

COMPARING RECENT ENTANGLEMENT TESTS TO A COSMIC BELL TEST: LOOPHOLES & SPACETIME DIAGRAMMS



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RECENT ENTANGLEMENT TESTS

Three recent entanglement experiments have closed the “locality” and “detection” loopholes simultaneously (Delft, Vienna, NIST)

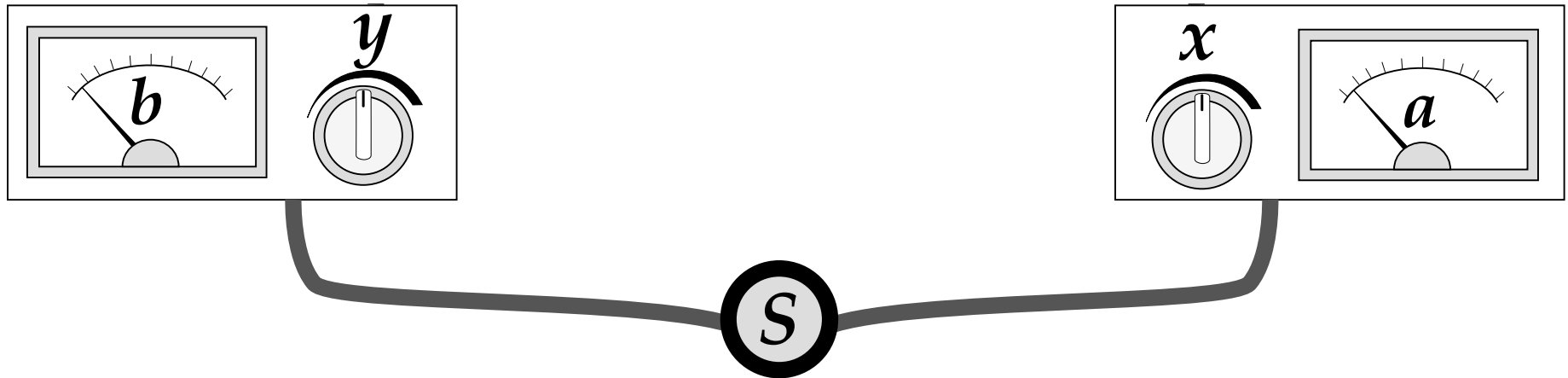
These are amazing experiments!

But none of them was designed to fully address the “freedom-of-choice” loophole

A cosmic Bell test will attempt to do so

We are still very far from a definitive “loophole free” experiment

EPR / BELL TESTS



S = Source of Entangled Particles

x, y = *Settings*

a, b = *Outcomes*

Big question: *Are non-quantum, local-realist, 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.
Well defined states are a prerequisite for deterministic dynamics connecting states.*

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 (Setting Independence / Free Will)

*Detector settings choices independent of any events in their shared past light cones.
Observers can choose settings “freely”. Choices only correlated with future LCs.*

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): $S_{\max} = 2\sqrt{2}$

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

BELL TEST RESULTS

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

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

Real Experiments:

$S_{\max} > 2 \rightarrow$ **At least one of 1,2,3,4 are false!**

Usual Story:

Experiments falsify “local realism” (2 or 1 or both).

Local HV theories ruled out. QM non-local, and/or non-realist.

Another Story:

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

Loopholes: Relax fair sampling or freedom! (3 and/or 4 false)

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

BELL'S THEOREM LOOPHOLES

A. Locality Loophole

Hidden communication between parties

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

Closing Method?

Spacelike separated measurements

B. Detection Loophole

Measured sub-sample not representative

CLOSED for atoms: **Rowe+2001**, superconducting qubits:

Ansmann+2009, photons: **Giustina+2013, Christensen+2013**

High efficiency detectors

C. Freedom of Choice Loophole

Settings correlated with local hidden variables

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

Spacelike separated settings, measurements (QRNGs)

TOWARD A LOOPHOLE FREE TEST

CLOSED Locality & Detection (electrons)

Hensen+2015 (Delft)

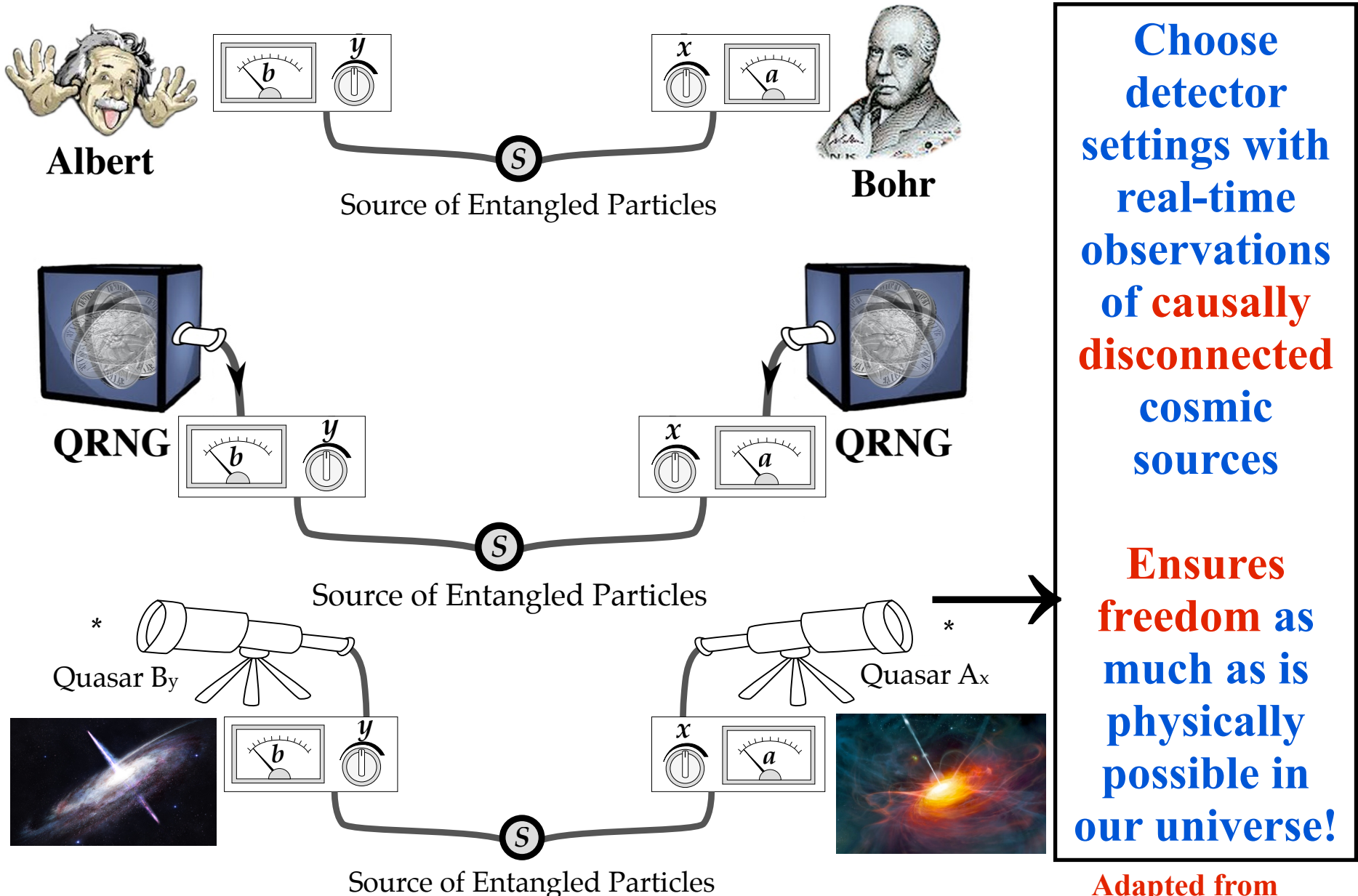
CLOSED Locality & Detection (photons)

Giustina+2015 (Vienna)
Shalm+2015 (NIST)

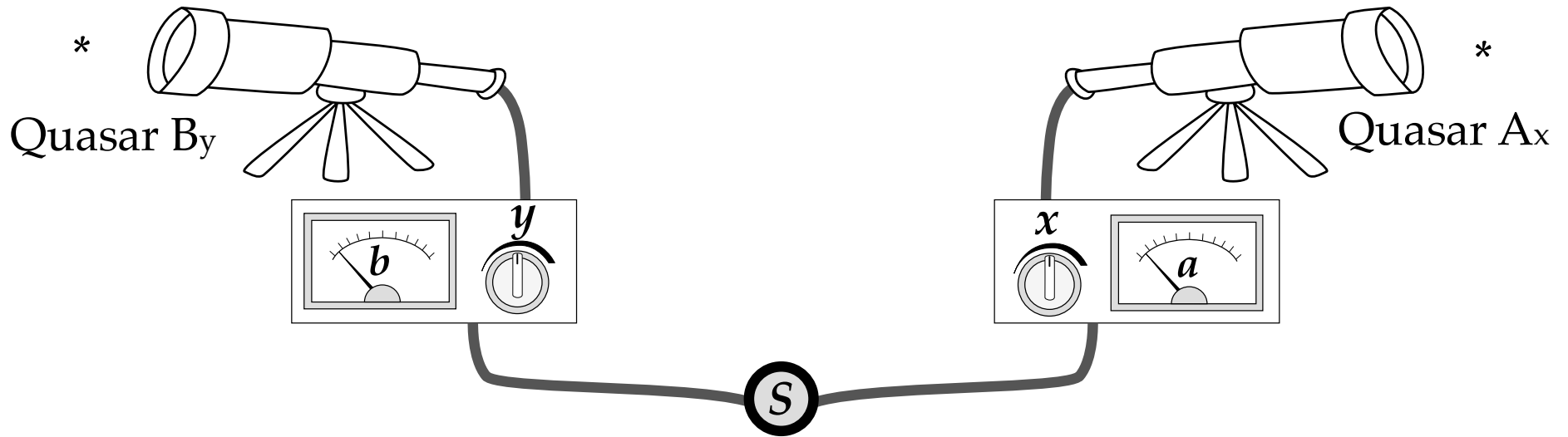
CLOSED Locality & Freedom (photons)

Scheidl+2010 (Vienna)

CHOOSING SETTINGS x, y



COSMIC BELL TEST

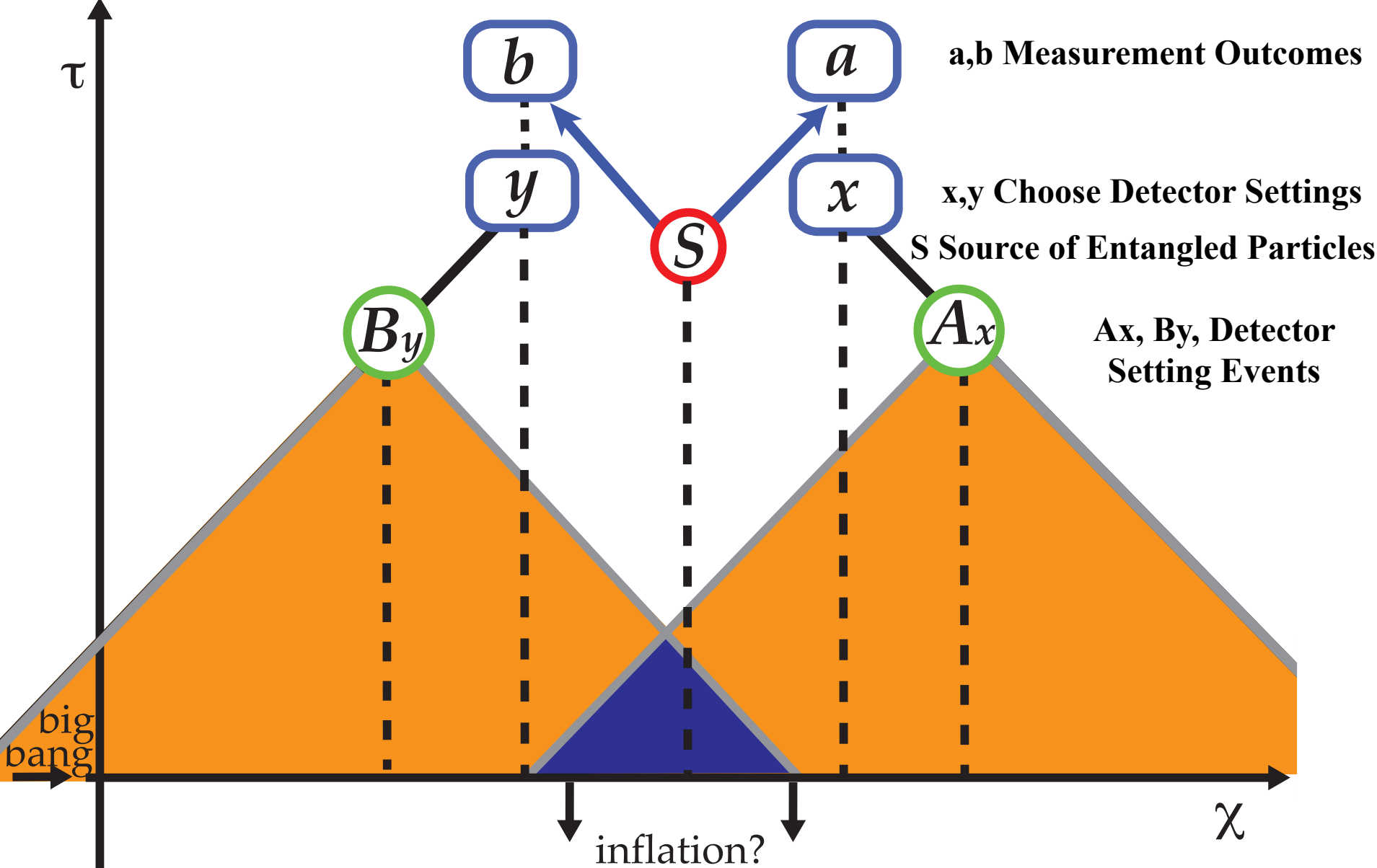


S = Source of Entangled Particles

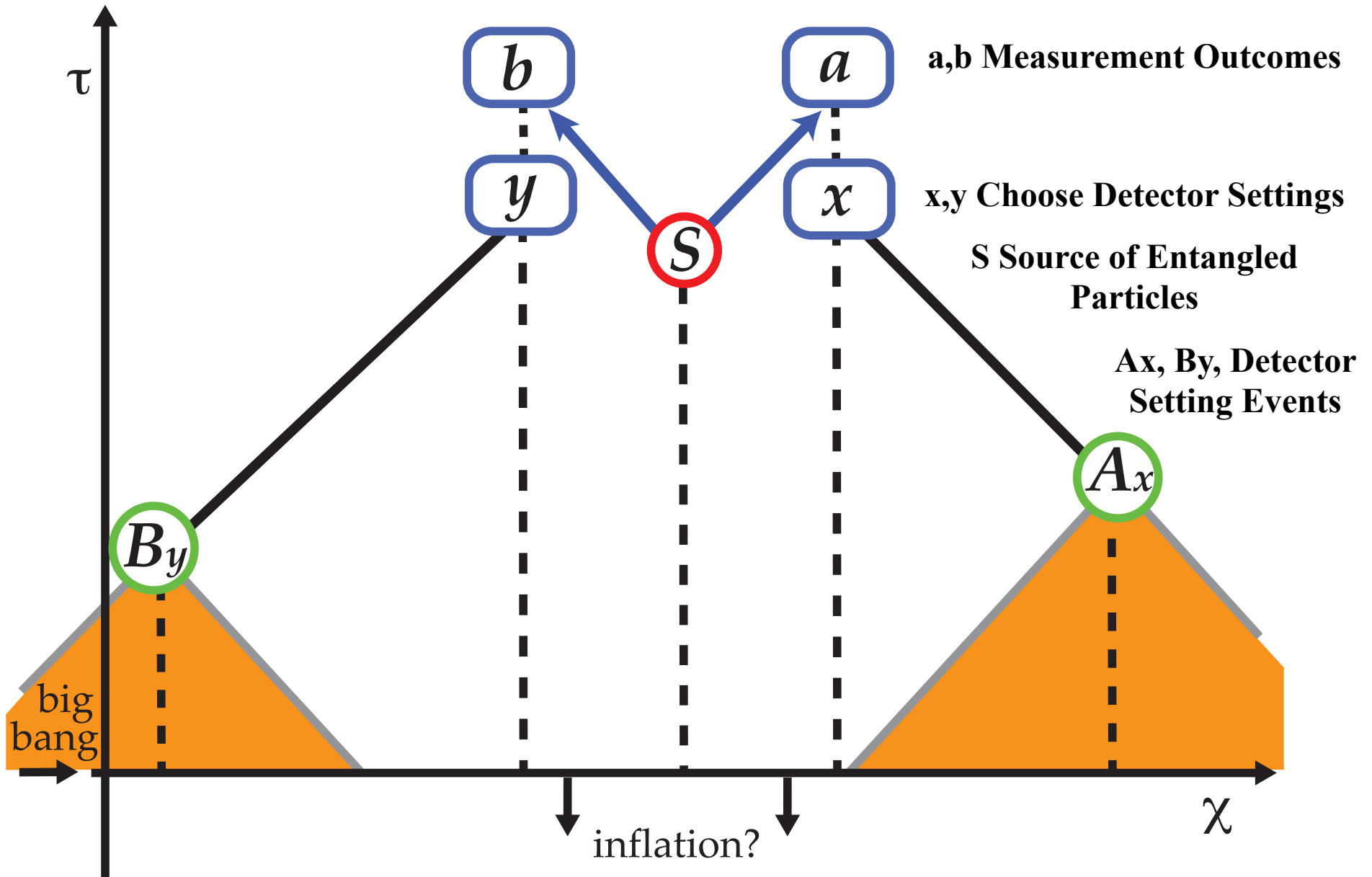
x, y = *Settings*

a, b = *Outcomes*

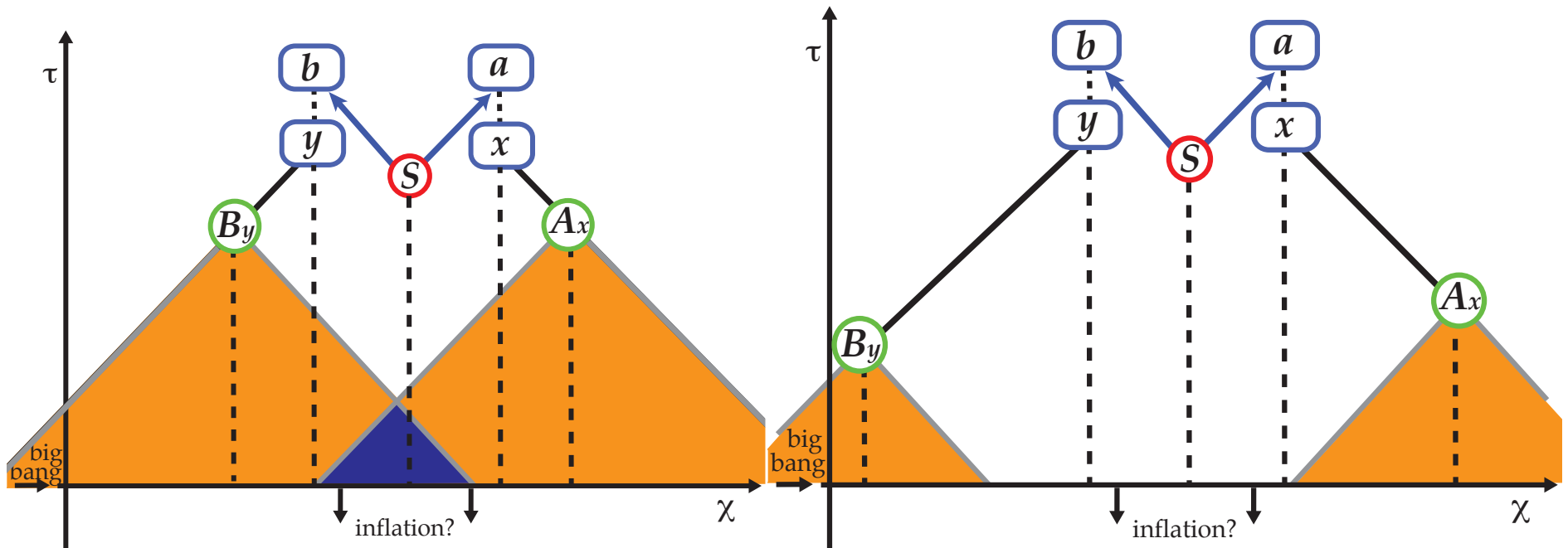
BELL TEST CONFORMAL DIAGRAM



COSMIC BELL CONFORMAL DIAGRAM



COMPARING CONFORMAL DIAGRAMS



STOCHASTIC VS. DETERMINISTIC

Is randomness intrinsic or apparent?

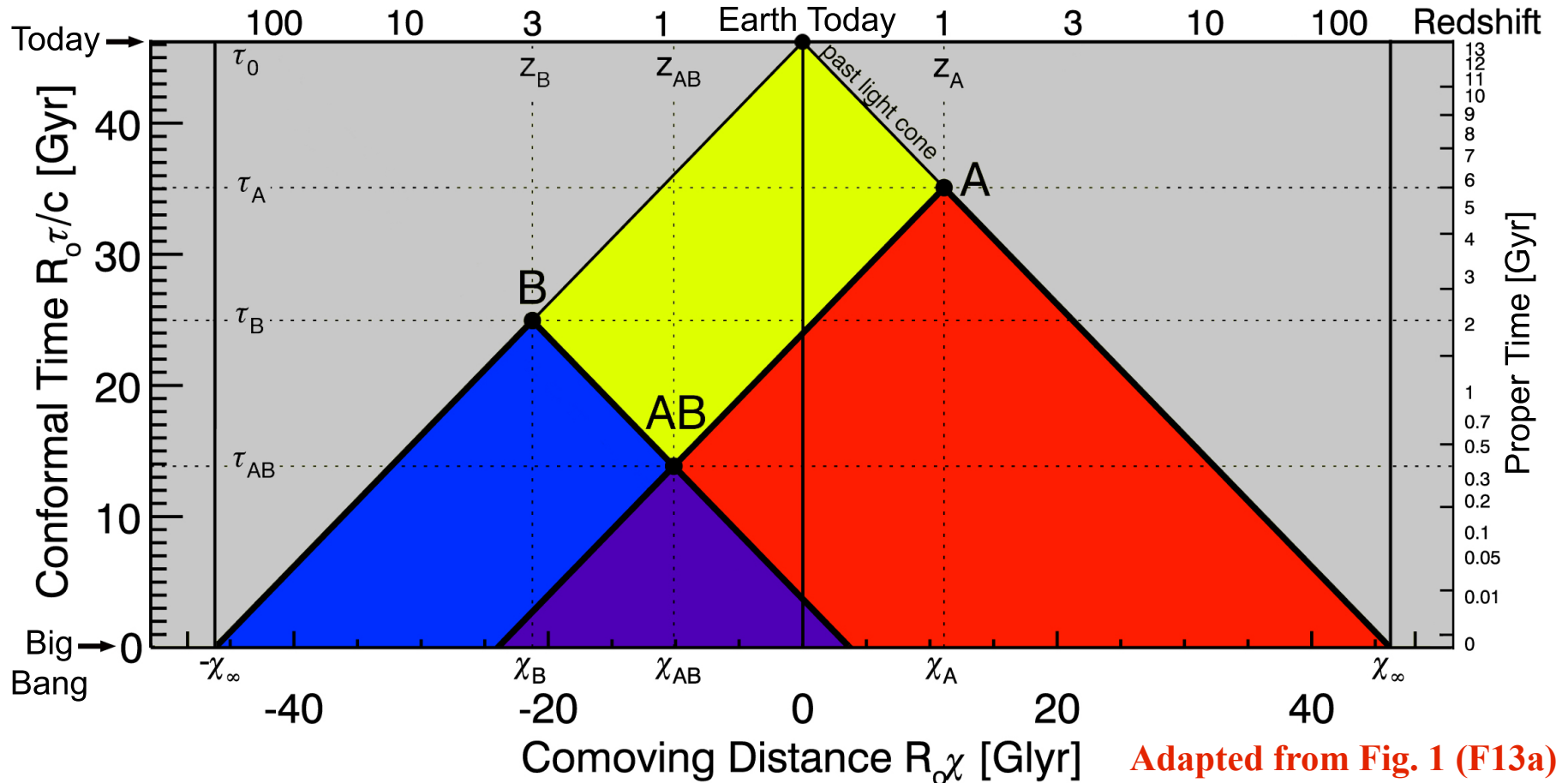
Problem with stochastic models: Don't assume quantum randomness if you are trying to test quantum randomness!

Ignores common causes or past interactions by fiat.

Deterministic models are testable with additional assumptions

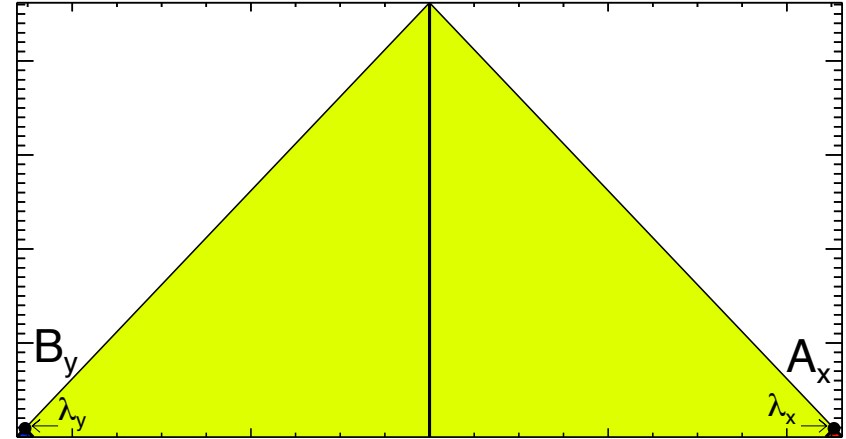
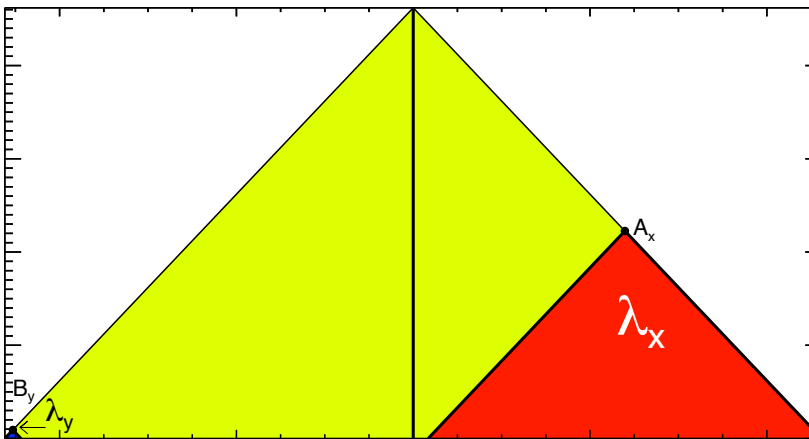
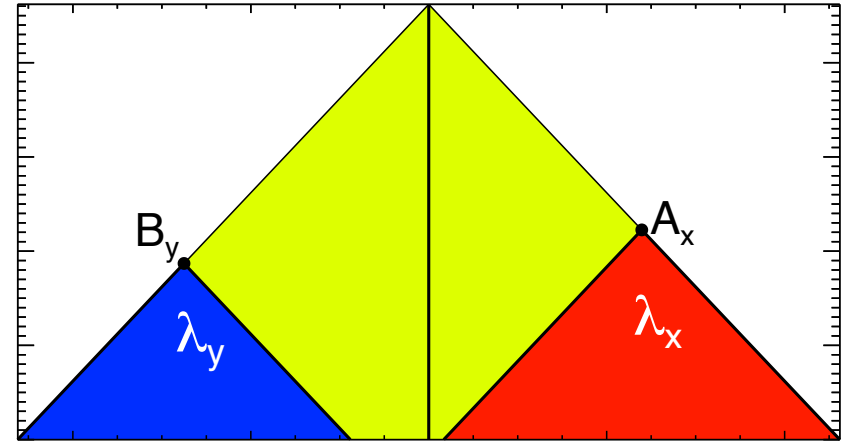
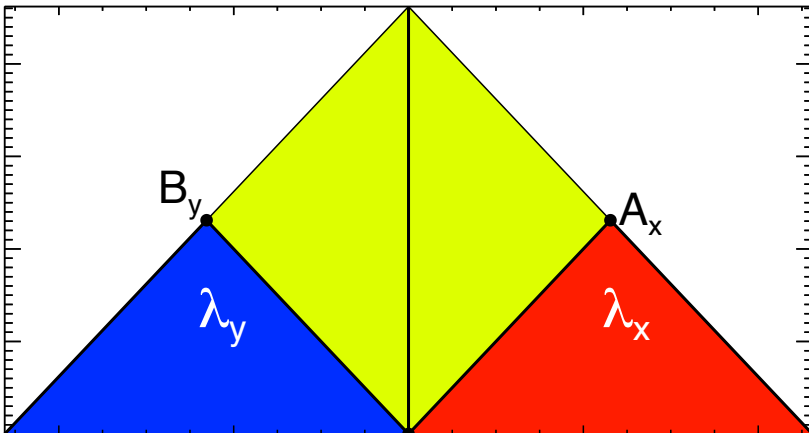
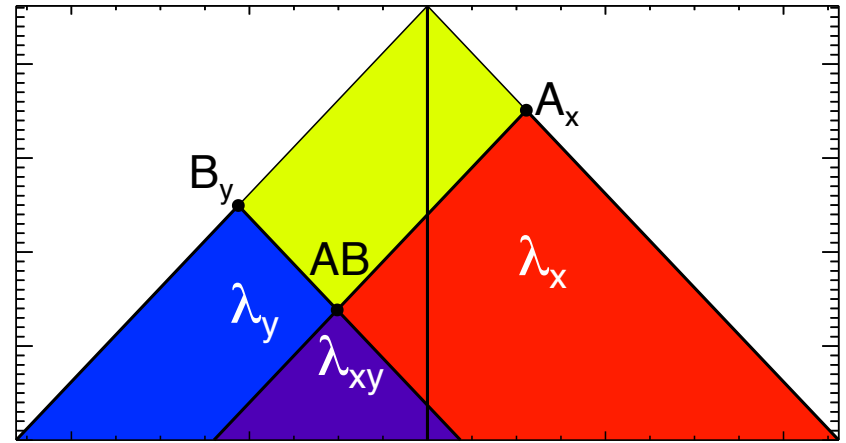
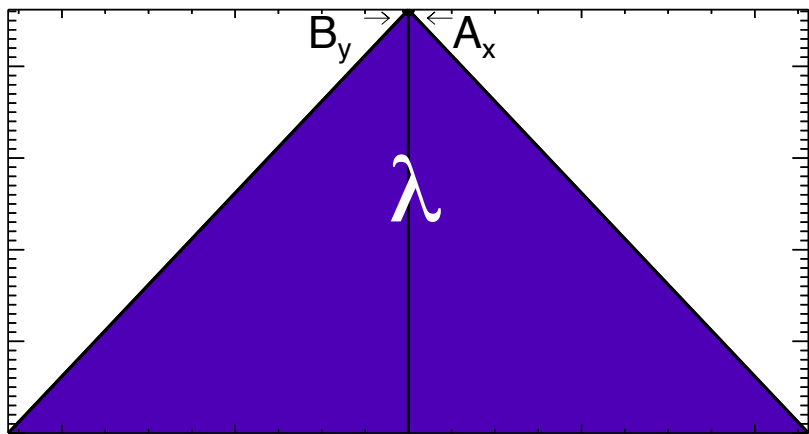
Relaxing setting independence does not imply superdeterminism

DO TWO COSMOLOGICAL EVENTS HAVE A SHARED PAST?



Adapted from Fig. 1 (F13a)

Since the hot big bang at the end of inflation



ARTICLES AND PAPERS

Popular articles

Delft experiment

http://mobile.nytimes.com/2015/10/22/science/quantum-theory-experiment-said-to-prove-spooky-interactions.html?_r&_r=1

Vienna experiment

http://www.myscience.at/en/news/2015/quantum_physics_confirms_spooky_action_at_a_distance-2015-univie

Vienna and NIST experiments (they wrote about the wrong Vienna experiment!)

<http://www.cnet.com/news/physicists-prove-einsteins-spooky-quantum-entanglement/>

Papers

Hensen+2015 (Delft)

<http://www.nature.com/nature/journal/v526/n7575/full/nature15759.html>

<http://arxiv.org/abs/1508.05949>

Giustina+2015 (Vienna)

<http://arxiv.org/abs/1511.03190>

Shalm+2015 (NIST)

<http://arxiv.org/abs/1511.03189>