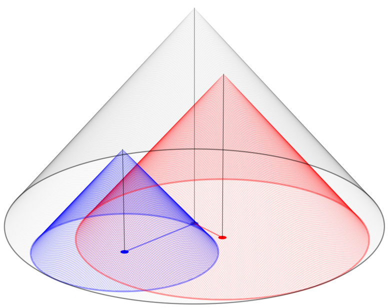
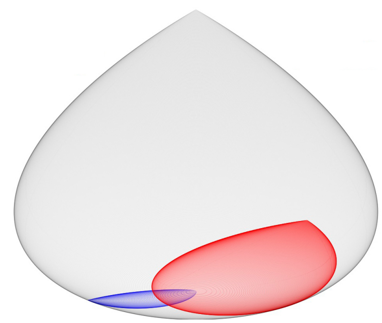
A COSMIC TEST OF QUANTUM ENTANGLEMENT

Choosing Experimental Bell Inequality Measurements with Light from High Redshift Quasars





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

3/18/2019

MIT Kavli Institute for Astrophysics & Space Research

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)

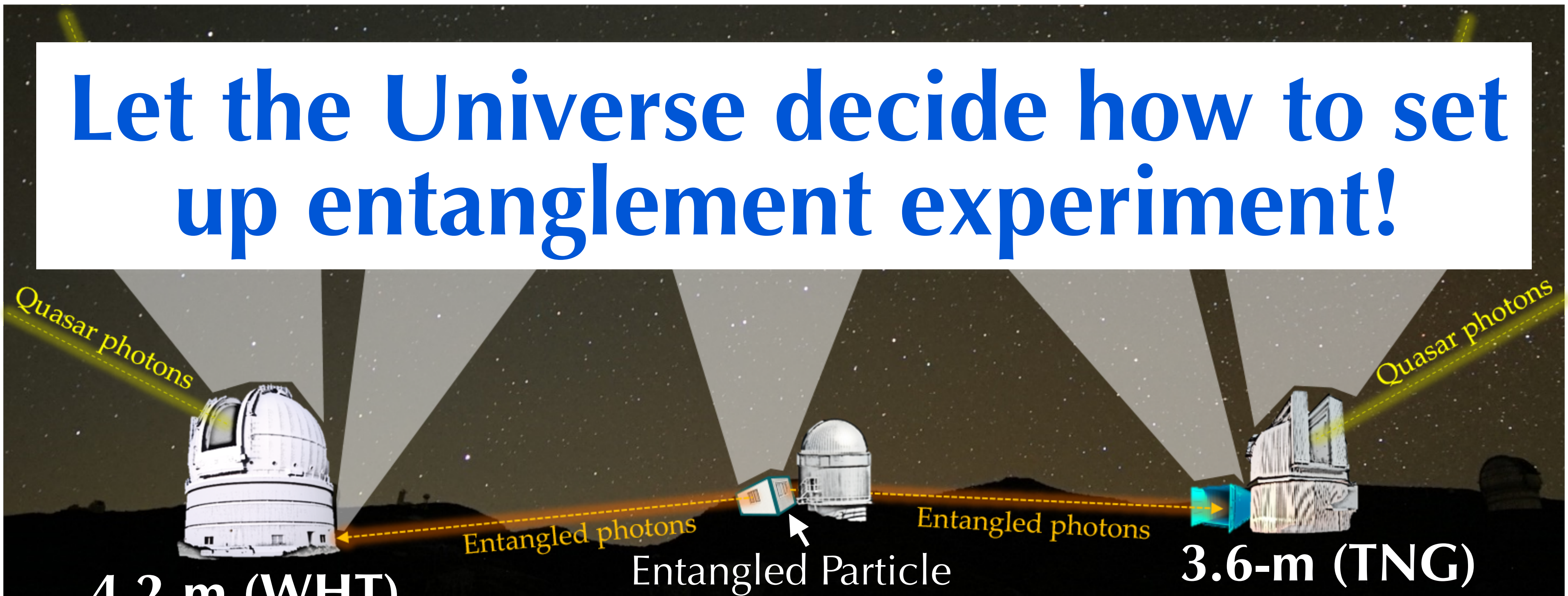

FIG. 1, Rauch + 2018

COSMIC BELL TEAM

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Dr. Andrew Friedman [1,5]

Prof. Alan Guth [1]

Prof. Brian Keating [5]

Prof. Anton Zeilinger [2]

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Dr. Johannes Kofler [4],
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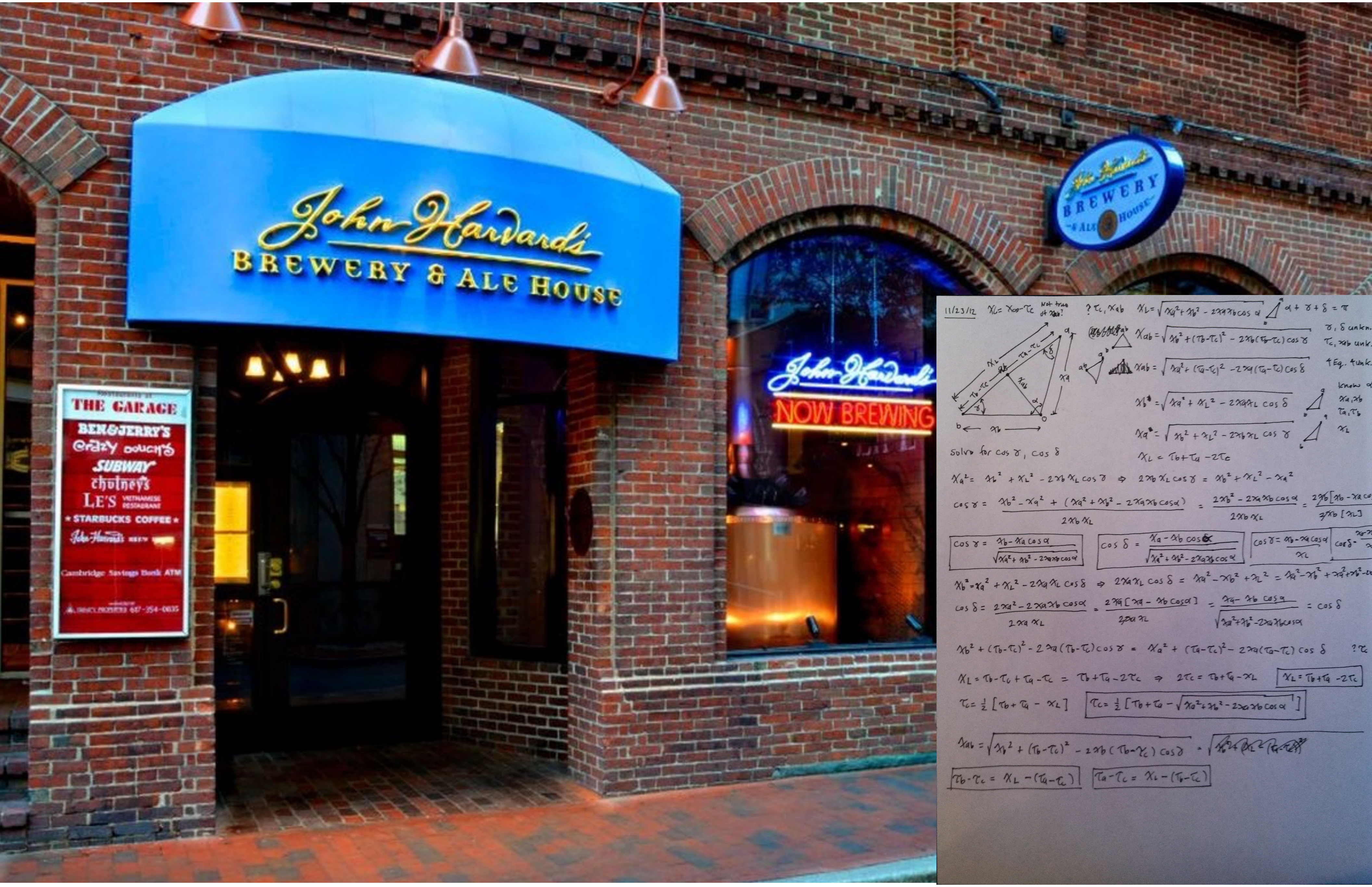
Calvin Leung [3]
et al.

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 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)

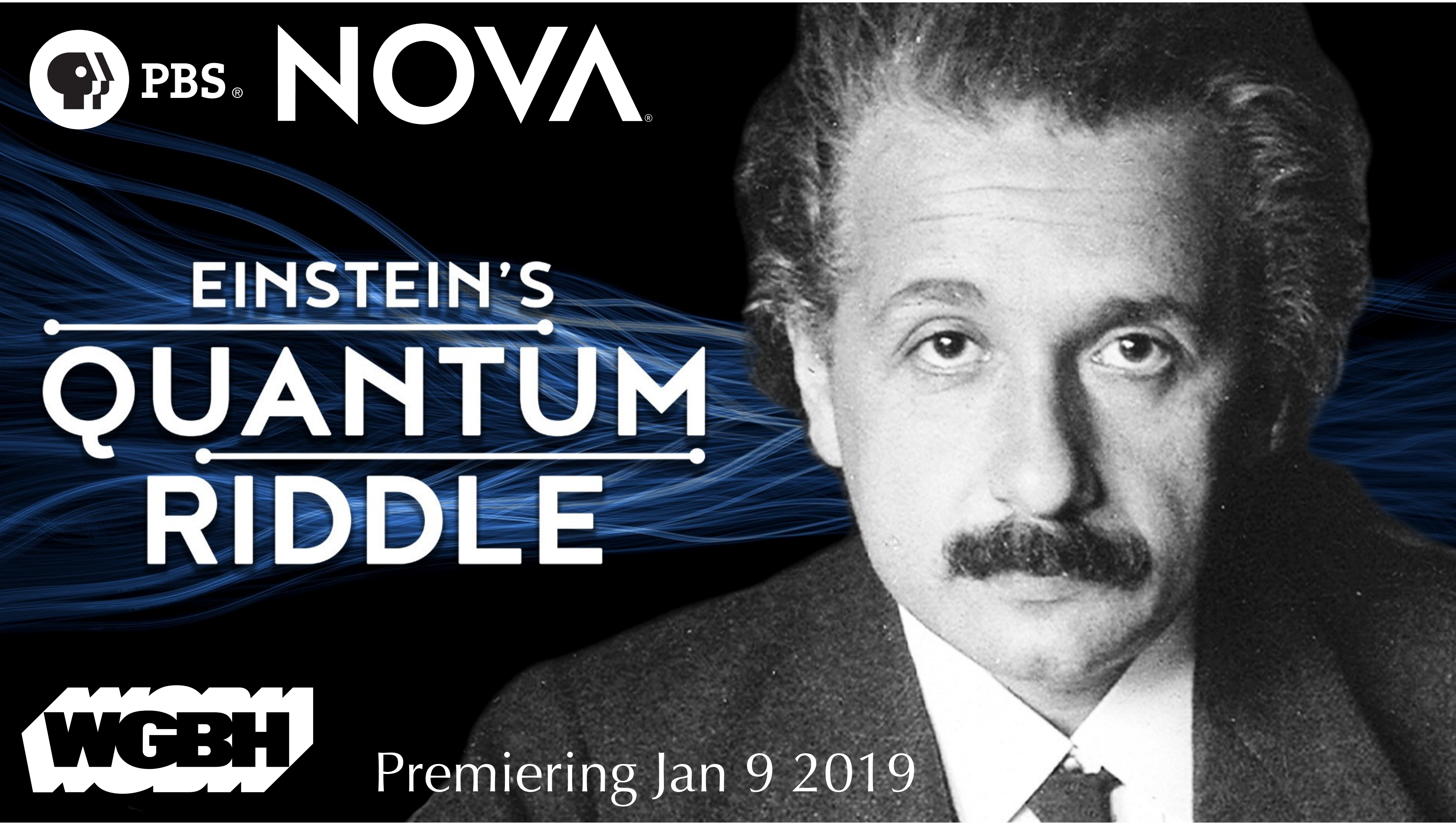
Cosmic Bell Test: Measurement Settings from Milky Way Stars,
Handsteiner, J., Friedman, A.S. + 2017, *Physical Review Letters*, Vol. 118, Issue 6, id. 060401, (arXiv:1611.06985 | PDF) (DOI) (Supplemental Material)

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]

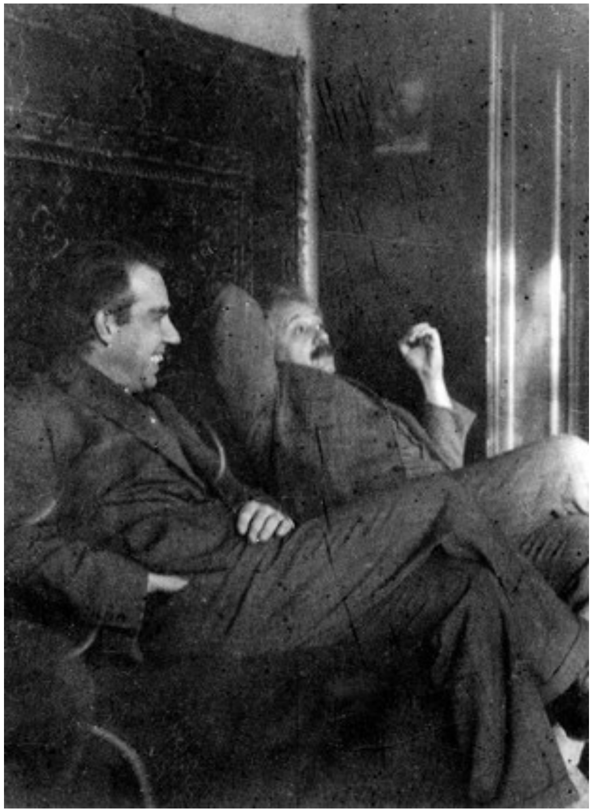
Relaxed Bell Inequalities with Arbitrary Measurement Dependence for Each Observer,
Friedman, A.S., Guth, A.H., Hall, M.J.W., Kaiser, D.I., and Gallicchio, J. 2019, *Physical Review A*, Vol. 99, Issue 1, id. 012121 (arXiv:1809.01307 | PDF) (DOI)

COSMIC BELL TEST ON TV!

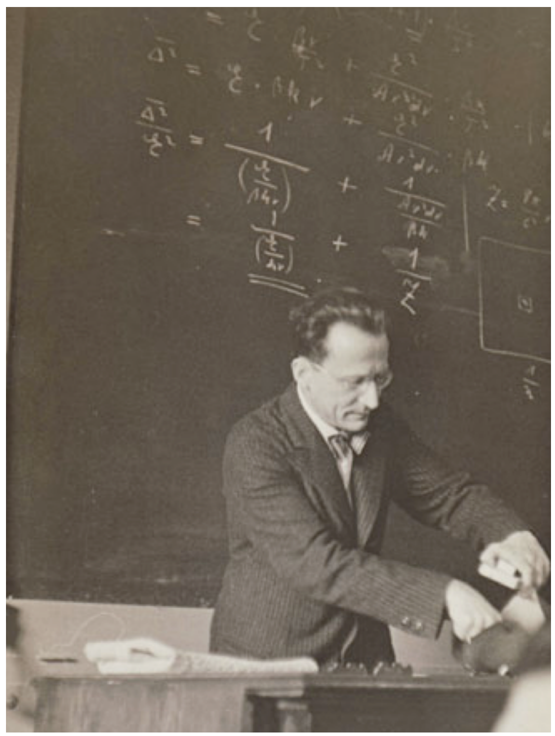


QUANTUM ENTANGLEMENT

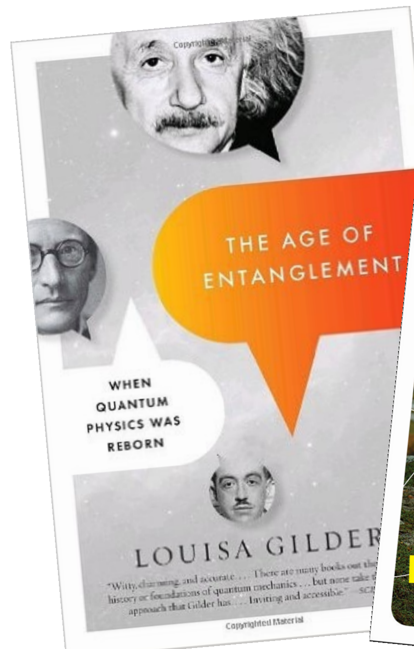
Beginning in the 1930s, the great architects of quantum theory struggled to understand the notion of "entanglement."

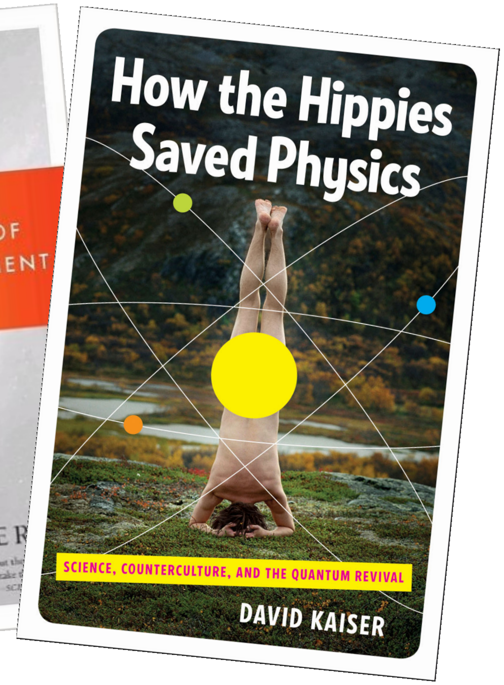


Niels Bohr and Albert Einstein

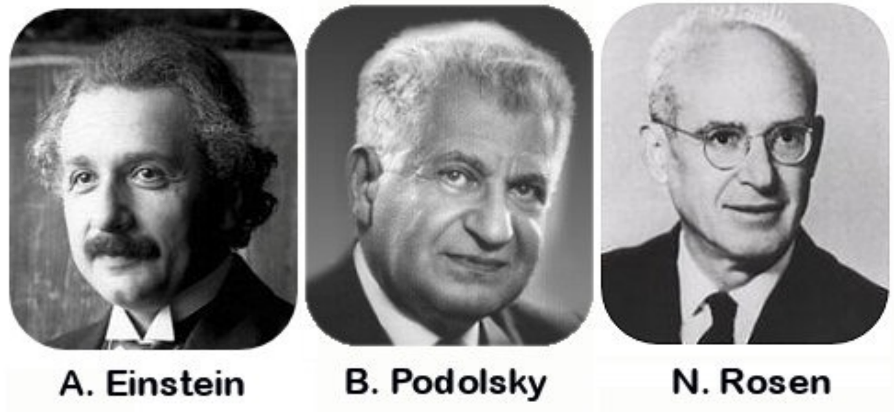


Erwin Schrödinger





EPR PARADOX



E P R

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

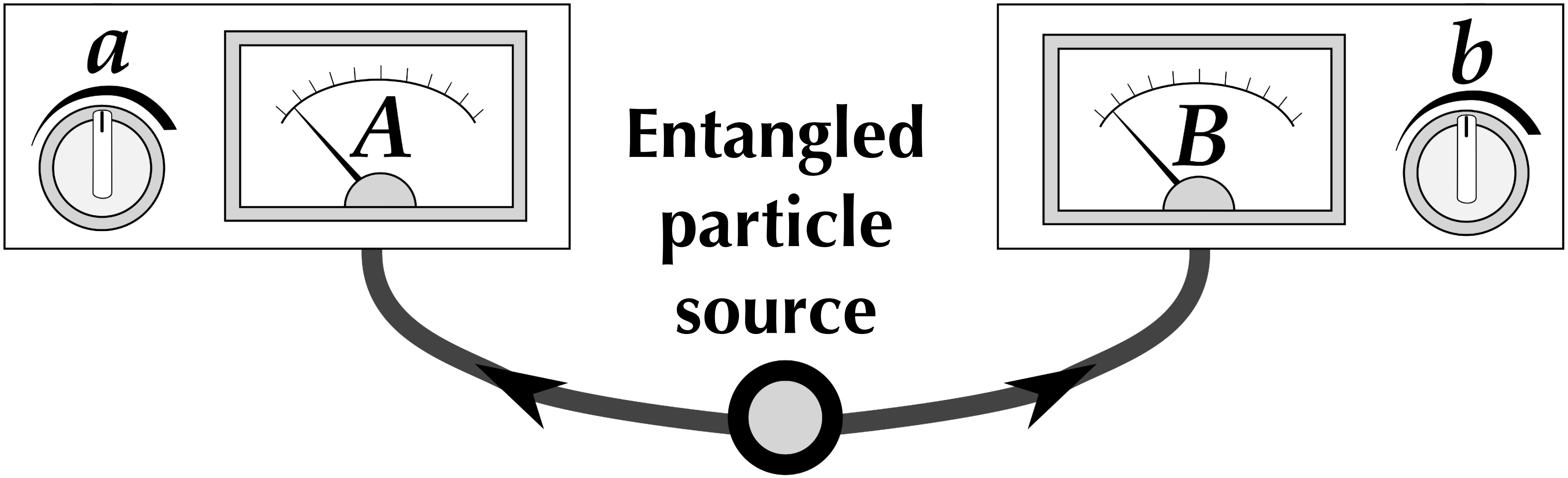
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(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*

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)

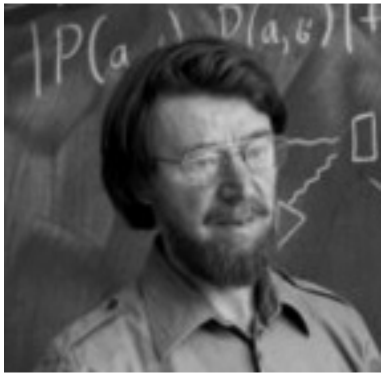
1,2,3 → Bell's Inequality

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

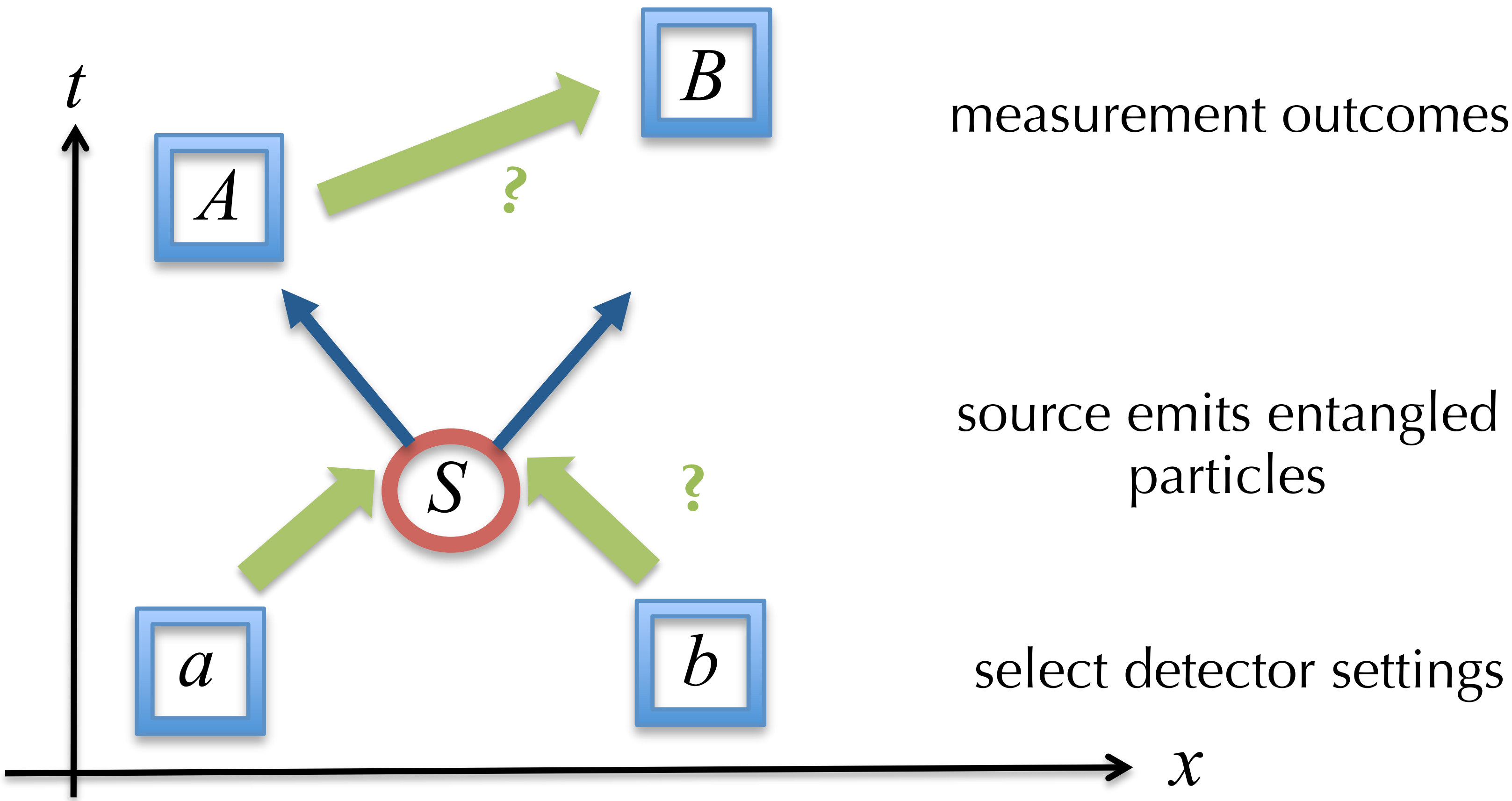
e.g. Can keep realism, locality. Relax Freedom.

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

LOCALITY LOOPHOLE

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

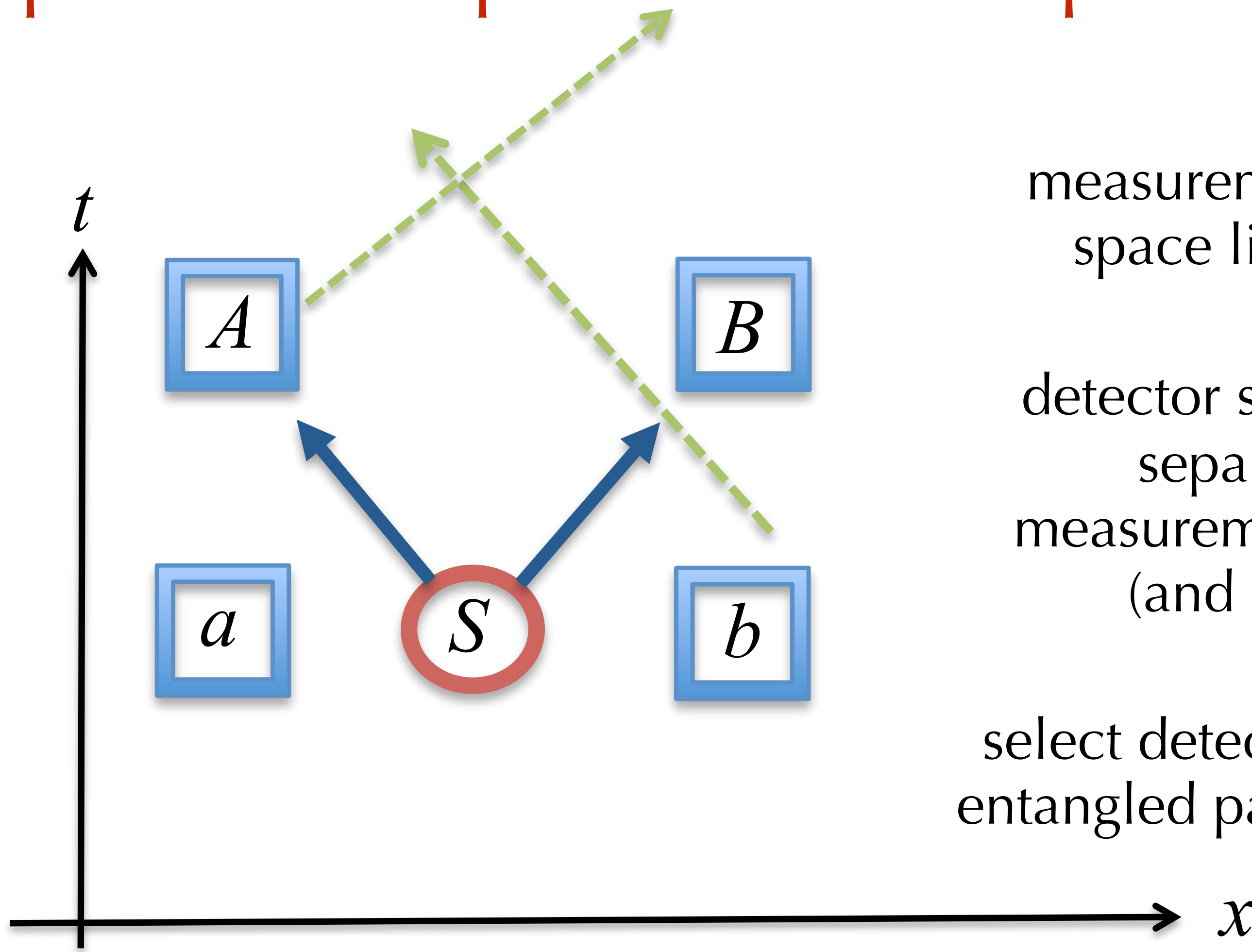
Hidden communication between parties?



CLOSING THE LOCALITY LOOPHOLE

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

Space-like separate relevant pairs of events



measurement outcomes space like separated

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

select detector settings while entangled particles are in flight

DETECTION EFFICIENCY LOOPHOLE

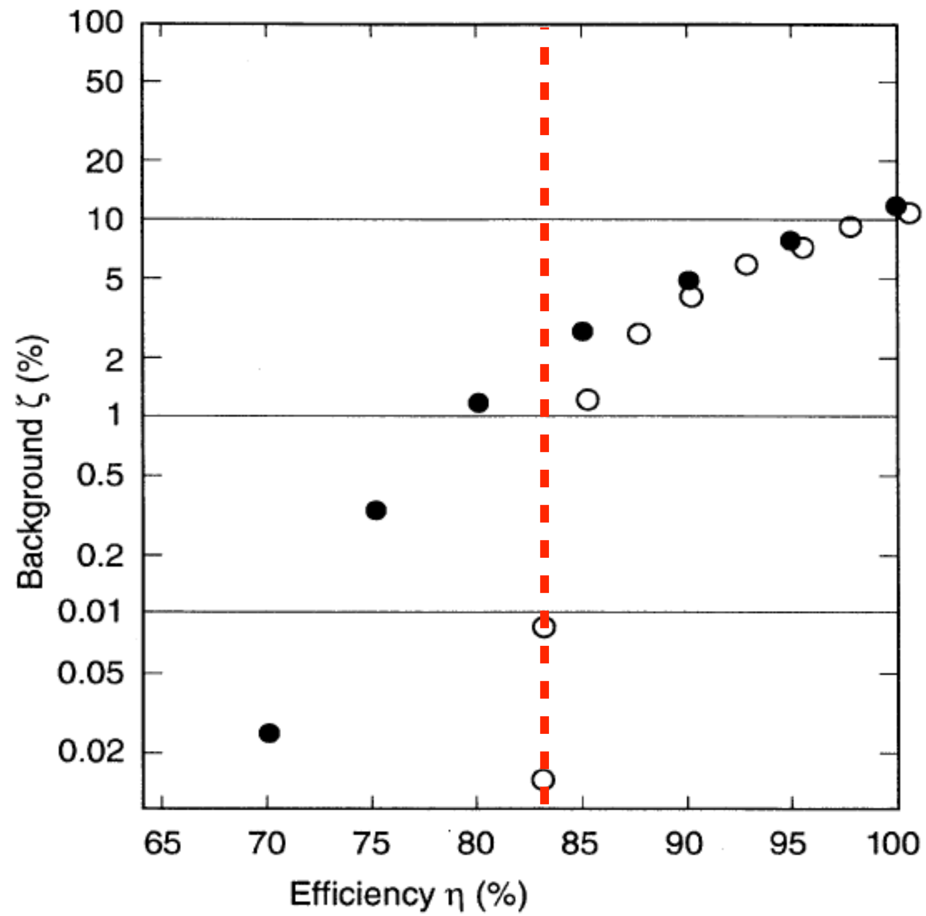
The standard interpretation of Bell tests — that "local realism" is incompatible with experiment — relies upon several assumptions.

Also called the "fair-sampling" loophole

No detectors are 100% efficient.

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

Closing loophole requires detector efficiencies ≥ 83%



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

FREEDOM OF CHOICE LOOPHOLE

λ Hidden variables

a, b Joint measurement settings

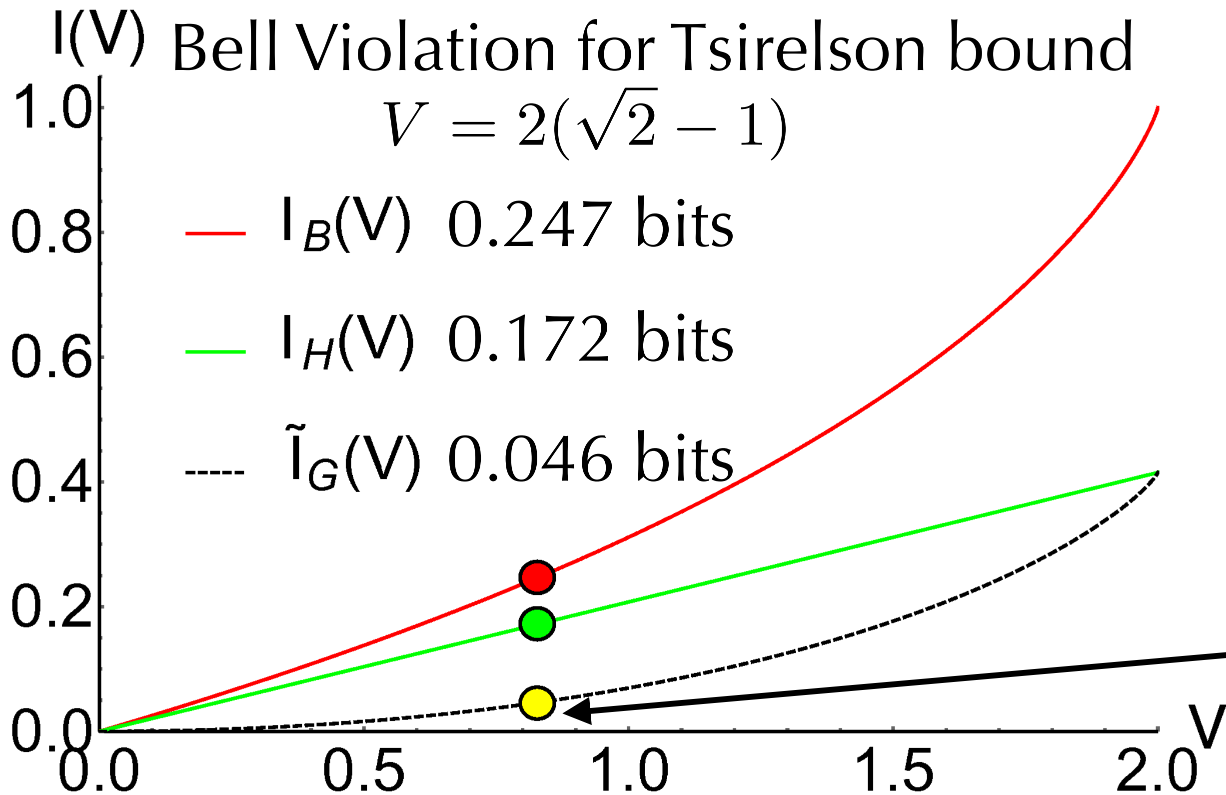
Freedom of choice assumption

$$p(\lambda|a,b) = p(\lambda) \quad \textbf{Eq. (1)}$$

Relaxing freedom of choice:

Mutual Information

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



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

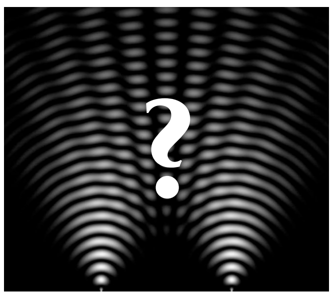
Friedman, Guth, Hall, Kaiser, & Gallicchio 2019, *Phys Rev A*, 99, 1, 012121 (arXiv:1809.01307)

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

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)

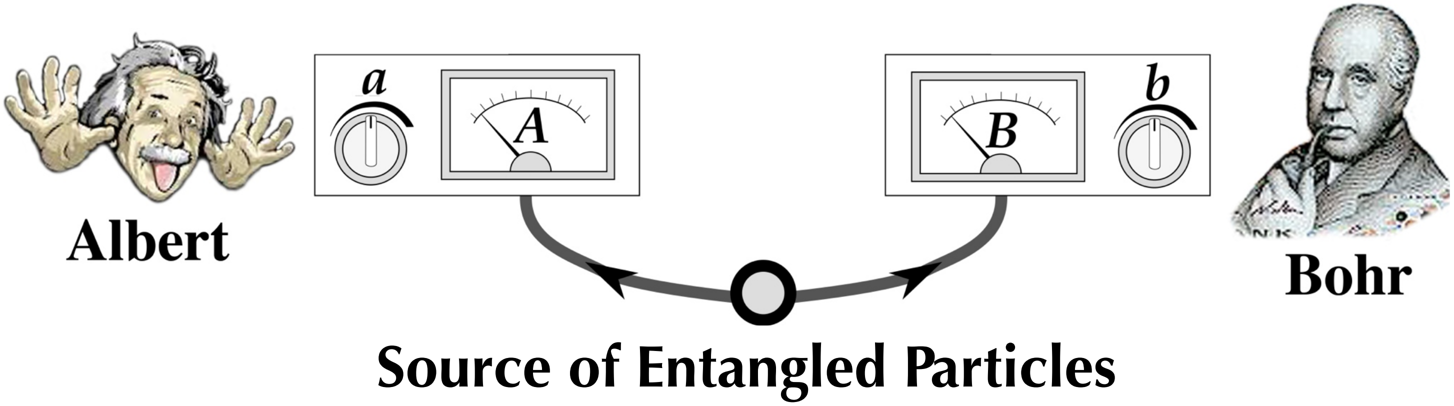
Settings from High Redshift Quasars. Closed locality, constrained freedom-of-choice to ~7.8 Billion years ago!

Locality & Detection & Freedom (photons)

Li+2018 (China)

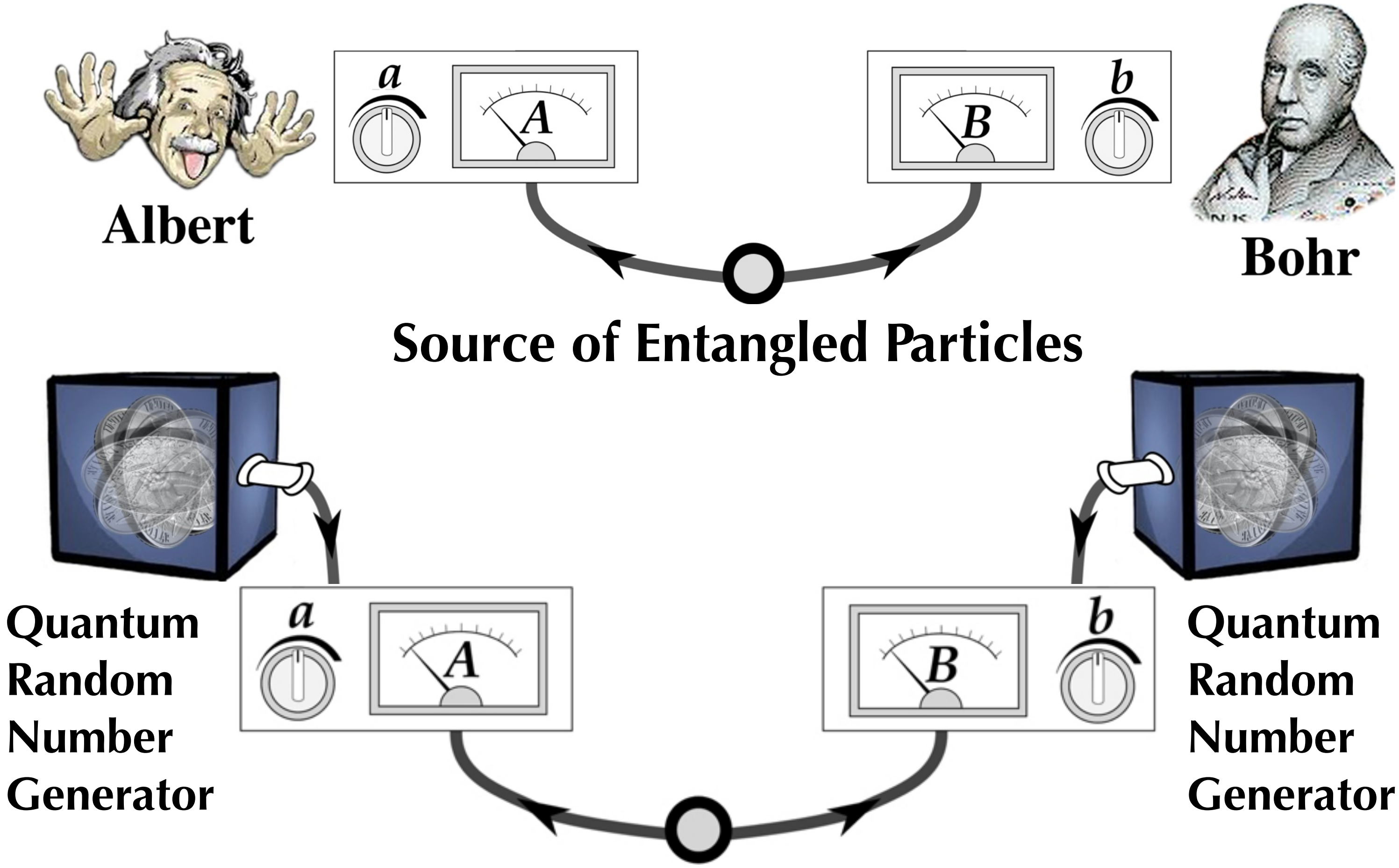
Closed locality and detection, constrained freedom-of-choice to ~11 years ago.

Choosing Detector Settings



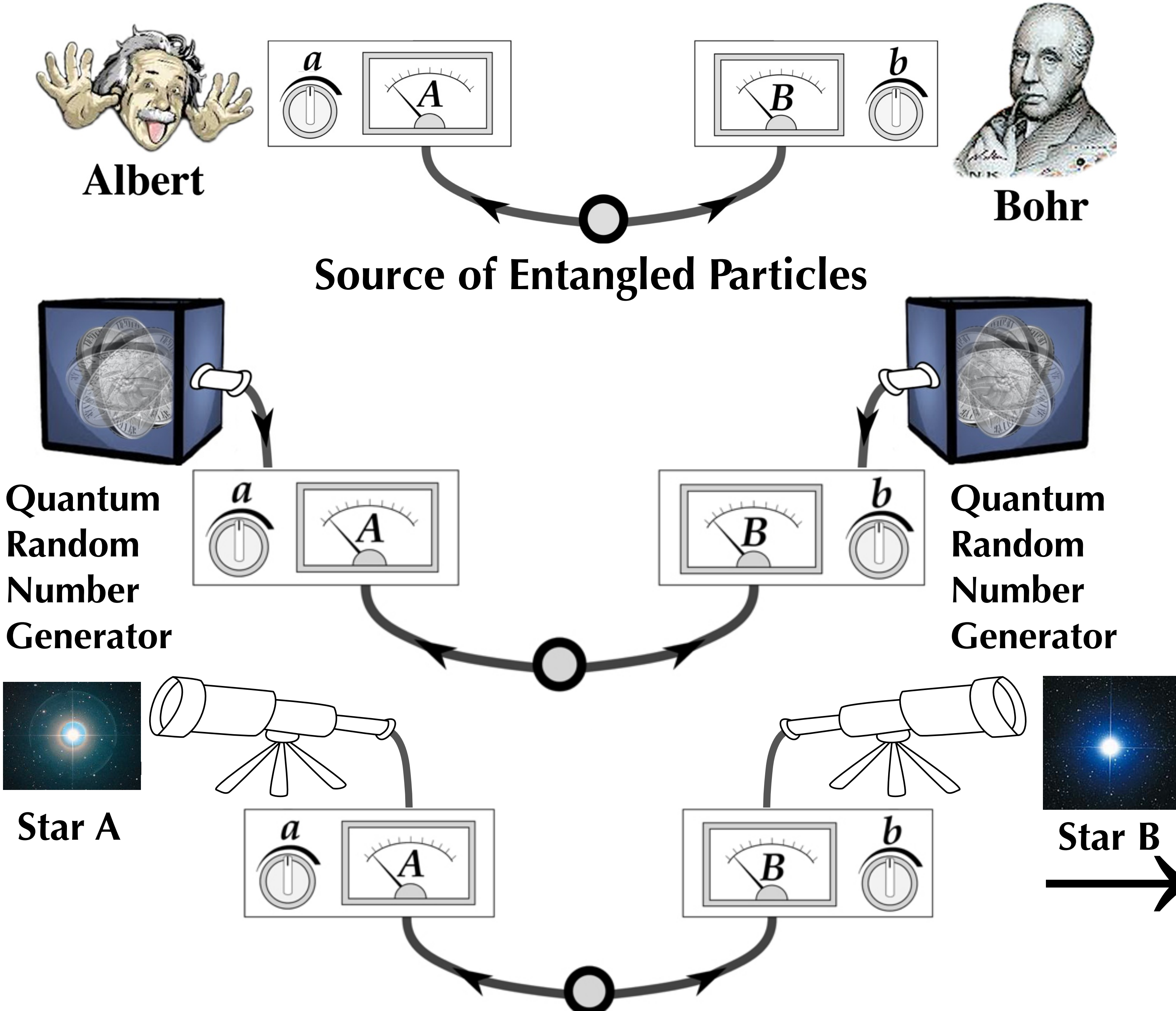
Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS



Adapted from:
Gallicchio, Friedman,
& Kaiser 2014

CHOOSING DETECTOR SETTINGS

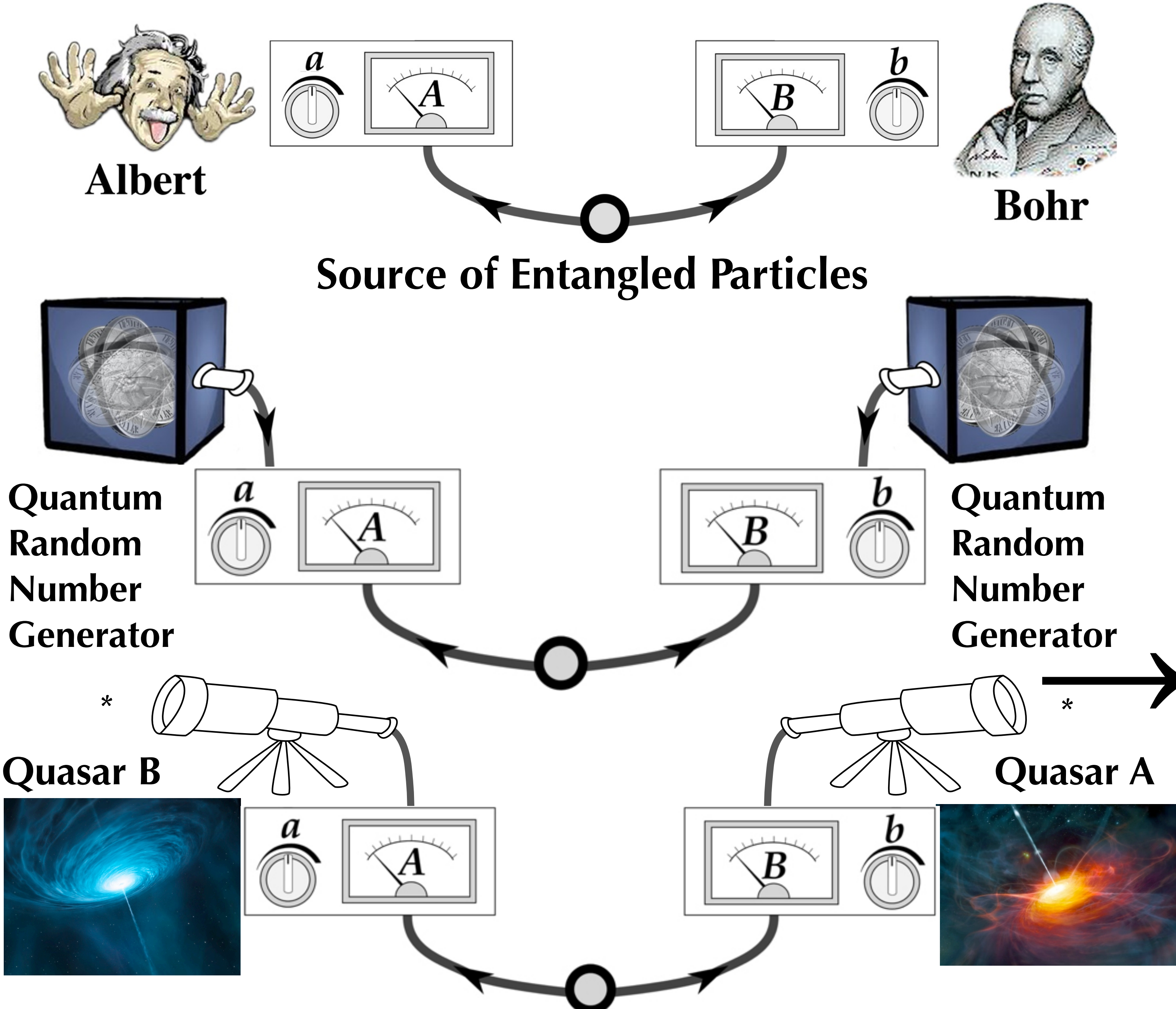


Choose settings with real-time observations of distant Milky Way stars

Requires alternative theories to act hundreds or thousands of years ago

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

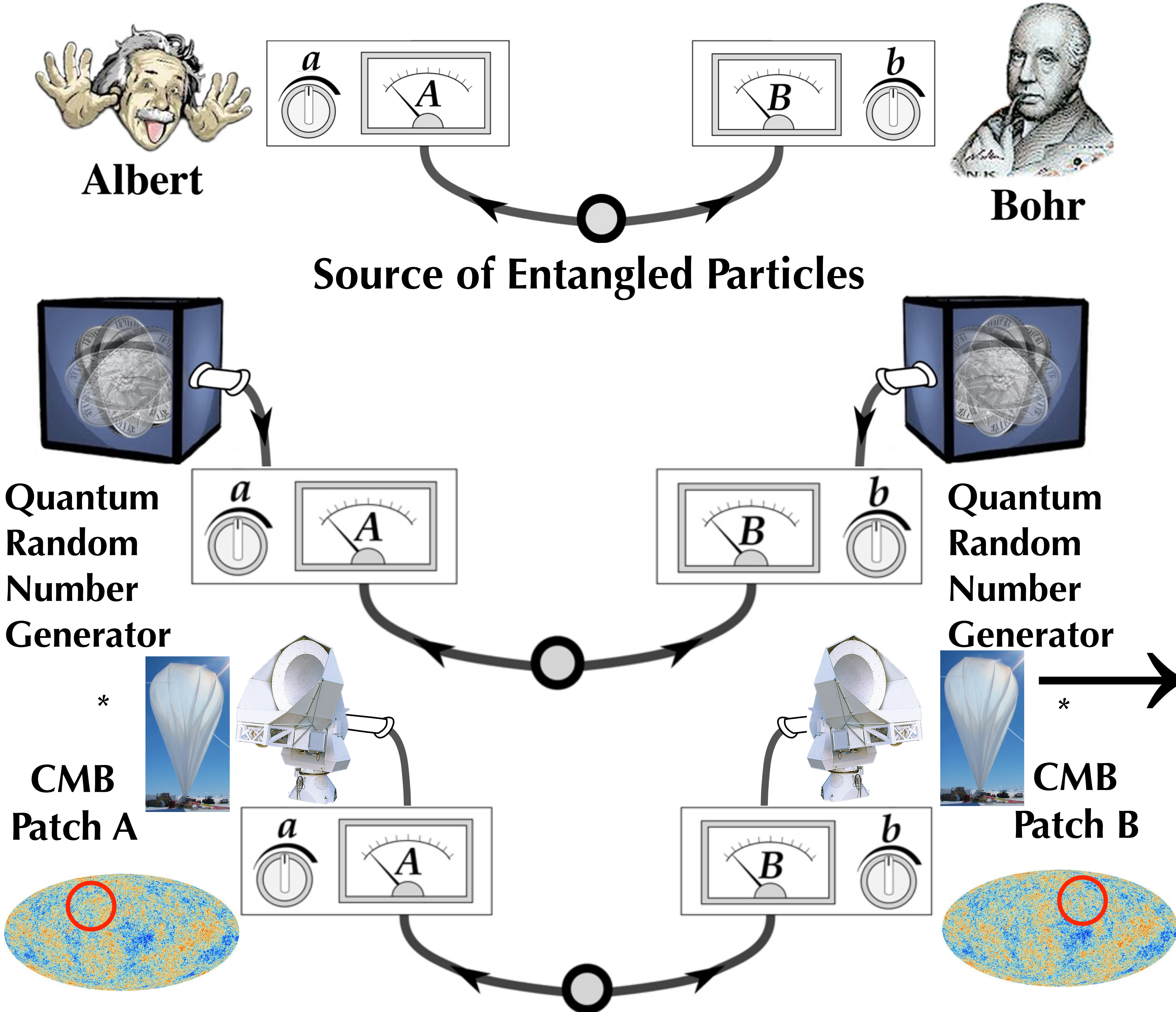


Choose settings with observations of high redshift cosmic sources

Relegates alternatives to billions of years ago!

Adapted from: Gallicchio, Friedman, & Kaiser 2014

CHOOSING DETECTOR SETTINGS

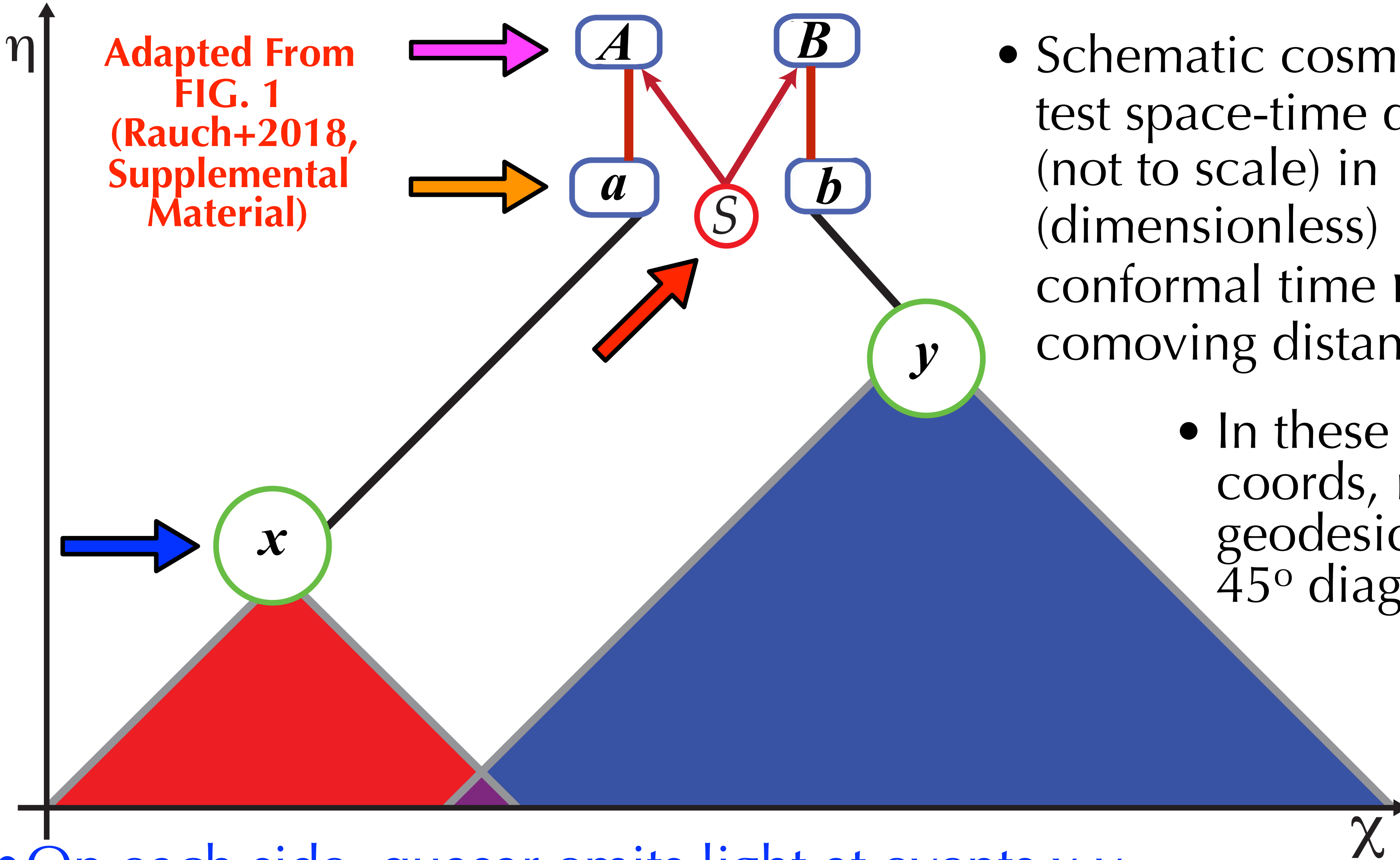


Choose settings with observations of CMB patches, etc…

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

Adapted from: Gallicchio, Friedman, & Kaiser 2014

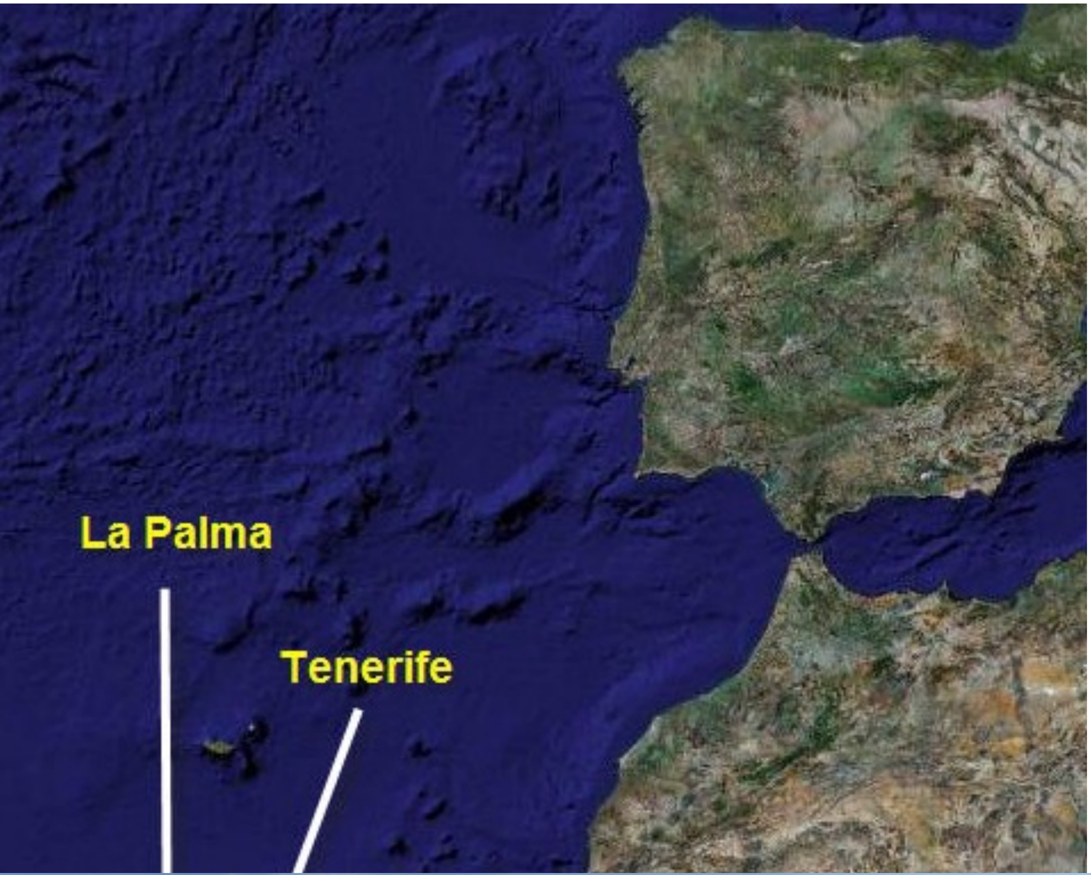
1+1D SPACETIME DIAGRAM

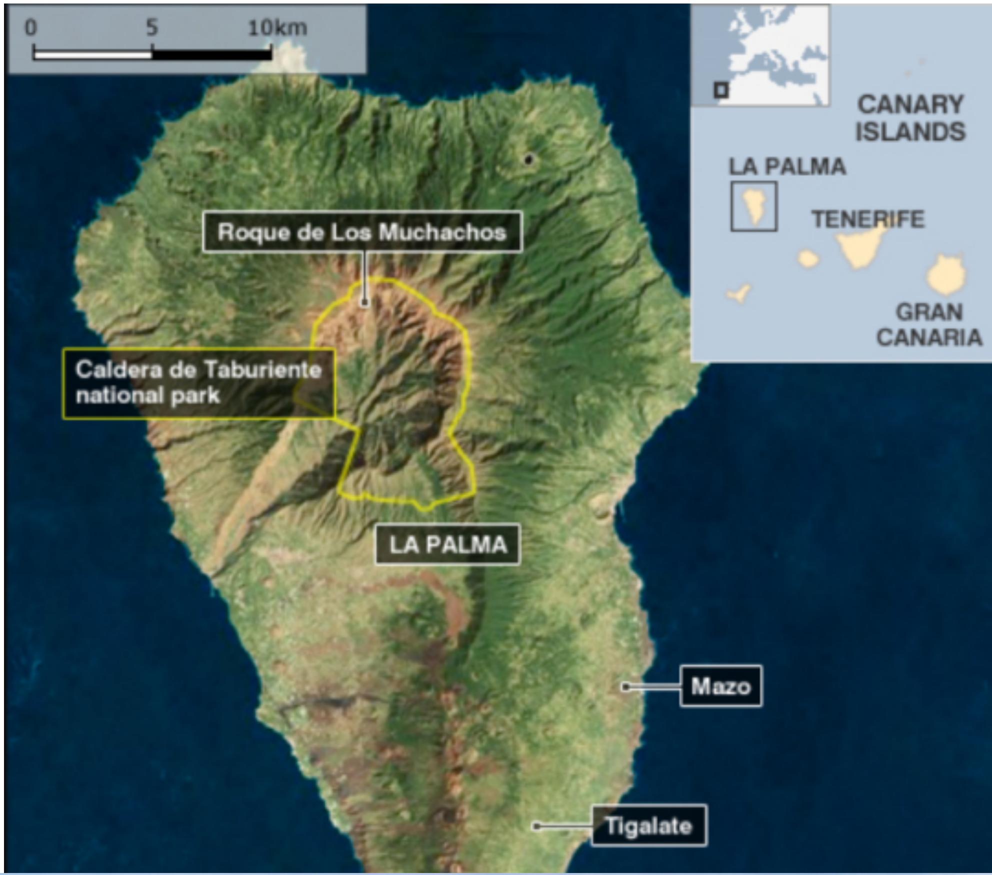


- Schematic cosmic Bell test space-time diagram (not to scale) in (dimensionless) conformal time η vs. comoving distance χ.
    - In these coords, null geodesics on 45° diagonals.

- 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

COSMIC BELL TEST: LA PALMA





COSMIC BELL TEST WITH QUASARS

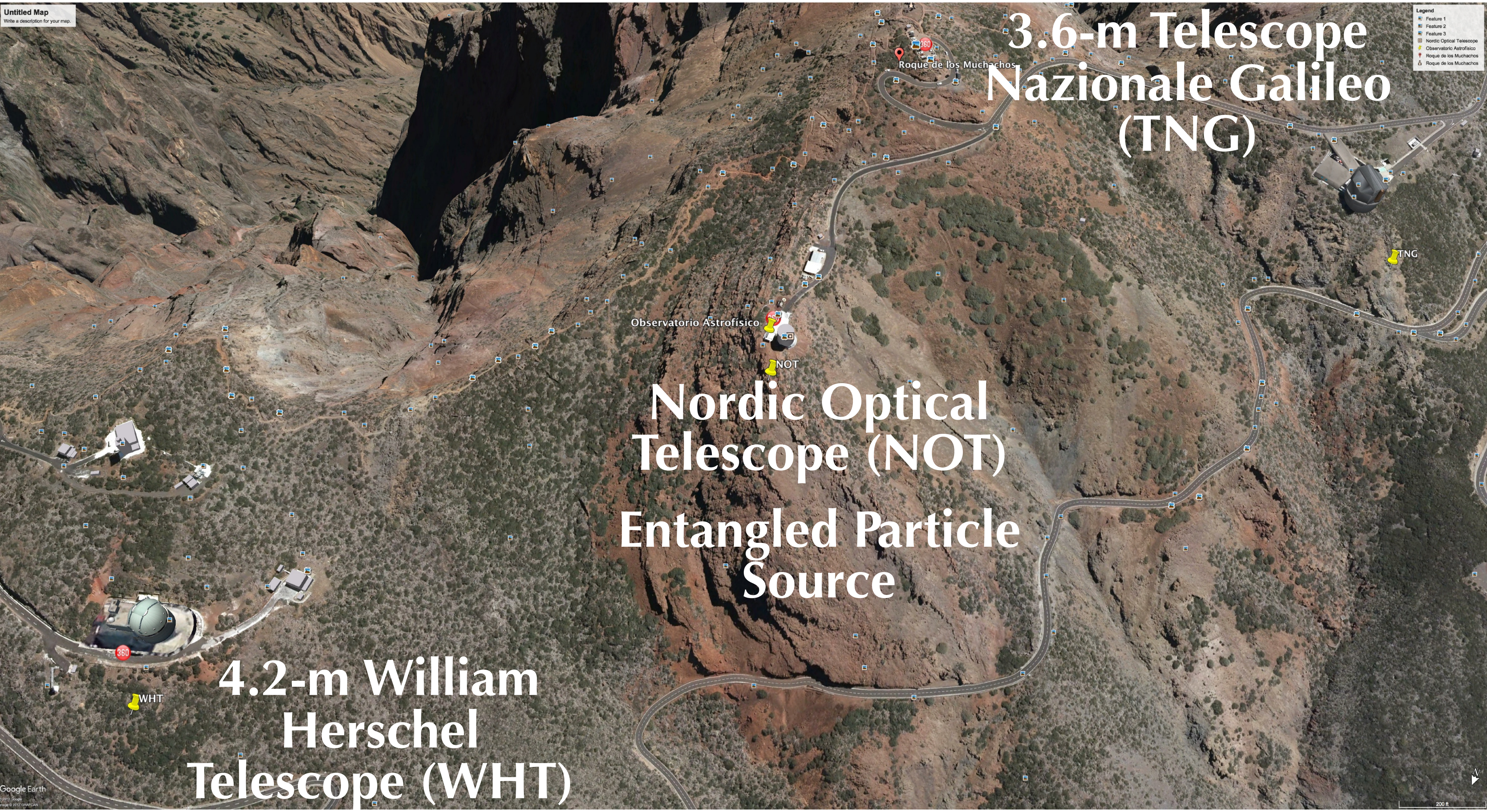


Image ©2018 DigitalGlobe (Google Earth)

COSMIC BELL TEST WITH QUASARS

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

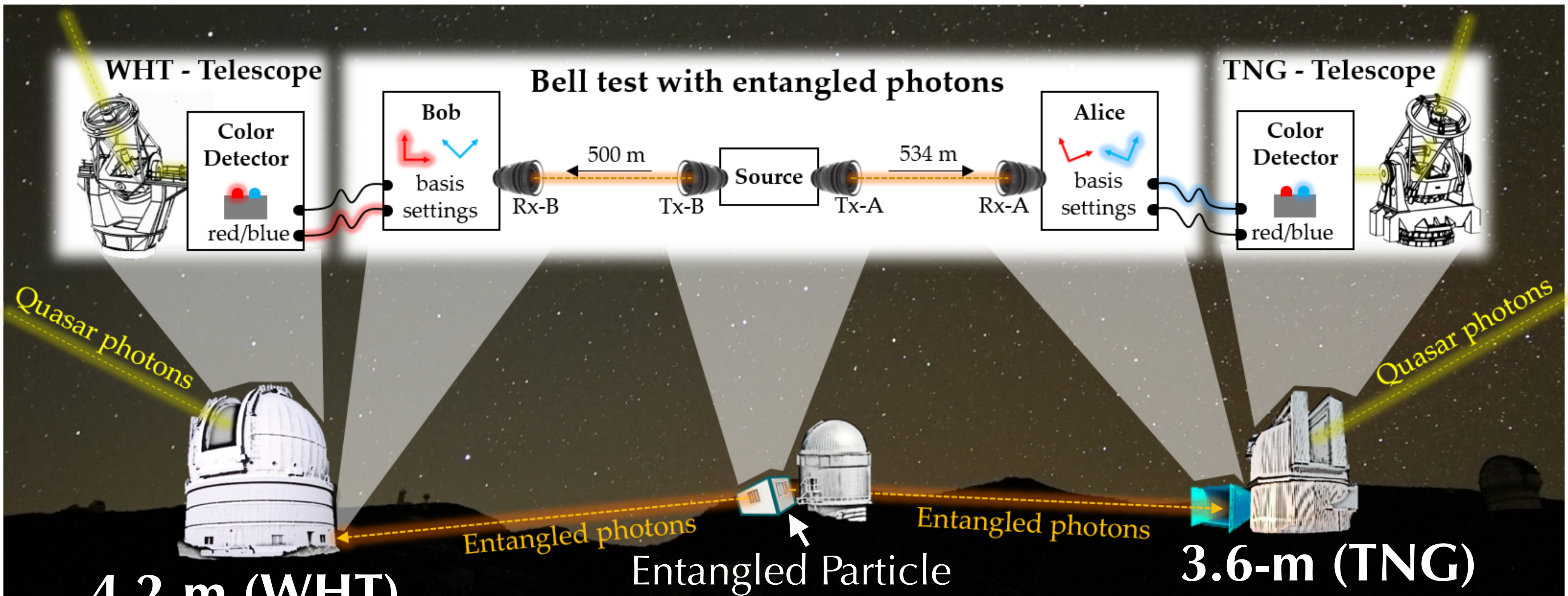

FIG. 1, Rauch + 2018

COSMIC BELL TEST WITH QUASARS

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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)

Pair	Side	ID	az°_{k}	alt°_{k}	z	t_{lb} [Gyr]	τ^{k}_{valid} [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

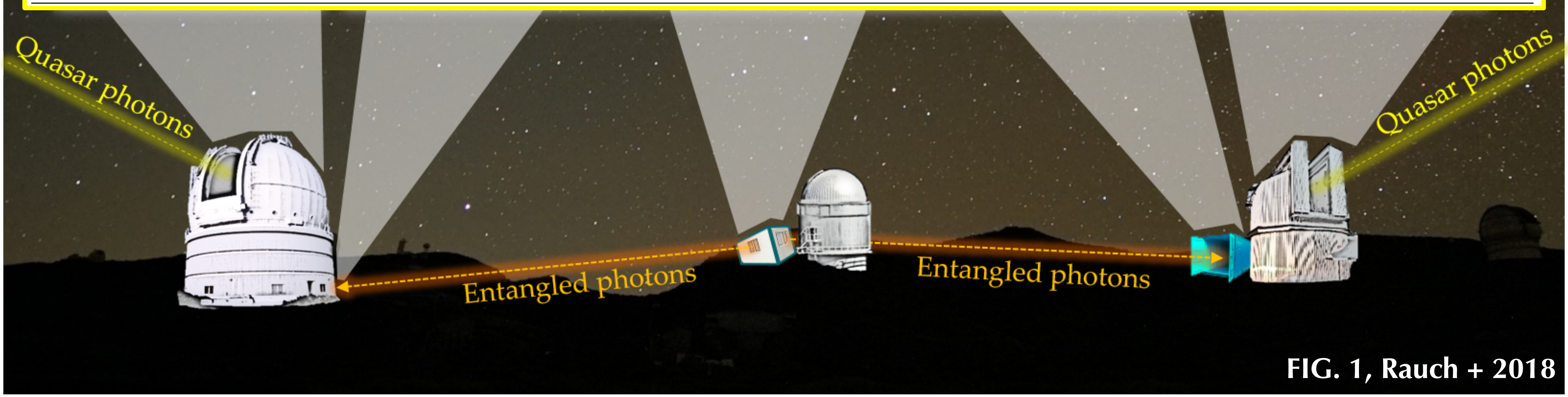


FIG. 1, Rauch + 2018

2+1D SPACETIME DIAGRAM

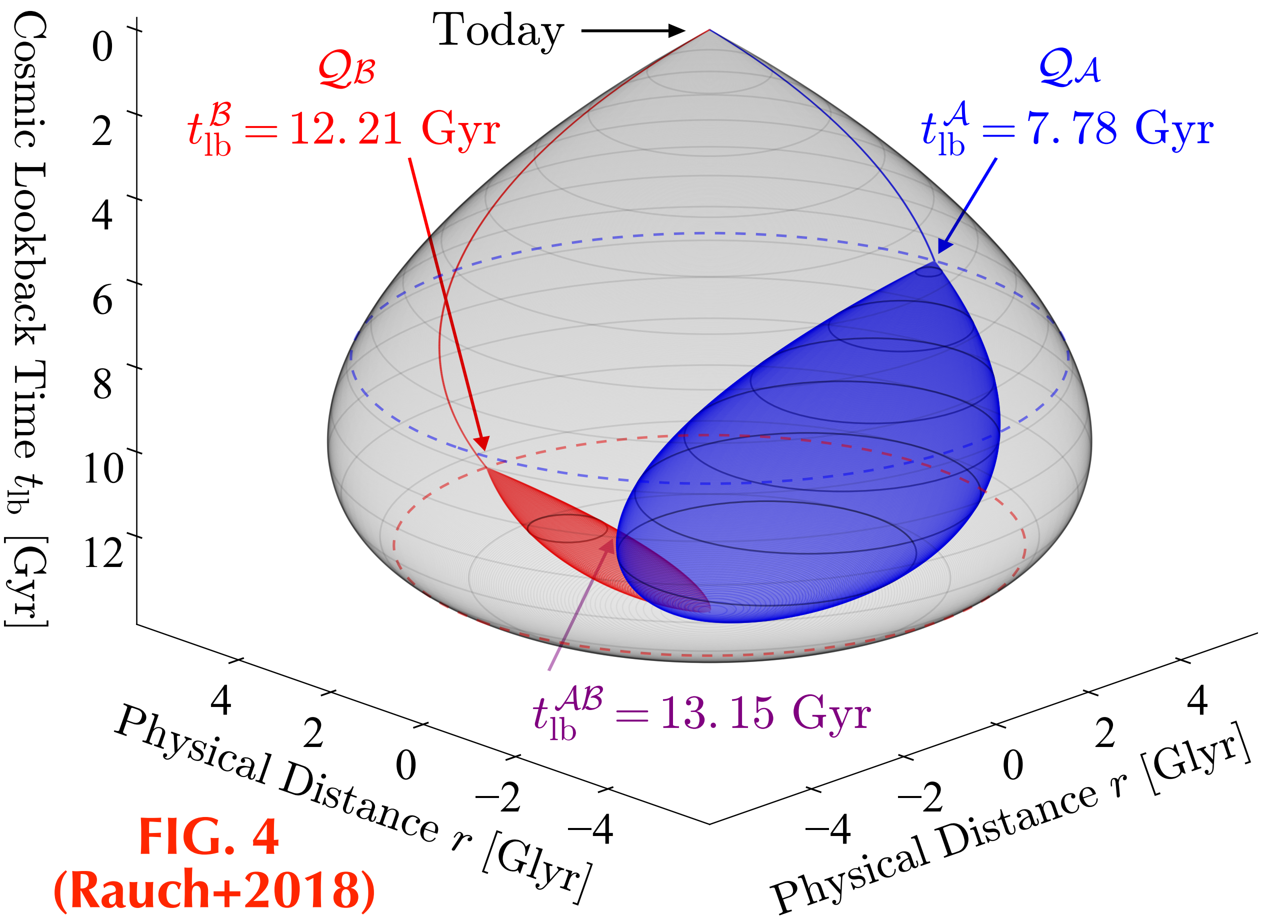


FIG. 4 (Rauch+2018)

- **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!**

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

LA PALMA COSMIC BELL TEST

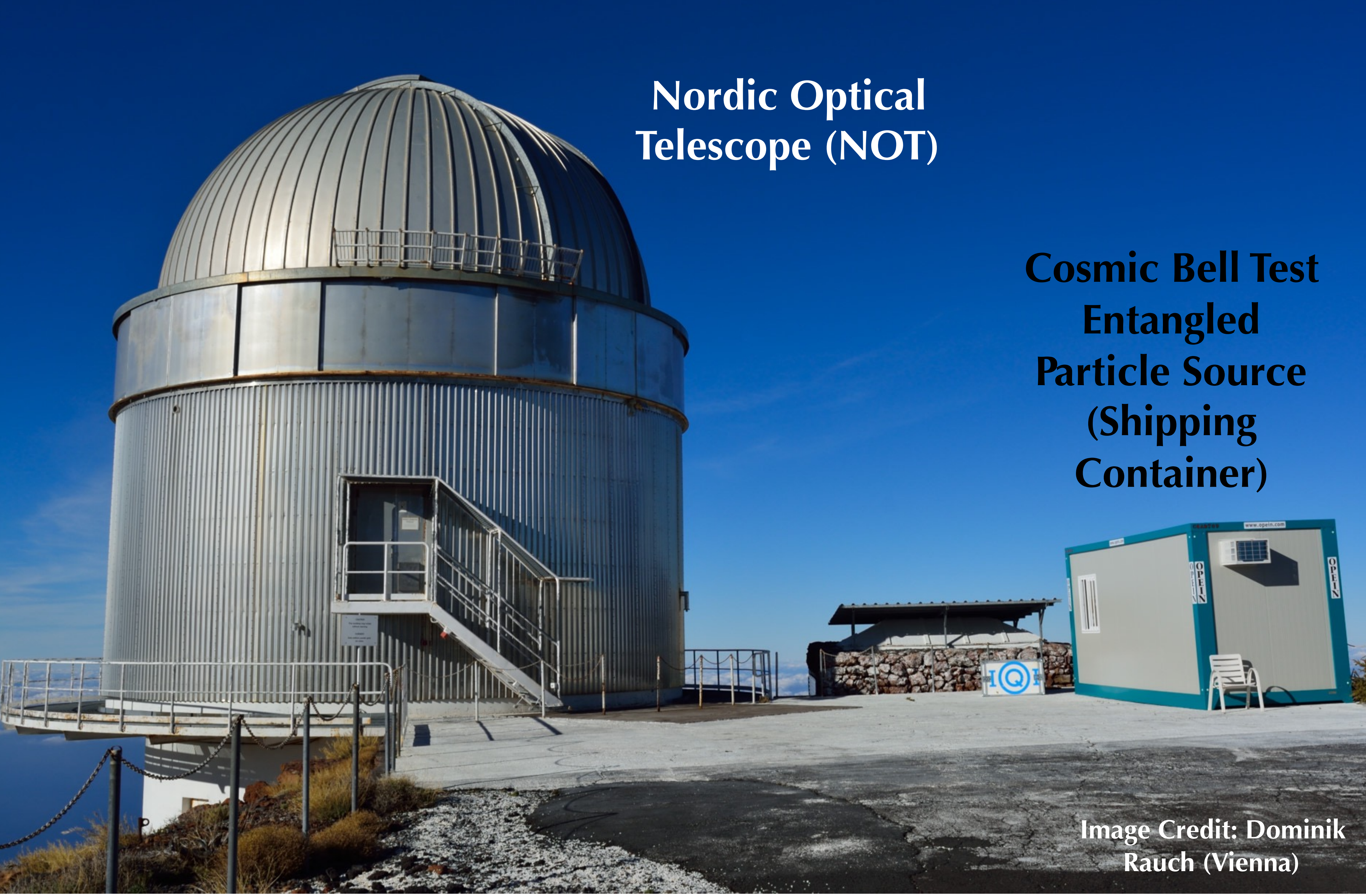
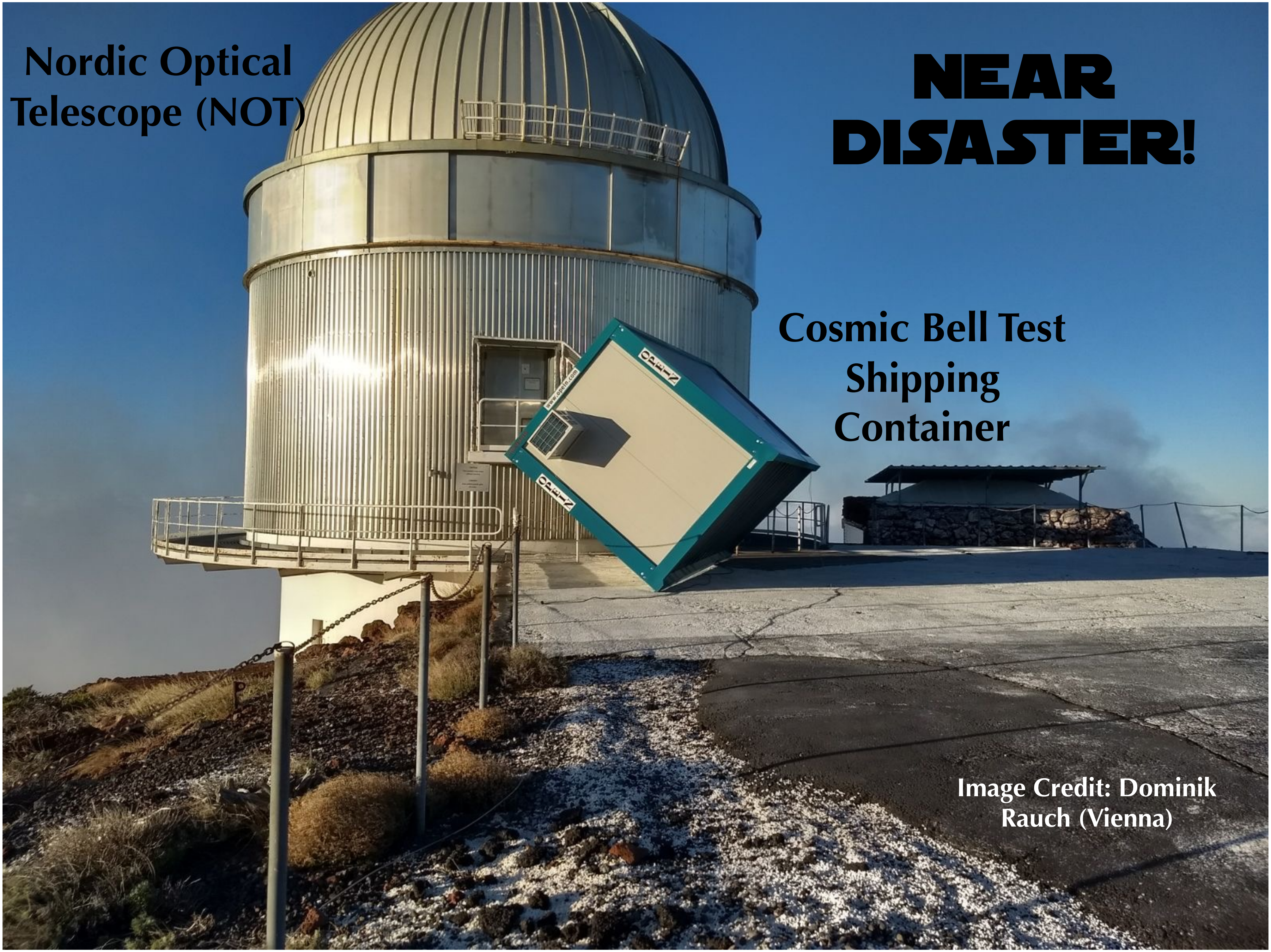


Image Credit: Dominik Rauch (Vienna)


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

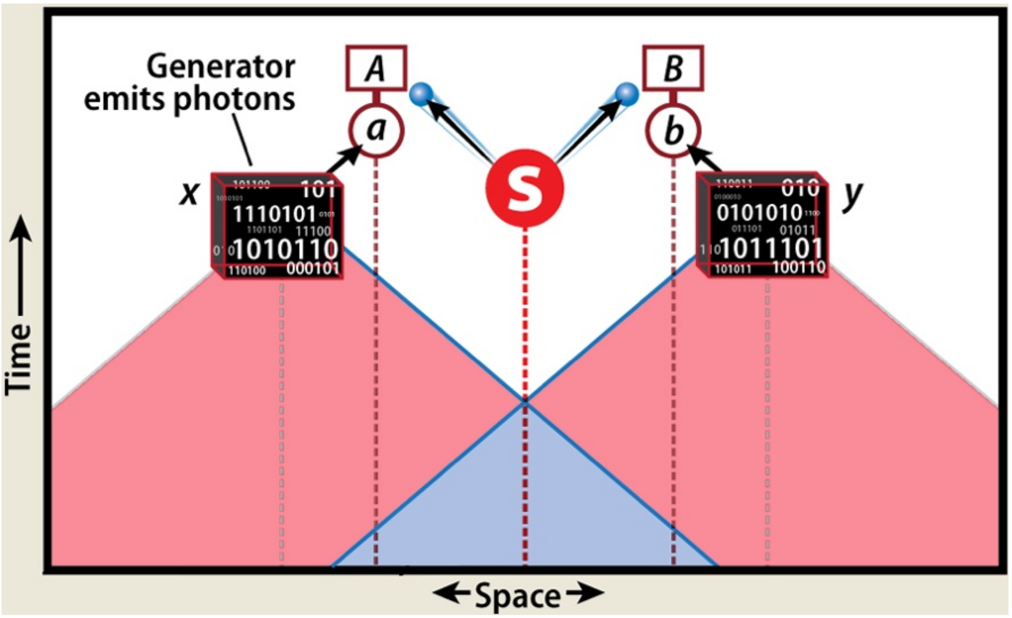
DISASTER AVERTED

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

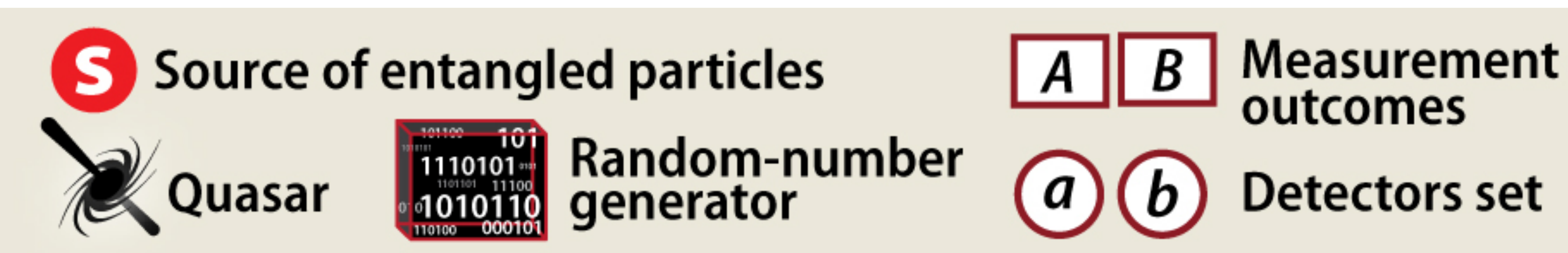
ADVENTURES IN LA PALMA

SPACE-TIME DIAGRAMS

Standard Bell Test



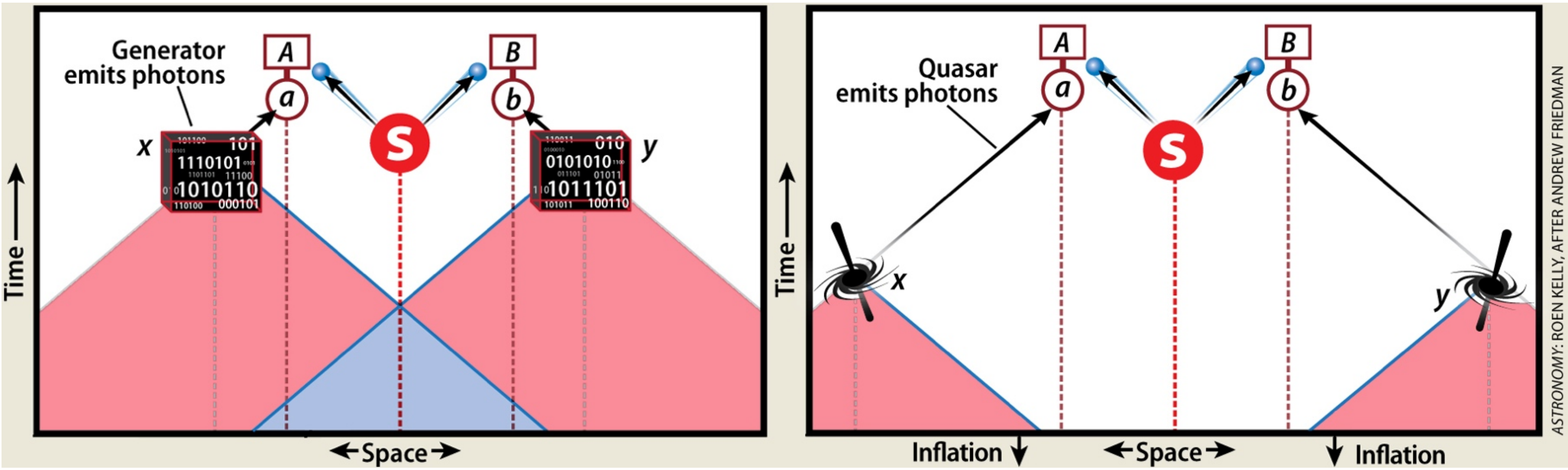
Past light cones from random number generators overlap milliseconds before test.



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

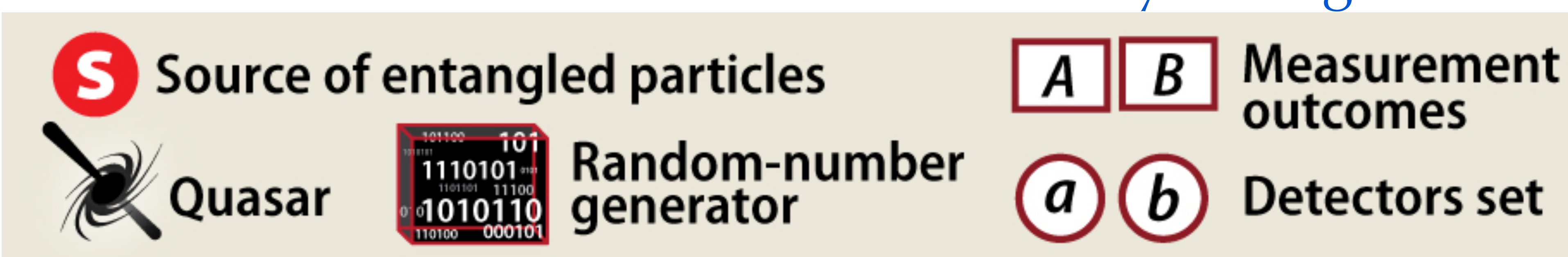
SPACE-TIME DIAGRAMS

Standard Bell Test | Cosmic Bell Test



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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2+1D CONFORMAL SPACETIME DIAGRAM

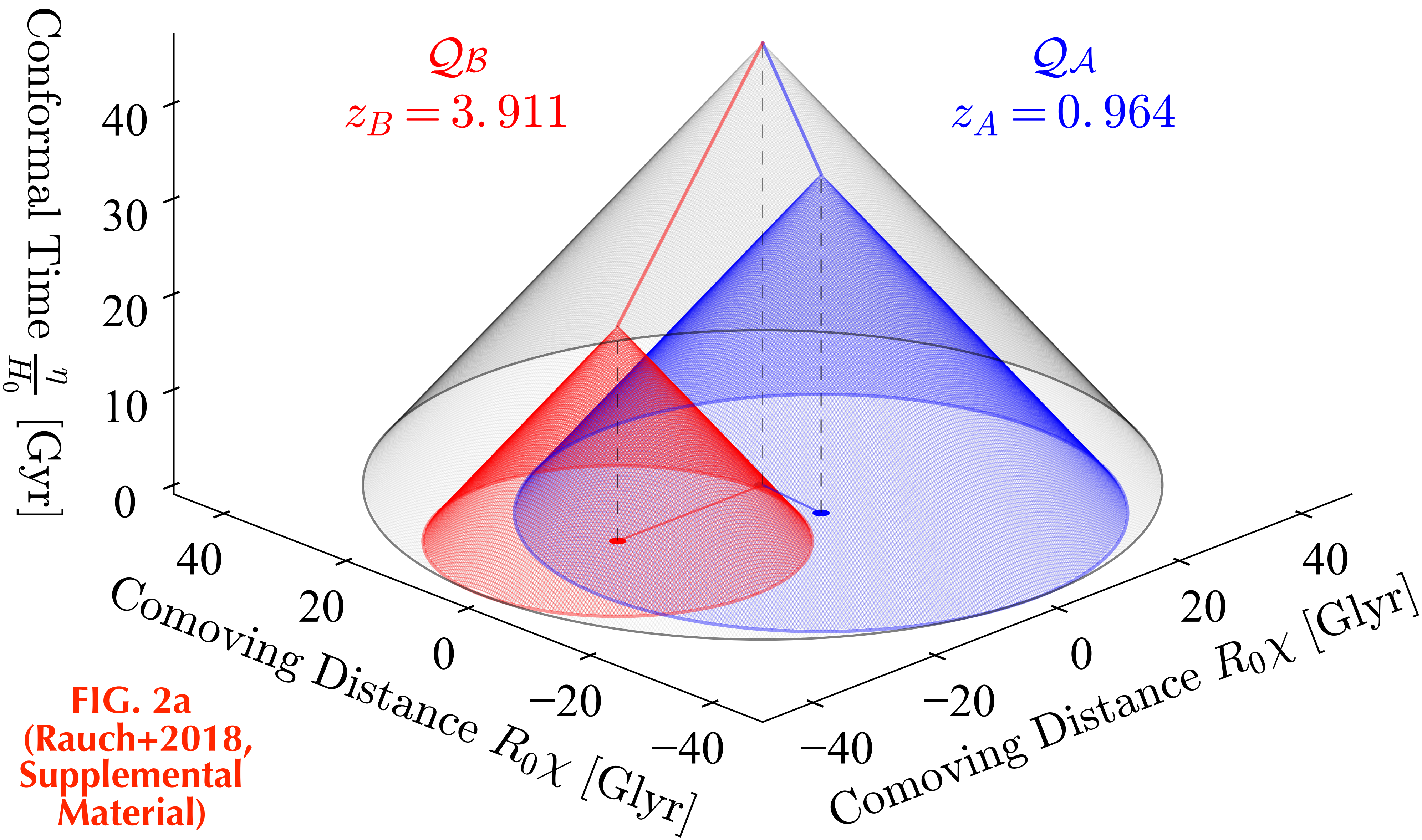

FIG. 2a
(Rauch+2018,
Supplemental
Material)

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

POSSIBLE OUTCOMES

Future 2-quasar 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!