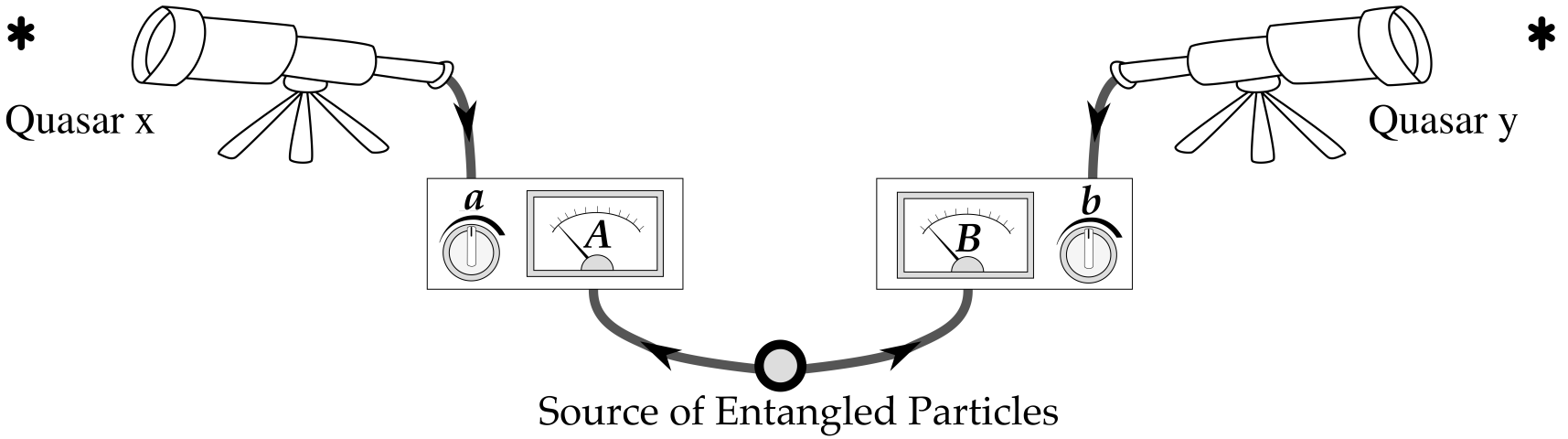

TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH ASTRONOMICAL OBSERVATIONS

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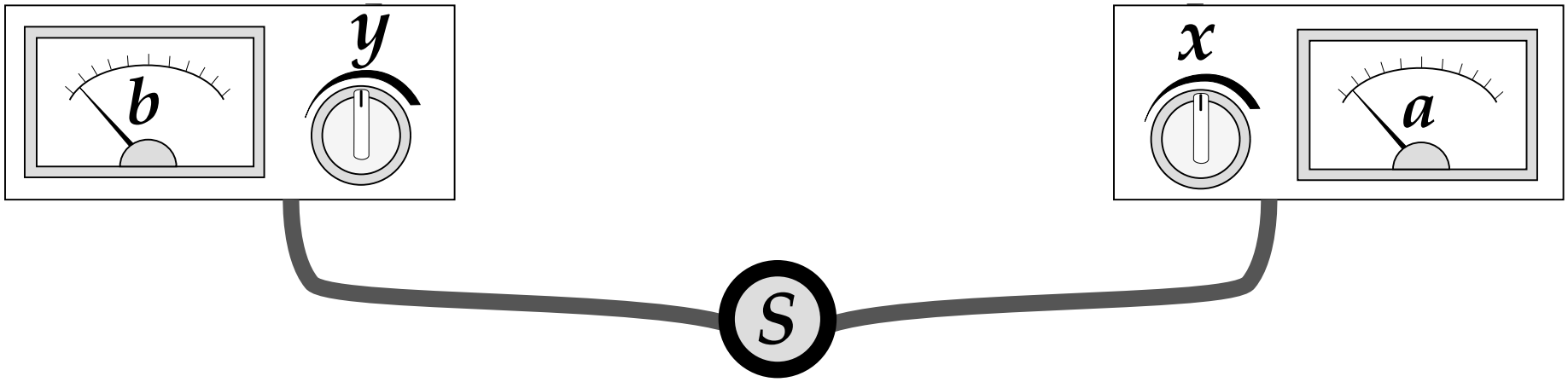
BELL TESTS



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

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

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

$S_{max} > 2$ → At least one of 1,2,3,4 are 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

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

Closing Method?

Spacelike separated measurements

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 Loophole

Settings correlated with local hidden variables

partially for photons: **Scheidl+2010**

Spacelike separated settings, measurements (QRNGs)

TOWARD A LOOPHOLE FREE TEST

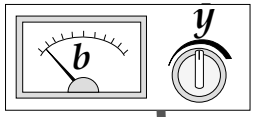
Locality & Detection (electrons) — **Hensen+2015 (Delft)**

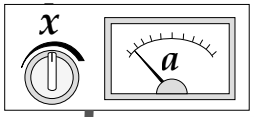
Locality, Detection, & *Freedom* (photons) — **Giustina+2015 (Vienna)**, **Shalm+2015 (NIST)**

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

CHOOSING DETECTOR SETTINGS

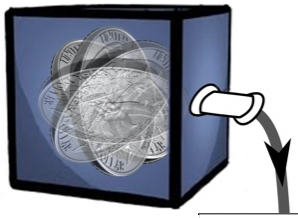
Albert



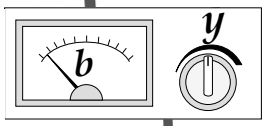


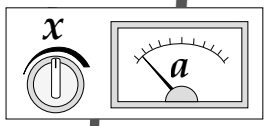
Bohr

Source of Entangled Particles



Quantum Random Number Generator

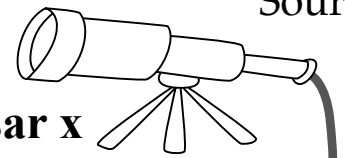




Quantum Random Number Generator

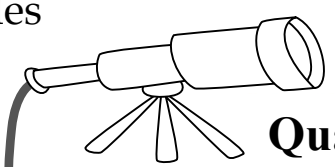
Source of Entangled Particles

*

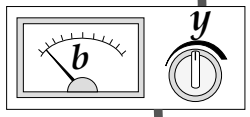


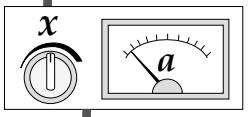
Quasar x

*



Quasar y





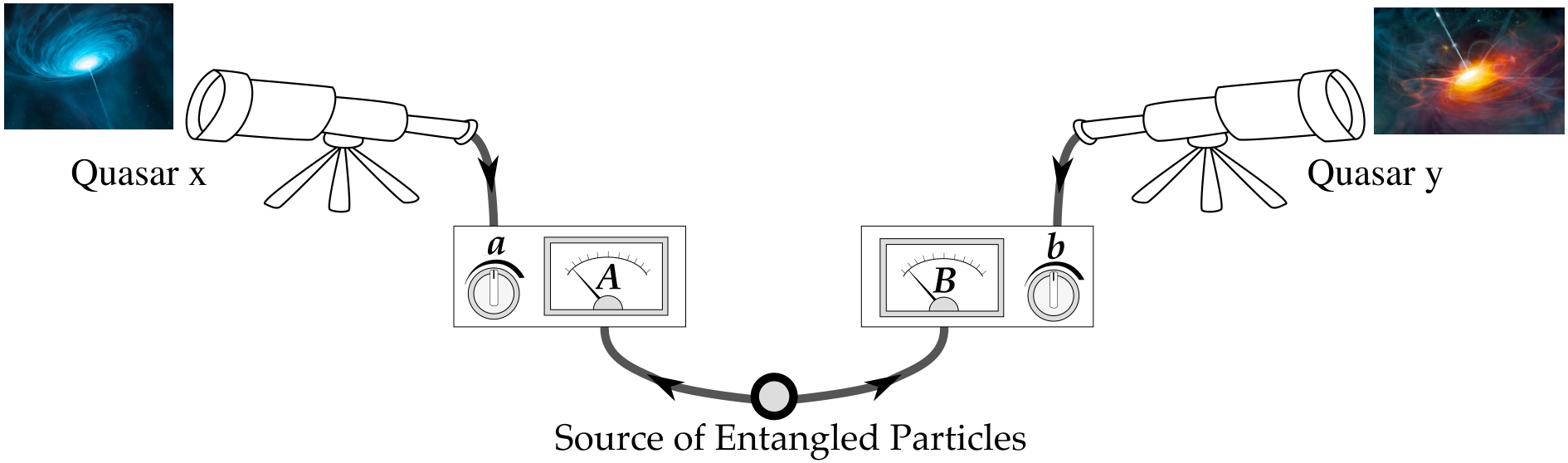
Source of Entangled Particles

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

Ensures freedom as much as is physically possible in our universe!

Adapted from Fig. 1 (GFK14)

COSMIC BELL TEST



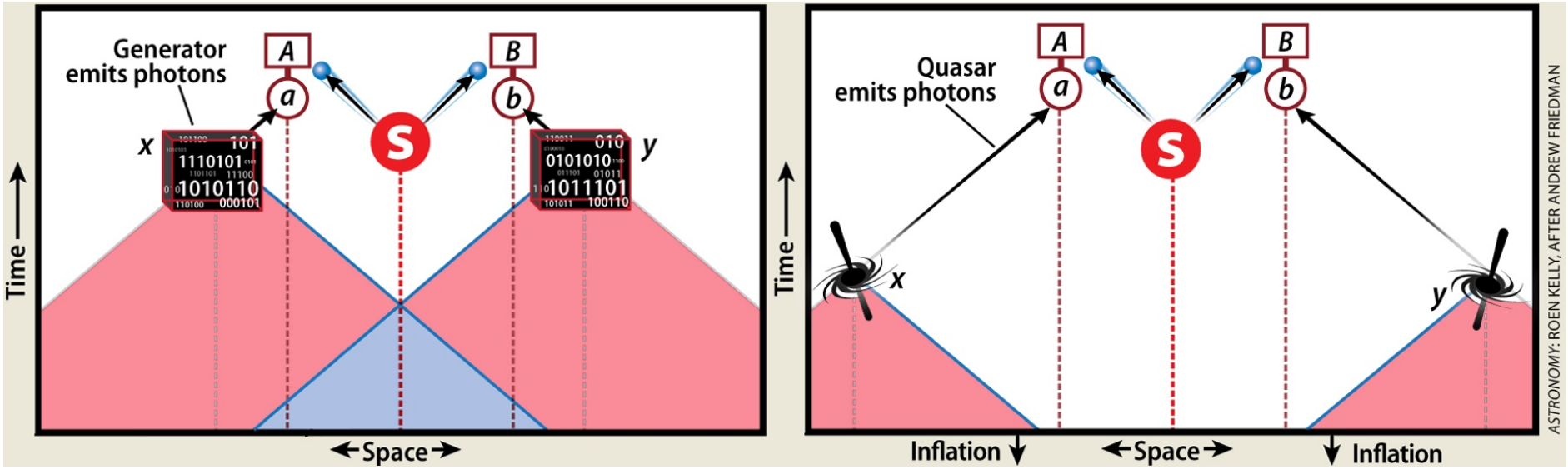
Let the Universe decide how to set up experiment!

Use quasars as cosmic random number generators

SPACE-TIME DIAGRAMS

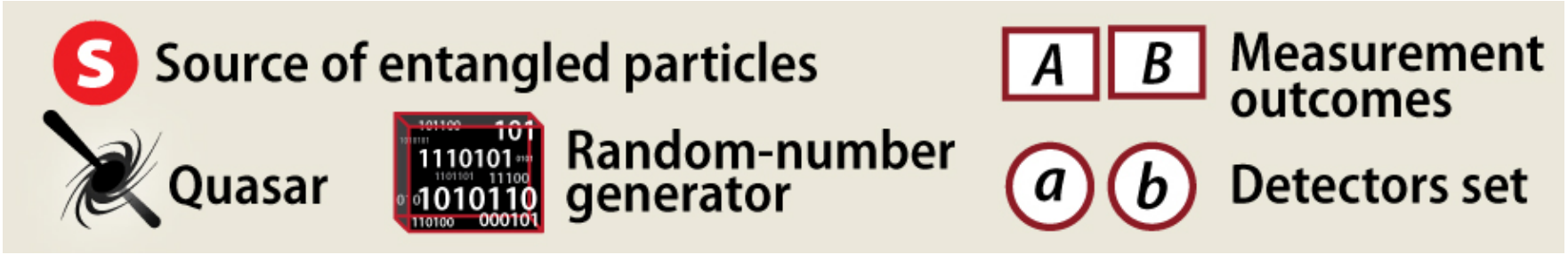
Standard Bell Test

Cosmic Bell Test

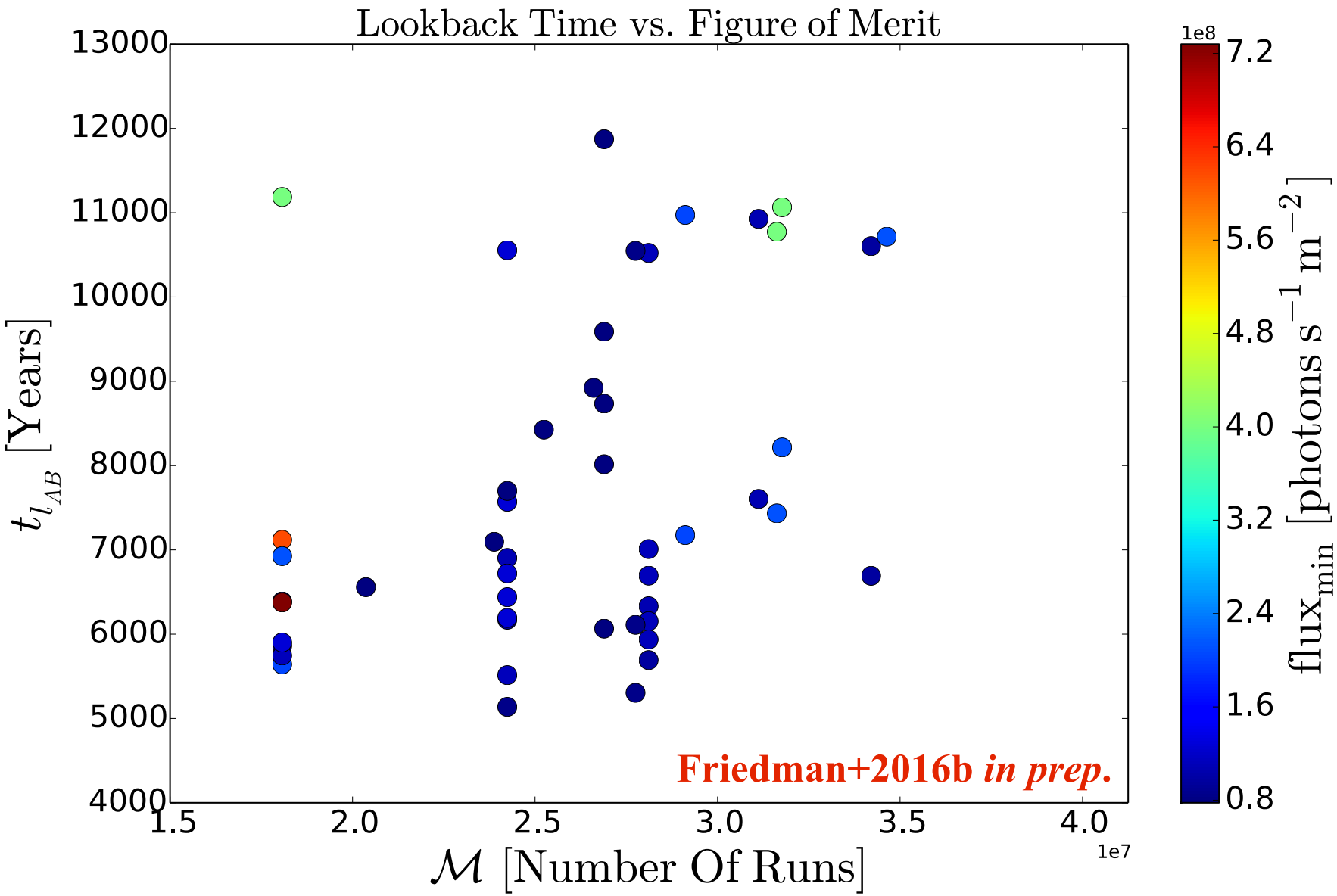


Past light cones from random number generators overlap milliseconds before test.

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



OPTIMAL HIPPARCOS STARS



POSSIBLE OUTCOMES

Expected

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

Unexpected

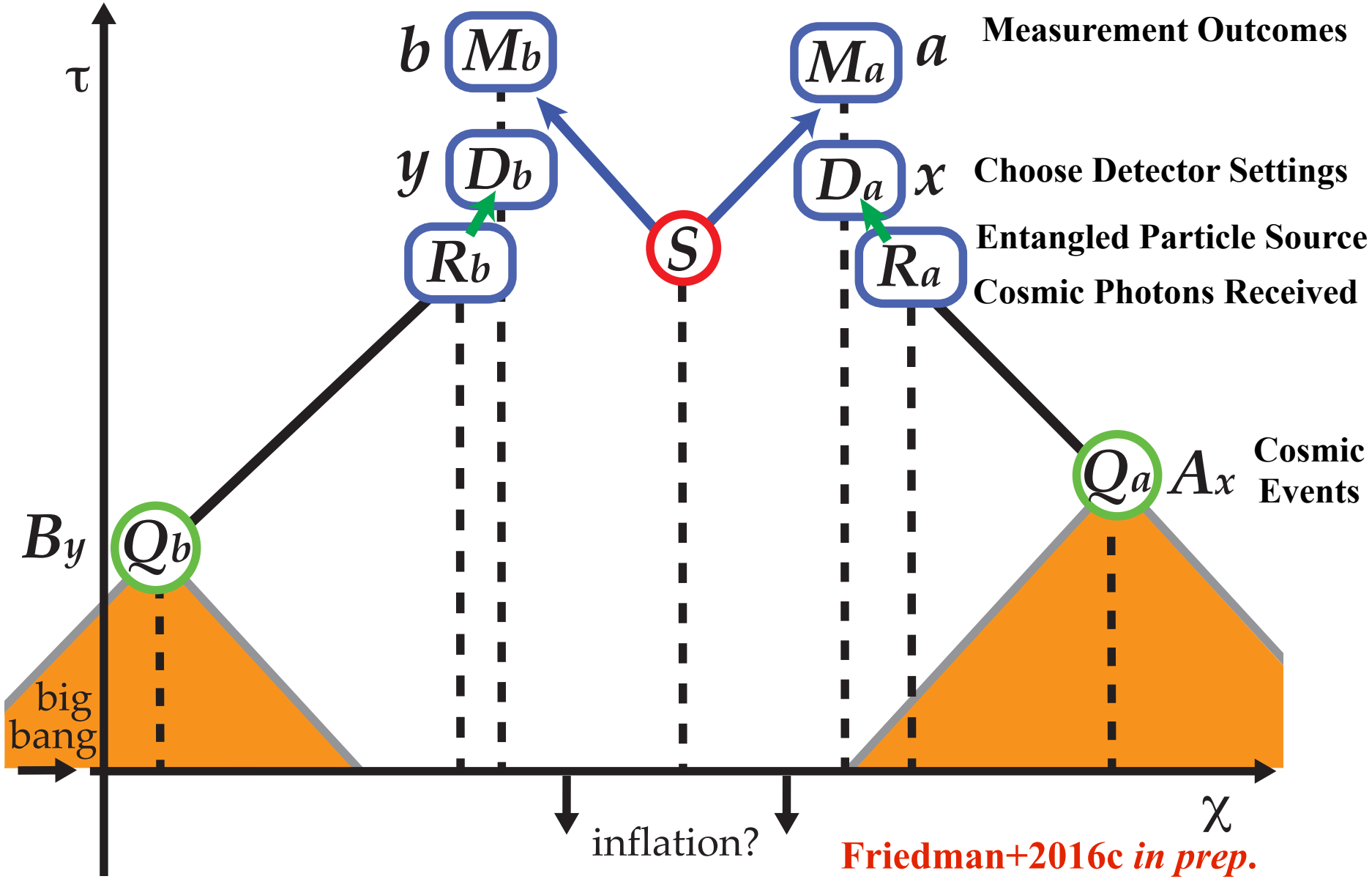
Degree of Bell violation depends on extent of shared causal past of cosmic sources.

Strangest

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

Implications for inflation? Quantum gravity?

CAUSAL ALIGNMENT



Friedman+2016c *in prep.*

CAUSAL ALIGNMENT

Modified version of locality loophole

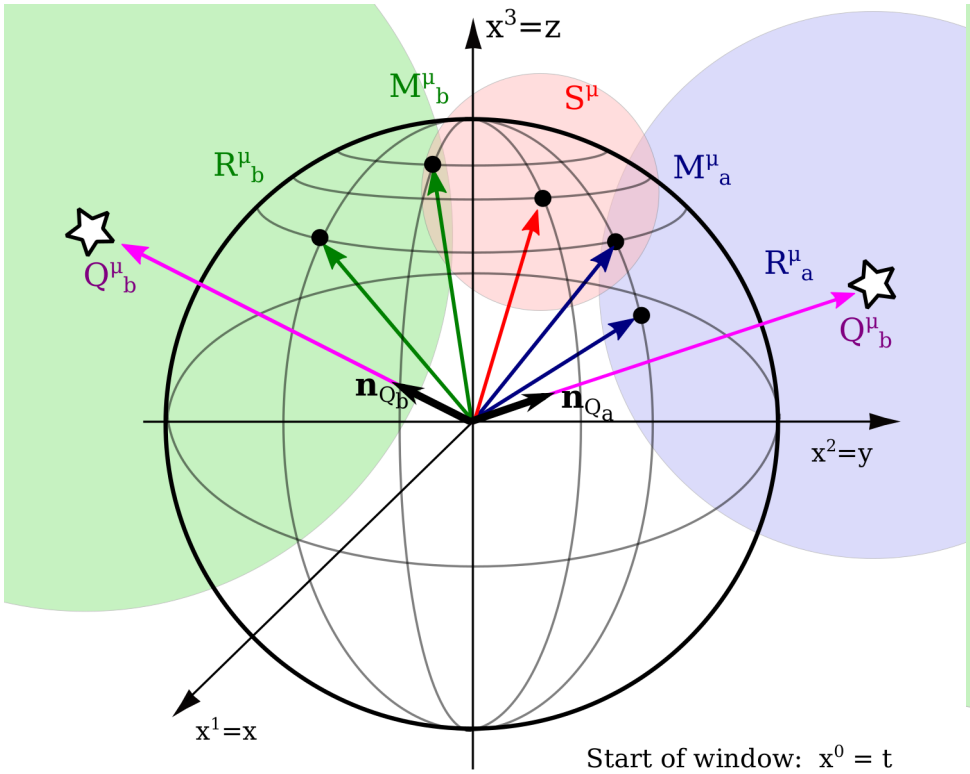
Space-like separate:
measurement outcomes from each other
measurement outcome 1 from detector setting 2 (and vice versa)

Must space-like separate new pairs of events

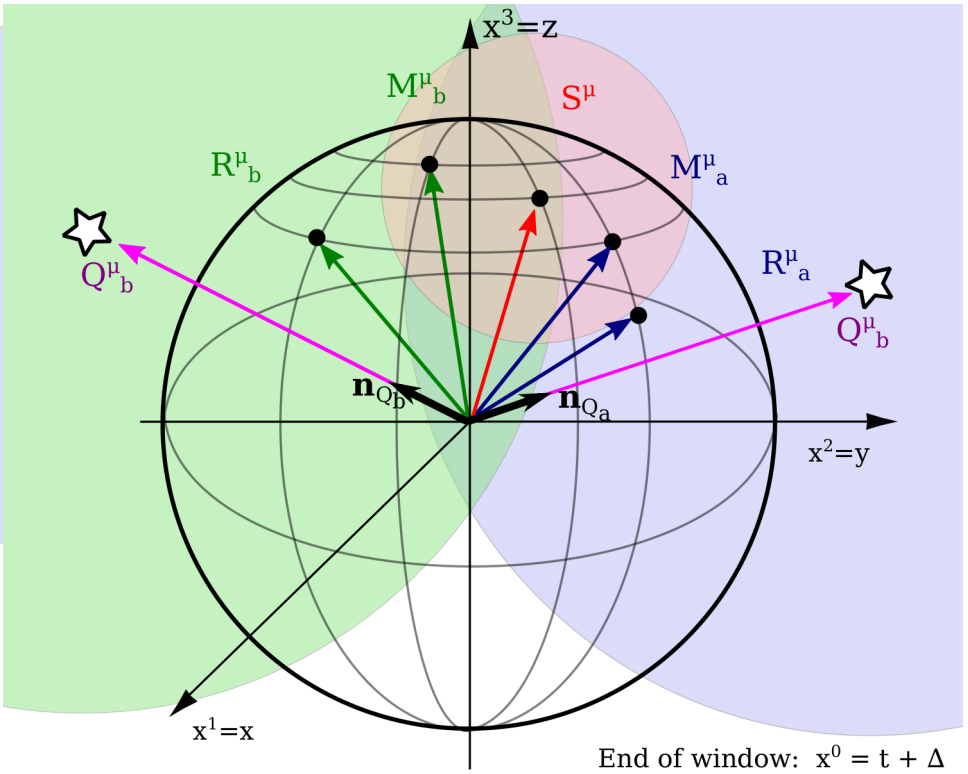
Need causal wavefront from quasar 1 to hit telescope 1 before telescope 2 or EPR source

3D SPACE-TIME DIAGRAMS

Valid light cones - fresh settings



Invalid light cones - stale settings



Start of window: detectors both set by stars and EPR photons are measured

End of window: Star b causal wavefront (purple) reaches opposite side measurement device (green)

purple/green: detector settings, red: EPR source Credit: Calvin Leung (HMC)

CAUSAL ALIGNMENT

How long are settings valid on each side with fresh random #s?

$$\Delta_a = \hat{n_{Q_a}} \cdot (\vec{r}_a - \vec{m}_b) + n\left[|\vec{m}_a - \vec{s}| - |\vec{m}_b - \vec{s}|\right] - n_a|\vec{r}_a - \vec{m}_a| - \kappa_a$$

$$\Delta_b = \hat{n_{Q_b}} \cdot (\vec{r}_b - \vec{m}_a) + n\left[|\vec{m}_b - \vec{s}| - |\vec{m}_a - \vec{s}|\right] - n_b|\vec{r}_b - \vec{m}_b| - \kappa_b$$

If either Delta < 0, configuration out of causal alignment.

$\hat{n_{Q_a}}$ $\hat{n_{Q_b}}$ **Unit vectors from Earth center to cosmic source**

Spatial 3-vectors $\vec{r}_a$ $\vec{r}_b$ **Telescopes** $\vec{s}$ **EPR source**

$\vec{m}_a$ $\vec{m}_b$ **EPR measurements**

Index of refraction n **Air** n_a n_b **Fiber from telescope to EPR detector**

Processing Delays κ_a κ_b **Telescope optics, FPGA board, Pockell Cell switching, etc...**

NOISE LOOPHOLE

Need triggers by genuine cosmic photons, not local "noise" photons.
Need sufficient signal-to-noise from cosmic sources.

$$f_{\rm n} = 1 - f \approx 1 - \left(\frac{f_{\rm r}}{1 + SNR_1^{-1}}\right)\left(\frac{f_{\rm r}}{1 + SNR_2^{-1}}\right) = 1 - f_{\rm r}^2 f_{\rm c}$$

noise fraction, fidelity of random number generators

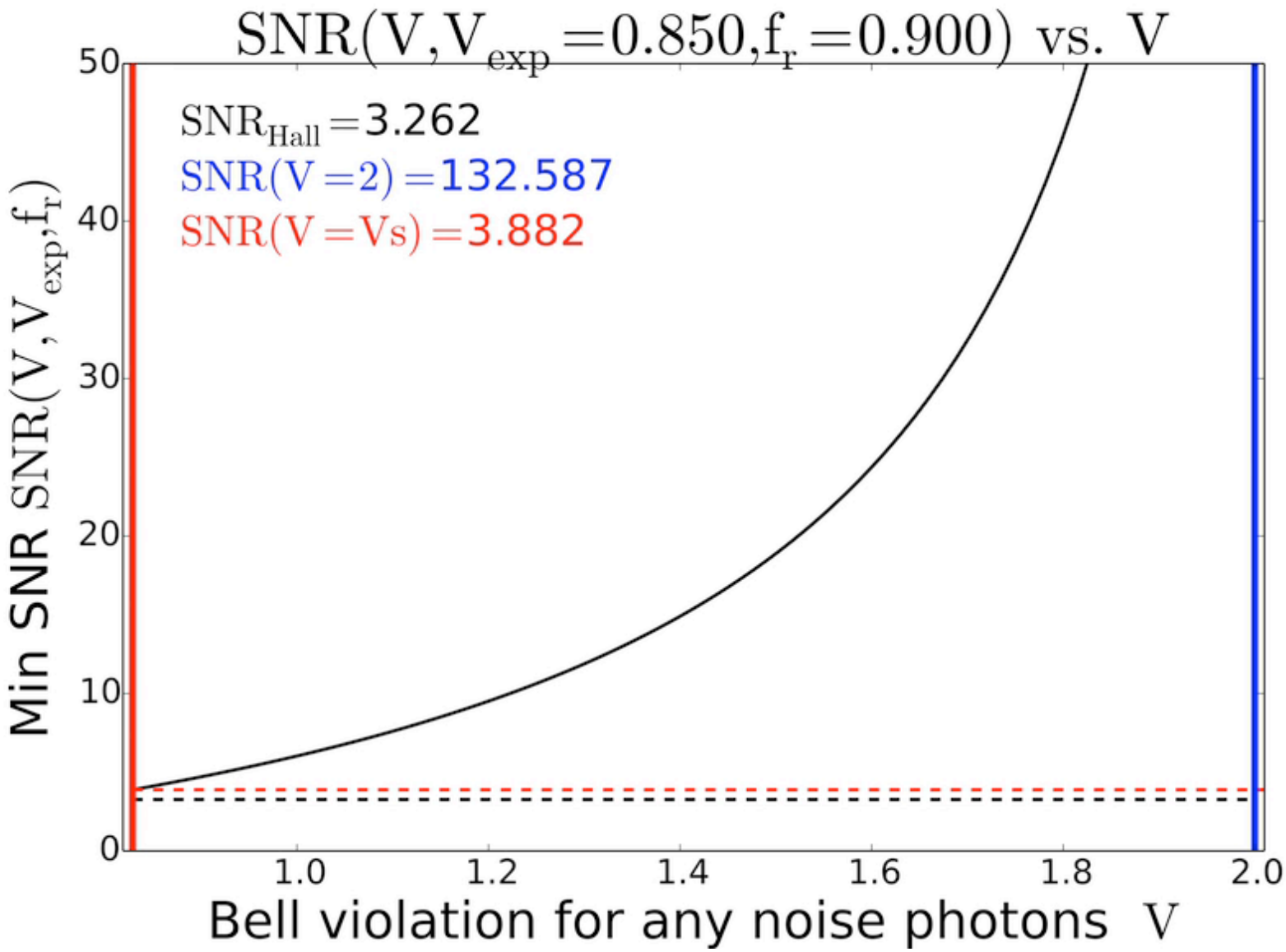
$$S = 2f + 4(1 - f) = 2f + 4 - 4f = 4 - 2f$$

$$S = 4 - 2f \leq \mathcal{V}_{\rm exp} 2\sqrt{2}$$

$$\rightarrow f \geq 2 - \mathcal{V}_{\rm exp}\sqrt{2} \gtrsim 59\%$$

experimental visibility

NOISE LOOPHOLE



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