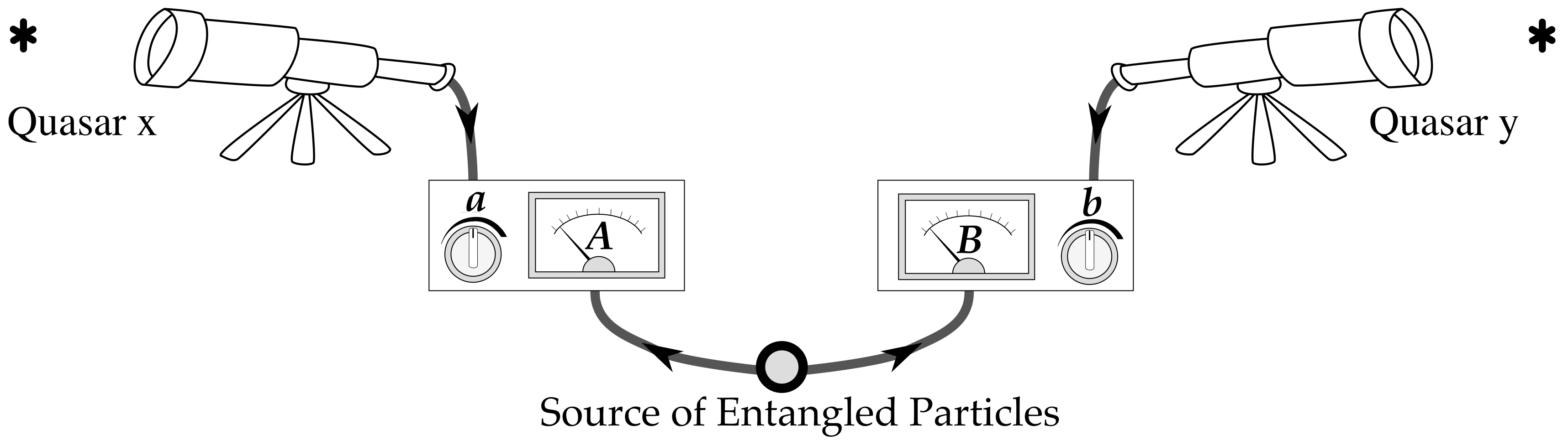

TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH ASTRONOMICAL OBSERVATIONS

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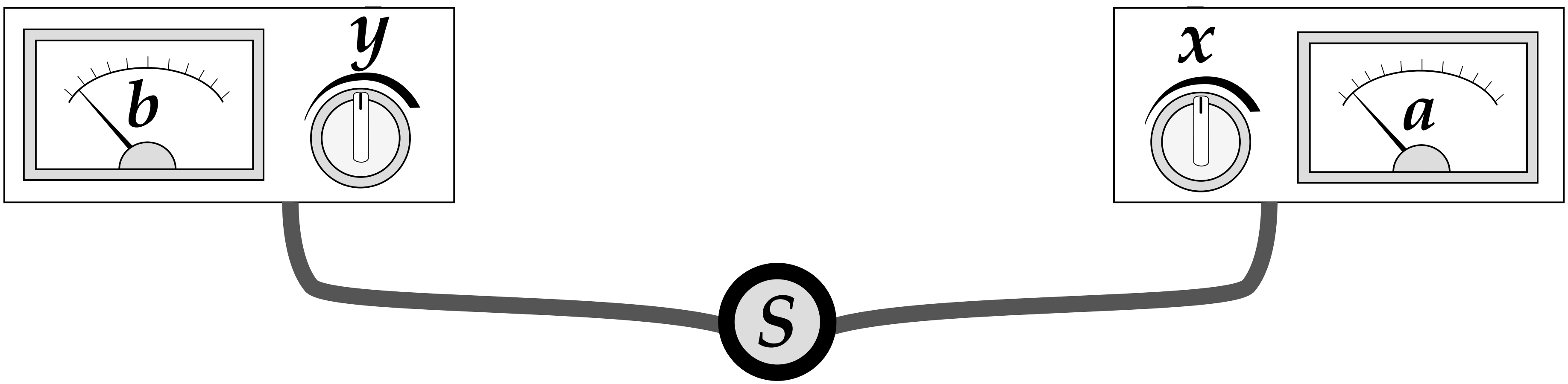
ENTANGLED PARTICLE / BELL TESTS



S = Source of Entangled Particles

x, y* = *Settings

a, b* = *Outcomes

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

If yes, QM incomplete → Hidden variables

BELL'S THEOREM ASSUMPTIONS

1. Determinism (Realism)

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

2. Locality

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

3. Fair Sampling

Probability of detector click uncorrelated with events in past light cone of experiment.

4. Freedom / Free Will

Detector settings choices independent of hidden variables in past light cones.
Observers can choose settings "freely and randomly".

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

BELL'S INEQUALITY VS. THEOREM

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

1,2,3,4 → Bell's Inequality

CHSH form: $S = |\langle ab \rangle + \langle ab' \rangle + \langle a'b \rangle - \langle a'b' \rangle| \leq 2$

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

Bell's Theorem

No local hidden variable theory can reproduce the quantum predictions!

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

FREE WILL LOOPHOLE

What Do Real Experiments Tell Us?

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

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

Usual Story: (2, 1, or both false)

"Local realist" HV theories ruled out

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

Keep locality, realism, but relax freedom

Bell's Theorem (Modified)

Relax freedom ⇨ local realist HV theories *can* reproduce the quantum predictions!

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

FREE WILL LOOPHOLE

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

Relax freedom assumption ⇨

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

Hall 2010, Barret & Gisin 2011, Hall 2011

BELL'S THEOREM LOOPHOLES

A. Locality Loophole

Closing Method?

Hidden communication between parties

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

Spacelike separated measurements, settings

B. Detection Loophole

Measured sub-sample not representative

for atoms: **Rowe+2001**, superconducting qubits: **Ansmann+2009**, photons: **Giustina+2013**, **Christensen+2013**

High efficiency detectors

C. Freedom-of-Choice / Free Will Loophole

Settings correlated with hidden variables

partially for photons: **Scheidl+2010**

Settings spacelike separated from EPR source

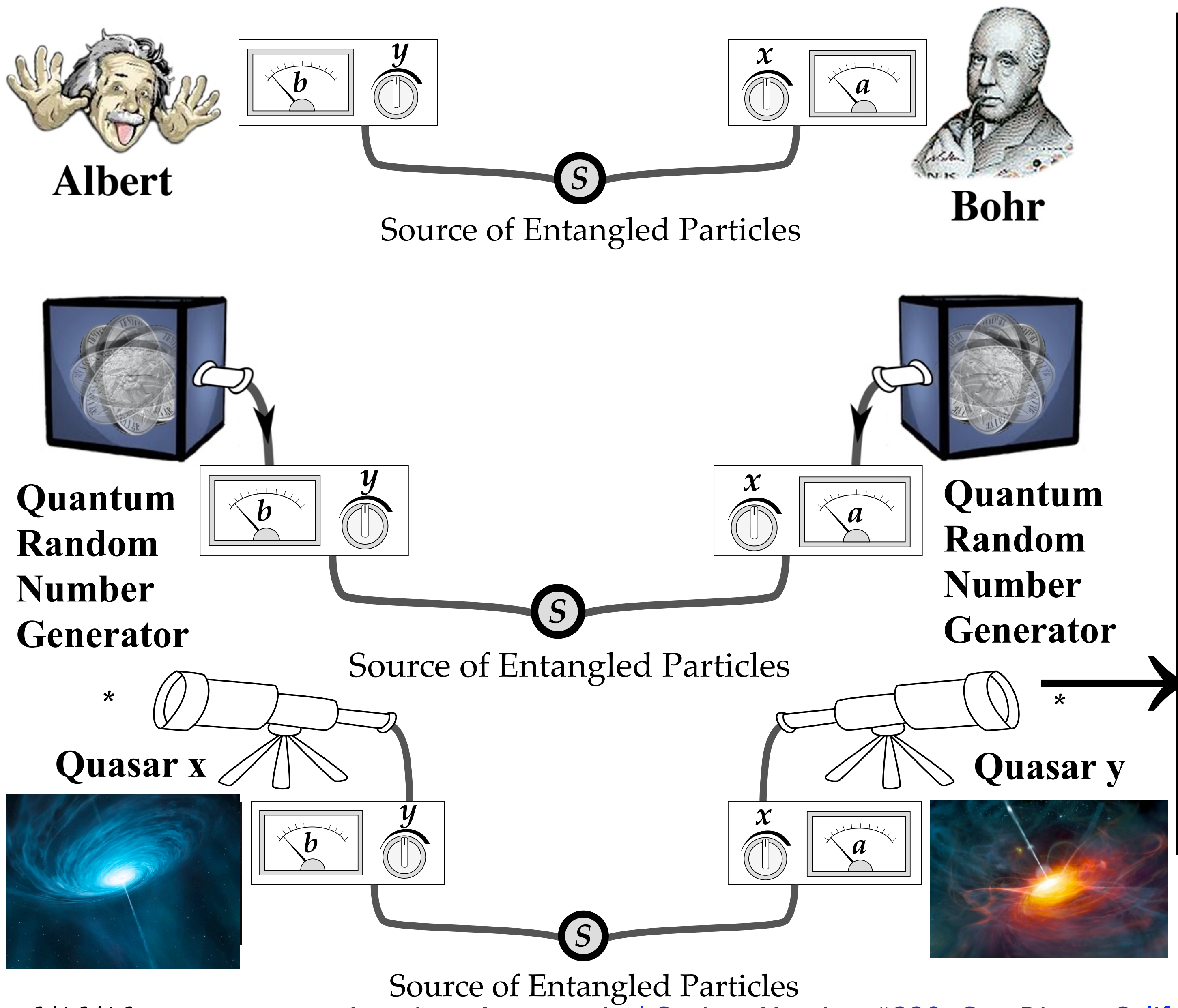
TOWARD A LOOPHOLE FREE TEST

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

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

Locality & *Freedom* (photons) — **Scheidl+2010 (Vienna)**

CHOOSING DETECTOR SETTINGS

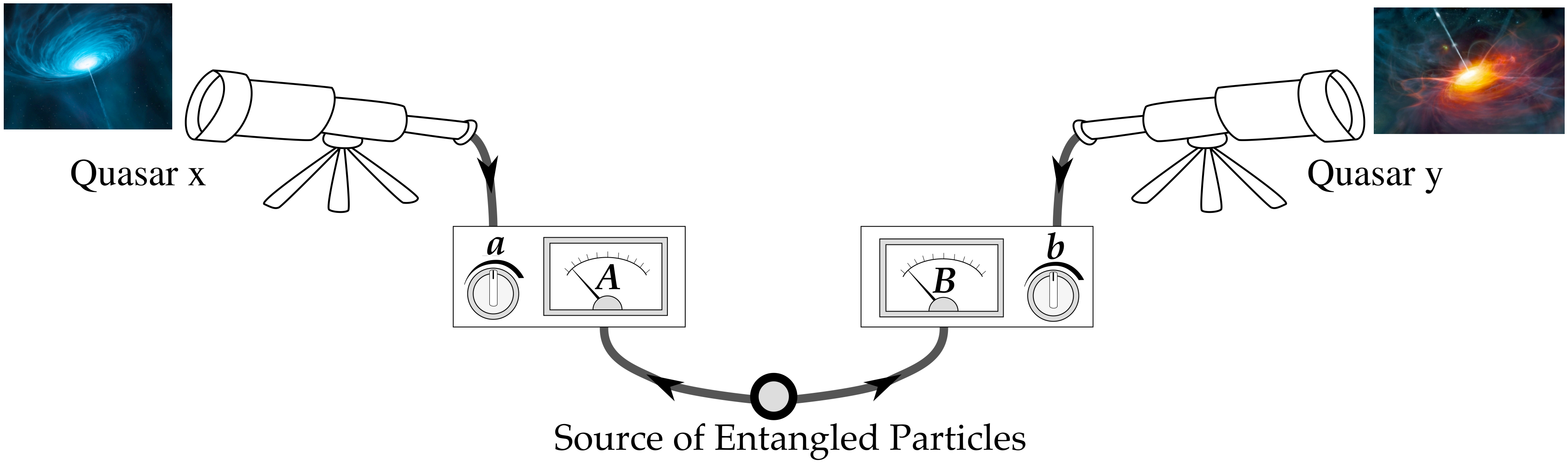


Choose settings with real-time observations of causally disconnected cosmic sources

Ensures freedom as much as possible in our universe!

Adapted from: Gallicchio, Friedman, & Kaiser 2014

COSMIC BELL TEST



Let the Universe decide how to set up experiment!

Use quasars as cosmic random number generators

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

PHYSICAL REVIEW D **88,** 044038 (2013)

The shared causal pasts and futures of cosmological events

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

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

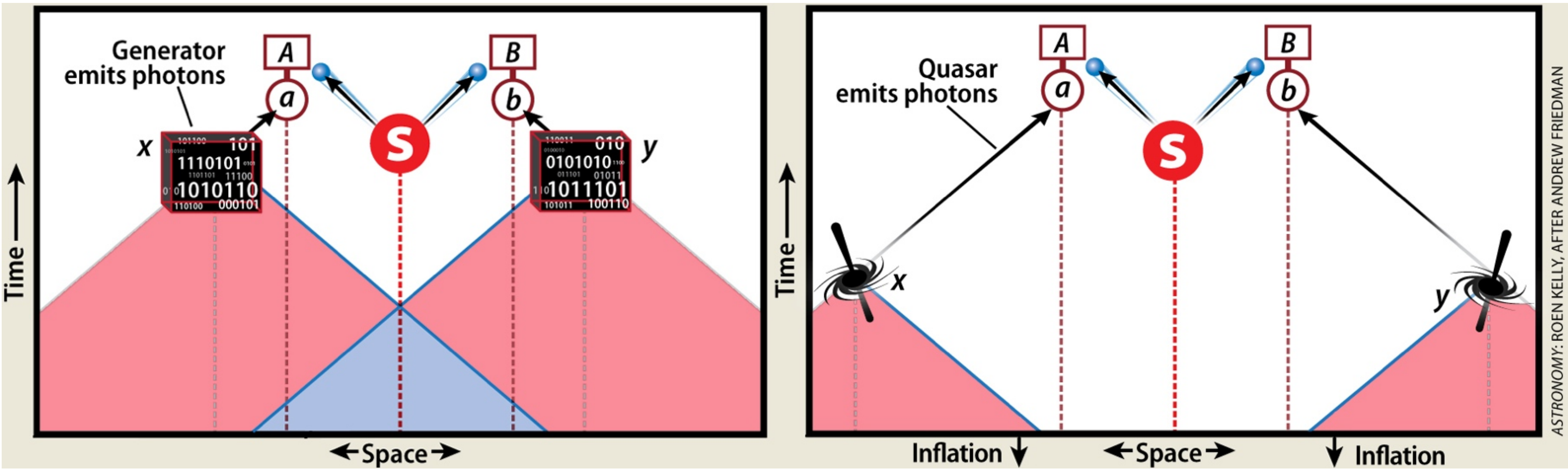
Why use quasars? Brightest continuous cosmological sources.

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

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

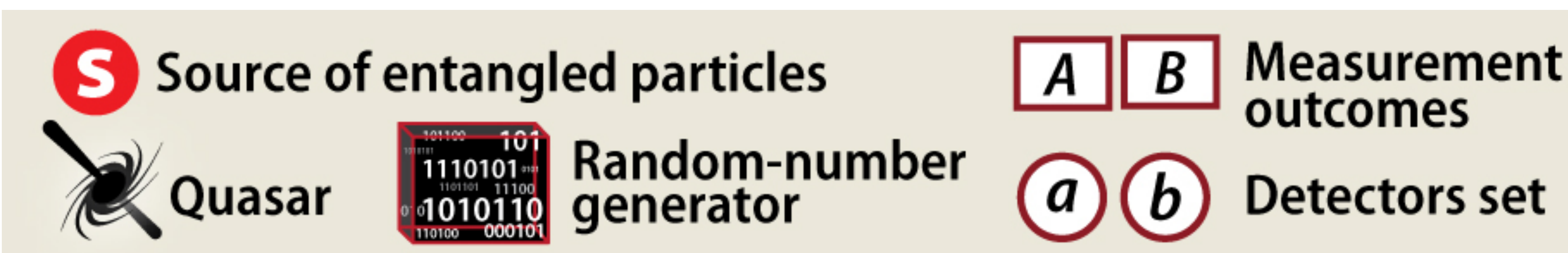
SPACE-TIME DIAGRAMS

Standard Bell Test | **Cosmic Bell Test**



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

Past light cones from quasars don't overlap since big bang, 13.8 billion years ago.



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

PRL **112,** 110405 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

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

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(Received 25 October 2013; published 18 March 2014)

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

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

Experiment feasible with existing technology!

z > 3.65 quasars bright enough
CMB an intriguing possibility

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

POSSIBLE OUTCOMES

Expected

Bell inequalities always violated. Rule out ("implausify") local HV theories as much as possible.

Unexpected

Degree of Bell violation depends on size of shared causal past of cosmic sources.

Strangest

Bell inequality not violated for very distant cosmic sources. Perhaps freedom assumption is false!

Implications for inflation? Quantum gravity?

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