Cosmic Bell Test: Measurement Settings from Milky Way Stars

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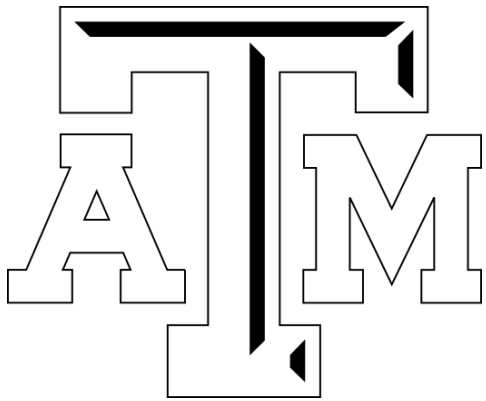
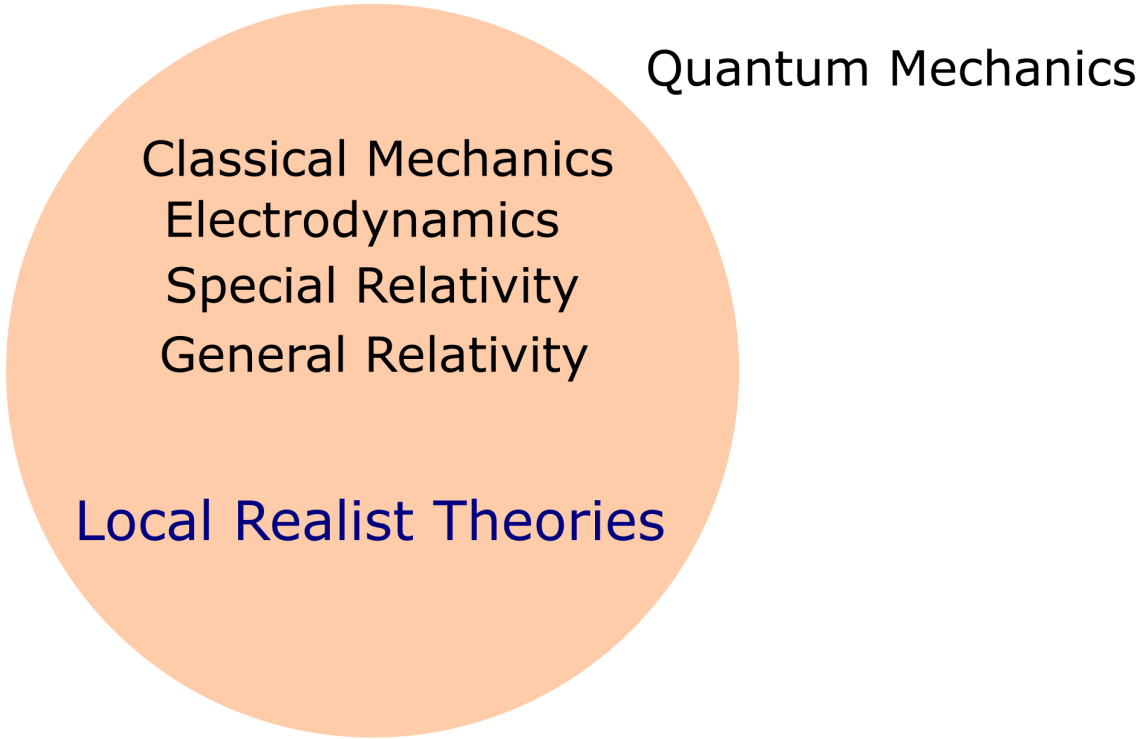


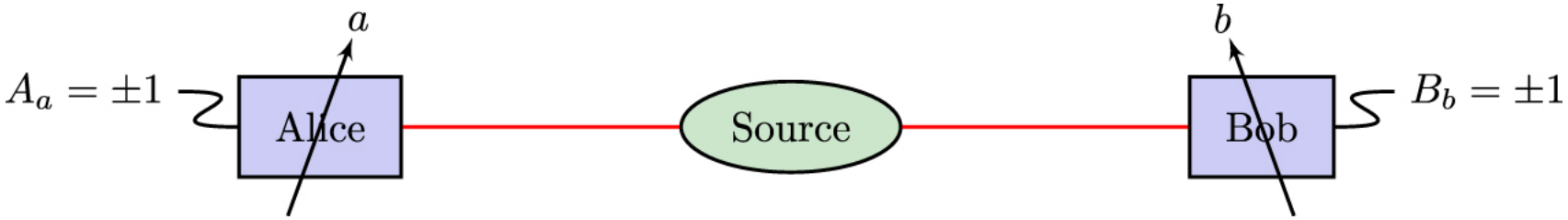
Local Realism



Definitions

- **Realism:** Physical properties are defined prior to and independent of measurement.
- **Local:** Physical influences cannot propagate faster than the speed of light.

Einstein-Podolsky-Rosen Paradox



Larsson [2014]

- A measurement preformed by Alice with settings a affects the result of the measurement preformed by Bob with settings b

In 1935 EPR write:

"This makes the reality of P and Q depend upon the process of measurement carried out on the first system, which does, not disturb the second system in any way. No reasonable definition of reality could be expected to permit this." Einstein et al. [1935]

Bell's Inequality

EPR proposed the existence of *local hidden variables* to resolve the paradox. In 1971 Bell proposed a statical consequence of these variables ($\lambda \in \Lambda$) through expectation values of an experiment

$$E(A) = \int_{\Lambda} A(\lambda)\rho(\lambda)d\lambda$$

Bell's Inequality

Enforcing the condition of local realism Bell used the following assumptions

Realism

$$A(a, b, \lambda) \qquad B(a, b, \lambda)$$

Random variables A and B represent measurements and depend on Alice's local settings (a), Bob's local settings (b), and hidden variable (λ).

Locality

$$A_i(\lambda) \equiv A(a_i, b_1, \lambda) = A(a_i, b_2, \lambda)$$

$$B_i(\lambda) \equiv B(a_1, b_i, \lambda) = B(a_2, b_i, \lambda)$$

Measurement outcomes are independent of the remote setting

to find the inequality

$$|E(A_2B_1) - E(A_2B_2)| \leq 1 + E(A_1B_2)$$

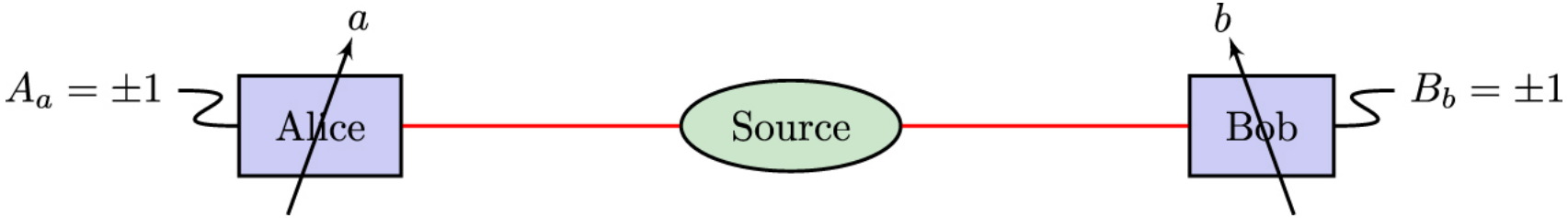
Clauser, Horne, Shimony, Holt (CHSH) Inequality

CHSH generalized the Bell inequality to by removing the assumption of perfect anticorrelation ($A_i = -B_i$) and lessing the outcome restriction to $|A_i| \leq 1$ and $|B_i| \leq 1$. The resulting inequality

$$|E(A_1B_1) + E(A_1B_2)| + |E(A_2B_1) - E(A_2B_2)| \leq 2$$

is experimentally realizable.

Locality (Freedom of Choice) Loophole



Larsson [2014]

In order to prove non-locality the experiment must be designed such that the measurement parameters a and b are set is such a way that there is no possibility of communication. This achieved by

- Selecting a and b within a fast enough time interval so that Alice and Bob are spacelike separated
- Randomizing a and b so that there is no "memory" effecting the measurement

Loophole

There could still be an event in the intersection of the past light cones of a and b that could cause a and b to "know" about each other.

Dealing with the Loophole: Stars!

Using the wavelength of light from stars in excess of 500 light years away from earth to set the measurement parameters.

Cosmic Bell Test: Measurement Settings from Milky Way Stars

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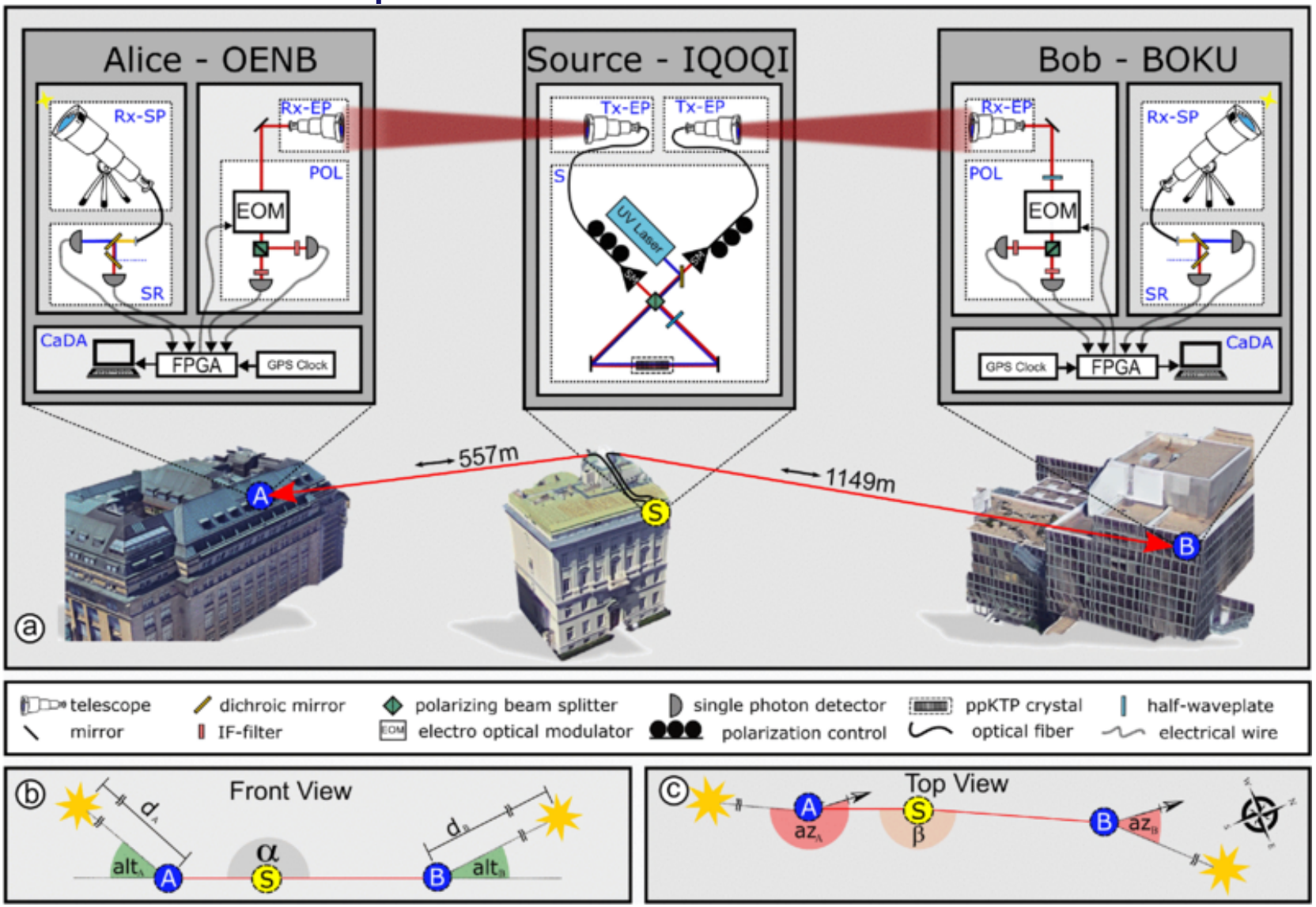
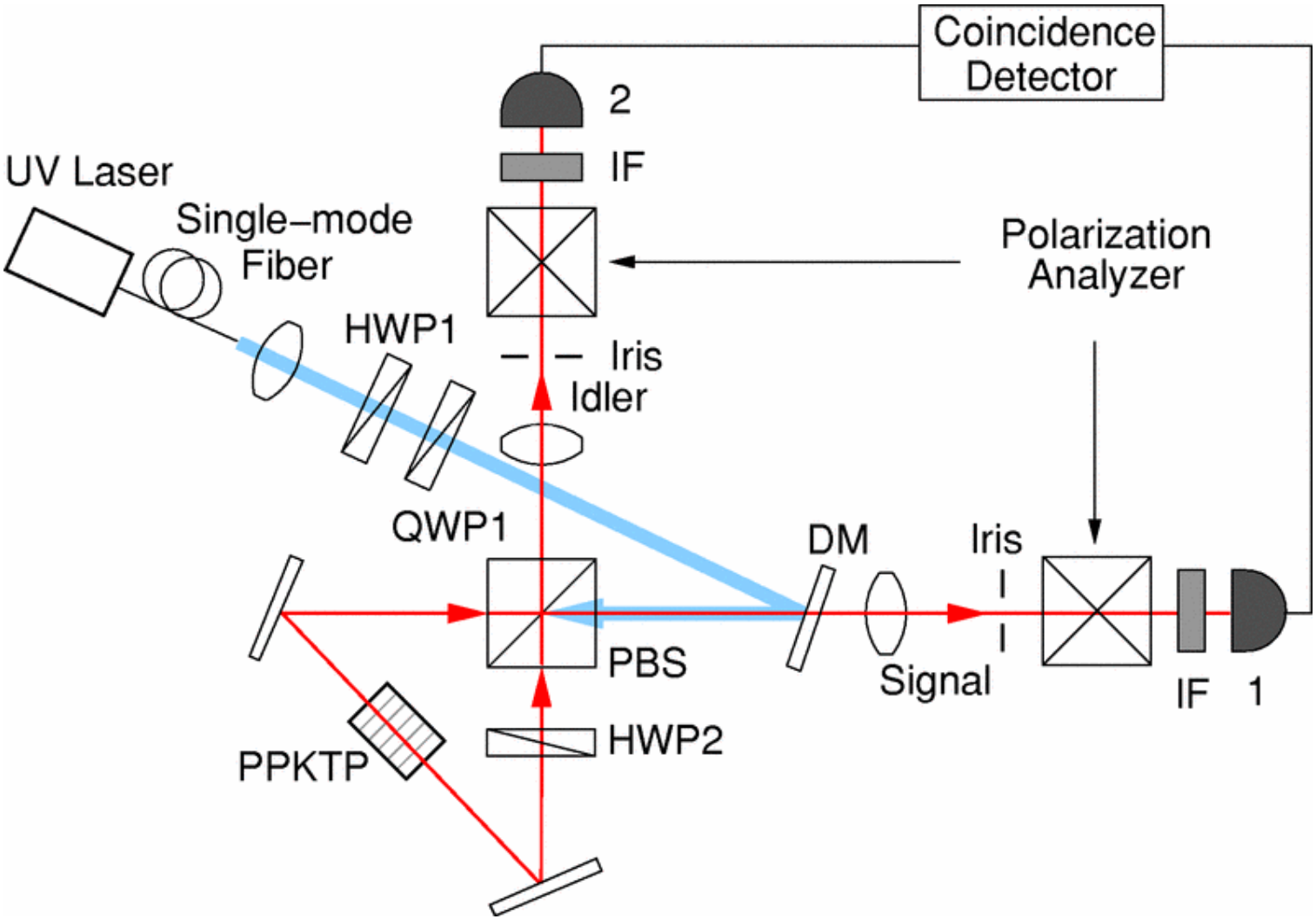
Experimental Setup



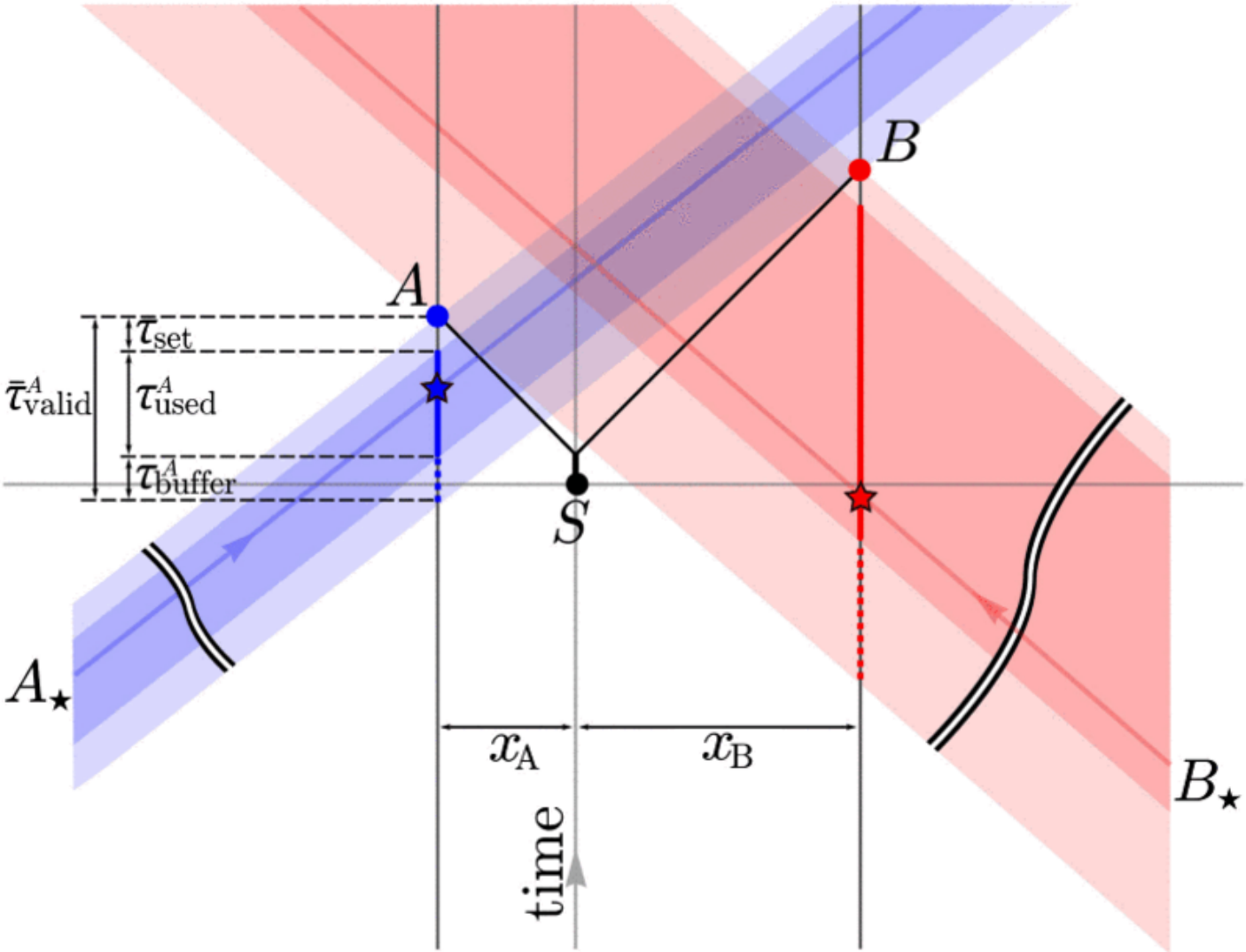
Handsteiner et al. [2016]

Sagnac Interferometer Entangled Photon Generator



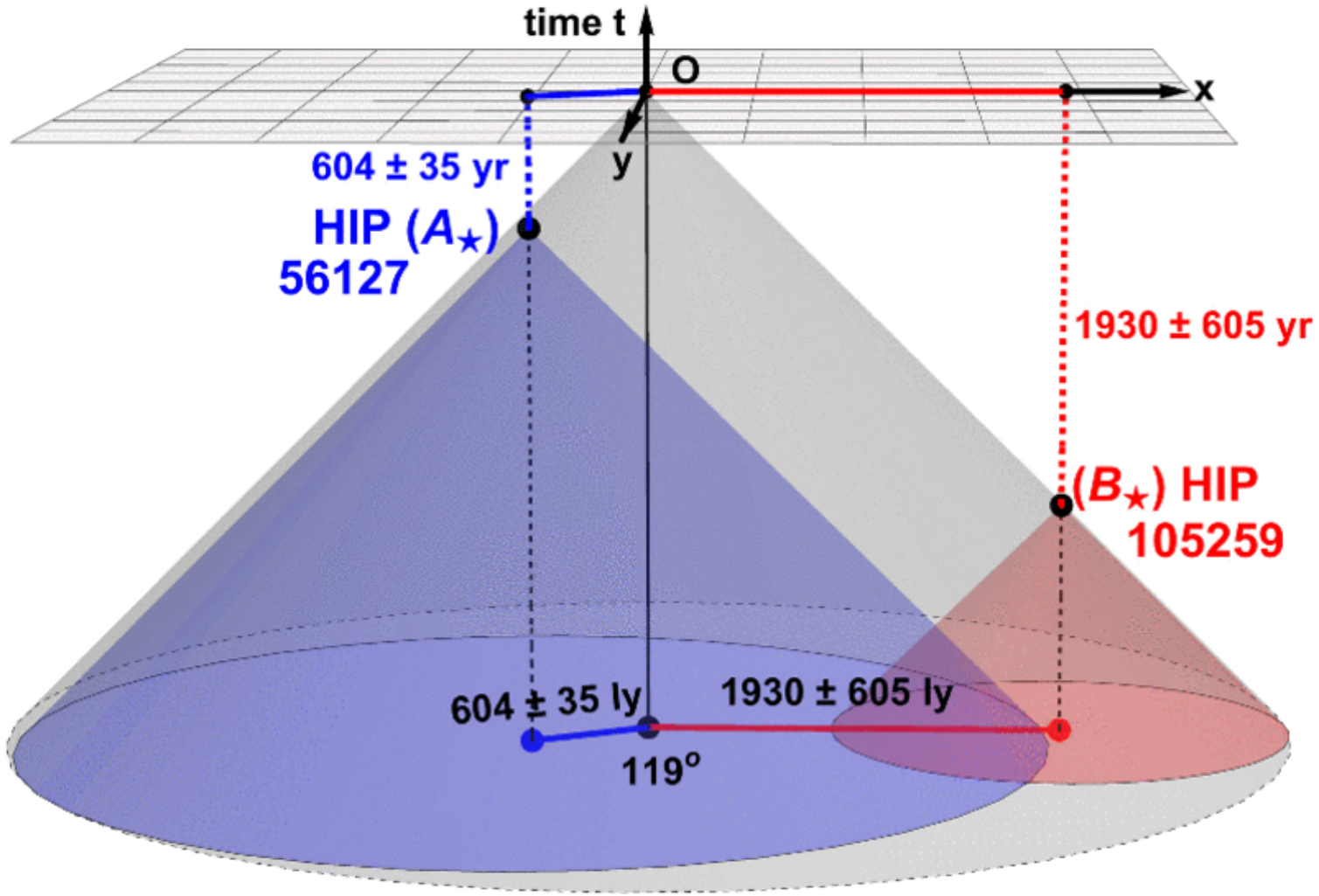
Kim et al. [2006]

Experimental Space-Time Diagram



Handsteiner et al. [2016]

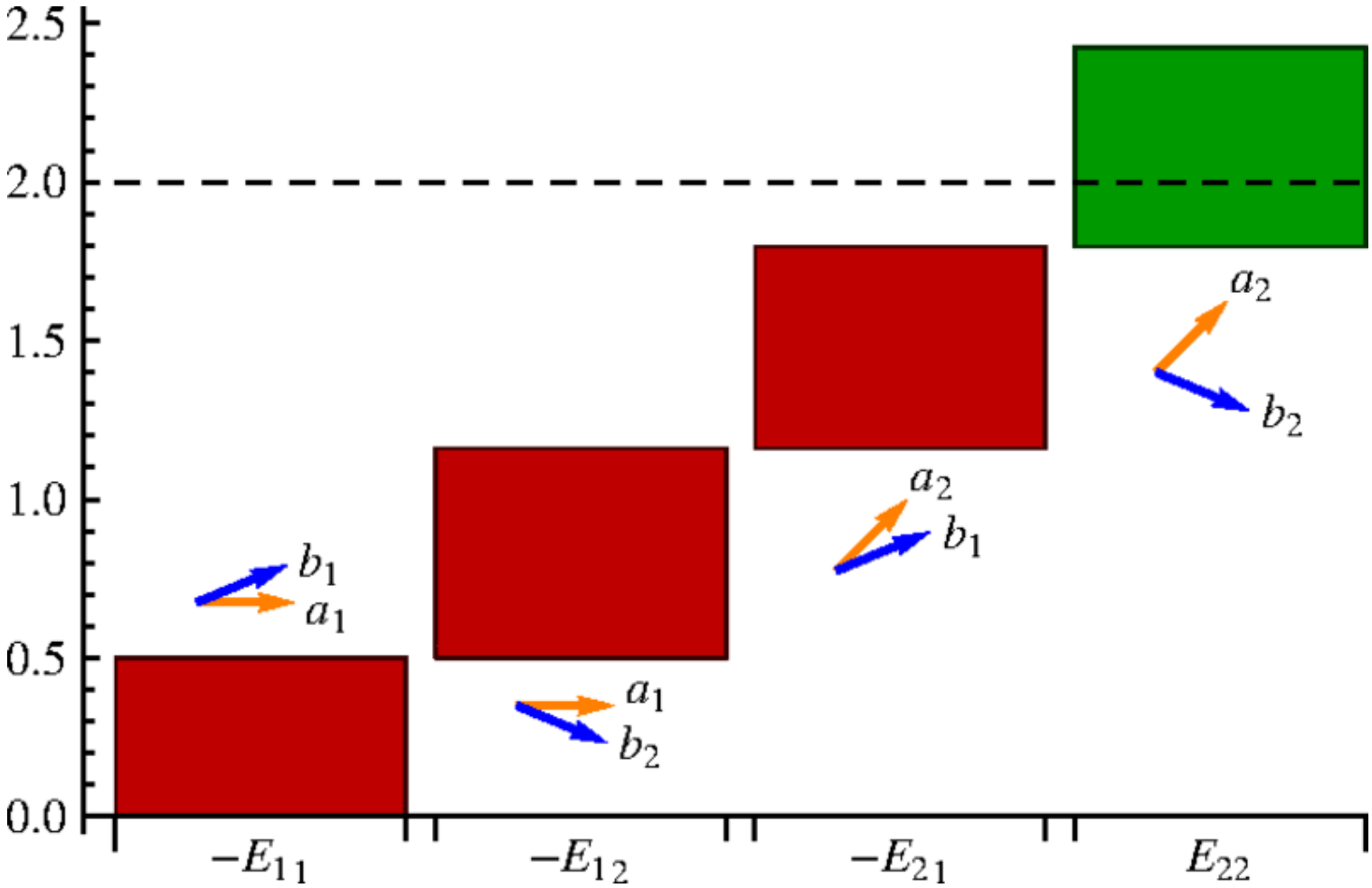
Experimental Past Light Cones



Handsteiner et al. [2016]

Results

$$|E(A_1B_1) + E(A_1B_2)| + |E(A_2B_1) - E(A_2B_2)| \leq 2$$



Handsteiner et al. [2016]

Results

Run	Side	HIP ID	az_k°	alt_k°	$d_k \pm \sigma_{d_k}$ [ly]	$\bar{\tau}^k_{\text{valid}}$ [μs]	S_{exp}	p-value	ν
1	A	56127	199	37	604 ± 35	2.55	2.43	1.8×10^{-13}	7.3
	B	105259A	25	24	1930 ± 605	6.93			
2	A	80620	171	34	577 ± 40	2.58	2.50	4.0×10^{-33}	11.9
	B	2876	25	26	3624 ± 1370	6.85			

Handsteiner et al. [2016]

Over two runs each using a different pair of stars they found a violation of the CHSH inequality with a statistical significance bound by at least 7.31 and 11.93 standard deviations for runs 1 and 2 respectively.

Conclusion

- This result forces any local realist model to have acted no more recently than 604 ± 35 and 577 ± 40 years ago
- And any common cause event must originate from the intersected past light cones at 2409 ± 598 and 4040 ± 1363 years ago.
- This dramatically limits the space-time region in which hidden variables can remain relevant.

"Therefore, any hidden variable mechanism exploiting the freedom of choice loophole would need to have been enacted prior to Gutenberg's invention of the printing press, which itself predates the publication of Newton's Principia by two and a half centuries." Handsteiner et al. [2016]

Further Reading

A. Einstein, B. Podolsky, and N. Rosen. Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? *Physical Review*, 47(10):777–780, may 1935. ISSN 0031-899X. doi: 10.1103/PhysRev.47.777. URL http://link.springer.com/10.1007/s10701-010-9411-9http://link.aps.org/doi/10.1103/PhysRev.47.777.

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