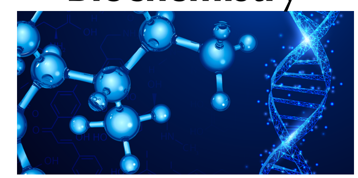
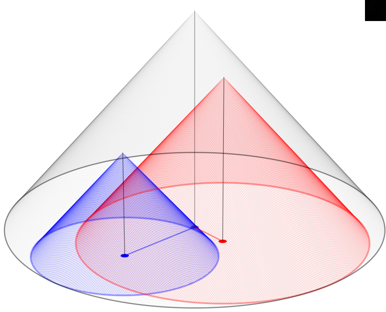
# A COSMIC TEST OF QUANTUM ENTANGLEMENT

SSP
THE SUMMER SCIENCE PROGRAM


UCSD

Biochemistry



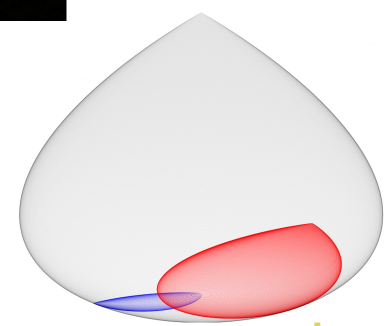



**Dr. Andrew Friedman**

UC San Diego

Center for Astrophysics and Space Sciences

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

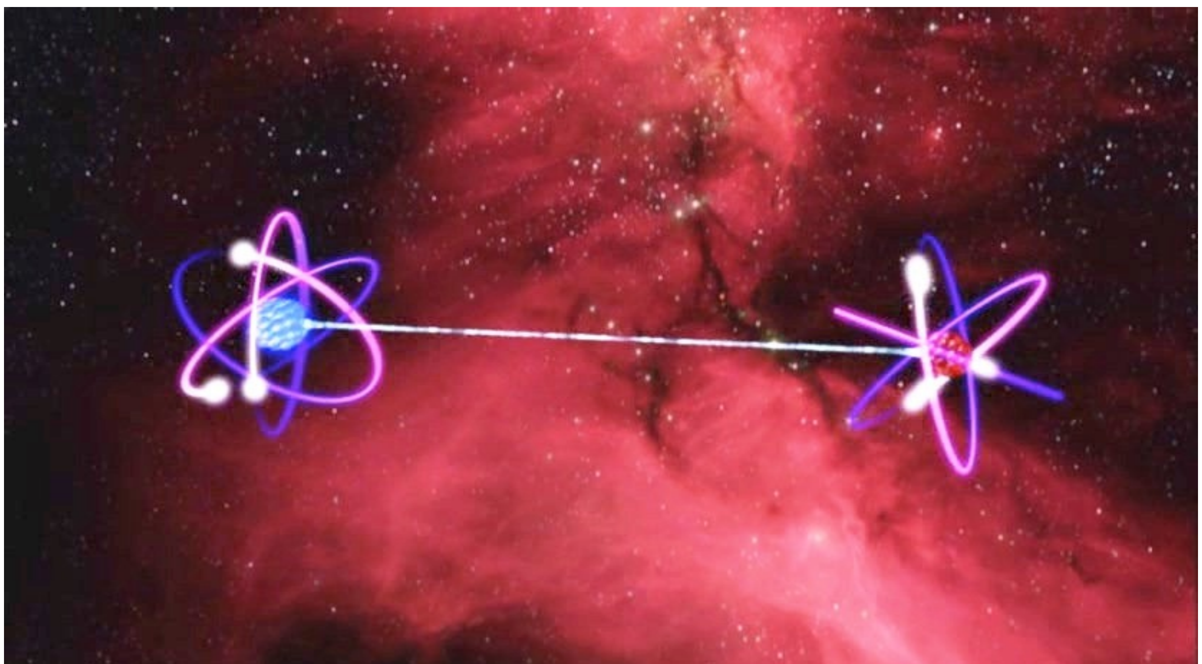
UCSD | CASS CENTER FOR ASTROPHYSICS AND SPACE SCIENCES | Massachusetts Institute of Technology | IQI Vienna | MPQ | HARVEY MUDD COLLEGE | NASA JPL | NSF

# QUANTUM ENTANGLEMENT 101

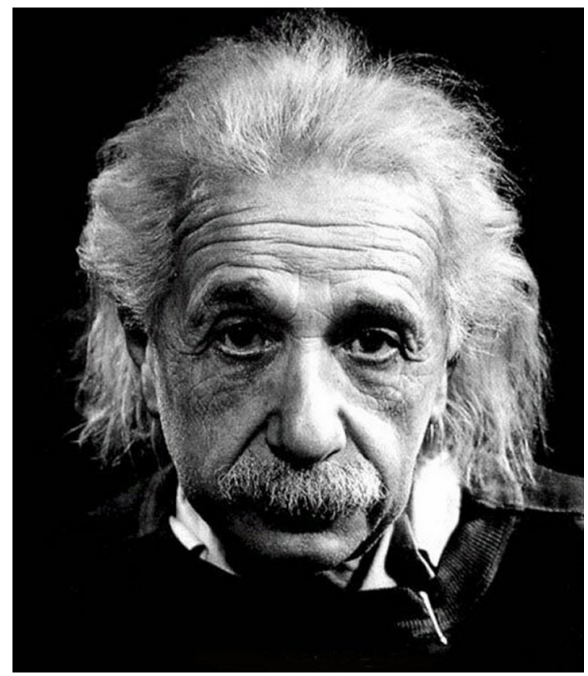
**Entanglement: Paired systems with correlated (or anti-correlated) properties**

**Measure #1, instantly know something about #2**

**Systems are NOT independent!**



https://kuleuvenblogt.files.wordpress.com/2014/06/entangled-atoms.jpg



http://xeon24.com/data/wallpapers/2/508769-albert-einstein.jpg

***Is quantum mechanics complete or just spooky?***

# COSMIC BELL TESTS

## Milky Way Stars (2017)

***Vienna, Austria***

**8, 10-inch telescopes**

**Light left nearest star ~600 years ago**

(C) IQOQI/ÖAW

## High Redshift Quasars (2018)

***The Canary Island of La Palma***

**3.6, 4.2-meter telescopes**

**Light left nearest quasar ~7.8 billion years ago!**

# SSP 2011 NEW MEXICO TECH

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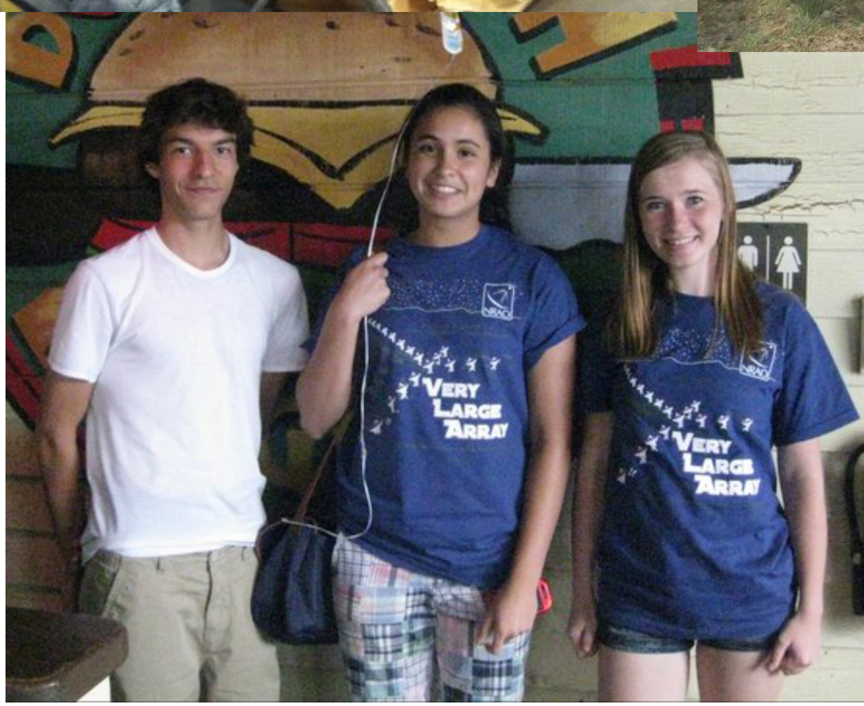


PRL **118,** 060401 (2017) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2017

# Cosmic Bell Test: Measurement Settings from Milky Way Stars

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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 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]

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Dr. Thomas Scheidl [2],
Dr. Johannes Kofler [4],
Dr. Hien Nguyen [6],
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Calvin Leung [3]
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1: MIT Physics/CTP
2: Vienna IQOQI
3: Harvey Mudd
4: Max Planck MPQ
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6: NASA JPL/Caltech

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NSF

ÖAW Austrian Academy of Sciences

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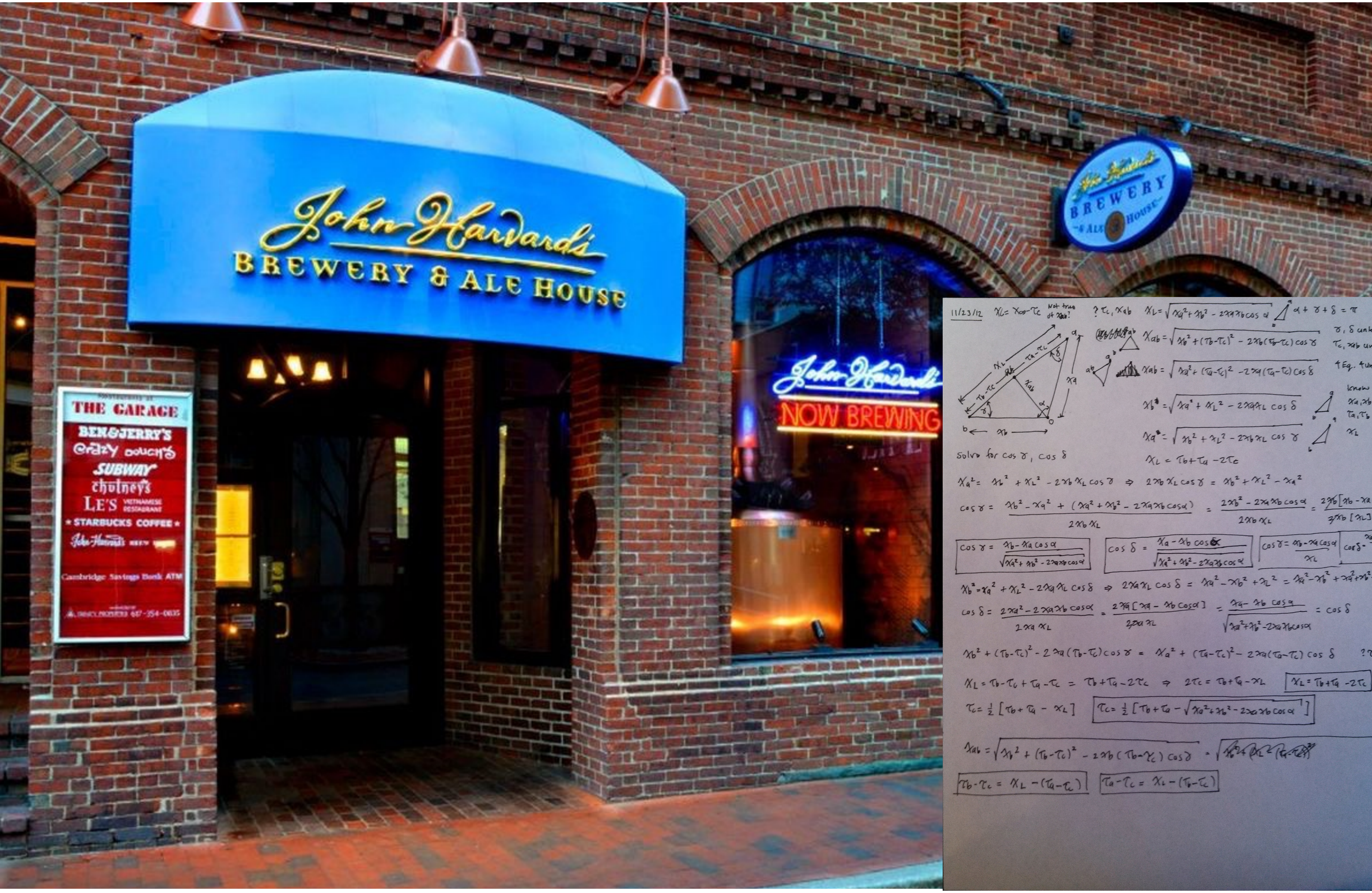
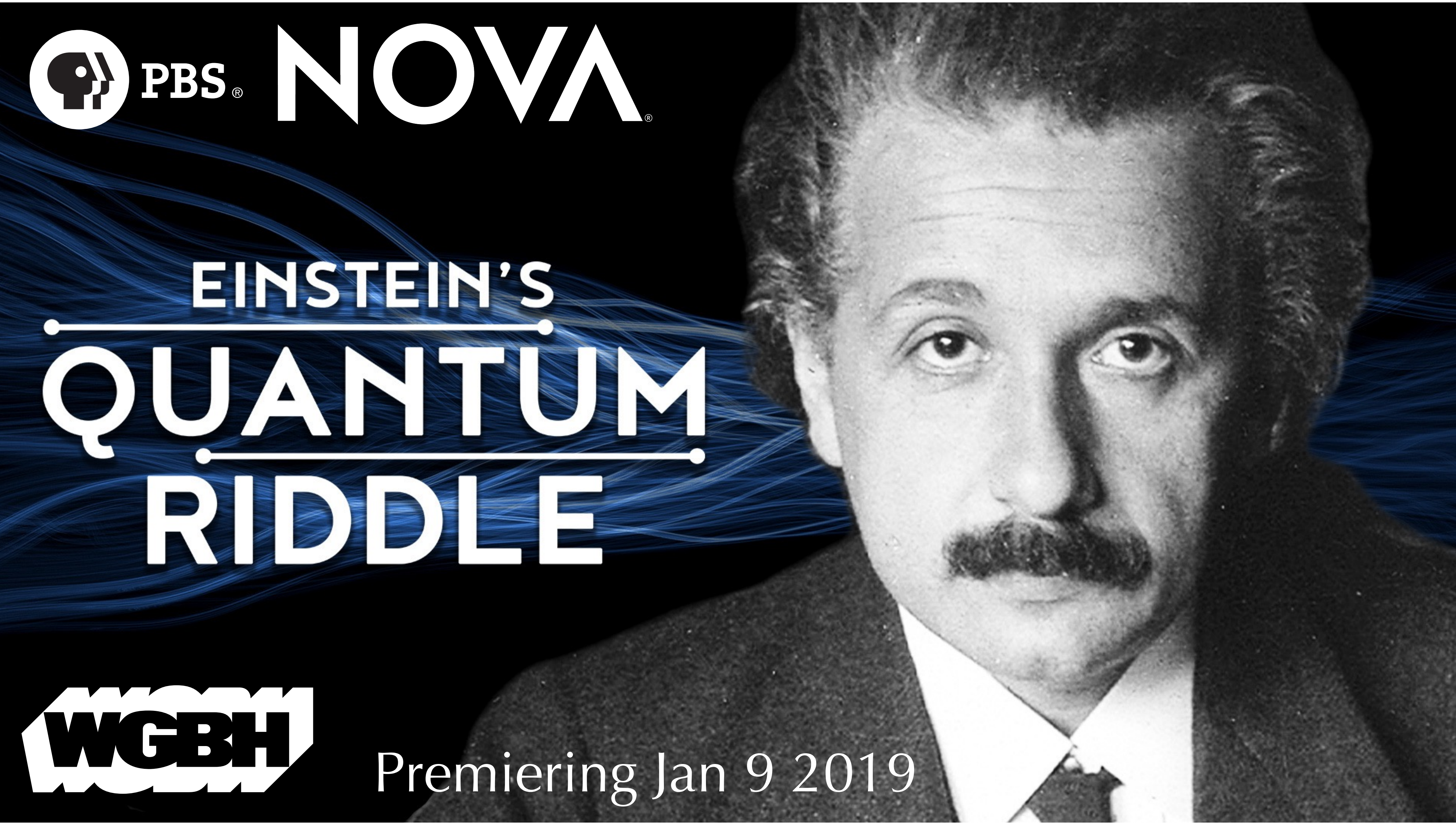
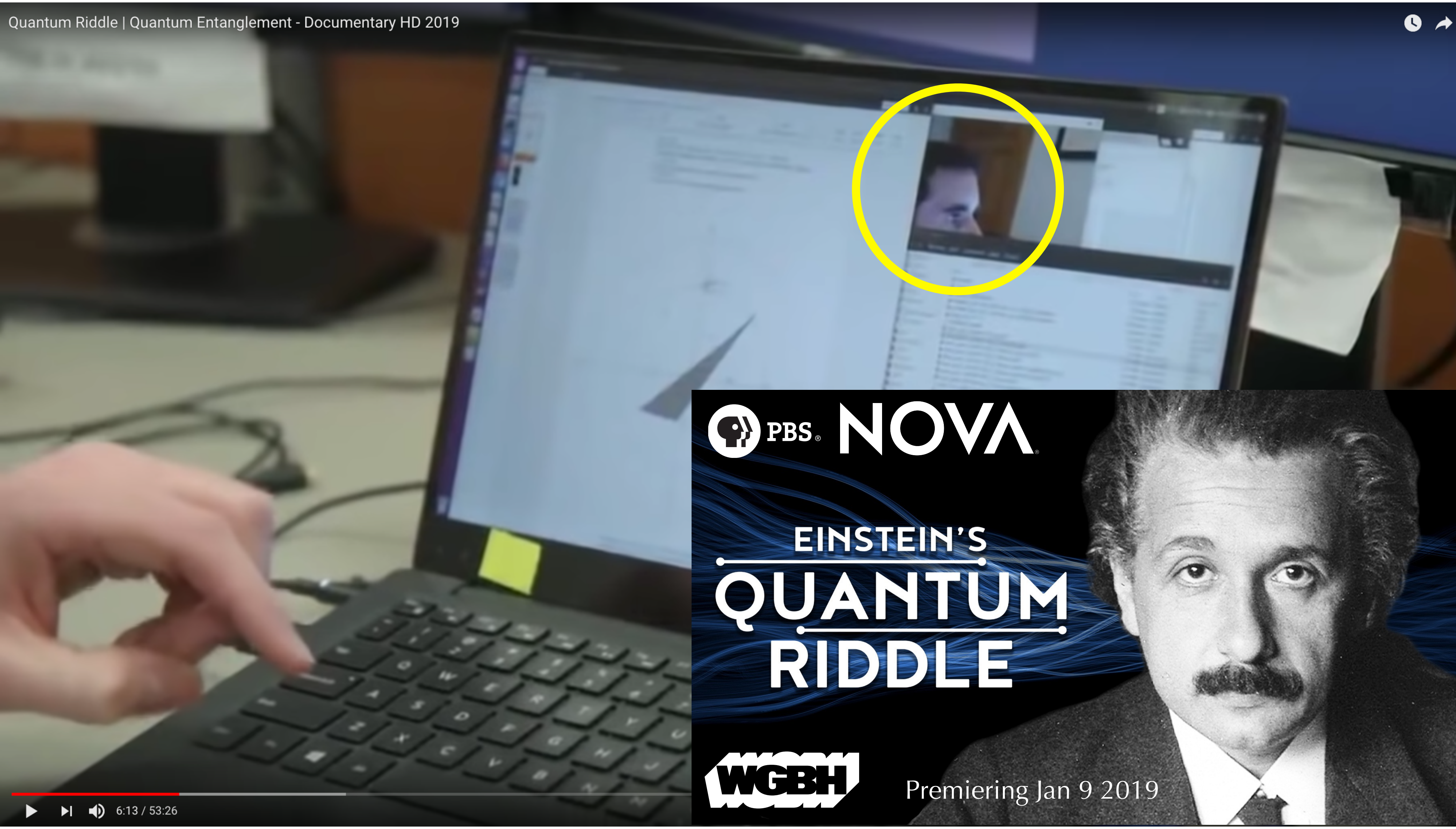
# BACK OF THE ENVELOPE



# COSMIC BELL TEST ON TV!



# 3 SECONDS OF FAME!




**Einstein's Quantum Riddle, PBS NOVA, Season 46, Episode 2, 6:12-6:15**

# 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

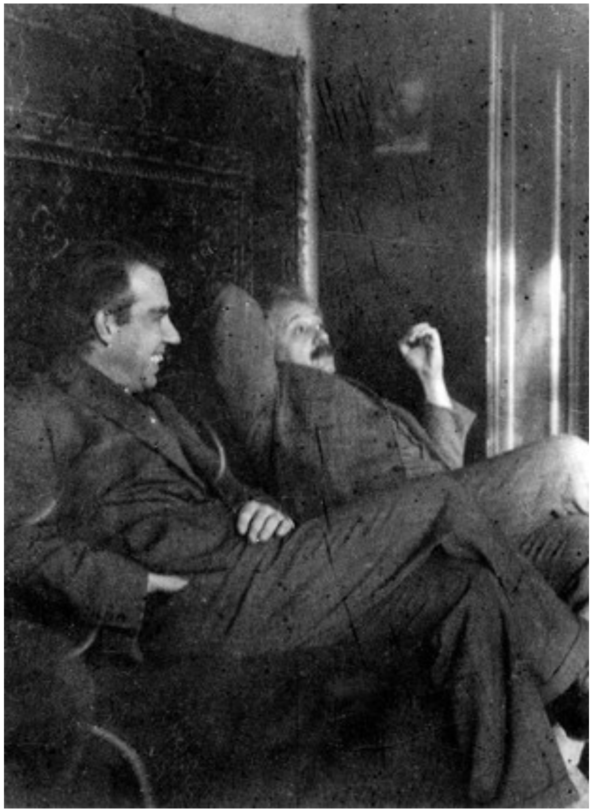
4. Cosmic Bell Test with Milky Way Stars

5. Cosmic Bell Test with Quasars

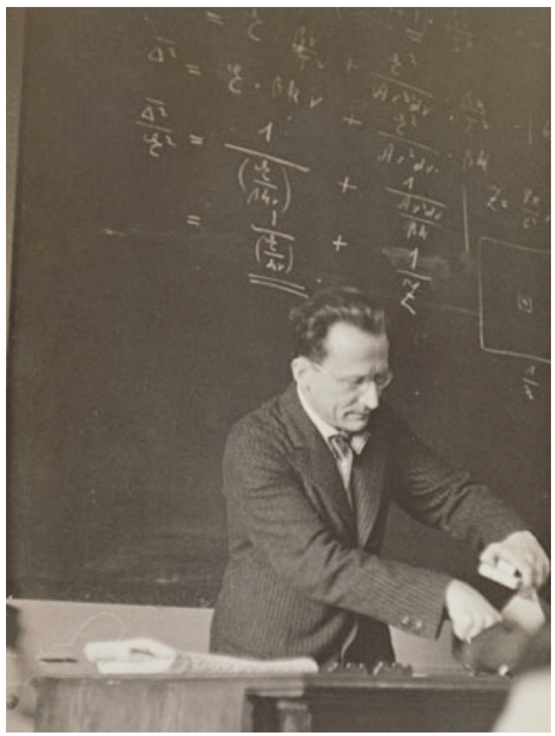
6. Future Tests

# QUANTUM ENTANGLEMENT

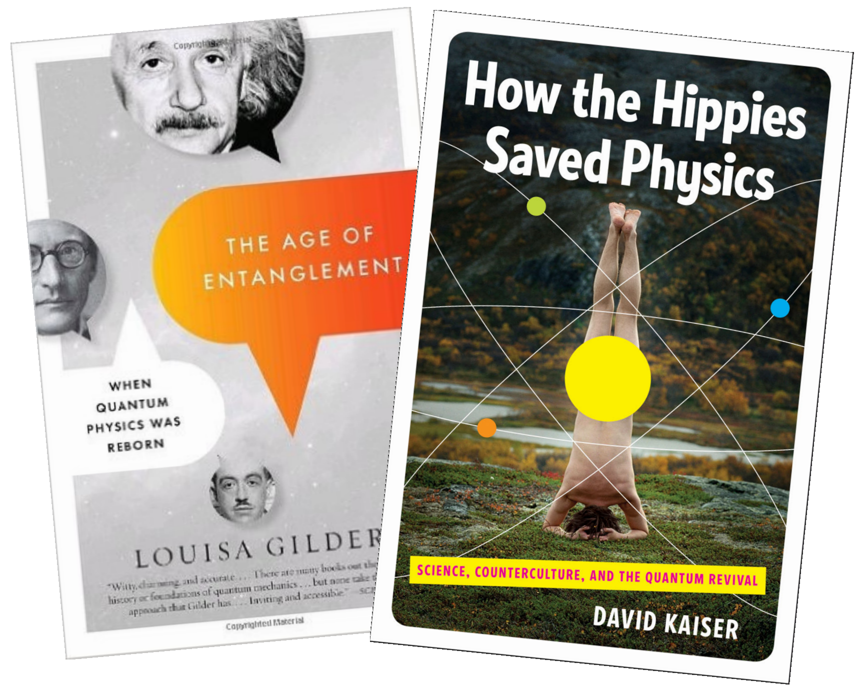
Beginning in the 1930s, the great architects of quantum theory struggled to understand the notion of "entanglement."



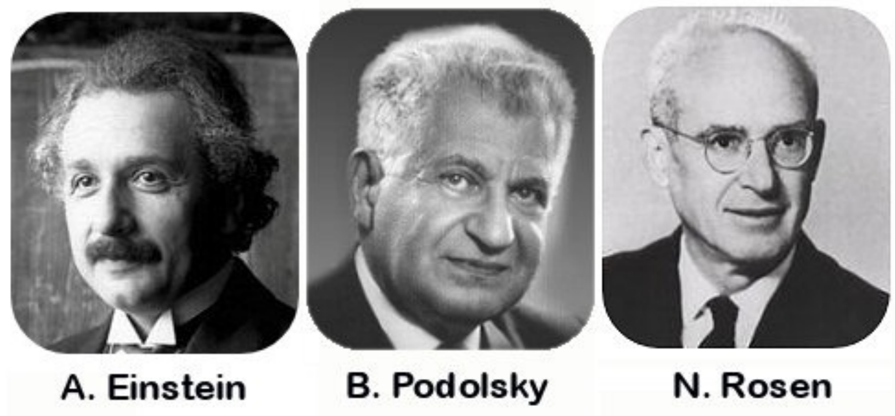
Niels Bohr and Albert Einstein



Erwin Schrödinger



# EPR PARADOX AND HIDDEN VARIABLES




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*

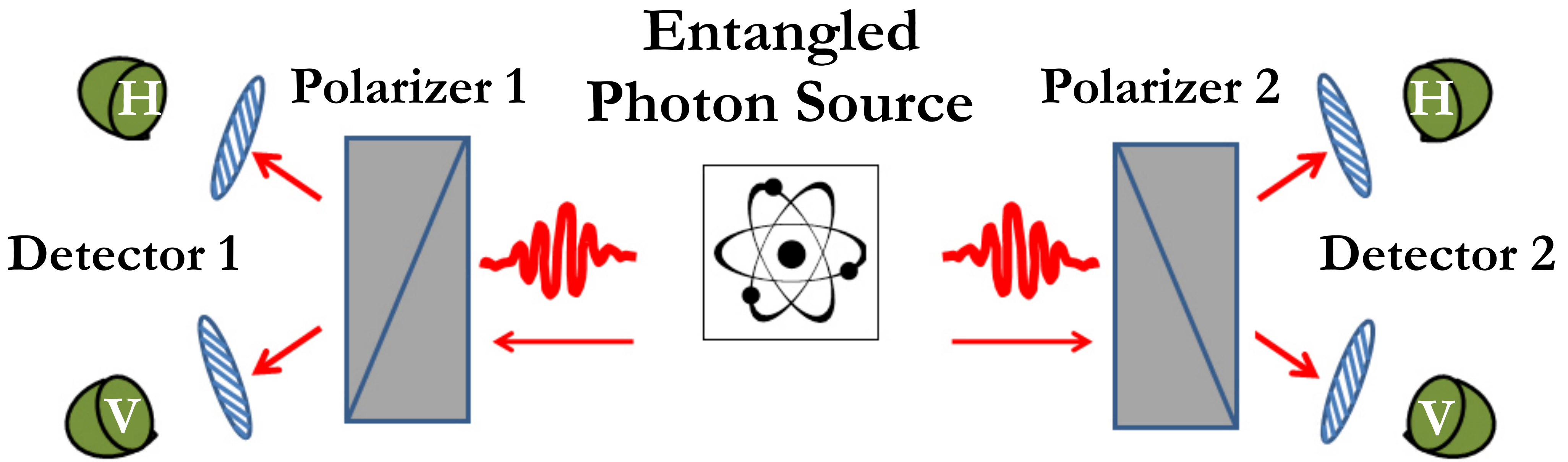
(Received March 25, 1935)

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

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

# ENTANGLED PARTICLE EXPERIMENTS

## "Bell Test"



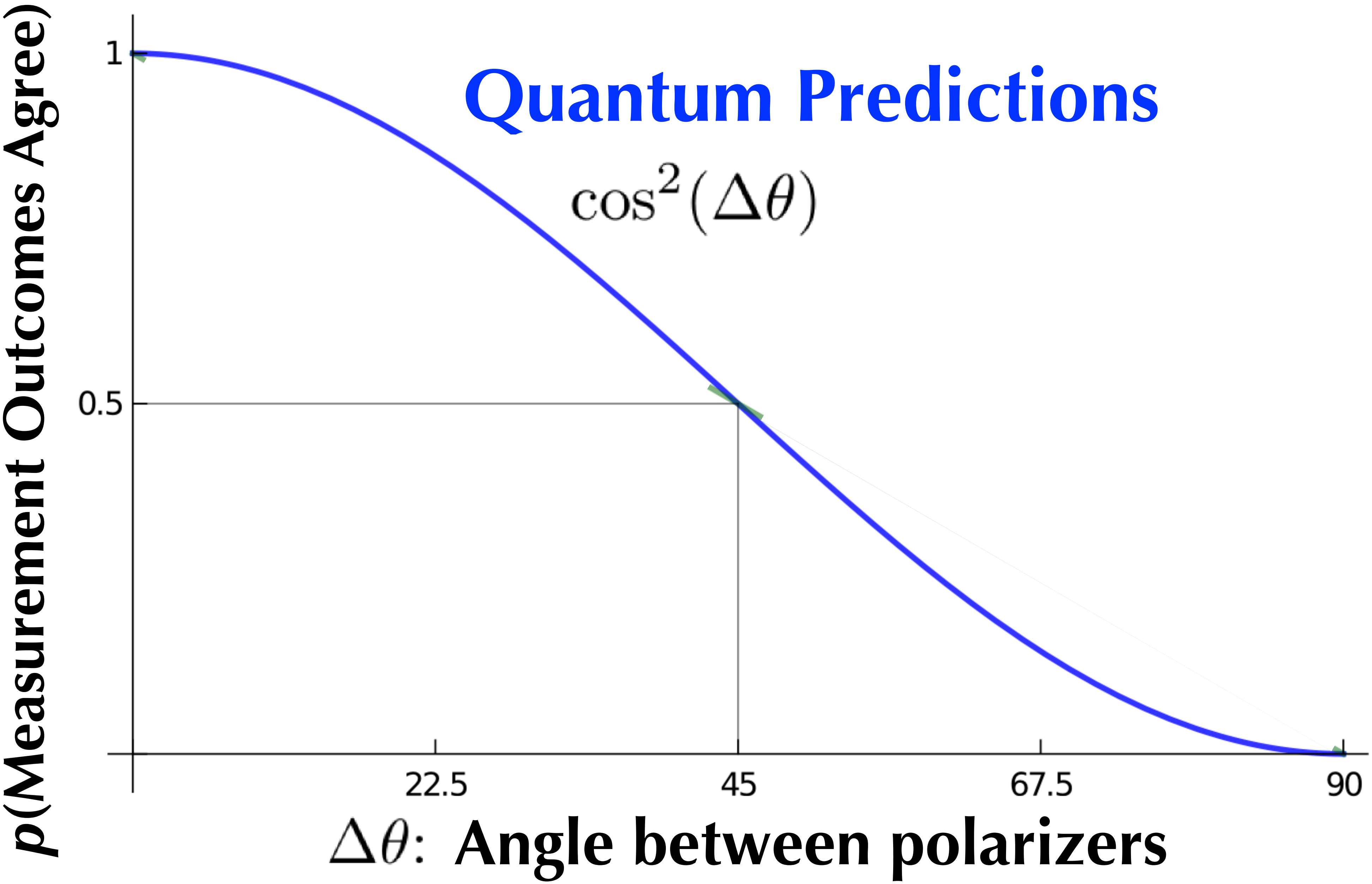

Can rotate polarizers

Same direction: same outcome (HH, VV)

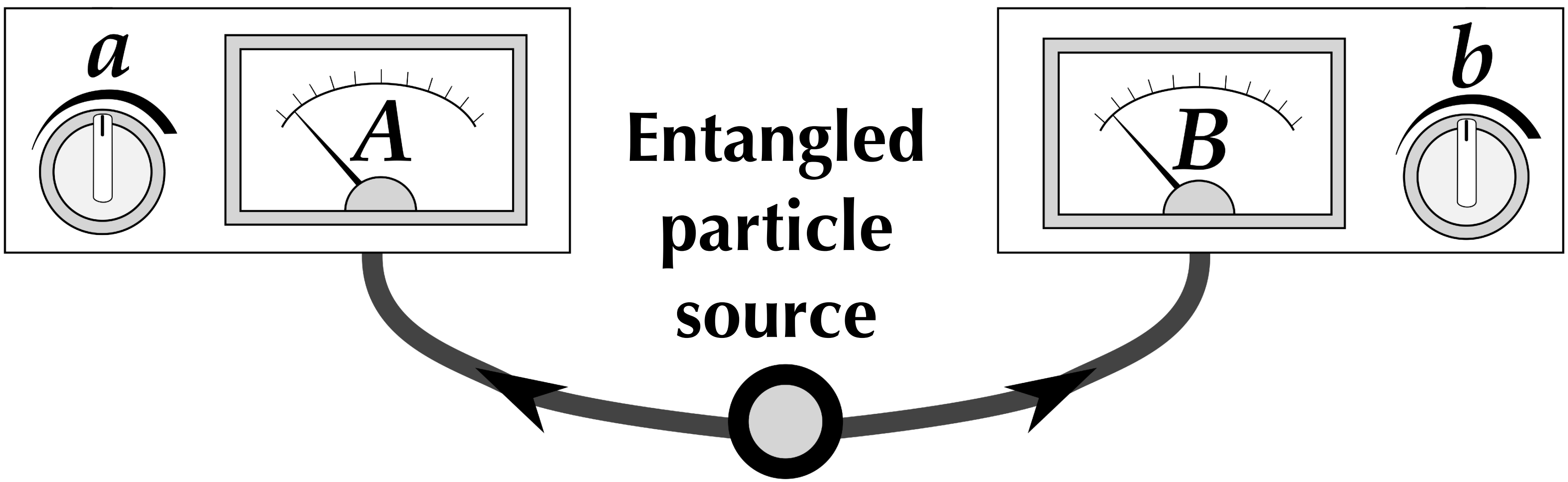
90 degrees: opposite outcome (HV, VH)

Image modified from http://blogs-images.forbes.com/chadorzel/files/2015/07/aspect3.png

# PHOTON POLARIZATION CORRELATION



# BELL TESTS




*a*, *b* : Settings

*A*, *B* : Outcomes

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

**If yes, QM incomplete → *Hidden variables***

# WHY CAUSAL EXPLANATIONS FAIL

**Quantum correlation is NOT like classical correlation!**




http://themassinvasion.com/wp-content/uploads/2015/07/Mystery-Box.jpg http://youwantmetowearwhat.com/wp-content/uploads/2010/11/Left-Right-Gloves.jpg

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# Bell's Inequality Assumptions

1. Realism
2. Locality
3. Freedom

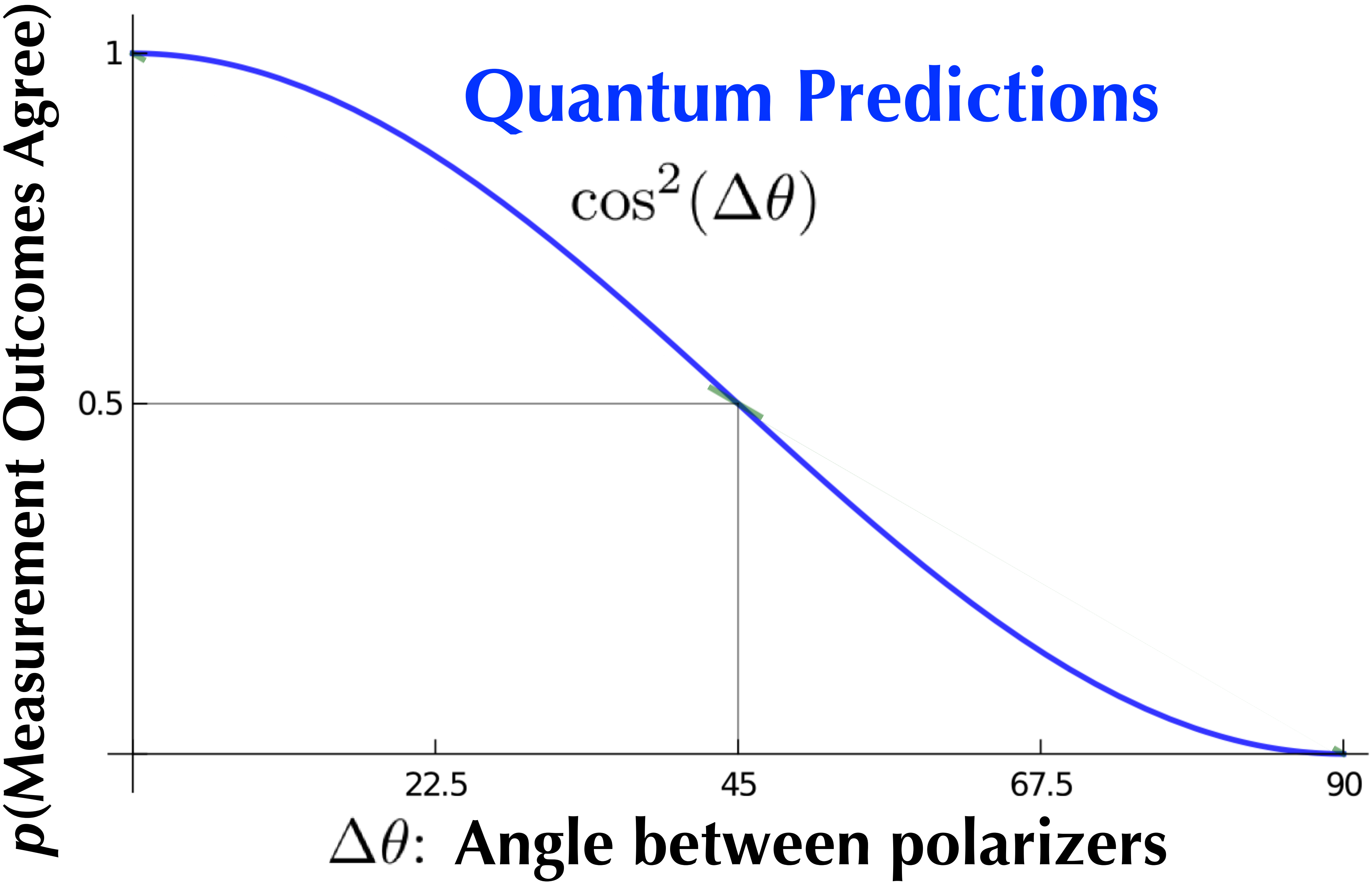
http://images.iop.org/objects/ccr/cern/54/7/19/CCfac8_07_14.jpg

John S. Bell (1928-1990)

**1,2,3 → Bell's Inequality**

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

# PHOTON POLARIZATION CORRELATION



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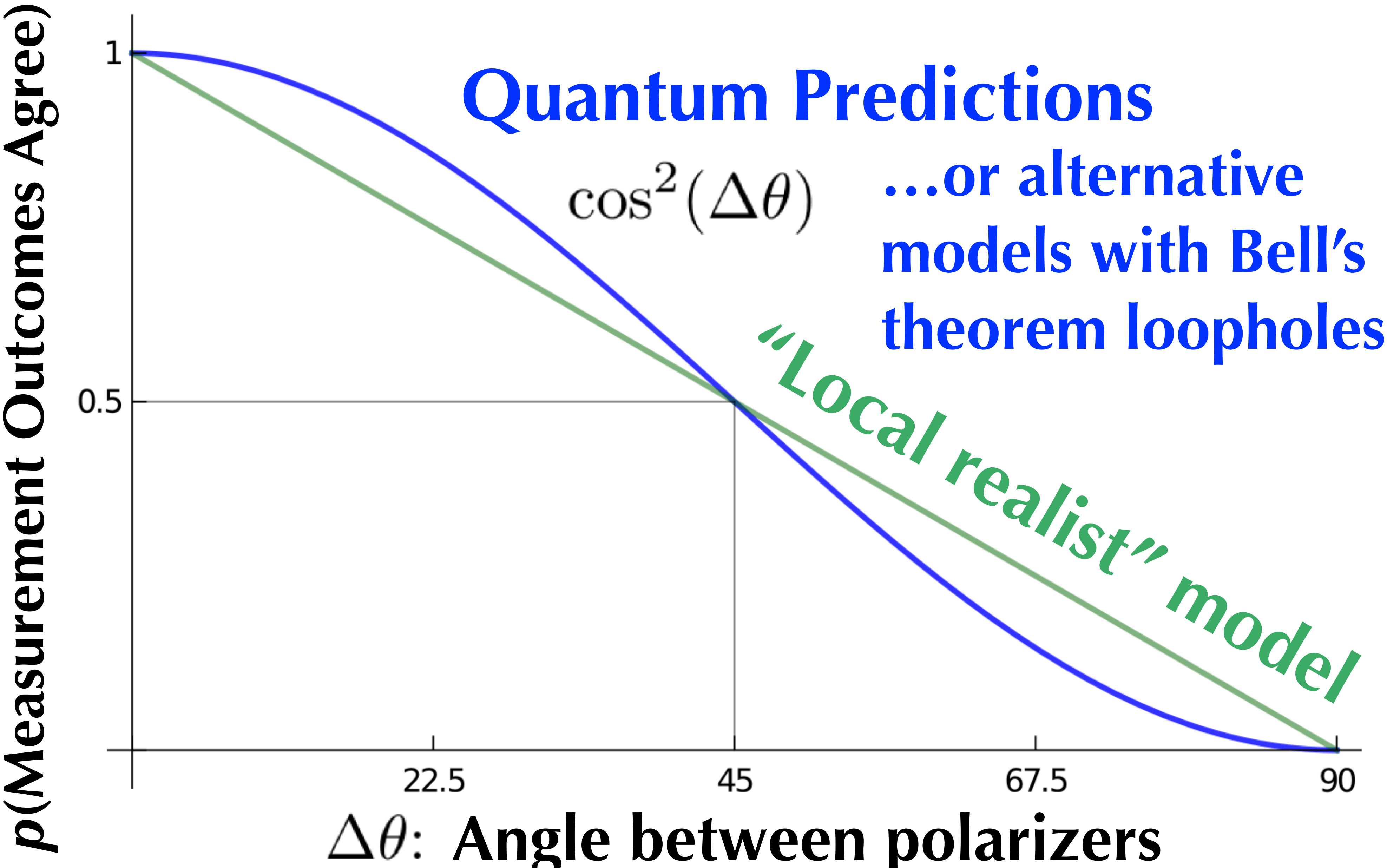


# BELL'S THEOREM

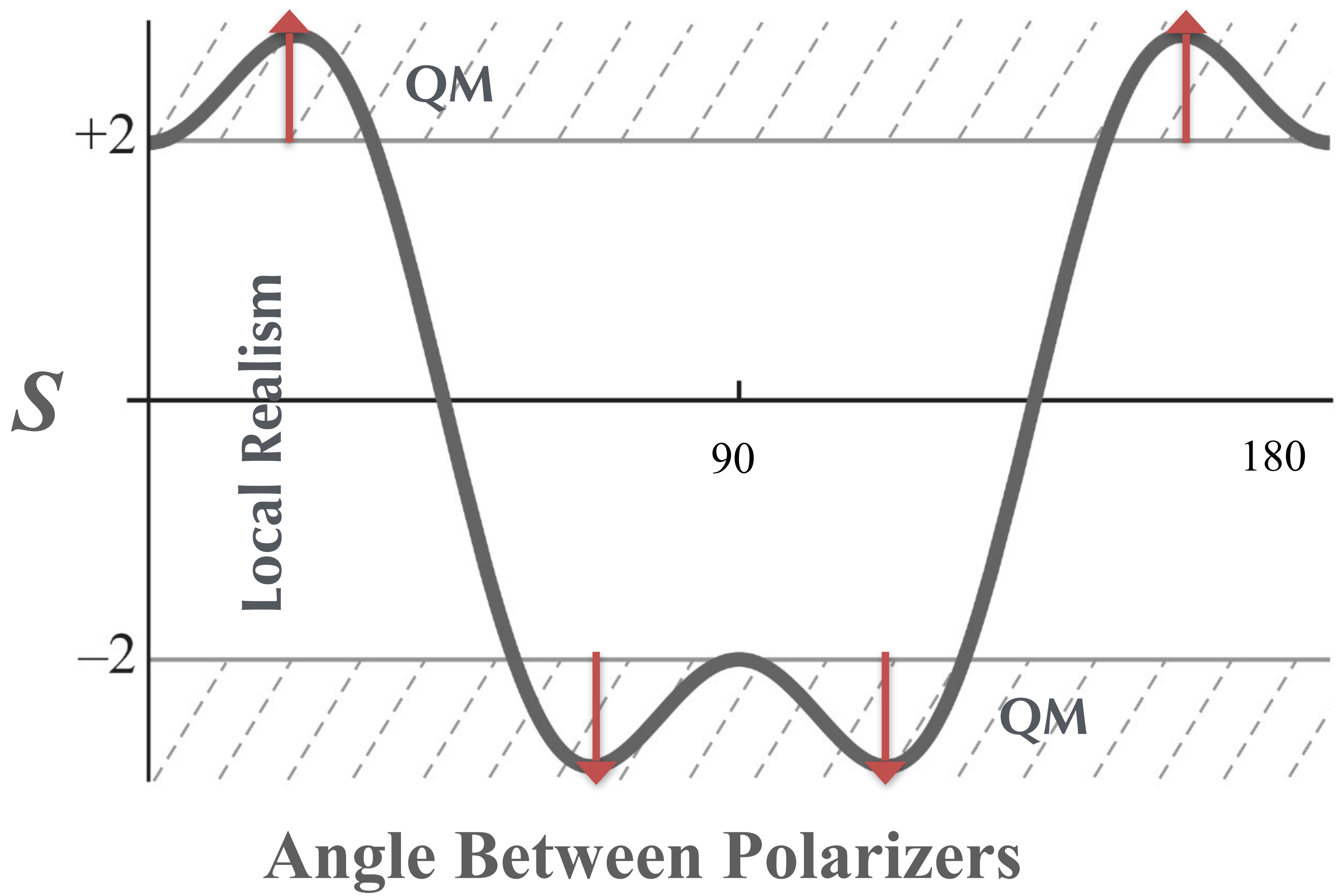
**No local-realist theories can reproduce the quantum predictions!**

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

Bell's assumptions imply $|S| \leq 2$.

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

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

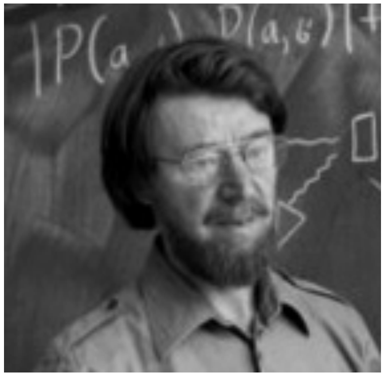



**Clauser, Horne, Shimony, & Holt (CHSH) 1969**

# RELAXING BELL'S ASSUMPTIONS

## 1. Realism 2. Locality 3. Freedom

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



## → At least one of 1,2,3 are false!

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

*Alternative models could mimic quantum theory*

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

Friedman, Guth, Hall, Kaiser, & Gallicchio 2019, *Phys Rev A*, 99, 1, 012121 (arXiv:1809.01307)

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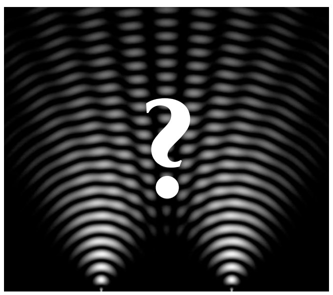
# LOOPHOLES & WHY THEY MATTER

**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?

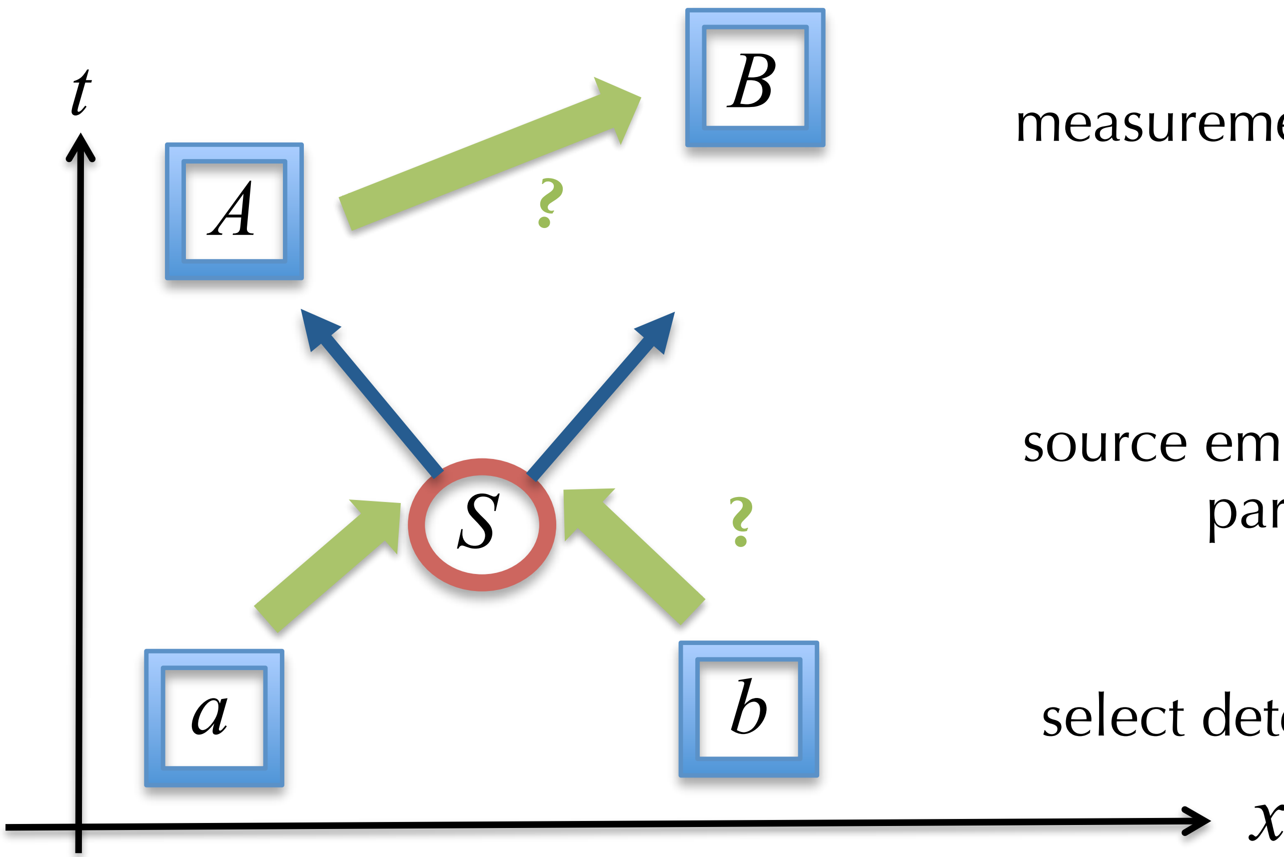

## Quantum cryptography security

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

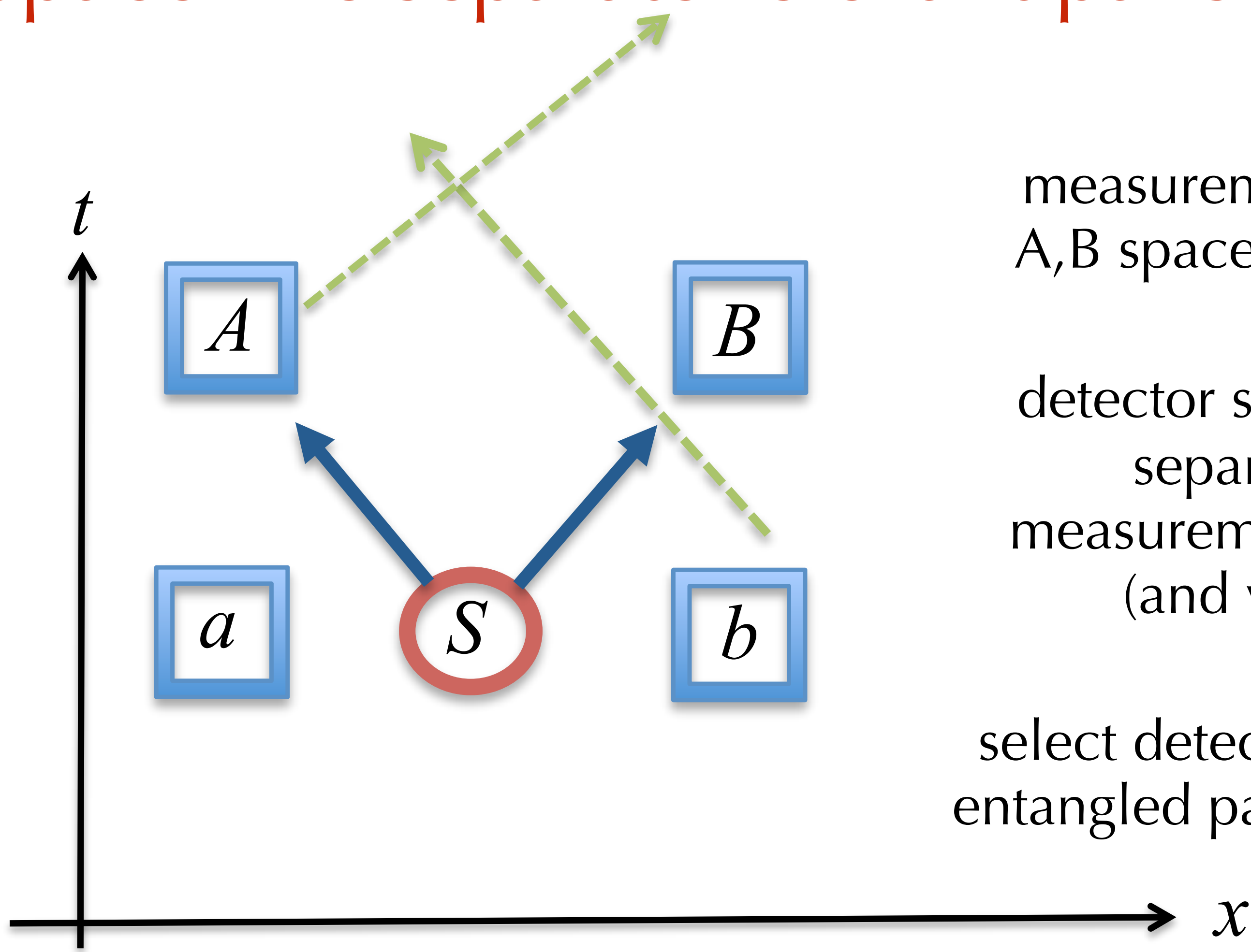
source emits entangled particles

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 A,B space like separated

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

select detector settings while entangled particles are in flight

# DETECTION EFFICIENCY LOOPHOLE

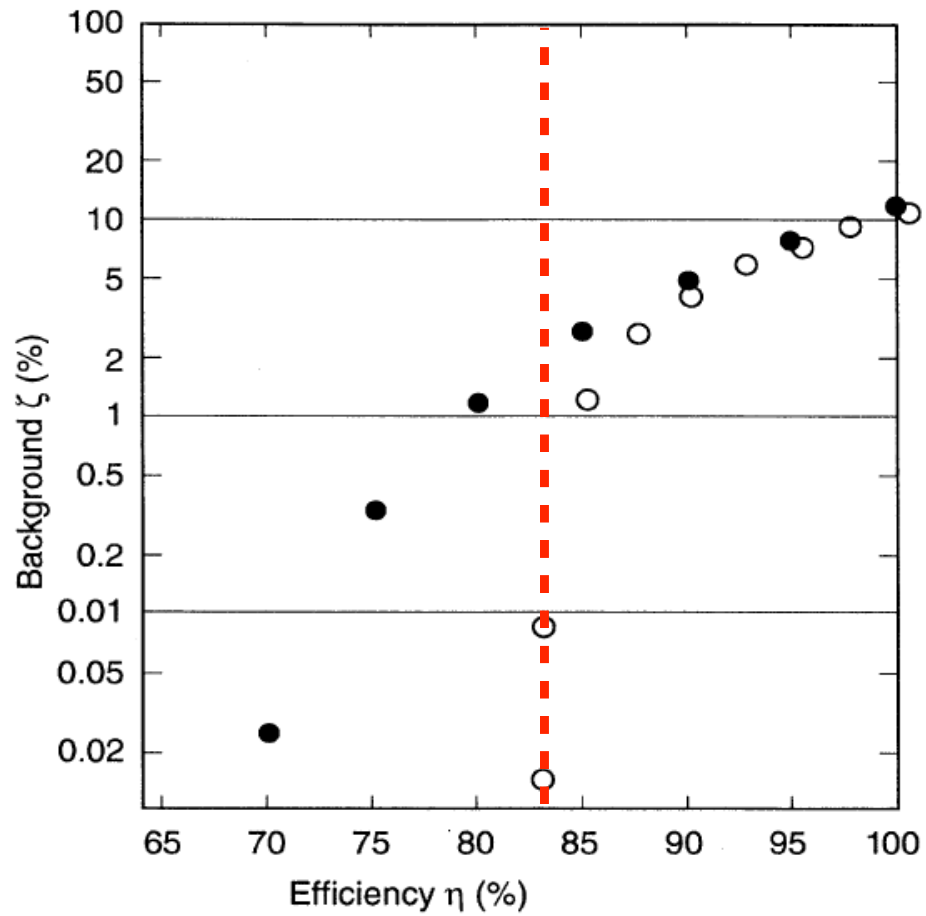
**The standard interpretation of Bell tests — that "local realism" is incompatible with experiment — relies upon several assumptions.**

Also called the "fair-sampling" loophole

No detectors are 100% efficient.

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

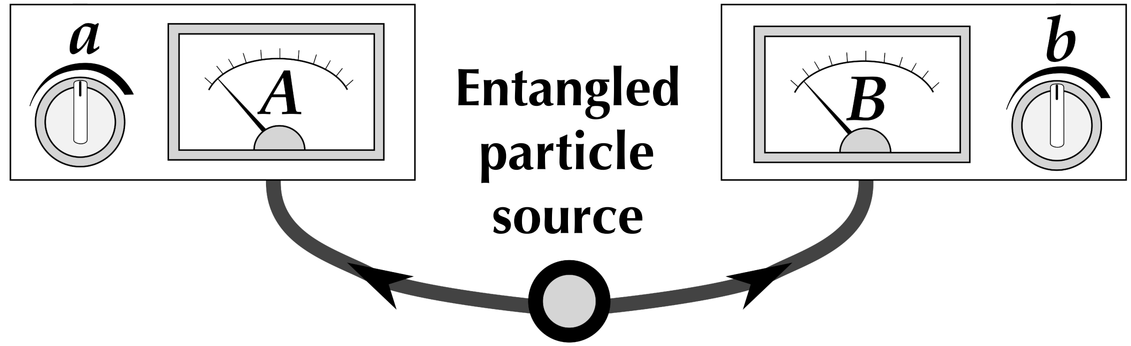
**Closing loophole requires detector efficiencies ≥ 83%**




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

# FREEDOM OF CHOICE LOOPHOLE


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




If detector settings depend on hidden variables $\lambda$ (e.g. from past events), experimental choices might not be perfectly free!

Still have free will!

But limited freedom

# 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**

# 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!*

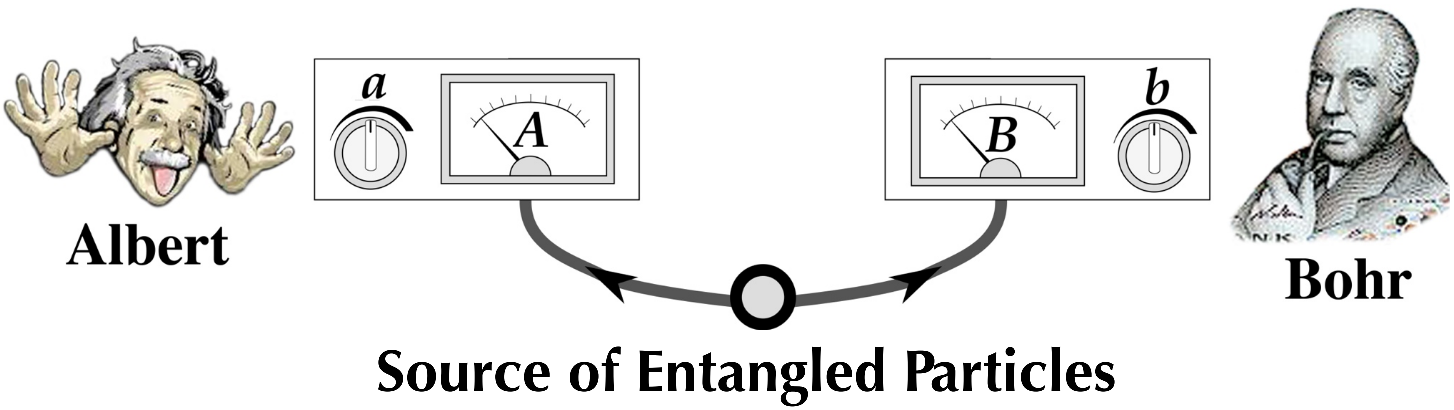
## Locality & Detection & Freedom (photons)

**Li+2018 (China)**




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

# Choosing Detector Settings




Adapted from: Gallicchio, Friedman, & Kaiser 2014

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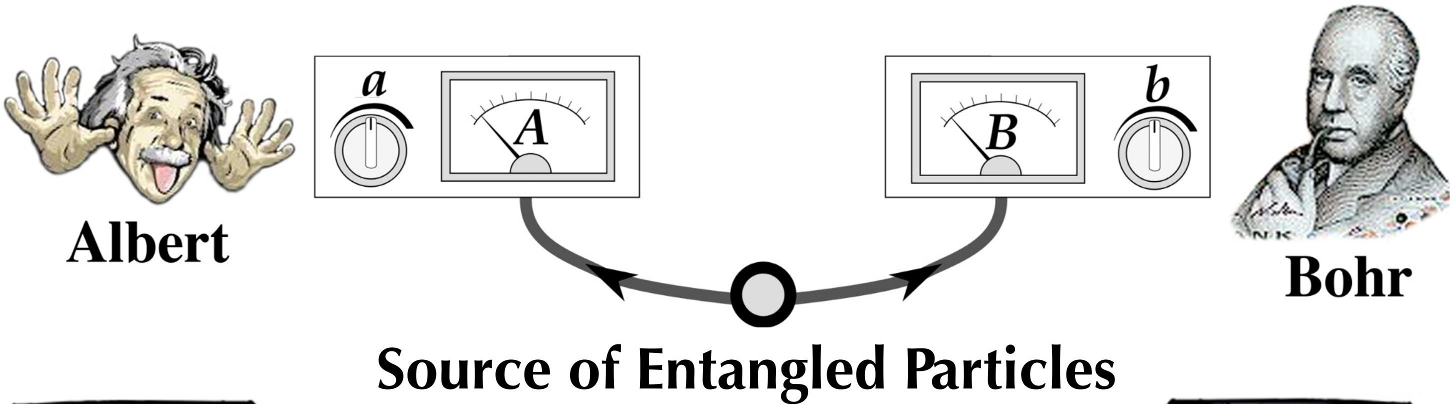


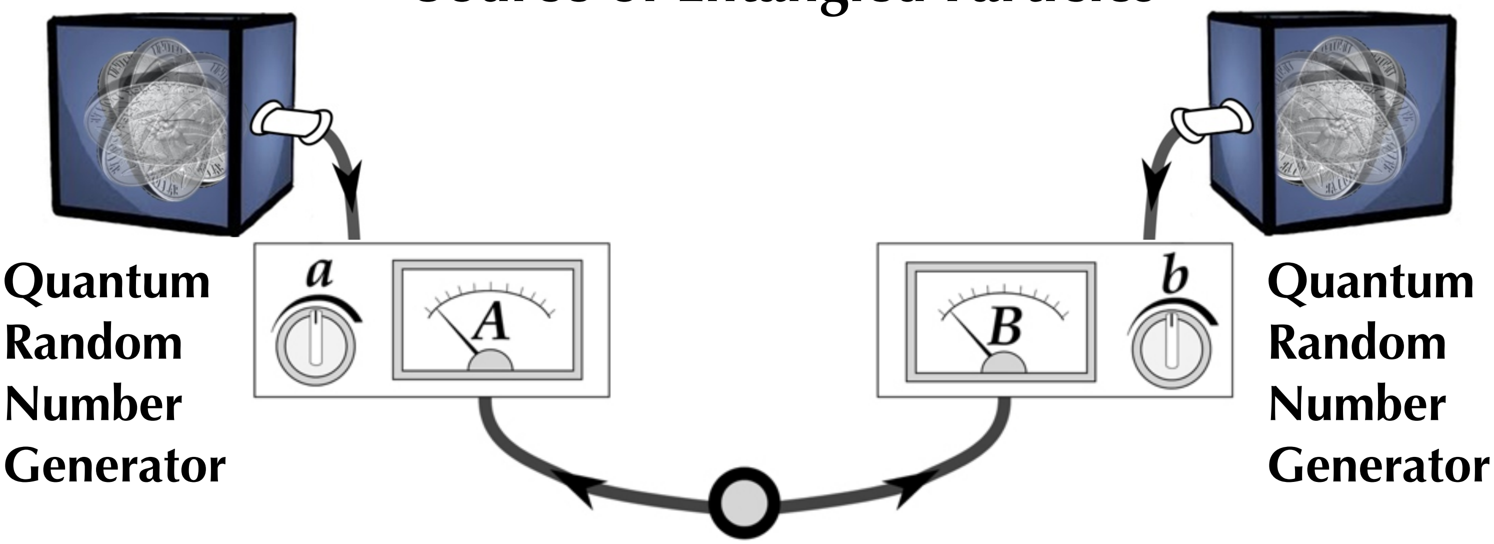


Adapted from:
Gallicchio, Friedman,
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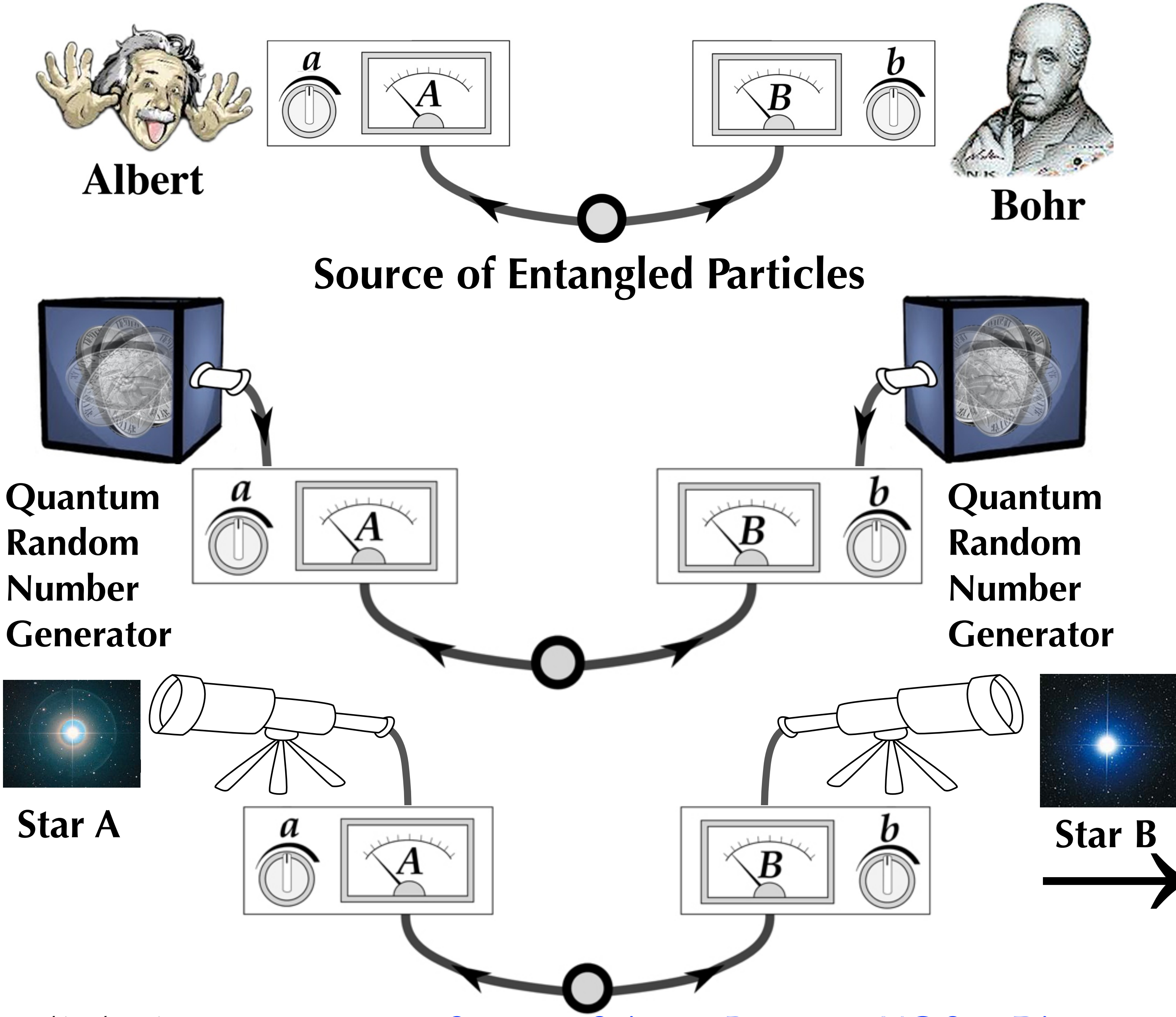
# CHOOSING DETECTOR SETTINGS

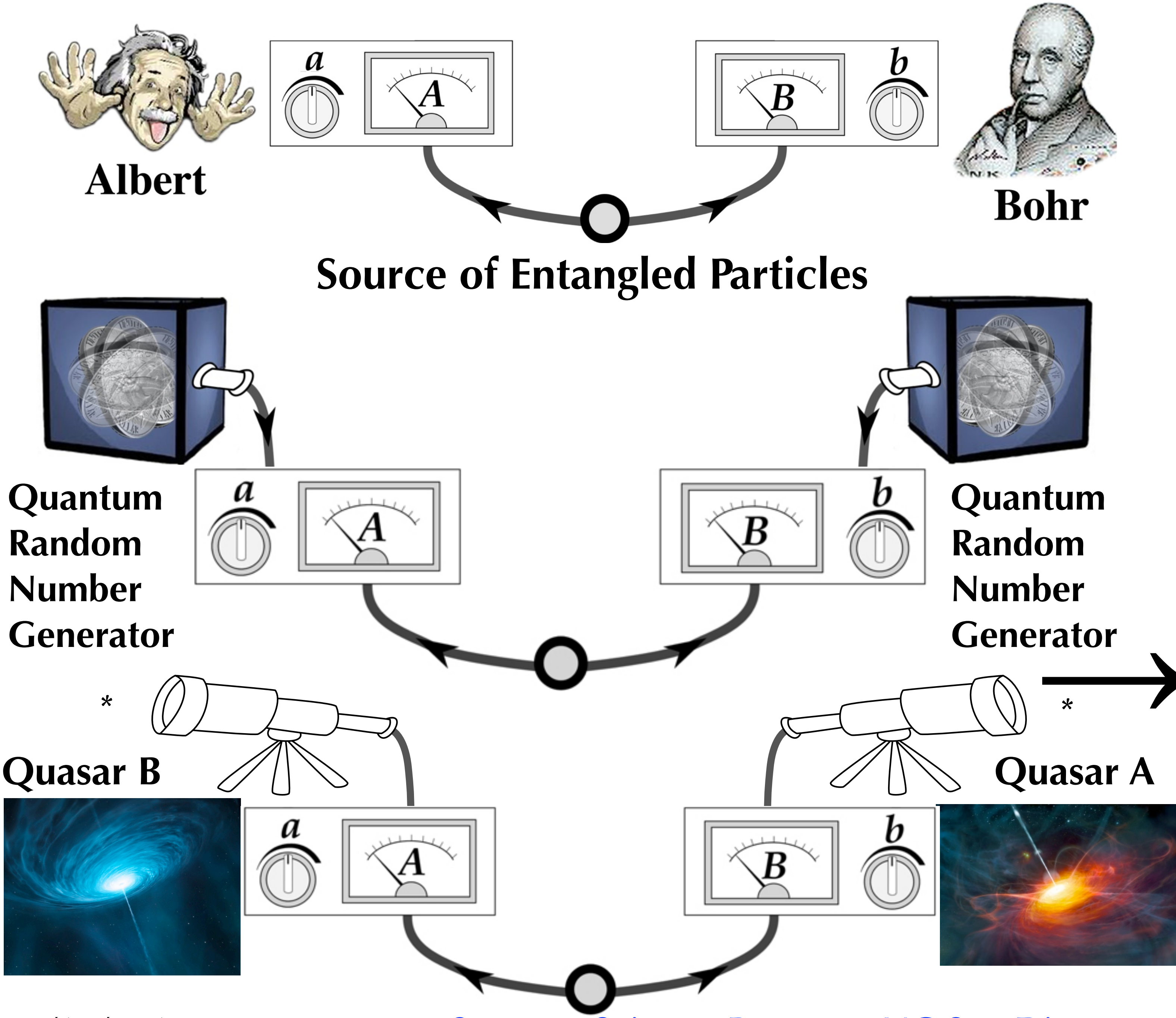



Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

# CHOOSING DETECTOR SETTINGS

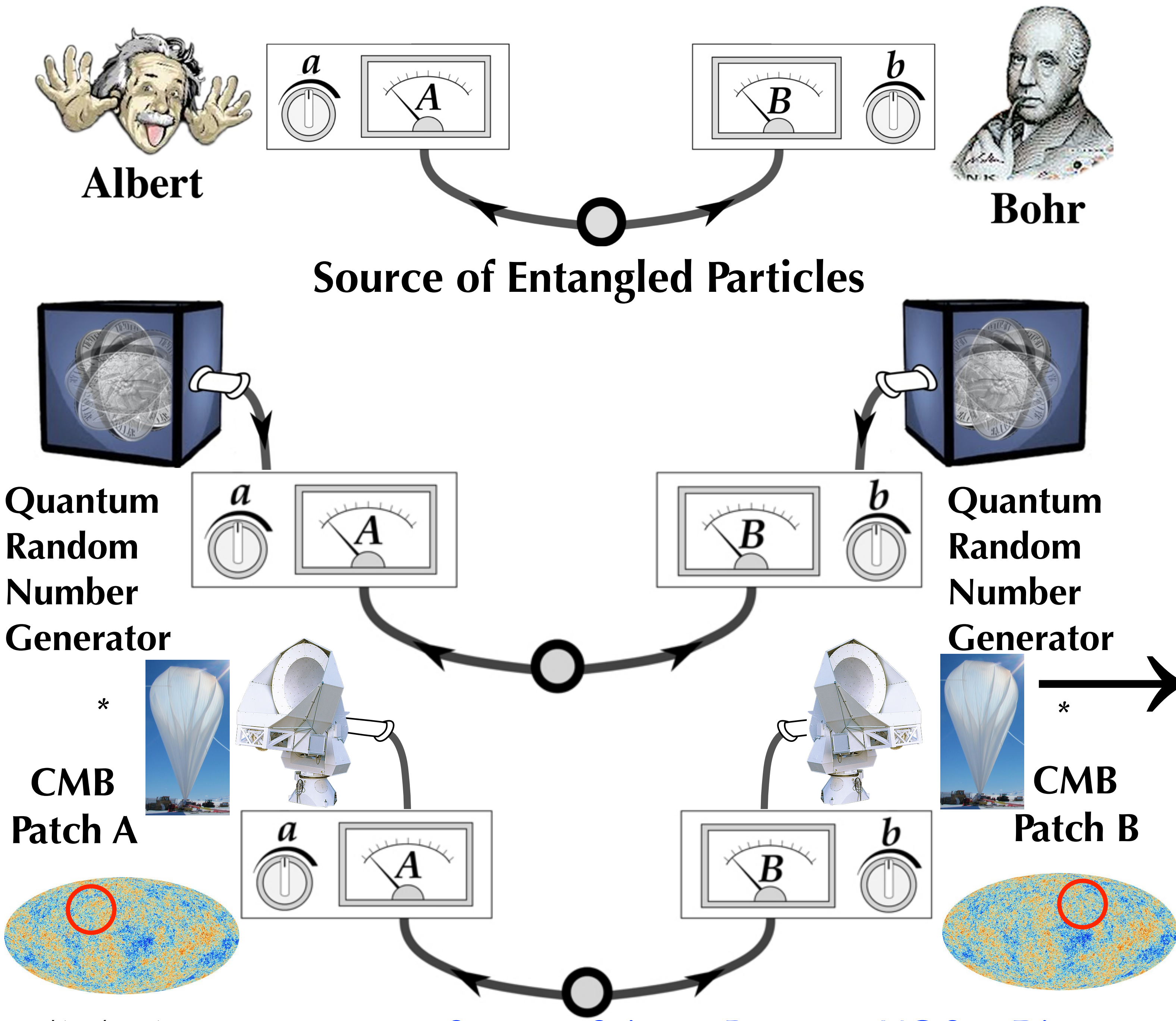



Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

Adapted from: Gallicchio, Friedman, & Kaiser 2014

# CHOOSING DETECTOR SETTINGS

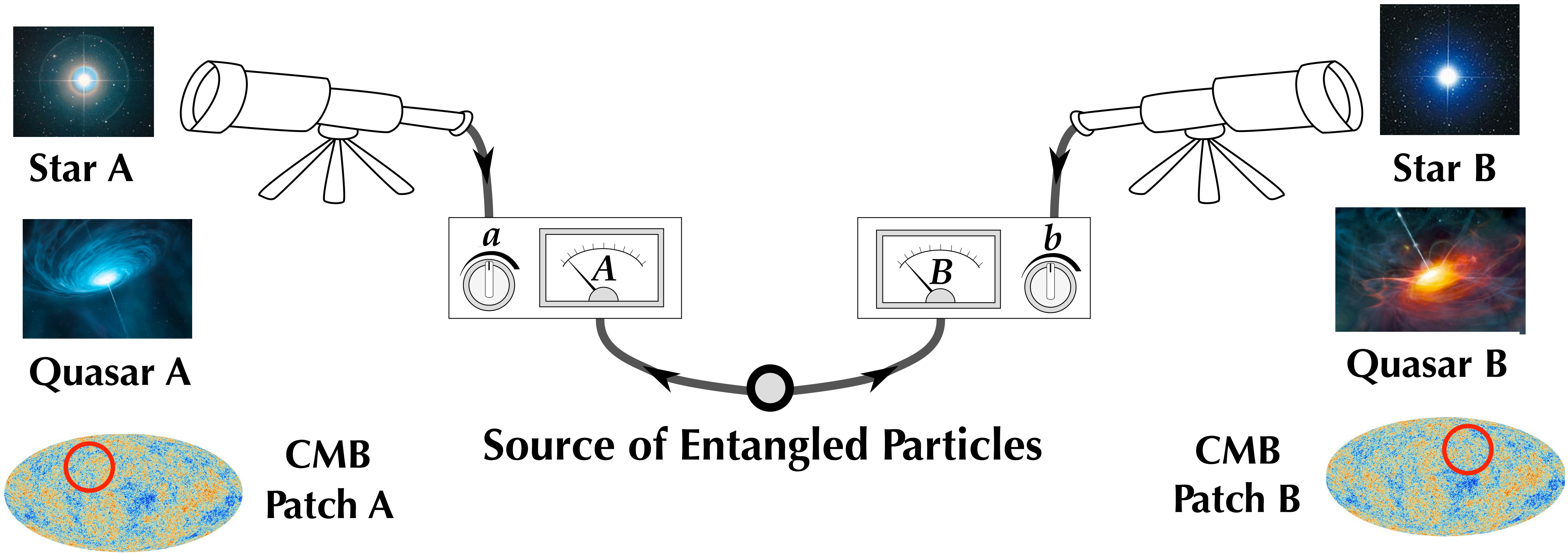



Choose settings with observations of CMB patches, etc…

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

Adapted from: Gallicchio, Friedman, & Kaiser 2014

# COSMIC BELL TESTS



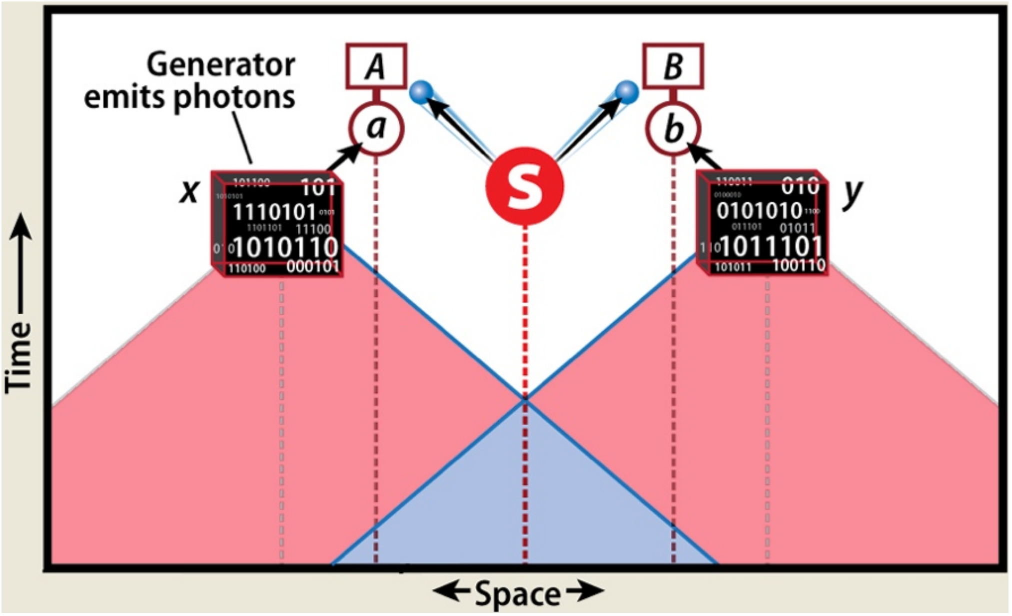

## Let the Universe decide how to set up entanglement experiment!

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

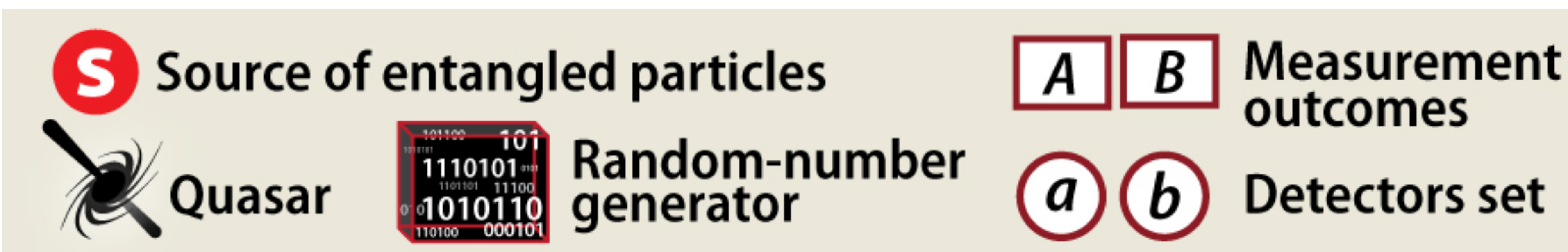
Gallicchio, Friedman, & Kaiser 2014, *Phys. Rev. Lett., Vol. 112, Issue 11, id. 110405,* (arXiv:1310.3288)

# SPACE-TIME DIAGRAMS

## Standard Bell Test



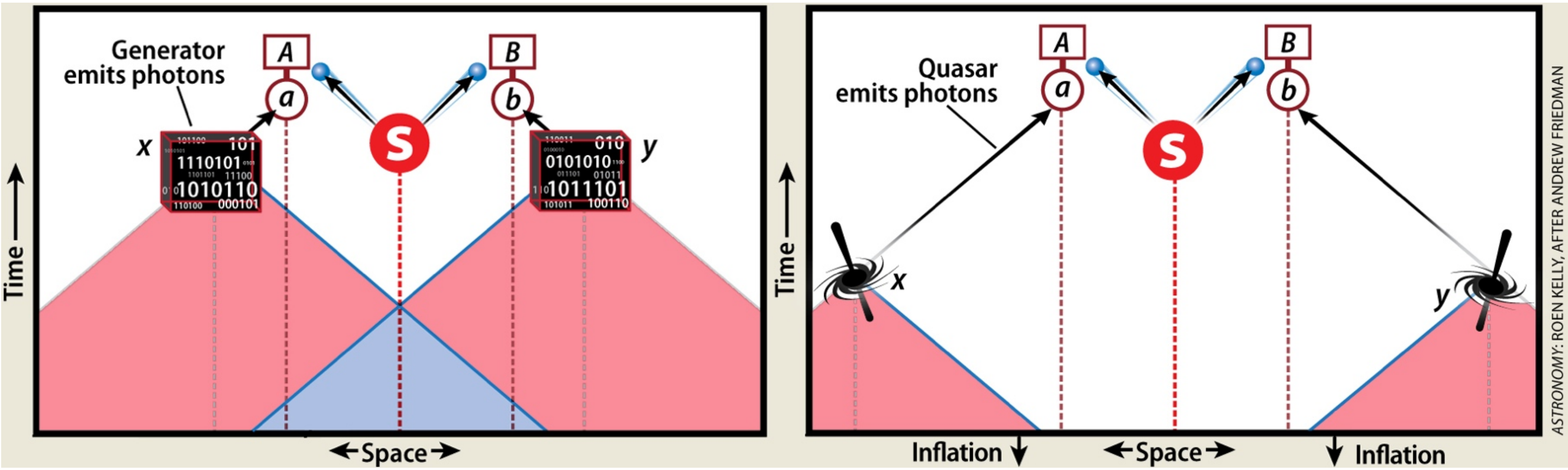

Past light cones from random number generators overlap milliseconds before test.




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

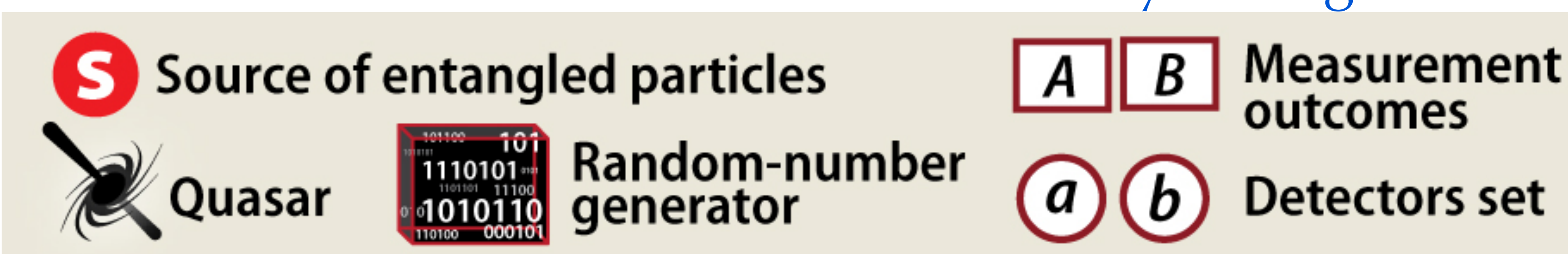
# SPACE-TIME DIAGRAMS

**Standard Bell Test** | ***Ideal* 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.

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# FIRST COSMIC BELL TEST (VIENNA)

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

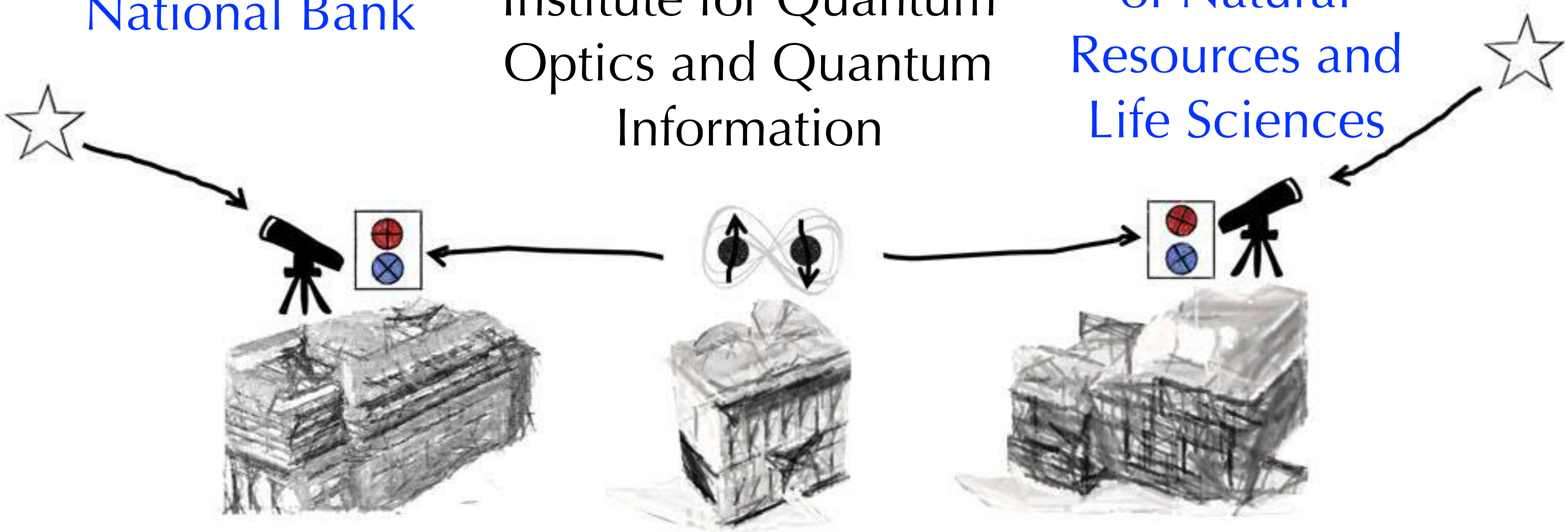
**Cosmic Bell Test: Measurement Settings from Milky Way Stars**

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

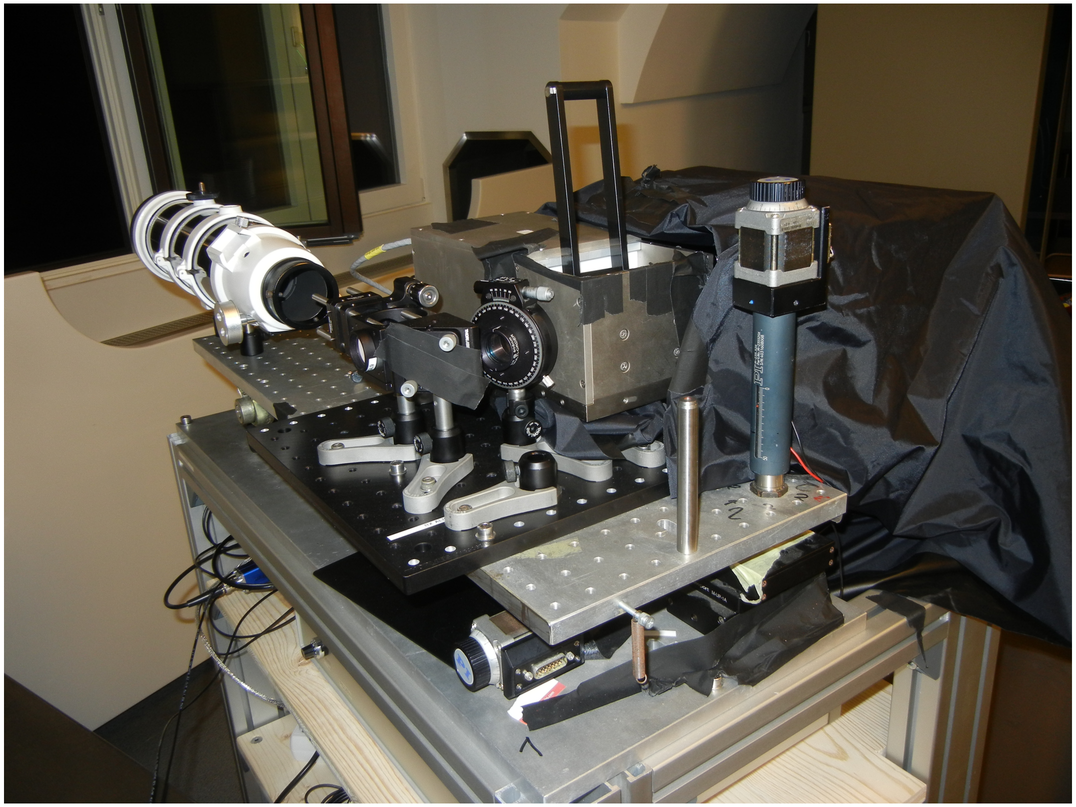


Handsteiner, Friedman+2017, *Physical Review Letters*, 118, 6, 060401(arXiv:1611.06985)

# Vienna Cosmic Bell Test


Johannes Handsteiner
with 8-inch stellar
photon telescope

# VIENNA COSMIC BELL TEST



Entangled photon receiver and polarization analyzer

# COSMIC SETTING GENERATOR


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

**Leung+2018, *Physical Review A*, Vol. 97, Issue 4, id. 042120 (arXiv:1706.02276)**

# VIENNA COSMIC BELL TEST

Occupational Hazards

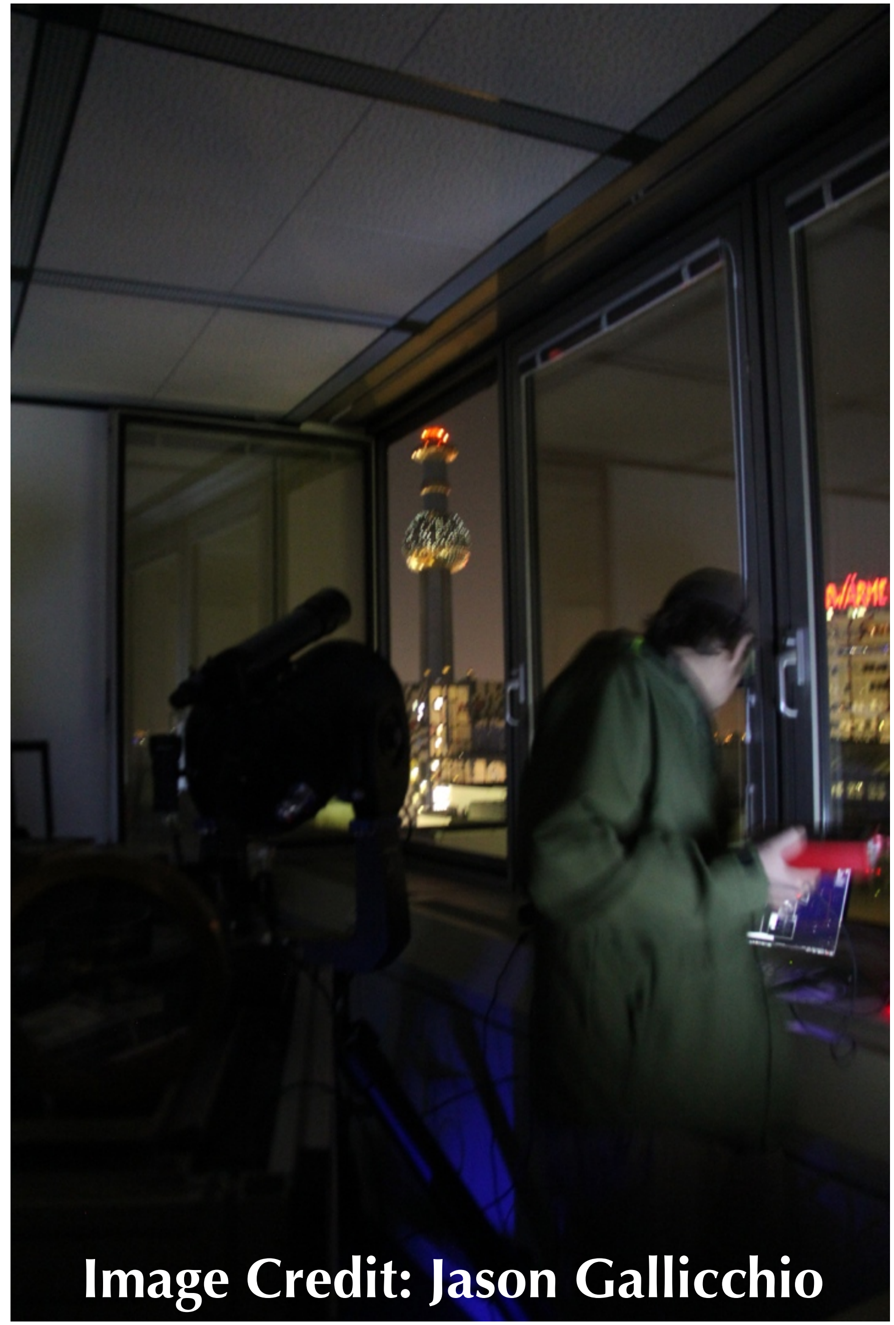


Image Credit: Jason Gallicchio

# VIENNA COSMIC BELL TEST

## Star Selection

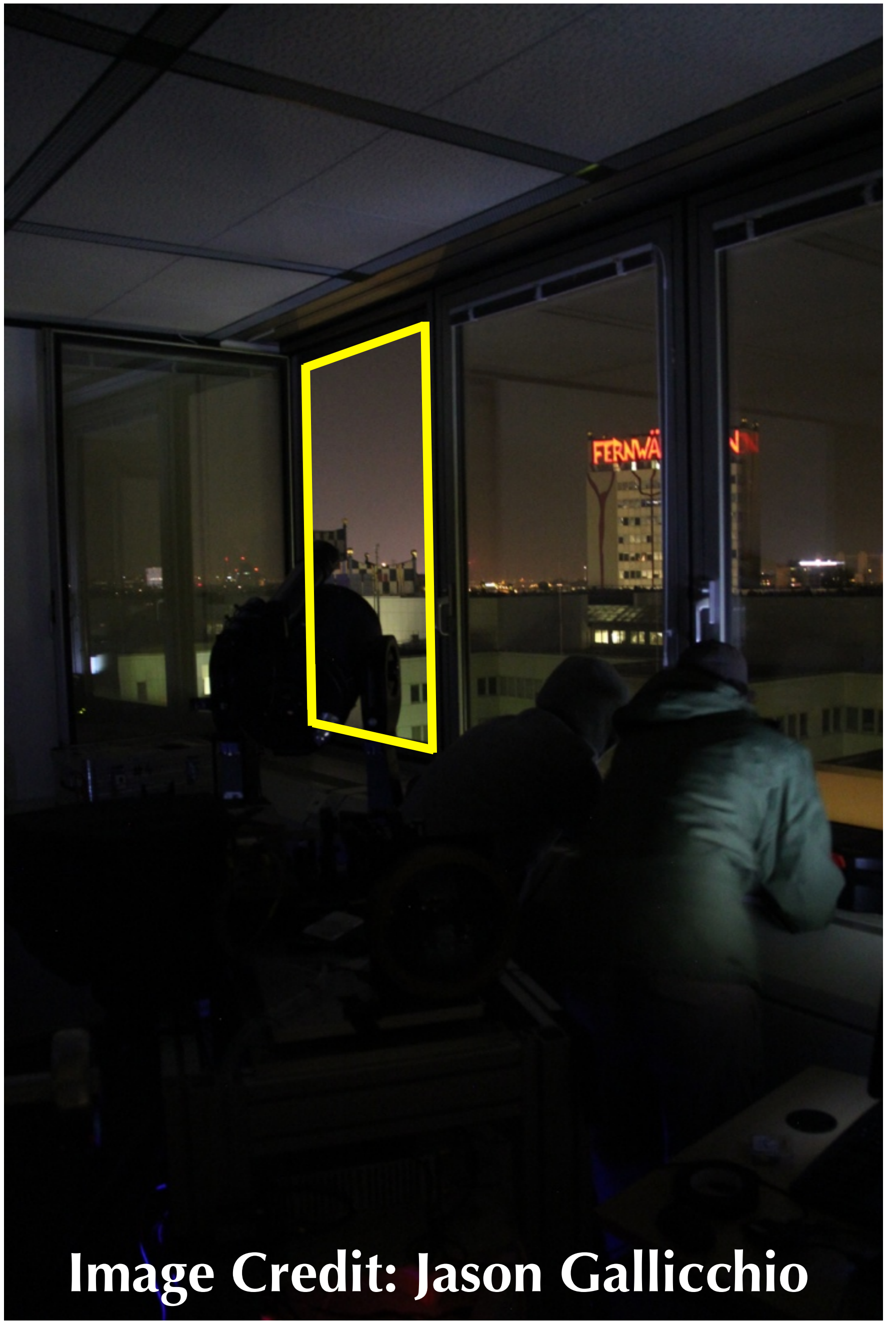
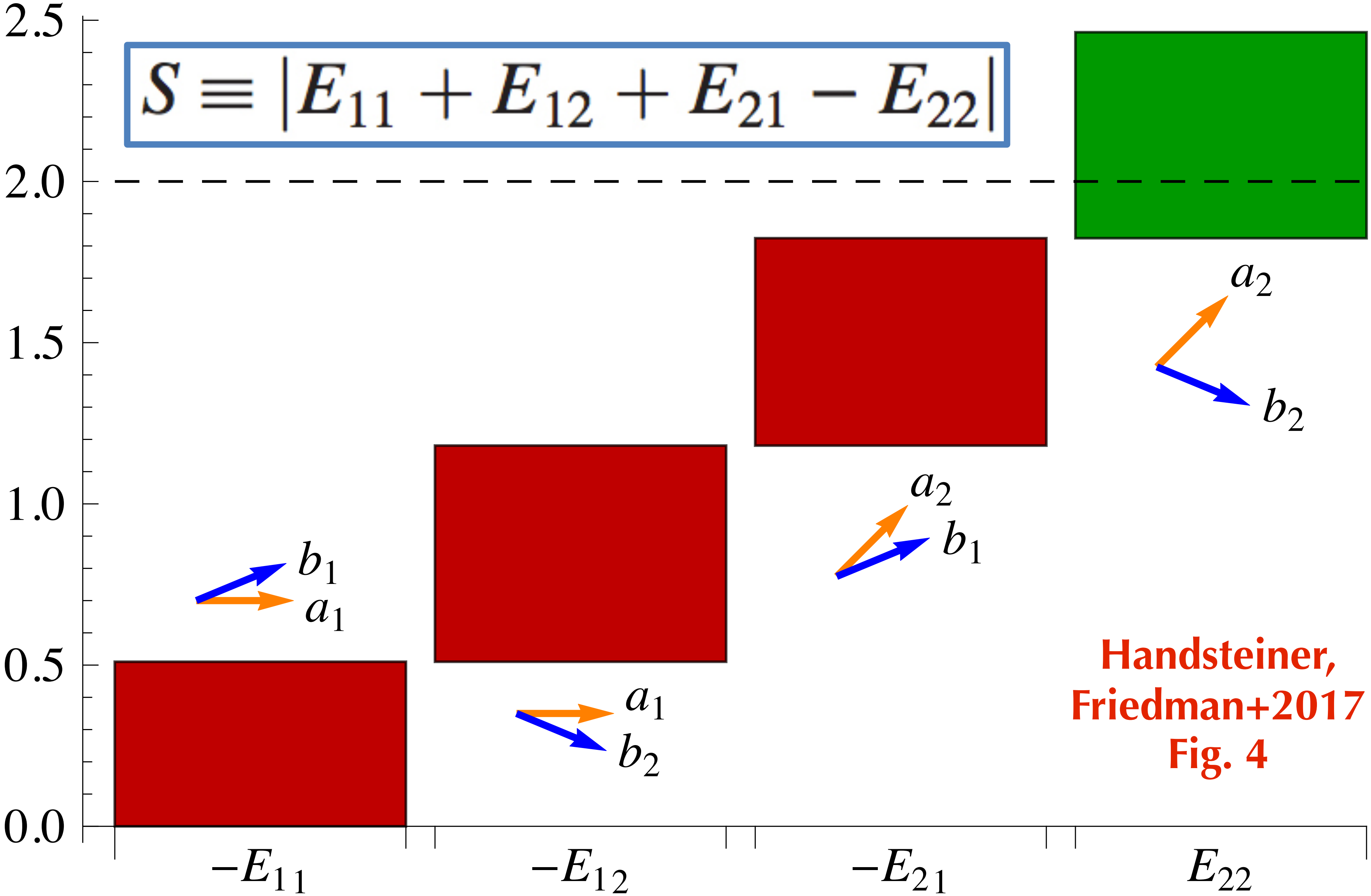


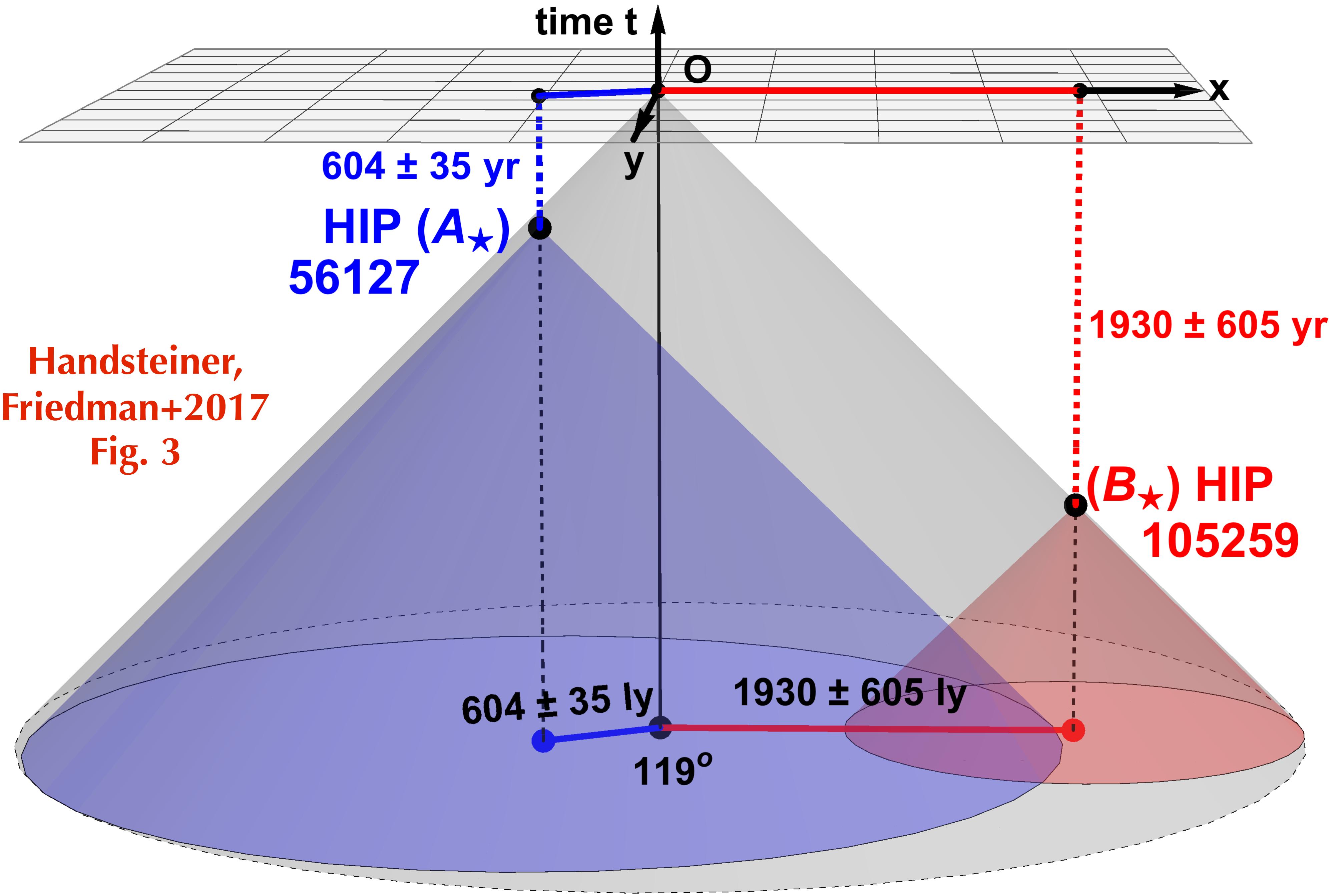

Image Credit: Jason Gallicchio

# OBSERVED BELL VIOLATION




Handsteiner, Friedman+2017 Fig. 4

# SPACE-TIME DIAGRAM: STARS




Handsteiner, Friedman+2017 Fig. 3

# OUTLINE

1. Entanglement Tests

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

3. Loopholes / Freedom-Of-Choice Loophole

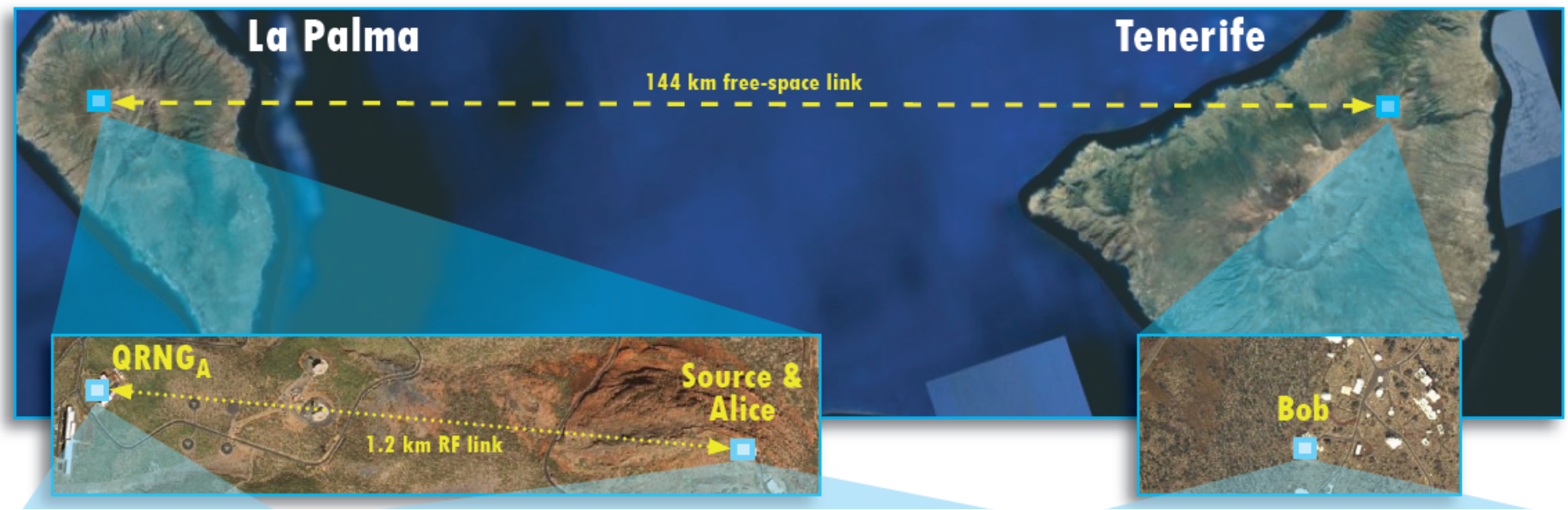
4. Cosmic Bell Test with Milky Way Stars

5. Cosmic Bell Test with Quasars

6. Future Tests

# 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 the Canary Island of La Palma**

# COSMIC BELL TEST WITH QUASARS

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

Editors' Suggestion

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

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

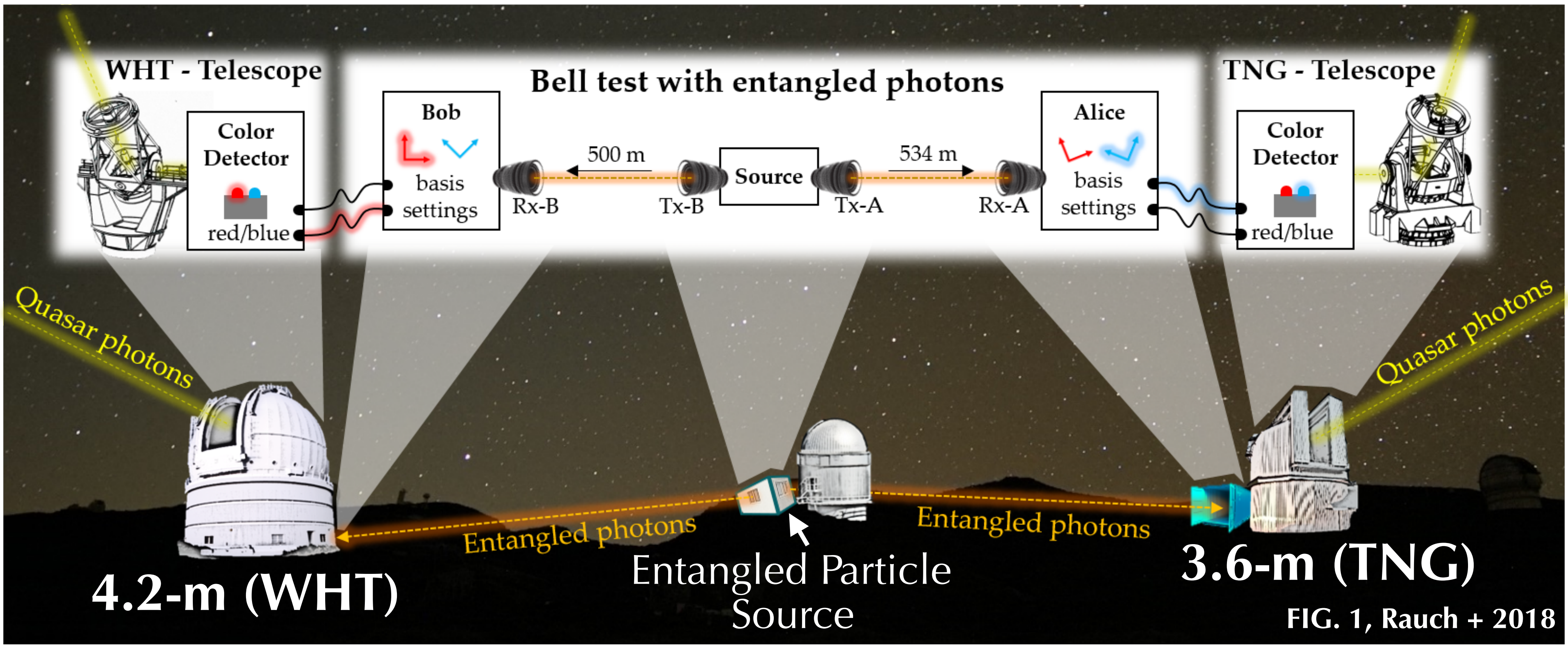


**FIG. 1, Rauch + 2018**

# COSMIC BELL TEST WITH QUASARS

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

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

| Pair | Side | ID | $az_k^\circ$ | $alt_k^\circ$ | $z$ | $t_{lb}$ [Gyr] | $\tau_{valid}^k$ [$\mu$s] | $S_{exp}$ | $p$ value | $\nu$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $\mathcal{A}$ | QSO B0350 − 073 | 233 | 38 | 0.964 | 7.78 | 2.34 | 2.65 | $7.4 \times 10^{-21}$ | 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 | $7.0 \times 10^{-13}$ | 7.1 |
| | $\mathcal{B}$ | QSO J0831 + 5245 | 21 | 64 | 3.911 | 12.21 | 0.53 | | | |

**Standard Deviations**

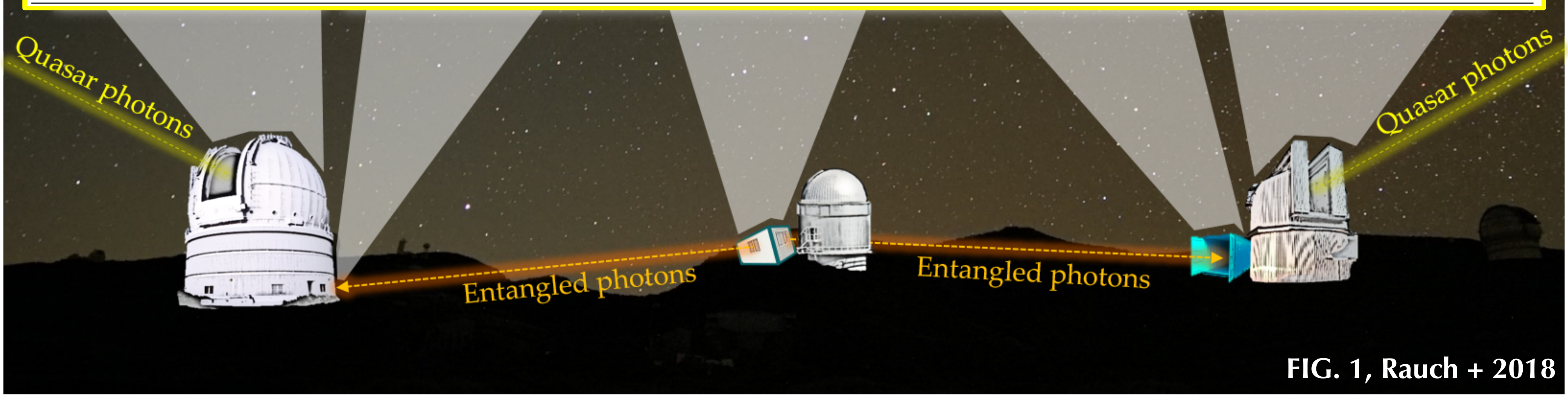



**FIG. 1, Rauch + 2018**

# 2+1D SPACETIME DIAGRAM

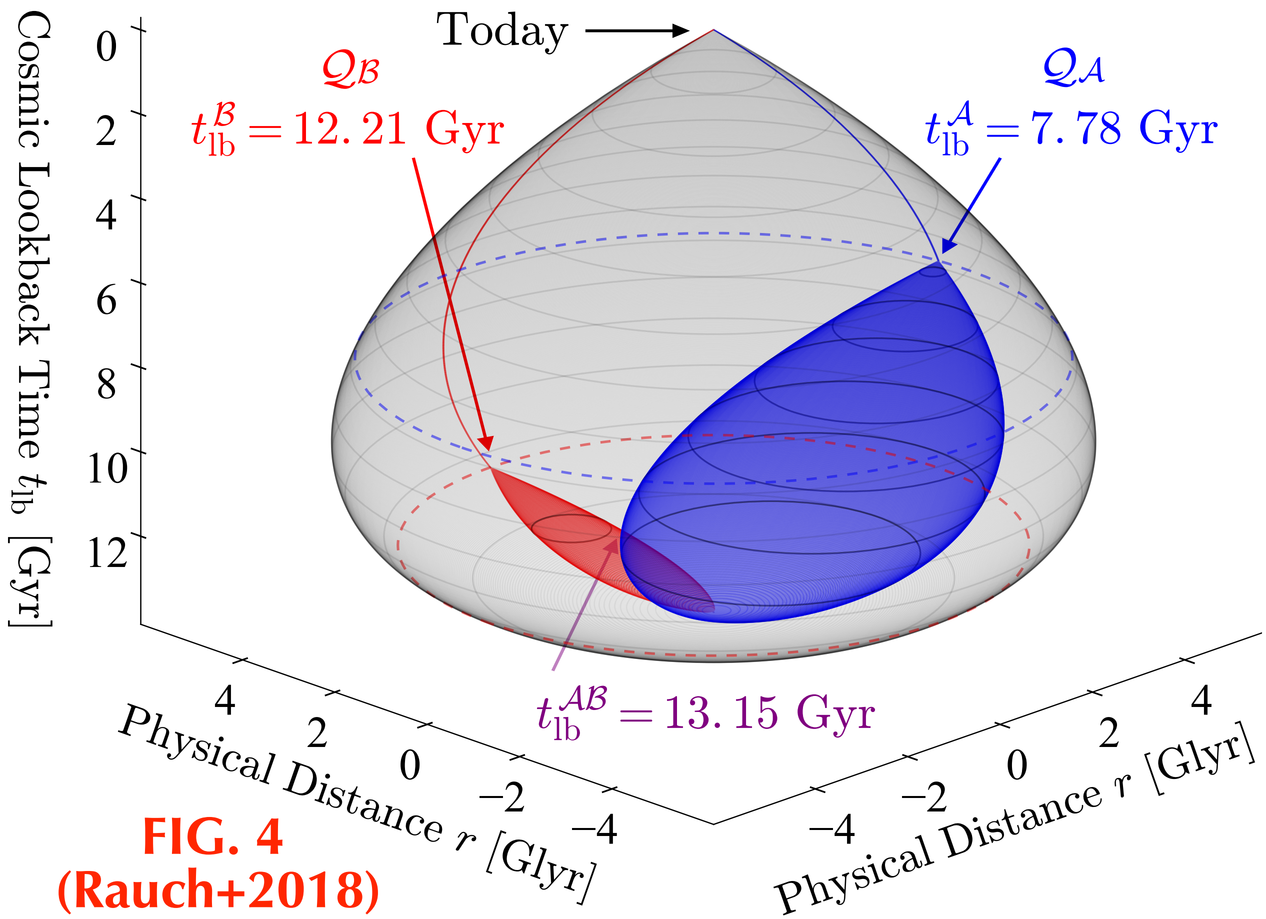



**FIG. 4 (Rauch+2018)**

- **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

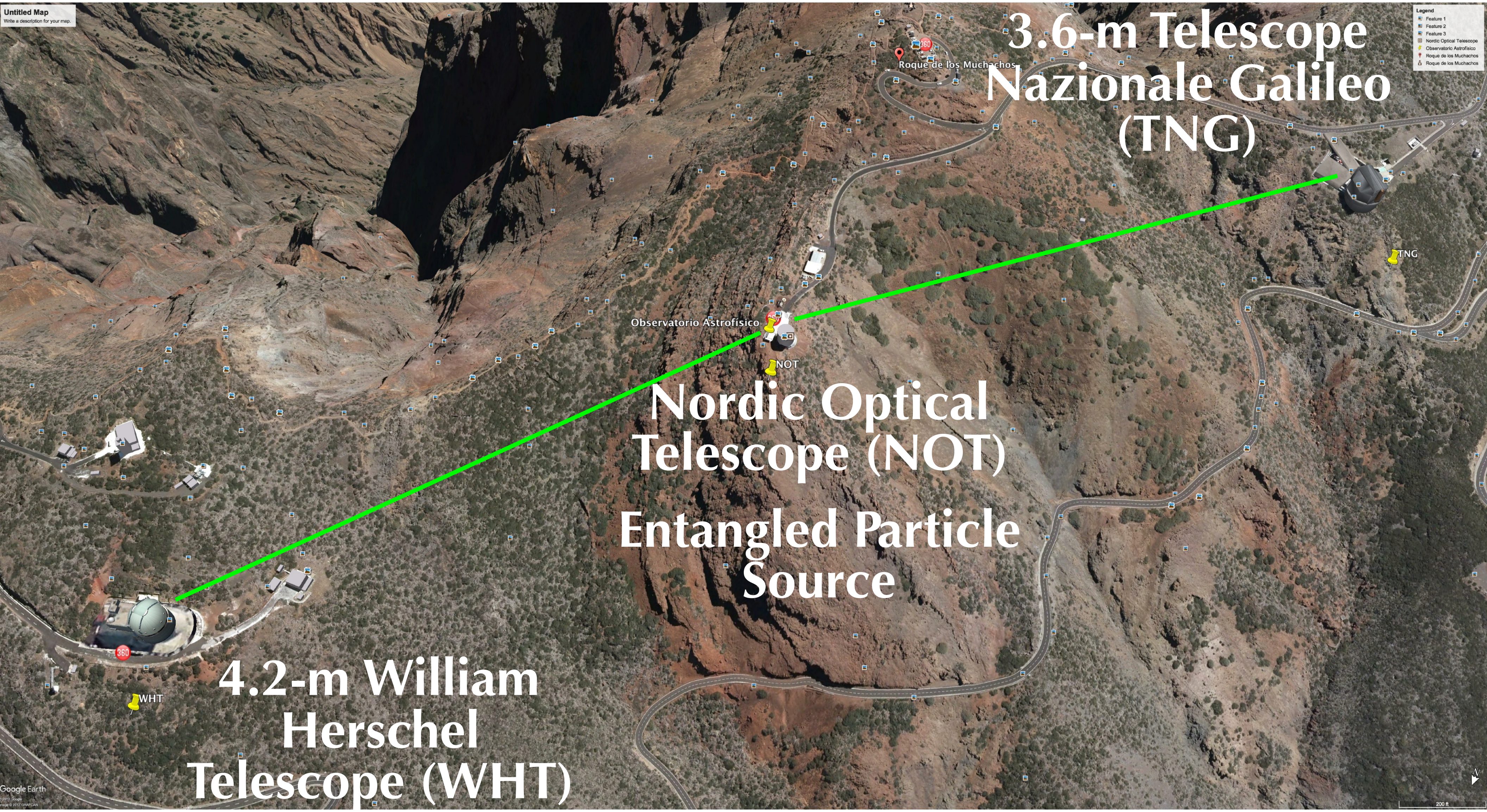



Image ©2018 DigitalGlobe (Google Earth)

# CHOOSING THE BEST QUASARS

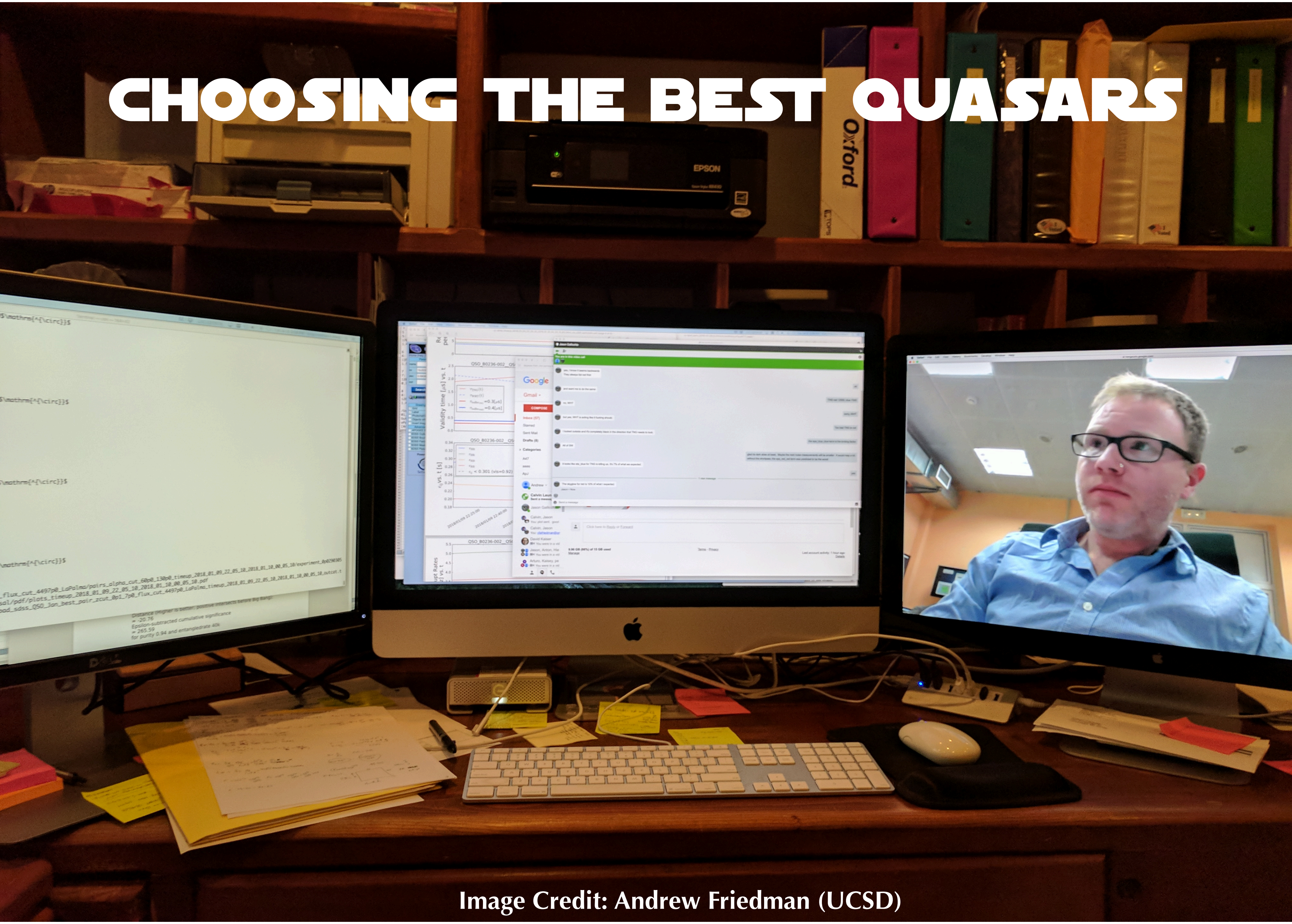



Image Credit: Andrew Friedman (UCSD)

# REMOTE ASSISTANCE

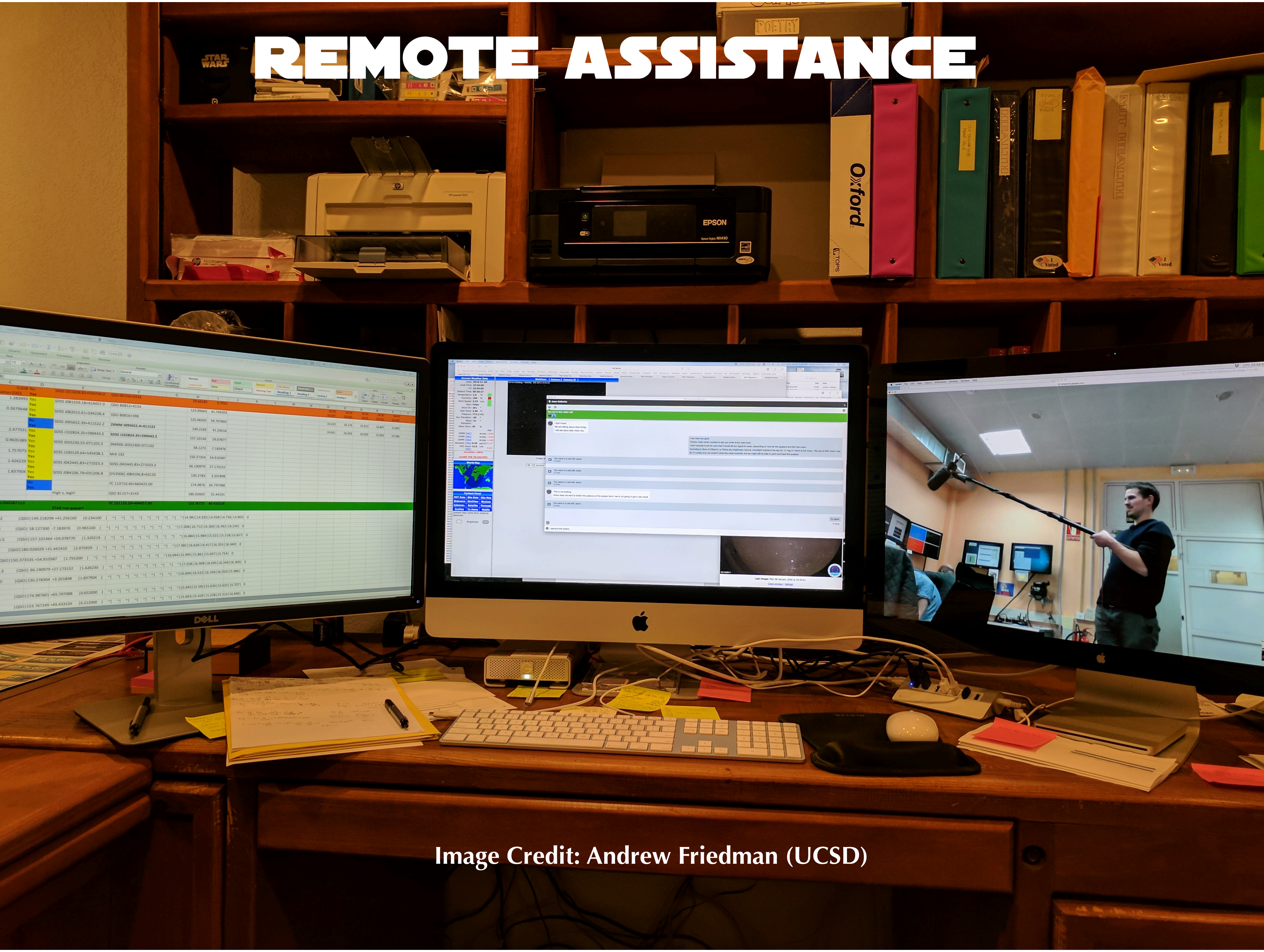
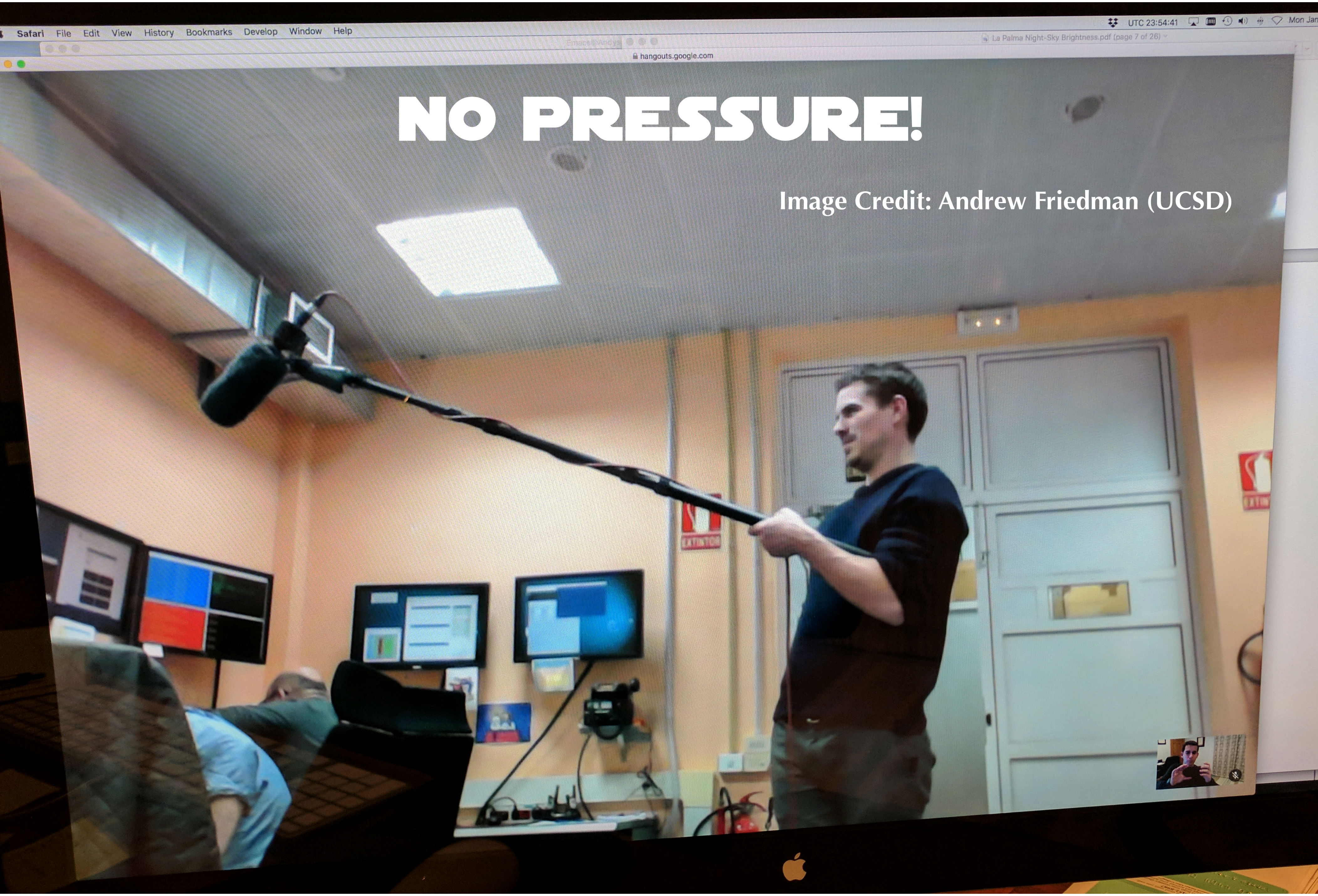



Image Credit: Andrew Friedman (UCSD)


NO PRESSURE!
Image Credit: Andrew Friedman (UCSD)
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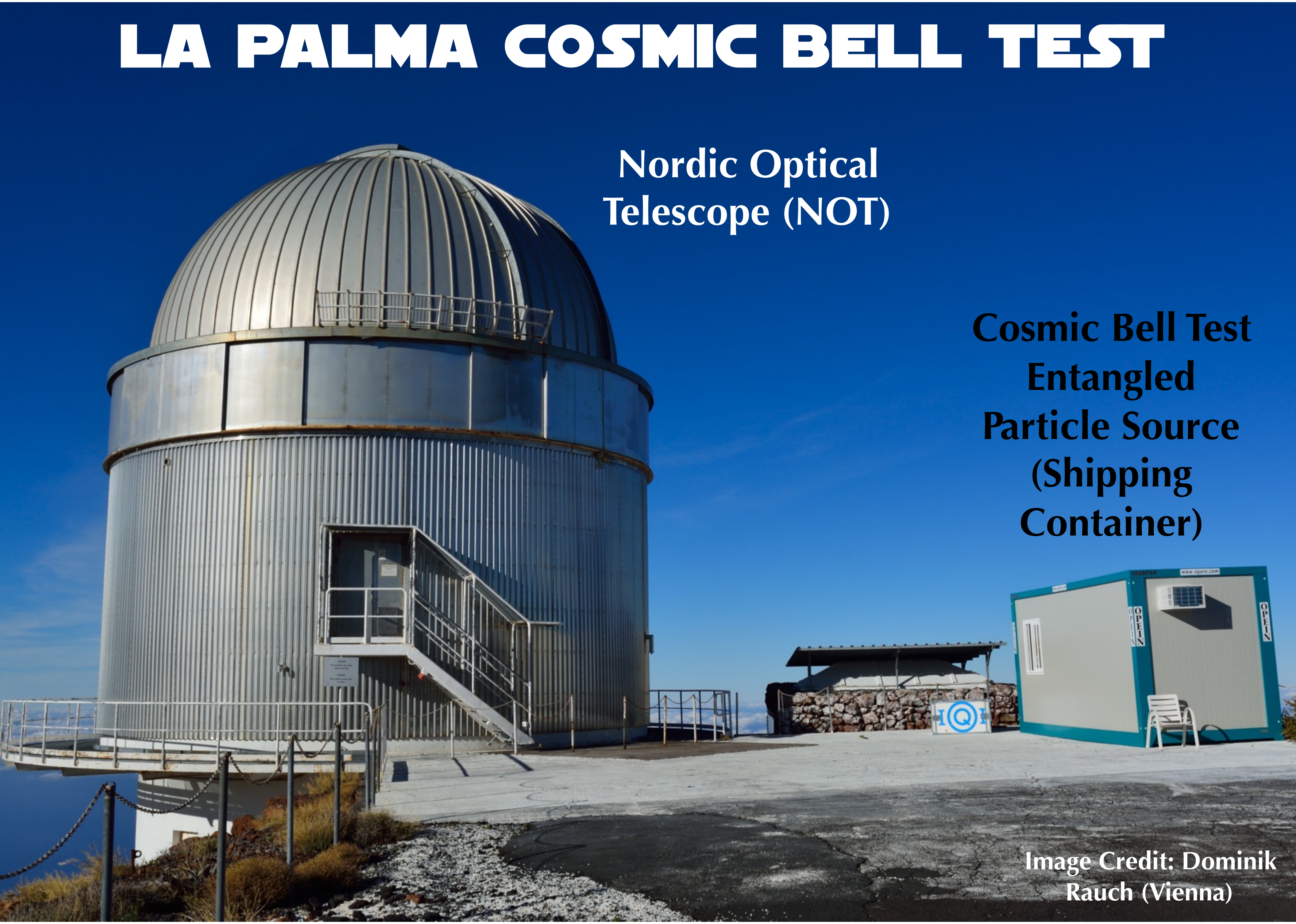
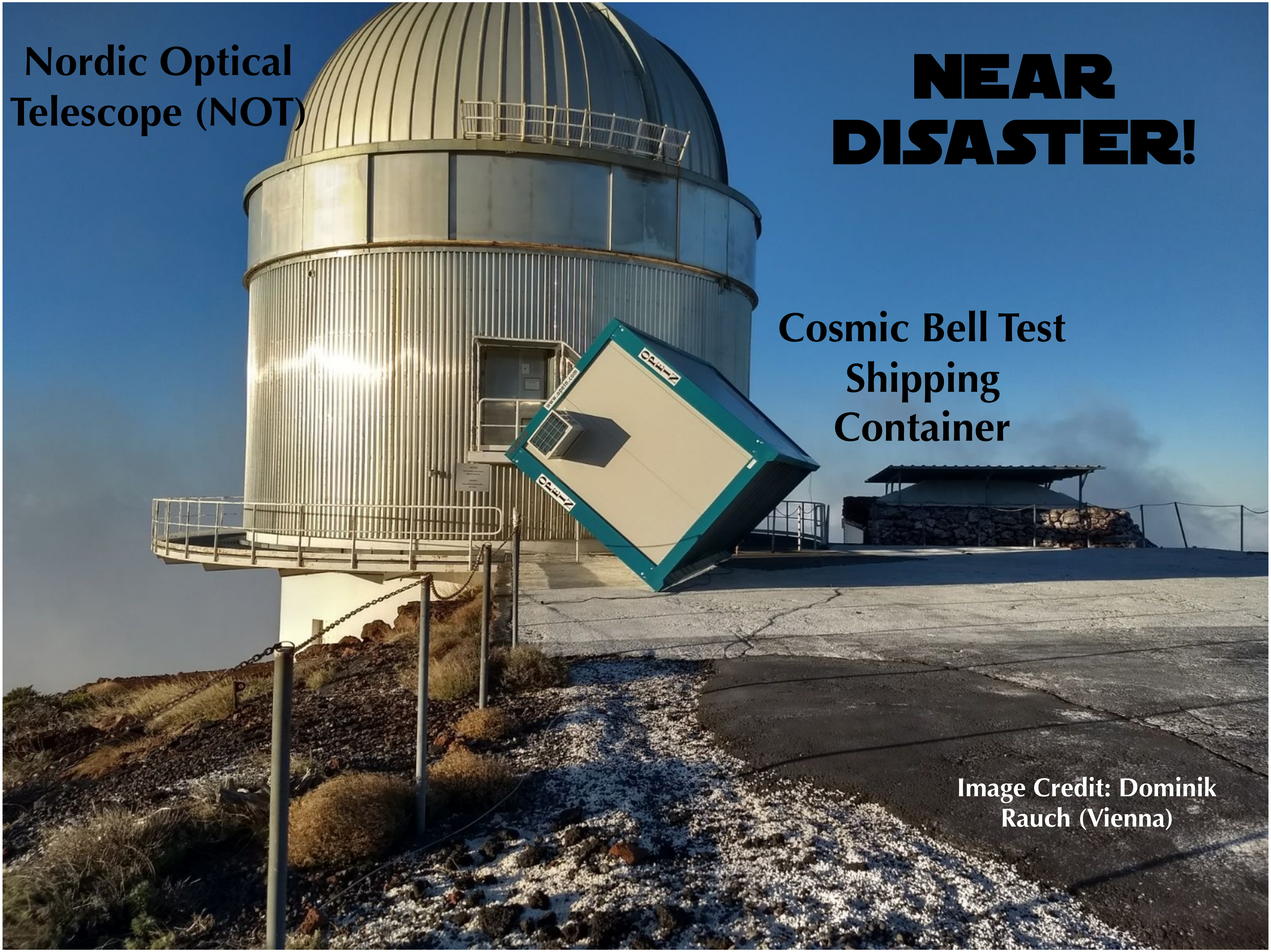
# LA PALMA COSMIC BELL TEST




Nordic Optical Telescope (NOT)
NEAR DISASTER!
Cosmic Bell Test Shipping Container
Image Credit: Dominik Rauch (Vienna)


NEAR
DISASTER!
Image Credit: Dominik
Rauch (Vienna)

# NEAR DISASTER!


Image Credit: Dominik Rauch (Vienna)


Image Credit: Dominik Rauch (Vienna)
DISASTER AVERTED
Cosmic Bell Test Shipping Container
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OPEIN
OPEIN
TRANSPORTES
659 01 37 03
ALBERTO
GRÚAS
922 49 70 44
7367 CYY
SP

# DISASTER AVERTED


Entangled photon source fixed, reinstalled in now secured shipping container control room.

# ADVENTURES IN LA PALMA

# 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)

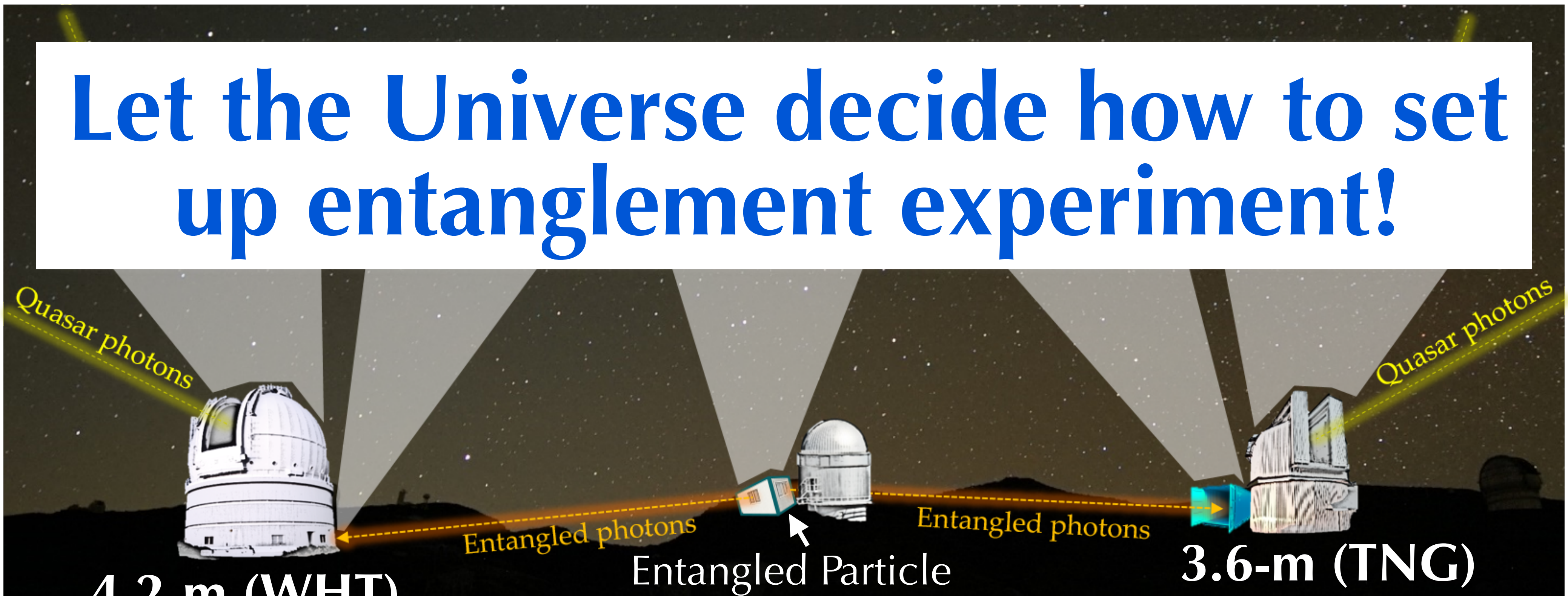
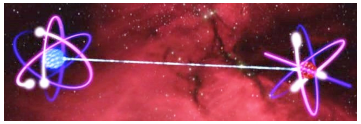


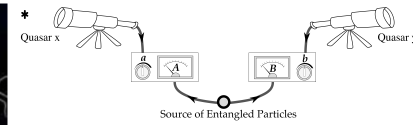

FIG. 1, Rauch + 2018

# COSMIC BELL IN THE NEWS

**MIT News**

ON CAMPUS AND AROUND THE WORLD



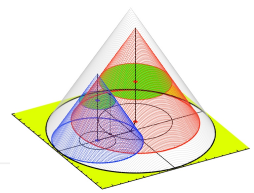


https://asfriedman.physics.ucsd.edu/media_coverage.shtml

## 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

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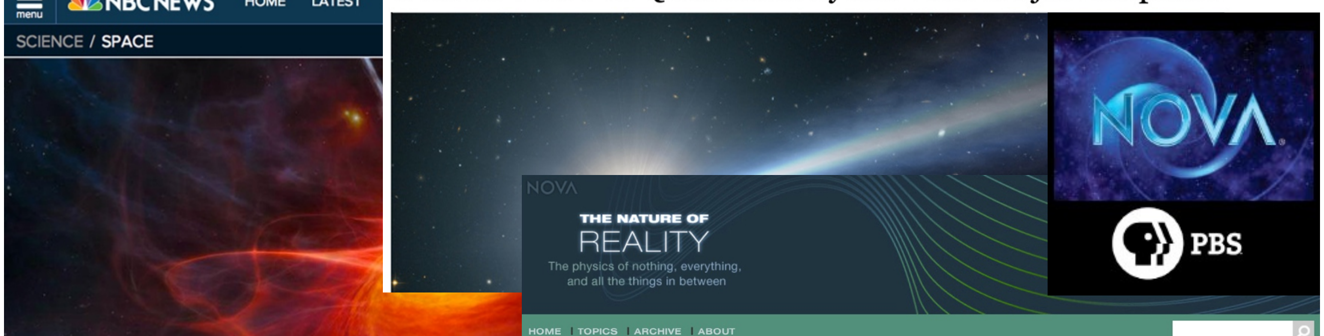


Quasar Experiment May Shed Light on Quantum Physics and Free Will

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

# COSMIC BELL IN THE NEWS

SECTIONS THE NEW YORKER

ELEMENTS

## QUANTUM THEORY BY STARLIGHT

By David Kaiser February 7, 2017

New Scientist

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NEWS & TECHNOLOGY 7 February 2017

## Starlight test shows quantum world has been weird for 600 years

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

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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

WIRED

ANIL ANANTHASWAMY SCIENCE 08.05.18 07:00 AM

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

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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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.

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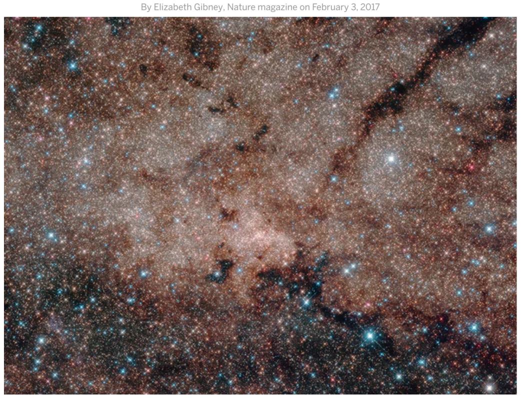
## Cosmic Test Bolsters Einstein's "Spooky Action at a Distance"

Physicists harness starlight to support the case for entanglement.

By Elizabeth Gibney, Nature magazine on February 3, 2017



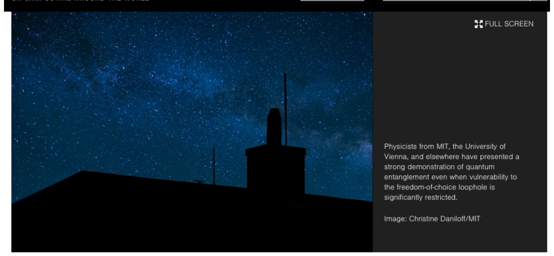
SPACE.com

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

MIT News ON CAMPUS AND AROUND THE WORLD



## Stars align in test supporting "spooky action at a distance"

Physicists address loophole in tests of Bell's inequality, using 600-year-old starlight.

Jennifer Chu | MIT News Office
February 6, 2017

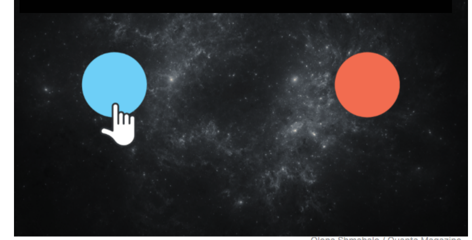
QUANTA MAGAZINE

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

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

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

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

# COSMIC BELL IN THE NEWS


SCIENTIFIC AMERICAN

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*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

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D-brief

## Black Holes Bolster Case For Quantum Physics' Spooky Action

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

104

symmetry topics follow +

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.

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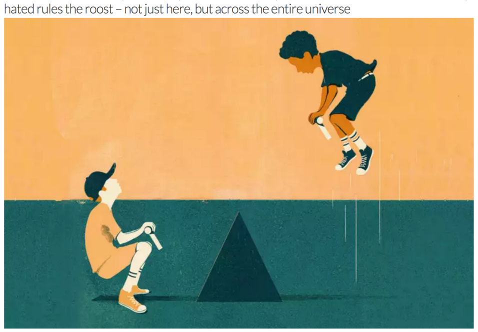
NewScientist

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 Nanotechnology Physics Earth Astronomy & Space

Home » Physics » Quantum Physics » August 27, 2018

## Physicists race to demystify Einstein's 'spooky' science

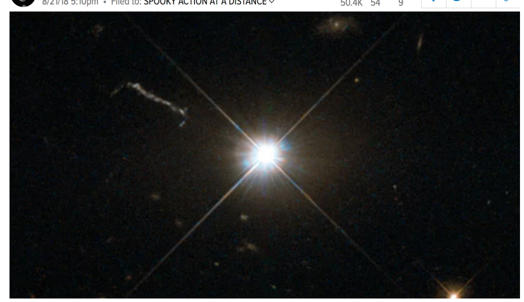
August 27, 2018 by Cynthia Dillon, University of California - San Diego

GIZMODO

PHYSICS

## 'Spooky' Quantum Entanglement Confirmed Using Distant Quasars

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



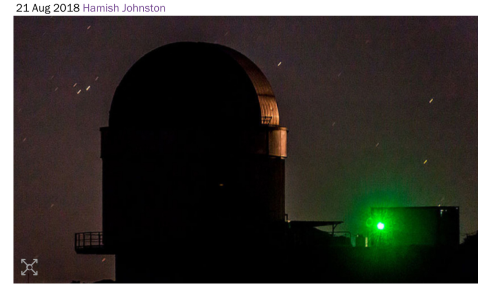
physicsworld MENU

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

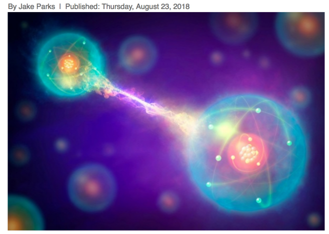
By Chelsea Gohd, Space.com Staff Writer | August 21, 2018 04:58pm ET

Astronomy SUBSCRIBE

## Quantum entanglement loophole quashed by quasar light

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

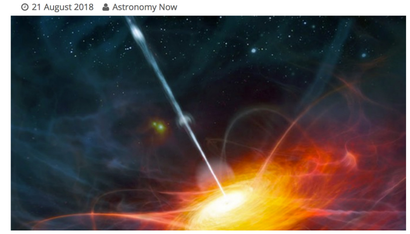
By Jake Parks | Published: Thursday, August 23, 2018



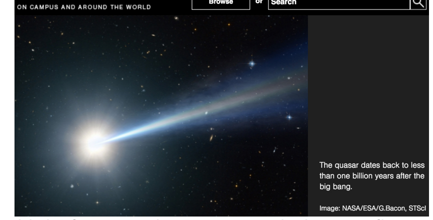
Astronomy Now
The UK's best astronomy magazine

## 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

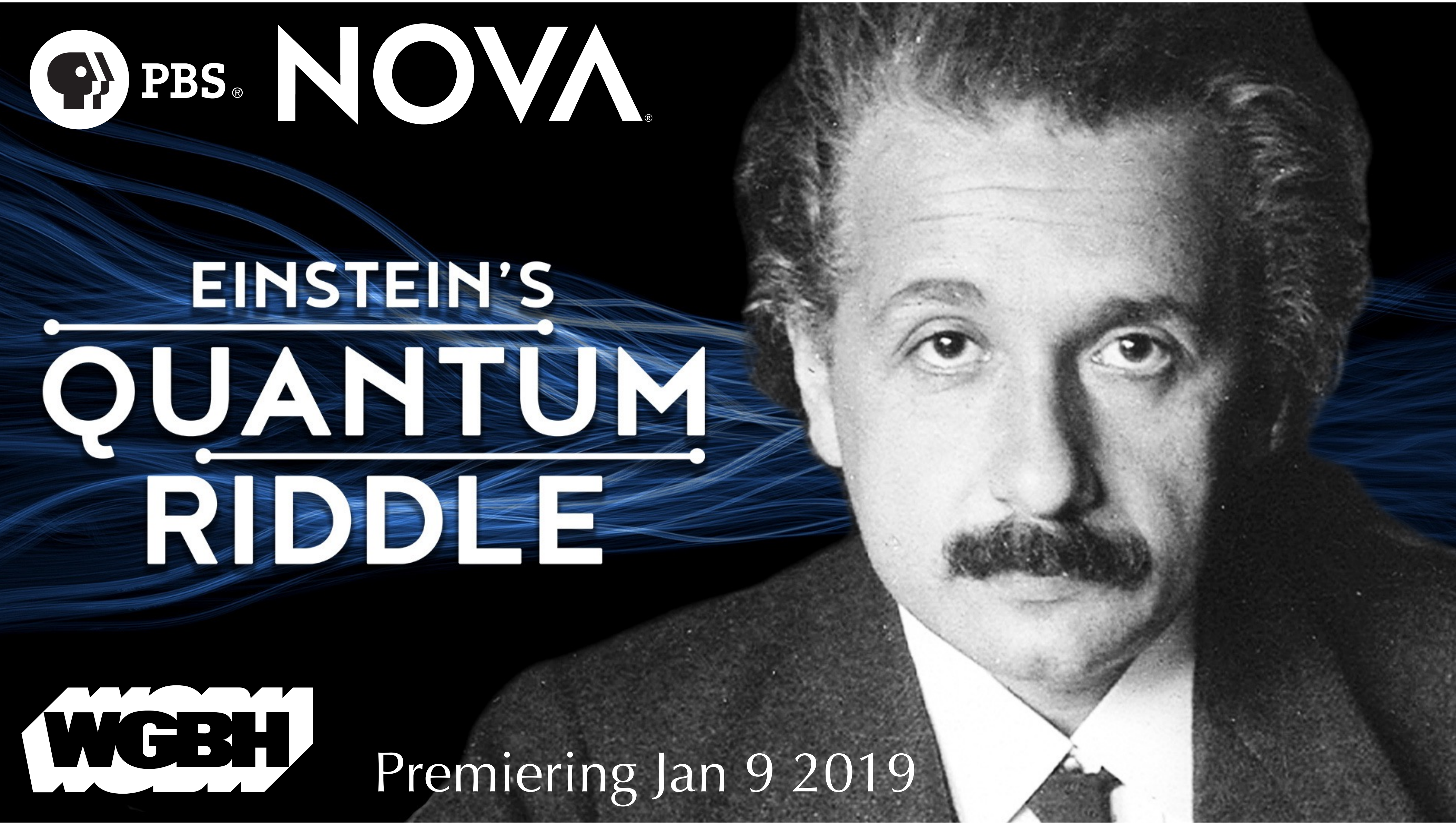
## Light from ancient quasars helps confirm quantum entanglement

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

Jennifer Chu | MIT News Office
August 19, 2018

Press Inquiries PRESS MENTIONS

# COSMIC BELL TEST ON TV!



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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

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6. Future Tests

# 2+1D CONFORMAL SPACETIME DIAGRAM

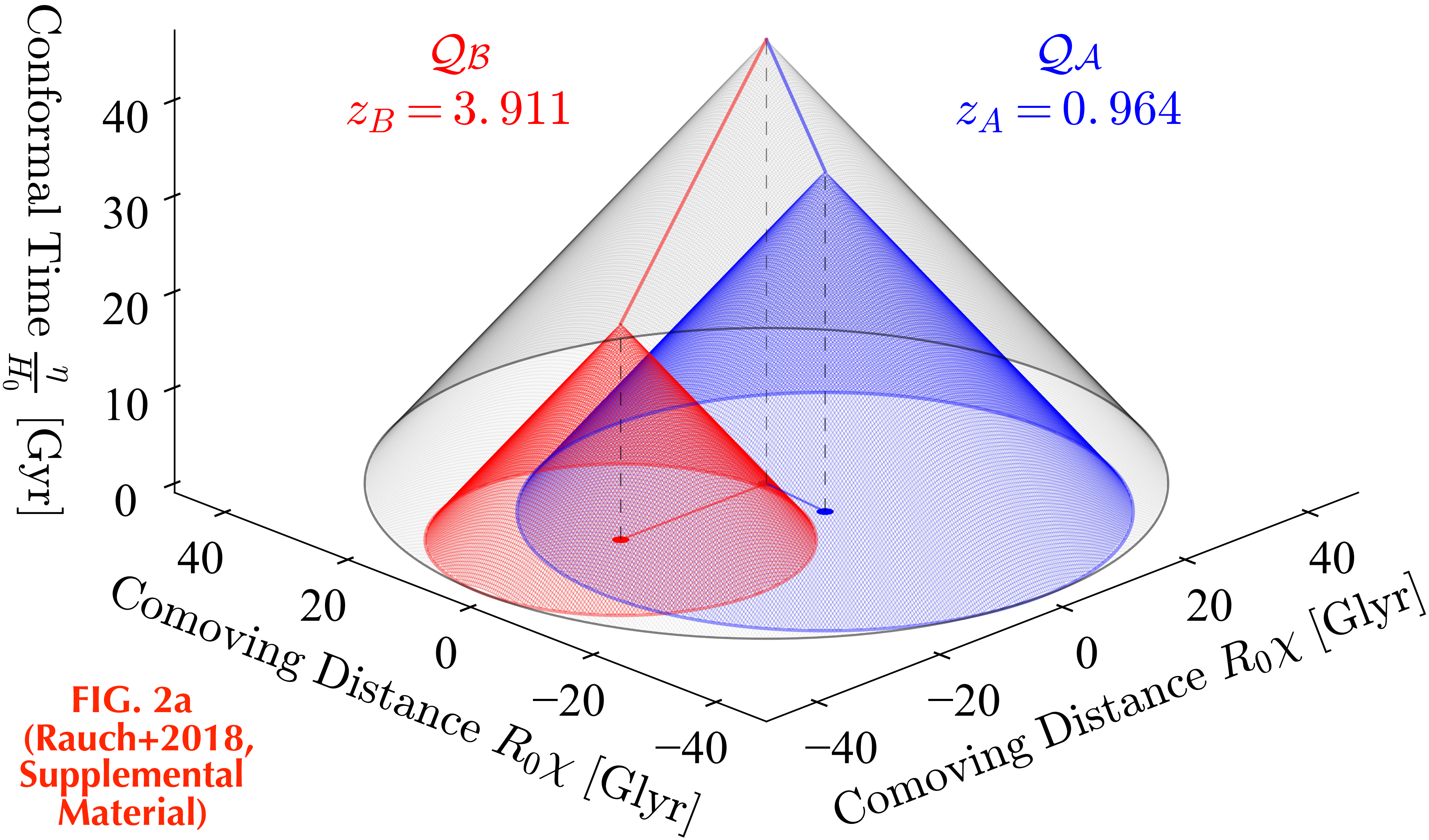


FIG. 2a (Rauch+2018, Supplemental Material)

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

# POSSIBLE OUTCOMES

**Future 2-quasar/CMB Cosmic Bell tests with no causal overlap**

## Safe Bet

Bell 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 PAPERS

*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)

*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)

*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)

*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 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]

*Relaxed Bell Inequalities with Arbitrary Measurement Dependence for Each Observer*,
Friedman, A.S., Guth, A.H., Hall, M.J.W., Kaiser, D.I., and Gallicchio, J. 2019, *Physical Review A*, Vol. 99, Issue 1, id. 012121 (arXiv:1809.01307 | PDF) (DOI)

# 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

# COSMIC BELL EXPERIMENTS

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,‡]

Handsteiner, Friedman+2017, *Physical Review Letters*, 118, 6, 060401(arXiv:1611.06985)

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

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)

Pushed this back to > 7.8 billion years ago! Excluded 96% of spacetime that could have causally influenced our experiment!

# OTHER RELEVANT PAPERS

PHYSICAL REVIEW A **97**, 042120 (2018)

Featured in Physics

**Astronomical random numbers for quantum foundations experiments**

Calvin Leung,[1,*] Amy Brown,[1,†] Hien Nguyen,[2,‡] Andrew S. Friedman,[3,§] David I. Kaiser,[4,¶] and Jason Gallicchio[1,**]

**Leung+2018, *Physical Review A*, Vol. 97, Issue 4, id. 042120 (arXiv:1706.02276)**

Describes an "Astronomical Random Number Generator", built in Jason Gallicchio's lab, used to turn cosmic photon colors into random numbers.

PHYSICAL REVIEW A **99**, 012121 (2019)

**Relaxed Bell inequalities with arbitrary measurement dependence for each observer**

Andrew S. Friedman,[1,*] Alan H. Guth,[2,†] Michael J. W. Hall,[3,4,‡] David I. Kaiser,[2,§] and Jason Gallicchio[5,‖]

**Friedman+2019a, *Physical Review A*, Vol. 99, Issue 1, id. 012121 (arXiv:1809.01307)**

Derives relaxed version of Bell's inequality without the "freedom-of-choice" assumption. Shows local realistic models that can simulate quantum theory by quantitatively reducing freedom by only a minuscule amount.

# 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)
Friedman, Guth, Hall, Kaiser, & Gallicchio 2019, *Physical Review A,* Vol. 99, Issue 1, id. 012121 (arXiv:1809.01307)
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.