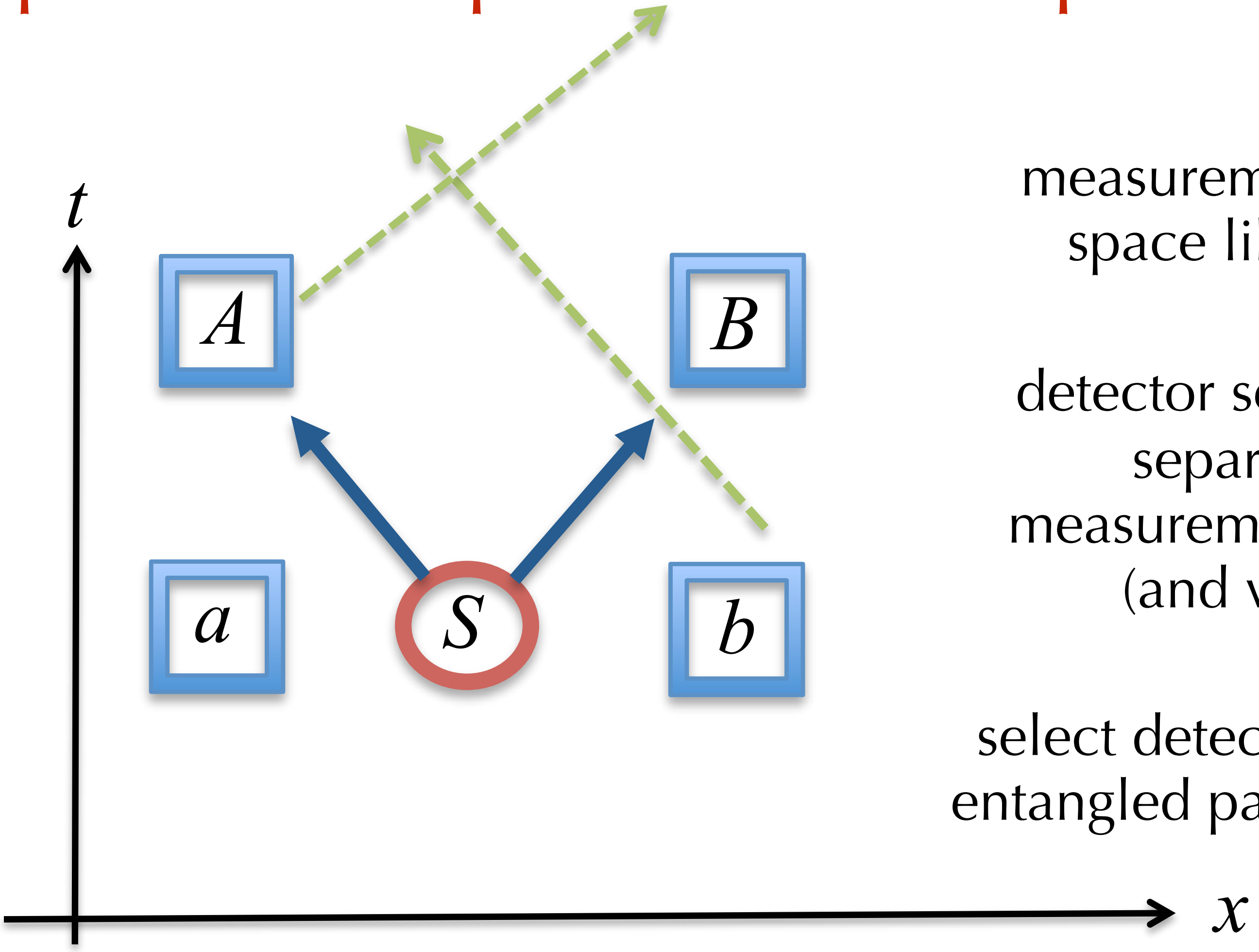
source emits entangled particles

select detector settings

CLOSING THE LOCALITY LOOPHOLE

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

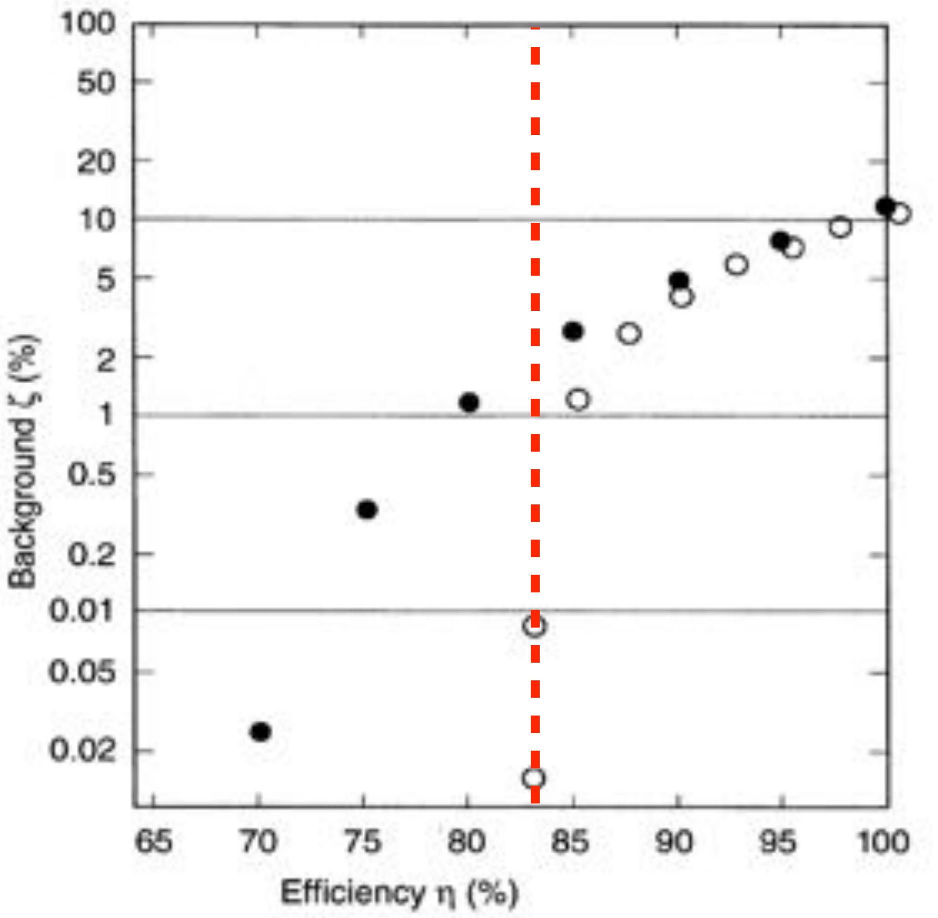
The standard interpretation of Bell tests — that "local realism" is incompatible with experiment — relies upon several assumptions.

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 ≥ 83%



Garg and Mermin, *Phys Rev D* (1987), Eberhard, *Phys Rev A* (1993)

TOWARD A LOOPHOLE FREE TEST

A. Locality Loophole

Hidden communication between parties

for photons: **Aspect+1982, Weihs+1998**

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 LOOPHOLES IN SAME TEST!

Locality & Detection

Hensen+2015 (Delft) (electrons)
Giustina+2015 (Vienna)
Shalm+2015 (NIST) (photons)
Rosenfeld+2017 (Germany) (atoms)

TOWARD A LOOPHOLE FREE TEST

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

DELFT

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

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

The New York Times

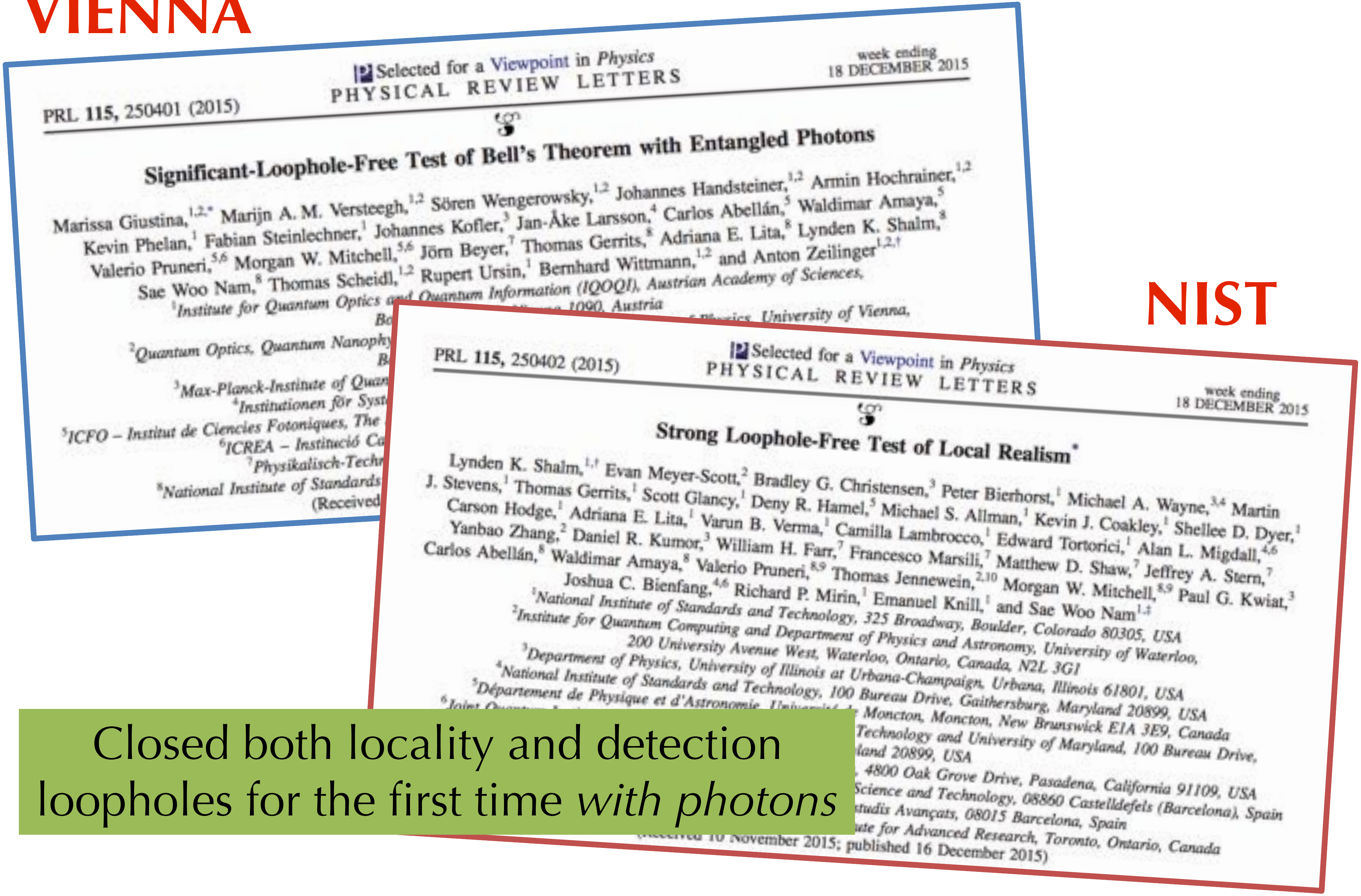
Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015

First experiment to close *both* the locality and detection loopholes.

LATEST EXPERIMENTS

VIENNA



PRL **115**, 250401 (2015)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2015

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,[1,2]
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 Beyer,[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 Zeilinger[1,2,†]

[1]Institute for Quantum Optics a… Quantum Information (IQOQI), Austrian Academy of Sciences,
Bo… 1090, Austria … Physics, University of Vienna,
[2]Quantum Optics, Quantum Nanophy…
B…
[3]Max-Planck-Institute of Quan…
[4]Institutionen för Syst…
[5]ICFO – Institut de Ciencies Fotoniques, The …
[6]ICREA – Institució Ca…
[7]Physikalisch-Techn…
[8]National Institute of Standards…
(Received…

NIST

PRL **115**, 250402 (2015)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2015

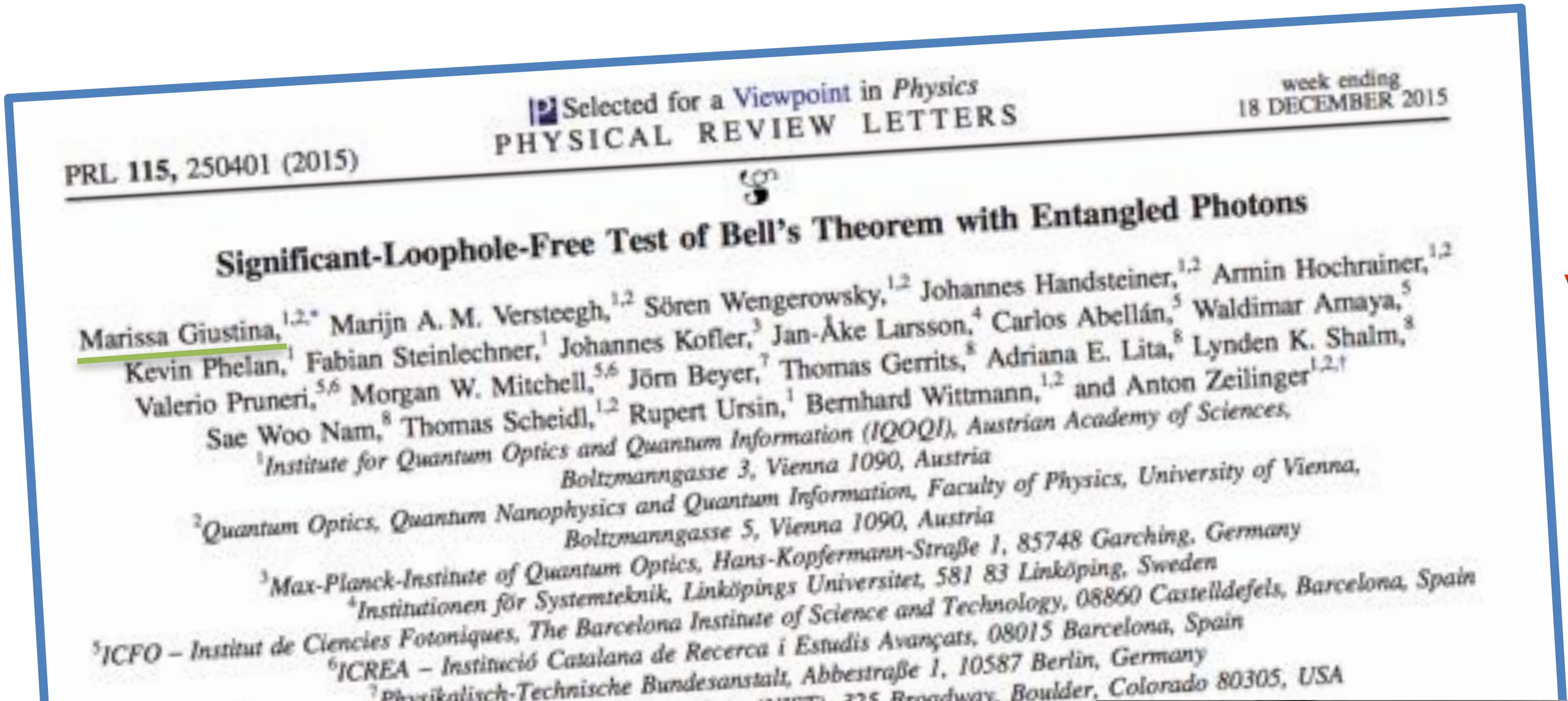
Strong Loophole-Free Test of Local Realism*

Lynden K. Shalm,[1,†] Evan Meyer-Scott,[2] Bradley G. Christensen,[3] Peter Bierhorst,[1] Michael A. Wayne,[3,4] Martin
J. Stevens,[1] Thomas Gerrits,[1] Scott Glancy,[1] Deny R. Hamel,[5] Michael S. Allman,[1] Kevin J. Coakley,[1] Shellee D. Dyer,[1]
Carson Hodge,[1] Adriana E. Lita,[1] Varun B. Verma,[1] Camilla Lambrocco,[1] Edward Tortorici,[1] Alan L. Migdall,[4,6]
Yanbao Zhang,[2] Daniel R. Kumor,[3] William H. Farr,[7] Francesco Marsili,[7] Matthew D. Shaw,[7] Jeffrey A. Stern,[7]
Carlos Abellán,[8] Waldimar Amaya,[8] Valerio Pruneri,[8,9] Thomas Jennewein,[2,10] Morgan W. Mitchell,[8,9] Paul G. Kwiat,[3]
Joshua C. Bienfang,[4,6] Richard P. Mirin,[1] Emanuel Knill,[1] and Sae Woo Nam[1,‡]

[1]National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA
[2]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo,
200 University Avenue West, Waterloo, Ontario, Canada, N2L 3G1
[3]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
[4]National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA
[5]Département de Physique et d'Astronomie, Université … Moncton, Moncton, New Brunswick E1A 3E9, Canada
[6]Joint Quantum … Technology and University of Maryland, 100 Bureau Drive,
…land 20899, USA
… 4800 Oak Grove Drive, Pasadena, California 91109, USA
… Science and Technology, 08860 Castelldefels (Barcelona), Spain
… Estudis Avançats, 08015 Barcelona, Spain
… ute for Advanced Research, Toronto, Ontario, Canada
(Received 10 November 2015; published 16 December 2015)

Closed both locality and detection loopholes for the first time *with photons*

LATEST EXPERIMENTS



PRL **115,** 250401 (2015)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

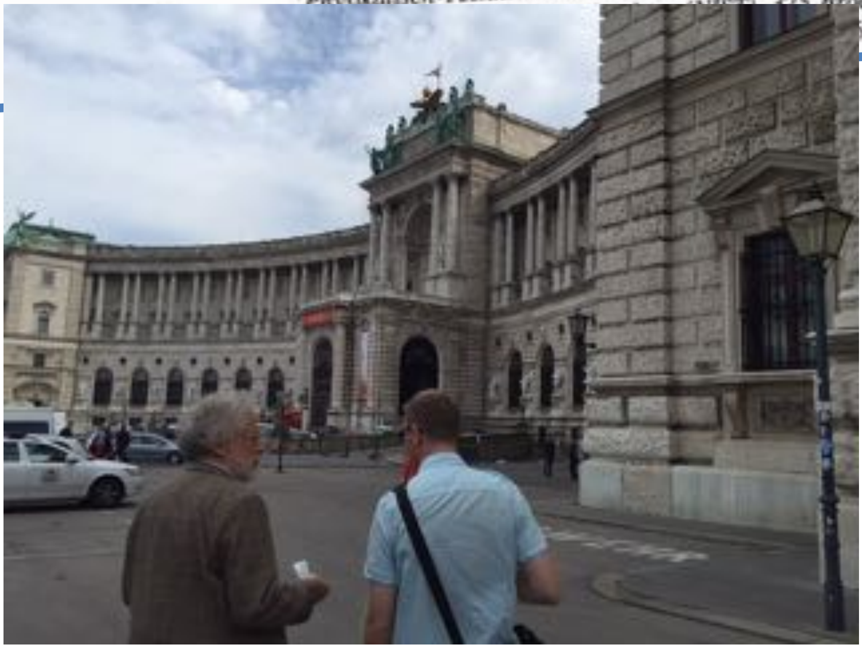
week ending
18 DECEMBER 2015

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,[1,2]
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 Beyer,[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 Zeilinger[1,2,†]

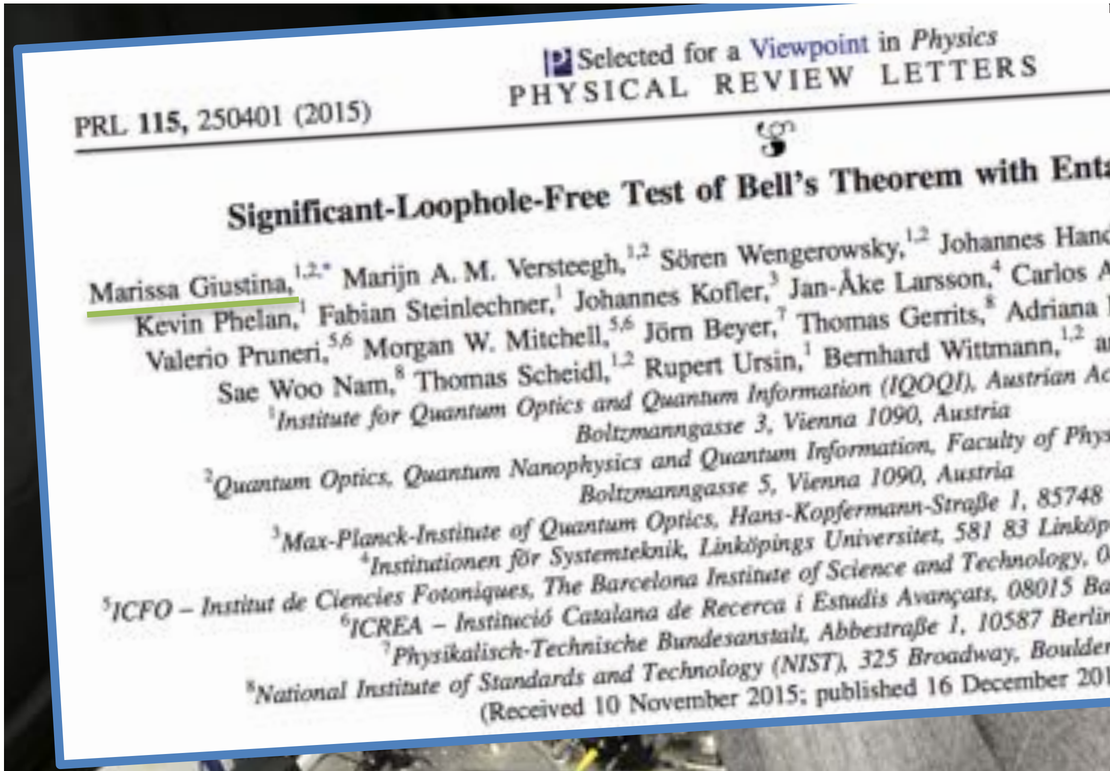
[1]*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences,*
Boltzmanngasse 3, Vienna 1090, Austria
[2]*Quantum Optics, Quantum Nanophysics and Quantum Information, Faculty of Physics, University of Vienna,*
Boltzmanngasse 5, Vienna 1090, Austria
[3]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany*
[4]*Institutionen för Systemteknik, Linköpings Universitet, 581 83 Linköping, Sweden*
[5]*ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*
[6]*ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
[7]*Physikalisch-Technische Bundesanstalt, Abbestraße 1, 10587 Berlin, Germany*
325 Broadway, Boulder, Colorado 80305, USA
December 201

VIENNA



HOFBURG PALACE, VIENNA

HOFBURG PALACE BASEMENT



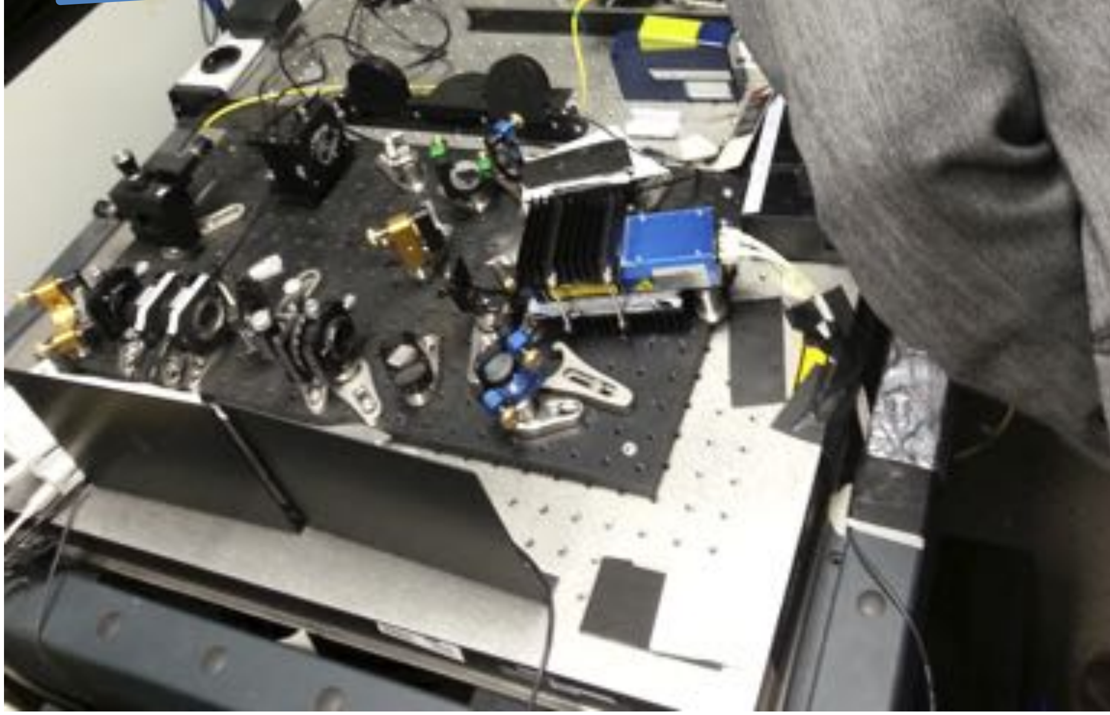
PRL **115**, 250401 (2015)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

Significant-Loophole-Free Test of Bell's Theorem with Ent

Marissa Giustina,[1,2,*] Marijn A. M. Versteegh,[1,2] Sören Wengerowsky,[1,2] Johannes Han
Kevin Phelan,[1] Fabian Steinlechner,[1] Johannes Kofler,[3] Jan-Åke Larsson,[4] Carlos A
Valerio Pruneri,[5,6] Morgan W. Mitchell,[5,6] Jörn Beyer,[7] Thomas Gerrits,[8] Adriana
Sae Woo Nam,[8] Thomas Scheidl,[1,2] Rupert Ursin,[1] Bernhard Wittmann,[1,2] a

[1]*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Ac*
Boltzmanngasse 3, Vienna 1090, Austria
[2]*Quantum Optics, Quantum Nanophysics and Quantum Information, Faculty of Phys*
Boltzmanngasse 5, Vienna 1090, Austria
[3]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748*
[4]*Institutionen för Systemteknik, Linköpings Universitet, 581 83 Linköp*
[5]*ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 0*
[6]*ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Ba*
[7]*Physikalisch-Technische Bundesanstalt, Abbestraße 1, 10587 Berlin*
[8]*National Institute of Standards and Technology (NIST), 325 Broadway, Boulder*
(Received 10 November 2015; published 16 December 201



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

FREEDOM OF CHOICE LOOPHOLE

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

$$p(A,B|a,b) = \int d\lambda\, \underbrace{p(A,B|a,b,\lambda)}\, \underbrace{p(\lambda|a,b)}$$

Bell explicitly *assumed*

$$\underbrace{p(\lambda|a,b) = p(\lambda)}_{p(a,b|\lambda) = p(a,b)}$$

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.

RELAXING FREEDOM OF CHOICE

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

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

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

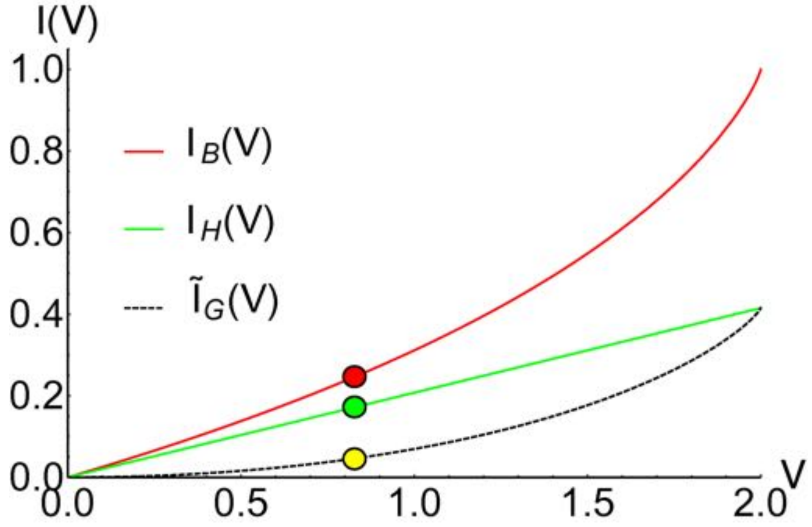
A *minuscule* amount of correlation between λ and *a*,*b* would suffice to mimic QM, with $|S| \to 2\sqrt{2}$.

Mutual Information

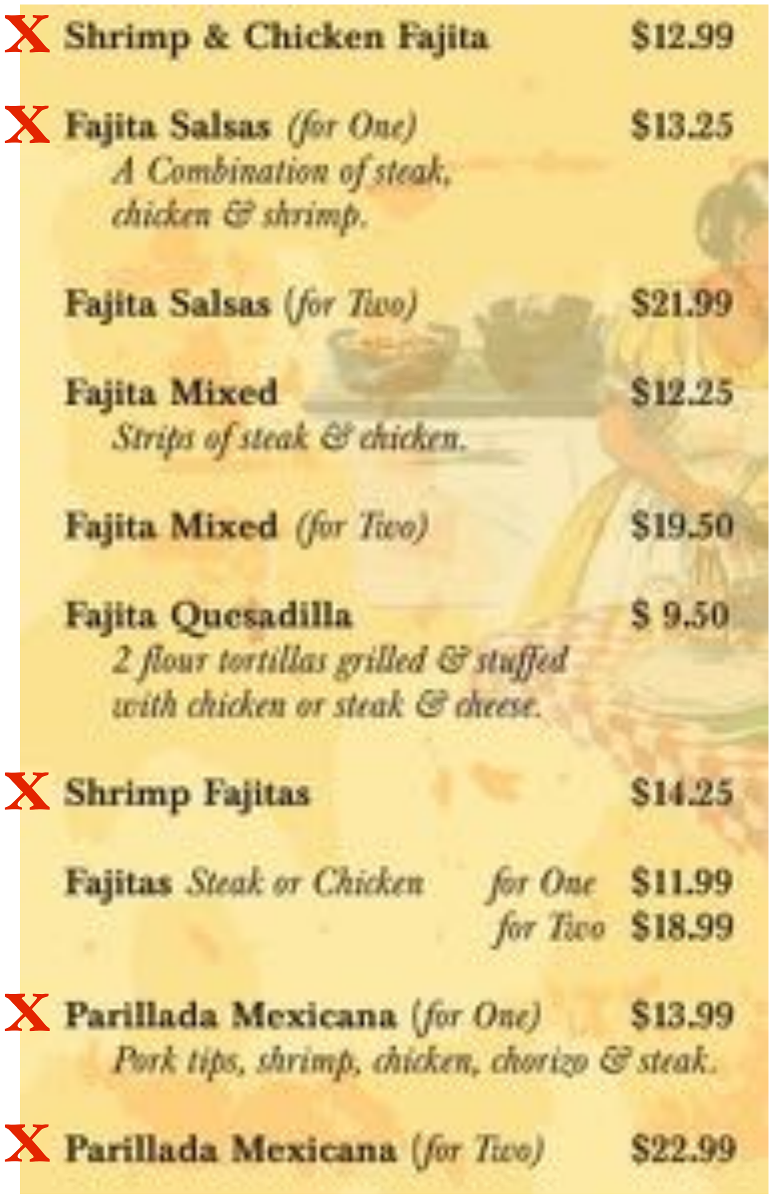
$$I = \sum_{\lambda,a,b} p(\lambda|a,b)\, p(a,b) \log_2 \frac{p(\lambda|a,b)}{p(\lambda)}$$

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

Friedman, Guth, Hall, Kaiser, Gallicchio, 1809.01307

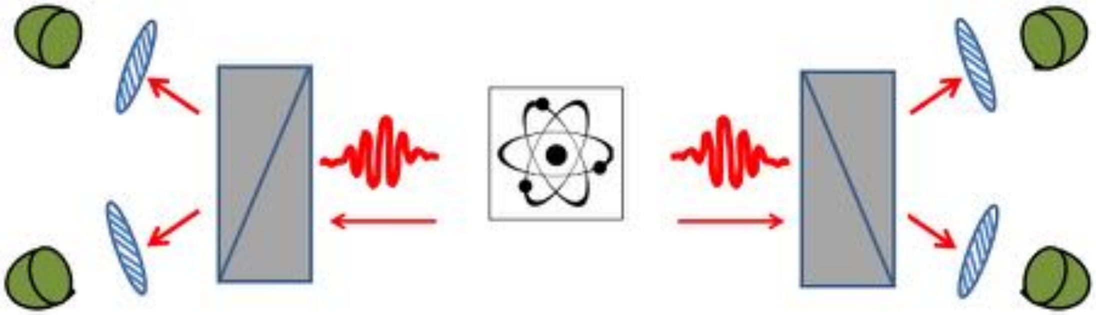


FREEDOM OF CHOICE LOOPHOLE



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

http://salsasmexrestaurants.com/test/wp-content/uploads/2014/11/Fajitascombos.jpg



If detector settings depend on hidden variables λ 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?

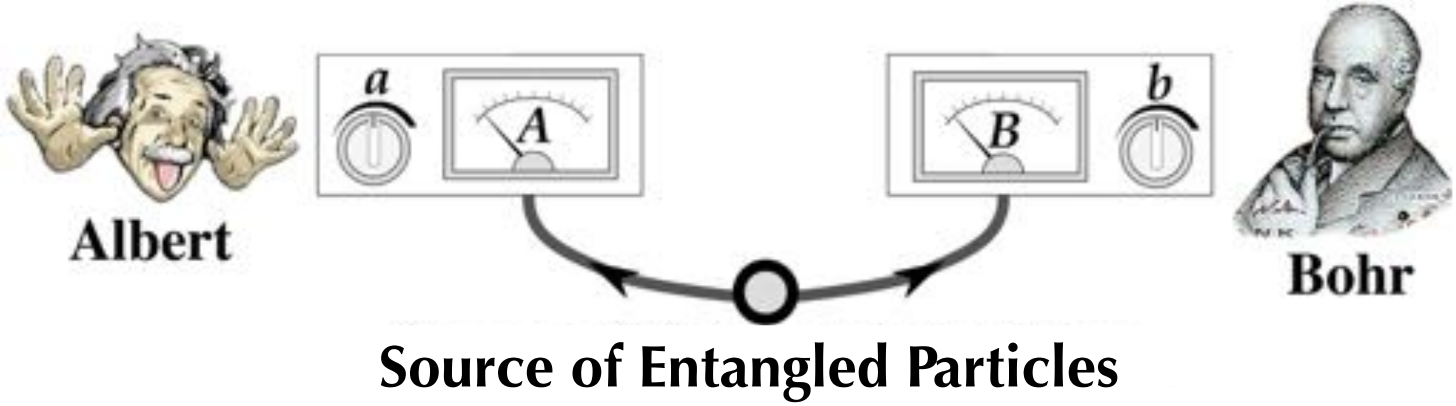
- Most recent experiments used QRNGs to select detector settings.

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

- *According to QM*, the outputs should be intrinsically random.

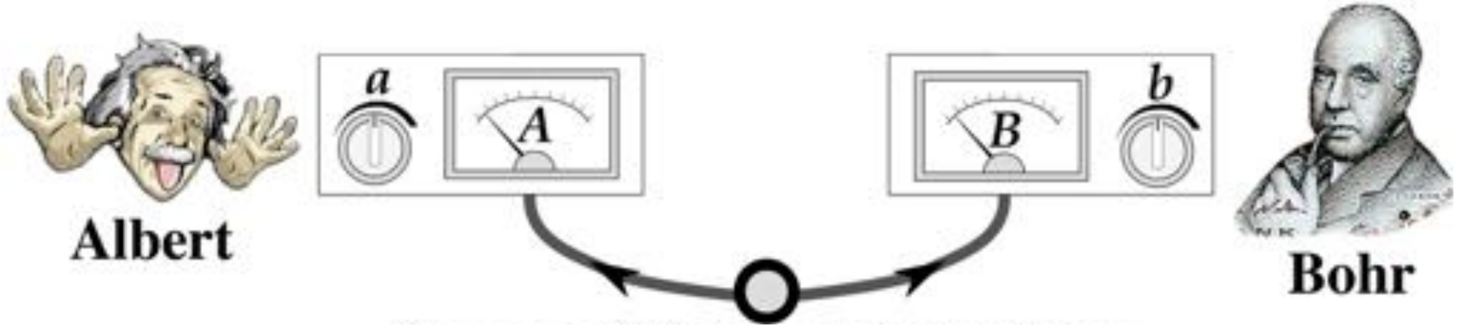
But the purported intrinsic randomness of QM is part of what is *at stake* in tests of Bell's inequality…

CHOOSING DETECTOR SETTINGS

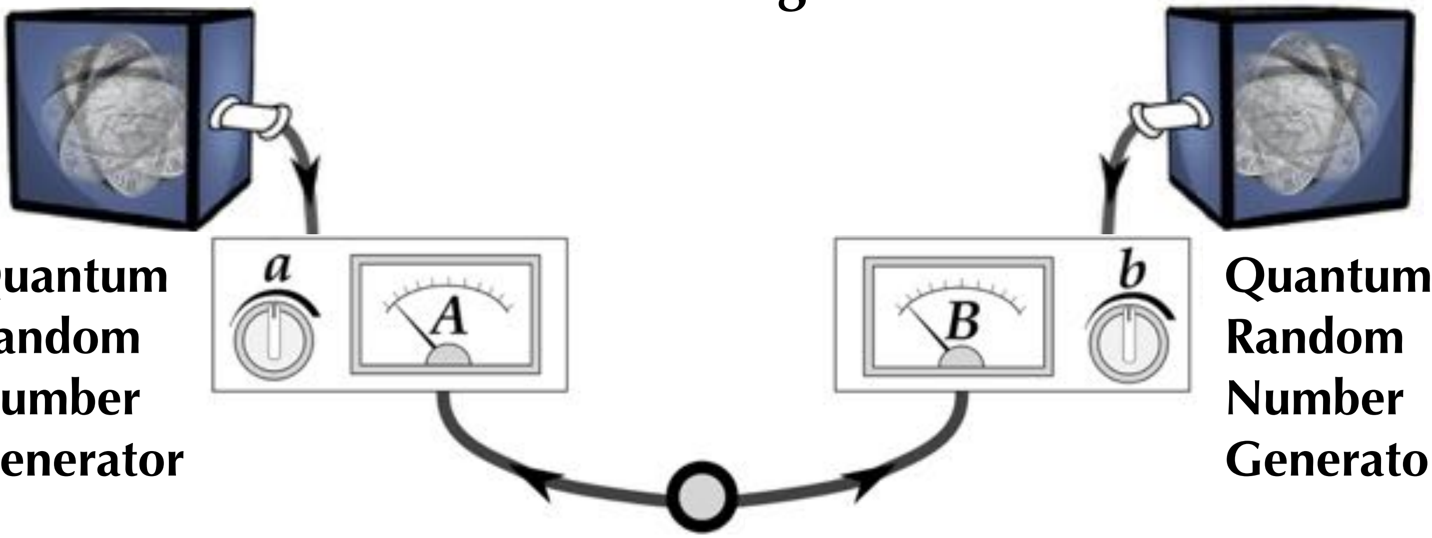


Adapted from:
Gallicchio, Friedman,
& Kaiser 2014

CHOOSING DETECTOR SETTINGS



Source of Entangled Particles

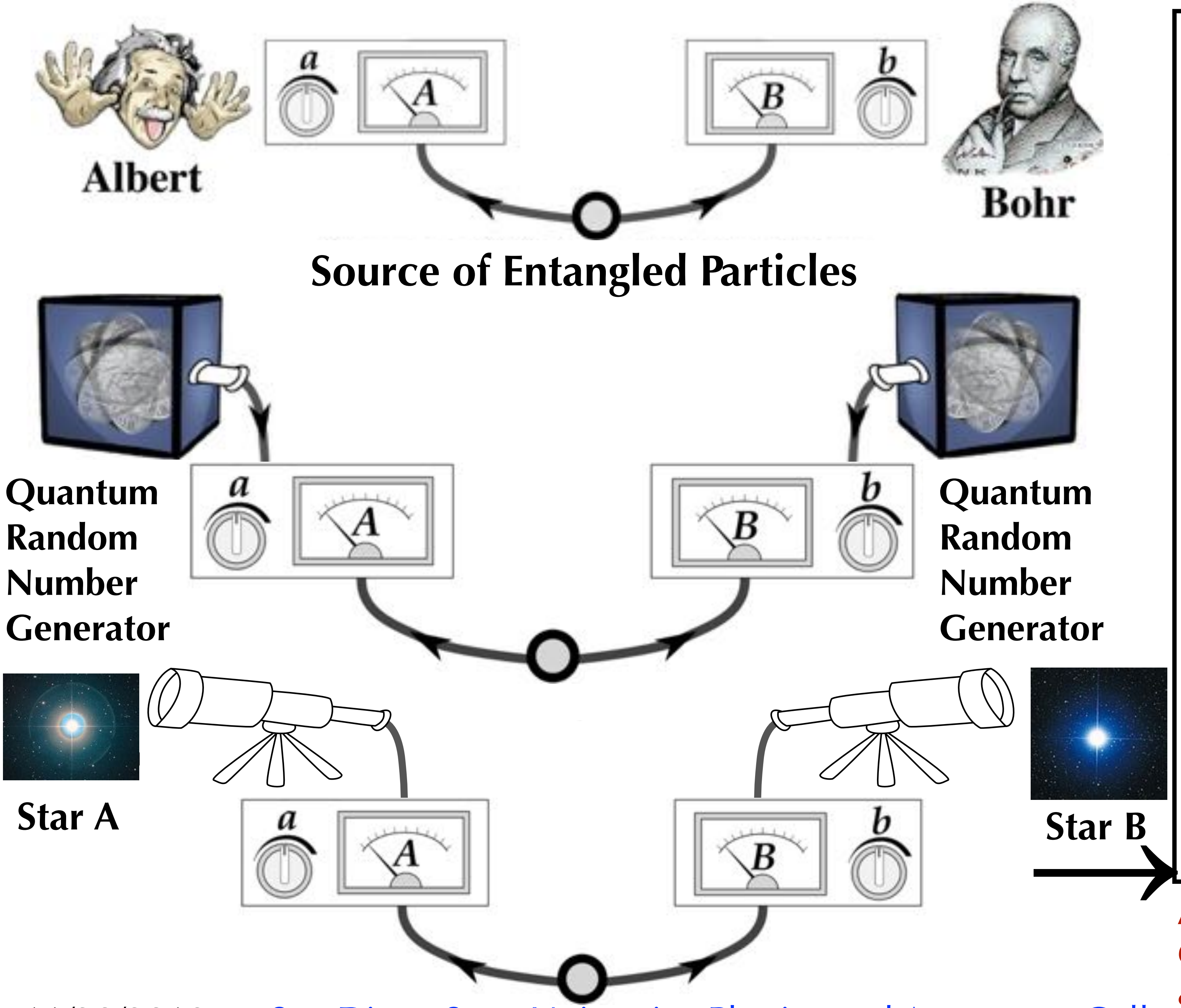


Quantum Random Number Generator

Quantum Random Number Generator

Adapted from:
Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

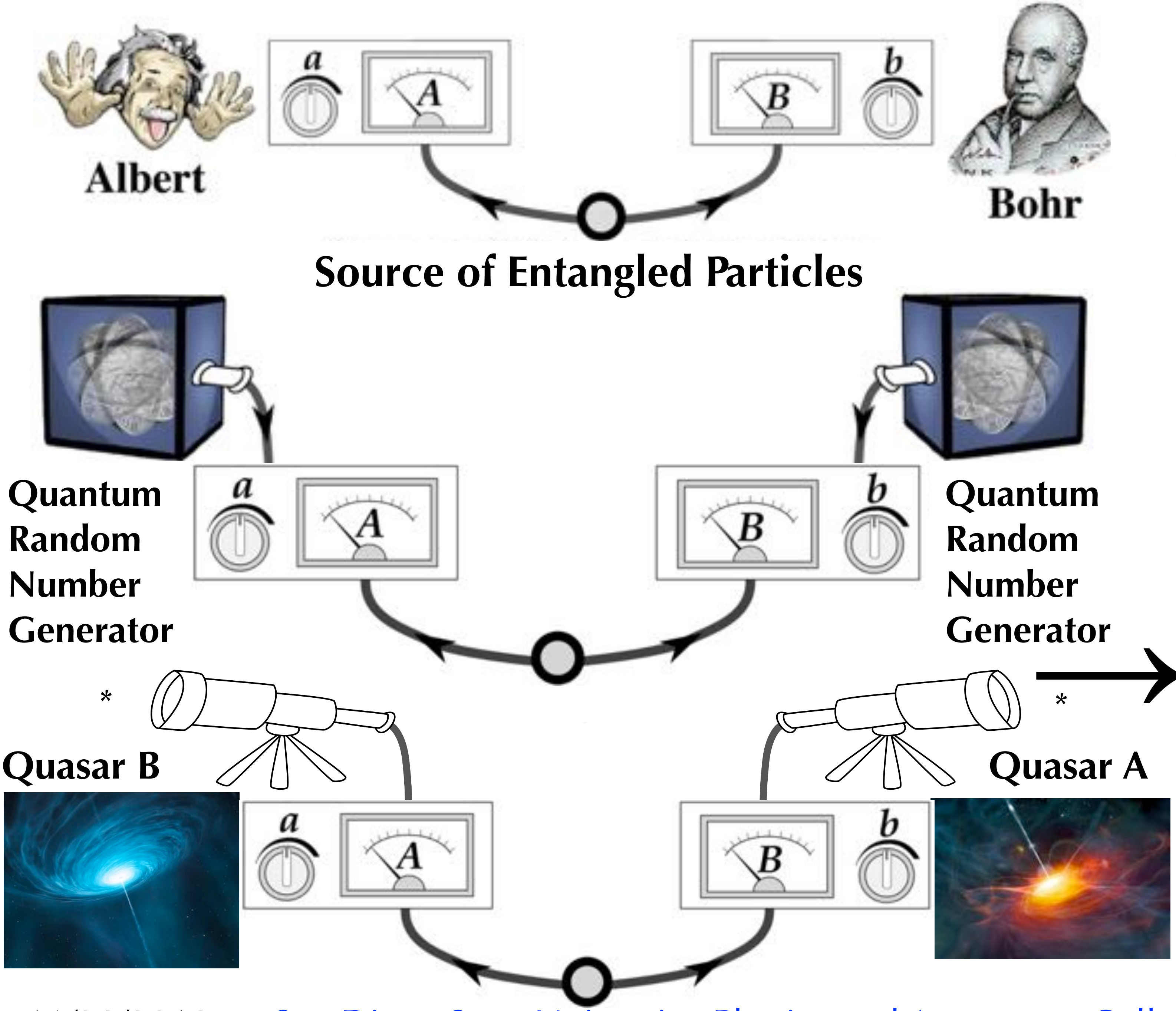


Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

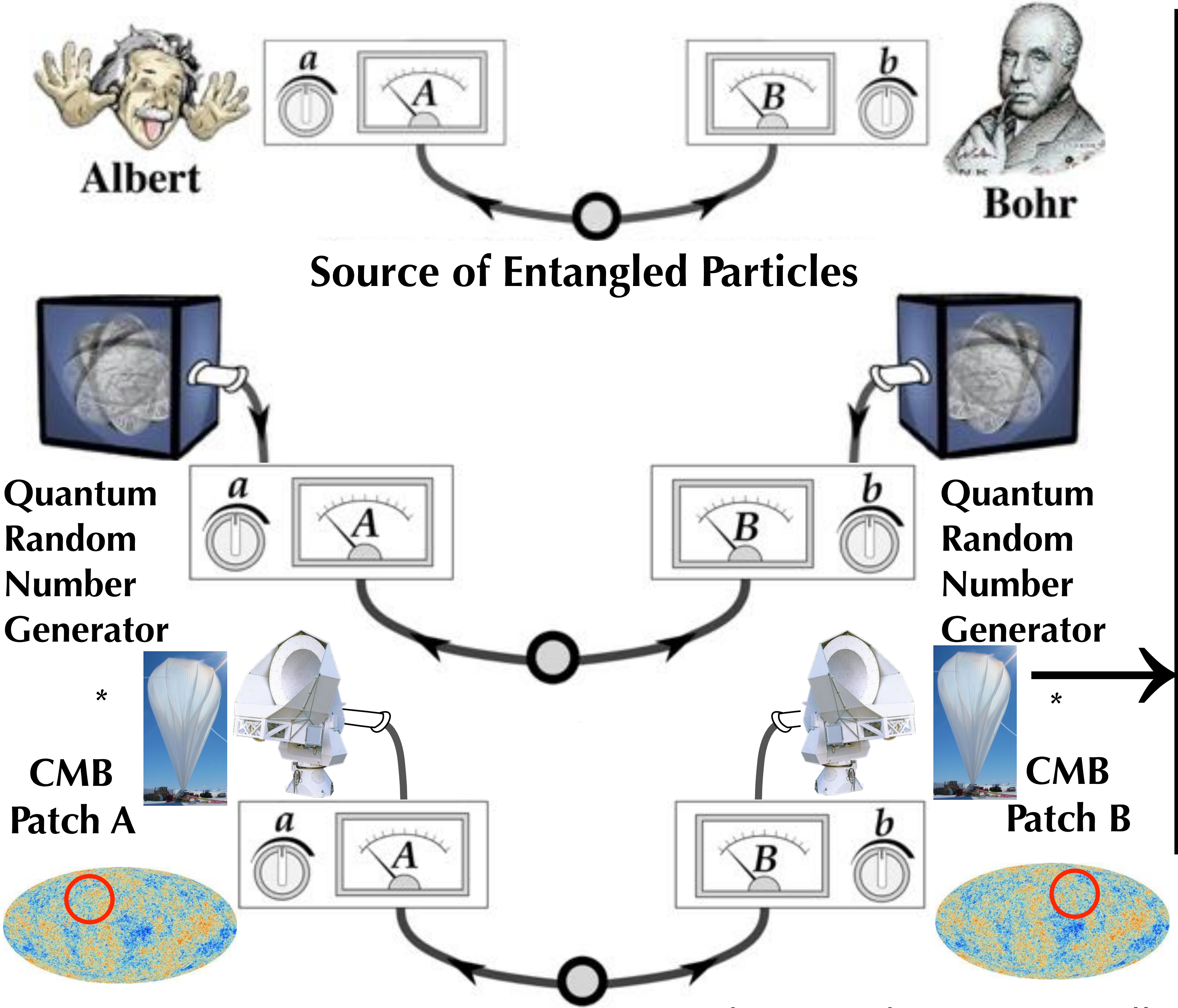


Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS



Source of Entangled Particles

Quantum
Random
Number
Generator

Quantum
Random
Number
Generator

*

CMB
Patch A

*

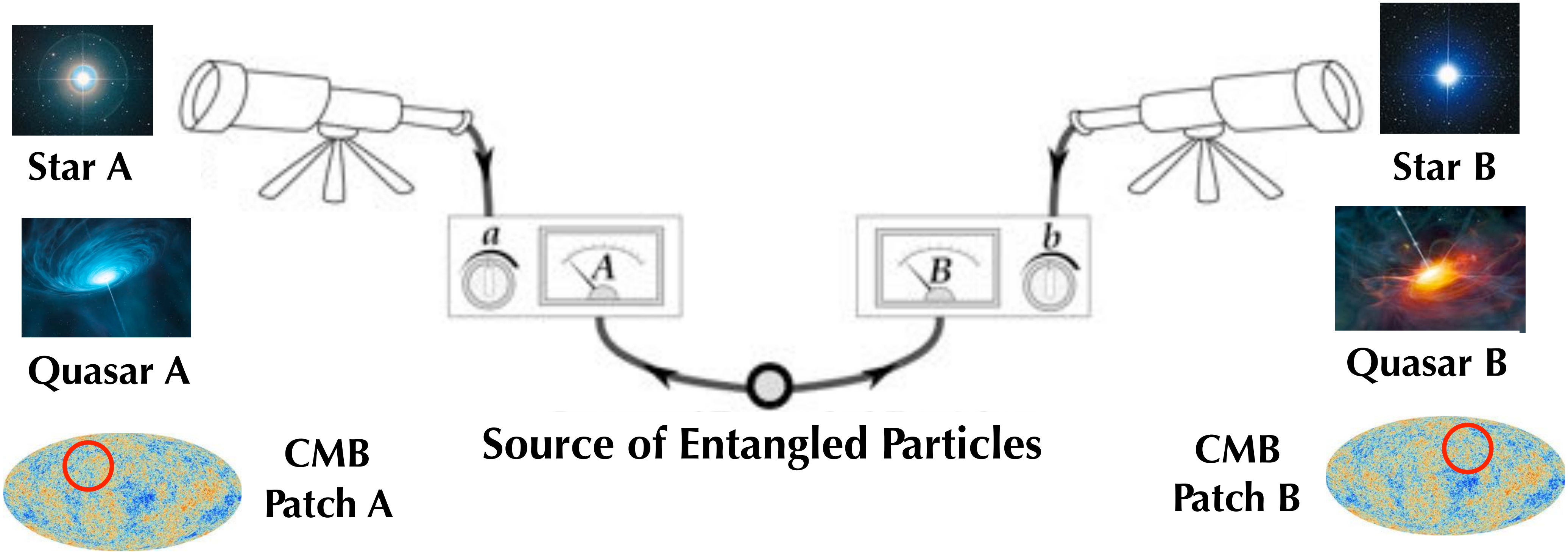
CMB
Patch B

Choose settings with observations of CMB patches, etc…

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

Adapted from:
Gallicchio, Friedman,
& Kaiser 2014

COSMIC BELL TESTS



Star A

Quasar A

CMB Patch A

Source of Entangled Particles

Star B

Quasar B

CMB Patch B

Let the Universe decide how to set up entanglement experiment!

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

Gallicchio, Friedman, & Kaiser 2014, *Phys. Rev. Lett., Vol. 112, Issue 11, id. 110405,* (arXiv:1310.3288)

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

FIRST COSMIC BELL TEST (VIENNA)

PRL 118, 060401 (2017) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2017

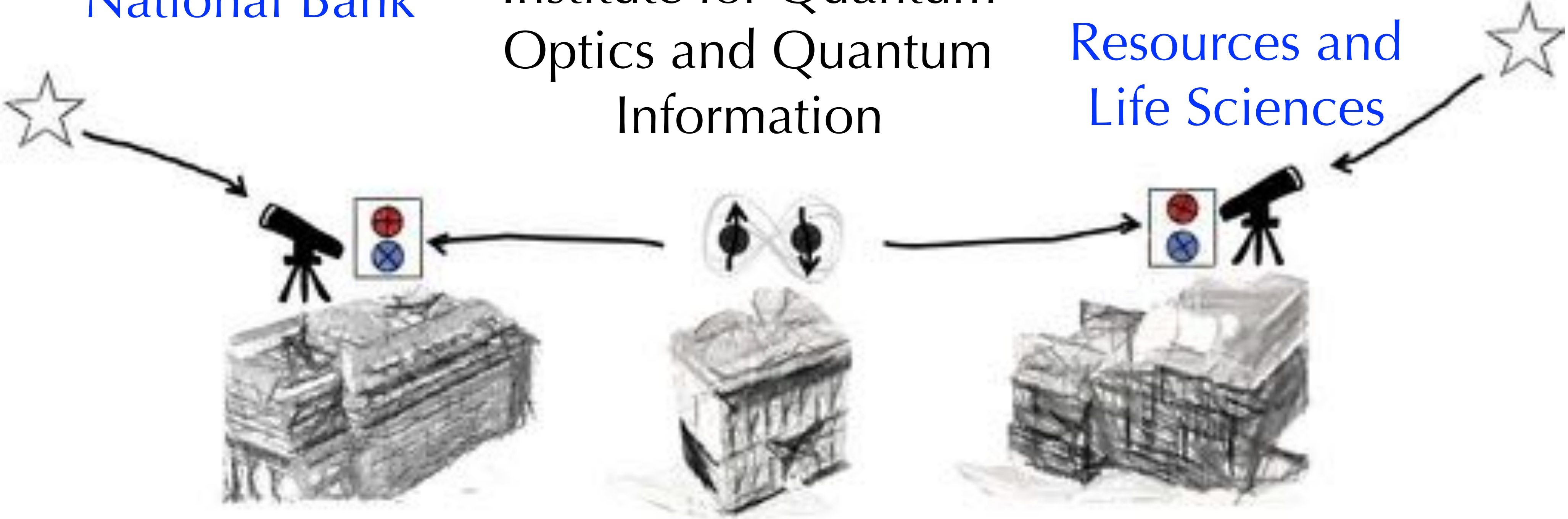
Cosmic Bell Test: Measurement Settings from Milky Way Stars

Johannes Handsteiner,[1,*] Andrew S. Friedman,[2,†] Dominik Rauch,[1] Jason Gallicchio,[3]
Bo Liu,[1,4] Hannes Hosp,[1] Johannes Kofler,[5] David Bricher,[1] Matthias Fink,[1] Calvin Leung,[3]
Anthony Mark,[2] Hien T. Nguyen,[6] Isabella Sanders,[2] Fabian Steinlechner,[1] Rupert Ursin,[1,7]
Sören Wengerowsky,[1] Alan H. Guth,[2] David I. Kaiser,[2]
Thomas Scheidl,[1] and Anton Zeilinger[1,7,‡]

Alice: Austrian National Bank

Entangled Particles: Institute for Quantum Optics and Quantum Information

Bob: University of Natural Resources and Life Sciences



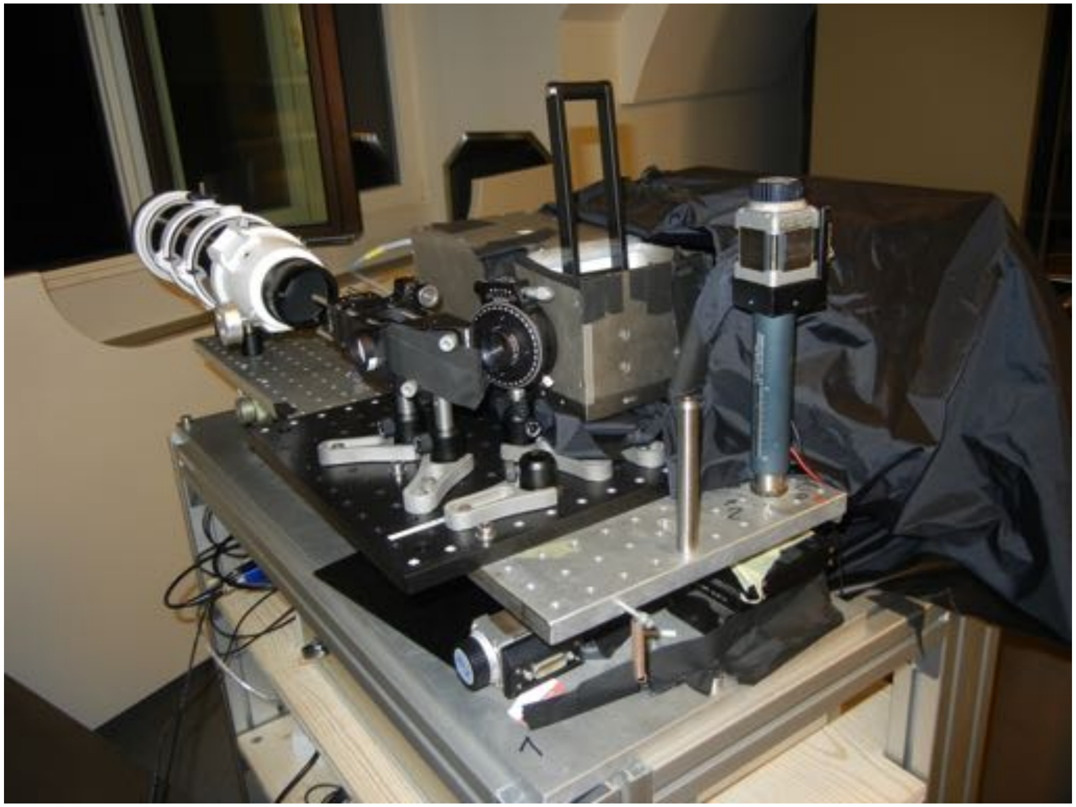
Handsteiner, Friedman+2017 (arXiv:1611.06985)

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

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

VIENNA COSMIC BELL TEST

Occupational Hazards

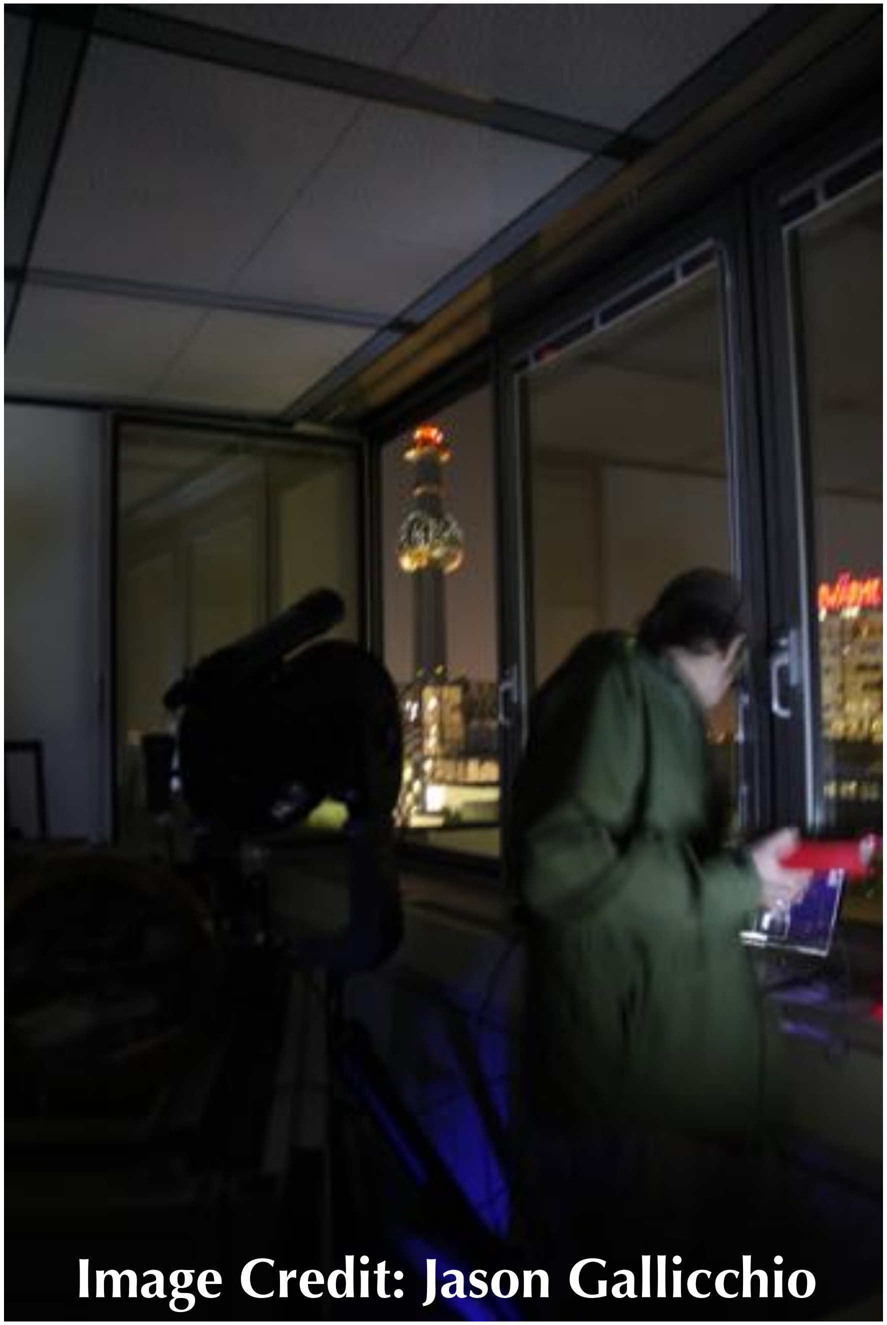


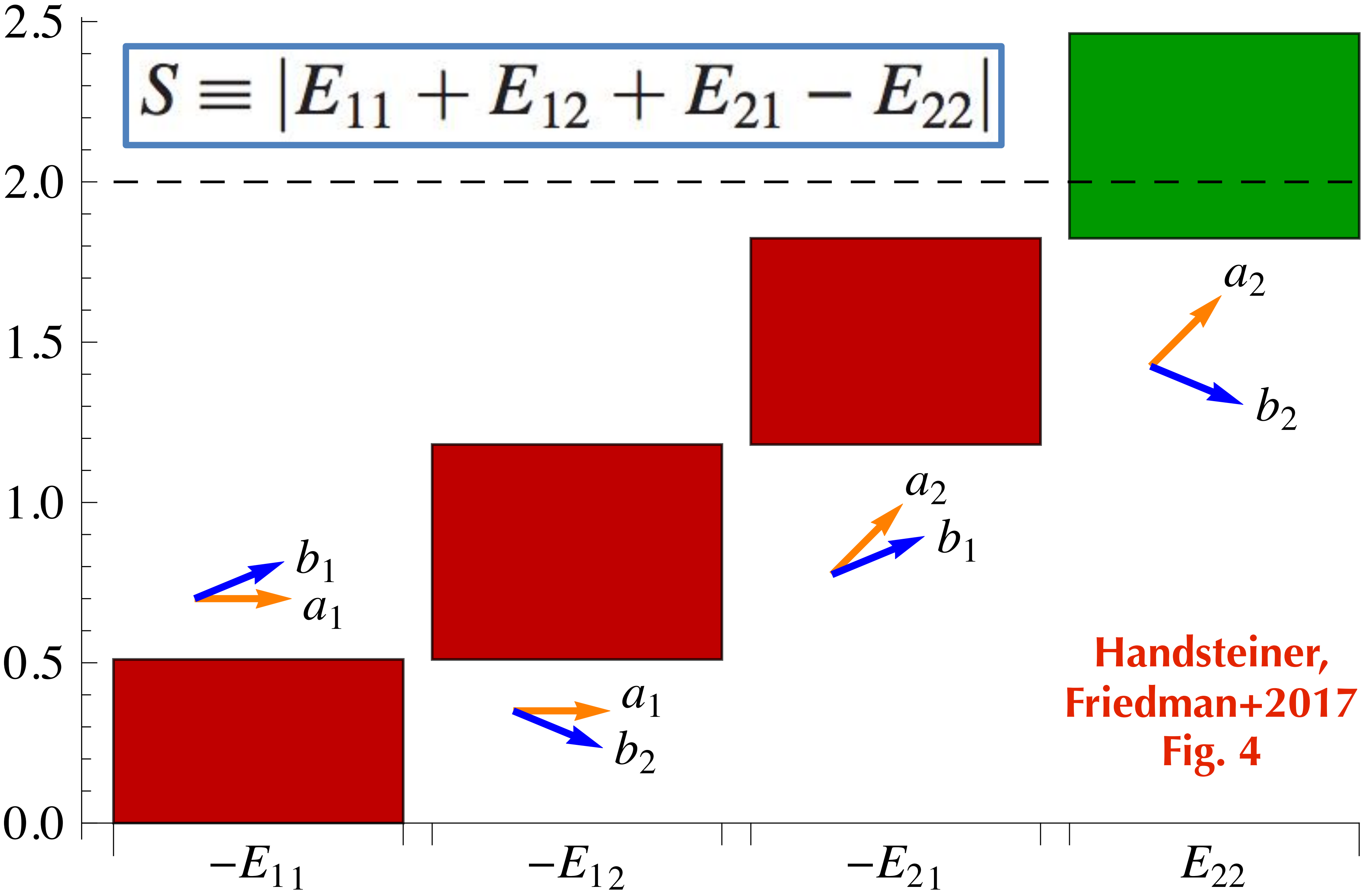
Image Credit: Jason Gallicchio

VIENNA COSMIC BELL TEST

Star Selection


Image Credit: Jason Gallicchio

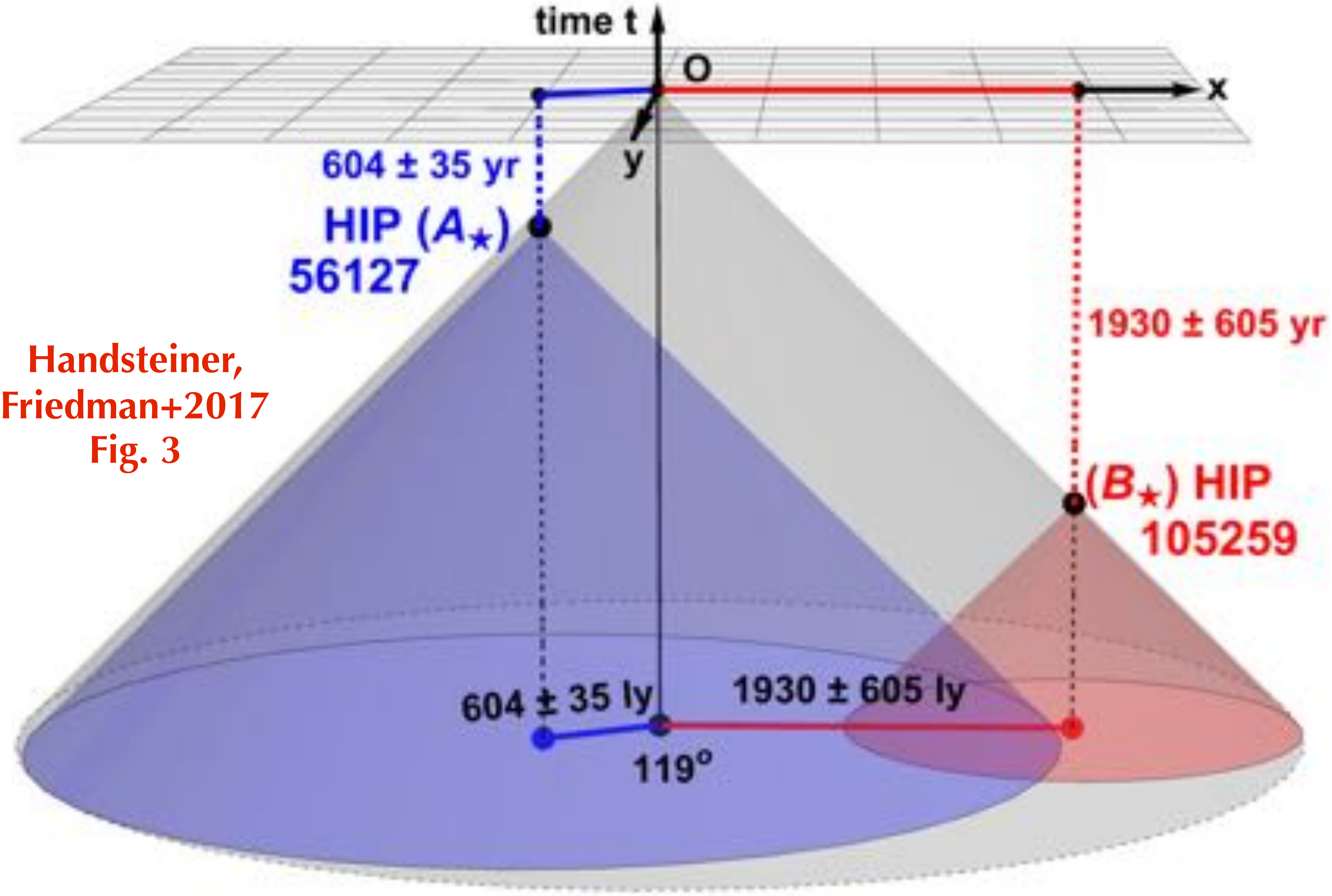
OBSERVED BELL VIOLATION



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

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 (Supplemetal Material)**

OUTLINE

1. Entanglement Tests

2. Bell's Inequality vs. Bell's Theorem

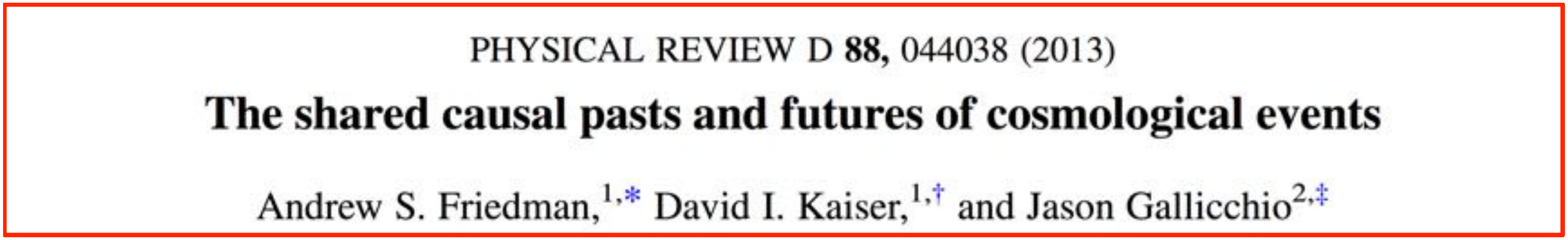
3. Loopholes / Freedom-Of-Choice Loophole

4. Cosmic Bell Test with Milky Way Stars

5. Cosmic Bell Test with Quasars

6. Future Tests

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 Gallicchio[2,‡]

Friedman, Kaiser, & Gallicchio 2013a, *Phys. Rev. D,* Vol. 88, Iss. 4, id. 044038, 18 p. (arXiv:1305.3943)

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 week ending 21 MARCH 2014

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

Jason Gallicchio,[1,*] Andrew S. Friedman,[2,†] and David I. Kaiser[2,‡]

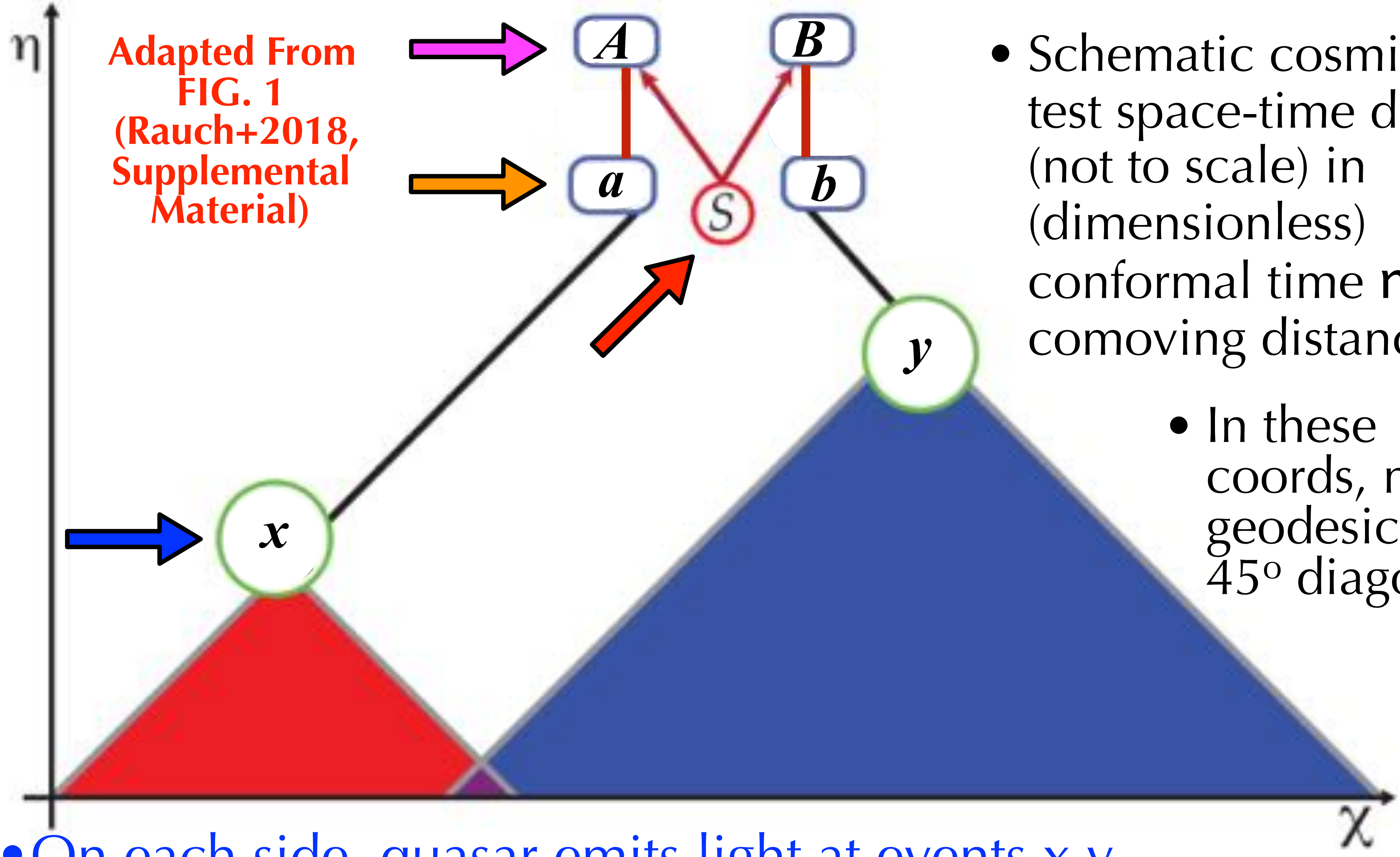
Gallicchio, Friedman, & Kaiser 2014, *Phys. Rev. Lett., Vol. 112, Issue 11, id. 110405,* (arXiv:1310.3288)

Experiment feasible with existing technology!

$z > 3.65$ quasars bright enough

CMB an intriguing possibility

1+1D SPACETIME DIAGRAM

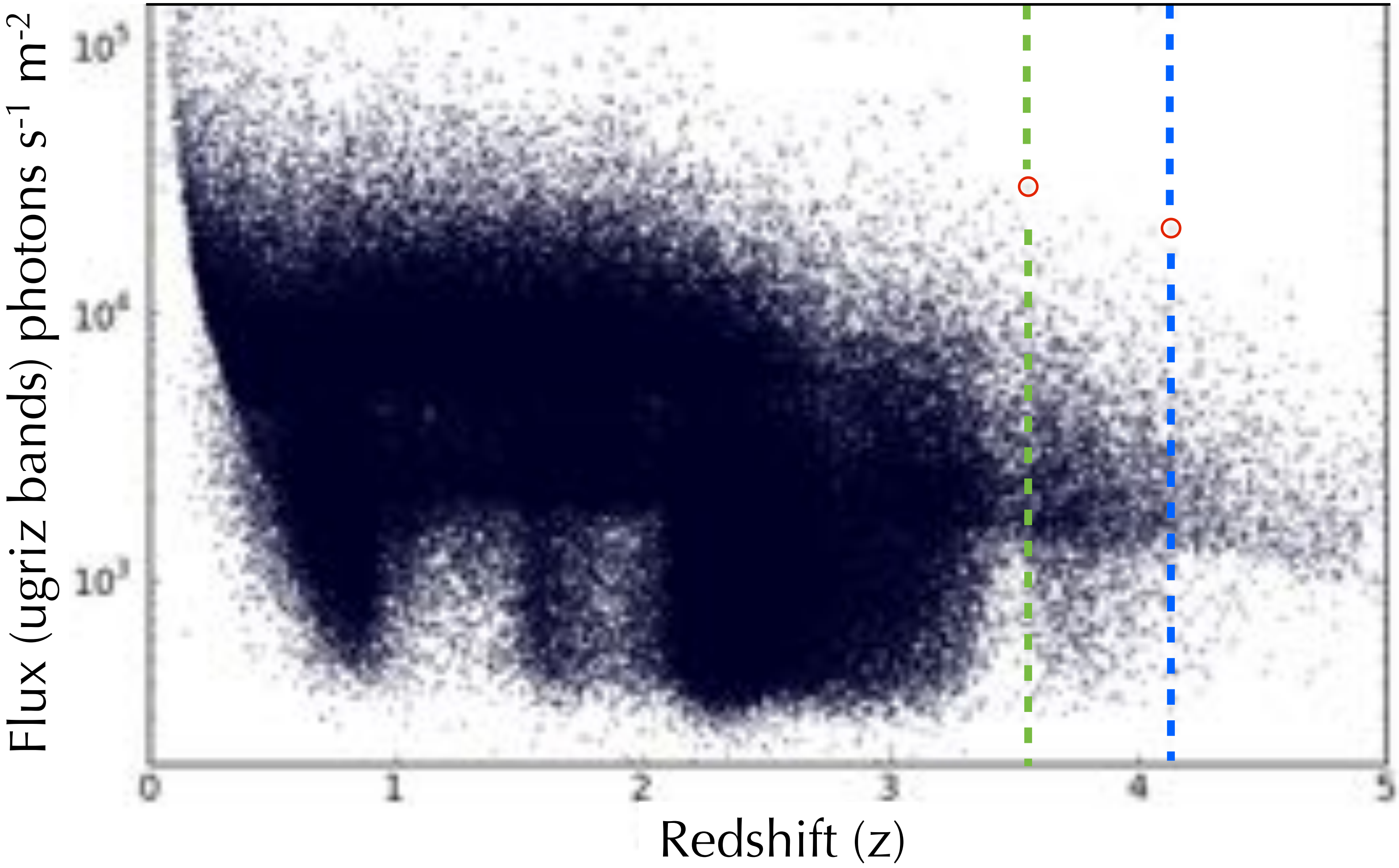


Adapted From FIG. 1 (Rauch+2018, Supplemental Material)

- Schematic cosmic Bell test space-time diagram (not to scale) in (dimensionless) conformal time η vs. comoving distance χ.
  - 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

QUASAR FLUX VS. REDSHIFT



Ground based optical flux.

IR only usable from space

Local Sky noise!

Adapted from Fig. 3 (GFK14)

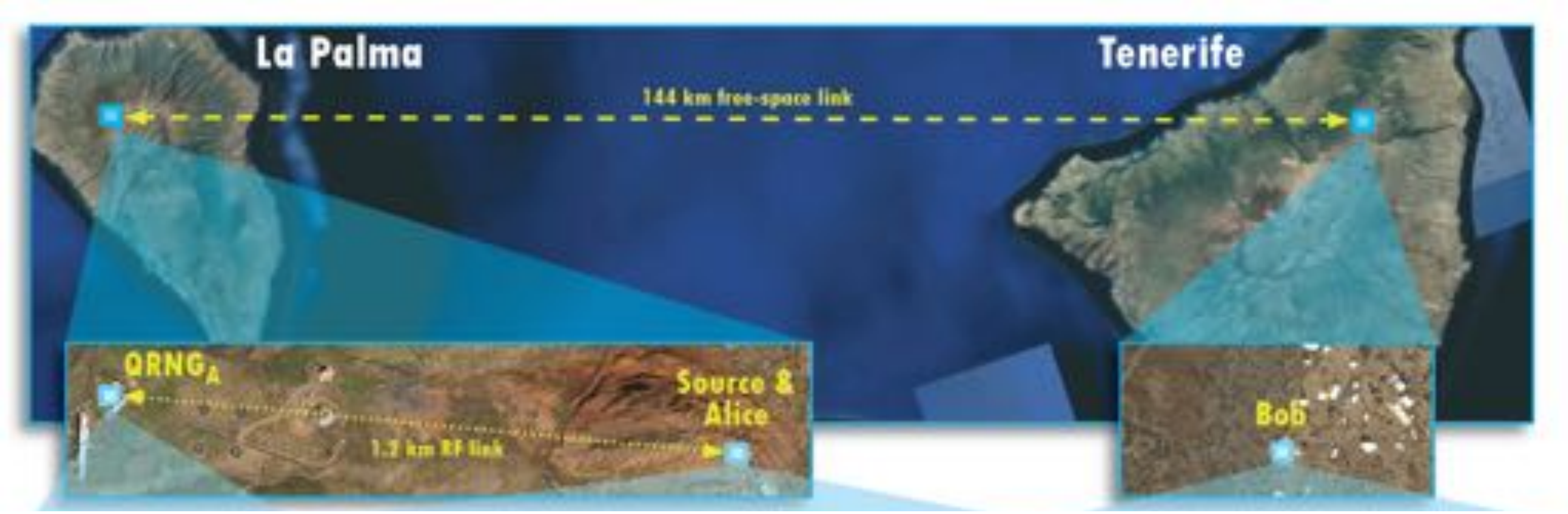
z~3.65 : $F_{Opt} \sim 3 \times 10^4$ photons s^{-1} m^{-2} 180 degrees

z~4.13 : $F_{Opt} \sim 2 \times 10^4$ photons s^{-1} m^{-2} 130 degrees

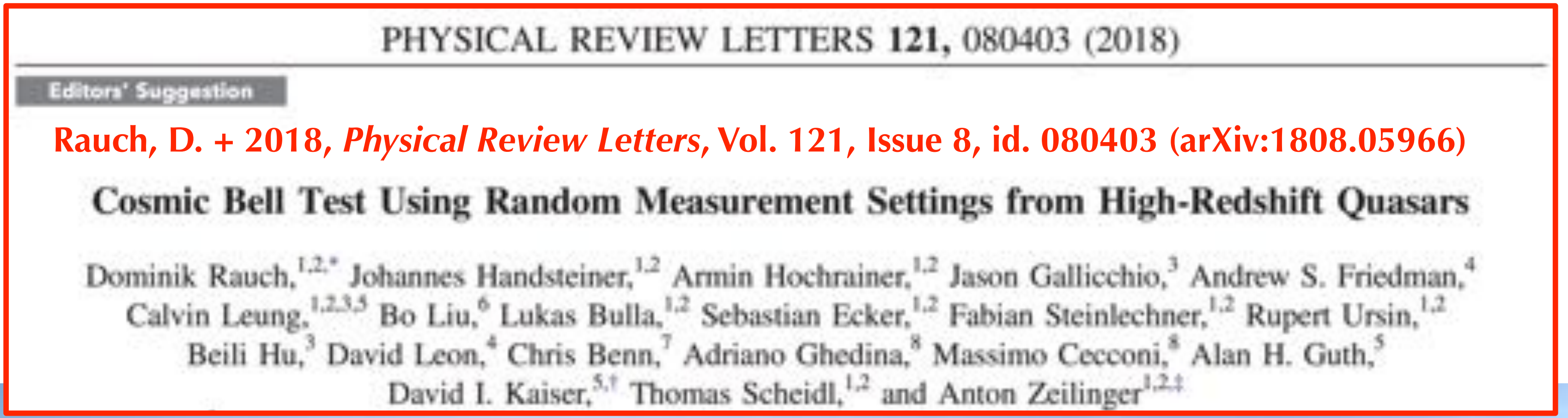
SDSS quasars - photometric and spectroscopic redshifts

ZEILINGER GROUP EXPERIMENTS

Prof. Anton Zeilinger



COSMIC BELL TEST WITH QUASARS



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

Editors' Suggestion

Rauch, D. + 2018, *Physical Review Letters*, Vol. 121, Issue 8, id. 080403 (arXiv:1808.05966)

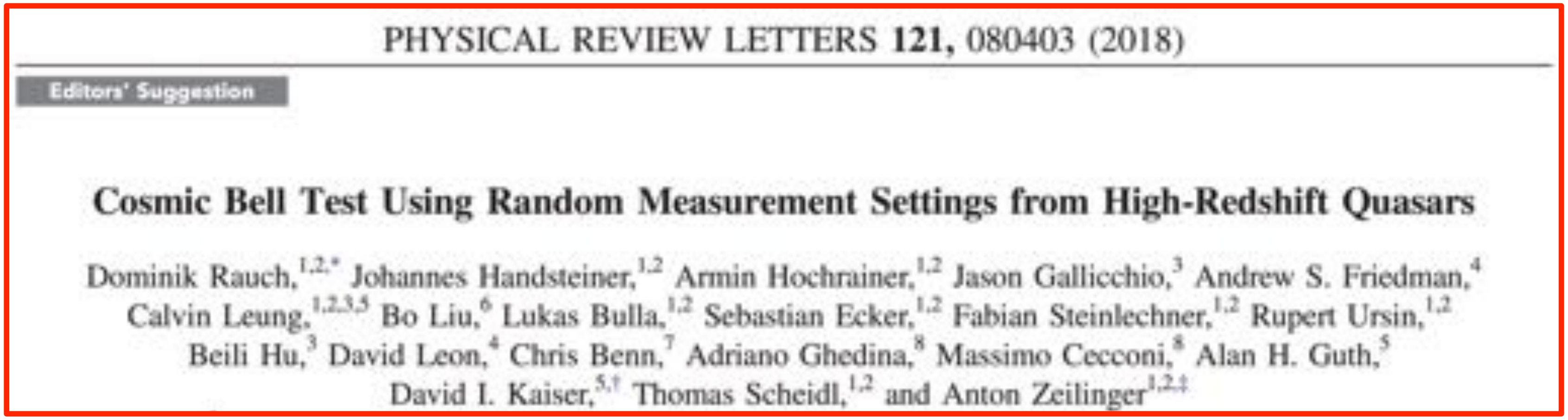
Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars

Dominik Rauch,[1,2,*] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Jason Gallicchio,[3] Andrew S. Friedman,[4]
Calvin Leung,[1,2,3,5] Bo Liu,[6] Lukas Bulla,[1,2] Sebastian Ecker,[1,2] Fabian Steinlechner,[1,2] Rupert Ursin,[1,2]
Beili Hu,[3] David Leon,[4] Chris Benn,[7] Adriano Ghedina,[8] Massimo Cecconi,[8] Alan H. Guth,[5]
David I. Kaiser,[5,†] Thomas Scheidl,[1,2] and Anton Zeilinger[1,2,‡]

Roque de los Muchachos Observatory on Canary Island of La Palma

Image Credit: Jason Gallicchio (Harvey Mudd)

COSMIC BELL TEST WITH QUASARS



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

Editors' Suggestion

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

Dominik Rauch,[1,2,*] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Jason Gallicchio,[3] Andrew S. Friedman,[4]
Calvin Leung,[1,2,3,5] Bo Liu,[6] Lukas Bulla,[1,2] Sebastian Ecker,[1,2] Fabian Steinlechner,[1,2] Rupert Ursin,[1,2]
Beili Hu,[3] David Leon,[4] Chris Benn,[7] Adriano Ghedina,[8] Massimo Cecconi,[8] Alan H. Guth,[5]
David I. Kaiser,[5,†] Thomas Scheidl,[1,2] and Anton Zeilinger[1,2,‡]

Rauch, D. + 2018, *Physical Review Letters*, Vol. 121, Issue 8, id. 080403 (arXiv:1808.05966)

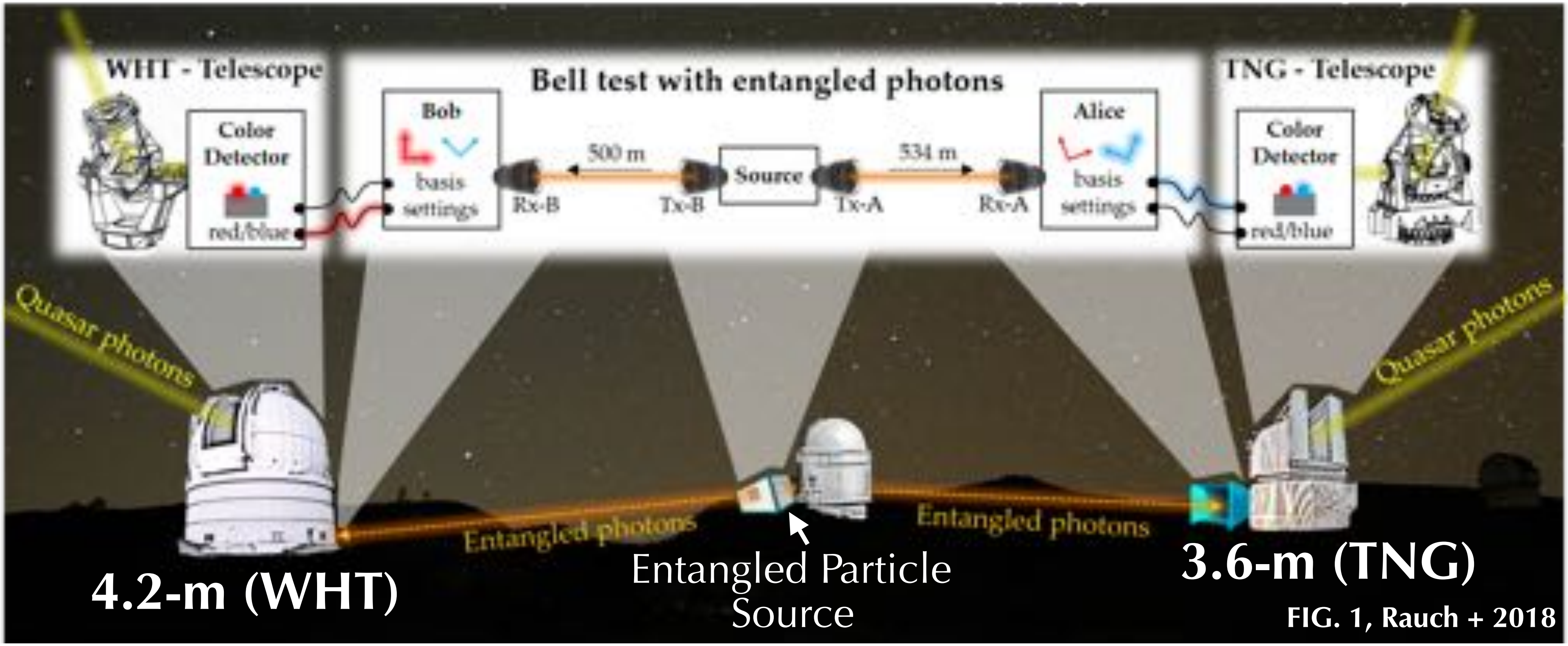
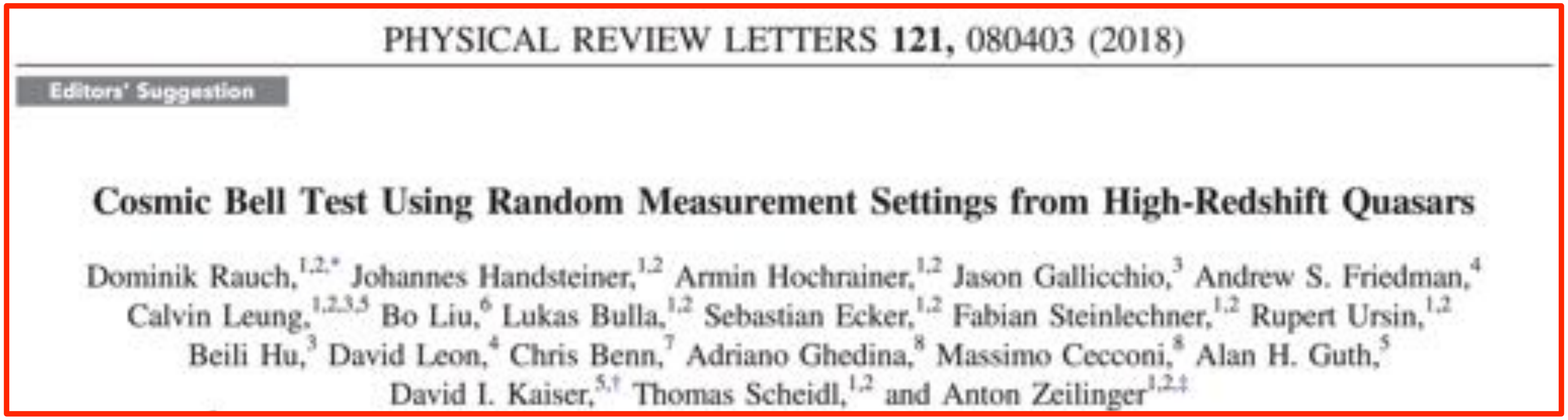


FIG. 1, Rauch + 2018

COSMIC BELL TEST WITH QUASARS



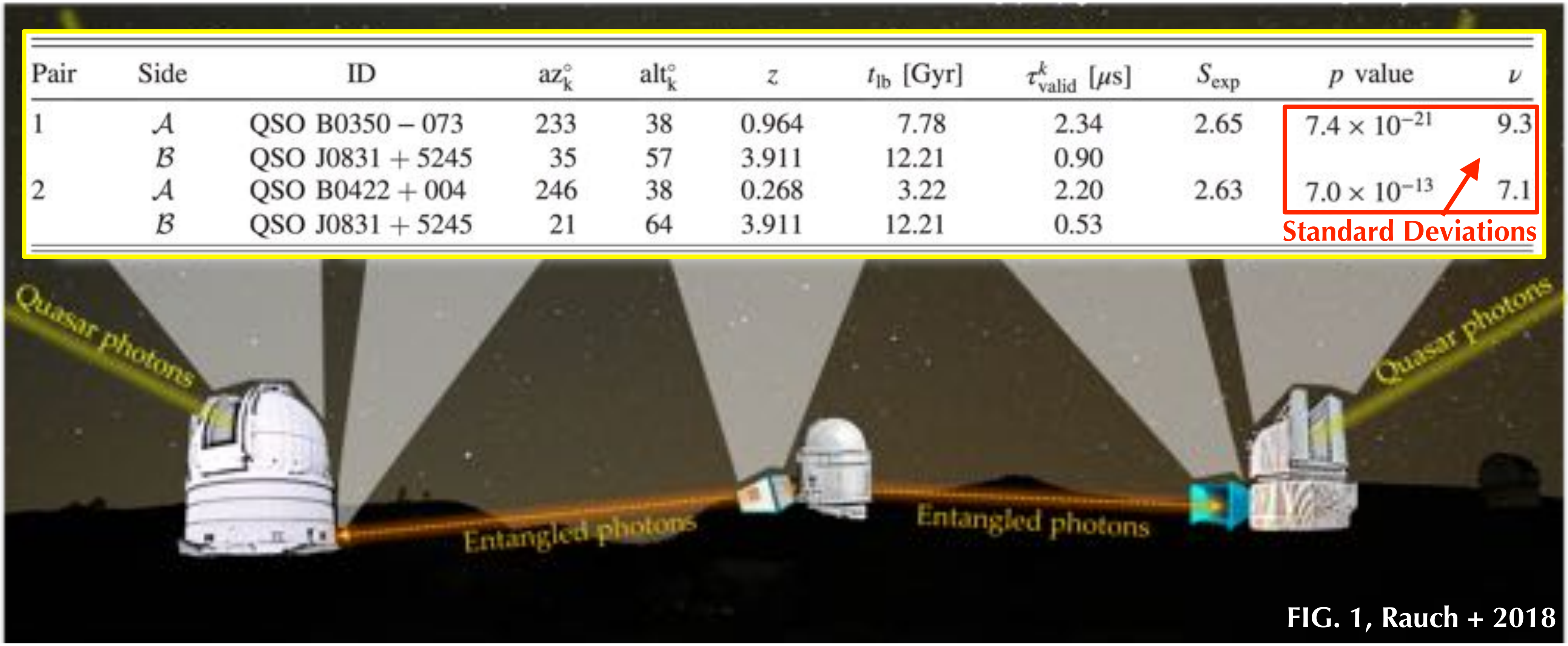
PHYSICAL REVIEW LETTERS **121**, 080403 (2018)

Editors' Suggestion

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

Dominik Rauch,[1,2,*] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Jason Gallicchio,[3] Andrew S. Friedman,[4]
Calvin Leung,[1,2,3,5] Bo Liu,[6] Lukas Bulla,[1,2] Sebastian Ecker,[1,2] Fabian Steinlechner,[1,2] Rupert Ursin,[1,2]
Beili Hu,[3] David Leon,[4] Chris Benn,[7] Adriano Ghedina,[8] Massimo Cecconi,[8] Alan H. Guth,[5]
David I. Kaiser,[5,†] Thomas Scheidl,[1,2] and Anton Zeilinger[1,2,‡]

Rauch, D. + 2018, *Physical Review Letters*, Vol. 121, Issue 8, id. 080403 (arXiv:1808.05966)



Pair	Side	ID	az_k°	alt_k°	z	t_{lb} [Gyr]	τ_{valid}^k [μs]	S_{exp}	p value	ν
1	$\mathcal{A}$	QSO B0350 − 073	233	38	0.964	7.78	2.34	2.65	7.4×10^{-21}	9.3
	$\mathcal{B}$	QSO J0831 + 5245	35	57	3.911	12.21	0.90			
2	$\mathcal{A}$	QSO B0422 + 004	246	38	0.268	3.22	2.20	2.63	7.0×10^{-13}	7.1
	$\mathcal{B}$	QSO J0831 + 5245	21	64	3.911	12.21	0.53			

Standard Deviations

FIG. 1, Rauch + 2018

2+1D SPACETIME DIAGRAM

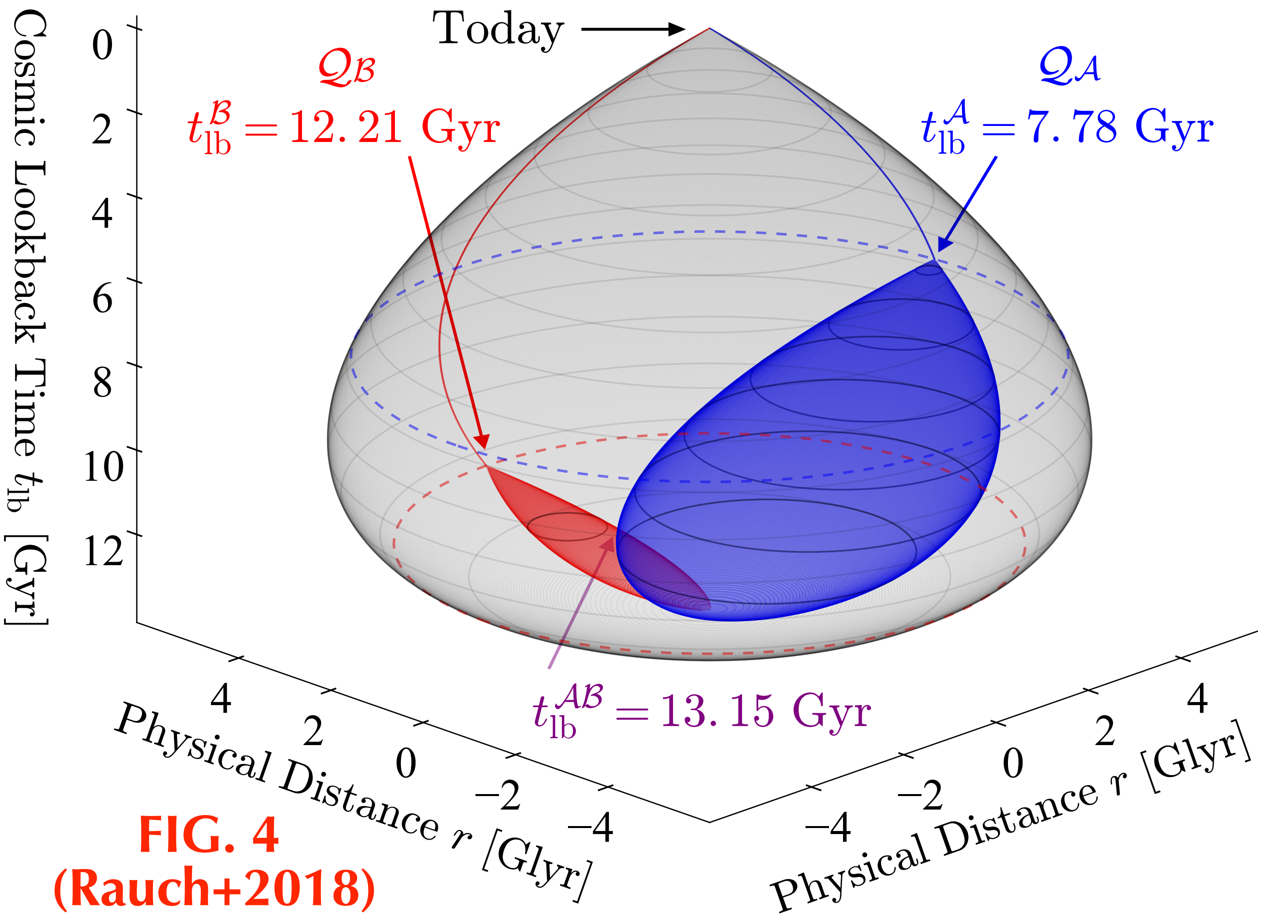


FIG. 4
(Rauch+2018)

- 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.

- 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.

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

$$F_{\rm excl} = 1 - \left(\frac{V_Q^{(4)}(\tau_A, \tau_B, \alpha)}{V_{\rm exp}^{(4)}(\tau_0)} \right) = 0.960$$

COSMIC BELL TEST WITH QUASARS

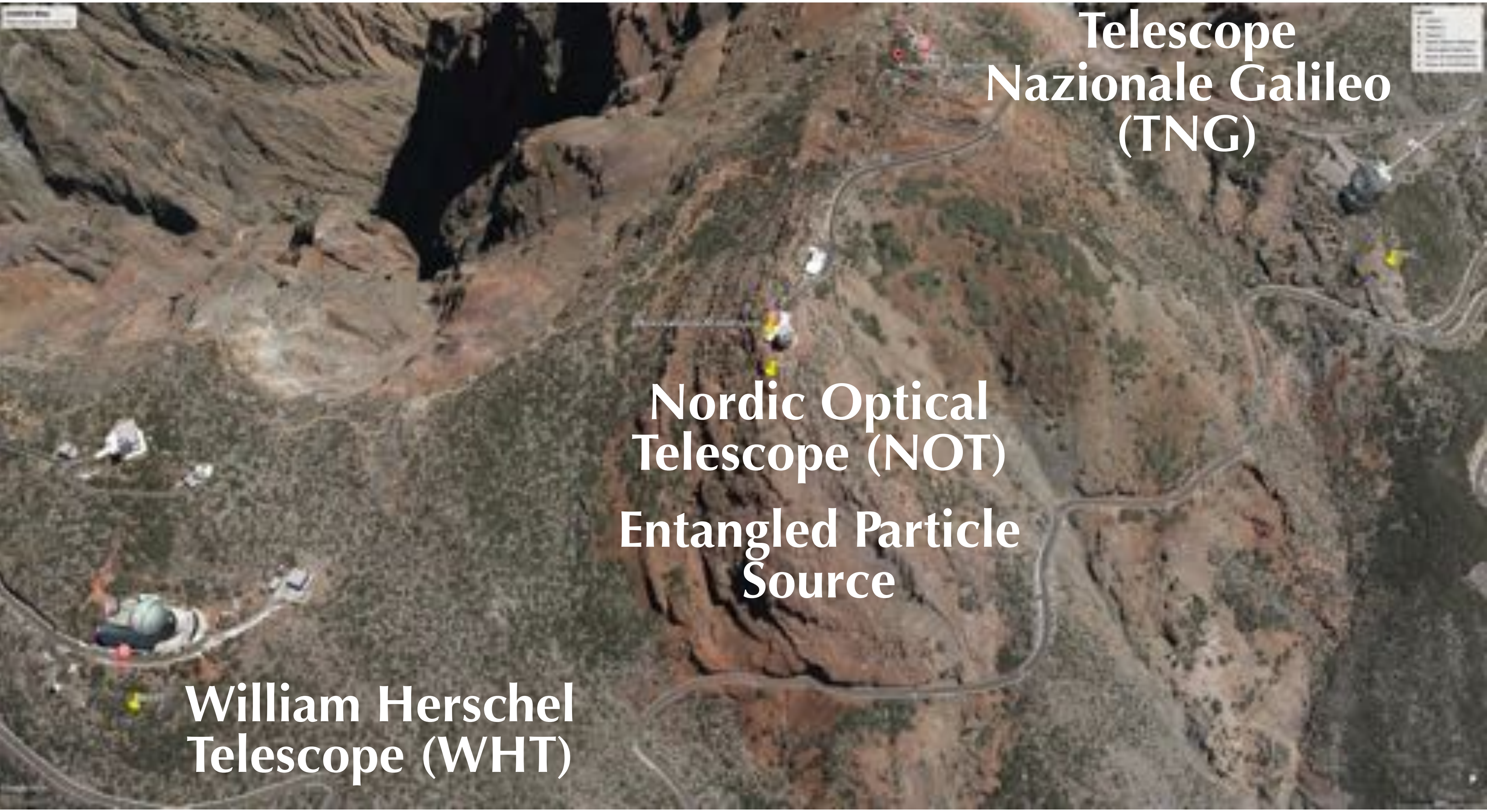


Image ©2018 DigitalGlobe (Google Earth)

LA PALMA COSMIC BELL TEST

Nordic Optical Telescope (NOT)

Cosmic Bell Test Entangled Particle Source (Shipping Container)

Image Credit: Dominik Rauch (Vienna)

NEAR DISASTER!

Nordic Optical Telescope (NOT)

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)

DISASTER AVERTED

Cosmic Bell Test Shipping Container

DISASTER AVERTED

Cosmic Bell Test Shipping Container

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

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 ≳7.8Gyr ago most recent time when any local-realist influences could have exploited "freedom-of-choice" loophole to engineer observed Bell violation. *(Previous tests ~600yr 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


New Scientist

BEYOND FAST AND SLOW The truth about how we think

NASAL DEFENCE The secret weapon in your nose

PRINT ME A HEART Living human organs from a 3D printer

WEEKLY 17 November 2018

THE QUANTUM COSMOS

We've looked at the whole universe. And it's all weird

SMART BABIES IVF screening for intelligence is here

PLUS PICTISH WRITING / PRIVATE MISSION TO ENCELADUS


SCIENTIFIC AMERICAN

Observations

Photons, Quasars and the Possibility of Free Will

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

By Brian Koberlein on November 21, 2018


Discover SCIENCE FOR THE CURIOUS

MAGAZINE | BLOGS | TOPICS | PHOTOS | PODCASTS | SEARCH

D-brief

Black Holes Bolster Case For Quantum Physics' Spooky Action

By Jake Parks | August 23, 2018 1:28 pm

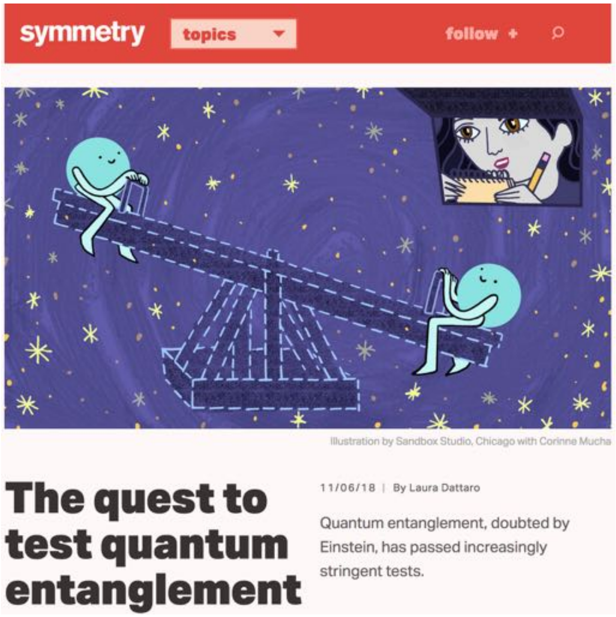

symmetry

Illustration by Sandbox Studio, Chicago with Corinne Mucha

The quest to test quantum entanglement

11/06/18 | By Laura Dattaro

Quantum entanglement, doubted by Einstein, has passed increasingly stringent tests.

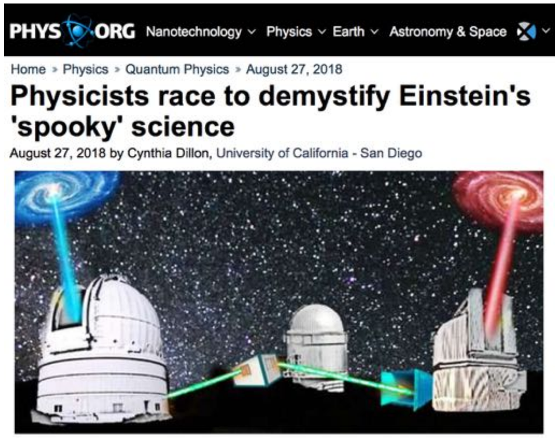

Home | Features | Physics

NewScientist

FEATURE 14 November 2018

Einstein was wrong: Why 'normal' physics can't explain reality

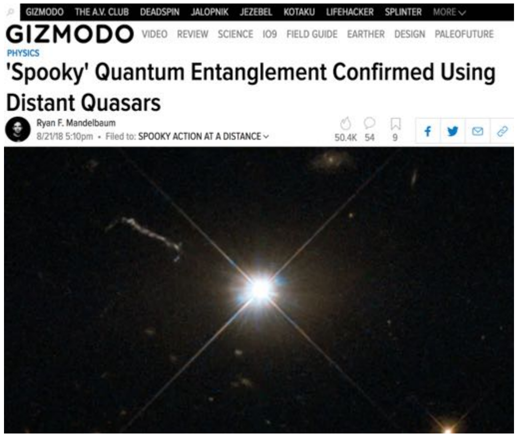
The most ambitious experiments yet show that the quantum weirdness Einstein famously hated rules the roost – not just here, but across the entire universe


PHYS.ORG

Home » Physics » Quantum Physics » August 27, 2018

Physicists race to demystify Einstein's 'spooky' science

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

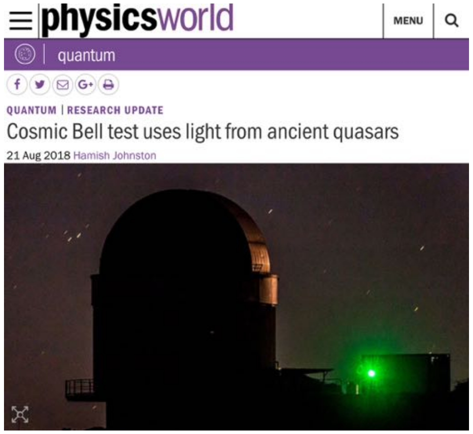

GIZMODO

PHYSICS

'Spooky' Quantum Entanglement Confirmed Using Distant Quasars

Ryan F. Mandelbaum

8/21/18 5:10pm • Filed to: SPOOKY ACTION AT A DISTANCE


physicsworld

quantum

QUANTUM | RESEARCH UPDATE

Cosmic Bell test uses light from ancient quasars

21 Aug 2018 Hamish Johnston


MOTHERBOARD VICE

ENTANGLEMENT | By Daniel Oberhaus | Aug 21 2018, 7:38am

Ancient Starlight Just Helped Confirm the Reality of Quantum Entanglement

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


SPACE.com

Space.com > Science & Astronomy

Ancient Quasars Provide Incredible Evidence for Quantum Entanglement

By Chelsea Gohd, Space.com Staff Writer | August 21, 2018 04:58pm ET


Astronomy

Quantum entanglement loophole quashed by quasar light

That's what happens when you let quasars decide what to measure.

By Jake Parks | Published: Thursday, August 23, 2018


Astronomy Now The UK's best astronomy magazine

Closing a loophole in Bell's theorem with light from ancient quasars

21 August 2018 Astronomy Now


MIT News ON CAMPUS AND AROUND THE WORLD

The quasar dates back to less than one billion years after the big bang.

Image: NASA/ESA/G.Bacon, STScI

Light from ancient quasars helps confirm quantum entanglement

Results are among the strongest evidence yet for "spooky action at a distance."

Jennifer Chu | MIT News Office

August 19, 2018

COSMIC BELL IN THE NEWS


SECTIONS THE NEW YORKER

ELEMENTS

QUANTUM THEORY BY STARLIGHT

By David Kaiser February 7, 2017


New Scientist

HOME NEWS TECHNOLOGY SPACE PHYSICS HEALTH EARTH HUMANS LIFE TOPICS EVENTS JOBS

104

NEWS & TECHNOLOGY 7 February 2017

Starlight test shows quantum world has been weird for 600 years


SCIENTIFIC AMERICAN

Subscribe SHARE LATEST

PHYSICS

Cosmic Test Bolsters Einstein's "Spooky Action at a Distance"

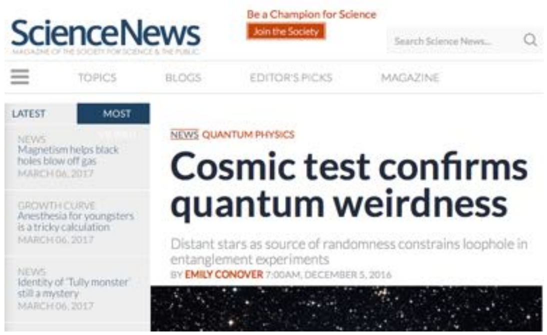
Physicists harness starlight to support the case for entanglement.

By Elizabeth Gibney, Nature magazine on February 3, 2017


CBS NEWS NEWS SHOWS VIDEO

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

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


ScienceNews MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

Be a Champion for Science

Join the Society

Search Science News...

TOPICS BLOGS EDITOR'S PICKS MAGAZINE

LATEST MOST

NEWS
Magnetism helps black holes blow off gas
MARCH 06, 2017

GROWTH CURVE
Anesthesia for youngsters is a tricky calculation
MARCH 06, 2017

NEWS
Identity of 'Tully monster' still a mystery
MARCH 06, 2017

NEWS QUANTUM PHYSICS

Cosmic test confirms quantum weirdness

Distant stars as source of randomness constrains loophole in entanglement experiments

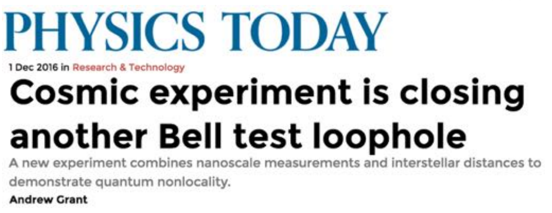
BY EMILY CONOVER 7:00AM, DECEMBER 5, 2016


SPACE.com

Space.com › Science & Astronomy

600-Year-Old Starlight Bolsters Einstein's 'Spooky Action at a Distance'

By Calla Cofield, Space.com Senior Writer | February 13, 2017 01:25am ET


PHYSICS TODAY

1 Dec 2016 in Research & Technology

Cosmic experiment is closing another Bell test loophole

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

Andrew Grant


WIRED SUBSCRIBE

ANIL ANANTHASWAMY SCIENCE 08.05.18 07:00 AM

LOOPHOLES AND THE 'ANTI-REALISM' OF THE QUANTUM WORLD


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audi

News & Comment › News › 2017 › March › Article

NATURE | NEWS

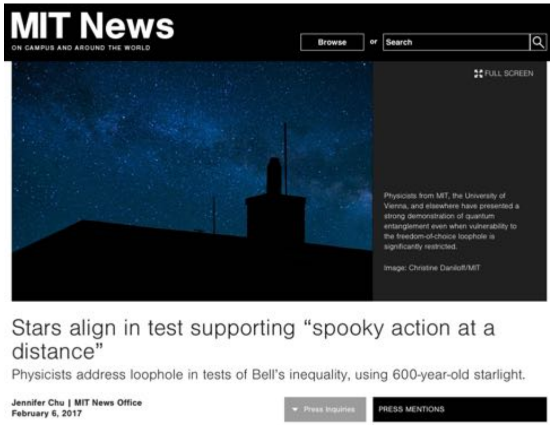
Cosmic test backs 'quantum spookiness'

Physicists harness starlight to support the case for entanglement.

Elizabeth Gibney

02 February 2017

Rights & Permissions


MIT News ON CAMPUS AND AROUND THE WORLD

Browse or Search

FULL SCREEN

Physicists from MIT, the University of Vienna, and elsewhere have presented a strong demonstration of quantum entanglement even when vulnerability to the freedom-of-choice loophole is significantly restricted.

Image: Christine Daniloff/MIT

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

Press Inquiries PRESS MENTIONS

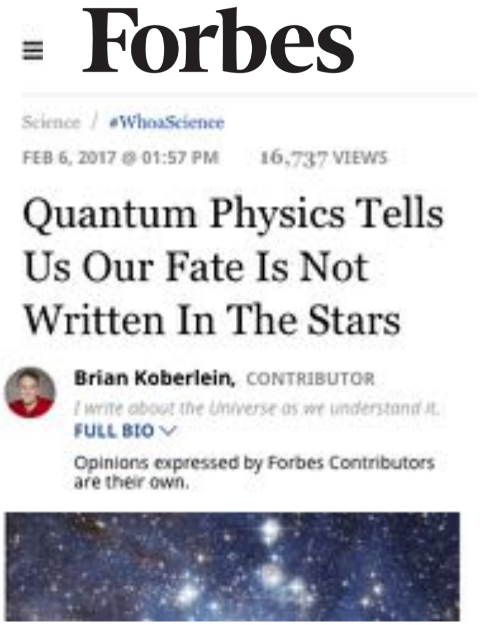

engadget

600-year-old starlight addressed a loophole in quantum theory

Physicists created a cosmic experiment to help prove quantum entanglement is real.

Andrew Dalton, @dolftown
02.08.17 in Space

13 Comments 1273 Shares


Forbes

Science / #WhoaScience

FEB 6, 2017 @ 01:57 PM 16,737 VIEWS

Quantum Physics Tells Us Our Fate Is Not Written In The Stars

Brian Koberlein, CONTRIBUTOR

I write about the Universe as we understand it.

FULL BIO

Opinions expressed by Forbes Contributors are their own.


QUANTA MAGAZINE illuminating science

PHYSICS MATHEMATICS BIOLOGY COMPUTER SCIENCE BLOG MORE ALL SUBSCRIBE

QUANTUM MECHANICS

Experiment Reaffirms Quantum Weirdness

Physicists are closing the door on an intriguing loophole around the quantum phenomenon Einstein called "spooky action at a distance."


the Atlantic

Olena Shmahalo / Quanta Magazine

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

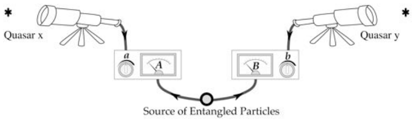
http://web.mit.edu/asf/www/media_coverage.shtml

COSMIC BELL IN THE NEWS


Cosmic conundrum

Can the cosmos test quantum entanglement?

Albert Einstein hated the idea he called "spooky actions at a distance," but astronomers now are hoping to illuminate some of these tricky quantum puzzles. by Andrew Friedman

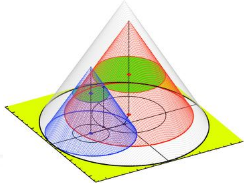


https://asfriedman.physics.ucsd.edu/media_coverage.shtml

Closing the 'free will' loophole

MIT researchers propose using distant quasars to test Bell's theorem.

Jennifer Chu, MIT News Office
February 20, 2014



Forbes / Tech

JUN 18, 2014 @ 07:00 AM 16,356 VIEWS

Cosmic Test For Quantum Physics' Last Major Loophole

Quasar Experiment May Shed Light on Quantum Physics and Free Will

BY CHARLES Q. CHOI, INSIDE SCIENCE

QUANTUM PHYSICS

19 MAR

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

By Andrew Friedman on Wed, 19 Mar 2014

M. KORNMESSER / ESO


SundayReview

The New York Times

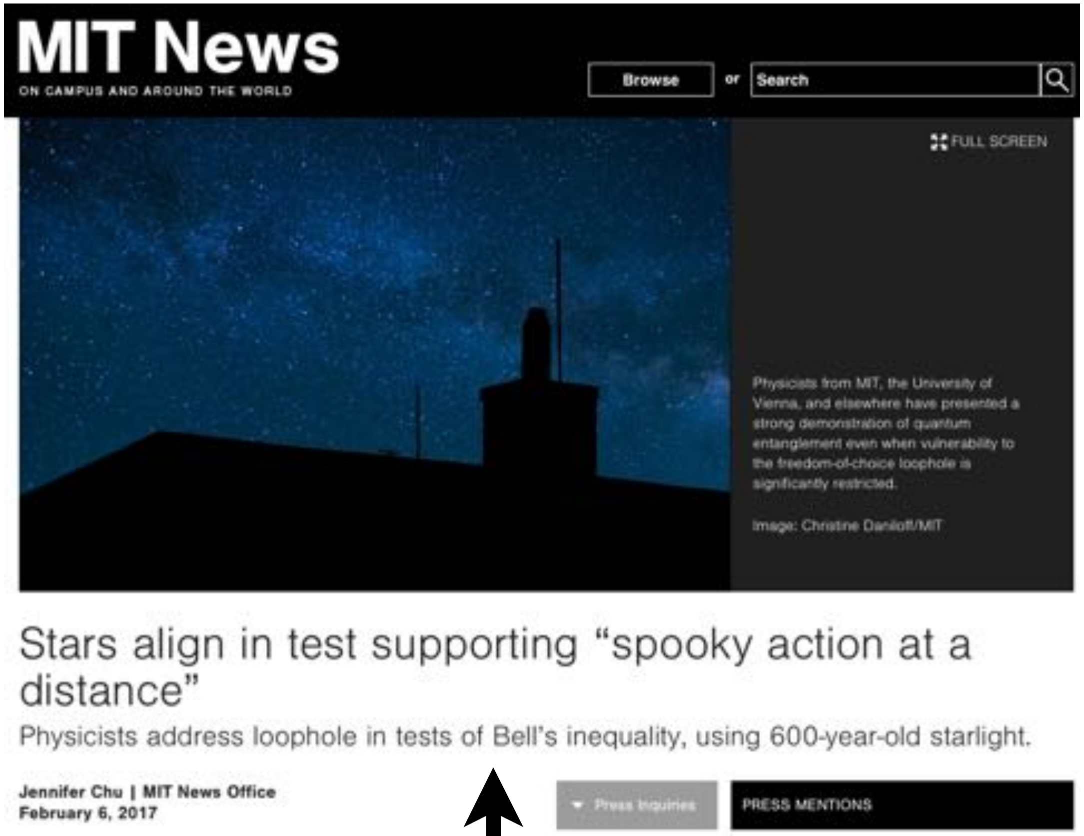
Is Quantum Entanglement Real?

Gray Matter

NOV. 14, 2014

By DAVID KAISER

GAME OF TELEPHONE



Physicists from MIT, the University of Vienna, and elsewhere have presented a strong demonstration of quantum entanglement even when vulnerability to the freedom-of-choice loophole is significantly restricted.

Image: Christine Daniloff/MIT

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

QUANTUM PHYSICS SHOCKER: Scientists discover we have LESS free will than we thought

BY using quantum physics, scientists have been able to determine that we do not have as much free will as we are led to believe, according to the laws of the universe.

By SEAN MARTIN

PUBLISHED: 14:30, Sat, Feb 11, 2017

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

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

BIG BELL TEST

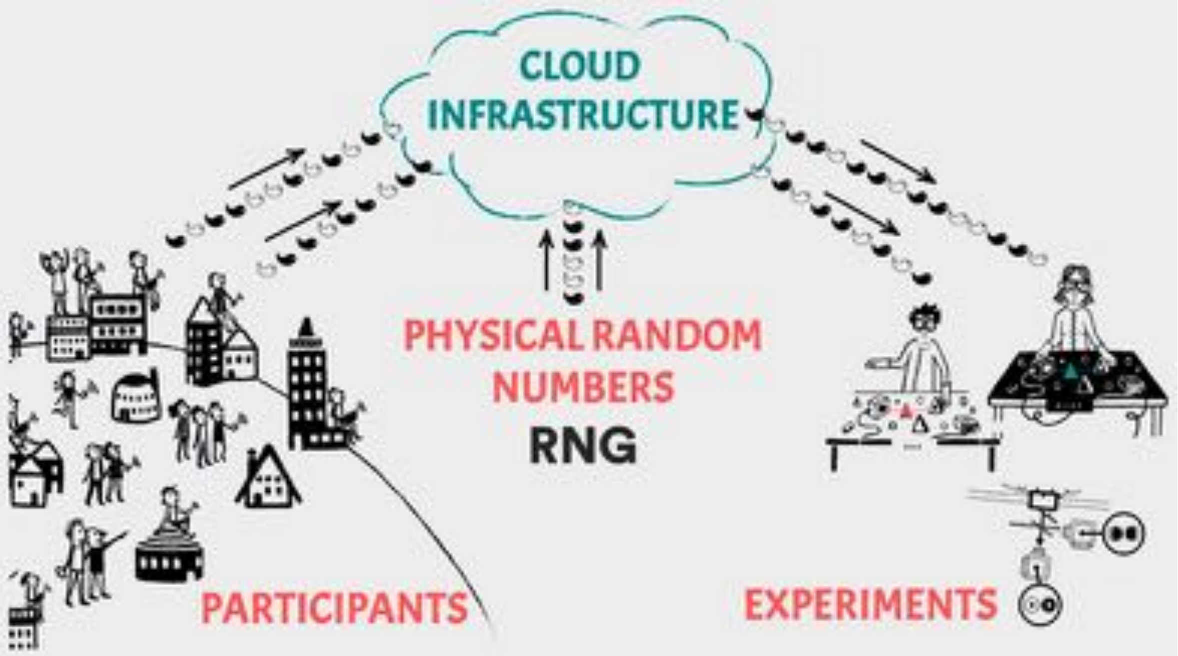
nature
International journal of science

Letter | Published: 09 May 2018

Challenging local realism with human choices

The BIG Bell Test Collaboration

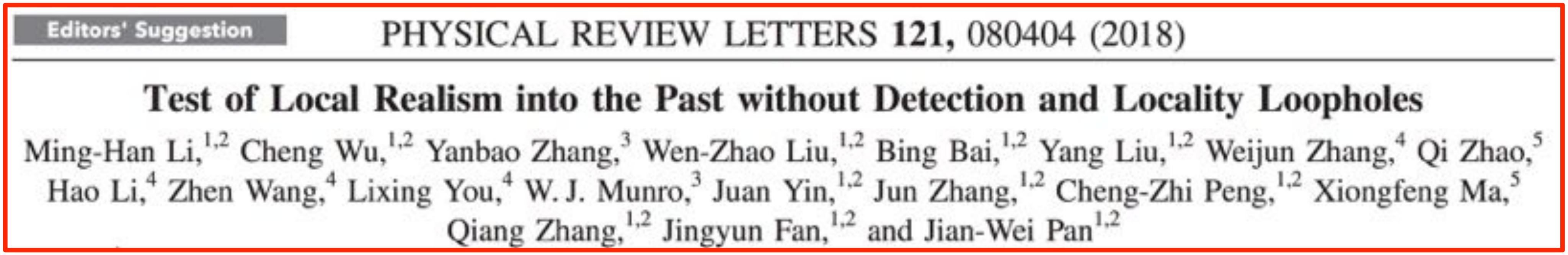
Nature **557**, 212–216 (2018)



THE BIG BELL TEST
Worldwide physics experiments powered by human randomness

12 labs in 11 countries on 5 continents, plus 10^5 "Bellster" volunteers who produced 10^8 (quasi) random 0's and 1's

DETECTION LOOPHOLE PROGRESS



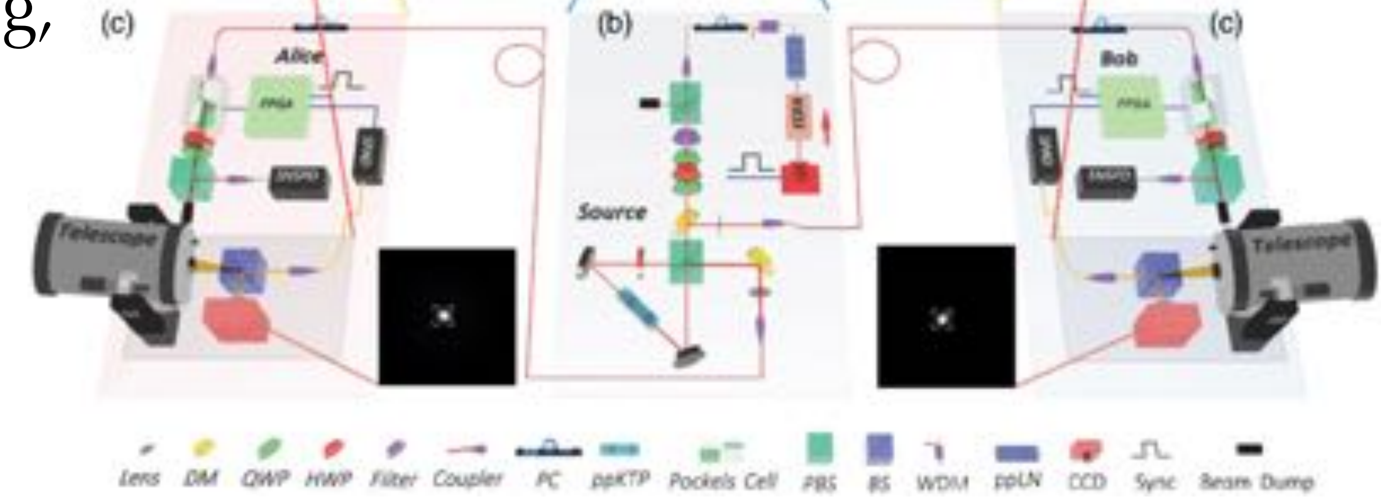
Editors' Suggestion

PHYSICAL REVIEW LETTERS **121,** 080404 (2018)

Test of Local Realism into the Past without Detection and Locality Loopholes

Ming-Han Li,[1,2] Cheng Wu,[1,2] Yanbao Zhang,[3] Wen-Zhao Liu,[1,2] Bing Bai,[1,2] Yang Liu,[1,2] Weijun Zhang,[4] Qi Zhao,[5] Hao Li,[4] Zhen Wang,[4] Lixing You,[4] W. J. Munro,[3] Juan Yin,[1,2] Jun Zhang,[1,2] Cheng-Zhi Peng,[1,2] Xiongfeng Ma,[5] Qiang Zhang,[1,2] Jingyun Fan,[1,2] and Jian-Wei Pan[1,2]

Progress in closing detection loophole in a cosmic Bell test



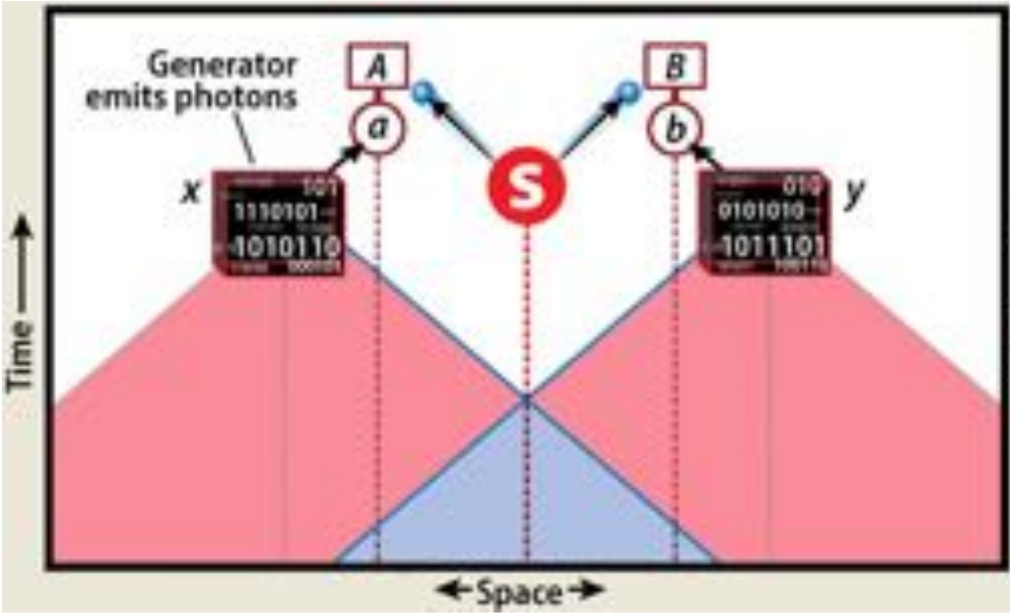
Jian-Wei Pan

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

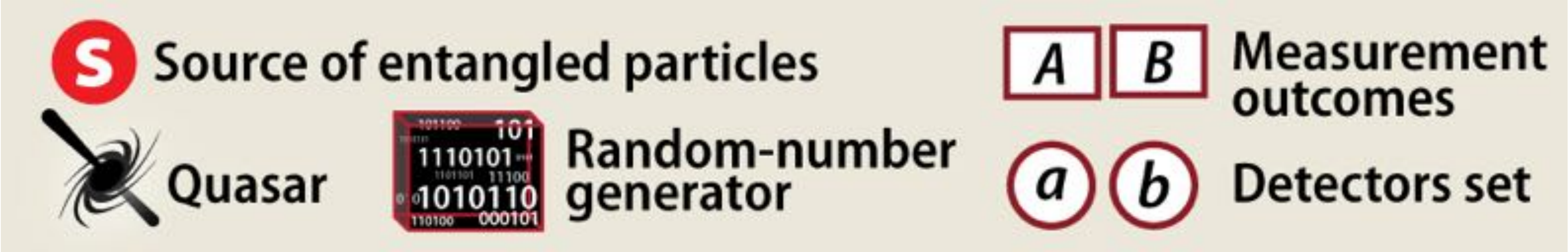
Li et al., 1808.07653

SPACE-TIME DIAGRAMS

Standard Bell Test



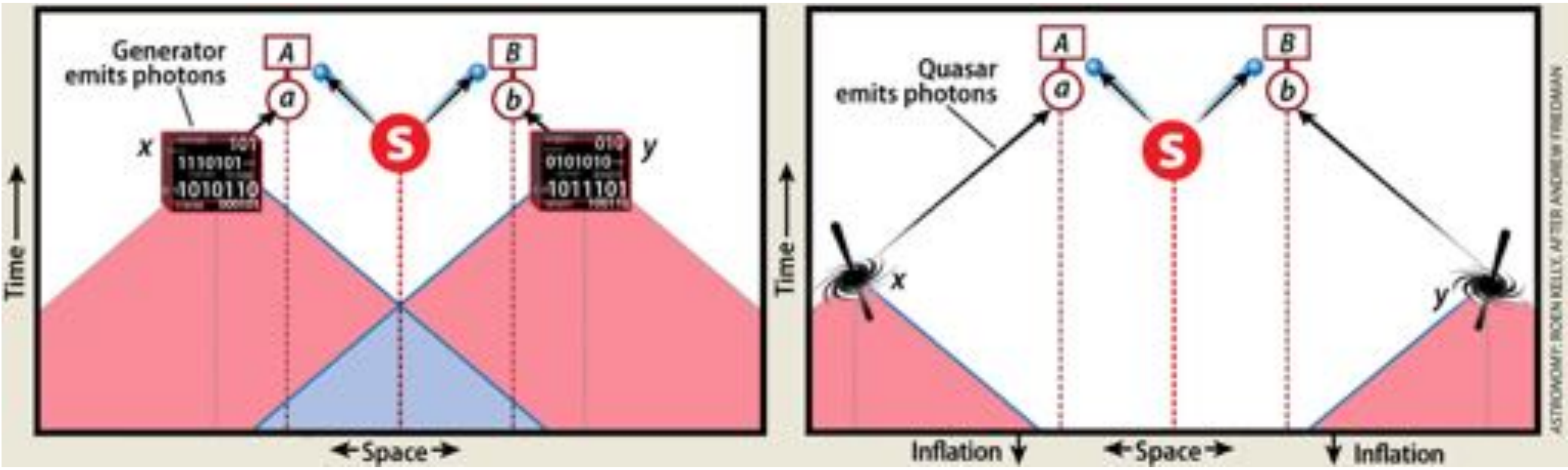
Past light cones from random number generators overlap milliseconds before test.



Adapted from: Friedman, Kaiser, & Gallicchio 2013a, *Phys. Rev. D,* Vol. 88, Iss. 4, id. 044038, 18 p. (arXiv:1305.3943)

SPACE-TIME DIAGRAMS

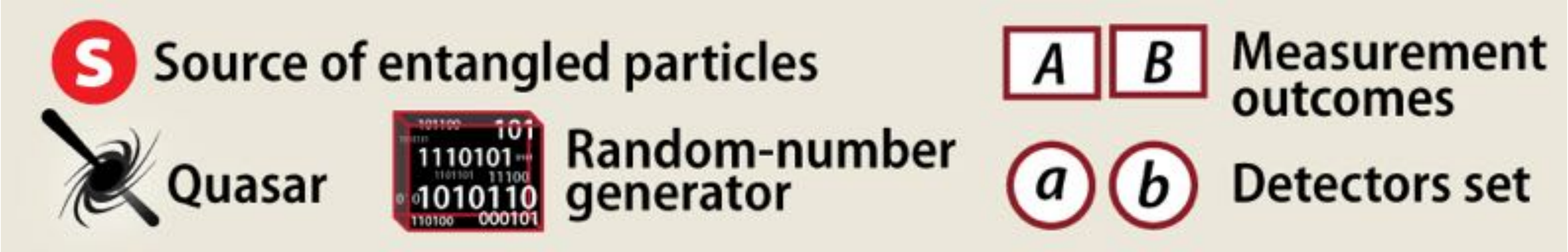
Standard Bell Test　　Cosmic Bell Test



ASTRONOMY: ROEN KELLY, AFTER ANDREW FRIEDMAN

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.



Adapted from: Friedman, Kaiser, & Gallicchio 2013a, *Phys. Rev. D,* Vol. 88, Iss. 4, id. 044038, 18 p. (arXiv:1305.3943)

2+1D CONFORMAL SPACETIME DIAGRAM

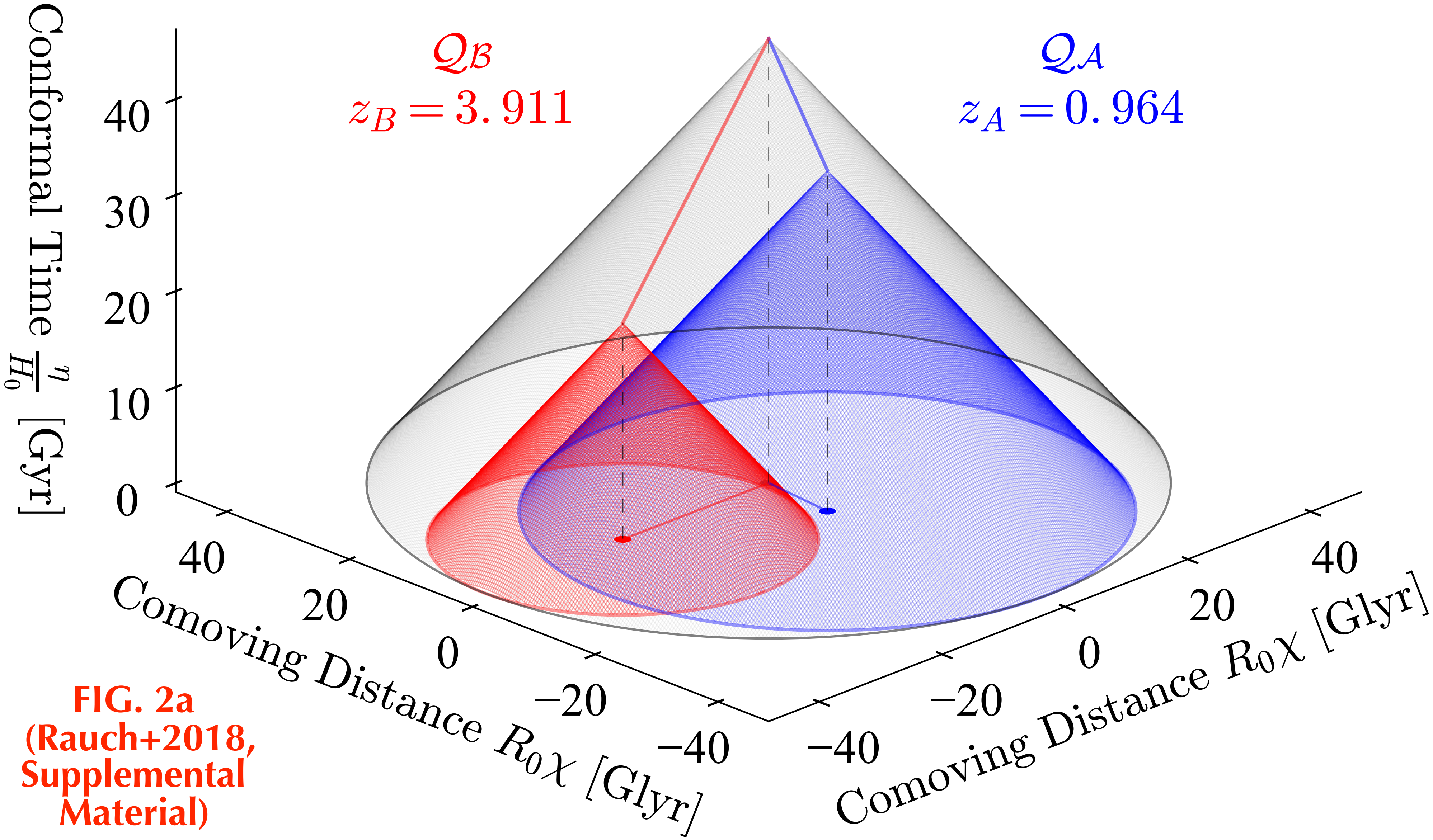
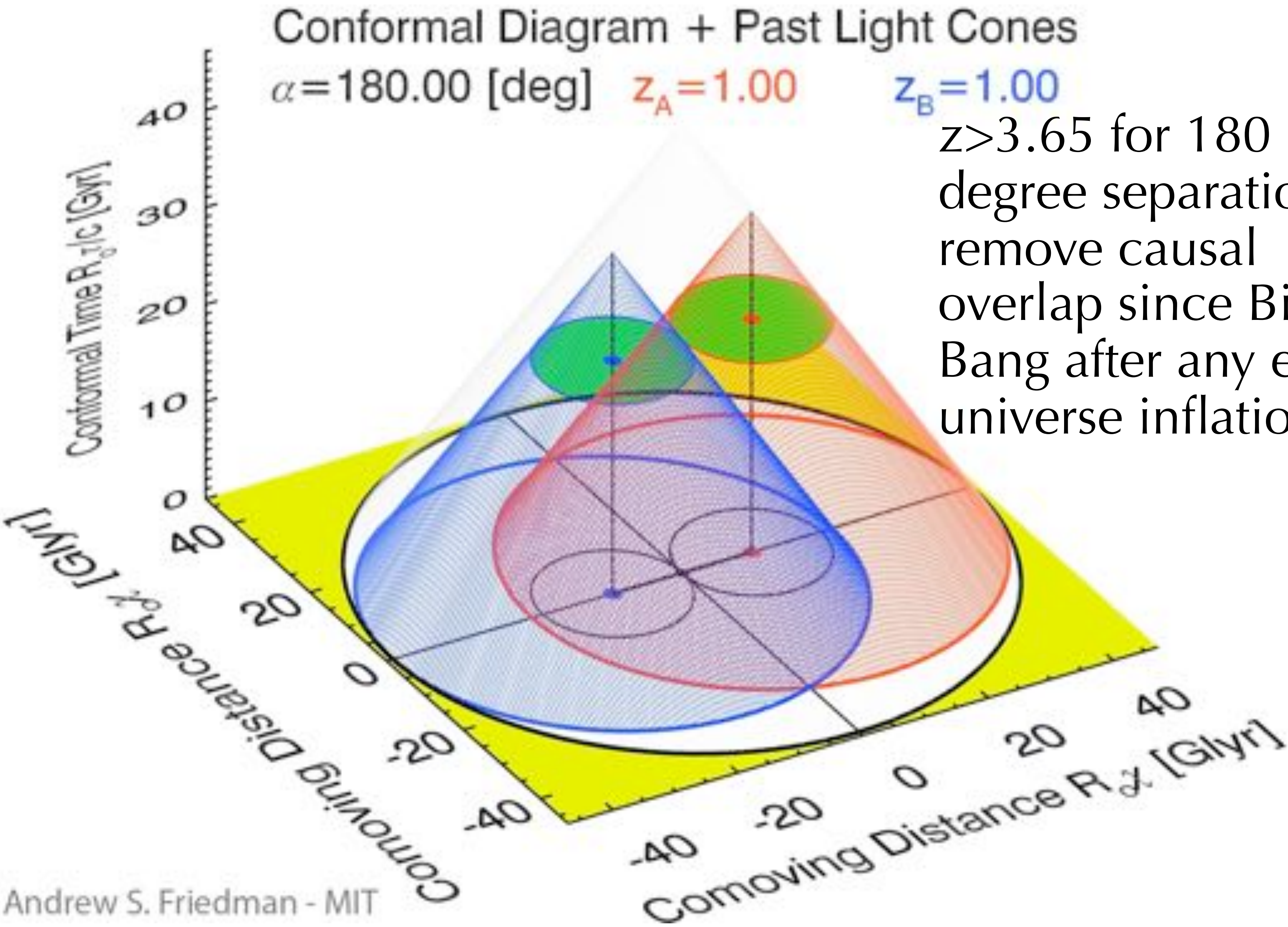


FIG. 2a (Rauch+2018, Supplemental Material)

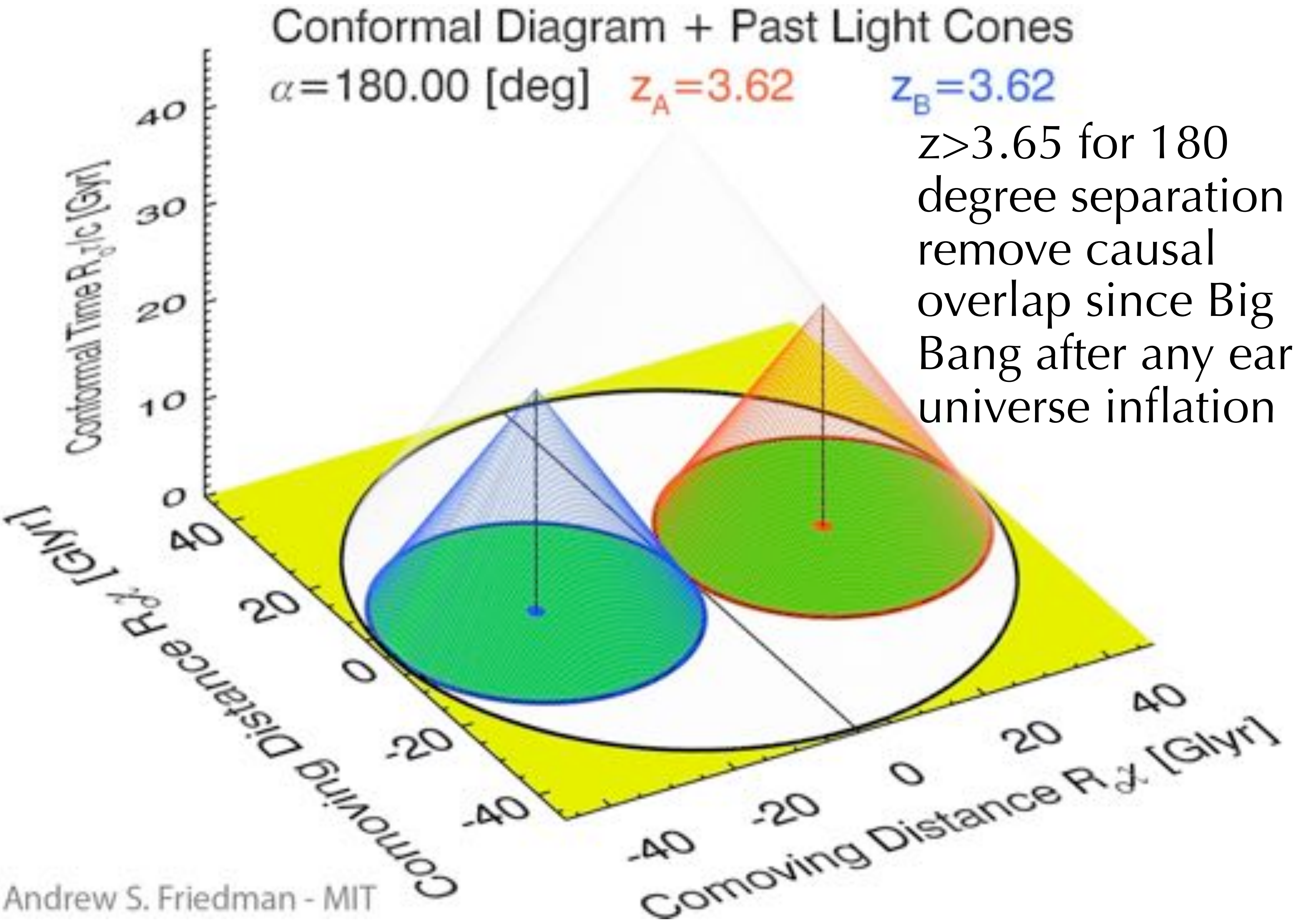
La Palma cosmic Bell test didn't completely remove causal overlap

FUTURE COSMIC BELL TESTS



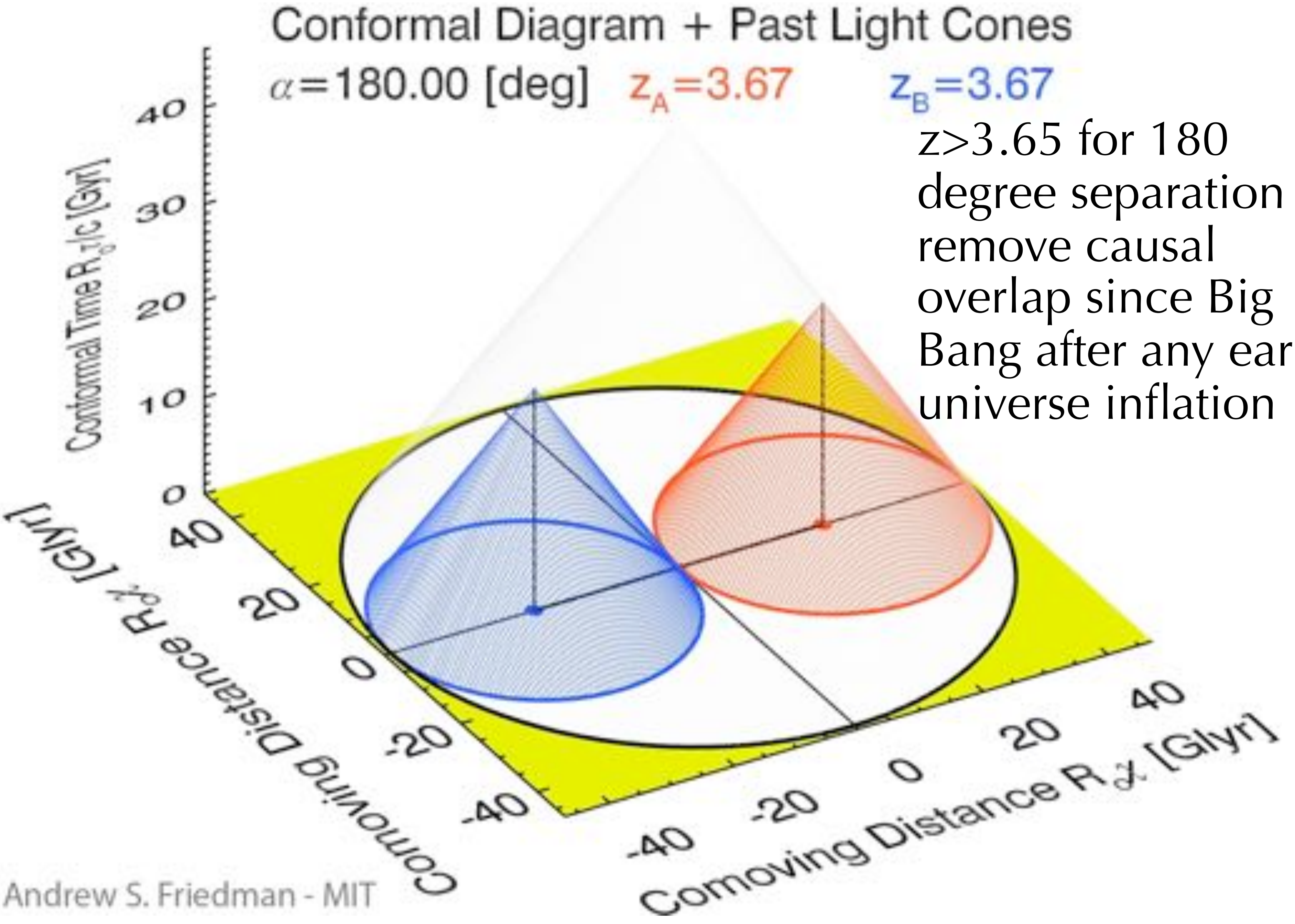
z>3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation

NO SHARED CAUSAL PAST



z>3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation

NO SHARED CAUSAL PAST



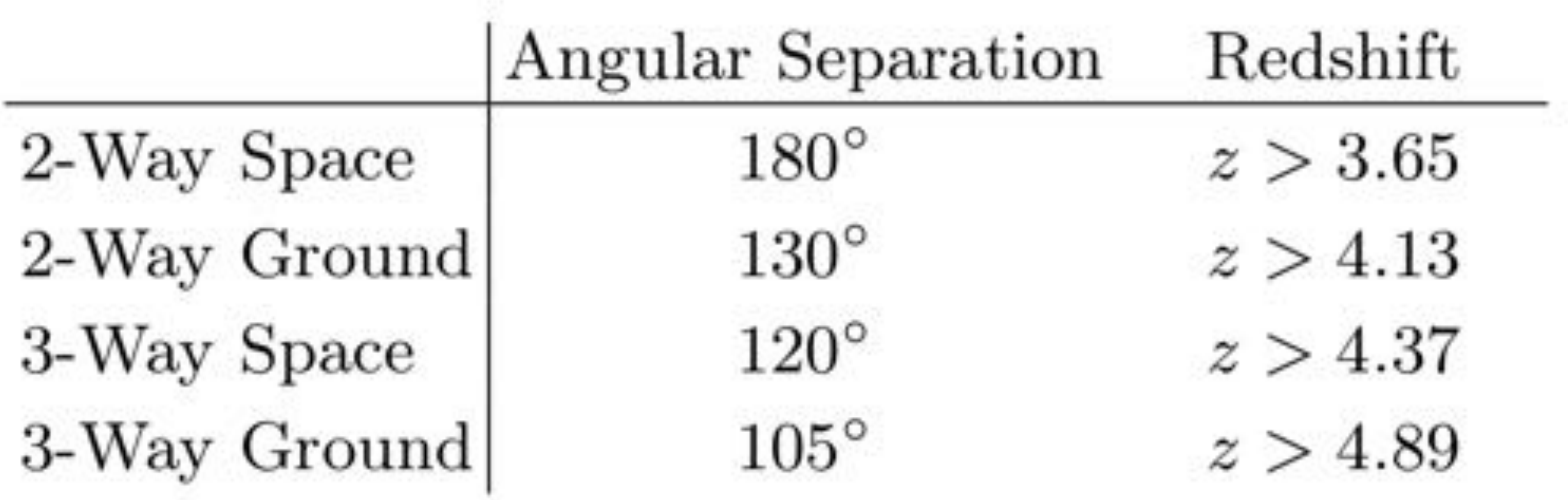
z>3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation

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



	Angular Separation	Redshift
2-Way Space	180°	$z > 3.65$
2-Way Ground	130°	$z > 4.13$
3-Way Space	120°	$z > 4.37$
3-Way Ground	105°	$z > 4.89$

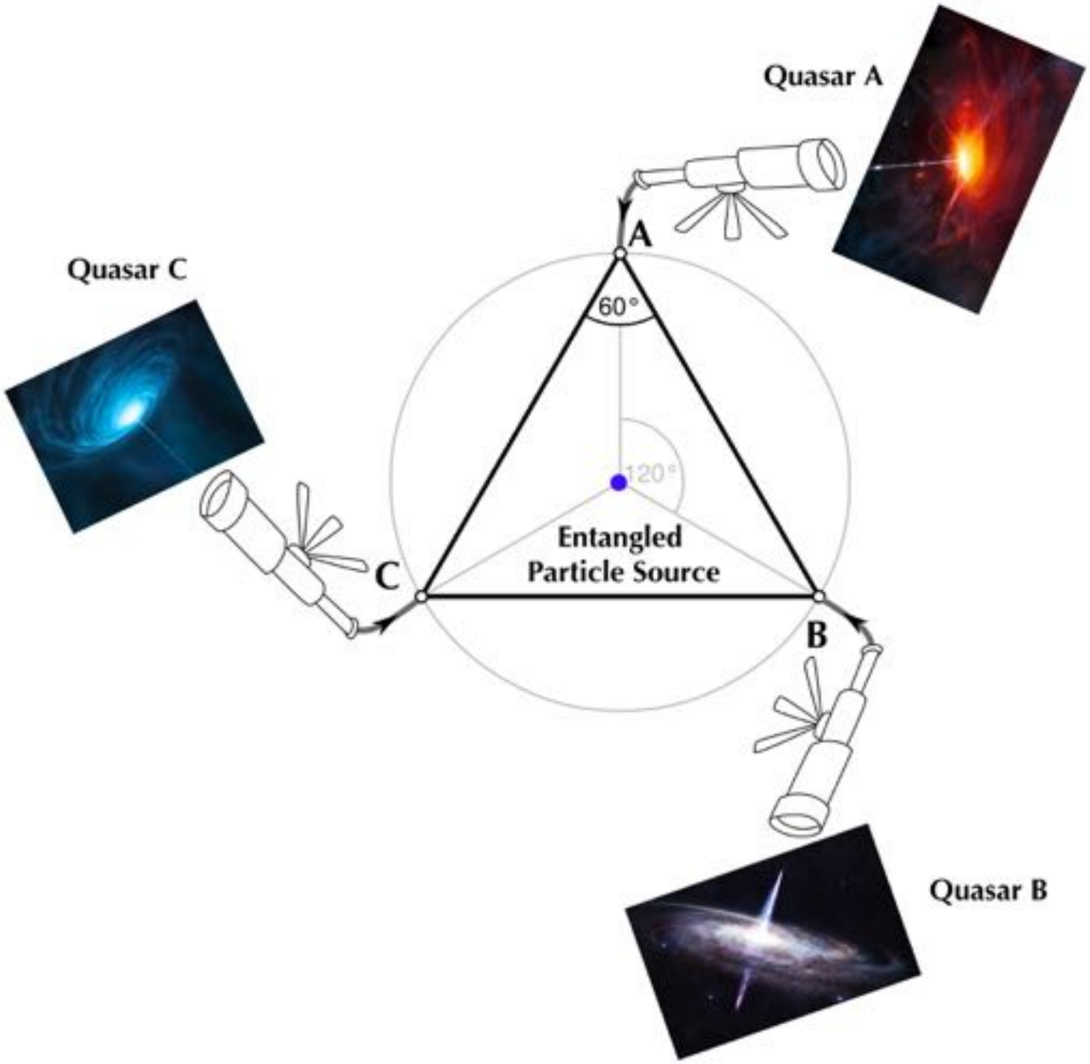
Gallicchio, Friedman, & Kaiser 2014; Friedman+2019 *in prep*.

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.

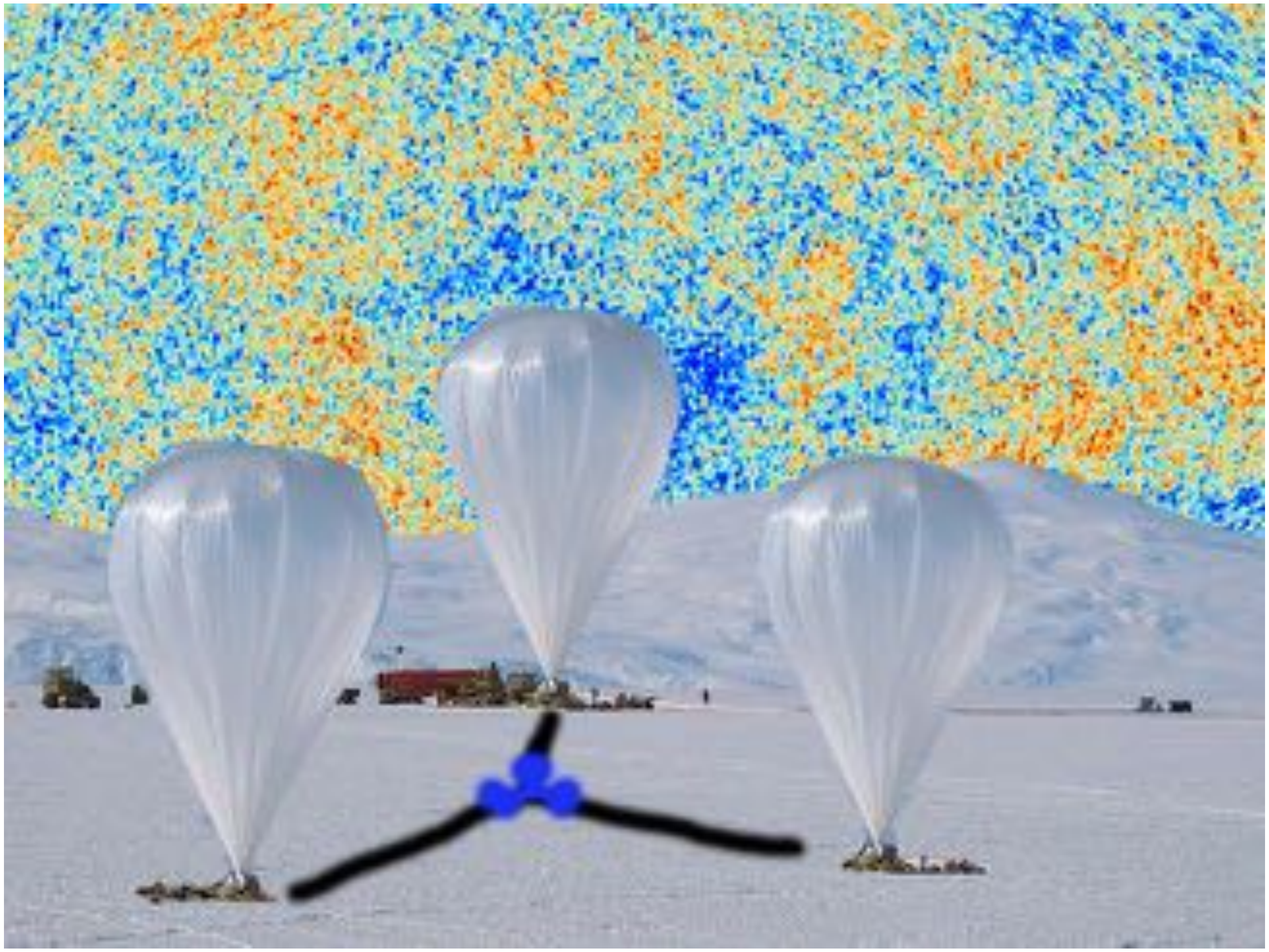
But GHZ pilot test with stars and with brighter, moderate redshift quasars is technologically possible

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



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**)

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 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!

COSMIC BELL PUBLICATIONS

Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars, **Rauch, D., Handsteiner, J., Hochrainer, A., Gallicchio, J., Friedman, A.S. + 2018, *Physical Review Letters*, Vol. 121, Issue 8, id. 080403 (arXiv:1808.05966 | PDF) (DOI) (Supplemental Material) [Editors' Suggestion]**

Astronomical Random Numbers for Quantum Foundations Experiments, **Leung, C., Brown, A., Nguyen, H., Friedman, A.S., Kaiser, D.I., and Gallicchio, J., 2018, *Physical Review A*, Vol. 97, Issue 4, id. 042120 (arXiv:1706.02276) (DOI) [Featured in Physics]**

Cosmic Bell Test: Measurement Settings from Milky Way Stars, **Handsteiner, J., Friedman, A.S. + 2017, *Physical Review Letters*, Vol. 118, Issue 6, id. 060401, (arXiv:1611.06985 | PDF) (DOI) (Supplemental Material) [Featured in Physics, Editors' Suggestion]**

Testing Bell's Inequality with Cosmic Photons: Closing the Setting-Independence Loophole, **Gallicchio, J., Friedman, A.S., and Kaiser, D.I. 2014, *Physical Review Letters*, Vol. 112, Issue 11, id. 110405, 5 pp. (arXiv:1310.3288) (DOI)**

The Shared Causal Pasts and Futures of Cosmological Events, **Friedman, A.S., Kaiser, D.I., and Gallicchio, J. 2013, *Physical Review D*, Vol. 88, Issue 4, id. 044038, 18 pp. (arXiv:1305.3943) (DOI)**

Can the Cosmos Test Quantum Entanglement?, **Friedman, A.S. 2014, *Astronomy*, Vol. 42, Issue 10, October 2014, pg. 28-33 [PDF]**

The Universe Made Me Do It? Testing "Free Will" With Distant Quasars, **Friedman, A.S., *NOVA, The Nature of Reality*, PBS, WGBH Boston, March 19, 2014 [PDF]**

REFERENCES

Ade+2013, *A & A sub.*, (arXiv:1303.5076)
Aspect+1982, *Phys. Rev. Lett.*, Vol. 49, 25, December 20, p. 1804-1807
Barret & Gisin 2011, *Phys. Rev. Lett.*, vol. 106, 10, id. 100406
Bell 1964, *Physics* Vol. 1, No. 3, p. 195-200, *Physics Publishing Co.*
Bell+1989, *Speakable & Unspeakable in Quantum Mechanics, American Journal of Phys., Vol. 57, Issue 6, p. 567*
Clauser, Horne, Shimony, & Holt 1969, PRL 23, 880
Clauser & Shimony 1978, Rep. Prog. Phys. 41, 1881
Christensen+2013, Phys. Rev. Lett., 111, 120406
Einstein, Podolsky, & Rosen 1935, *Phys. Rev.*, Vol. 47, 10, p. 777-780
Freedman & Clauser 1972, Phys. Rev. Lett., vol. 28, 14, p. 938-941
Friedman, Kaiser, & Gallicchio 2013a, *Phys. Rev. D,* Vol. 88, Iss. 4, id. 044038, 18 p. (arXiv:1305.3943)
Gallicchio, Friedman, & Kaiser 2014=GFK14, *Phys. Rev. Lett., Vol. 112, Issue 11, id. 110405,* (arXiv:1310.3288)
Giustina+2013, *Nature*, Vol. 497, 7448, p. 227-230
Greenberger, Horne, & Zeilinger 1989, "*Going Beyond Bell's Theorem*", in Bell's Theorem, Quantum Theory, and Conceptions of the Universe, Ed. M. Kafatos, Kluwer Academic, Dordrecht, The Netherlands, p. 73-76
Greenberger+1990, American Journal of Physics, Volume 58, Issue 12, pp. 1131-1143
Guth 1981, *Phys. Rev. D*, Vol. 23, 2, p. 347-356
Guth & Kaiser 2005, *Science*, Vol. 307, 5711, p. 884-890
Handsteiner, J., Friedman, A.S. + 2017, *Physical Review Letters*, Vol. 118, Issue 6, id. 060401, (arXiv:1611.06985)
Hall 2010, *Phys. Rev. Lett.*, vol. 105, 25, id. 250404
Hall 2011, *Phys. Rev. A*, vol. 84, 2, id. 022102
Leung, C.+2018, *Physical Review A*, Vol. 97, Issue 4, id. 042120 (arXiv:1706.02276)
Maudlin 1994, "Quantum Non-Locality and Relativity", Wiley-Blackwell; 1st edition
Mermin 1990, American Journal of Physics, Volume 58, Issue 8, pp. 731-734
Rauch, D.+ 2018, *Physical Review Letters*, Vol. 121, Issue 8, id. 080403 (arXiv:1808.05966)
t'Hooft 2007, (arXiv:quant-ph/0701097)
Scheidl+2010, *PNAS,* 107, 46, p. 19708-19713
Weihs+1998, *Phys. Rev. Lett.*, Vol. 81, 23, Dec 7, p. 5039-5043
Zeilinger 2010, "*Dance of the Photons*", Farrar, Straus & Giroux; 1st Ed.