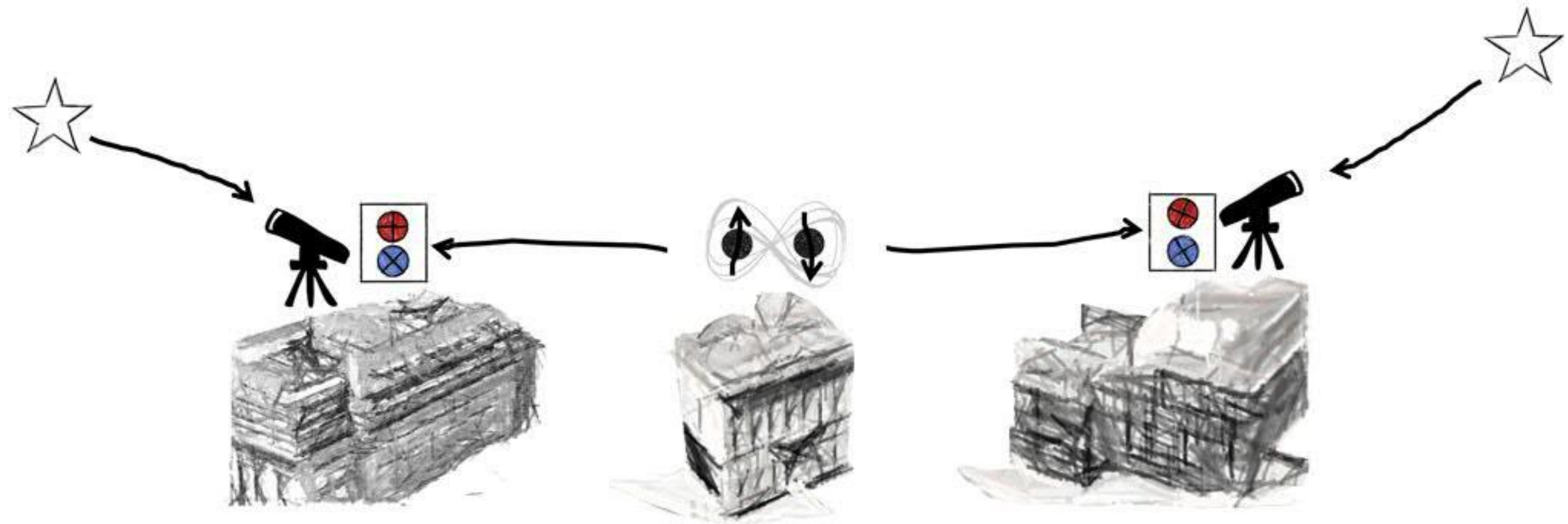
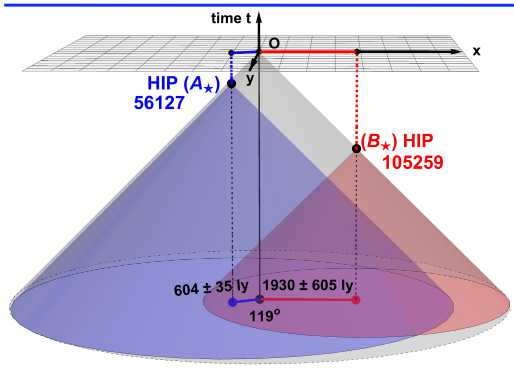


(C) IQOQI/ÖAW

A COSMIC BELL TEST WITH MEASUREMENT SETTINGS FROM MILKY WAY STARS

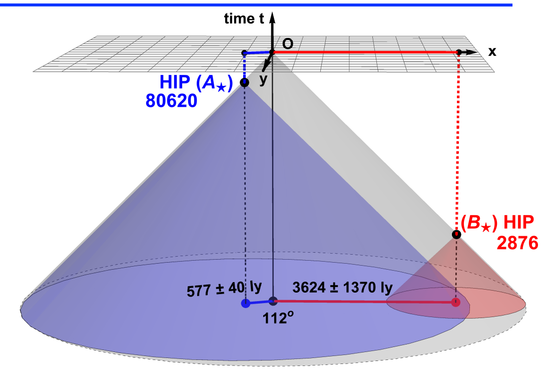


Dr. Andrew Friedman

UC San Diego Center for Astrophysics and Space Sciences

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

asf@ucsd.edu



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

3/8/17

UCSD Center for Astrophysics & Space Sciences

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], Dr. Thomas Scheidl [2], Dr. Johannes Kofler [4], Dr. Hien Nguyen [6], Isabella Sanders [1], Anthony Mark [1], Calvin Leung [3] et al.

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

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THE NEW YORKER

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QUANTUM THEORY BY STARLIGHT

By David Kaiser February 7, 2017

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DOI:10.1063/PT.5.2051

1 Dec 2016 in Research & Technology

Cosmic experiment is closing another Bell test loophole

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

Andrew Grant

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

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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

New Scientist

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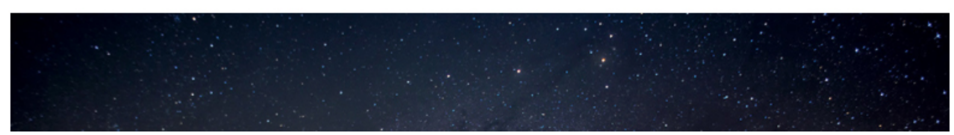
NEWS & TECHNOLOGY 7 February 2017

Starlight test shows quantum world has been weird for 600 years



MEDIA COVERAGE

nature International weekly journal of science

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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

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CBS NEWS NEWS SHOWS VIDEO MO

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

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

QUANTA MAGAZINE illuminating science

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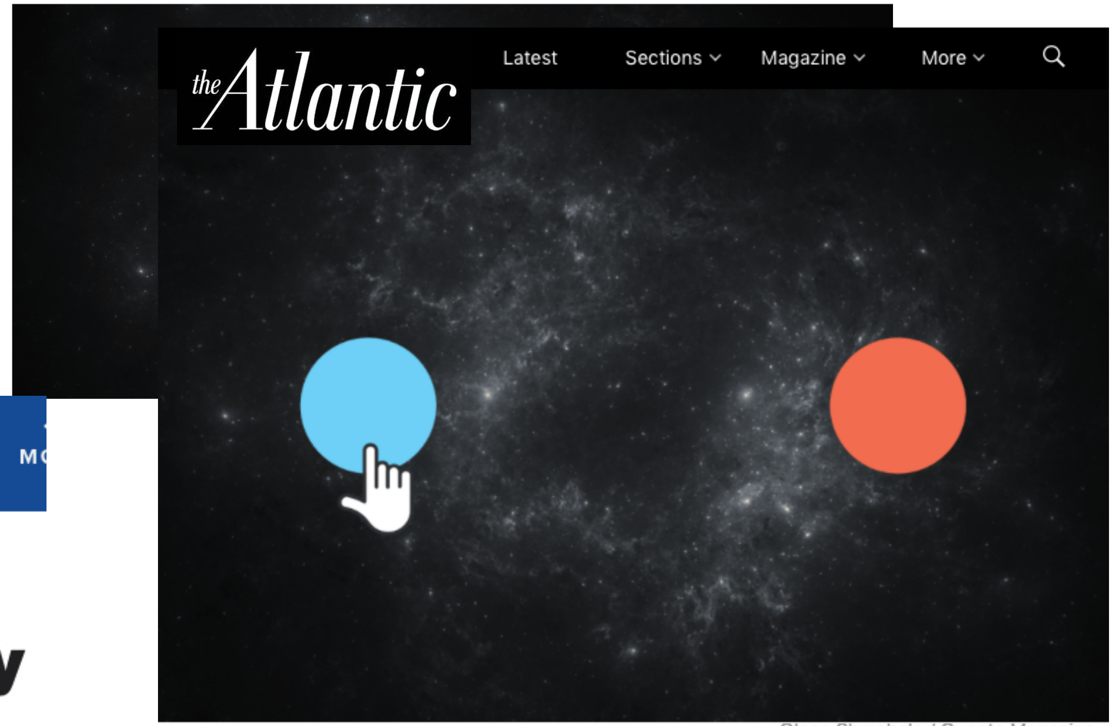
QUANTUM MECHANICS

Experiment Reaffirms Quantum Weirdness

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



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

GAME OF TELEPHONE

MIT News
ON CAMPUS AND AROUND THE WORLD

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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

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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

161 24

MIT press release

Author read actual paper!

Interviewed scientists. Fact checked!

Read press release (maybe)

Read 2nd and 3rd round articles

OUTLINE

1. Entanglement Tests

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

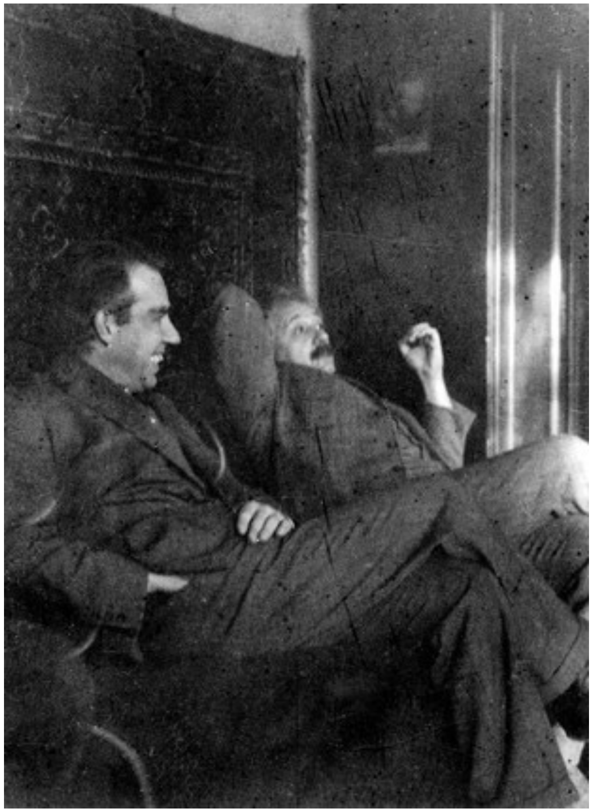
3. Bell's Theorem Loopholes

4. Freedom-Of-Choice Loophole

5. Cosmic Bell Test with Milky Way Stars

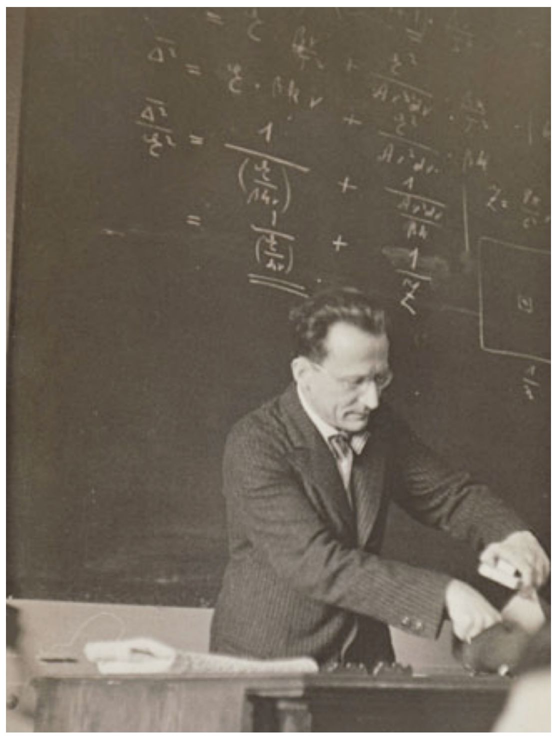
6. Future Cosmic Bell Tests with Quasars, CMB

QUANTUM ENTANGLEMENT

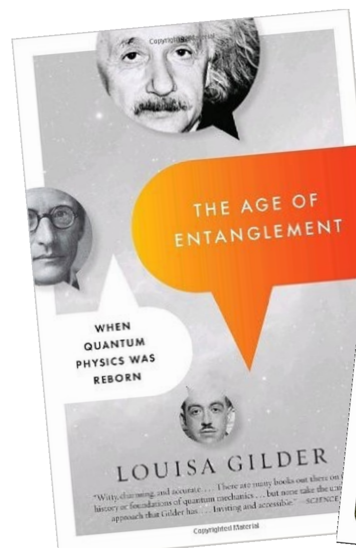


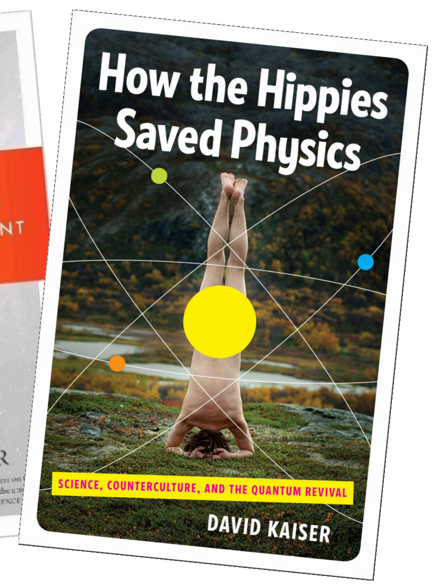
Niels Bohr and Albert Einstein

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



Erwin Schrödinger





EPR PARADOX

A. Einstein B. Podolsky N. Rosen

E P R

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

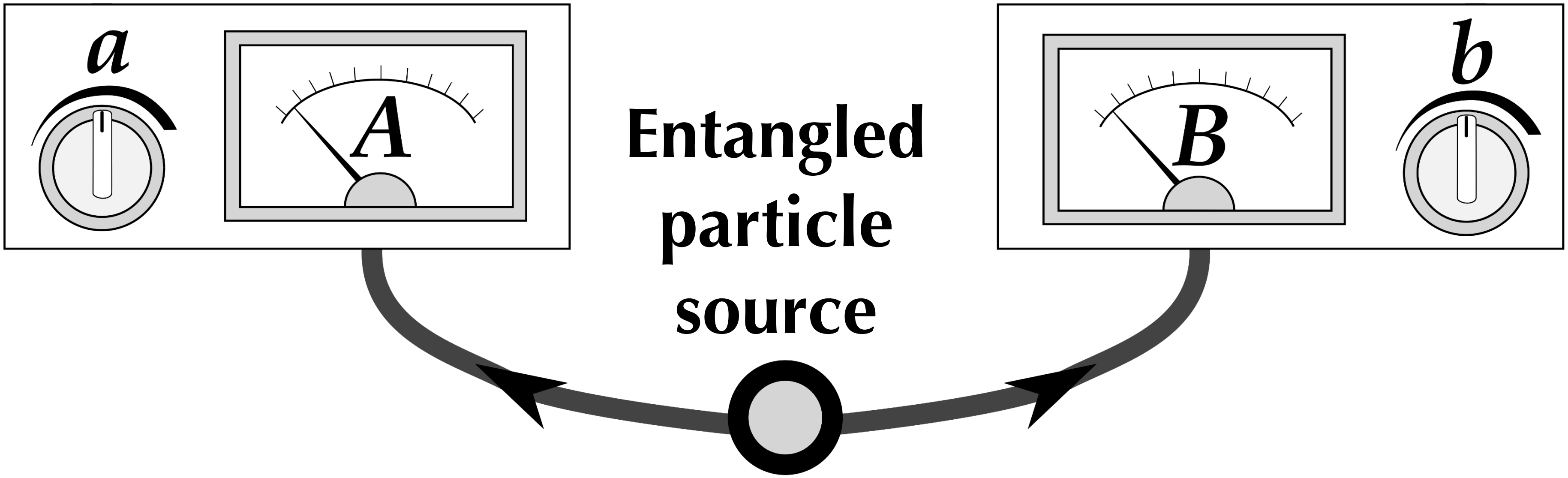
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(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).

EPR / BELL TESTS



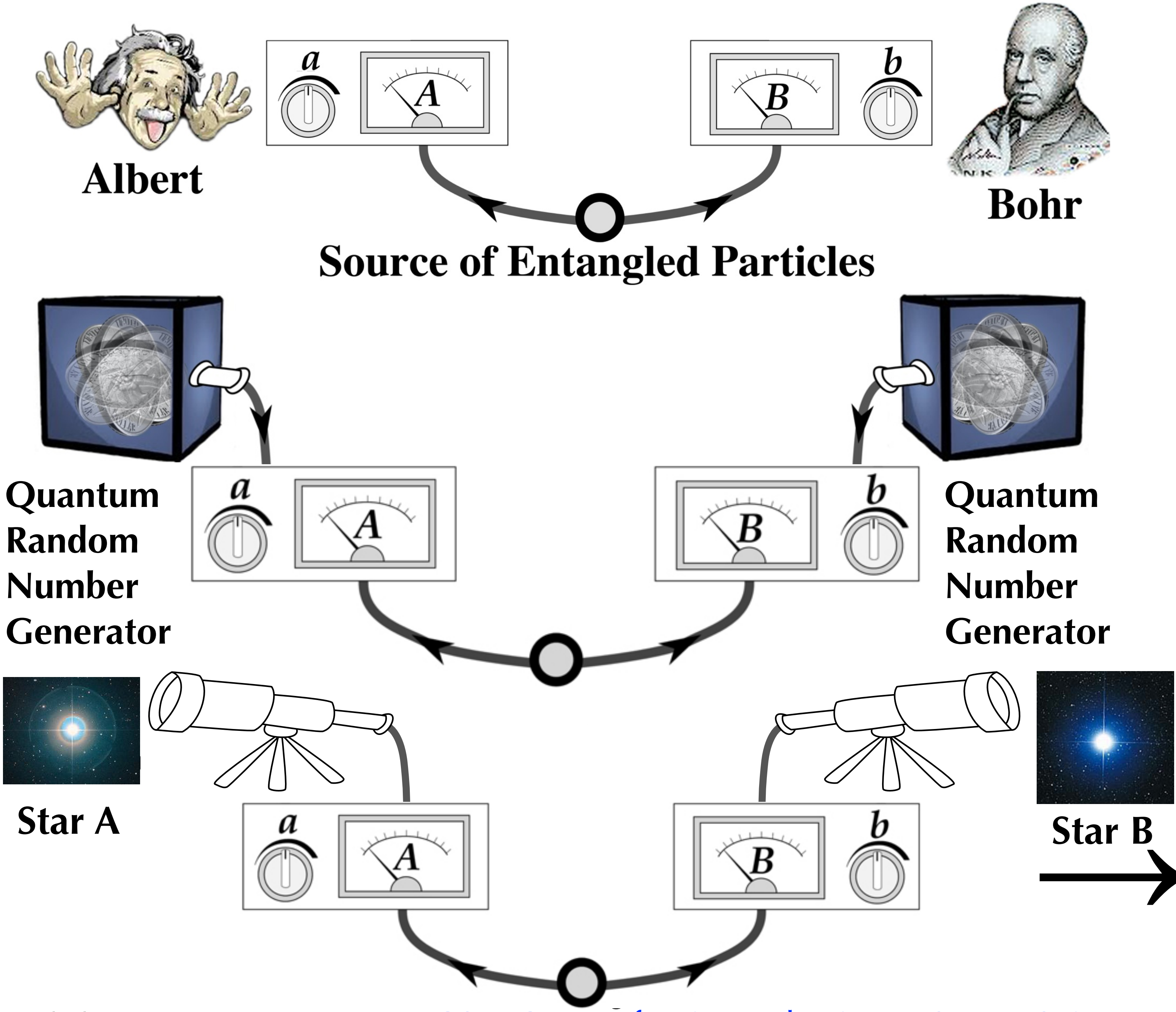
a, b* : *Settings

A, B* : *Outcomes

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

If yes, QM incomplete → Hidden variables

CHOOSING DETECTOR SETTINGS

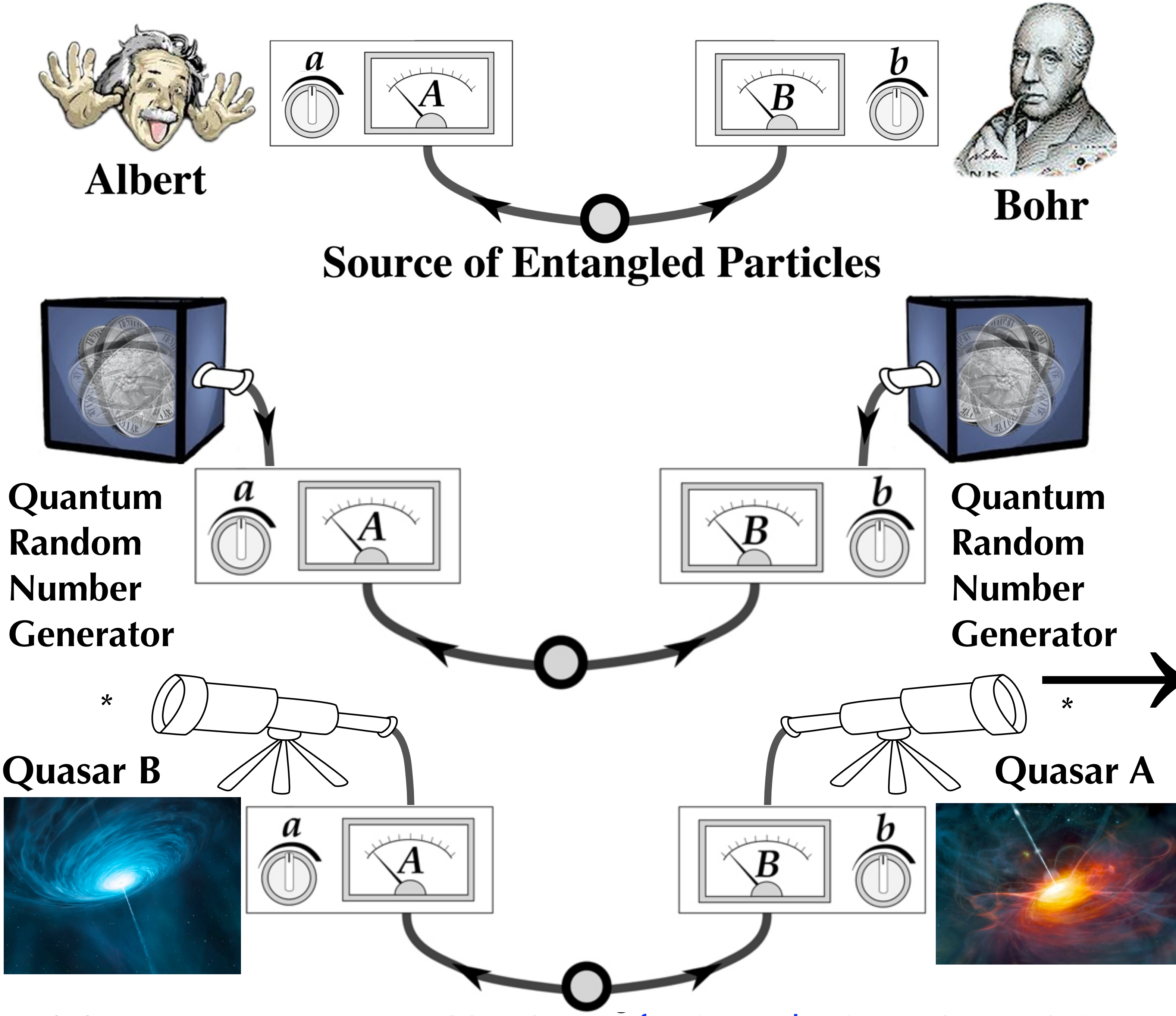


Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

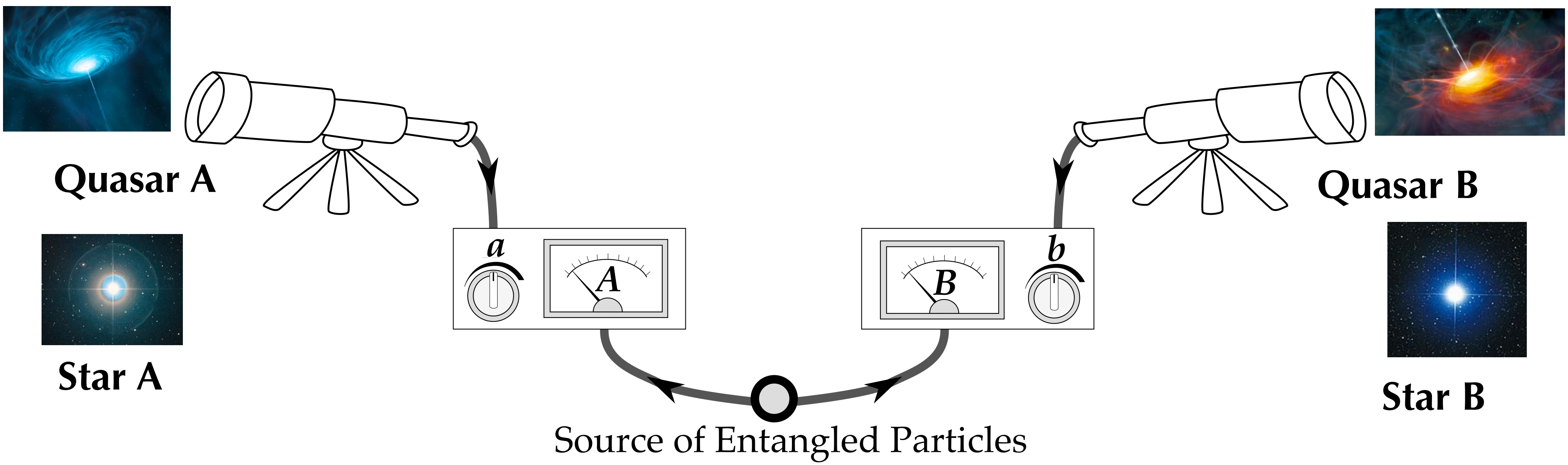


Choose settings with observations of causally disconnected cosmic sources

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

Adapted from: Gallicchio, Friedman, & Kaiser 2014

COSMIC BELL TEST



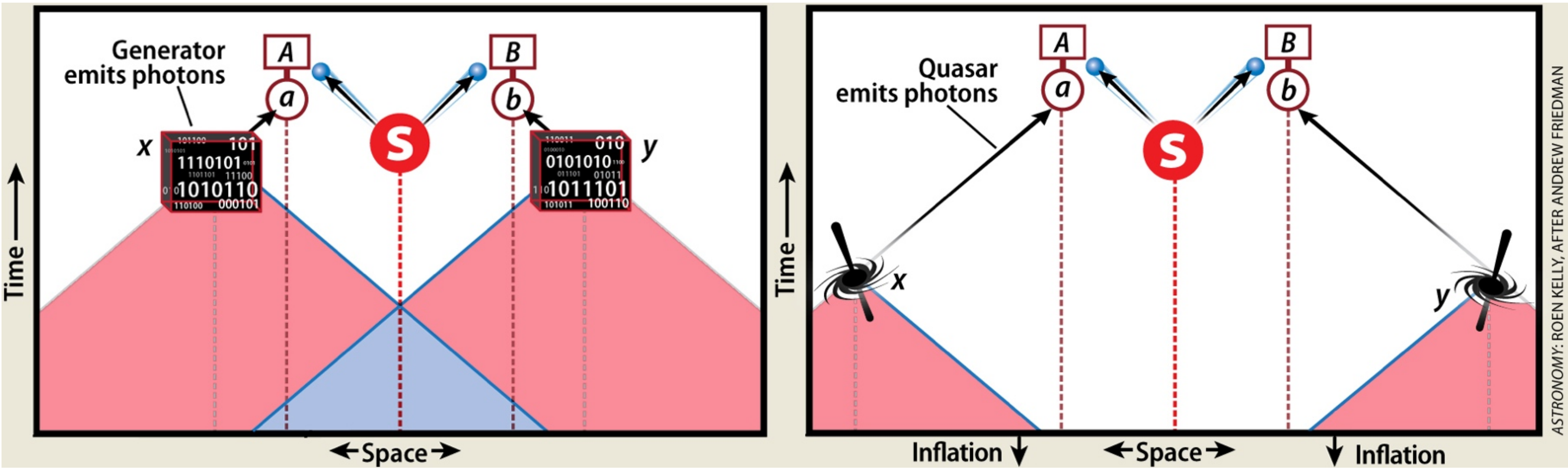
Let the Universe decide how to set up experiment!

Use stars or quasars as cosmic random number generators

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

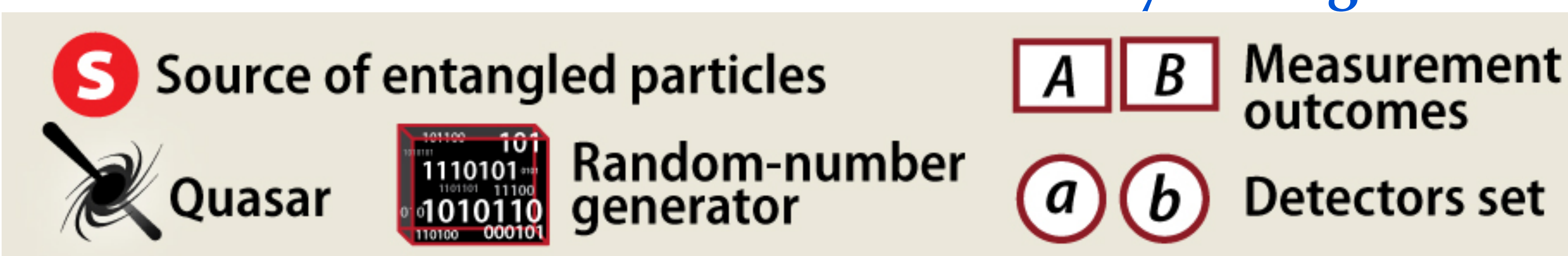
SPACE-TIME DIAGRAMS

Standard Bell Test　　　　Cosmic Bell 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.



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

OUTLINE

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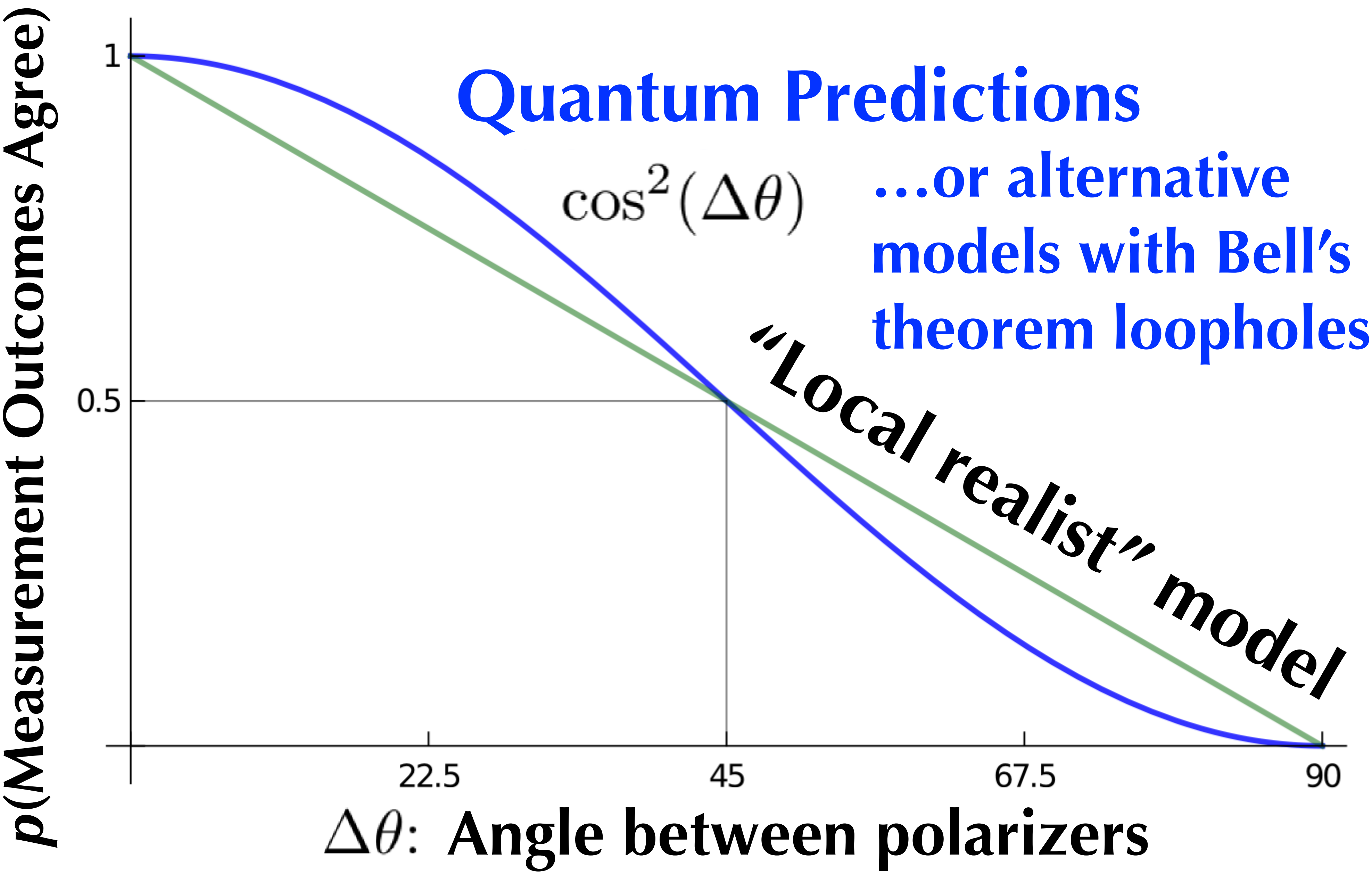
PHOTON POLARIZATION CORRELATION



BELL'S INEQUALITY ASSUMPTIONS

1. Determinism (Realism)

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

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

John S. Bell (1928-1990)

2. Locality

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

3. Fair Sampling

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

4. Freedom-of-Choice / Free Will

Detector settings choices independent of hidden variables in past light cones that could influence measurement outcomes. Observers can choose settings "freely and randomly".

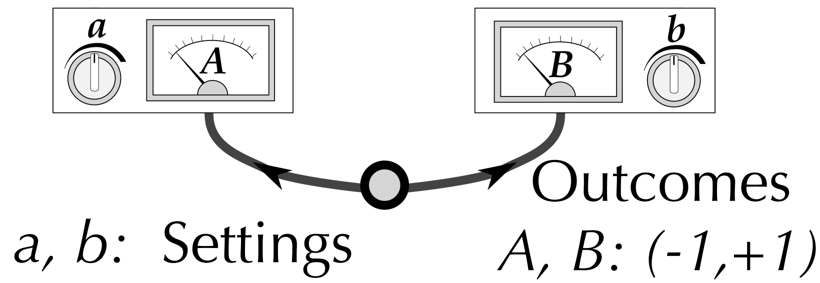
Einstein, Podolsky, & Rosen (EPR) 1935; Bell 1964; Clauser, Horne, Shimony, & Holt (CHSH) 1969; Hall 2015

CHSH CORRELATIONS

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

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

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



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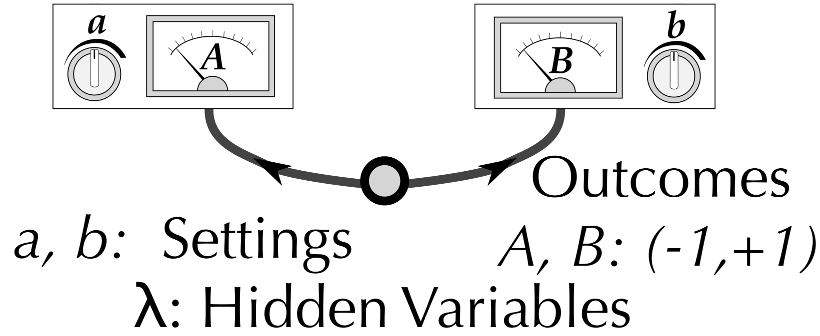

$$S = E(a,b) + E(a',b) + E(a,b') - E(a',b')$$

Bell: if

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

then $|\,S\,| \leq 2.$

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

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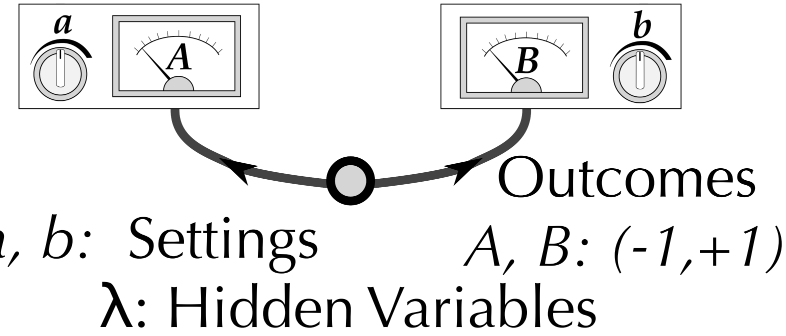

$$S = E(a,b) + E(a',b) + E(a,b') - E(a',b')$$

Bell: if

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

then $|S| \leq 2.$

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

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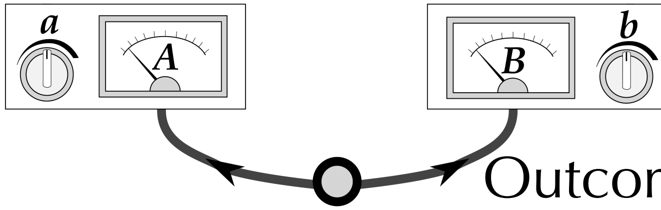
Clauser, Horne, Shimony, & Holt (CHSH) 1969

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



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

Bell: if

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

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

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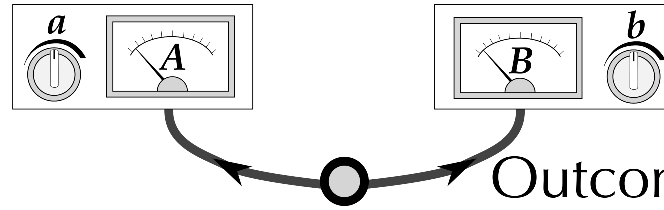

Outcomes

a, b: Settings

A, B: (-1,+1)

λ: Hidden Variables

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

Bell: if

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

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

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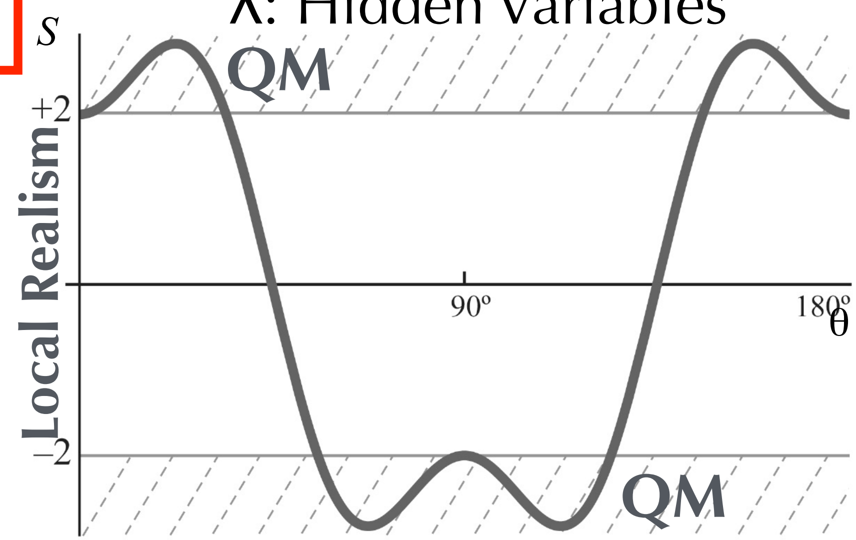

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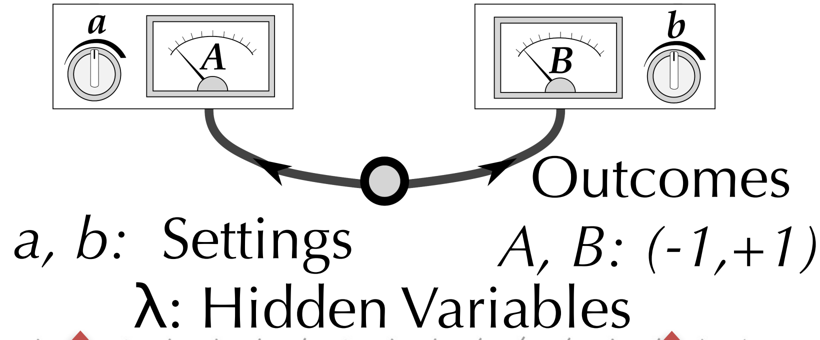

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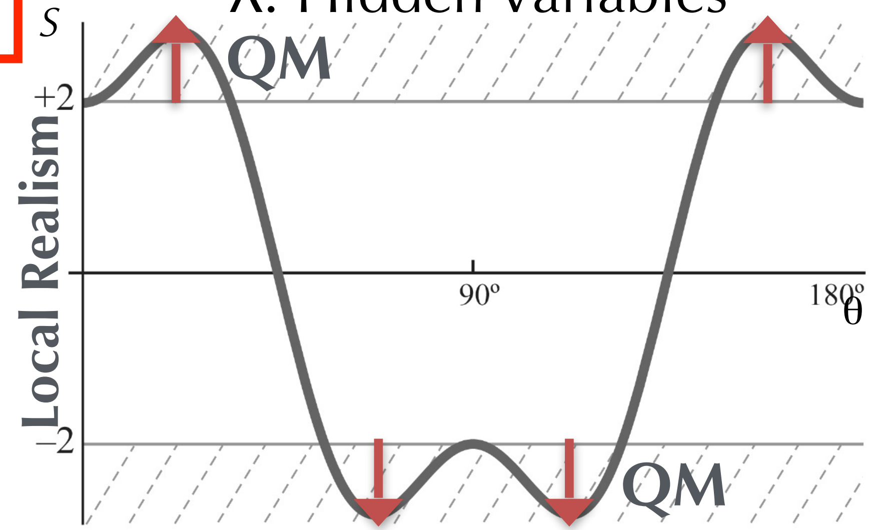
QM prediction: $S_{max} = 2\sqrt{2}$



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

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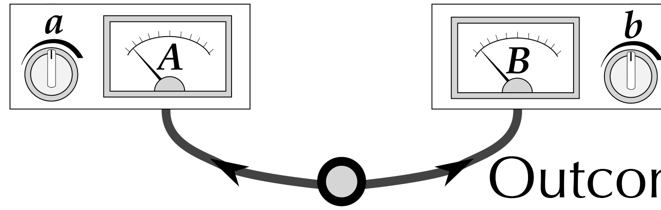
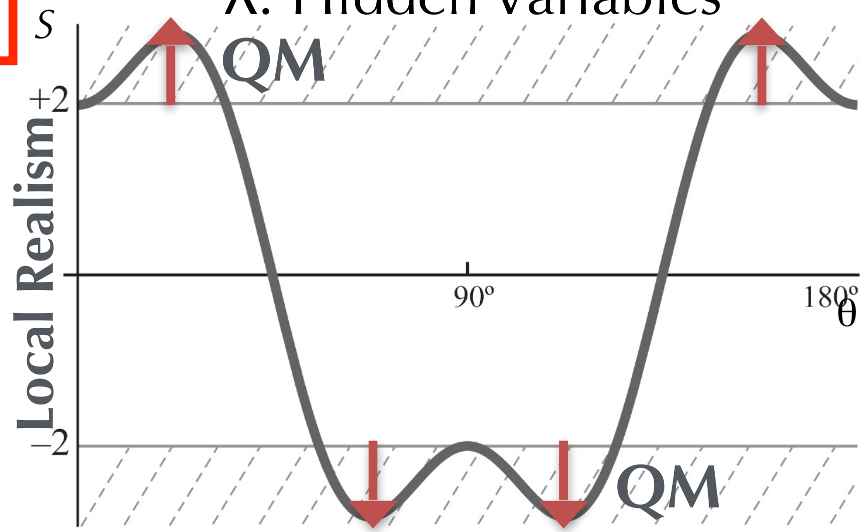
then $|S| \leq 2.$

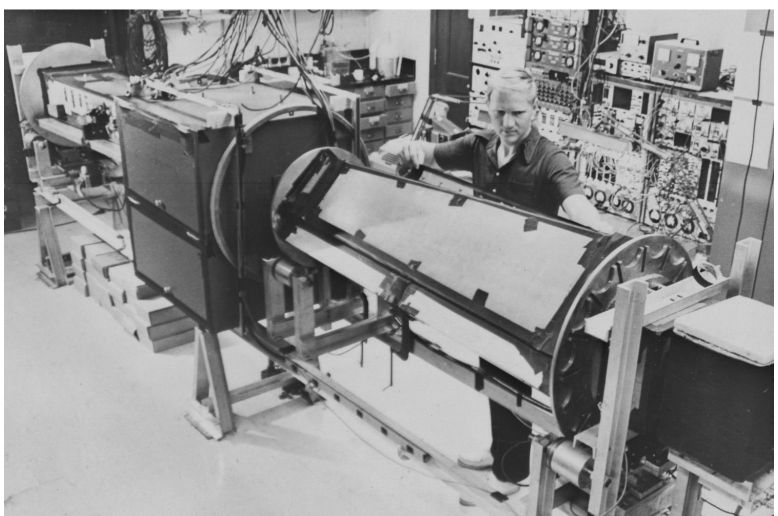
(Locality: *A* does not depend on *B* or *b*, and vice versa.)

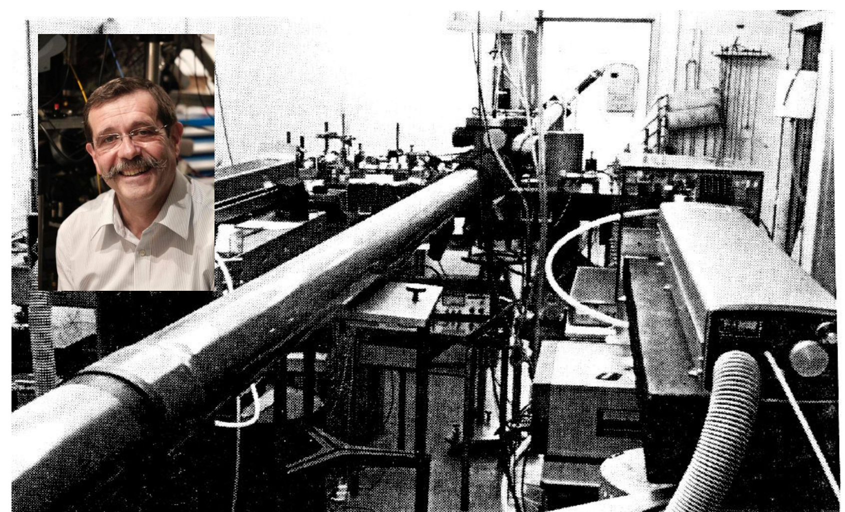
QM prediction: $S_{max} = 2\sqrt{2}$

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






John Clauser, LBNL, 1970s


Alain Aspect, Orsay, 1980s

BELL'S INEQUALITY VS. THEOREM

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

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

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

$$|\,S\,| \leq 2.$$

QM Prediction (Singlet State): $S_{max} = 2\sqrt{2} \quad > \quad 2$

Bell's Theorem

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

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

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BELL'S THEOREM LOOPHOLES

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

What Do Real Experiments Actually Tell Us?

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

Usual Story: (1, 2, or both false, 3, 4 true)

"Local realist" HV theories ruled out

Another Story: (1,2 true but 3 or 4 false)

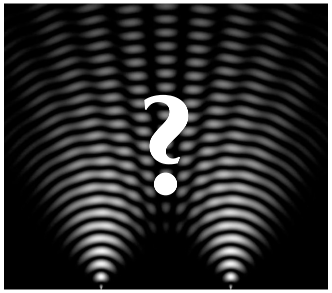
Keep deterministic local-realism, but relax fair sampling or freedom

Fully or partially relax any assumption:

→ Non-quantum alternatives still viable, can simulate quantum predictions!

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

LOOPHOLES AND WHY THEY MATTER



Quantum foundations!

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

Quantum cryptography security

Hackers can exploit loopholes to undermine quantum information schemes

TOWARD A LOOPHOLE FREE TEST

Closing Method?

A. Locality Loophole

Hidden communication between parties

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

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

C. Freedom-of-Choice Loophole

Settings correlated with hidden variables

partially for photons: **Scheidl+2010**

Settings spacelike separated from EPR source

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Settings correlated with hidden variables

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Settings spacelike separated from EPR source

2 LOOPHOLES IN SAME TEST!

Locality & Detection (electrons) — **Hensen+2015 (Delft)**

Locality & Detection (photons) — **Giustina+2015 (Vienna)**, **Shalm+2015 (NIST)**

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

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
PRL **115**, 250401 (2015)
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*
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[4]*Institutionen för Systemtek... Linköping, Sweden*
[5]*ICFO – Institut de Ciencies Fotoniques, The Barce... Barcelona, Spain*
[6]*ICREA – Institució Catalan...*
[7]*Physikalisch-Technische...*
[8]*National Institute of Standards and...*
(Received 10 N...

NIST

Selected for a Viewpoint in *Physics*
PRL **115**, 250402 (2015)
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*
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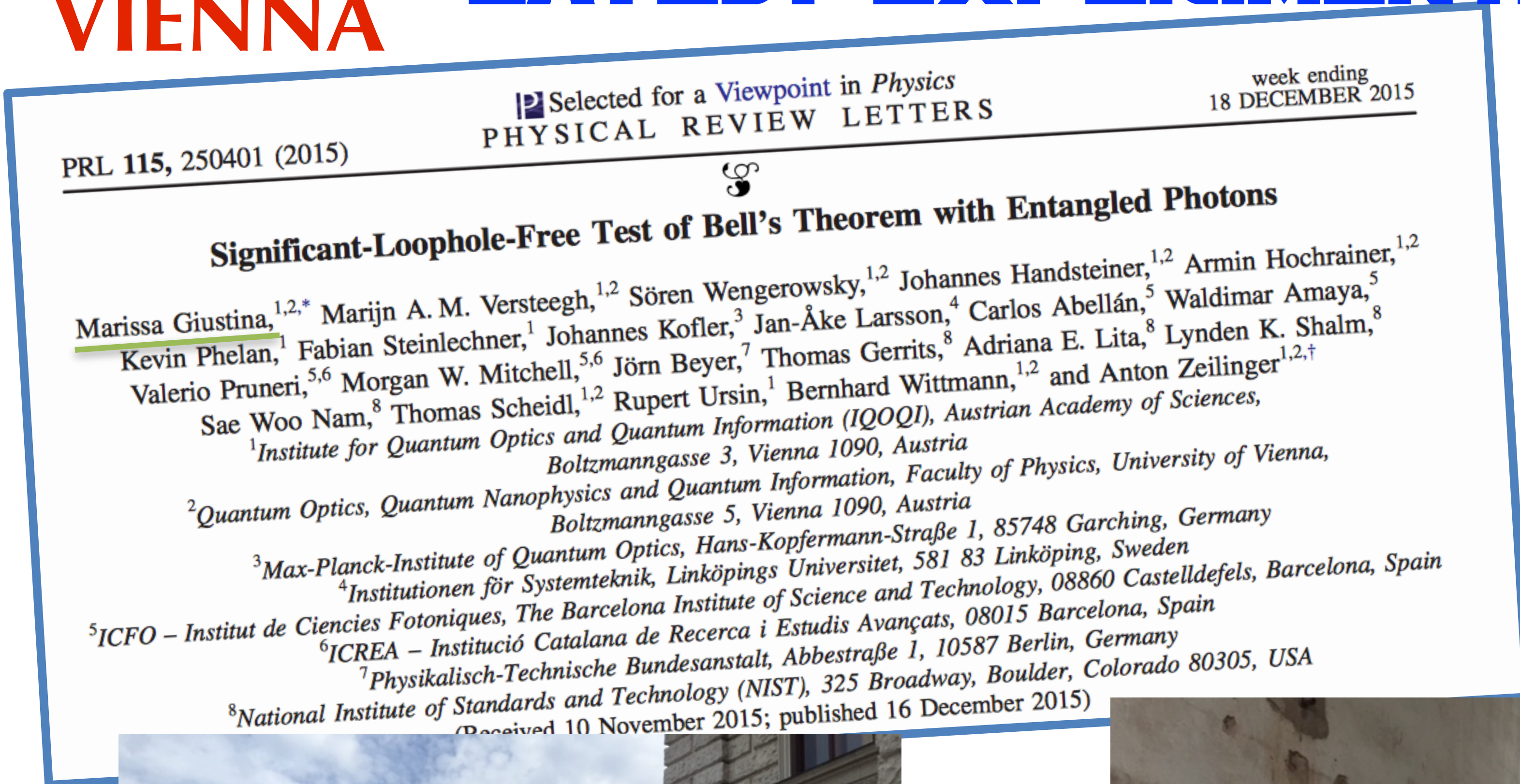
(Received 10 November 2015; published 16 December 2015)

VIENNA

LATEST EXPERIMENTS



Selected for a Viewpoint in *Physics*

PRL **115,** 250401 (2015) 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,†]

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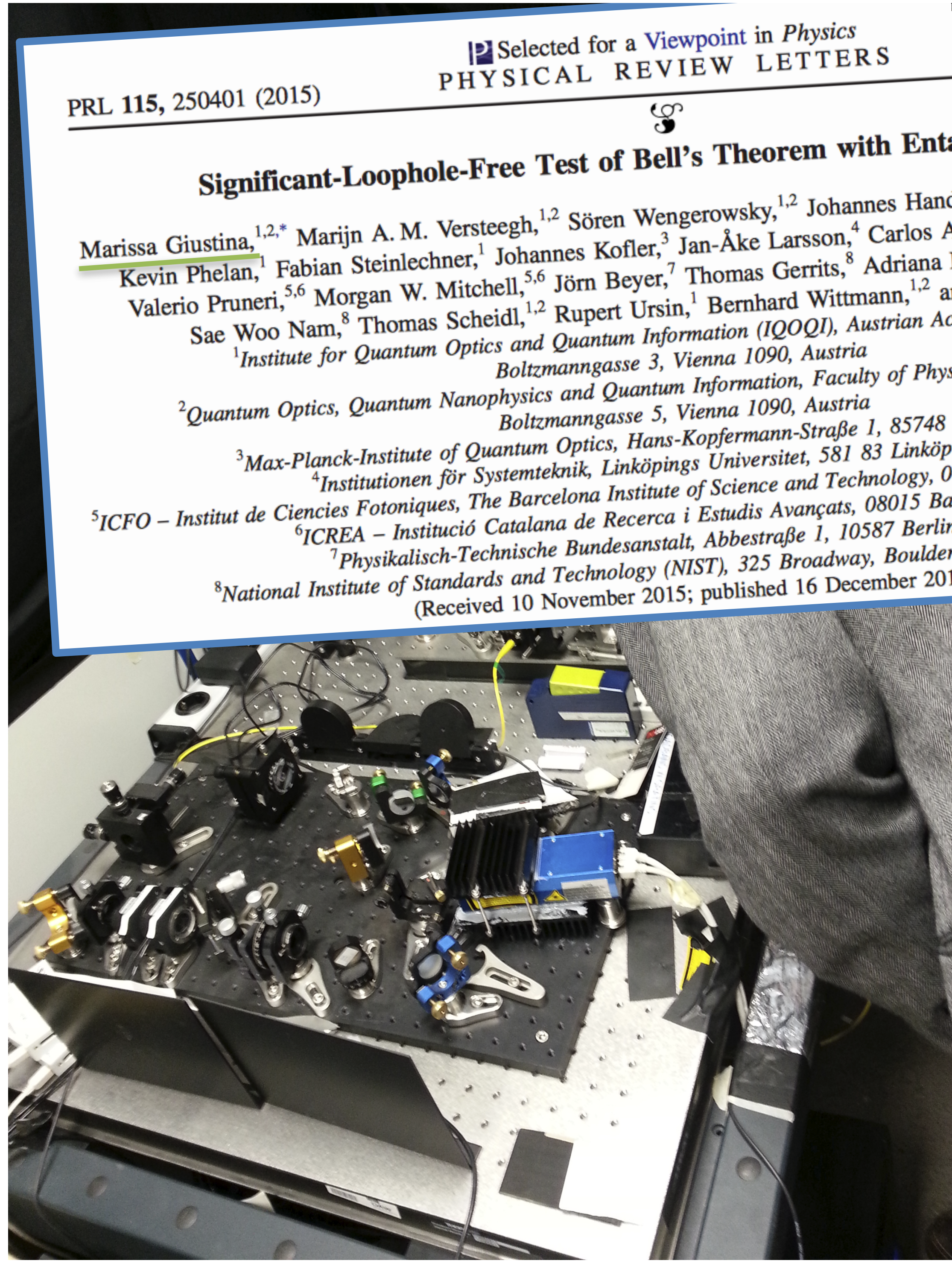
(Received 10 November 2015; published 16 December 2015)

HOFBURG PALACE, VIENNA


Selected for a Viewpoint in Physics
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6ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Ba
7Physikalisch-Technische Bundesanstalt, Abbestraße 1, 10587 Berlin
8National Institute of Standards and Technology (NIST), 325 Broadway, Boulder
(Received 10 November 2015; published 16 December 201

RECENT ENTANGLEMENT TESTS

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

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

These are amazing experiments!

Still very far from definitive "loophole free" experiment

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

Cosmic Bell tests will progressively attempt to do so

OUTLINE

1. Entanglement Tests

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

3. Bell's Theorem Loopholes

4. Freedom-Of-Choice Loophole

5. Cosmic Bell Test with Milky Way Stars

6. Future Cosmic Bell Tests with Quasars, CMB

FREEDOM-OF-CHOICE LOOPHOLE

Freedom assumption

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

a,b: detector settings
λ: HVs

Are experimental choices for detector settings really "free and random"?

Relax Eq. 1 →

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

Hall 2010, Barret & Gisin 2011, Hall 2011

FREEDOM-OF-CHOICE LOOPHOLE

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

*Also known as "measurement-independence" and "setting independence" loophole.

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

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

$$P(\lambda|a,b) = P(\lambda)$$

Bell explicitly *assumed*

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

Bell tacitly *assumed*

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

equivalent to

$$P(a,b|\lambda) = P(a,b), \qquad P(a,b,\lambda) = P(a,b)P(\lambda)$$

FREEDOM-OF-CHOICE LOOPHOLE

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Bell explicitly *assumed*

$$P(\lambda|a,b) = P(\lambda)$$

equivalent to

$$P(a,b|\lambda) = P(a,b), \quad P(a,b,\lambda) = P(a,b)P(\lambda)$$

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

MUTUAL INFORMATION

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

a,b measurement settings

H is the Shannon Entropy.

For a,b independent of λ, last term is by definition sum of first two. M=0.

For a,b determined completely by λ,
all 4 of these are equal and M is at a maximum.

Relaxing Freedom

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

- Freedom = most fragile loophole quantitatively.

  Communication models relaxing locality need ≥ 1 bit

  (e.g. **Toner & Bacon 2001**, **Hall 2010, 2011**)

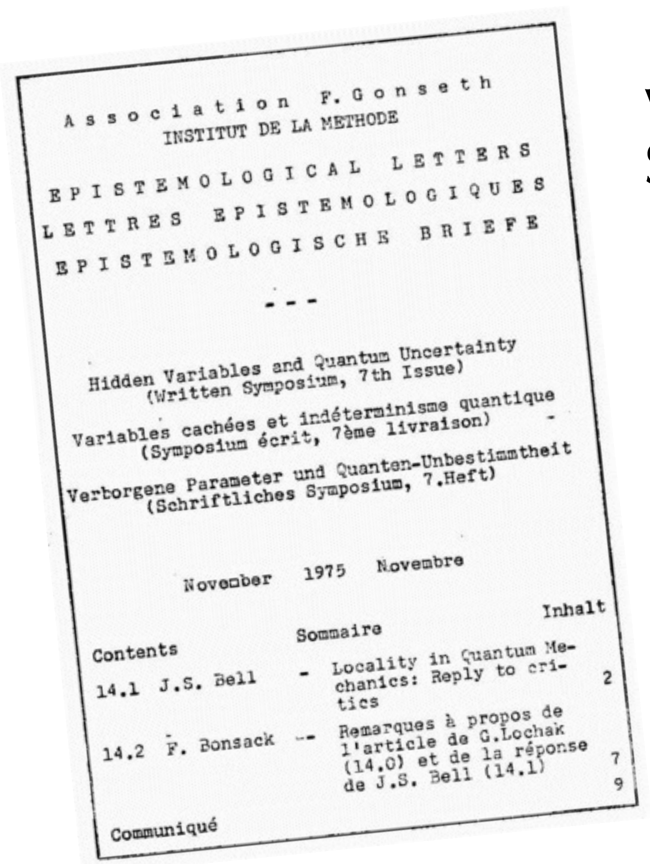
- Deterministic local HV theory (e.g. **Brans 1986**)

Quantitative models! Relaxing Freedom does not imply "superdeterministic cosmic conspiracy"

FREEDOM-OF-CHOICE LOOPHOLE

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

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



Association F. Gonseth
INSTITUT DE LA METHODE

EPISTEMOLOGICAL LETTERS
LETTRES EPISTEMOLOGIQUES
EPISTEMOLOGISCHE BRIEFE

Hidden Variables and Quantum Uncertainty
(Written Symposium, 7th Issue)

Variables cachées et indéterminisme quantique
(Symposium écrit, 7ème livraison)

Verborgene Parameter und Quanten-Unbestimmtheit
(Schriftliches Symposium, 7.Heft)

November 1975 Novembre

Contents Sommaire Inhalt

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

FREEDOM-OF-CHOICE LOOPHOLE

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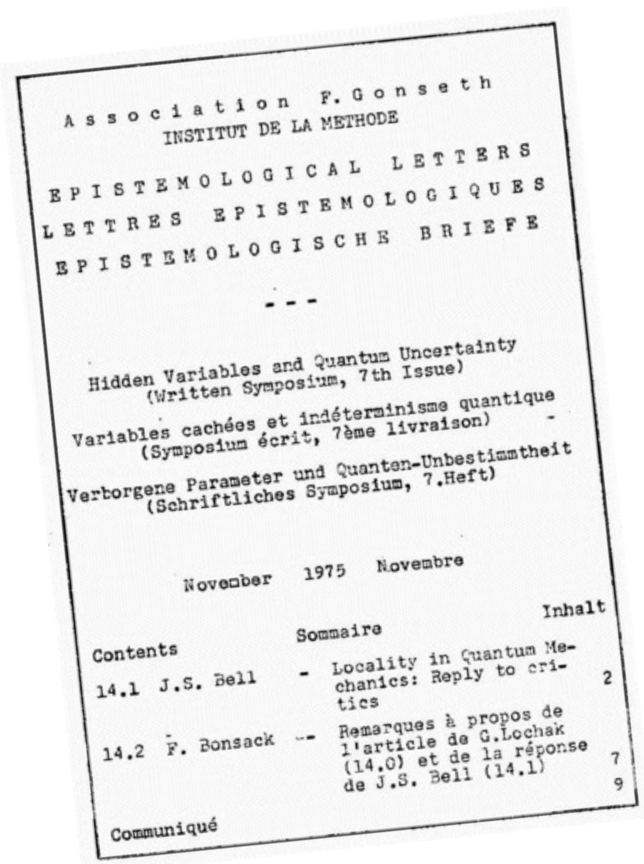

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EPISTEMOLOGICAL LETTERS
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was debated among Bell, Clauser, Horne, and Shimony in "Epistemological Letters," 1976-77.

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

Recent attention from Michael J. W. Hall, Nicolas Gisin, et al.

OUTLINE

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

3. Bell's Theorem Loopholes

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5. Cosmic Bell Test with Milky Way Stars

6. Future Cosmic Bell Tests with Quasars, CMB

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,‡]

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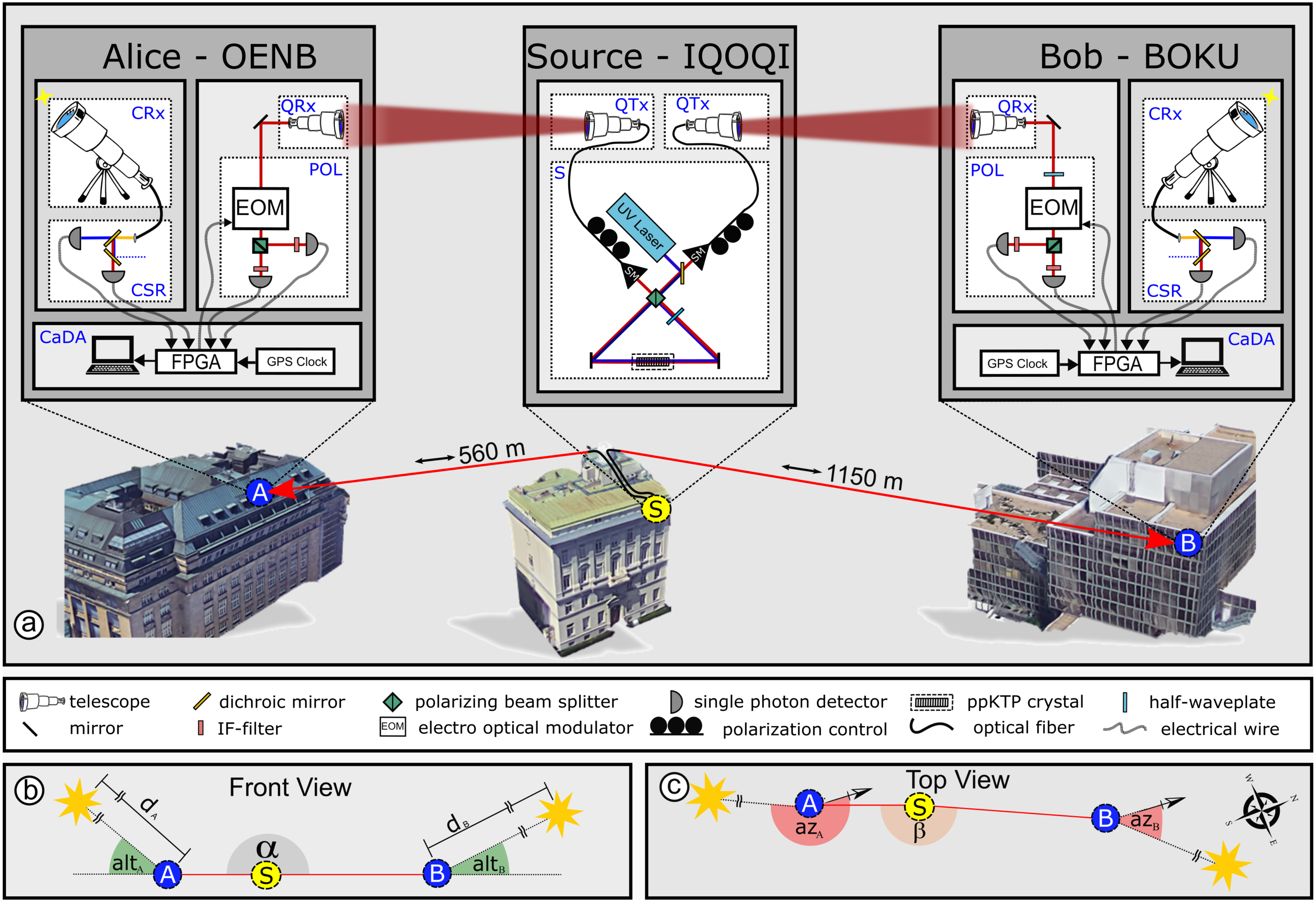
(Received 21 November 2016; revised manuscript received 13 January 2017; published 7 February 2017)

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

COSMIC BELL TEST SCHEMATIC



COSMIC SETTING GENERATOR

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

VIENNA COSMIC BELL TEST

PRL **118,** 060401 (2017) PHYSICAL REVIEW LET

Cosmic Bell Test: Measurement Settings fr

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Sören Wengerowsky,[1] Alan H. Guth,[2] Dav
Thomas Scheidl,[1] and Anton Zeilin
[1]*Institute for Quantum Optics and Quantum Information (IQOQI*
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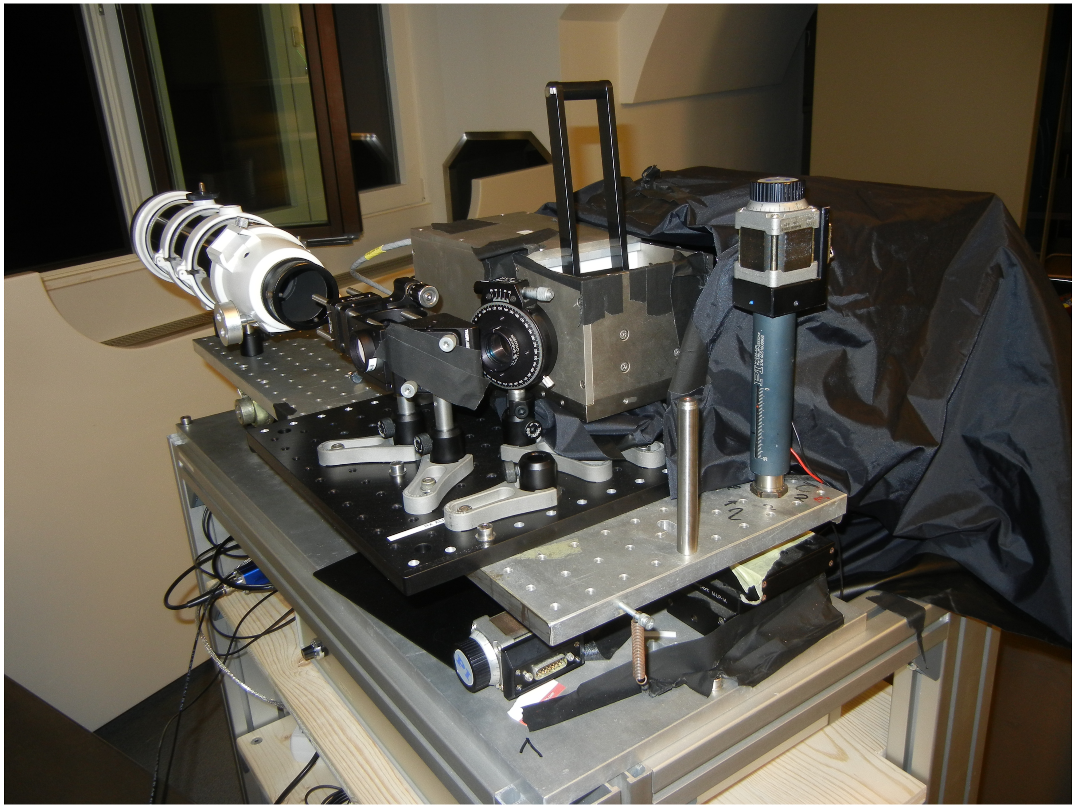
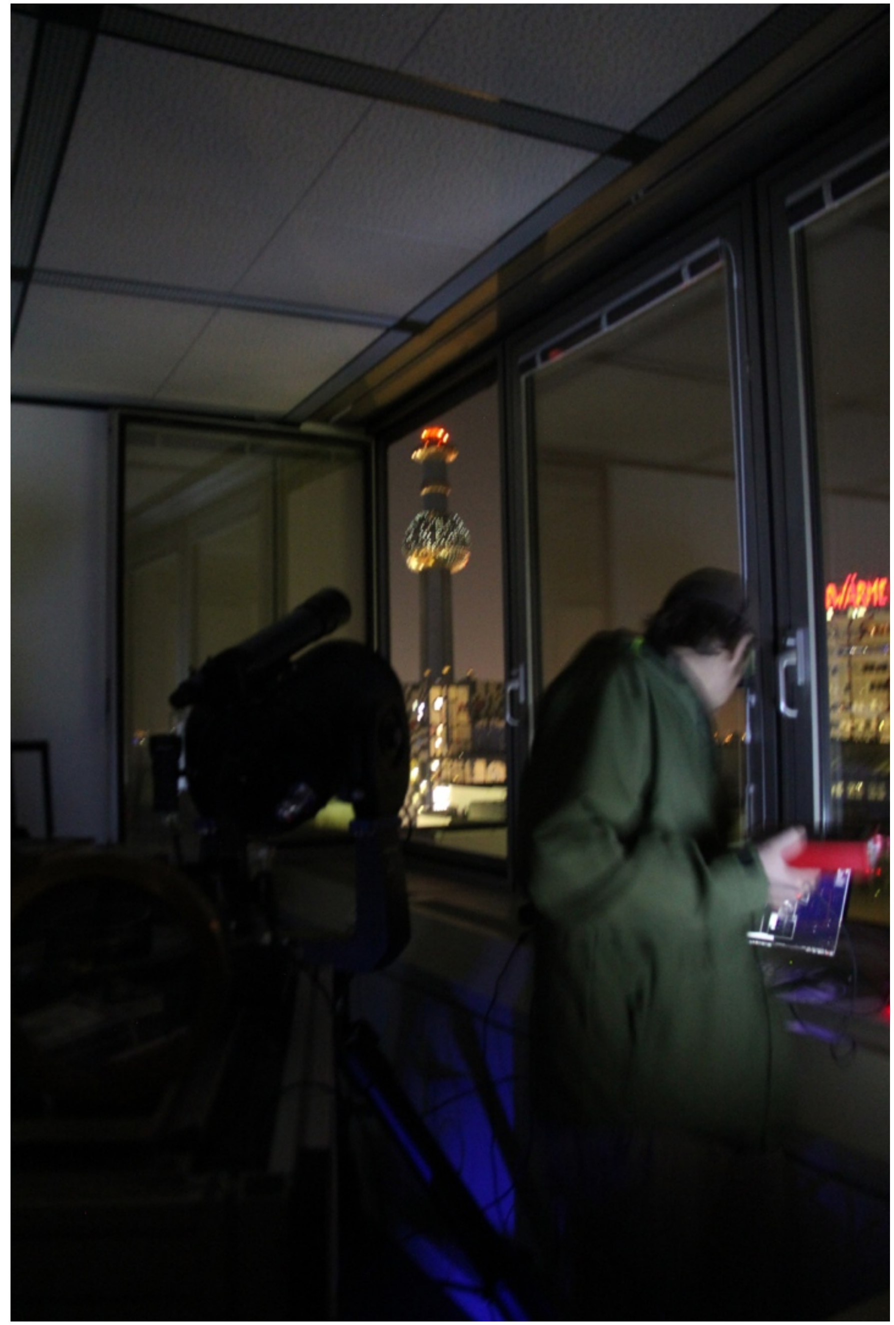
VIENNA COSMIC BELL TEST



Entangled photon receiver and polarization analyzer

VIENNA COSMIC BELL TEST

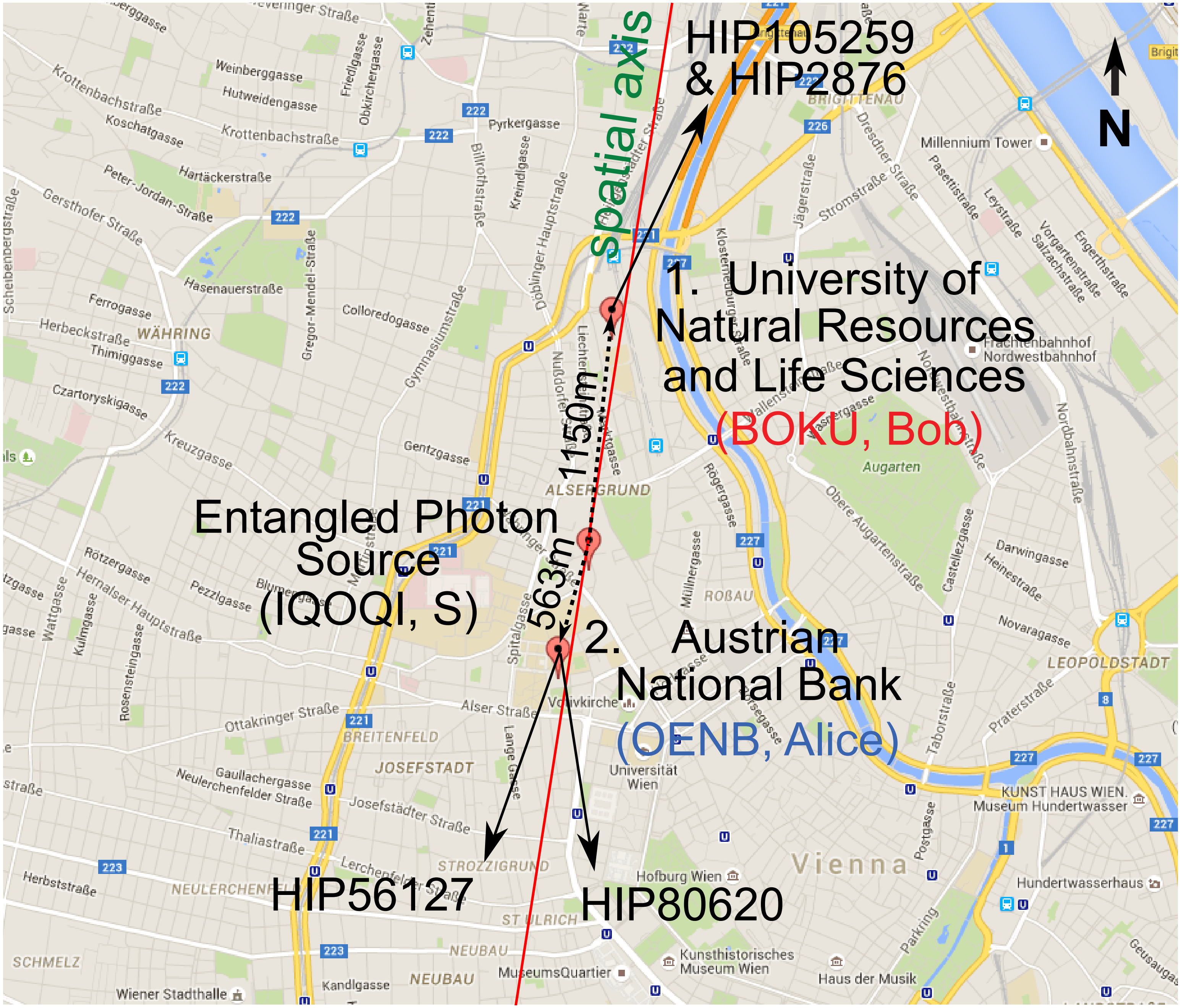


Occupational Hazards

VIENNA COSMIC BELL TEST

Star selection

GOOGLE MAPS IS THE BEST!



CAUSAL ALIGNMENT

Locality Loophole

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

Locality Loophole+ Causal Alignment

Must space-like separate new pairs of events

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

If final conditions are not met for either side at any time, can't use the data and also claim to have closed locality loophole.

CAUSAL ALIGNMENT

How long are settings valid on each side with fresh random #?

$$\tau^{A}_{\text{valid}}(t) = \frac{1}{c}\hat{n}_{S_A}(t)\cdot(\vec{r}_A - \vec{m}_B) + \frac{n}{c}\Big[|\vec{m}_A - \vec{s}| - |\vec{m}_B - \vec{s}|\Big] - \frac{\eta_A}{c}|\vec{r}_A - \vec{m}_A|$$

$$\tau^{B}_{\text{valid}}(t) = \frac{1}{c}\hat{n}_{S_B}(t)\cdot(\vec{r}_B - \vec{m}_A) + \frac{n}{c}\Big[|\vec{m}_B - \vec{s}| - |\vec{m}_A - \vec{s}|\Big] - \frac{\eta_B}{c}|\vec{r}_B - \vec{m}_B|$$

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

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

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

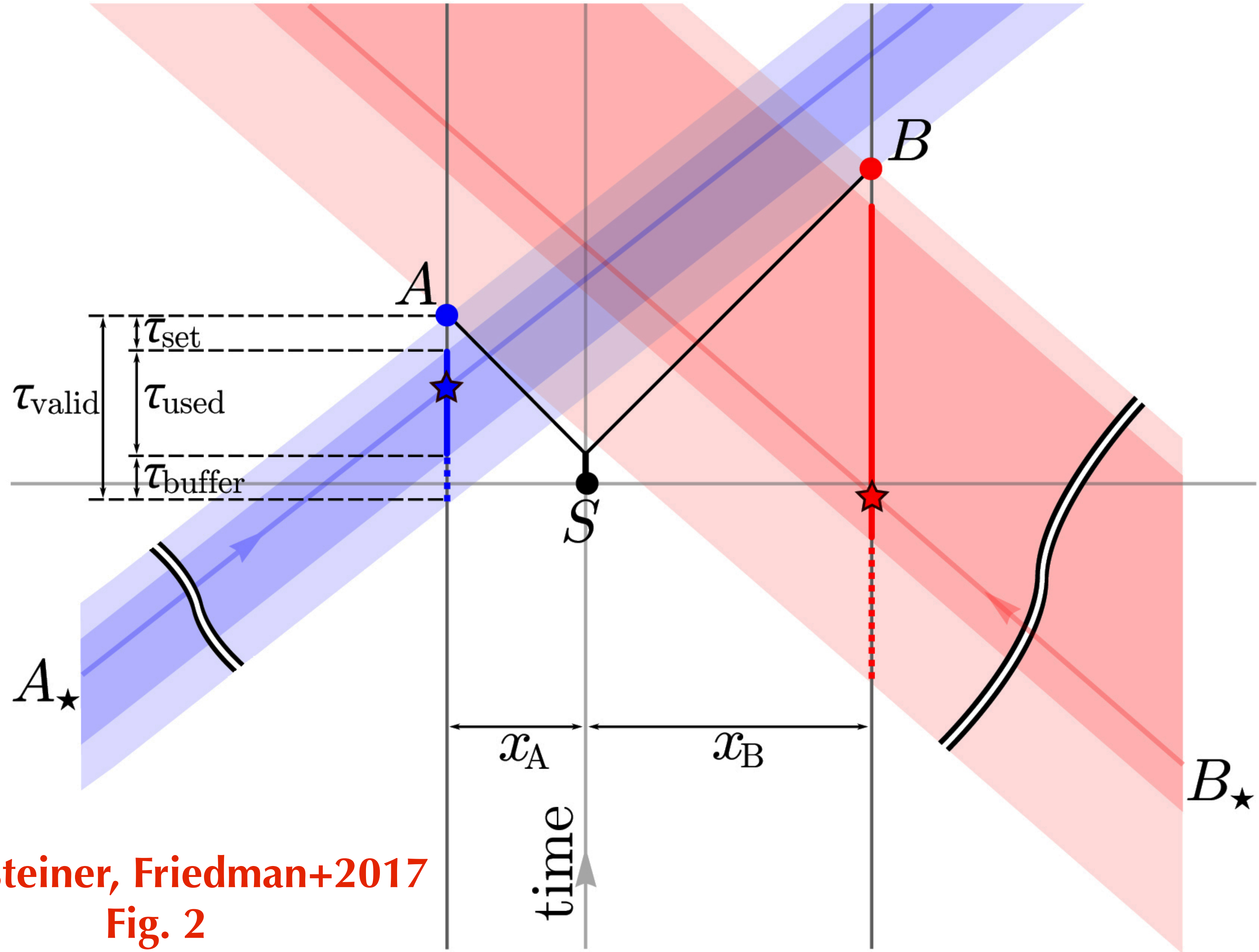
Refractive index n Air η_k Fiber from telescope to EPR detector

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

$$\tau^{k}_{\text{used}} = \min_{t}\left\{\tau^{k}_{\text{valid}}(t)\right\} - \tau^{k}_{\text{buffer}} - \tau_{\text{set}}$$

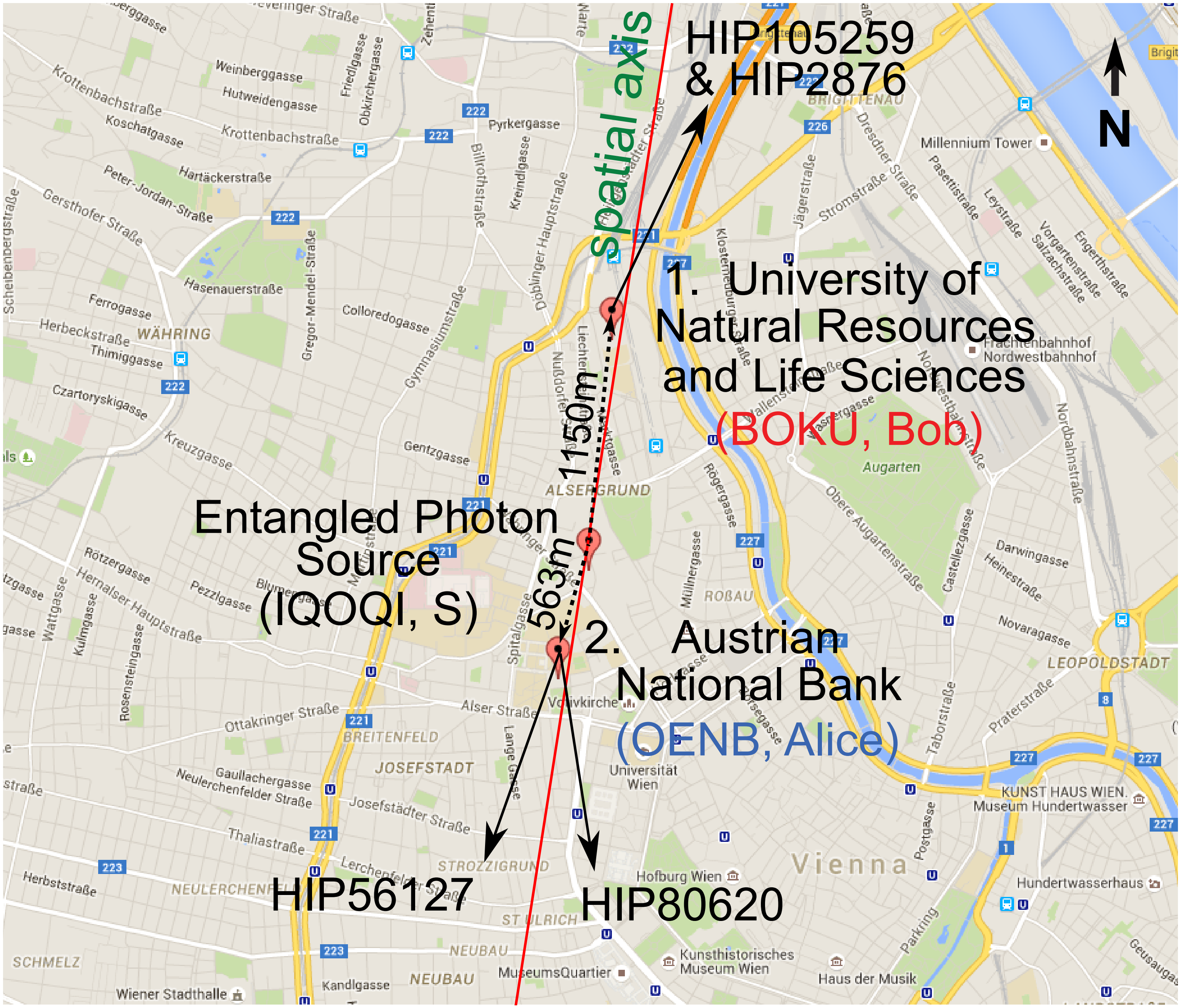
Handsteiner, Friedman+2017 (SM)
Friedman+2017 in prep.

SPACE-TIME DIAGRAM: RUN 1

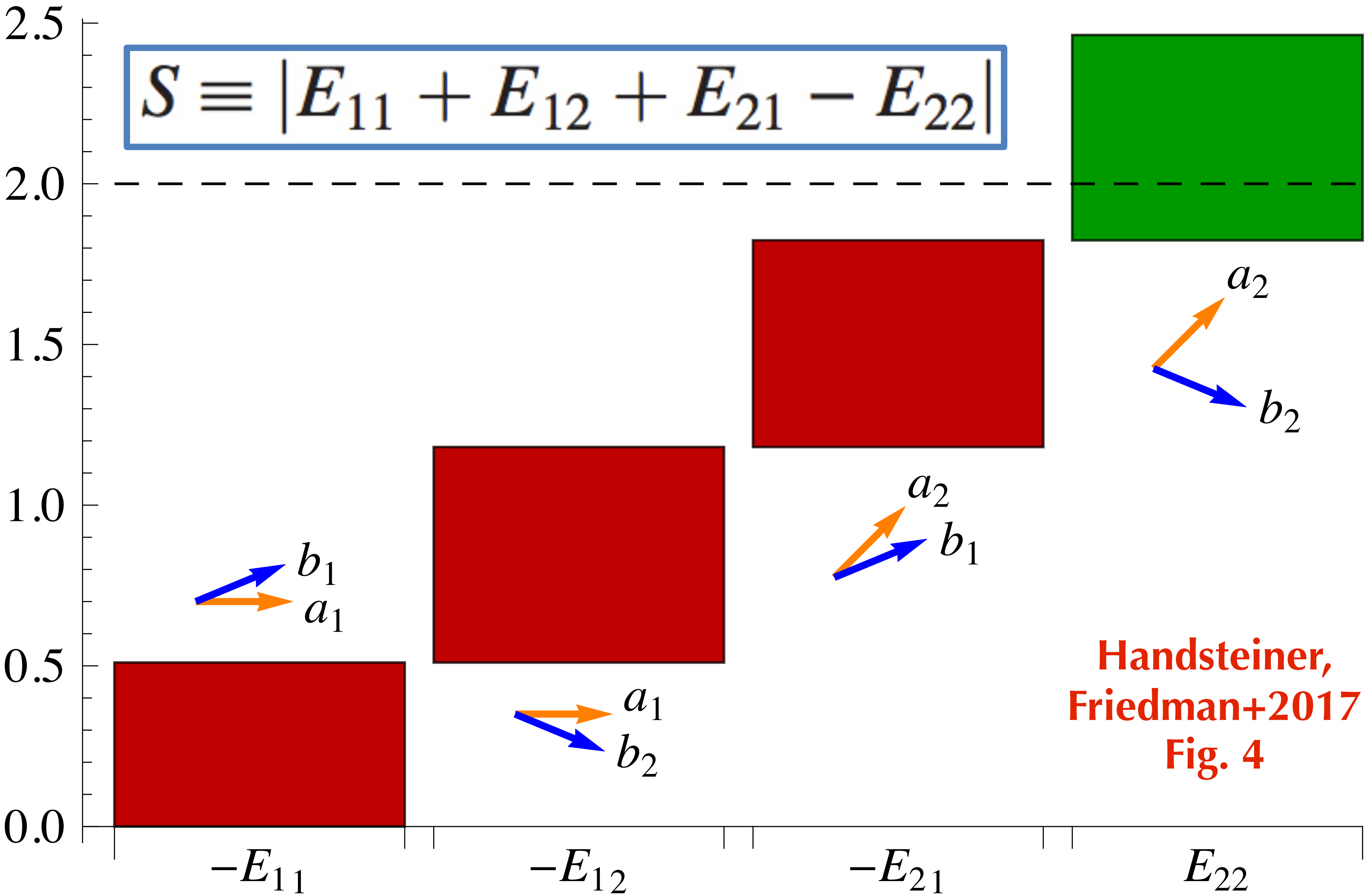


Handsteiner, Friedman+2017
Fig. 2

GOOGLE MAPS IS THE BEST!



OBSERVED BELL VIOLATION



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.

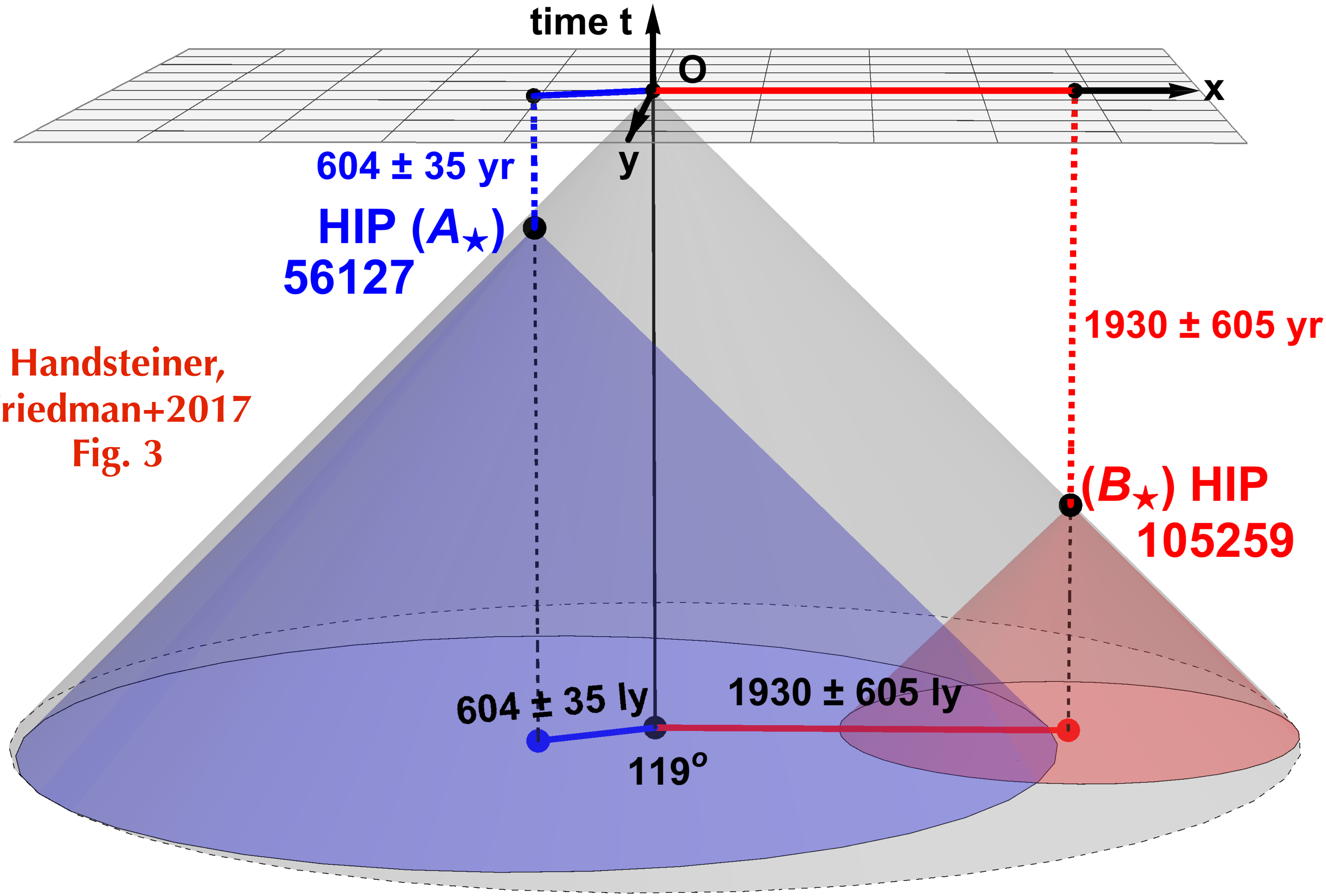
Observed sufficient signal-to-noise from cosmic sources.

Highly significant Bell violation still observed:

Run 1: 7.31 sigma, Run 2: 11.93 sigma

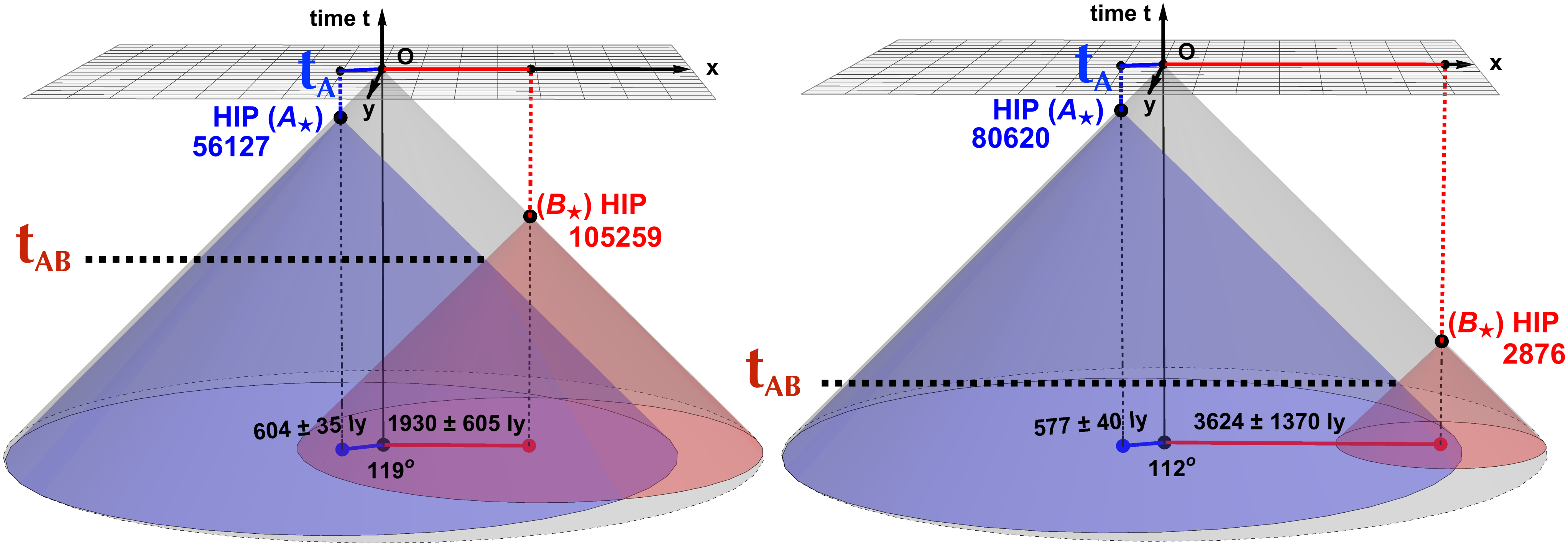
See Handsteiner, Friedman+2017 (Supplemetal Material)

SPACE-TIME DIAGRAM: STARS



Handsteiner, Friedman+2017 Fig. 3

SPACETIME DIAGRAMS: RUNS 1, 2



Run 1	Run 2
t_A= 604 +/- 35 yrs	t_A= 577 +/- 40 yrs
t_{AB} = 2409 +/- 598 yrs	t_{AB} = 4040 +/- 1363 yrs

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

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

Handsteiner, Friedman+2017 (SM Fig. 2)

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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,‡]
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[2]*Center for Theoretical Physics and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 25 October 2013; published 18 March 2014)

We propose a practical scheme to use photons from causally disconnected cosmic sources to set the detectors in an experimental test of Bell's inequality. In current experiments, with settings determined by quantum random number generators, only a small amount of correlation between detector settings and local hidden variables, established less than a millisecond before each experiment, would suffice to mimic the predictions of quantum mechanics. By setting the detectors using pairs of quasars or patches of the cosmic microwave background, observed violations of Bell's inequality would require any such coordination to have existed for billions of years—an improvement of 20 orders of magnitude.

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

Experiment feasible with existing technology!

$z > 3.65$ quasars bright enough

CMB an intriguing possibility

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

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,‡]

[1] *Center for Theoretical Physics and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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(Received 16 May 2013; published 21 August 2013)

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

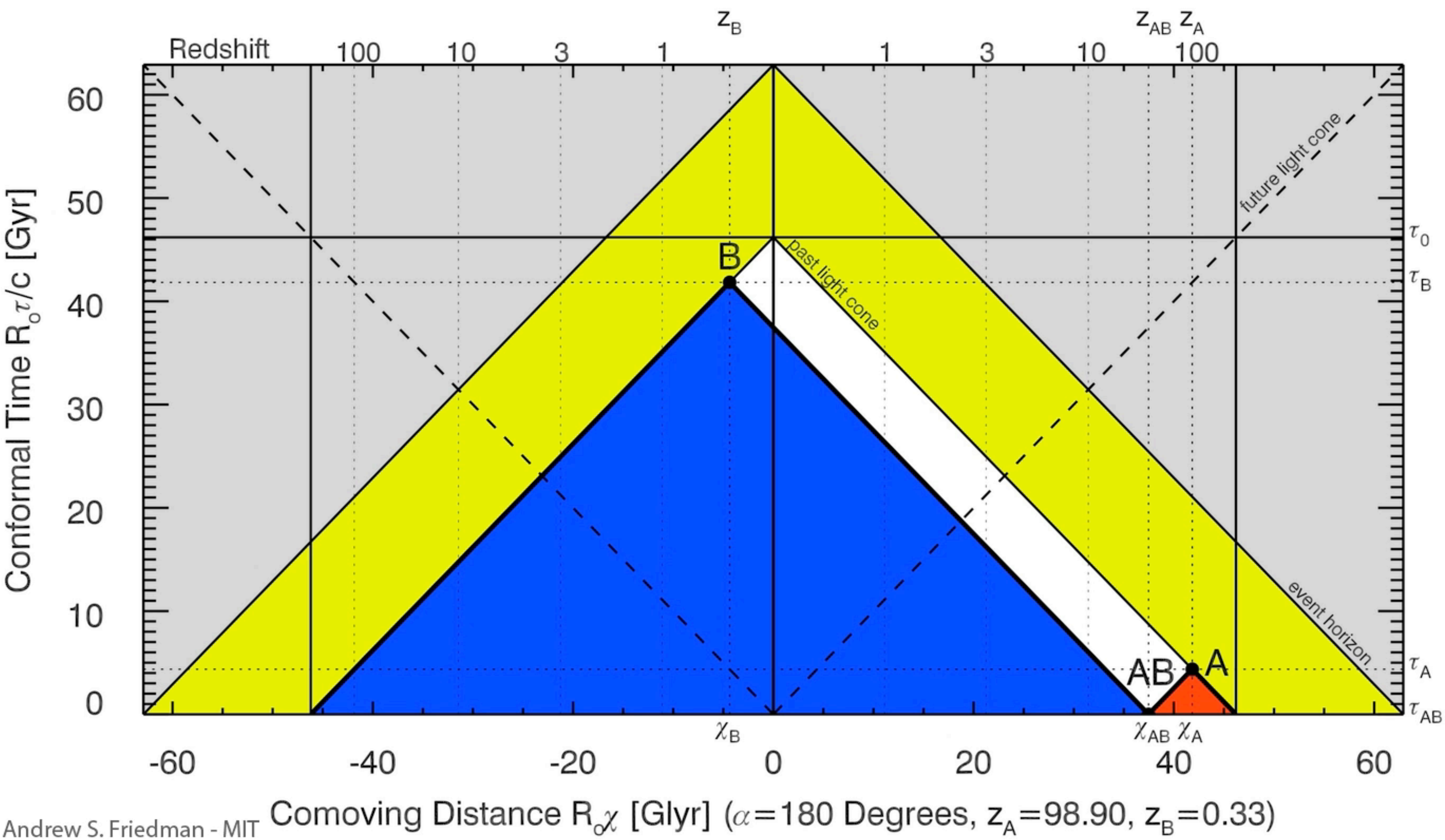
DOI: 10.1103/PhysRevD.88.044038 PACS numbers: 04.20.Gz, 98.80.−k

Why use quasars? Brightest continuous cosmological sources.

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

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

LC INTERSECTION @BIG BANG



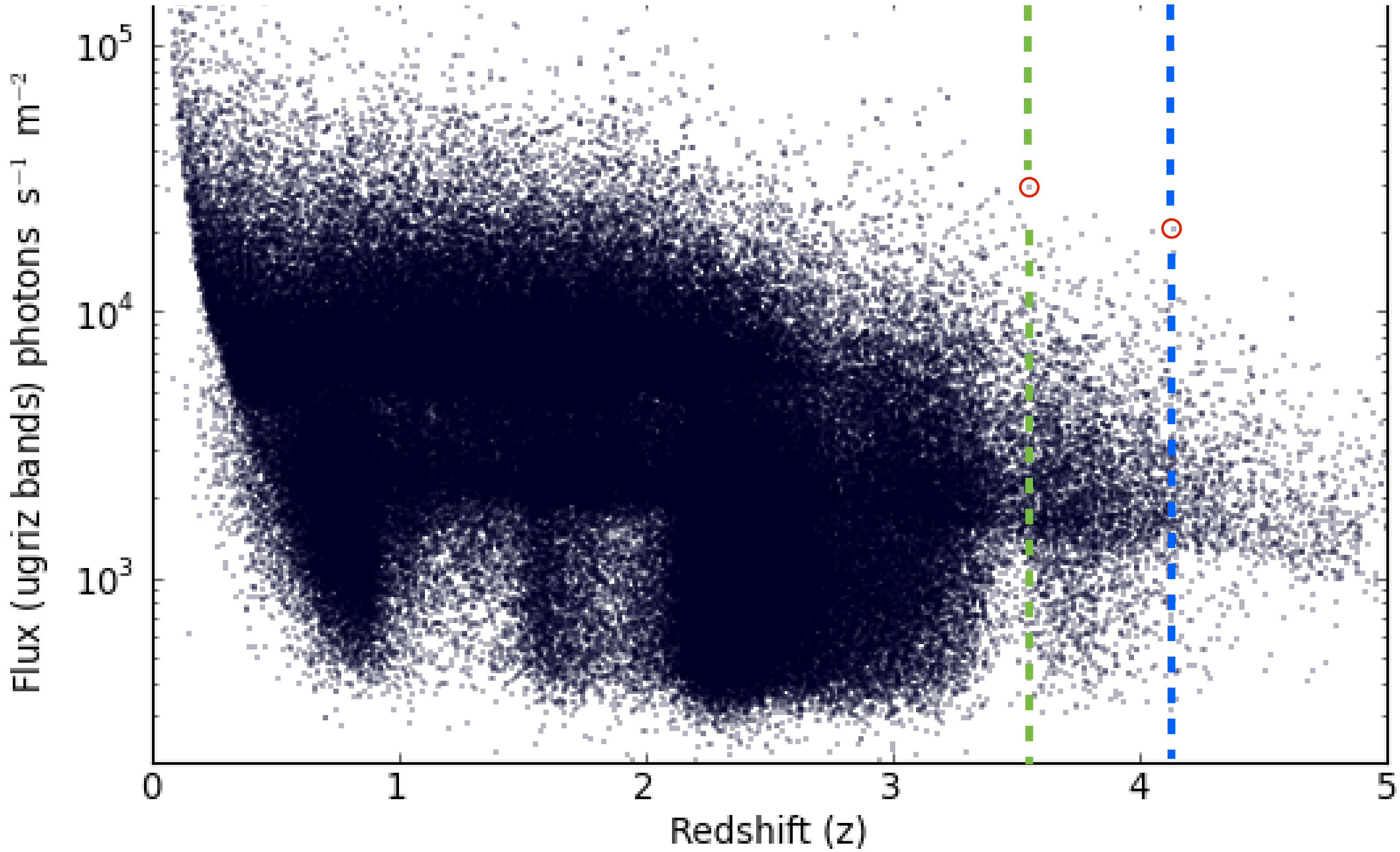
Animation 1 (F13a supplementary material)

http://prd.aps.org/supplemental/PRD/v88/i4/e044038

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

http://web.mit.edu/asf/www/01_conformal_movie.shtml

QUASAR FLUX VS. REDSHIFT



Ground based optical flux.

IR only usable from space

Local Sky noise!

Adapted from Fig. 3 (GFK13)

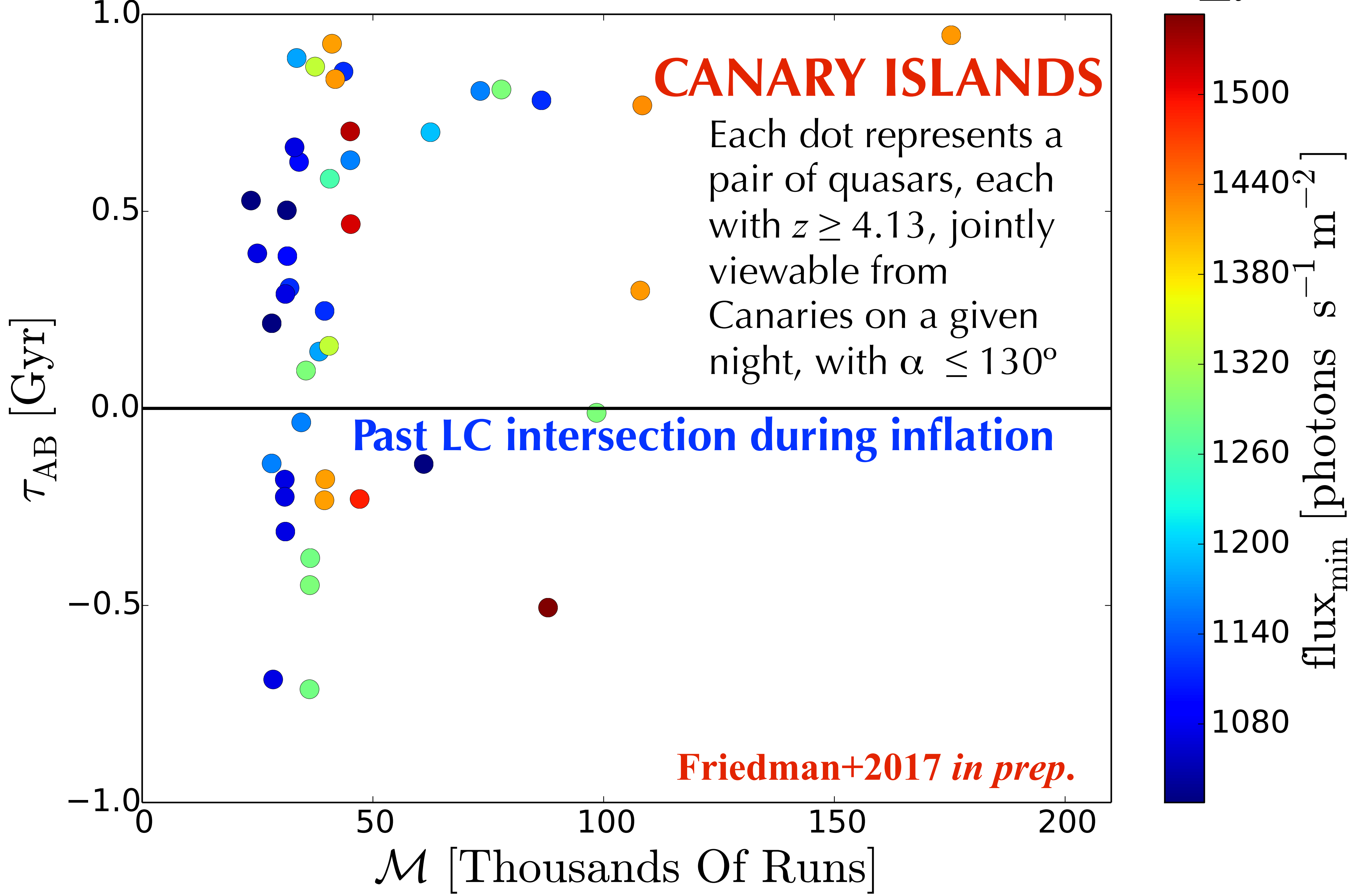
z~3.65 : $F_{Opt} \sim 3 \times 10^4$ photons s^{-1} m^{-2} **180 degrees**

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

SDSS quasars - photometric and spectroscopic redshifts

WHICH QUASARS TO USE?

$$\mathcal{M} \equiv \frac{T}{\Delta t} P_2 P_E$$



2 or more Cosmic Sources

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

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

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

	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	$105°$	$z > 4.89$

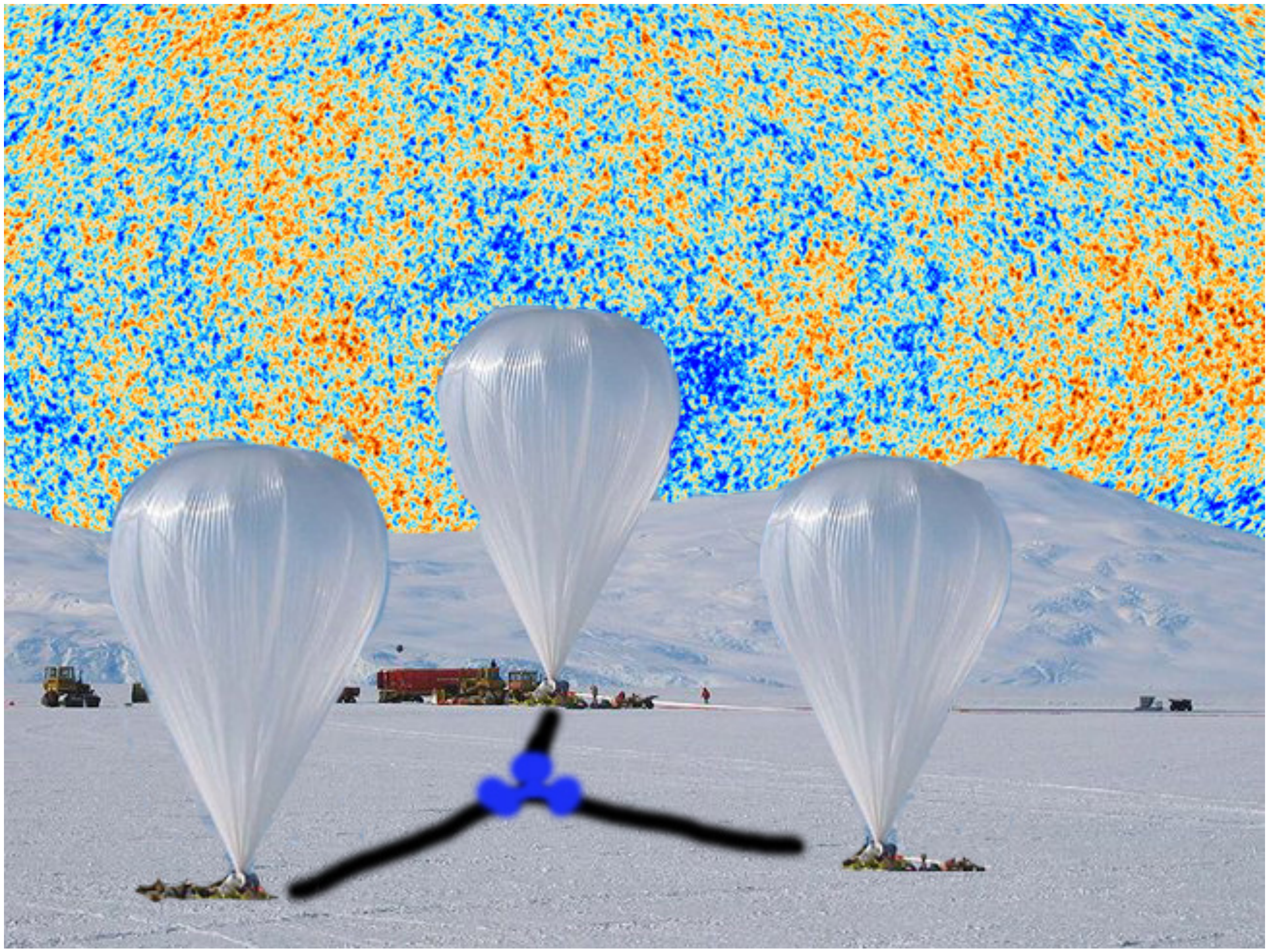
GFK13; Friedman+2017f *in prep*.

GHZ WITH CMB?

3+ particles, Bell's theorem without inequalities

QM, Local realism give opposite answers to yes/no questions

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



Balloon based test in Antarctica?

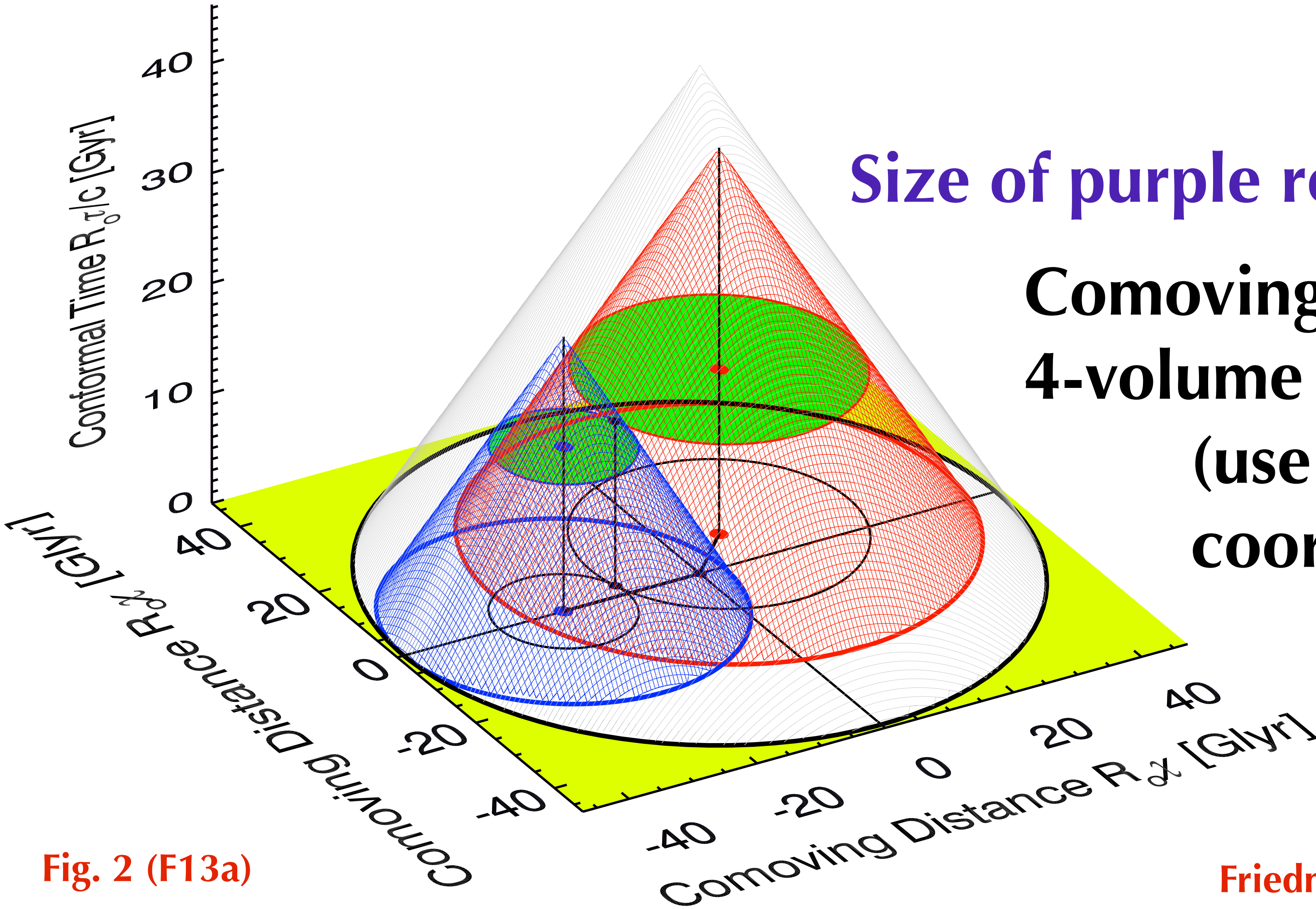
Easy! Pick 3 CMB patches, each separated by 2.3°

Hard! Local noise dominates from ground (GFK14)

Noise loophole limits better than 2-particle Bell test (Hall 2011)

EXTENT OF CAUSAL OVERLAP

What if Bell test correlations depended on causal overlap? Causal origin for entanglement via free will loophole?



Size of purple region.

Comoving spacetime 4-volume

(use physical coordinates)

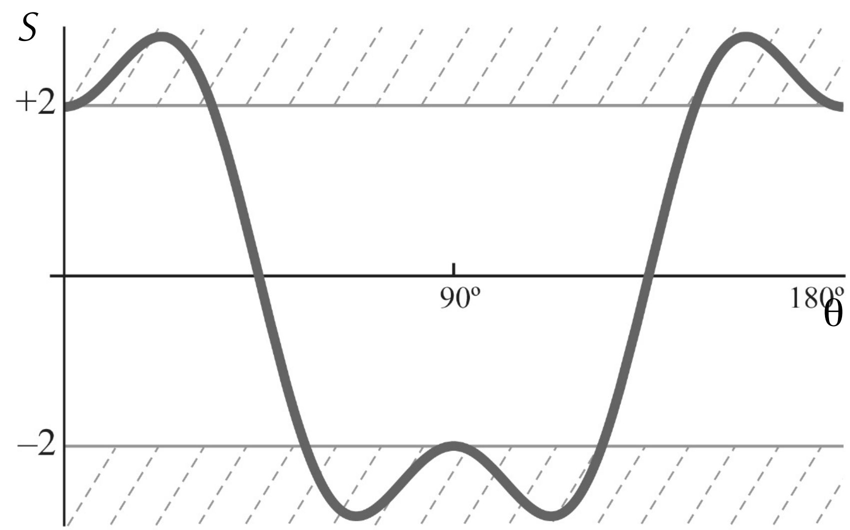
Fig. 2 (F13a)

Friedman+2017 *in prep.*

POSSIBLE OUTCOMES

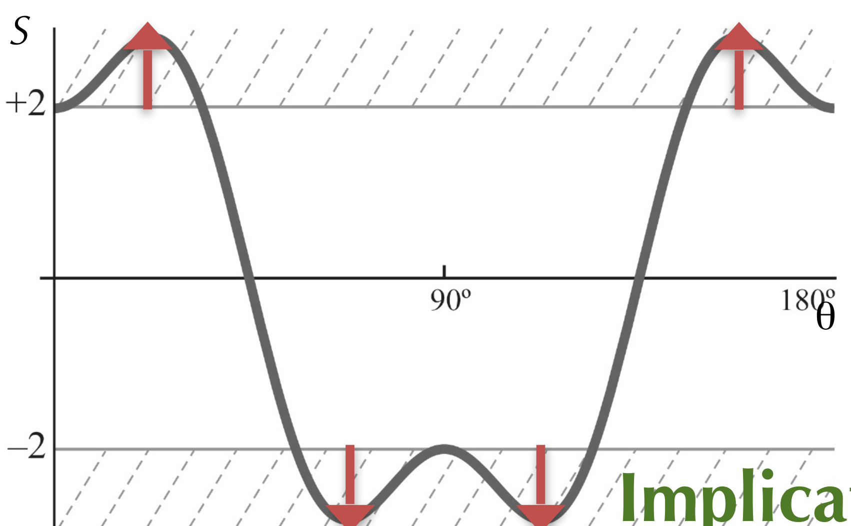
Expected:

Bell inequality always violated, for any *z* and α. That would rule out (or constrain) local hidden-variables theories as much as physically possible in our universe.



Unexpected:

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



Strangest:

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

Implications for inflation? Quantum gravity?

COSMIC BELL PUBLICATIONS

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

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] [2 Column PDF]

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t'Hooft 2007, (arXiv:quant-ph/0701097)
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Zeilinger 2010, "*Dance of the Photons*", Farrar, Straus & Giroux; 1st Ed.