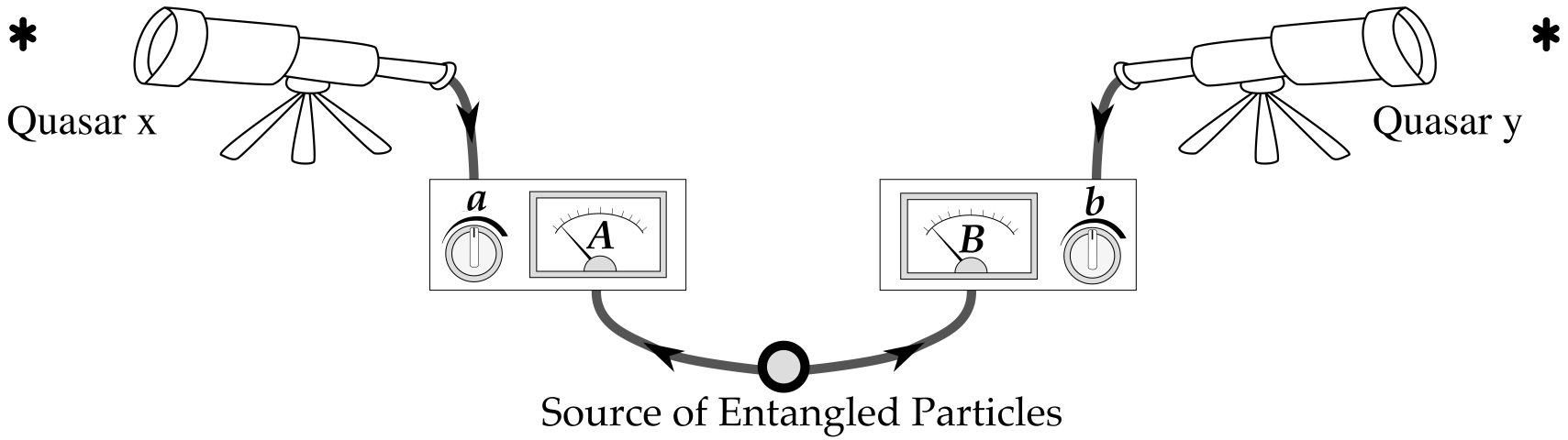


TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH COSMOLOGICAL OBSERVATIONS OF QUASARS

Andrew Friedman

NSF STS Postdoctoral Fellow, MIT
Visiting Research Scientist
MIT Center for Theoretical Physics

Massachusetts Institute of Technology

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

Dr. Jason Gallicchio
U. Chicago [4,5]

Dr. Andrew Friedman
MIT [1,2,3]

Prof. David Kaiser
MIT [1,2,3]

Prof. Alan Guth
MIT [1,2]

+***MIT UROP Students***
Isabella Sanders
Anthony Mark

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

Gallicchio, Friedman, & Kaiser 2014 = GFK14

***Phys. Rev. Lett. Vol. 112, 11, 110405*, arXiv:1310.3288**

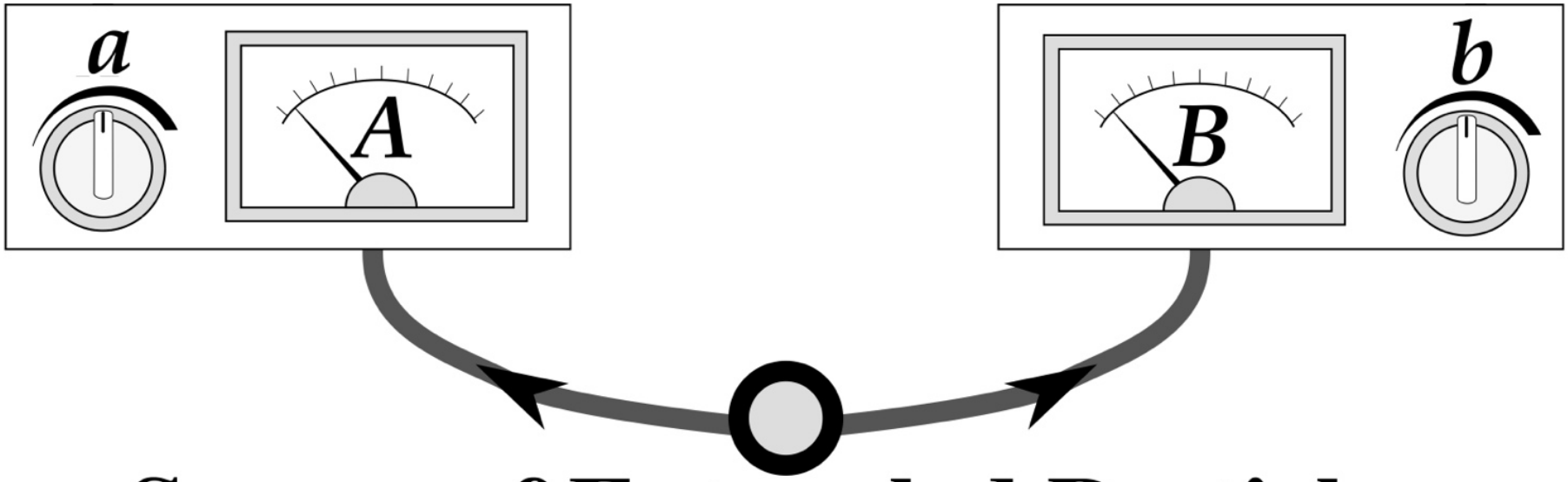
"*The Shared Causal Pasts and Futures of Cosmological Events*"

Friedman, Kaiser & Gallicchio 2013 = F13a

***Phys. Rev. D. Vol. 88, 4, 044038*, arXiv:1305.3943**

1:MIT Physics, 2:MIT CTP, 3:MIT STS, 4:U. Chicago KICP, 5:South Pole Telescope

EPR OR BELL EXPERIMENTS



Source of Entangled Particles

a, b = *Settings*

A, B = *Outcomes*

Big question: ***Is the world local or non-local?***

If local, QM incomplete →Hidden variables.

BELL'S THEOREM ASSUMPTIONS

1. Realism
2. Locality
3. Settings Indep.

1,2,3 → Bell's Inequality

CHSH form:

$$S = E(a_1,b_1) + E(a_1,b_2) + E(a_2,b_1) - E(a_2,b_2) \leq 2$$

QM Predictions + Experiments: $2 < S_{max} \leq 2\sqrt{2}$

The Usual Story:

QM incompatible with "local realism" (2 or 1 or both)

Local "hidden variable" (HV) theories ruled out by experiment ...

$S_{max} > 2$ → **At least one of 1,2,3 are false!**

...Another Consistent Story:

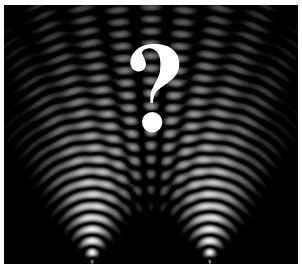
QM incomplete. Local HVs describe missing degrees of freedom (e.g. EPR 1935)

Possible loophole: Just relax settings independence! (3 false)

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

BELL'S THEOREM LOOPHOLES

Loopholes: Local Realism still tenable despite $S_{max} > 2$



Why Does it Matter?

Quantum foundations!

Security of quantum cryptography

A. Locality Loophole

Hidden communication between parties

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

Closing Method?

Spacelike separated measurements

B. Fair sampling / Detection Efficiency Loophole

Measured sub-sample not representative

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

High efficiency detectors

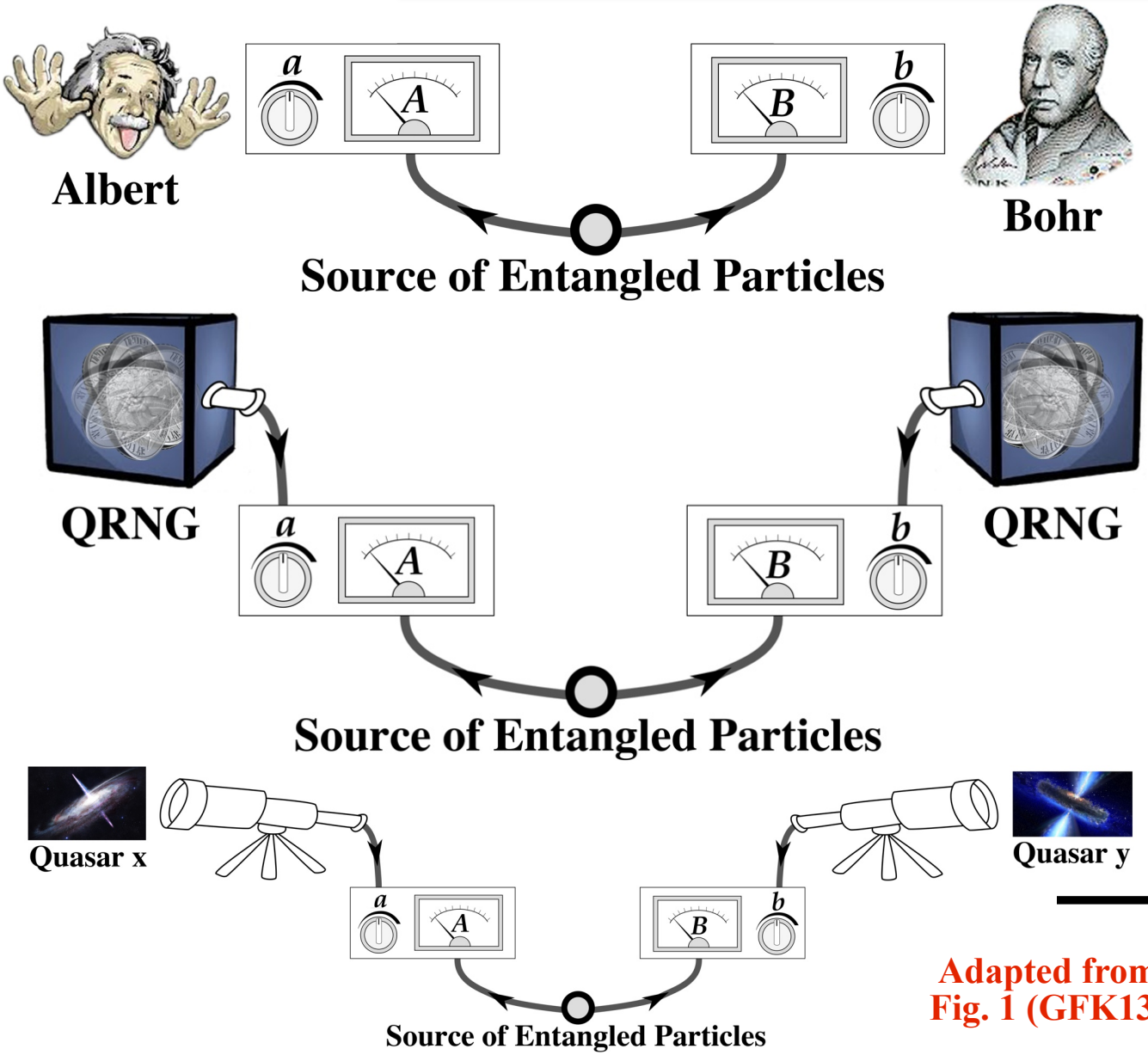
C. Settings Independence / Freedom of Choice Loophole

Settings correlated with local hidden variables

partially? for photons: **Scheidl+2010**

Spacelike separated settings (QRNGs)

CHOOSING SETTINGS *a, b*

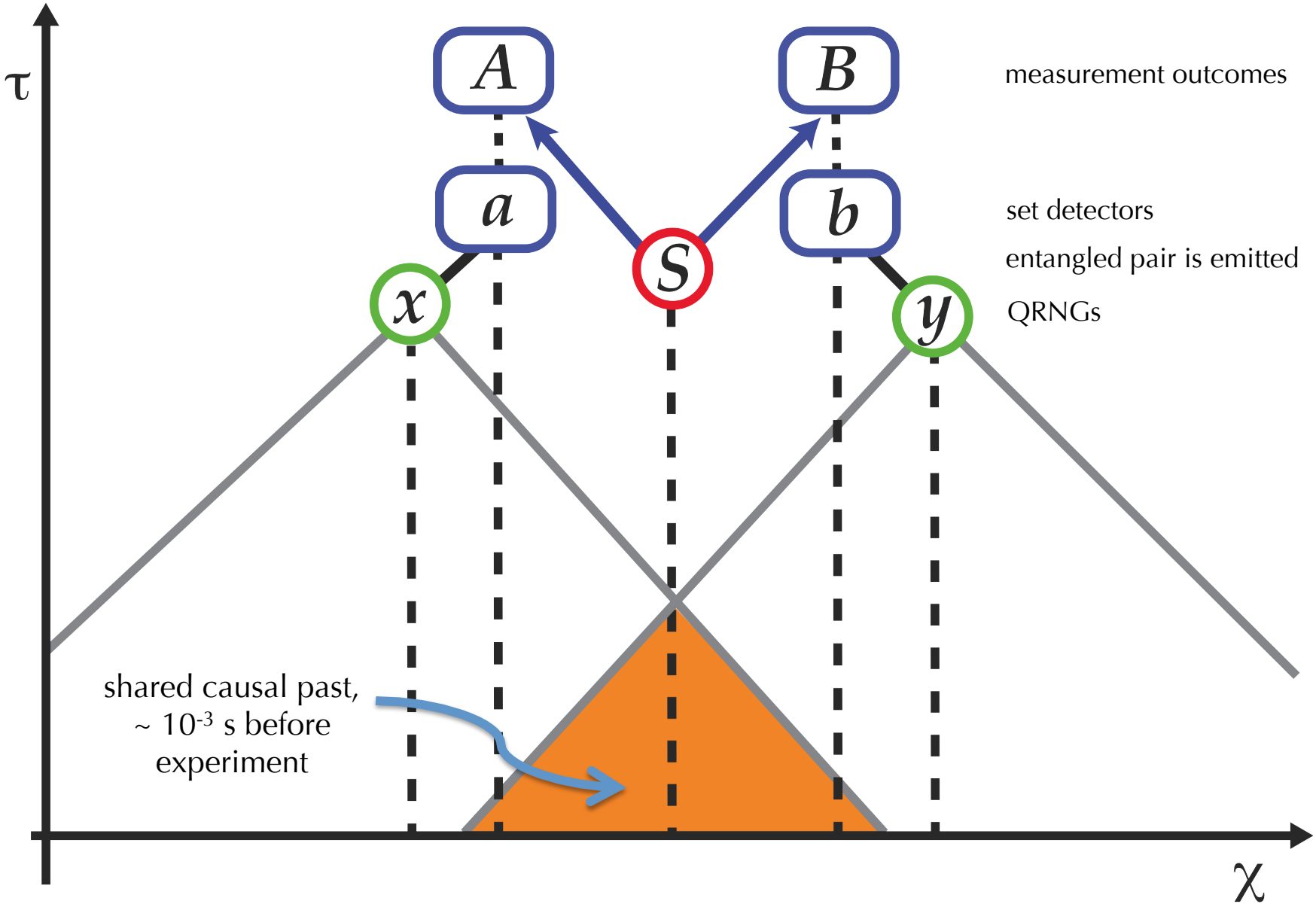


Adapted from Fig. 1 (GFK13)

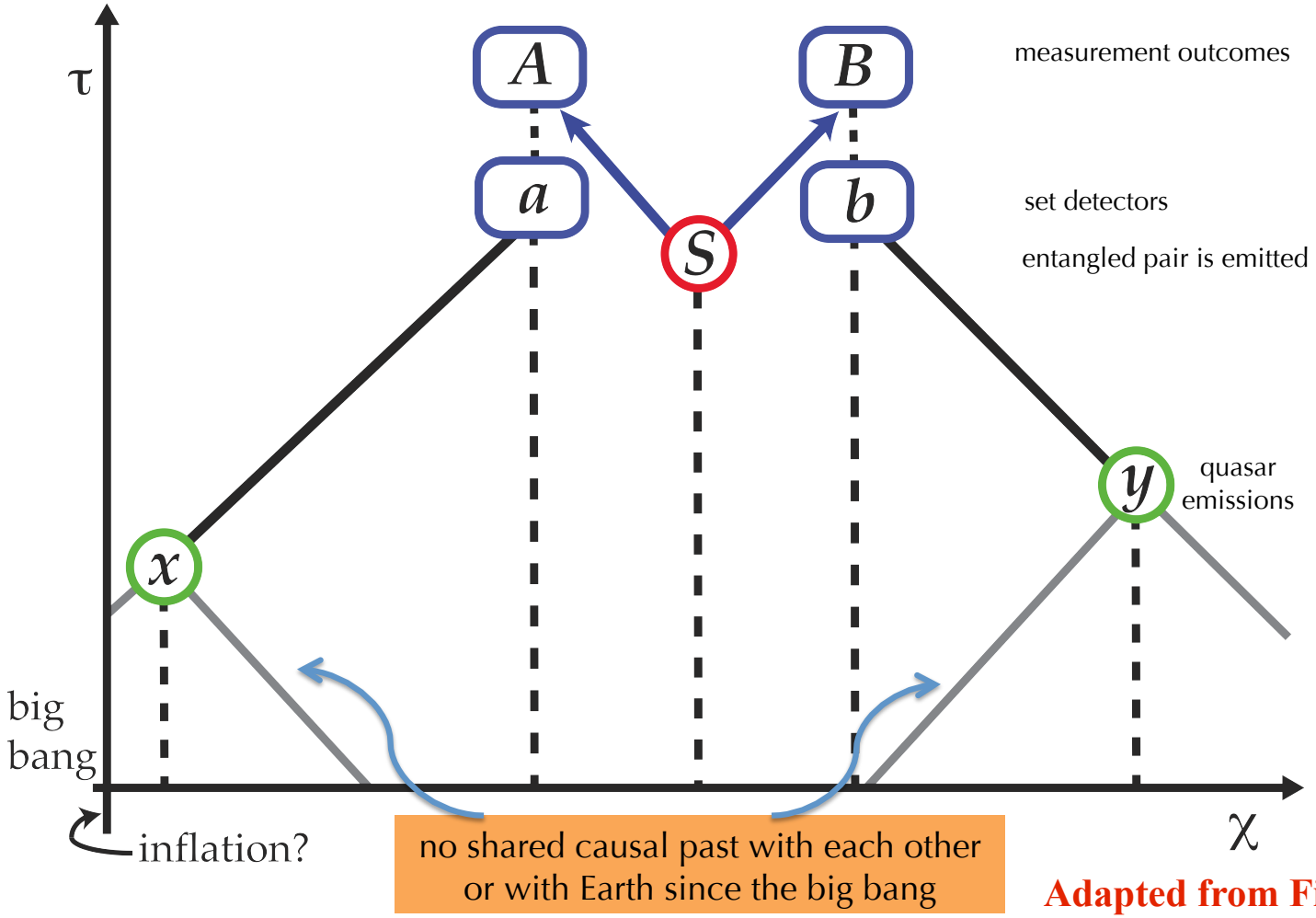
Choose detector settings with real-time observations of causally disconnected cosmic sources

Ensures settings independence as much as is physically possible in our universe!

BELL TEST CONFORMAL DIAGRAM

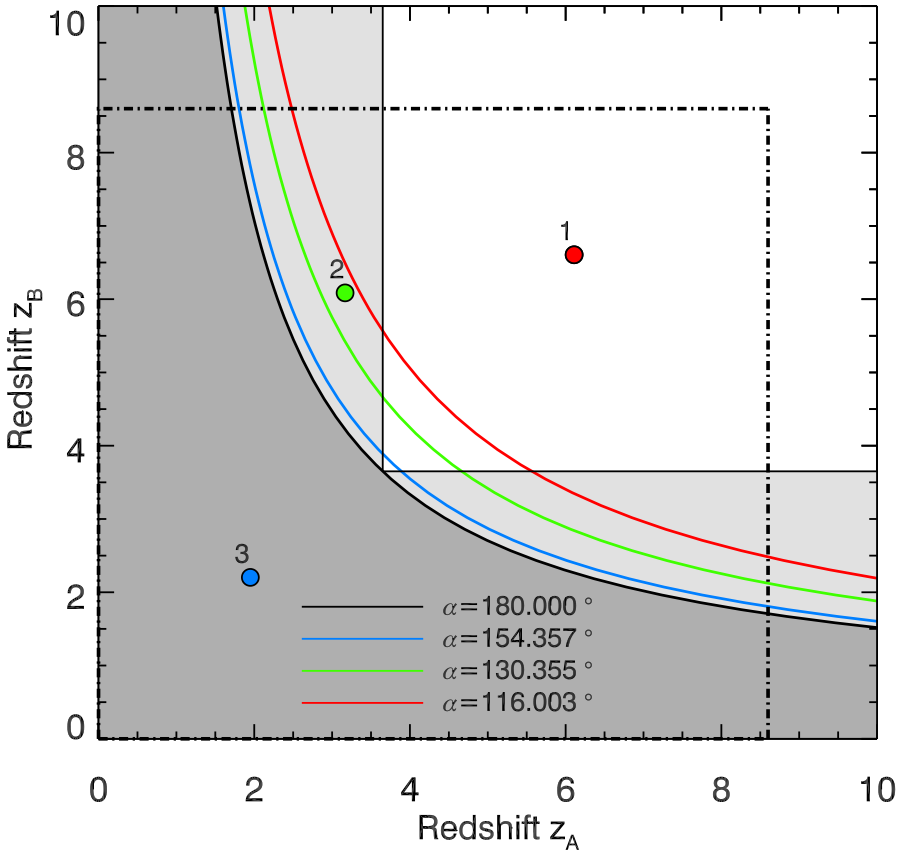


COSMIC BELL CONFORMAL DIAGRAM



Adapted from Fig. 2 (GFK13)

***x, y* need z >3.65 (at 180º) for no shared causal past with each other, source, detectors since end of inflation 13.8 Gyr ago**



EXAMPLE QUASAR PAIRS

pair 3 - YES shared past with each other & Earth

pair 2 - NO shared past with each other, but A_2 has shared past with Earth

pair 1 - NO shared past with each other or Earth

Fig. 5, Table I (F13a)

Pair	Separation Angle α_i [deg]	Event Labels	Redshifts z_{Ai}, z_{Bi}	Object Names	RA [deg]	DEC [deg]	R [mag]	B [mag]
1	116.003	A_1	6.109	SDSS_J031405.36-010403.8	48.5221	-1.0675	16.9	20.1
		B_1	6.606	SDSS_J171919.54+602241.0	259.8313	60.3781	18.6	16.9
2	130.355	A_2	3.167	KX_257	24.1229	15.0481	16.7	17.8
		B_2	6.086	SDSS_J110521.50+174634.1	166.3396	17.7761	16.4	25.1
3	154.357	A_3	1.950	Q_0023-4124	6.5496	-41.1381	14.2	15.4
		B_3	2.203	HS_1103+6416	166.5446	64.0025	14.7	15.4

LOOPHOLE FREE COSMIC BELL?

Settings Independence

Choose settings with cosmic sources.

Locality

Choose settings with cosmic sources ***while EPR pair is in flight****.*

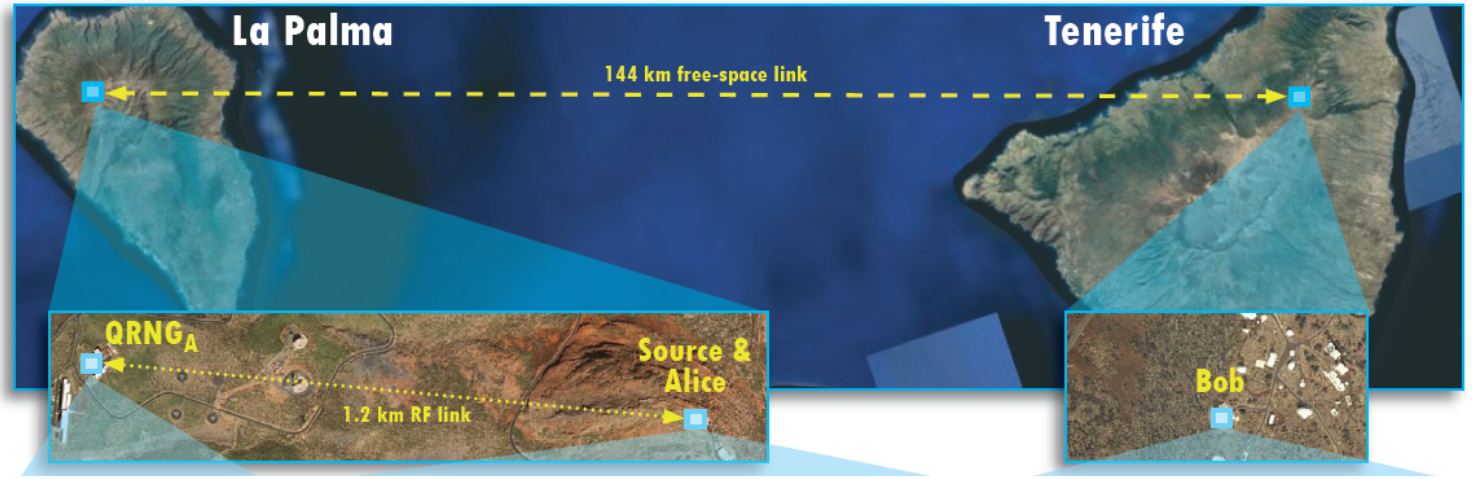
Fair Sampling / Detection Efficiency

Use existing detector technology: efficiency & time resolution

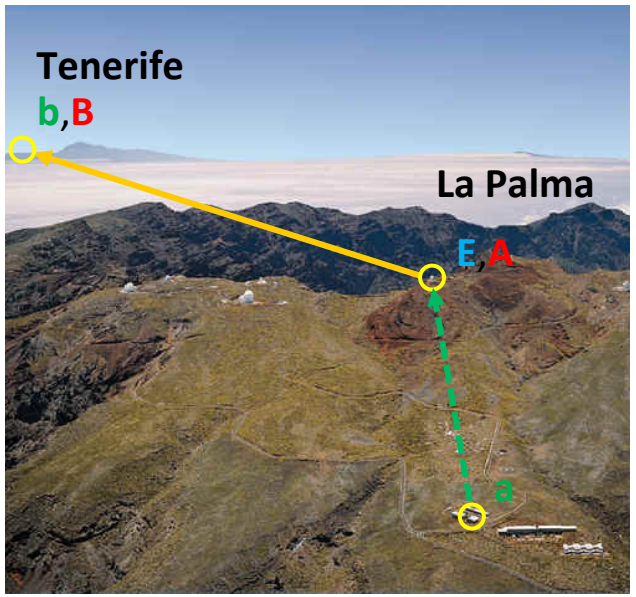
With reasonable experimental parameters, can close all three loopholes simultaneously during quasar visibility window!
~50% experimental runs triggered by cosmic photons. (GFK13)

~1-meter	**Telescope mirror diameters**
~100km	**Baseline between telescopes**
~ 2×10^4 photons s^{-1} m^{-2}	**Optical quasar flux at z~4.13, separated by 130°**
~50-98%	**Cosmic photon detector efficiency (APD / TES)**

ZEILINGER GROUP EXPERIMENTS



ESA - Optical Ground Station (OGS) 1-m receiver telescope, Laser guide to La Palma



Scheidl+2010, *PNAS*, 107, 46, p. 19708-19713

POSSIBLE OUTCOMES

Expected

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

Unexpected

Bell inequality not violated for some cosmic source pairs. Perhaps setting indep. was false until our cosmic bell test!

Strangest

Degree of Bell violation depends on size of causal overlap region.

Implications for inflation? Quantum gravity? The Multiverse?

TESTING THE MULTIVERSE?

Cosmic Bell Could Test Inflation

If S_{max} scales with extent of causal overlap during inflation.

***Any* test of inflation = indirect test of Level I multiverse.**

Quantum Gravity? Open Questions

Above not predicted by Quantum Theory → test new physics.

*** Could inflationary era correlations survive re-heating and persist to affect a Cosmic Bell test?**
*** Can inflation era entanglement yield new observable effects?**
*** Is entanglement more fundamental than space-time in QG?**
***Are regions beyond our cosmic event horizon really causally inaccessible forever? Or is this a naive classical GR view?**

***Could a cosmic Bell experiment or a modified version thereof directly test the Level I multiverse?**