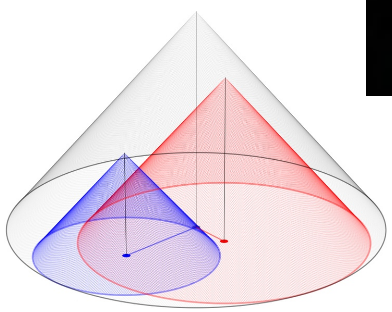
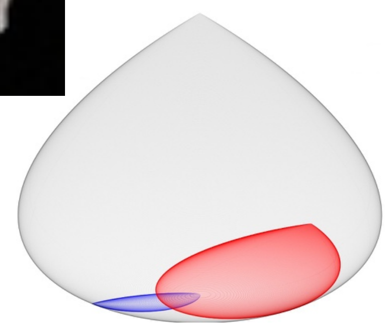
A COSMIC TEST OF QUANTUM ENTANGLEMENT AND BELL'S INEQUALITY

Choosing Measurements with Light from High Redshift Quasars





Dr. Andrew Friedman

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4/10/2019

UCSD CASS Astrophysics Seminar

COSMIC BELL TEST WITH QUASARS

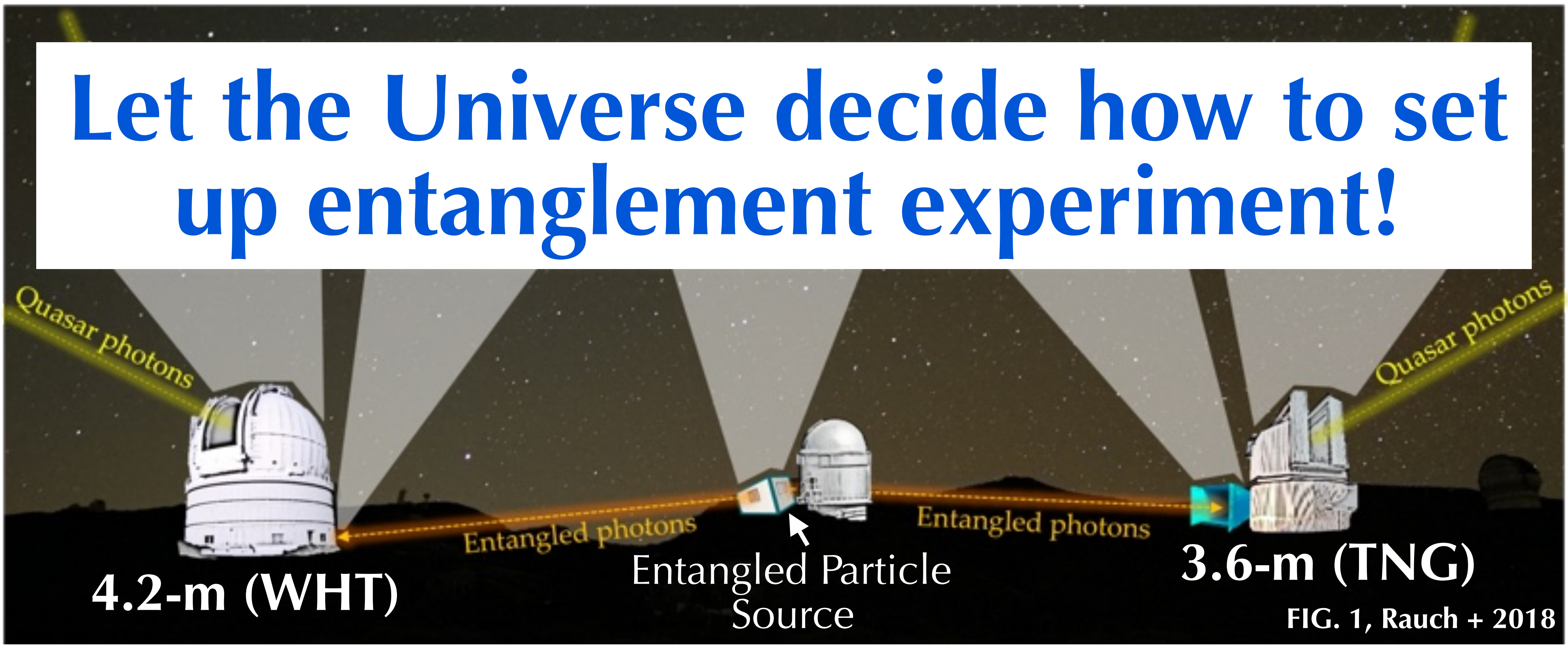
PHYSICAL REVIEW LETTERS **121**, 080403 (2018)

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)



COSMIC BELL COLLABORATION

NSF

ÖAW Austrian Academy of Sciences

MPQ

COSMIC BELL TEAM

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Dr. Andrew Friedman [1,5]

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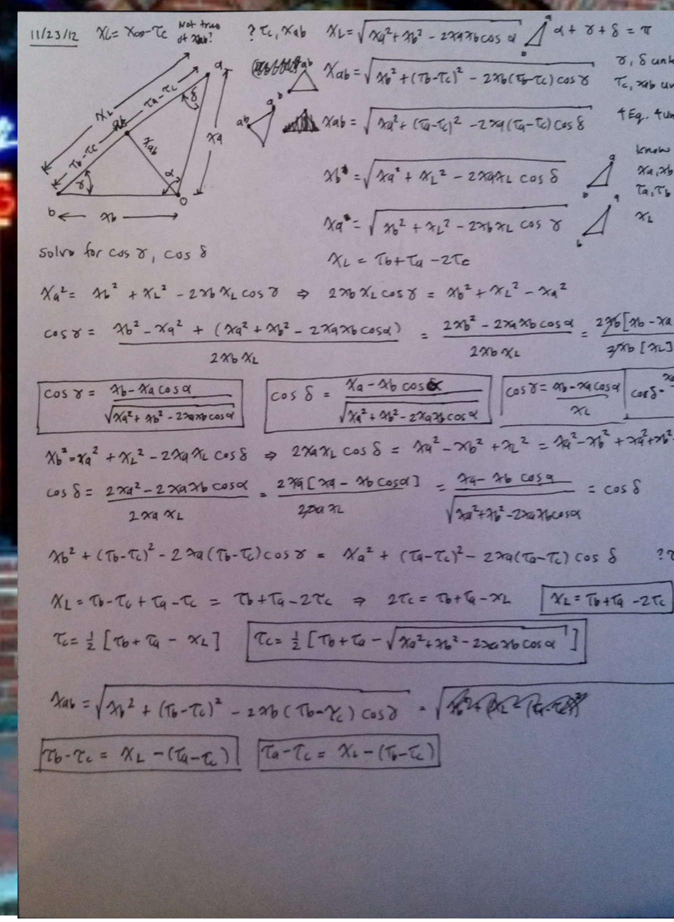
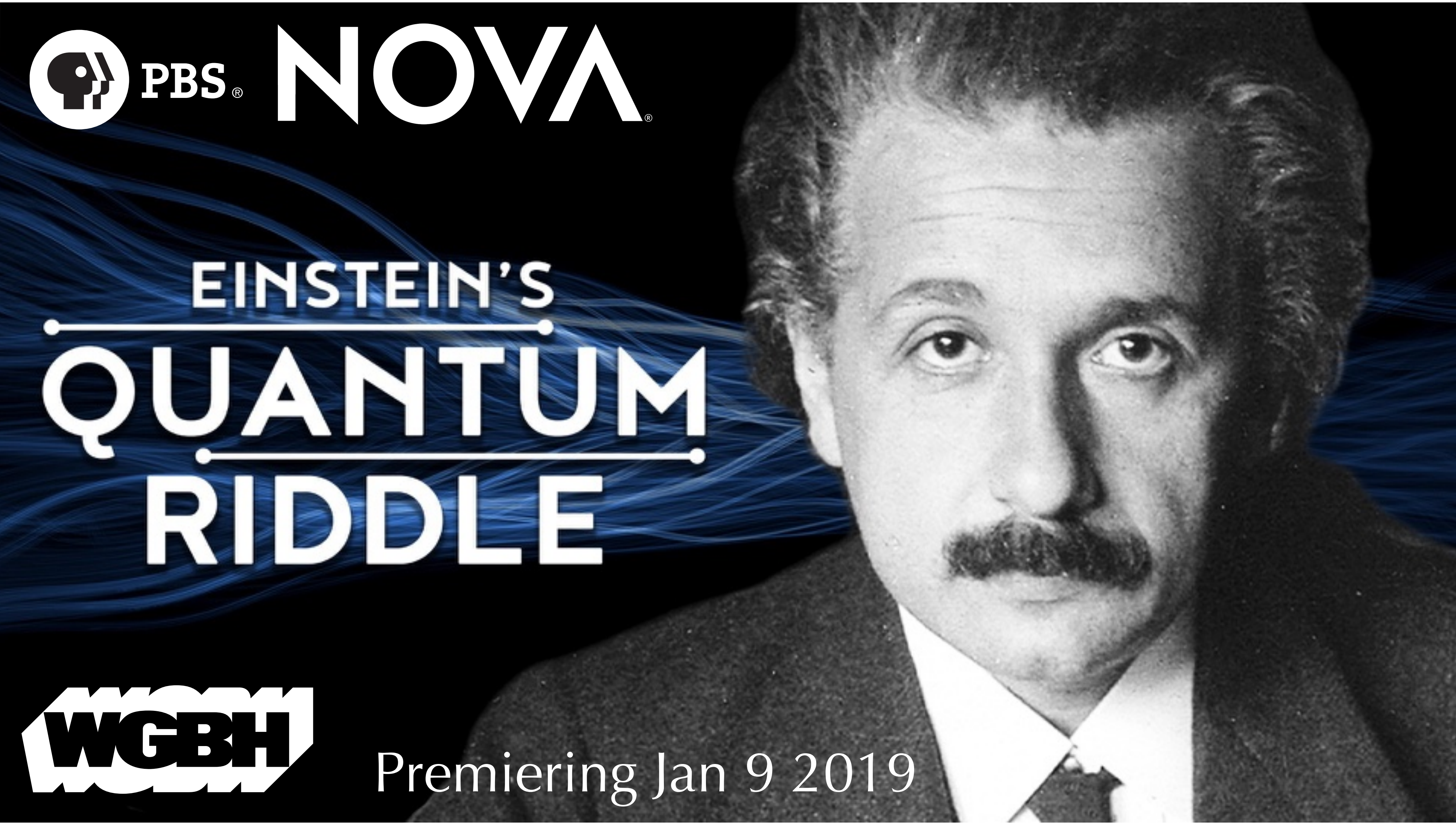
Dr. Hien Nguyen [6],
David Leon [5],
Calvin Leung [3]
et al.

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

BACK OF THE ENVELOPE



COSMIC BELL TEST ON TV!



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]
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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.

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

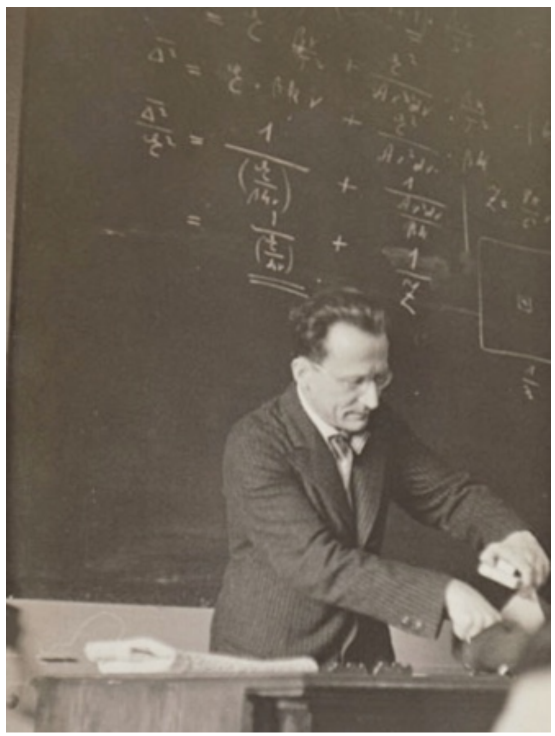
5. Cosmic Bell Test with Quasars

6. Future Tests

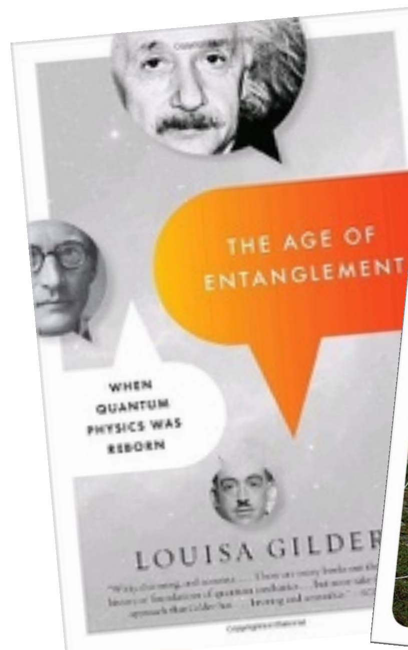
QUANTUM ENTANGLEMENT

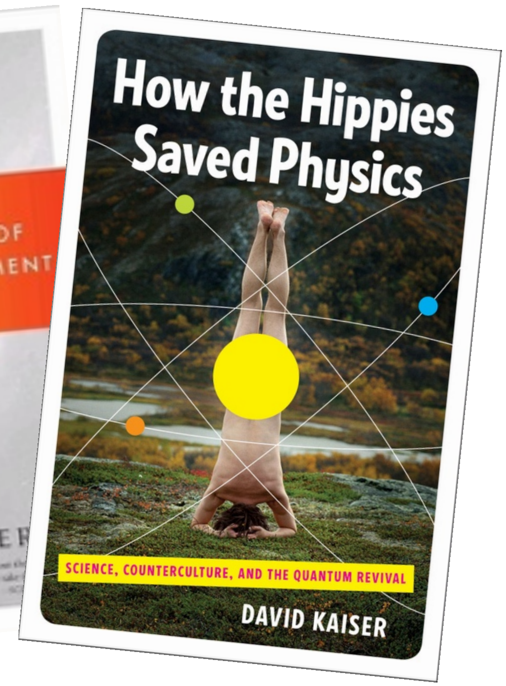
Beginning in the 1930s, the great architects of quantum theory struggled to understand the notion of "entanglement."

Niels Bohr and Albert Einstein



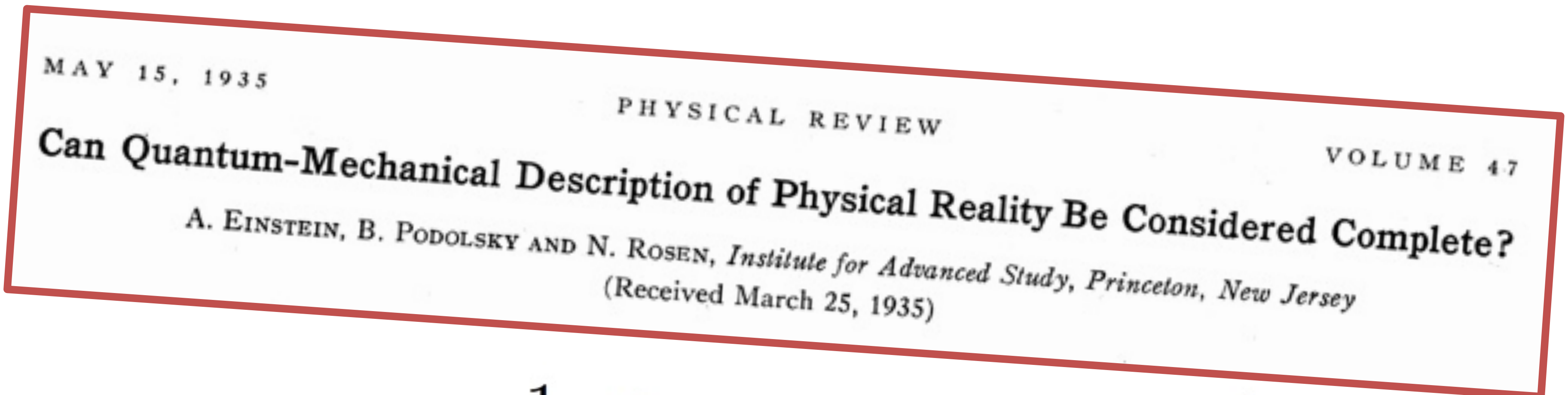
Erwin Schrödinger





EPR PARADOX

E P R


MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

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

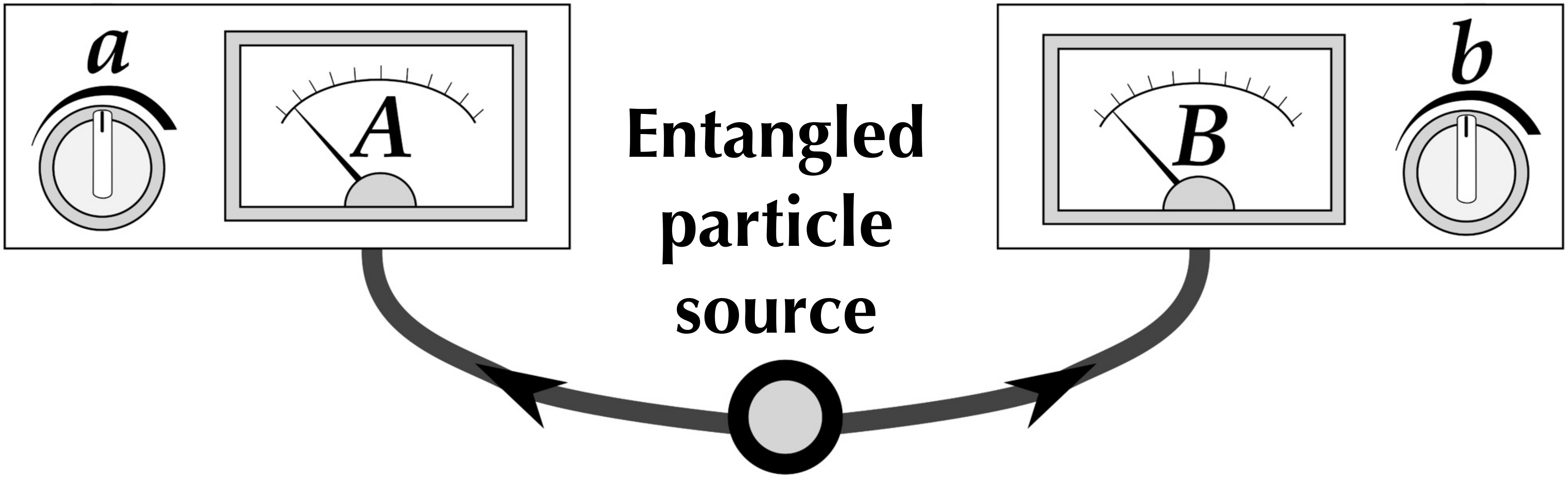
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(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

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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

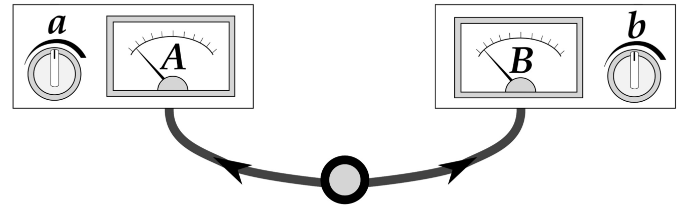
e.g. Can keep realism, locality. Relax Freedom.

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

CORRELATIONS AT A DISTANCE

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

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



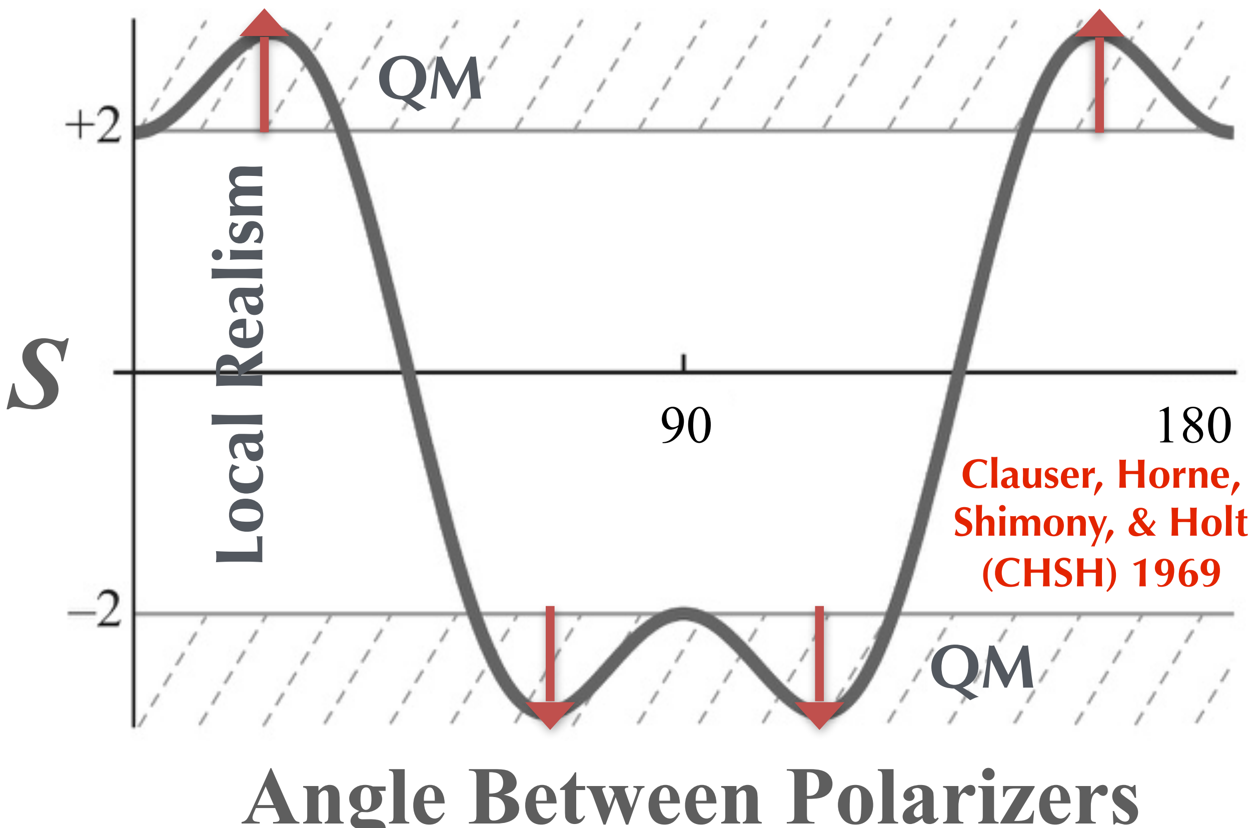
Bell: if $p(A,B|a,b) = \int d\lambda\, p(\lambda)\, \underbrace{p(A|a,\lambda)}\, p(B|b,\lambda)$

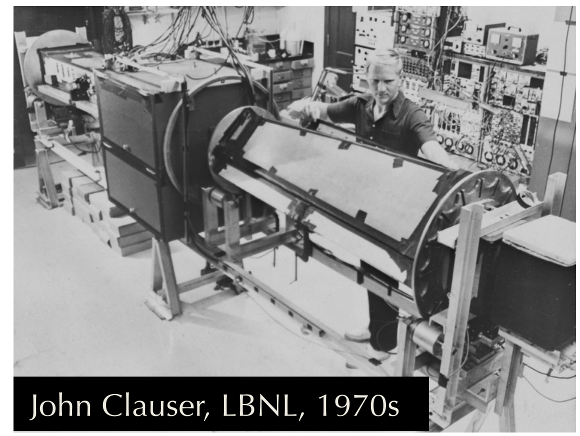
then $|S| \leq 2.$

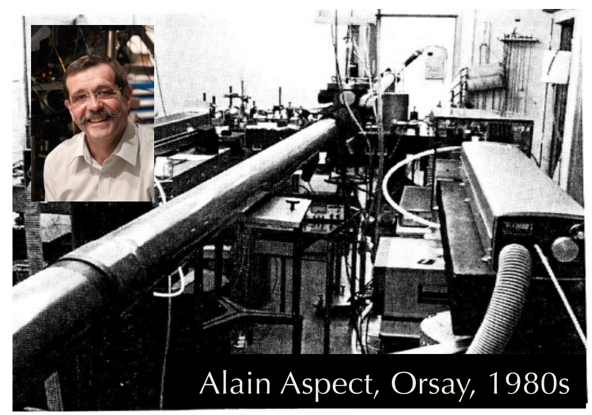
Locality: A does not depend on b or B, and vice versa.)

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

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

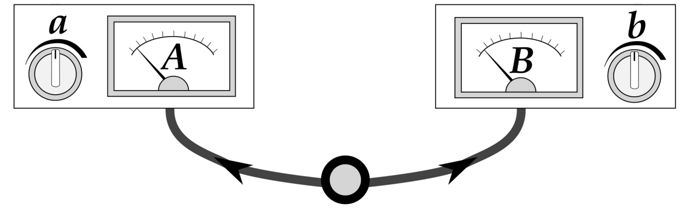



John Clauser, LBNL, 1970s


Alain Aspect, Orsay, 1980s

BELL'S INEQUALITY

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



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

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

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

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

- **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. Entangled 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

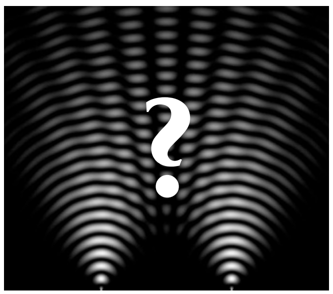
6. Future Tests

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?

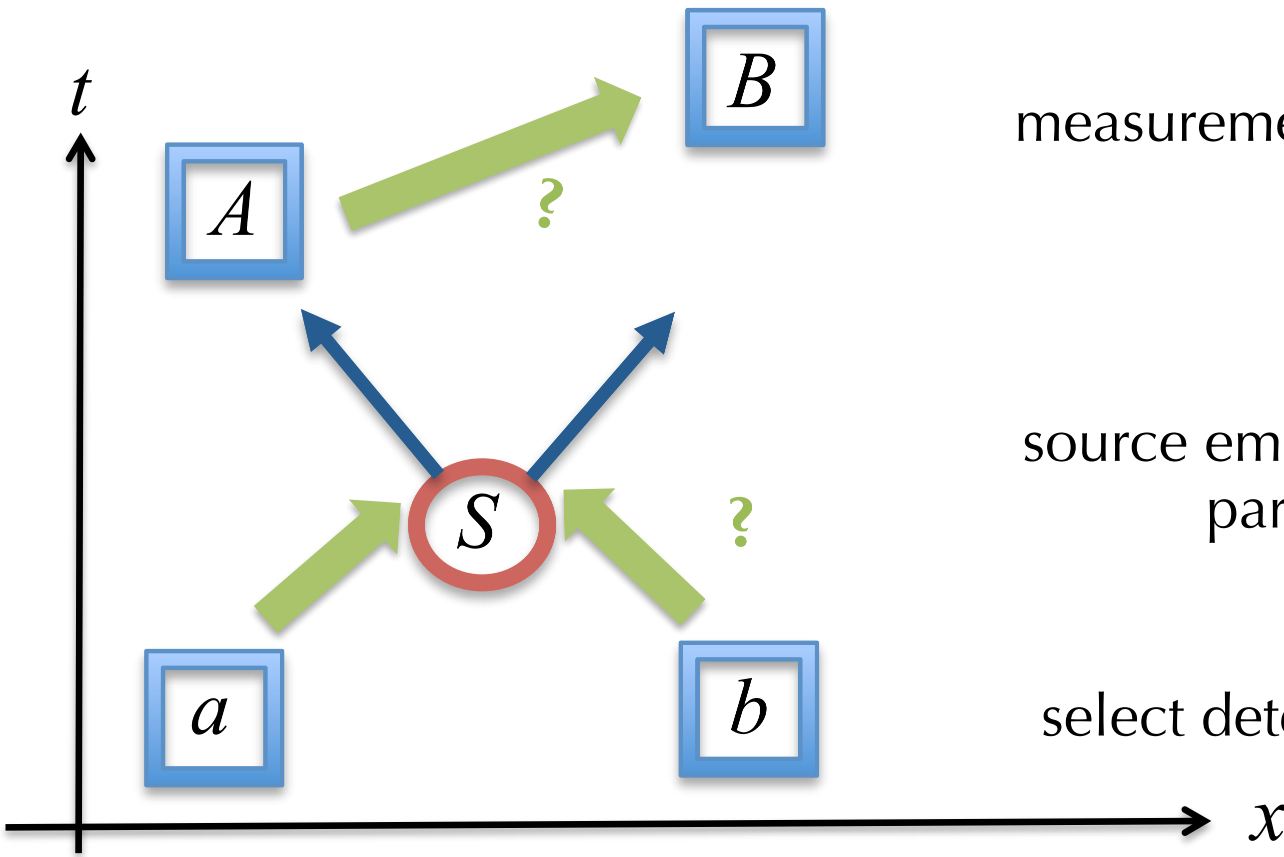
Quantum cryptography security

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

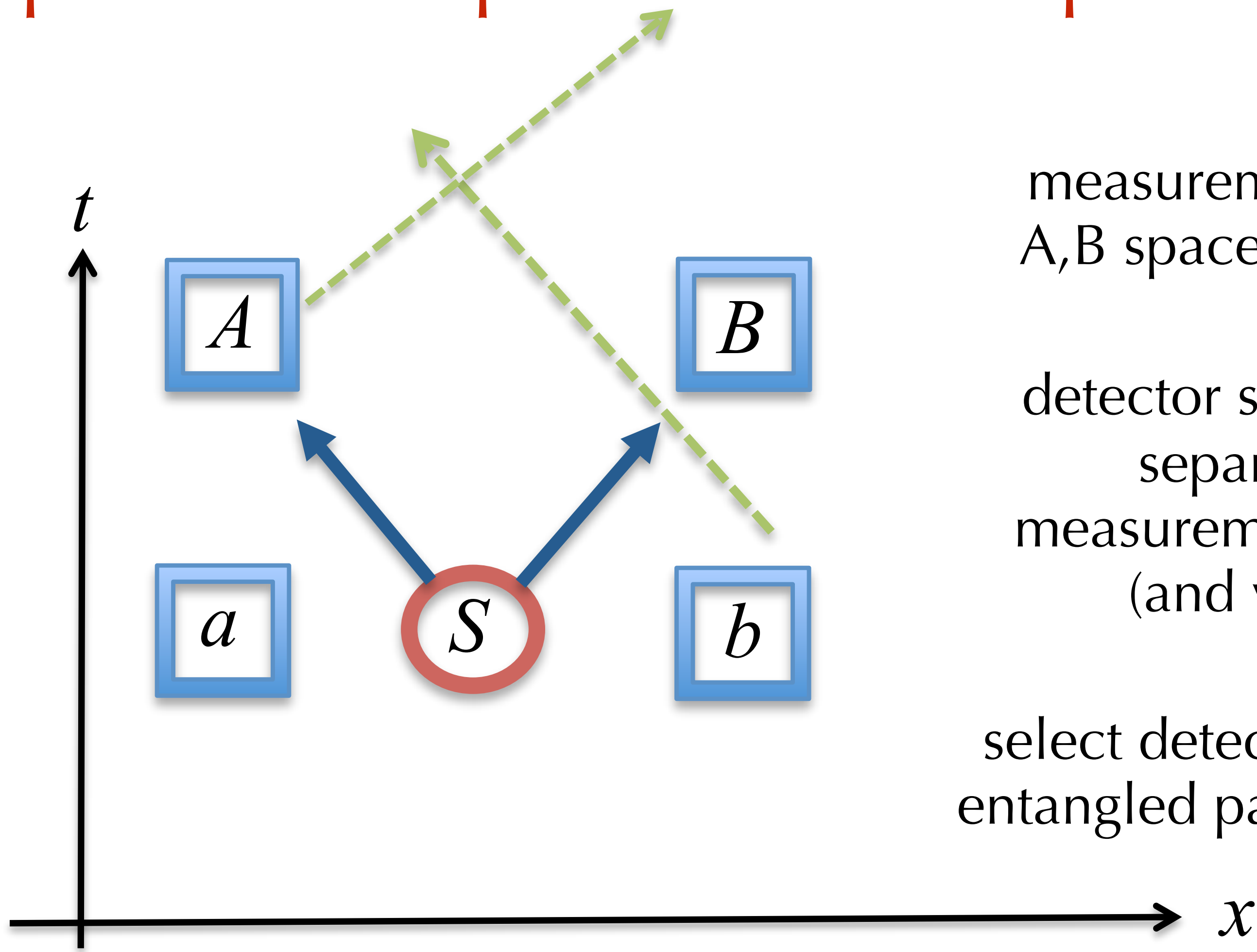
source emits entangled particles

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 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

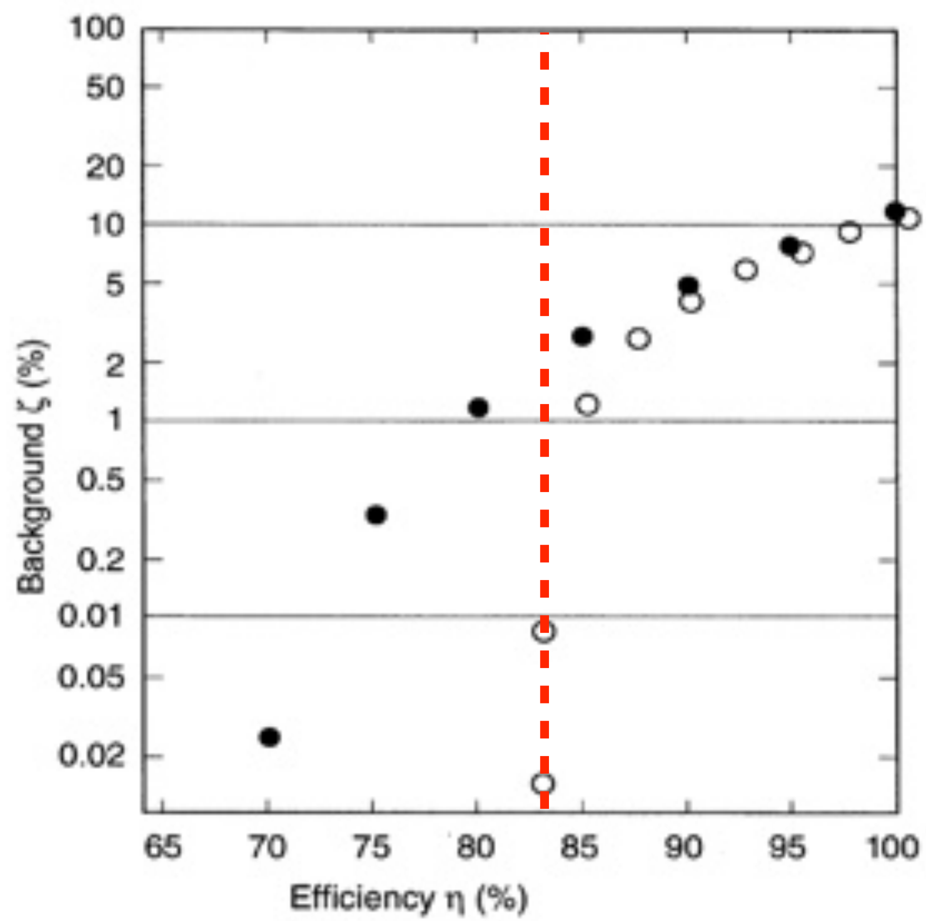
The standard interpretation of Bell tests — that "local realism" is incompatible with experiment — relies upon several assumptions.

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

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

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

Bell explicitly *assumed*

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

equivalent to

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

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

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

*Also known as the "measurement-independence" and "settings-independence" loophole.

RELAXING FREEDOM OF CHOICE

If we do *not* assume $p(\lambda|a,b) = p(\lambda)$, then local-realist models would be compatible with the relaxed Bell inequality

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

where
$$M_1 = \max\left\{\int d\lambda \left|p(\lambda|x,y) - p(\lambda|x',y)\right| , \int d\lambda \left|p(\lambda|x,y') - p(\lambda|x',y')\right|\right\}$$
$$M_2 = \max\left\{\int d\lambda \left|p(\lambda|x,y) - p(\lambda|x,y')\right| , \int d\lambda \left|p(\lambda|x',y) - p(\lambda|x',y')\right|\right\}$$

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

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

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

(M_1=M_2=M~0.276, F=1-M/2~86.2%, M/2~13.8%)

Hall 2010, *Phys Rev Lett*, 105, 250404 (arXiv:1007.5518)

Hall 2011, *Phys Rev A*, 84, 022102 (arXiv:1102.4467)

FREEDOM OF CHOICE LOOPHOLE

λ Hidden variables

a, b Joint measurement settings

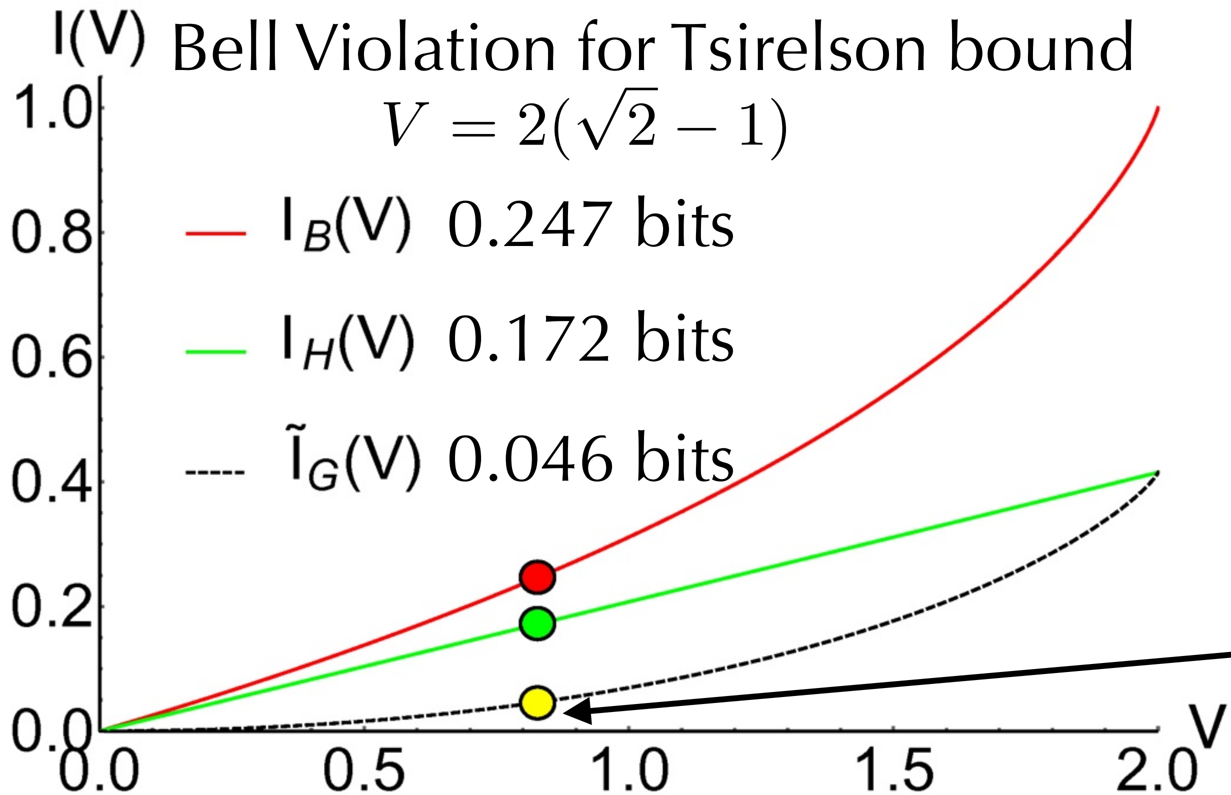
Freedom of choice assumption

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

Relaxing freedom of choice:

Mutual Information

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



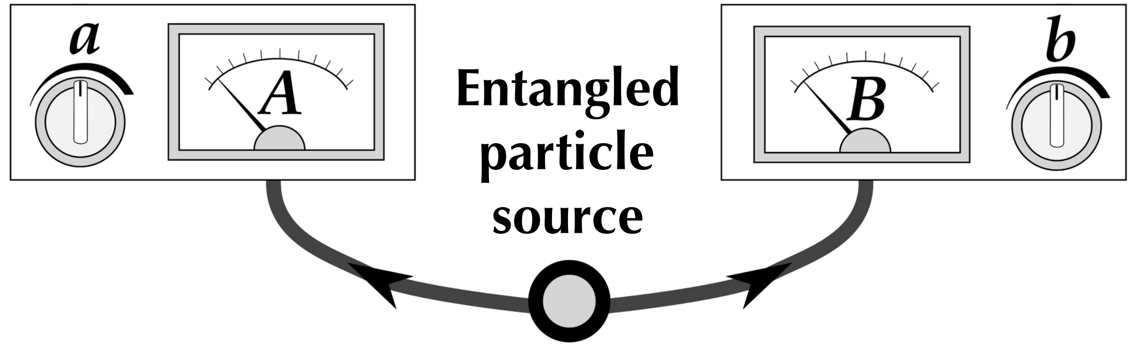
If we relax **Eq. (1)**, only require I=0.046~1/22 bit of correlation between hidden variables and joint settings to simulate QM

Friedman, Guth, Hall, Kaiser, & Gallicchio 2019, *Phys Rev A*, 99, 1, 012121 (arXiv: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*	$11.99
	for Two	$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 (e.g. from past events), experimental choices might not be perfectly free!

Still have free will!

But limited freedom

ADDRESSING FREEDOM OF CHOICE

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

- Most recent experiments used QRNGs to select detector settings.

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

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

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

TOWARD A 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

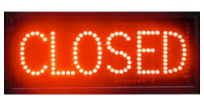
COSMIC BELL TESTS

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.

Recent Entanglement Tests

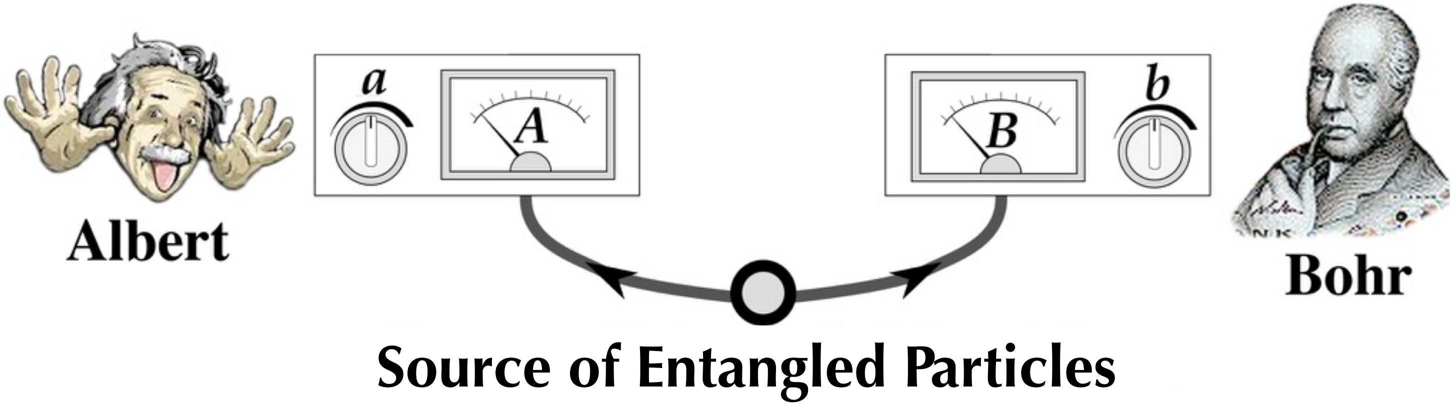
- Closed"locality" and "detection" loopholes simultaneously

Hensen+2015 (Delft), Giustina+2015 (Vienna), Shalm+2015 (NIST), Rosenfeld+2017 (Germany)

- None of these tests designed to fully address "freedom-of-choice" loophole

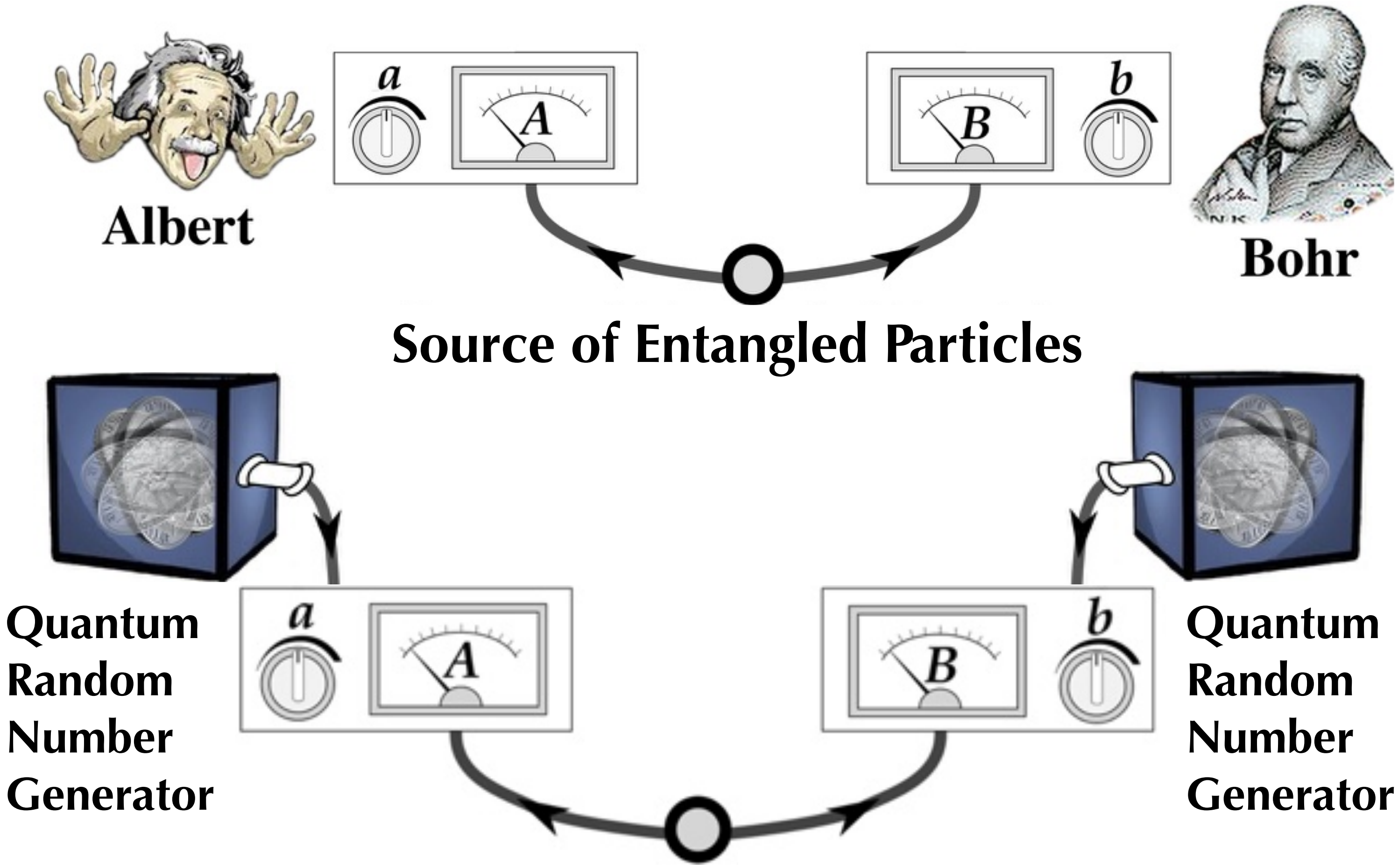
- Cosmic Bell tests attempt to do so progressively…

Choosing Detector Settings



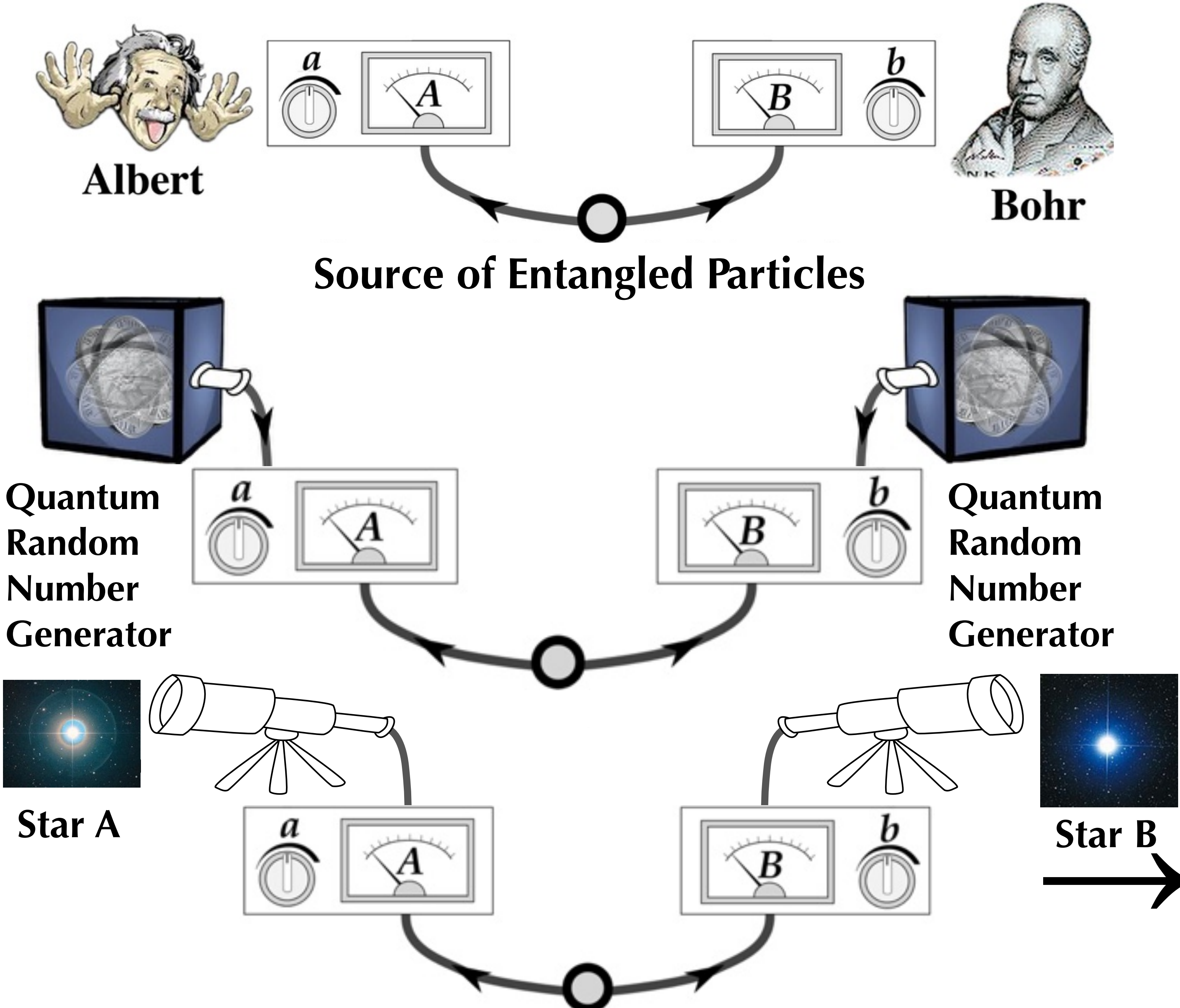
Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS



Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

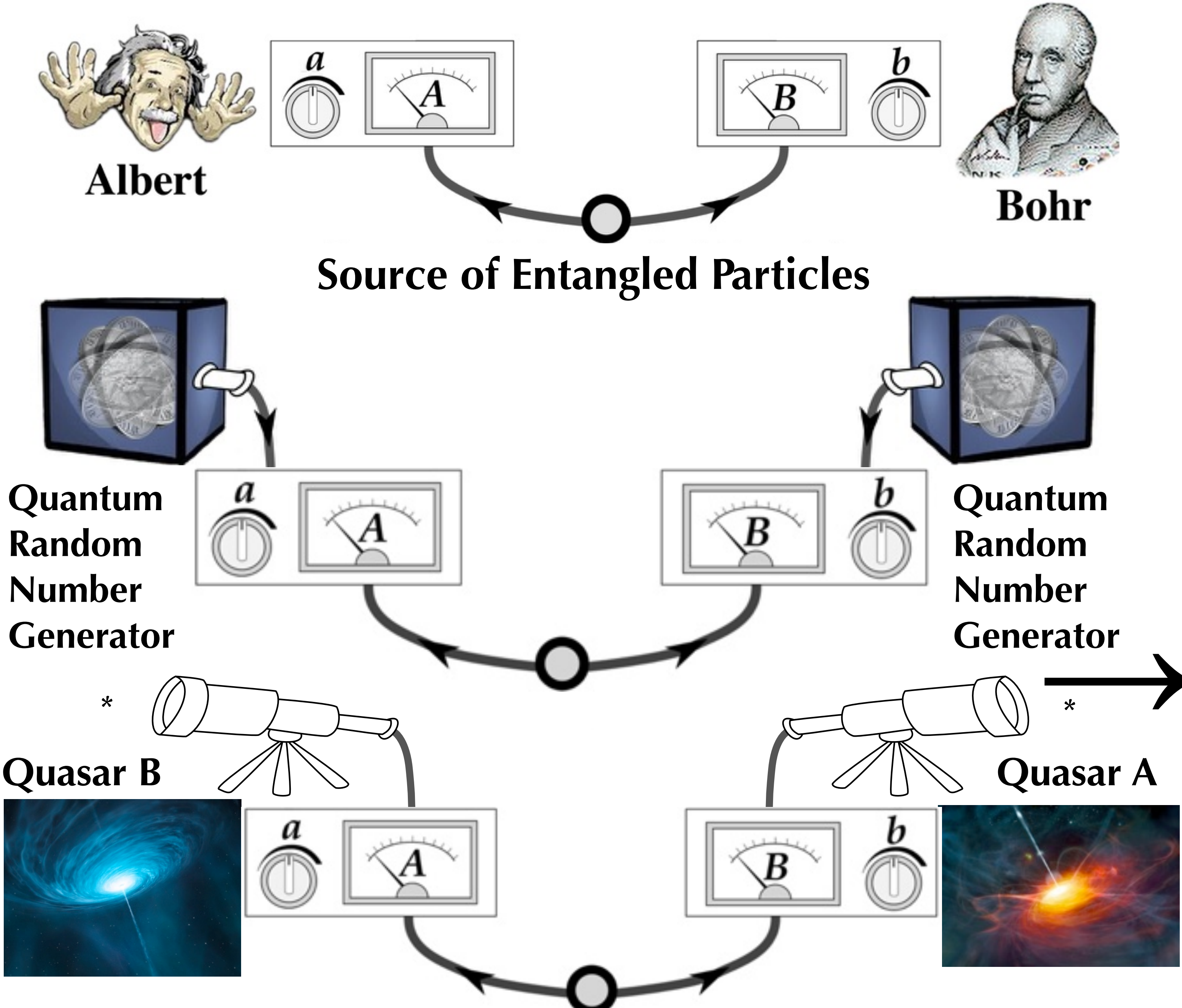


Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

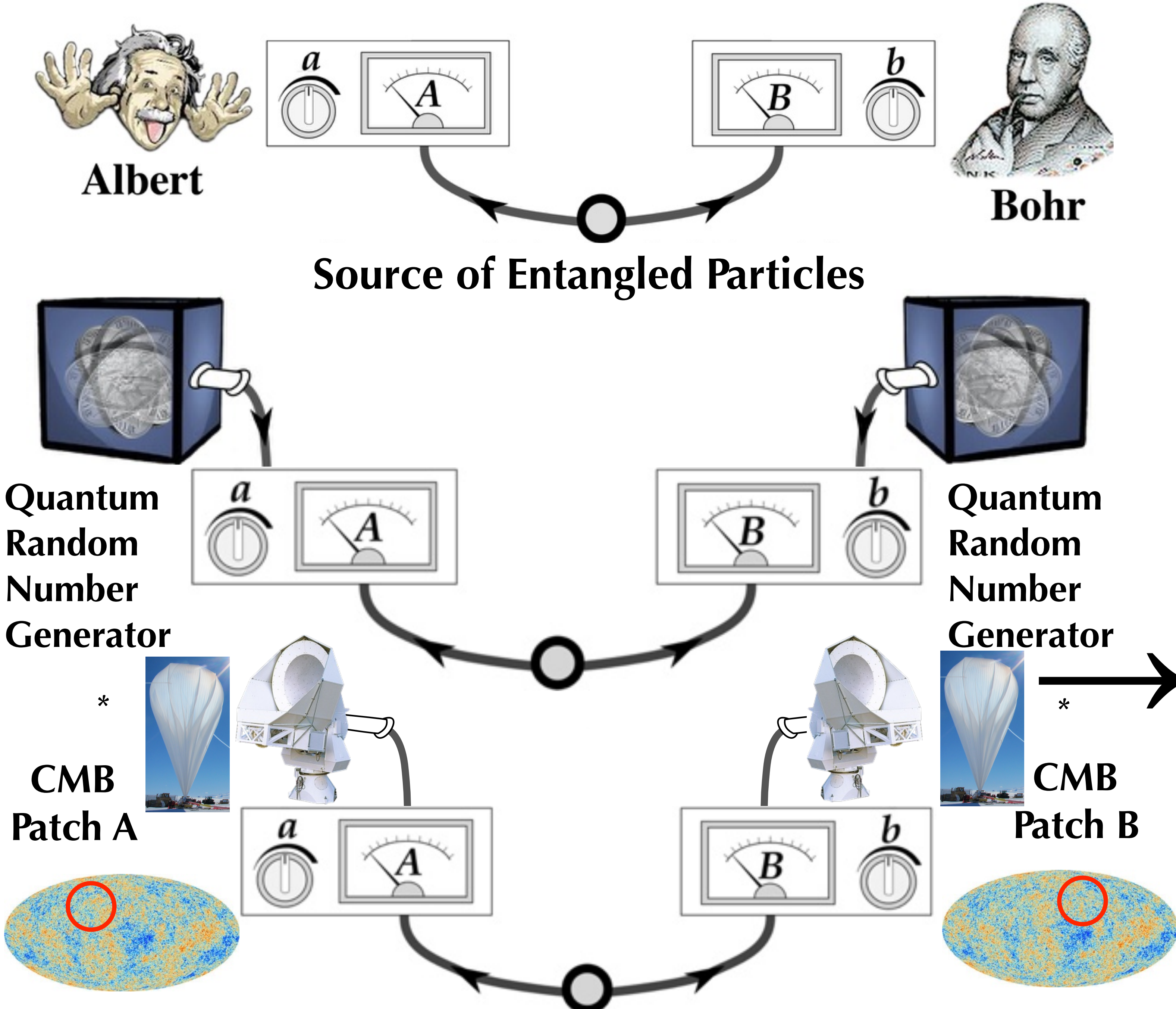


Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

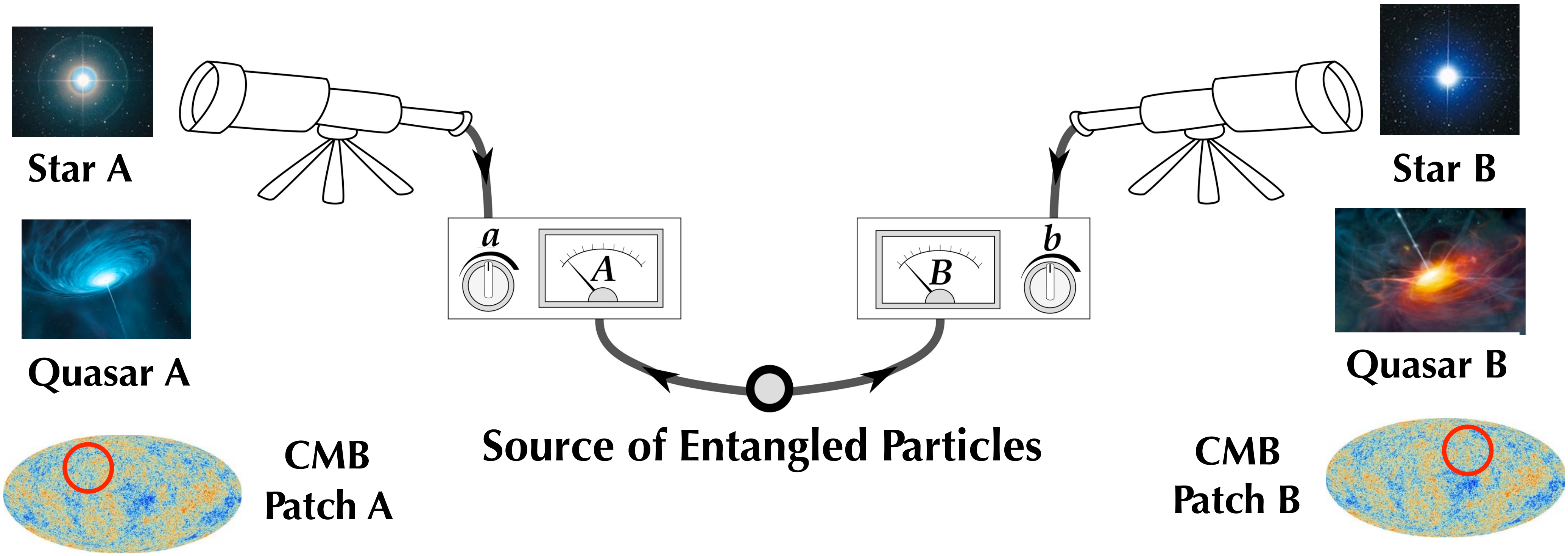


Choose settings with observations of CMB patches, etc…

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)

OUTLINE

1. Entangled 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

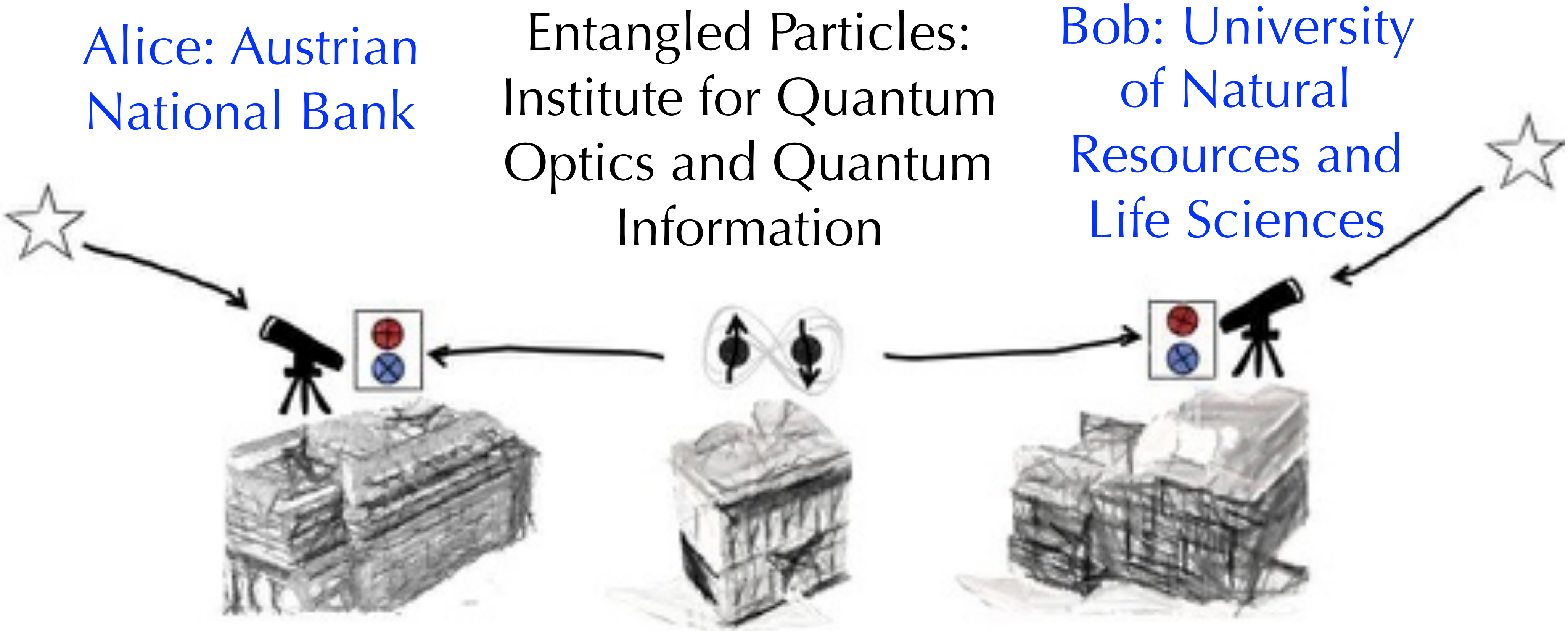
6. Future Tests

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,‡]

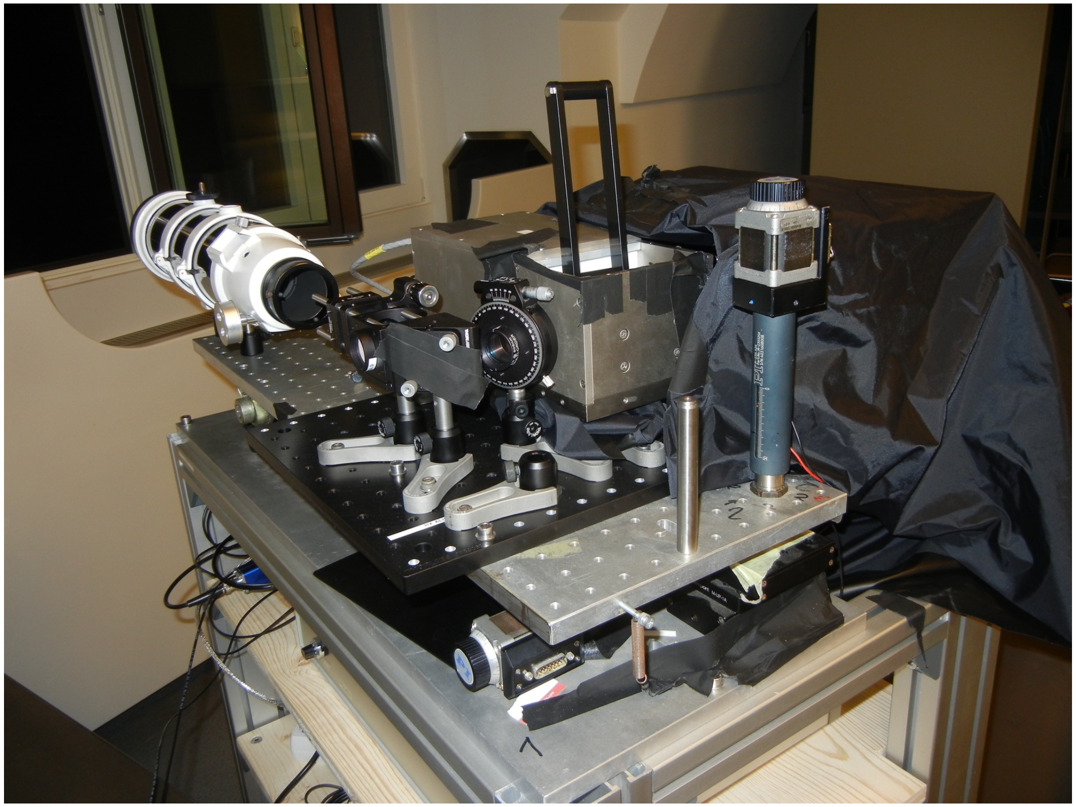


Handsteiner, Friedman+2017, *Physical Review Letters*, 118, 6, 060401(arXiv:1611.06985)

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

Red Arm
Guide Camera
Blue Arm
Light In

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

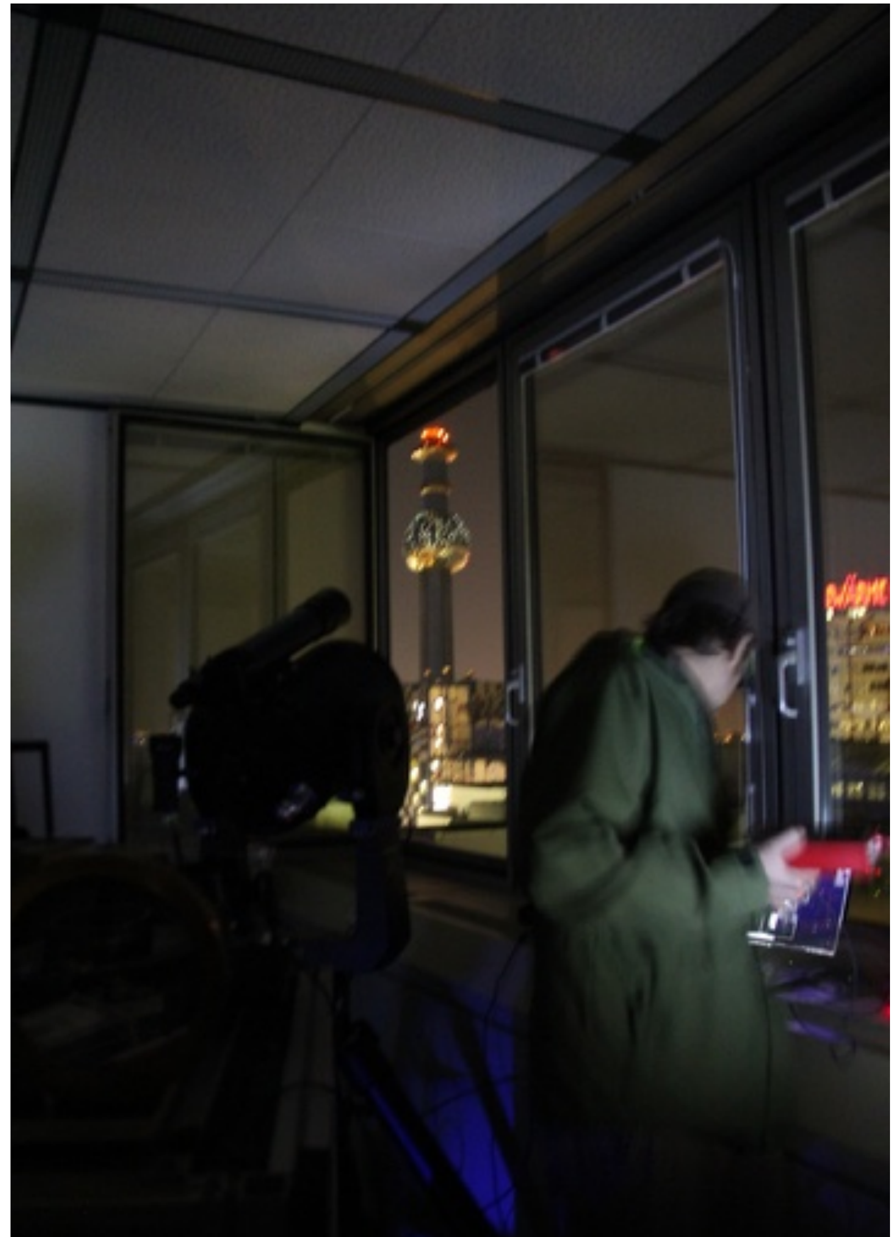


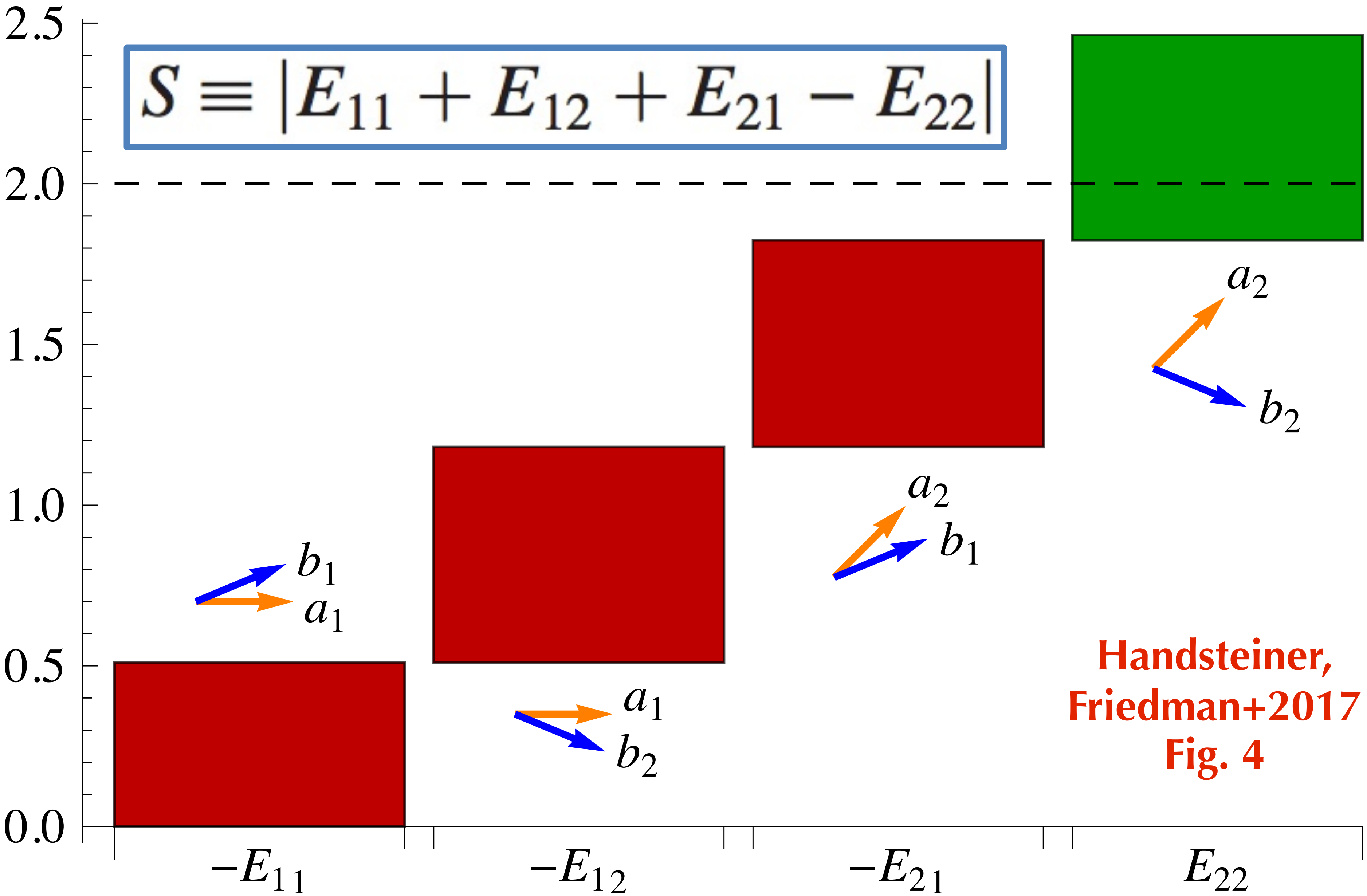
Image Credit: Jason Gallicchio

VIENNA COSMIC BELL TEST

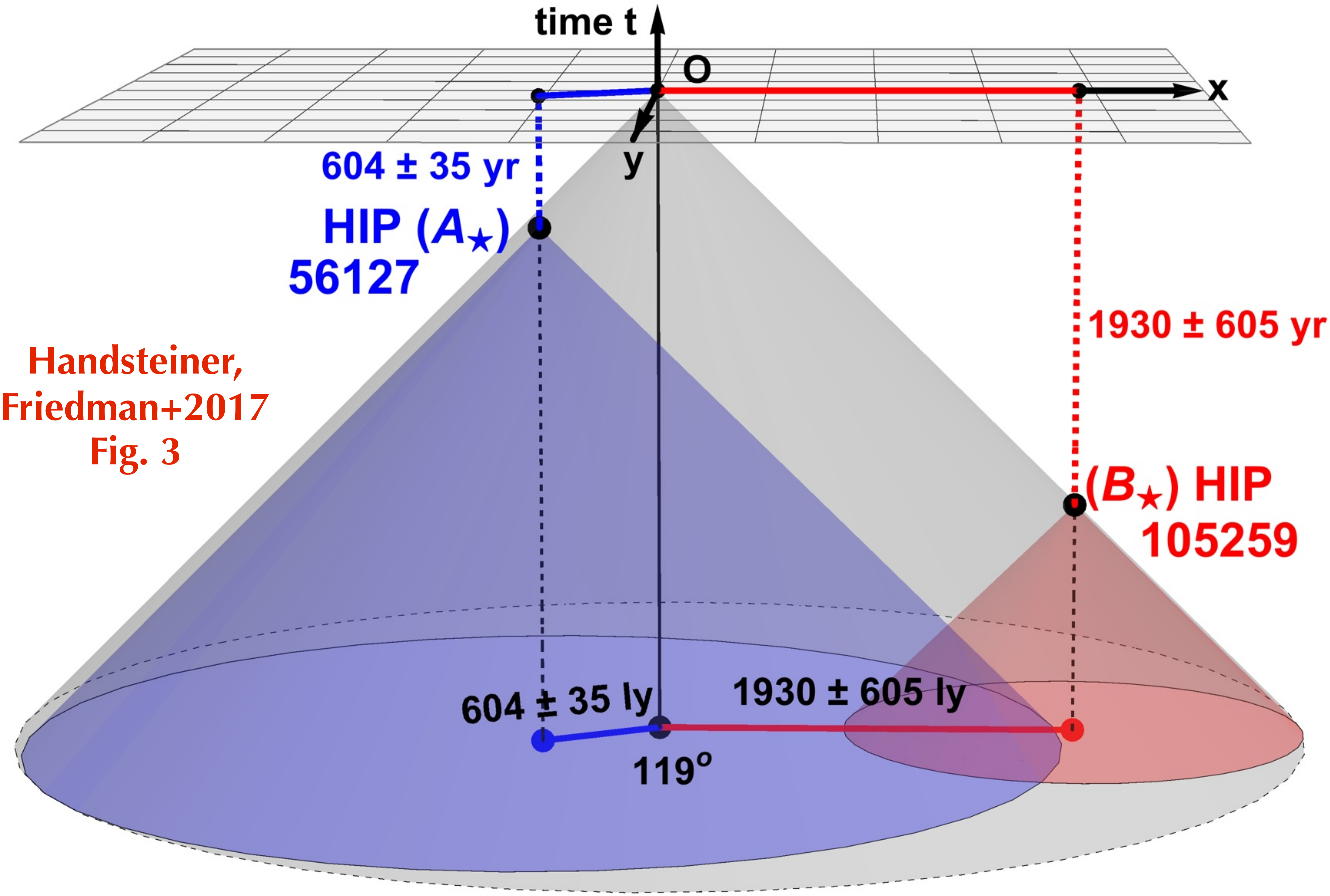
Star Selection

Image Credit: Jason Gallicchio

OBSERVED BELL VIOLATION



SPACE-TIME DIAGRAM: STARS



Handsteiner, Friedman+2017 Fig. 3

DATA ANALYSIS: NOISE LOOPHOLE

- Need triggers by genuine cosmic photons, not local "noise" photons: atmospheric airglow, thermal dark counts, errant dichroic mirror reflections

- Conservatively allow S=4 for any background events, S<2 for cosmic photons. Accounts for bias in red/blue ports.

- Observed sufficient signal-to-noise from cosmic sources

Highly significant Bell violation still observed:
Run 1: 7.31 sigma, Run 2: 11.93 sigma

***See* Handsteiner, Friedman+2017 (Supplemental Material)**

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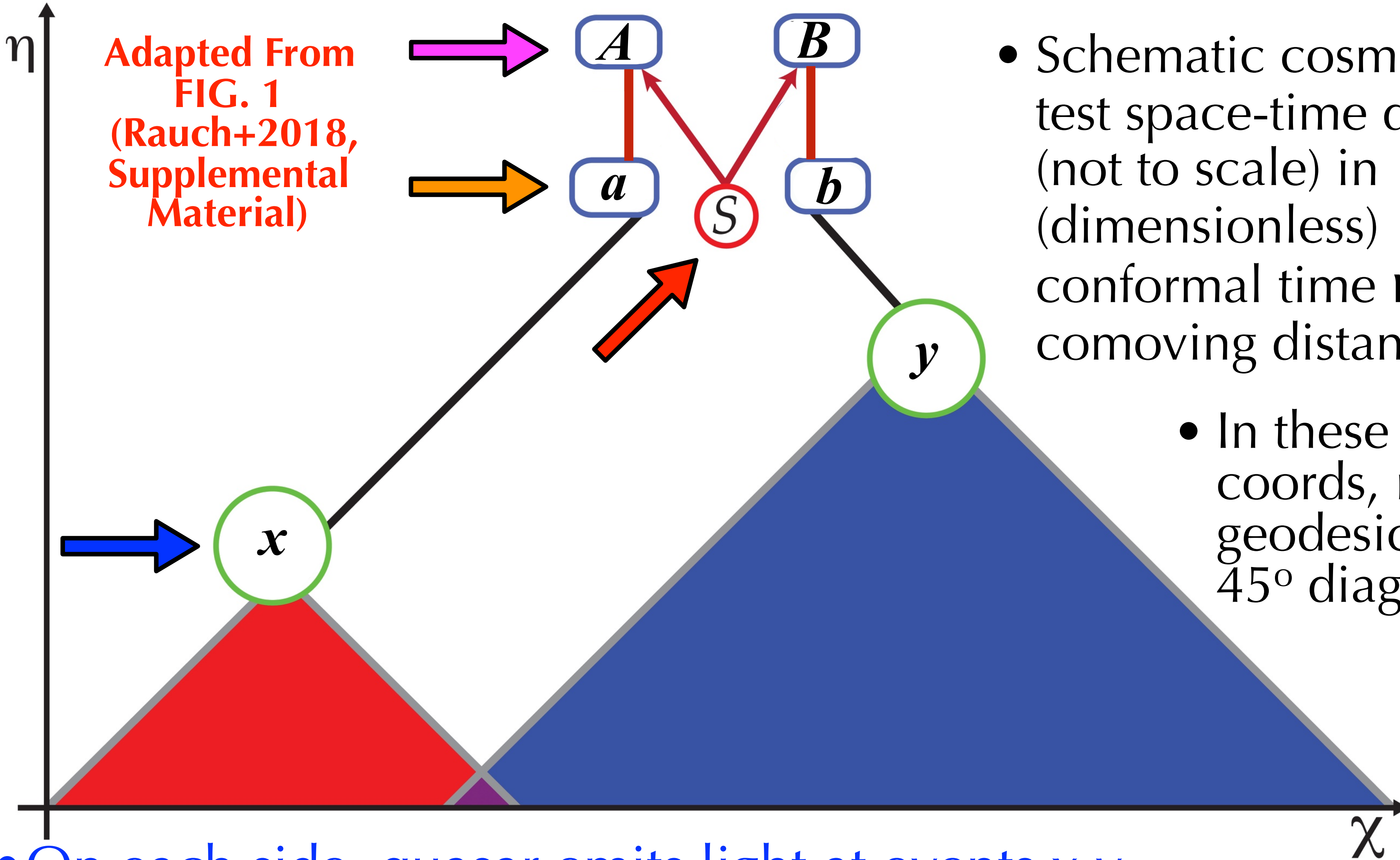
1+1D SPACETIME DIAGRAM

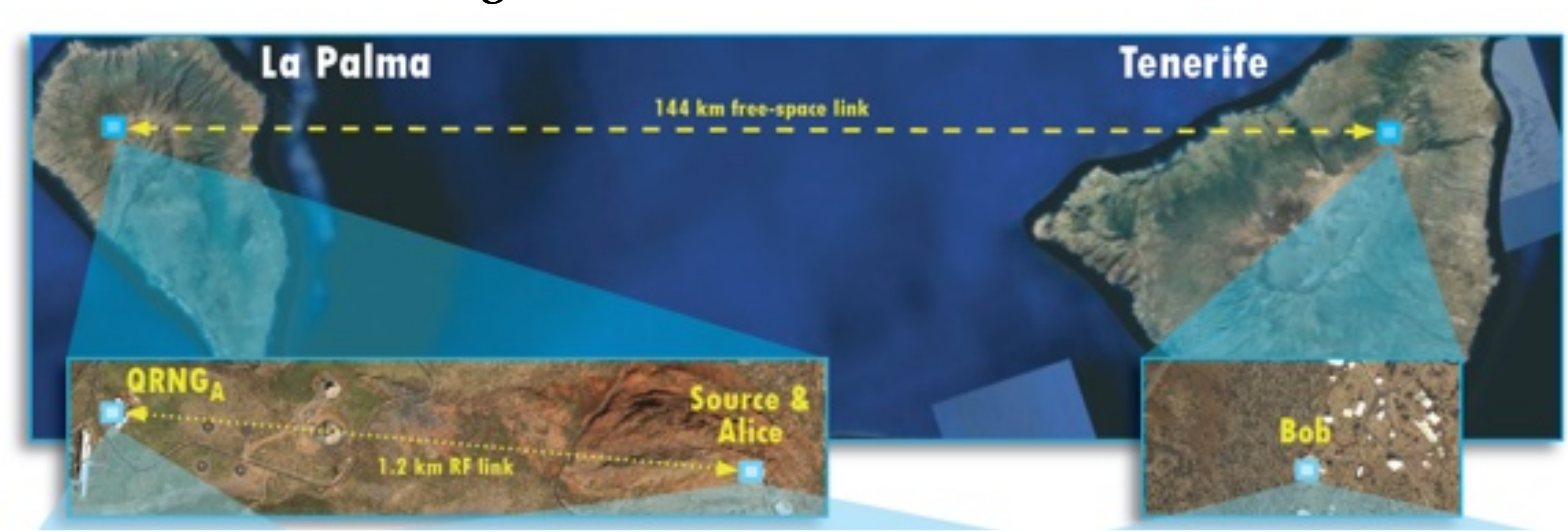


- Schematic cosmic Bell test space-time diagram (not to scale) in (dimensionless) conformal time η vs. comoving distance χ.
  - In these coords, null geodesics on 45° diagonals.

- 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

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

Image Credit: Jason Gallicchio (Harvey Mudd)

COSMIC BELL TEST WITH QUASARS

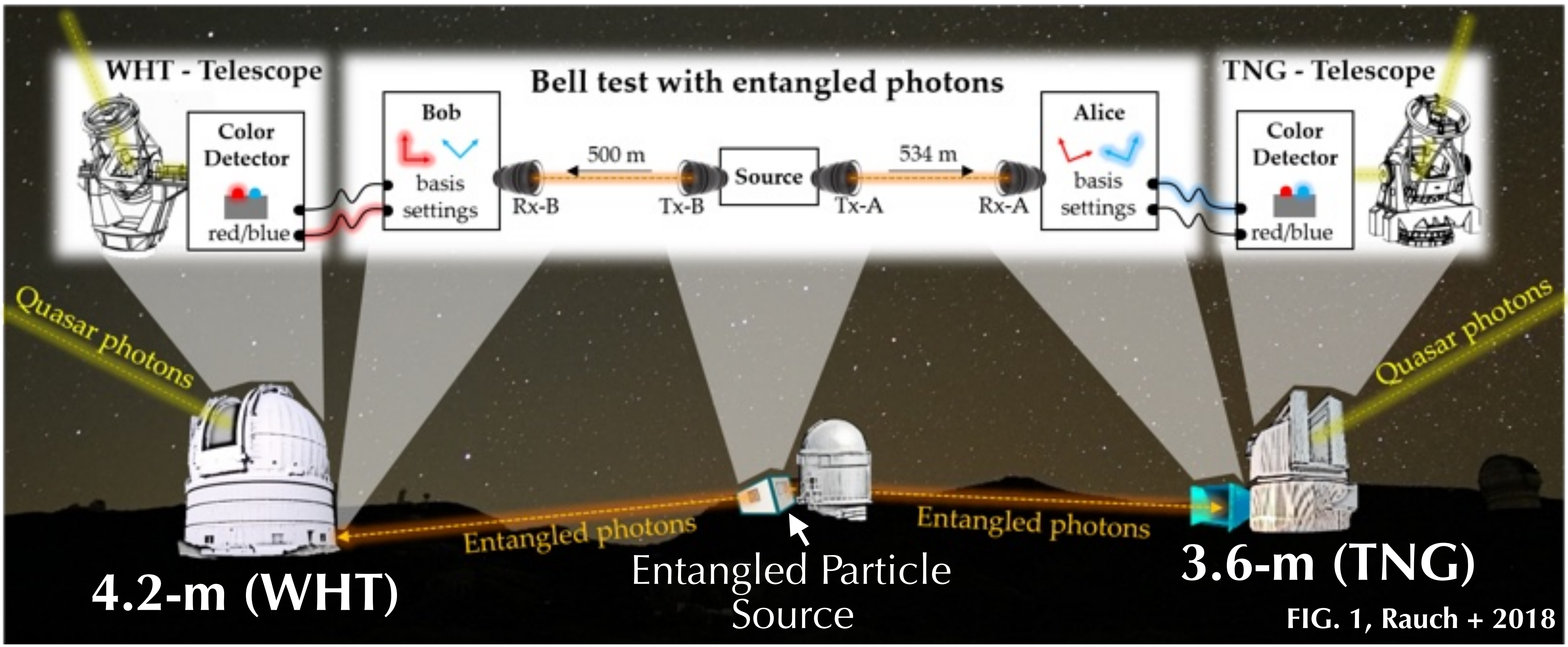
PHYSICAL REVIEW LETTERS **121,** 080403 (2018)

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)



COSMIC BELL TEST WITH QUASARS

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

Editors' Suggestion

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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

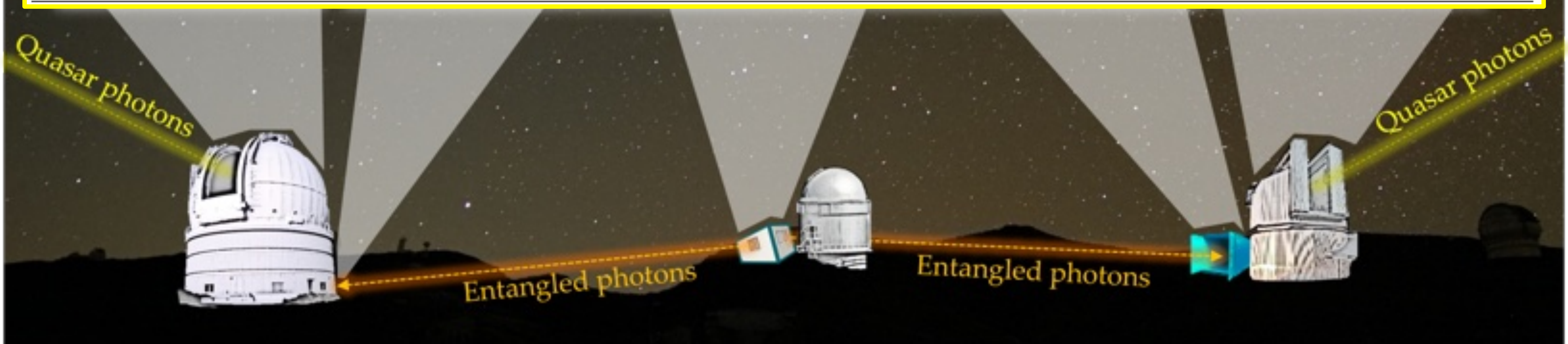


FIG. 1, Rauch + 2018

2+1D SPACETIME DIAGRAM

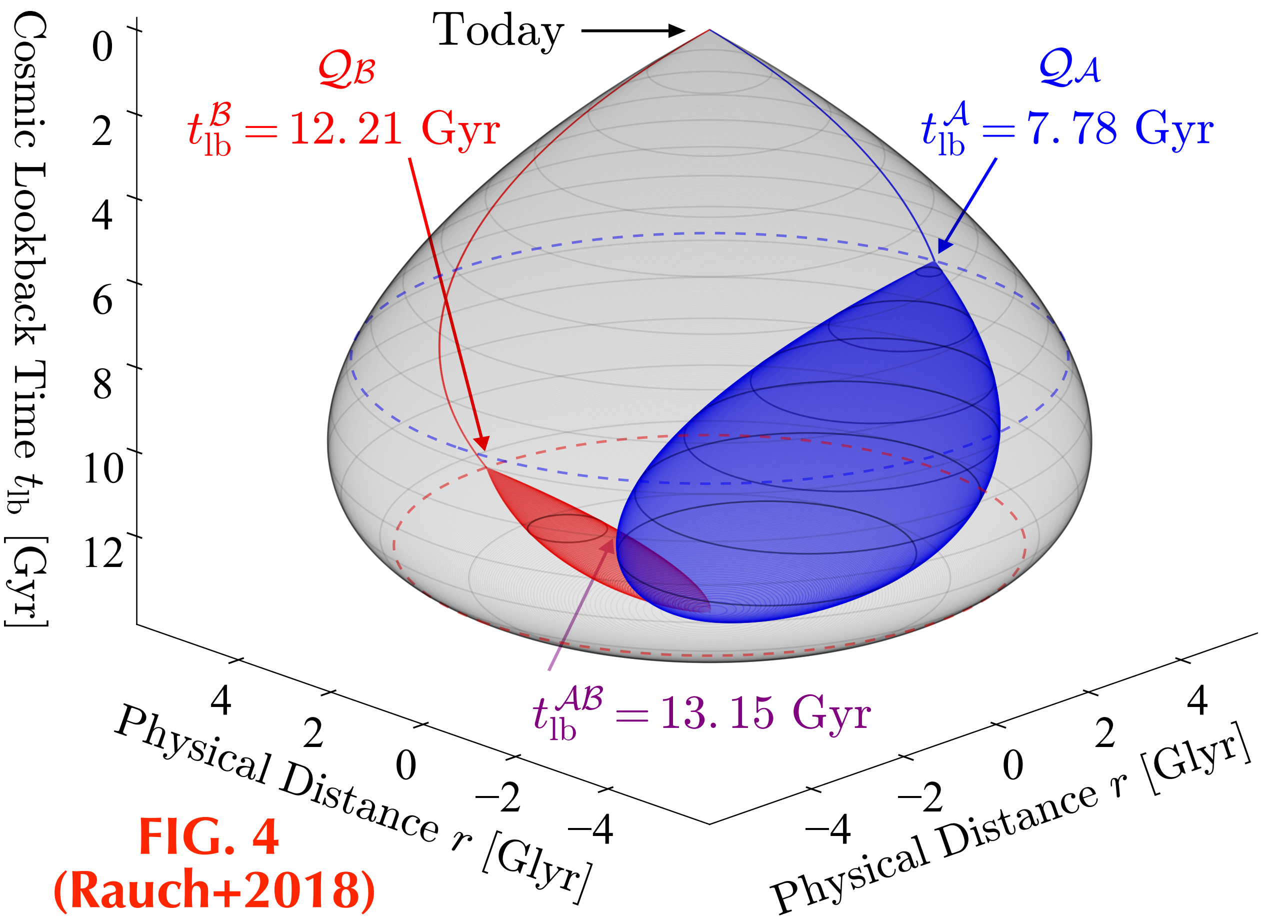


FIG. 4
(Rauch+2018)

- 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

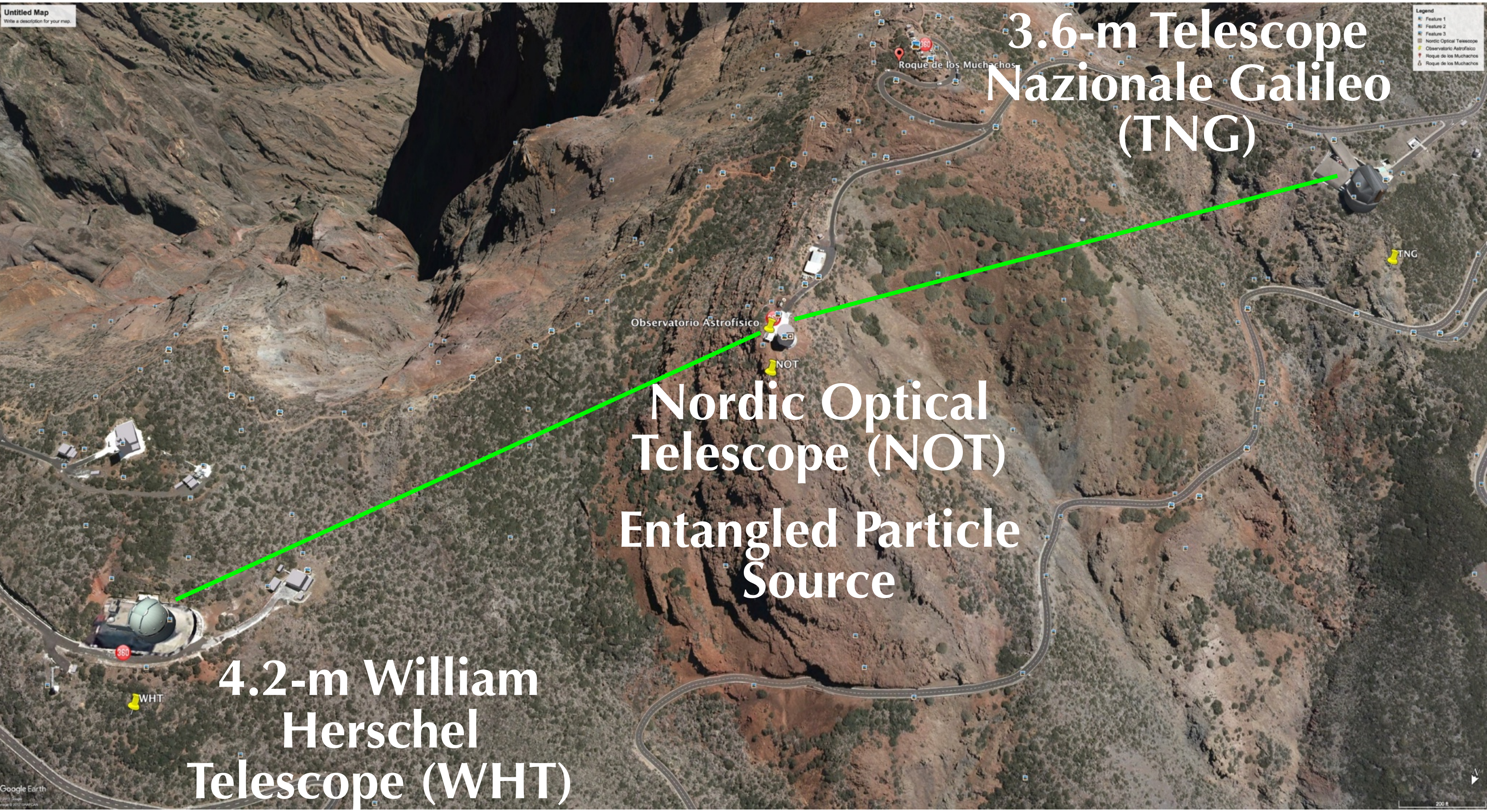


Image ©2018 DigitalGlobe (Google Earth)

CHOOSING THE BEST QUASARS

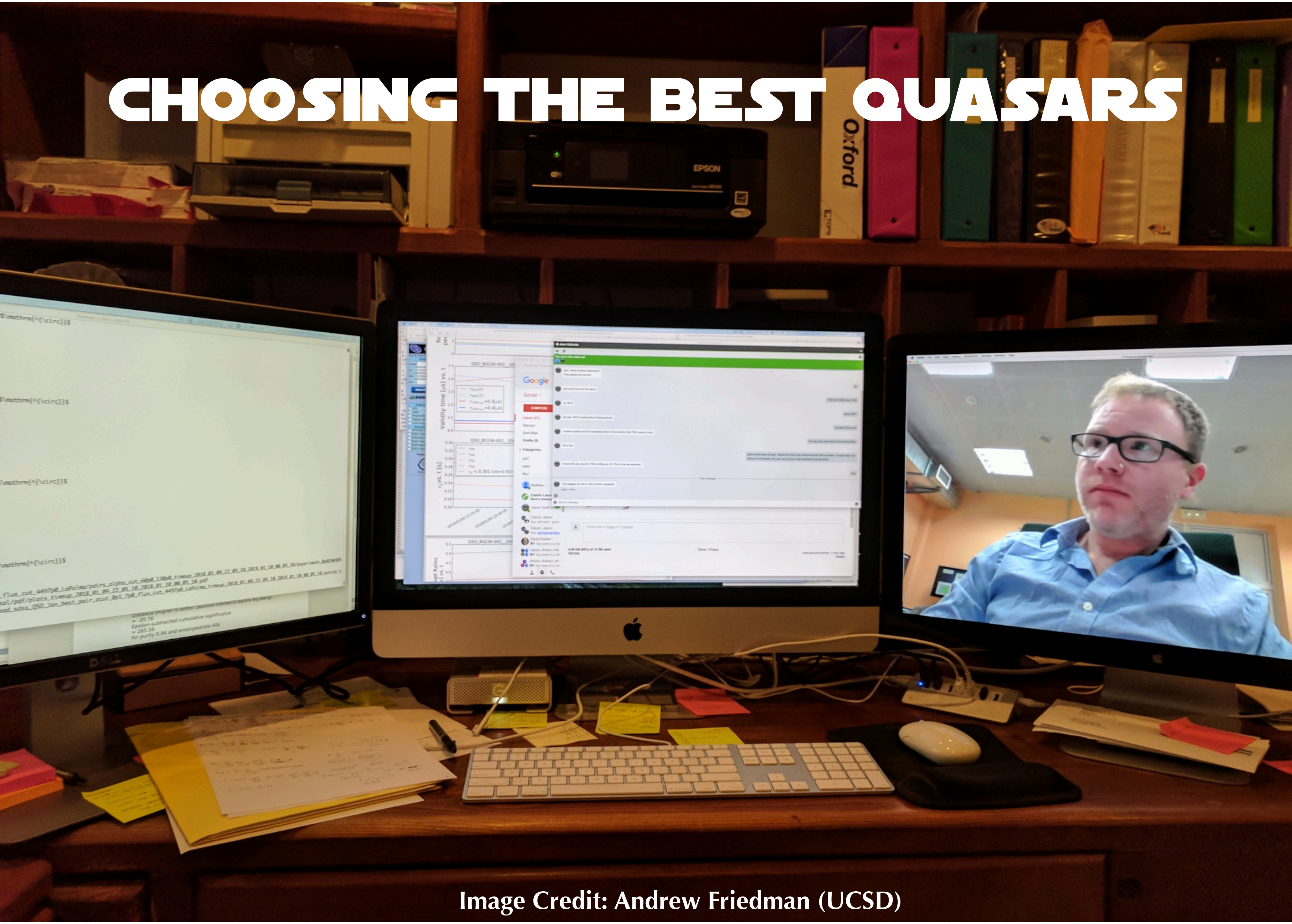


Image Credit: Andrew Friedman (UCSD)

REMOTE ASSISTANCE

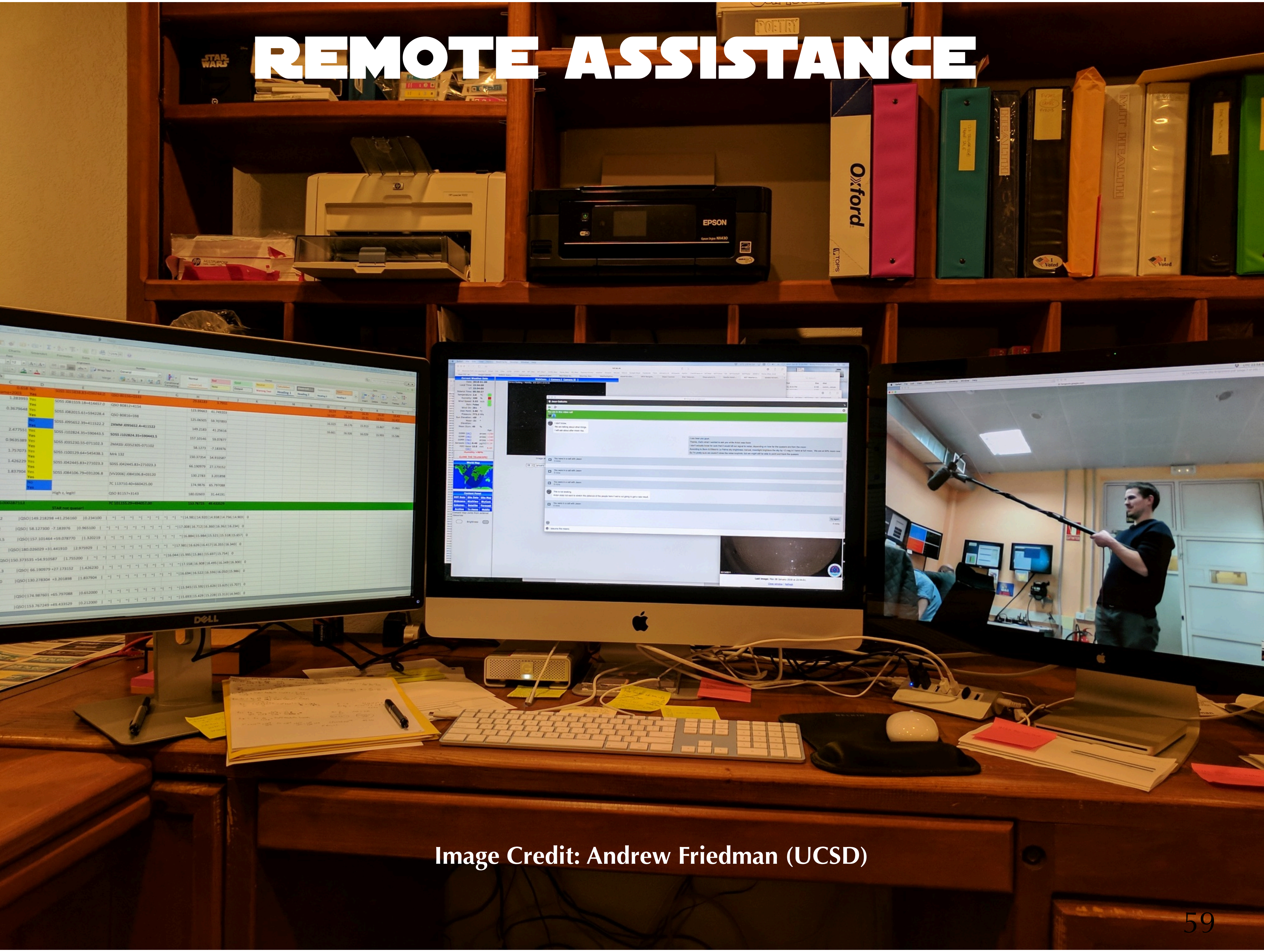
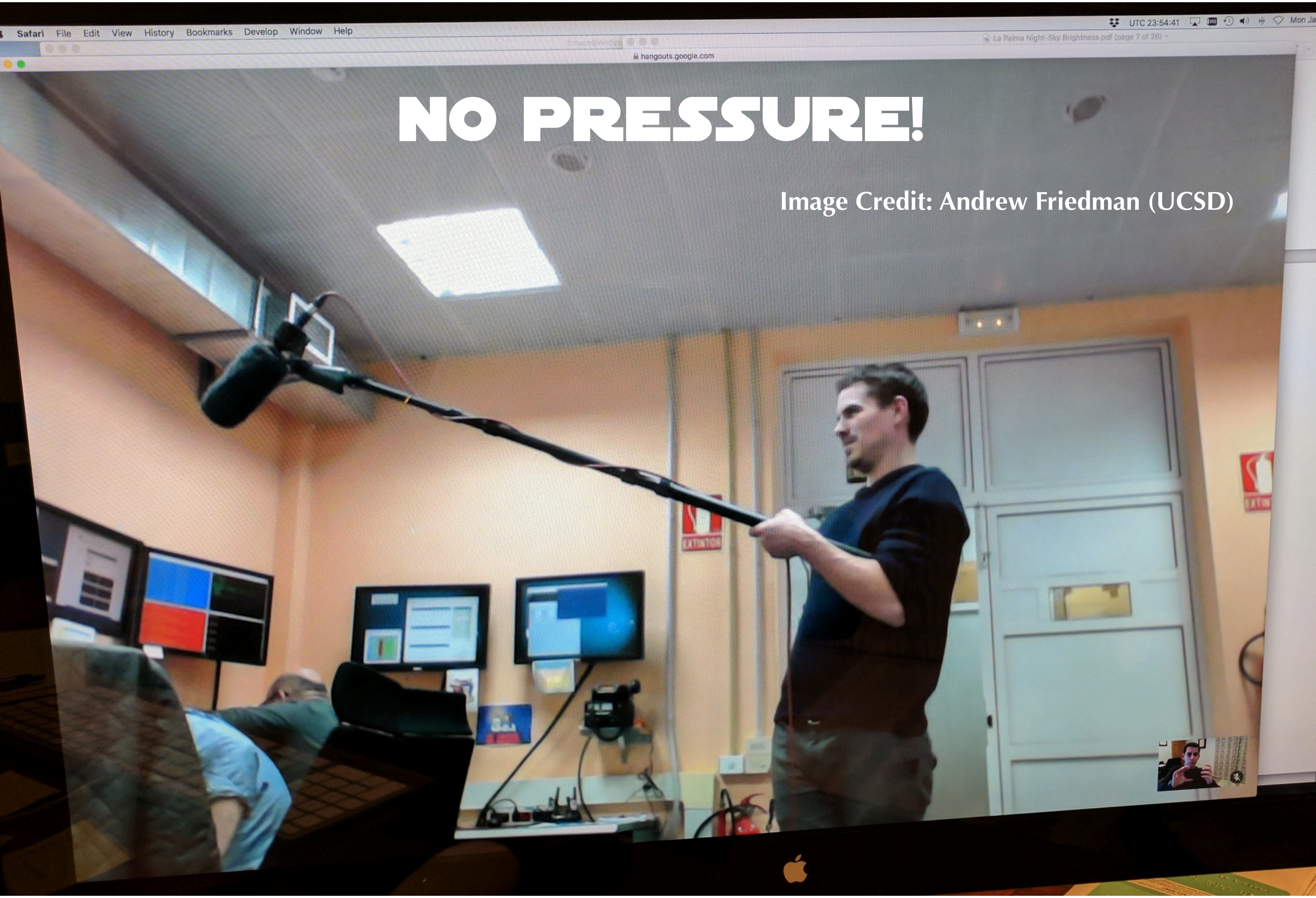
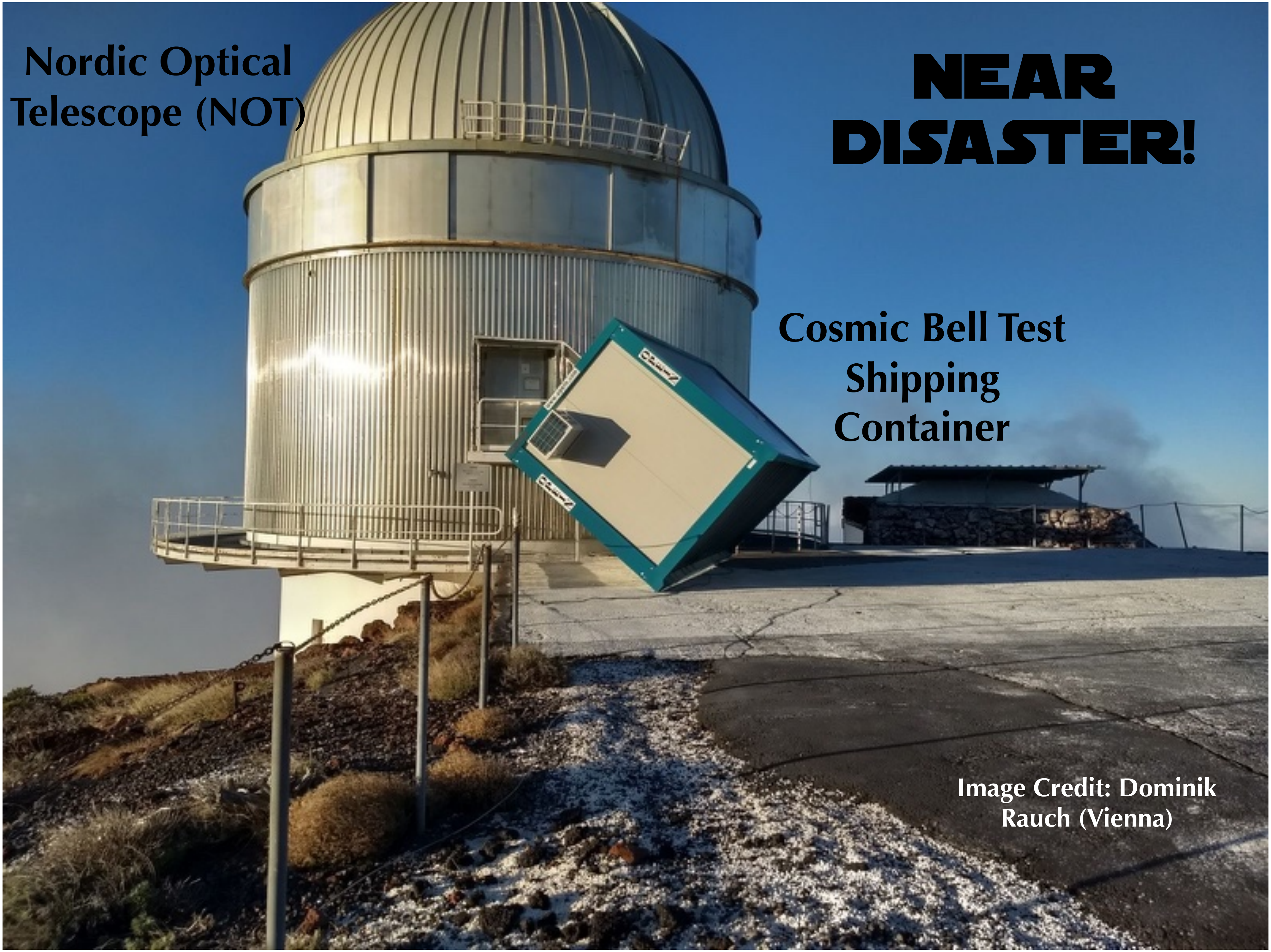


Image Credit: Andrew Friedman (UCSD)


NO PRESSURE!
Image Credit: Andrew Friedman (UCSD)
Safari File Edit View History Bookmarks Develop Window Help
hangouts.google.com
UTC 23:54:41

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!
ASA
Image Credit: Dominik Rauch (Vienna)

Image Credit: Dominik Rauch (Vienna)
DISASTER AVERTED
Cosmic Bell Test Shipping Container
www.opein.com
OPEIN
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
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)

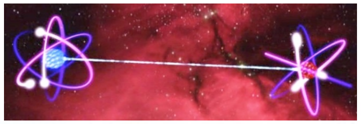
COSMIC BELL TEST (SUMMARY)

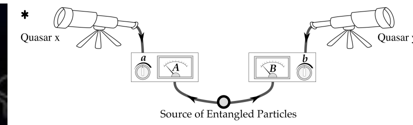
- Free space Bell test with polarization-entangled photons
- Detector settings from real-time wavelength measurements of **high-z quasar photons**, light emitted billions of years ago
- Experiment simultaneously ensures **locality**
- Assumptions: 1) fair sampling for all detected photons, 2) quasar 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

MIT News

ON CAMPUS AND AROUND THE WORLD



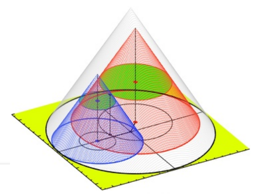


https://asfriedman.physics.ucsd.edu/media_coverage.shtml

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

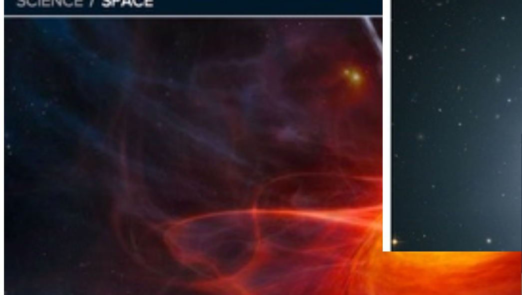
Cosmic Test For Quantum Physics' Last Major Loophole

NOVA

PBS

NBC NEWS HOME LATEST

SCIENCE / SPACE



Quasar Experiment May Shed Light on Quantum Physics and Free Will

BY CHARLES Q. CHOI, INSIDE SCIENCE

NOVA

THE NATURE OF REALITY

The physics of nothing, everything, and all the things in between

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QUANTUM PHYSICS

19 MAR

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

By Andrew Friedman on Wed, 19 Mar 2014

SundayReview

The New York Times

Is Quantum Entanglement Real?

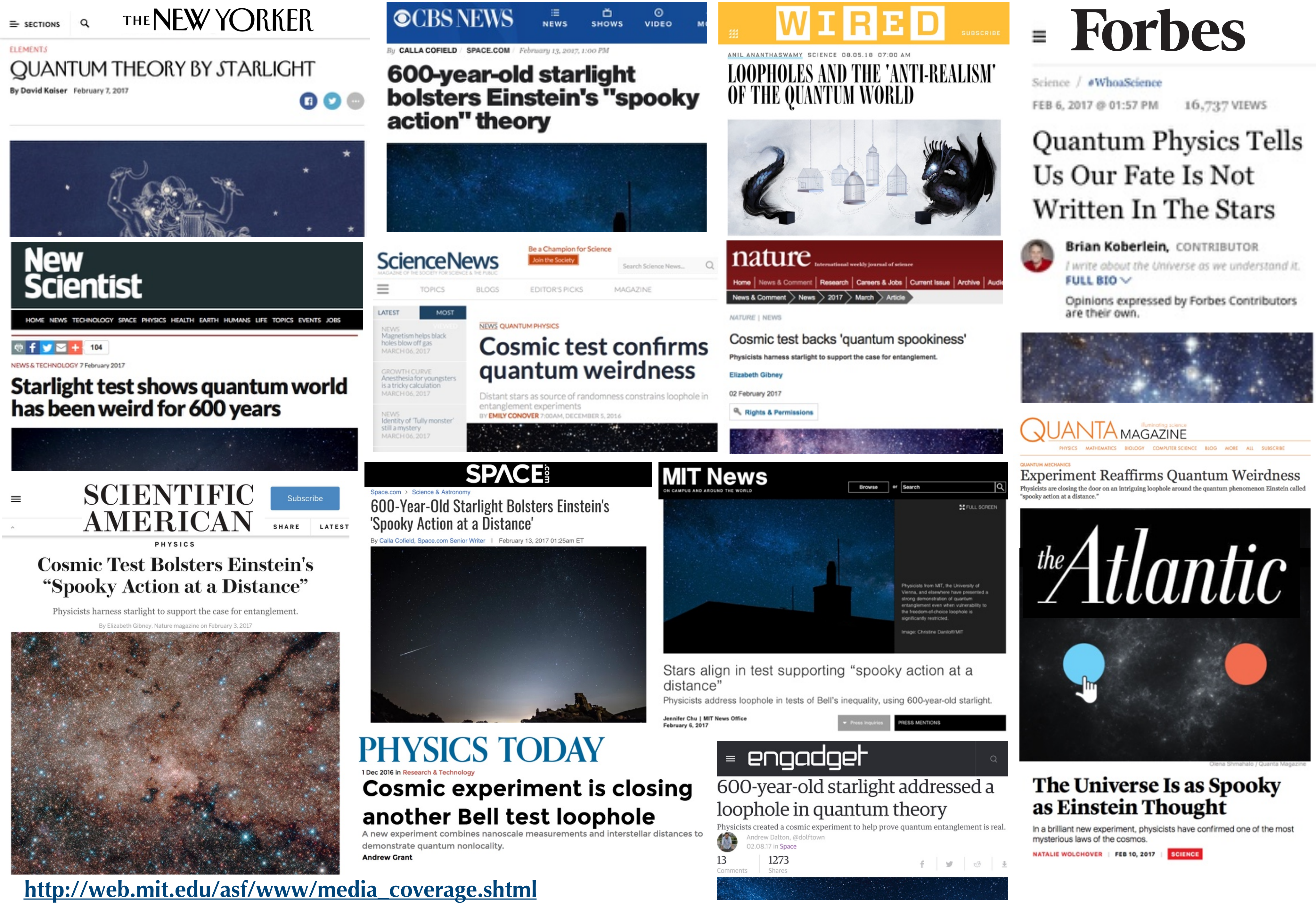
Gray Matter

NOV. 14, 2014

By DAVID KAISER

NSF

COSMIC BELL IN THE NEWS



THE NEW YORKER
ELEMENTS
QUANTUM THEORY BY STARLIGHT
By David Kaiser February 7, 2017

CBS NEWS
By CALLA COFIELD SPACE.COM February 13, 2017, 1:00 PM
600-year-old starlight bolsters Einstein's "spooky action" theory

WIRED
ANIL ANANTHASWAMY SCIENCE 08.05.18 07:00 AM
LOOPHOLES AND THE 'ANTI-REALISM' OF THE QUANTUM WORLD

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.
Opinions expressed by Forbes Contributors are their own.

New Scientist
NEWS & TECHNOLOGY 7 February 2017
Starlight test shows quantum world has been weird for 600 years

ScienceNews
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

nature
NATURE | NEWS
Cosmic test backs 'quantum spookiness'
Physicists harness starlight to support the case for entanglement.
Elizabeth Gibney
02 February 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."

SCIENTIFIC AMERICAN
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

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
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

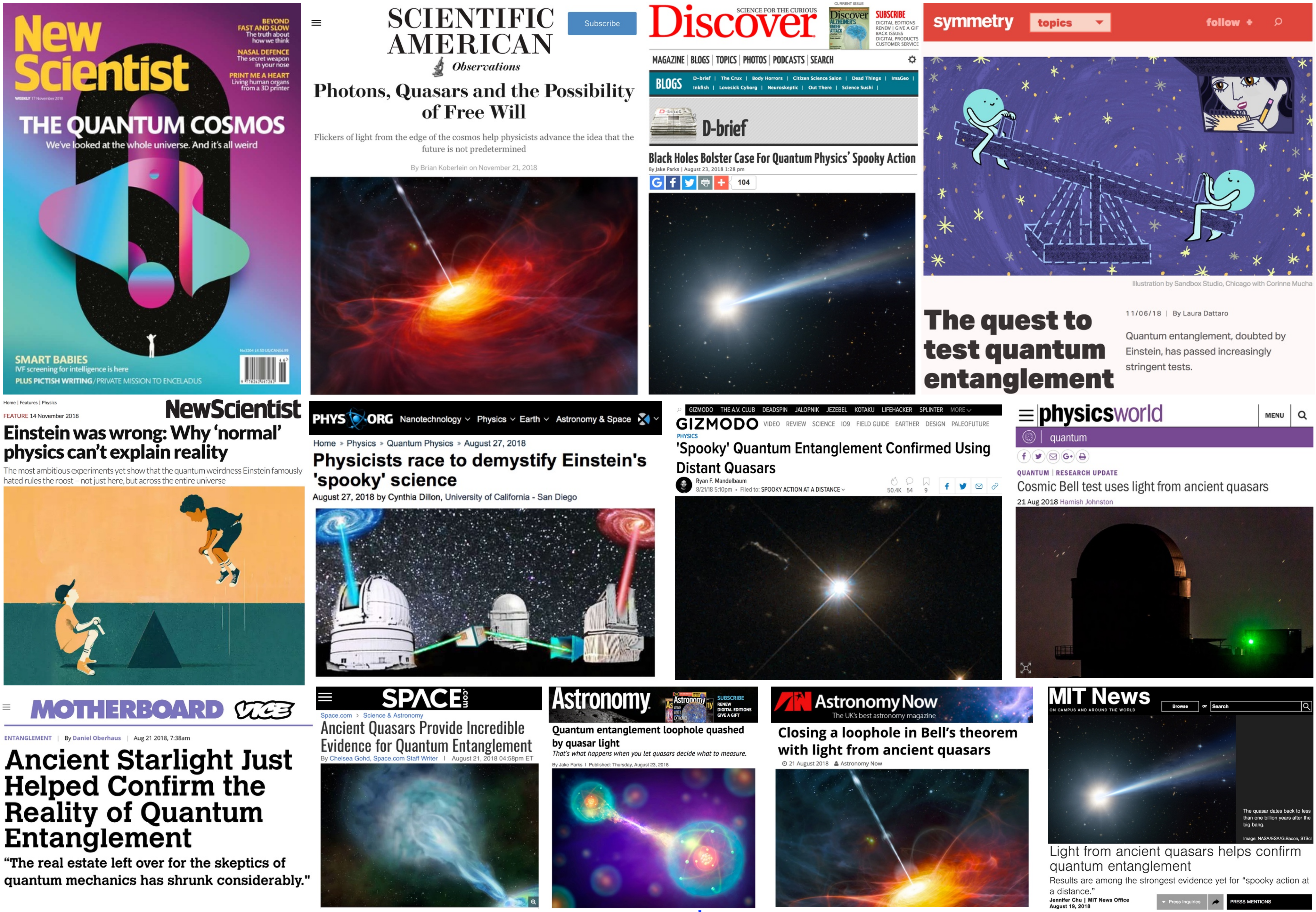
the Atlantic
The Universe Is as Spooky as Einstein Thought
In a brilliant new experiment, physicists have confirmed one of the most mysterious laws of the cosmos.
NATALIE WOLCHOVER | FEB 10, 2017 | SCIENCE

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

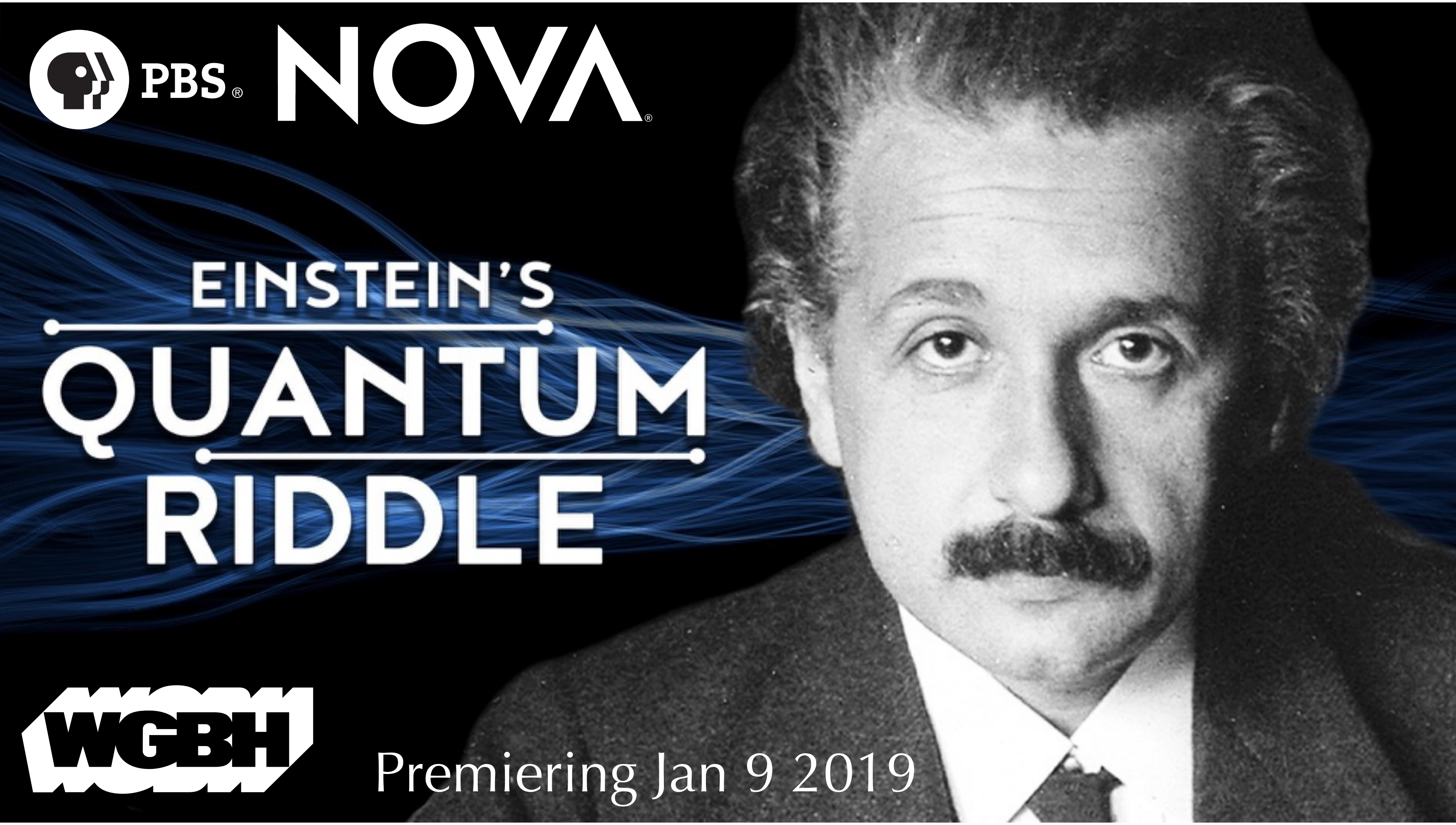
engadget
600-year-old starlight addressed a loophole in quantum theory
Physicists created a cosmic experiment to help prove quantum entanglement is real.
Andrew Dalton, @dolftown
02.08.17 in Space

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

COSMIC BELL IN THE NEWS



COSMIC BELL TEST ON TV!



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BIG BELL TEST

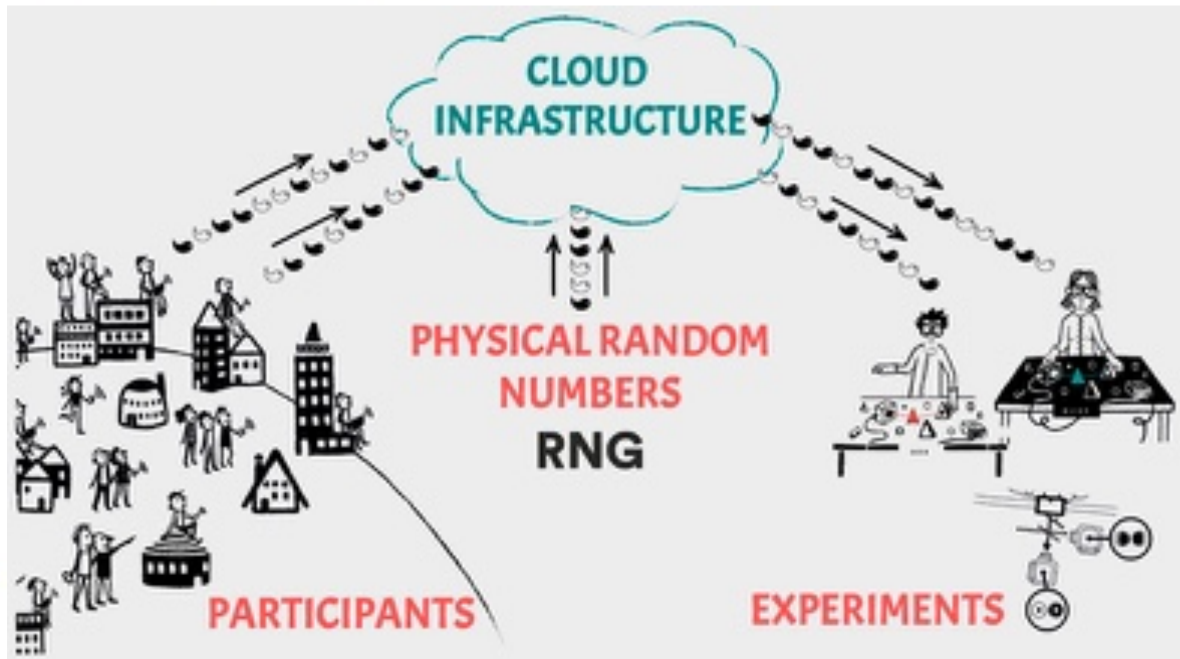
nature
International journal of science

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

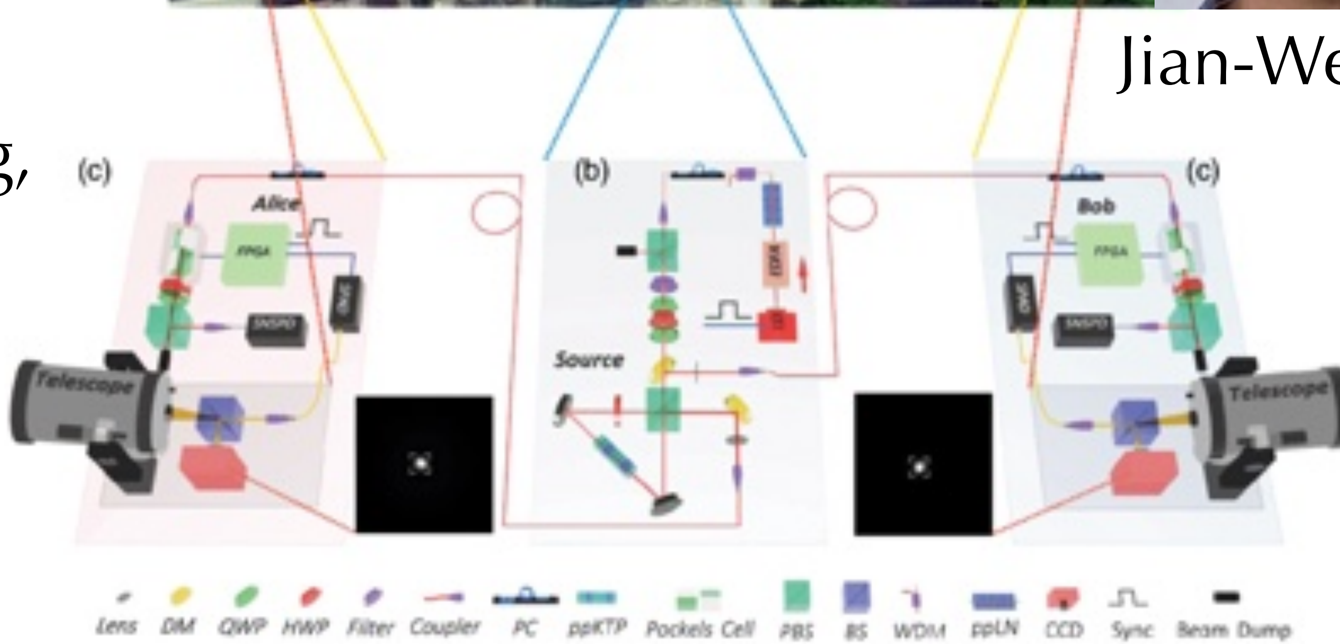
PHYSICAL REVIEW LETTERS **121,** 080404 (2018)

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

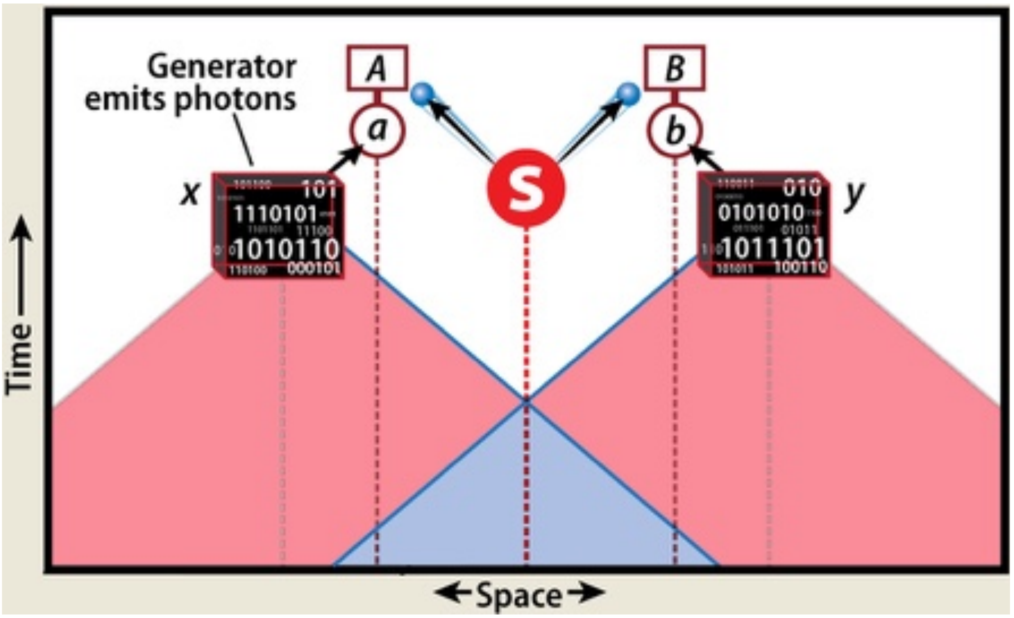


Closed locality and fair sampling, *and* constrained freedom-of-choice to ~11 years ago.

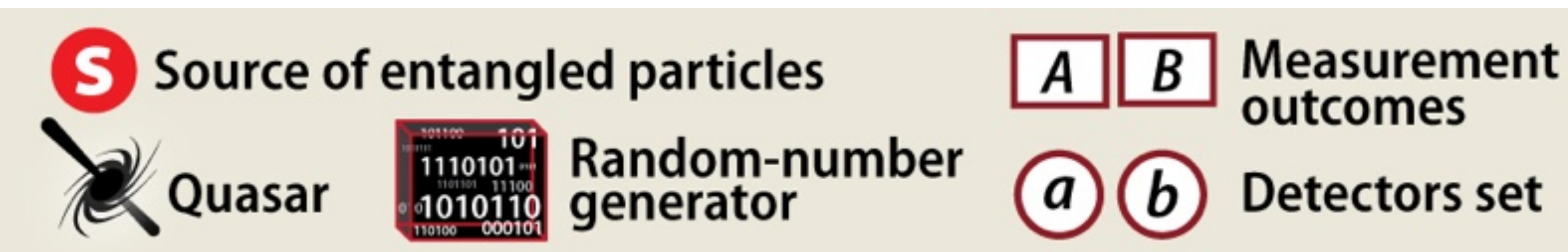
Li et al., 1808.07653

SPACE-TIME DIAGRAMS

Standard Bell Test



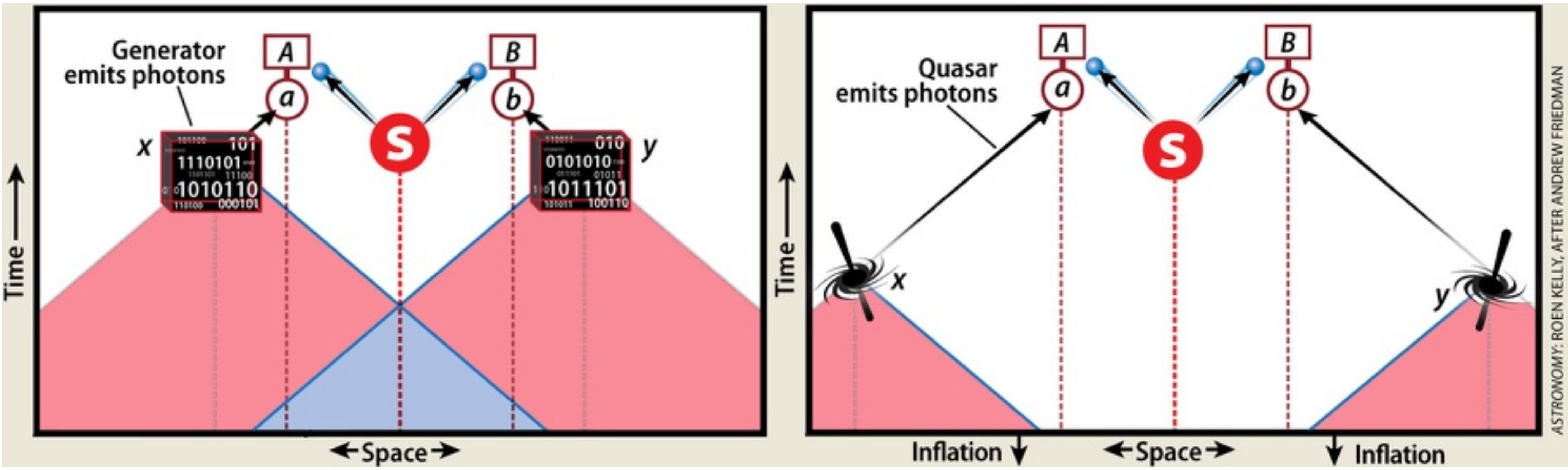
Past light cones from random number generators overlap milliseconds before test.



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

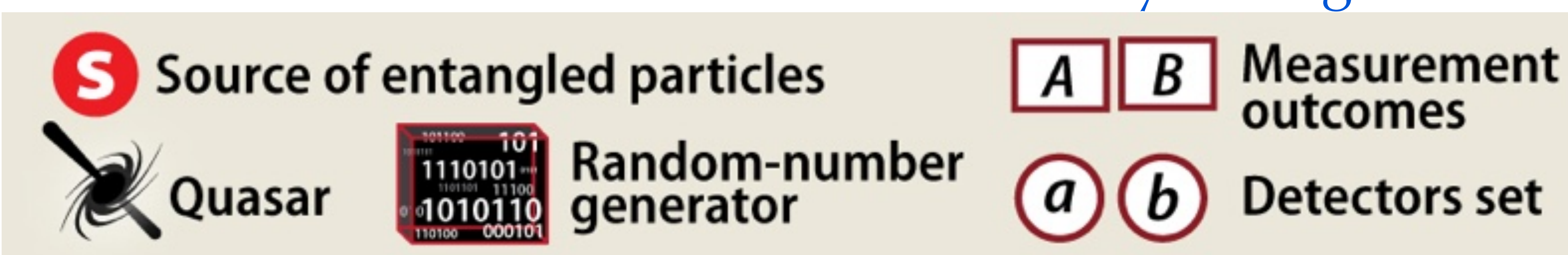
SPACE-TIME DIAGRAMS

Standard Bell Test | ***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.



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

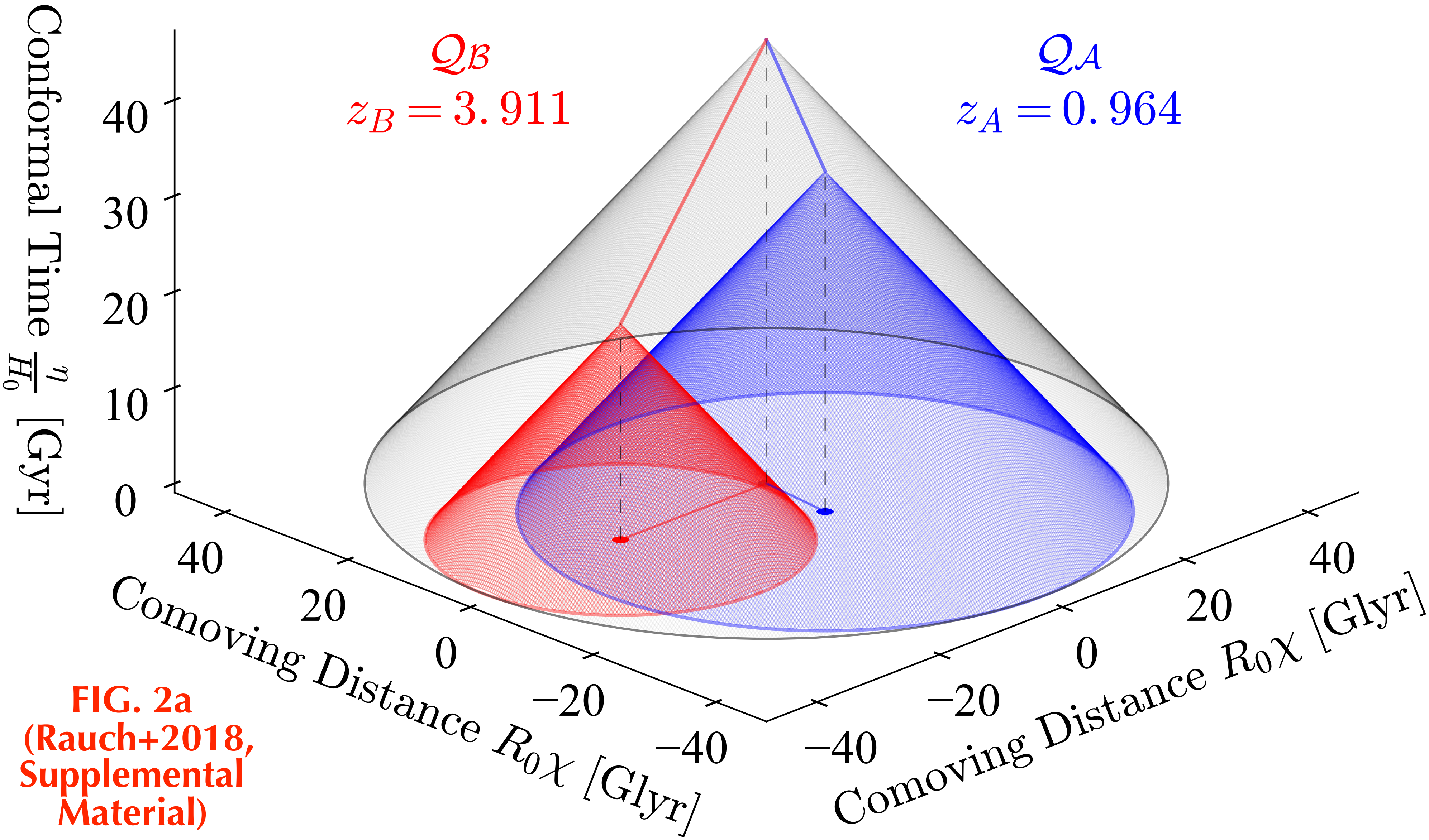
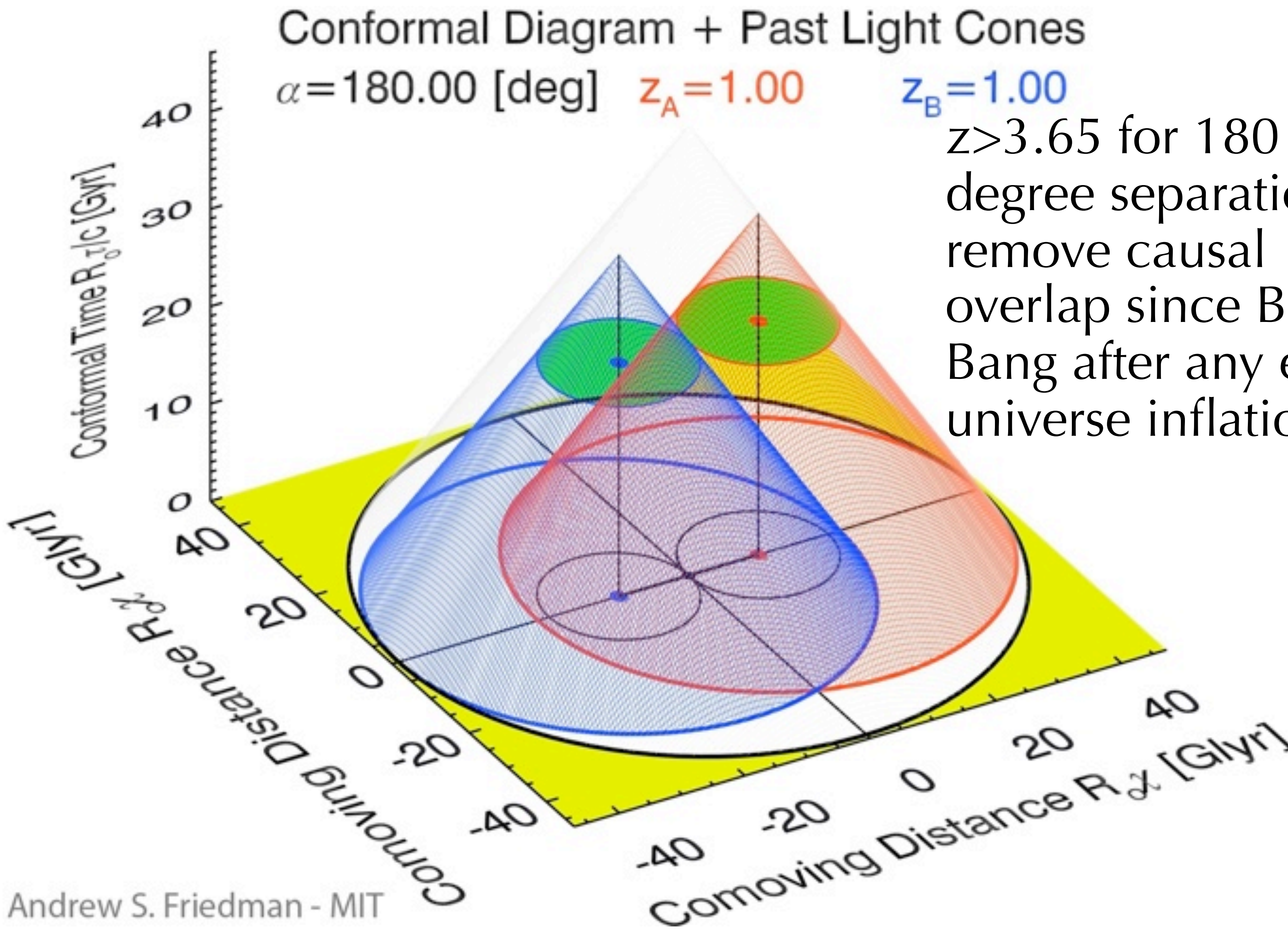


FIG. 2a (Rauch+2018, Supplemental Material)

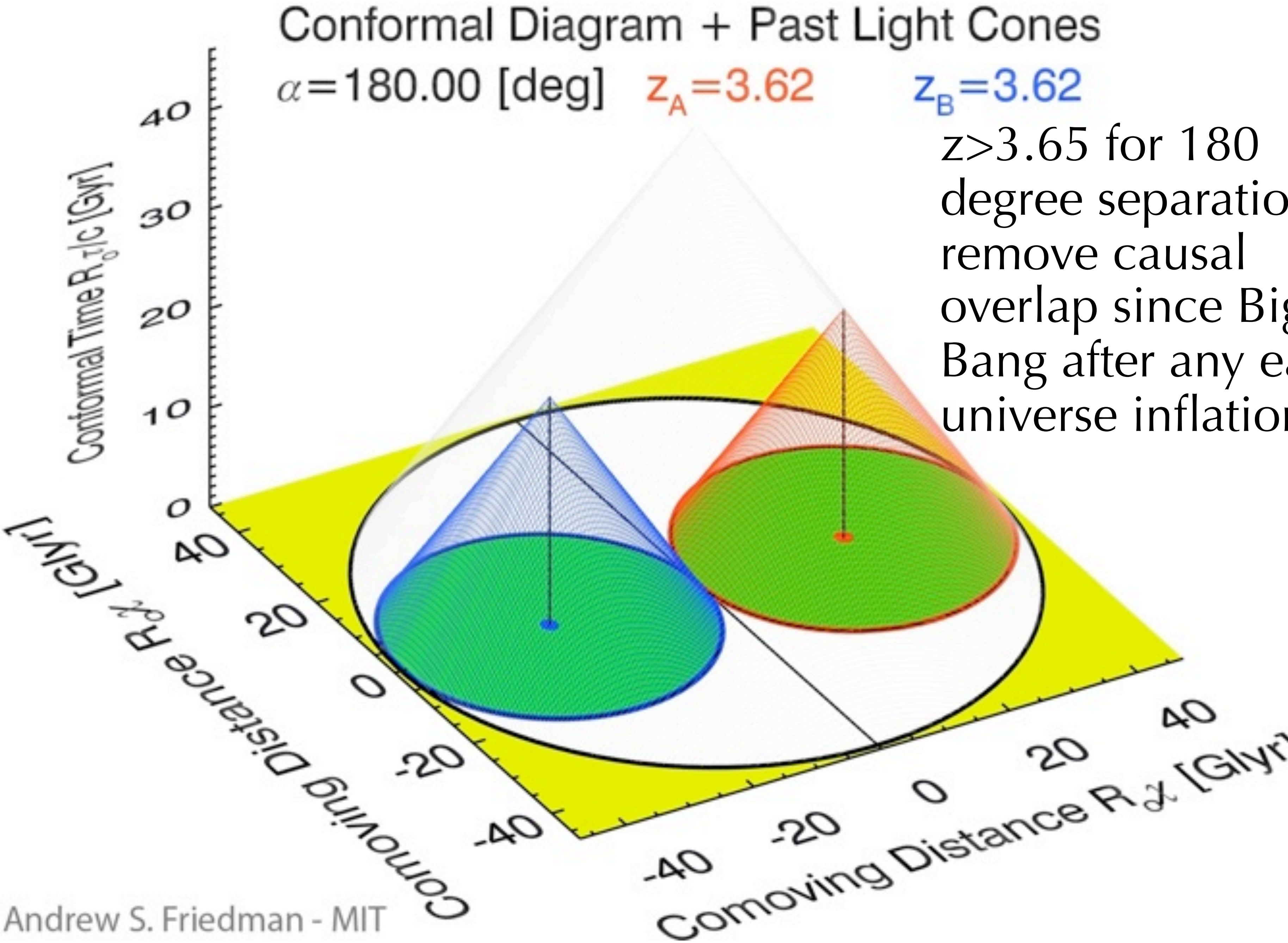
La Palma cosmic Bell test didn't completely remove causal overlap

FUTURE COSMIC BELL TESTS



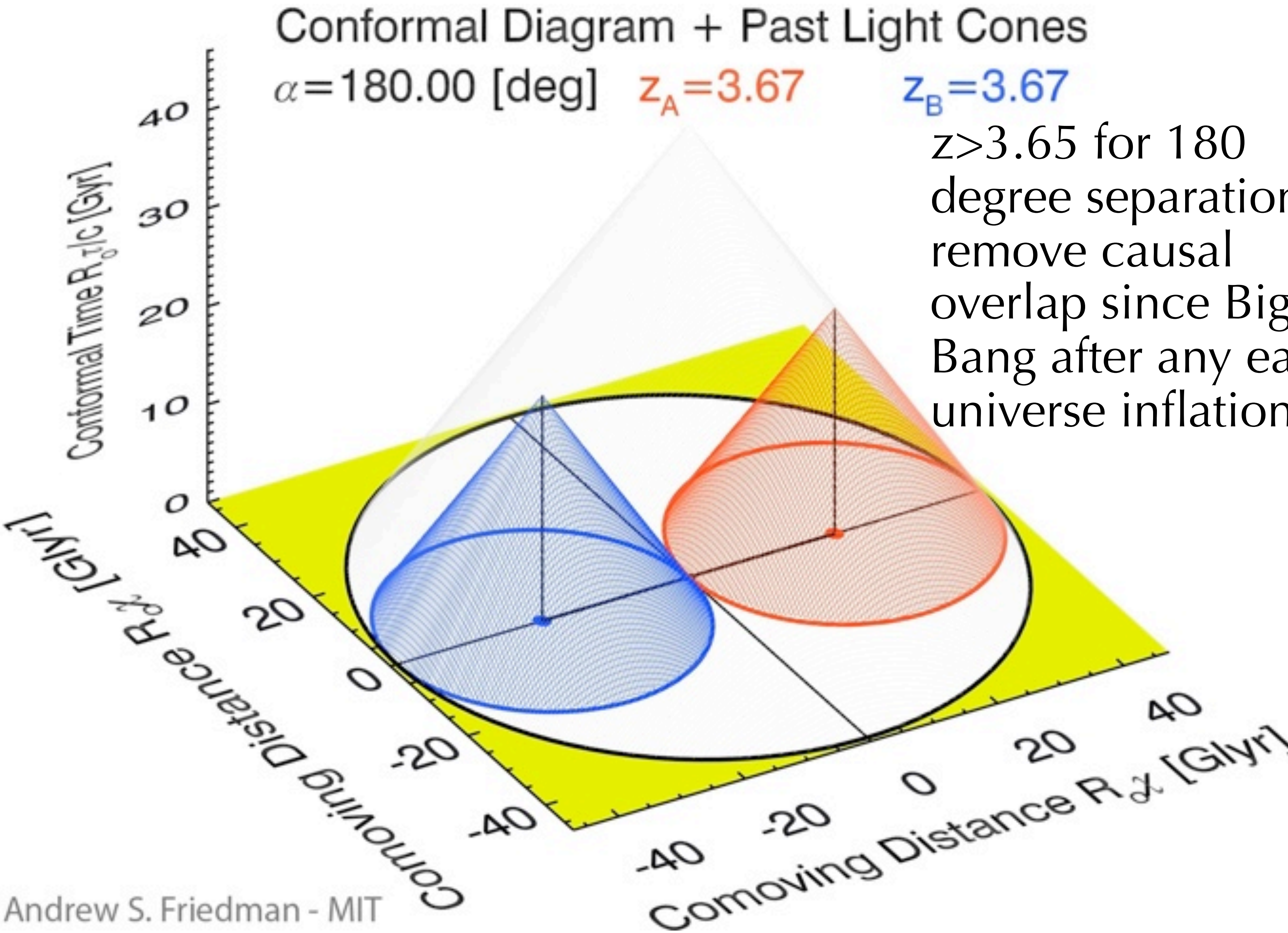
z>3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation

NO SHARED CAUSAL PAST



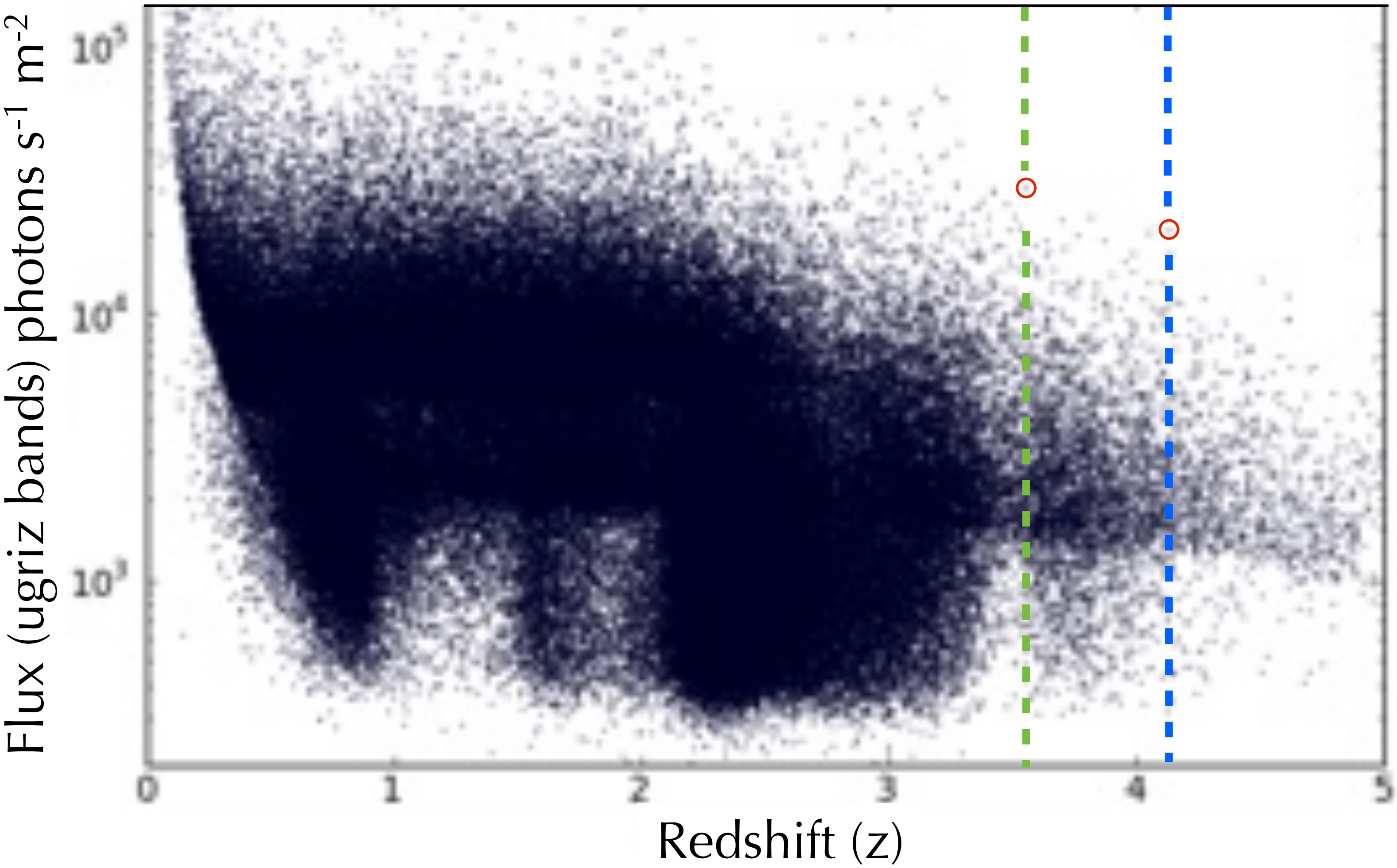
z>3.65 for 180 degree separation to remove causal overlap since Big Bang after any early universe inflation

NO SHARED CAUSAL PAST



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

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} ~ 3 × 10^4 photons s^{-1} m^{-2} **180 degrees**

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

SDSS quasars - photometric and spectroscopic redshifts

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

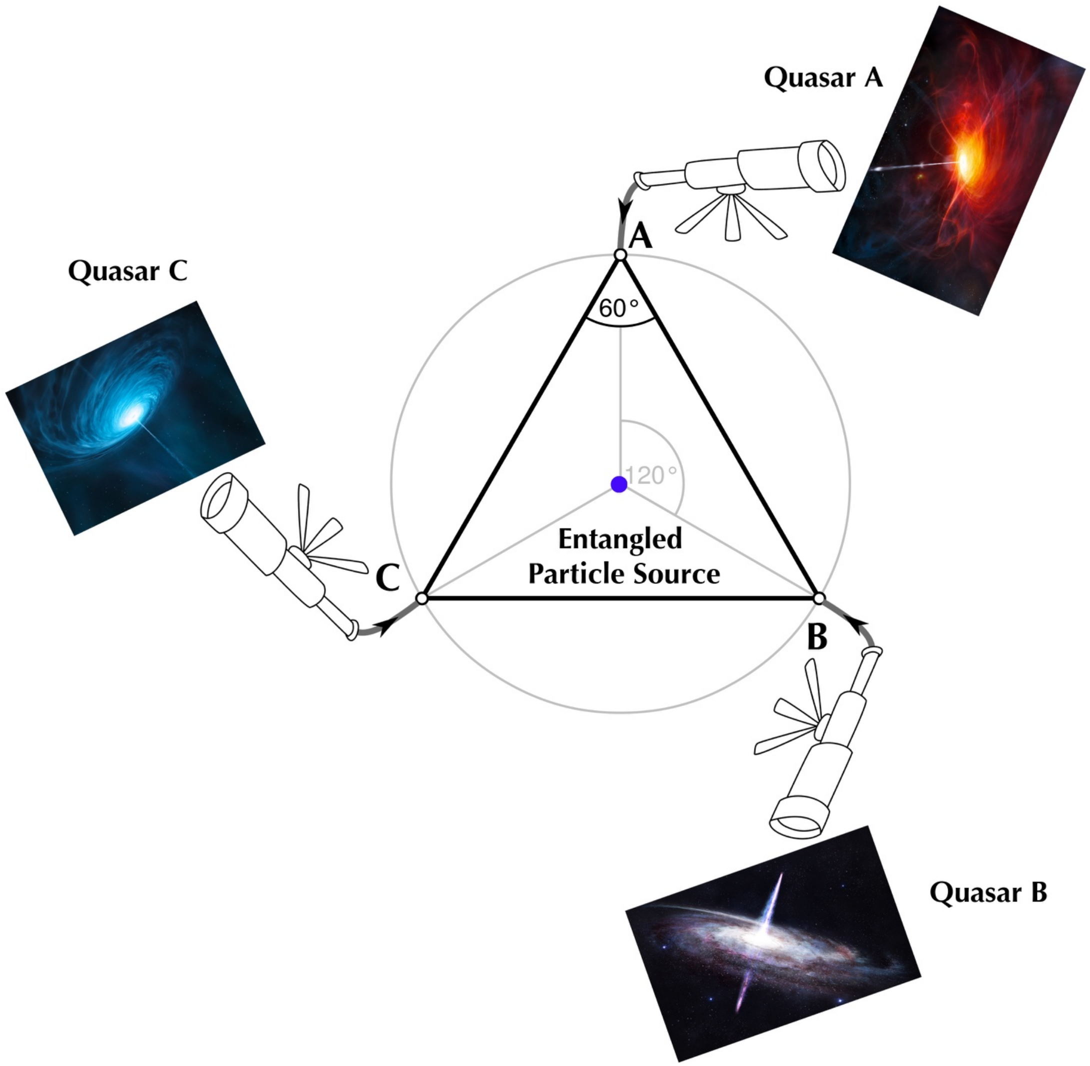
	Angular Separation	Redshift
2-Way Space	180°	$z > 3.65$
2-Way Ground	130°	$z > 4.13$
3-Way Space	120°	$z > 4.37$
3-Way Ground	105°	$z > 4.89$

Gallicchio, Friedman, & Kaiser 2014

GHZ WITH QUASARS?

3+ particles, Bell's theorem without inequalities
QM, Local realism give opposite answers to yes/no questions

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



Would be difficult to remove all pairwise causal overlap.

z>4.37 120°: space
z>4.89 105°: ground

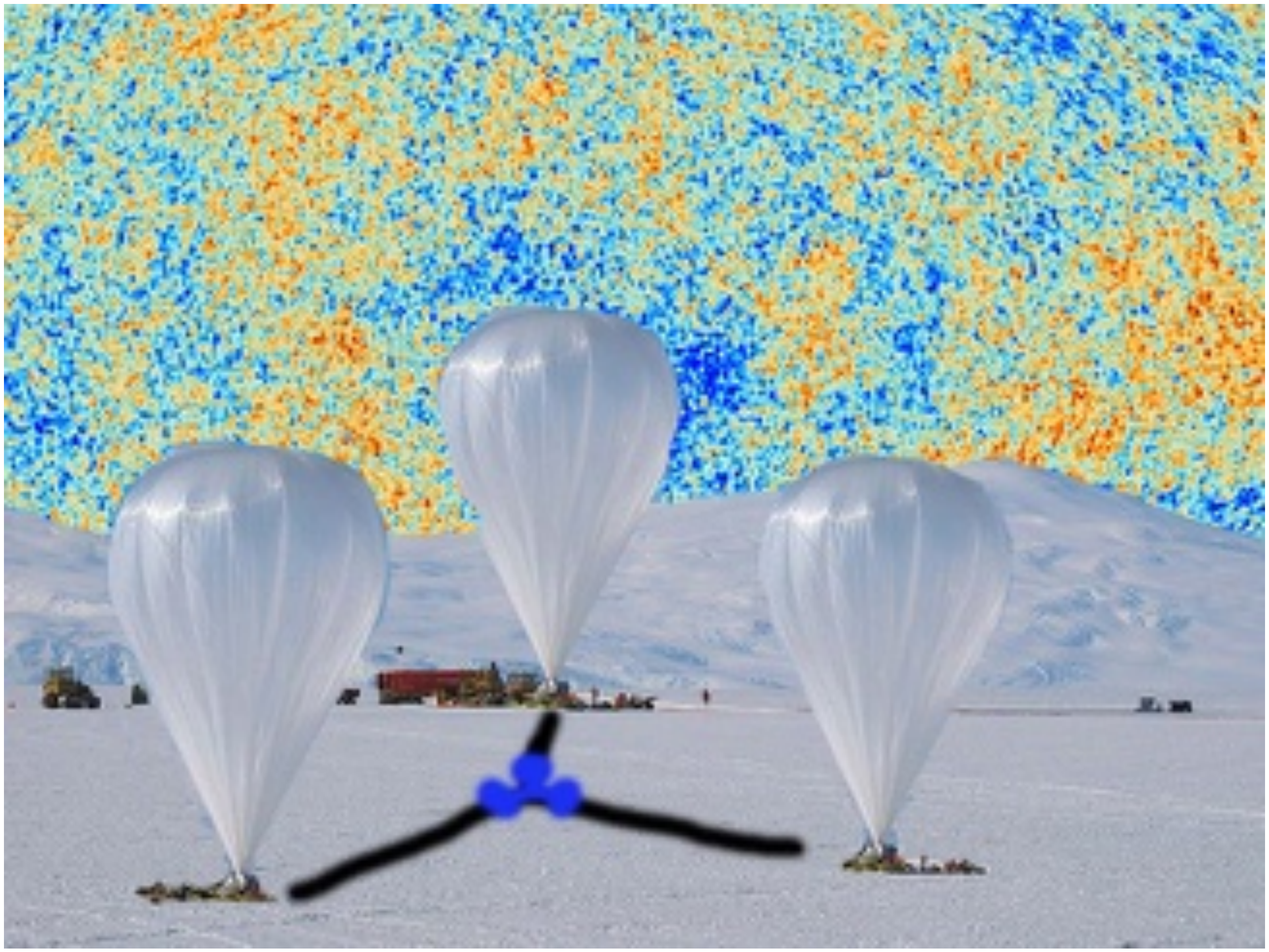
But GHZ pilot test with stars or brighter, moderate redshift quasars is technologically possible

GHZ WITH CMB?

3+ particles, Bell's theorem without inequalities

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

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



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/CMB Cosmic Bell tests with no causal overlap
3 CMB patch or 3-quasar GHZ test from ground, balloon, or space

Safe Bet

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

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

Longshot

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

Perhaps experimenter's lack complete freedom!

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