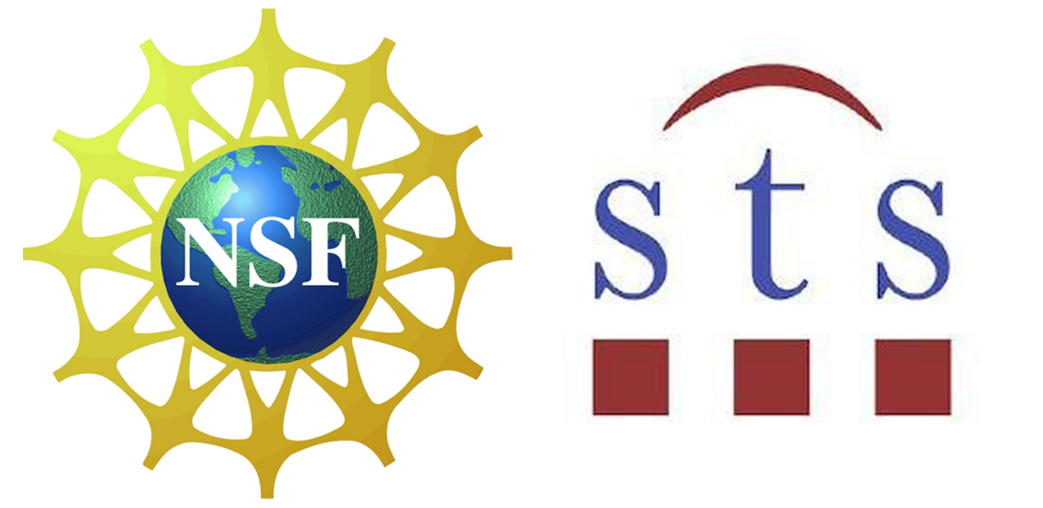




Massachusetts
Institute of
Technology

TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH ASTRONOMICAL OBSERVATIONS



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Fundamental Physics

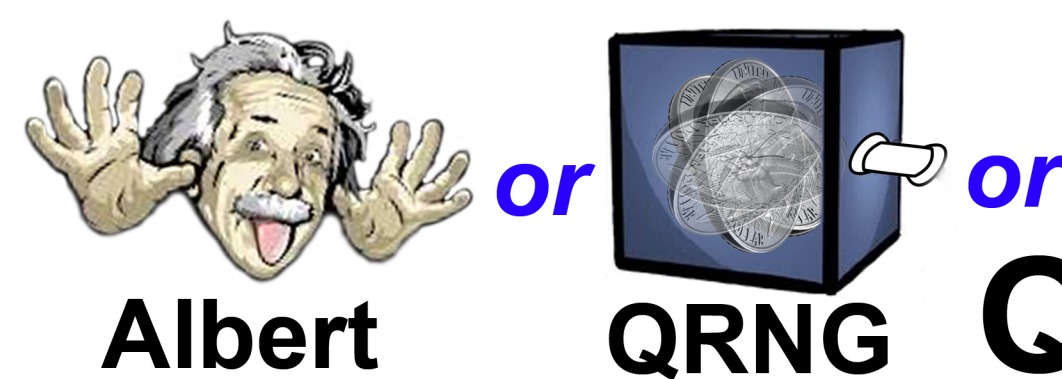
Quantum Foundations

What is the meaning of
quantum entanglement?

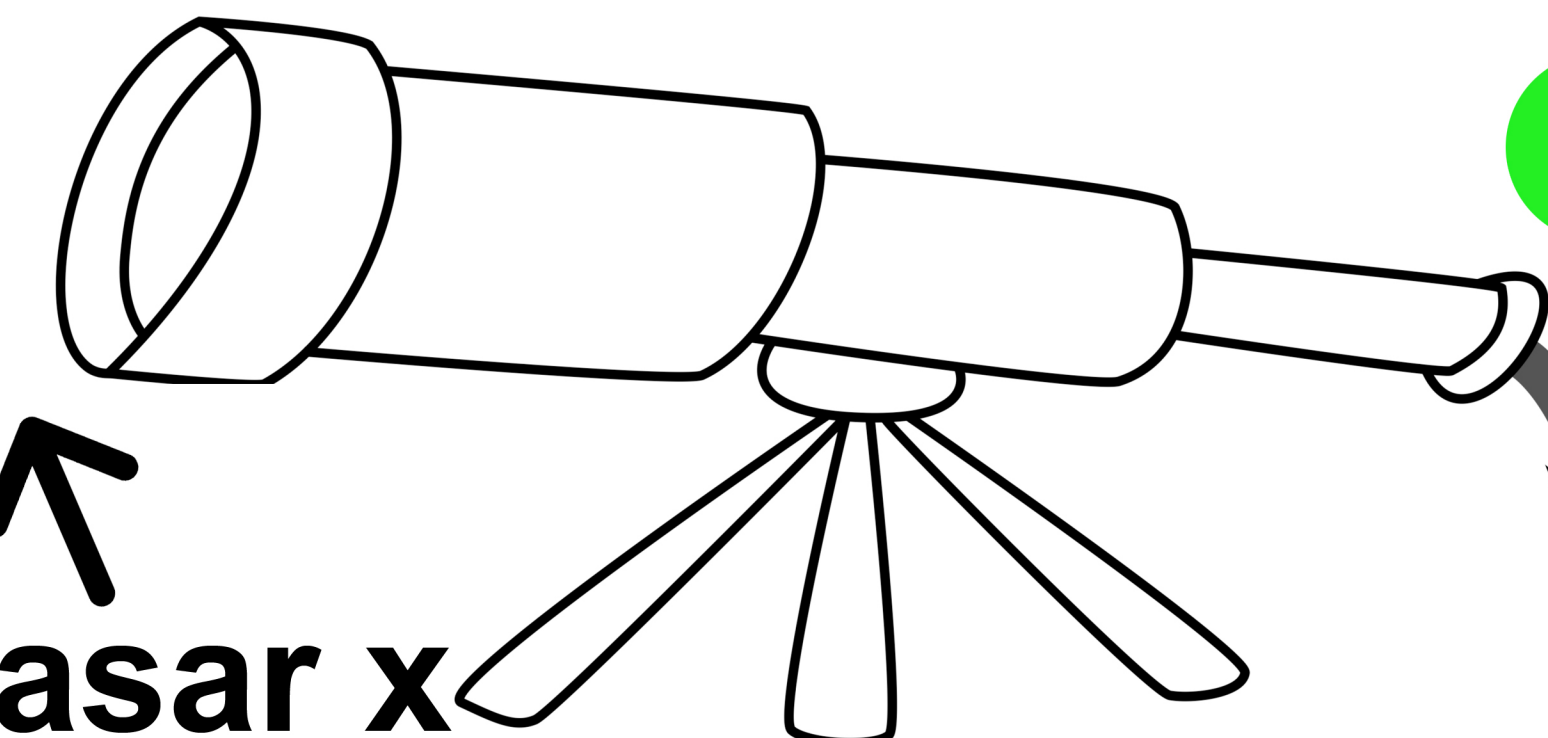
Is Quantum Mechanics complete
or are there hidden variables?

Is Nature truly non-local or
is "Local Realism" viable?

Choosing Settings



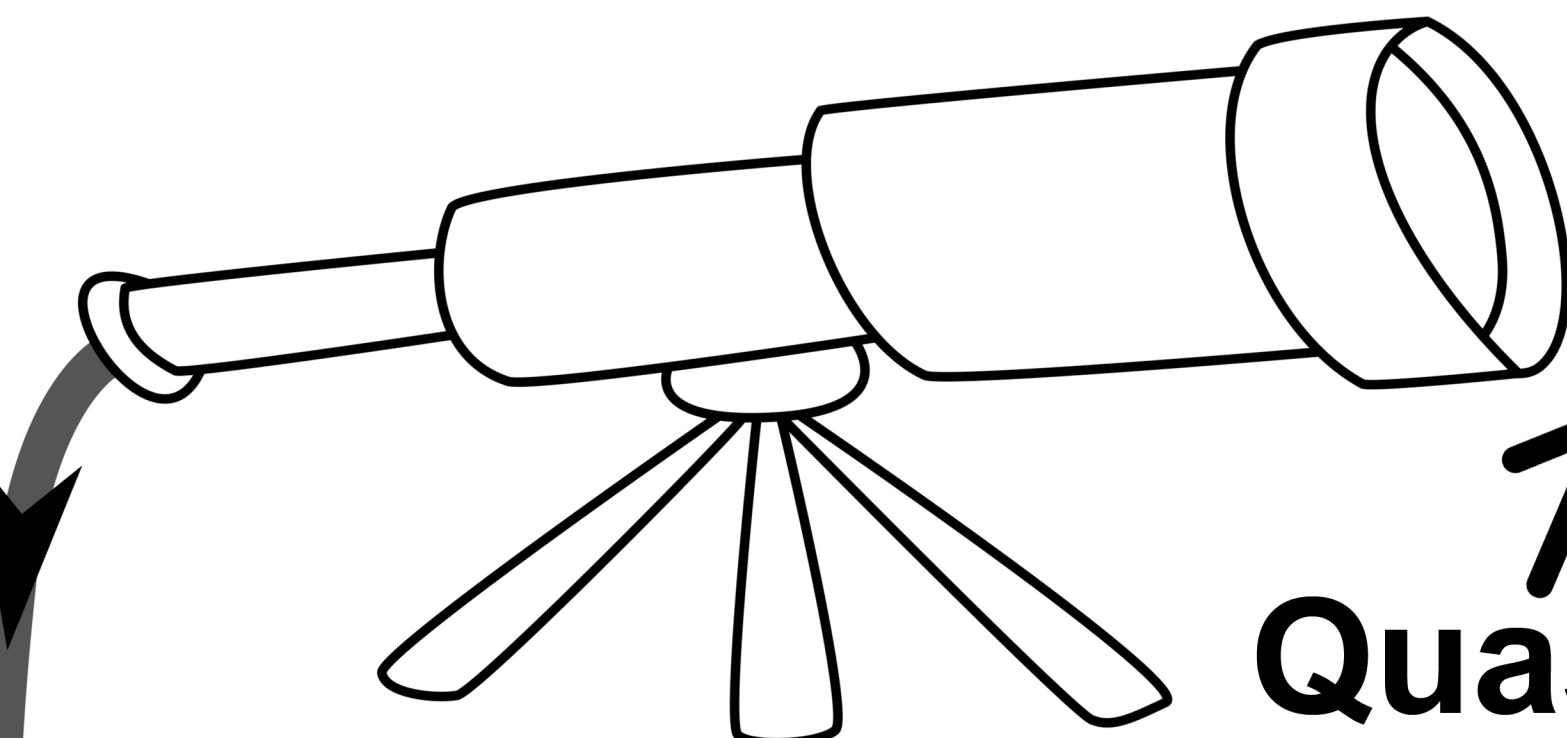
Quasar x



1

Proposed "Cosmic Bell" Experiment Schematic

Old: Standard test of Bell's inequality with 2 entangled particles.
New: Choose detector settings a, b using real-time observations of causally disconnected cosmic sources, i.e. sufficiently distant quasar pairs, while entangled pair still in flight. **Goal:** Confirm quantum predictions: Bell inequalities violated for all quasars.

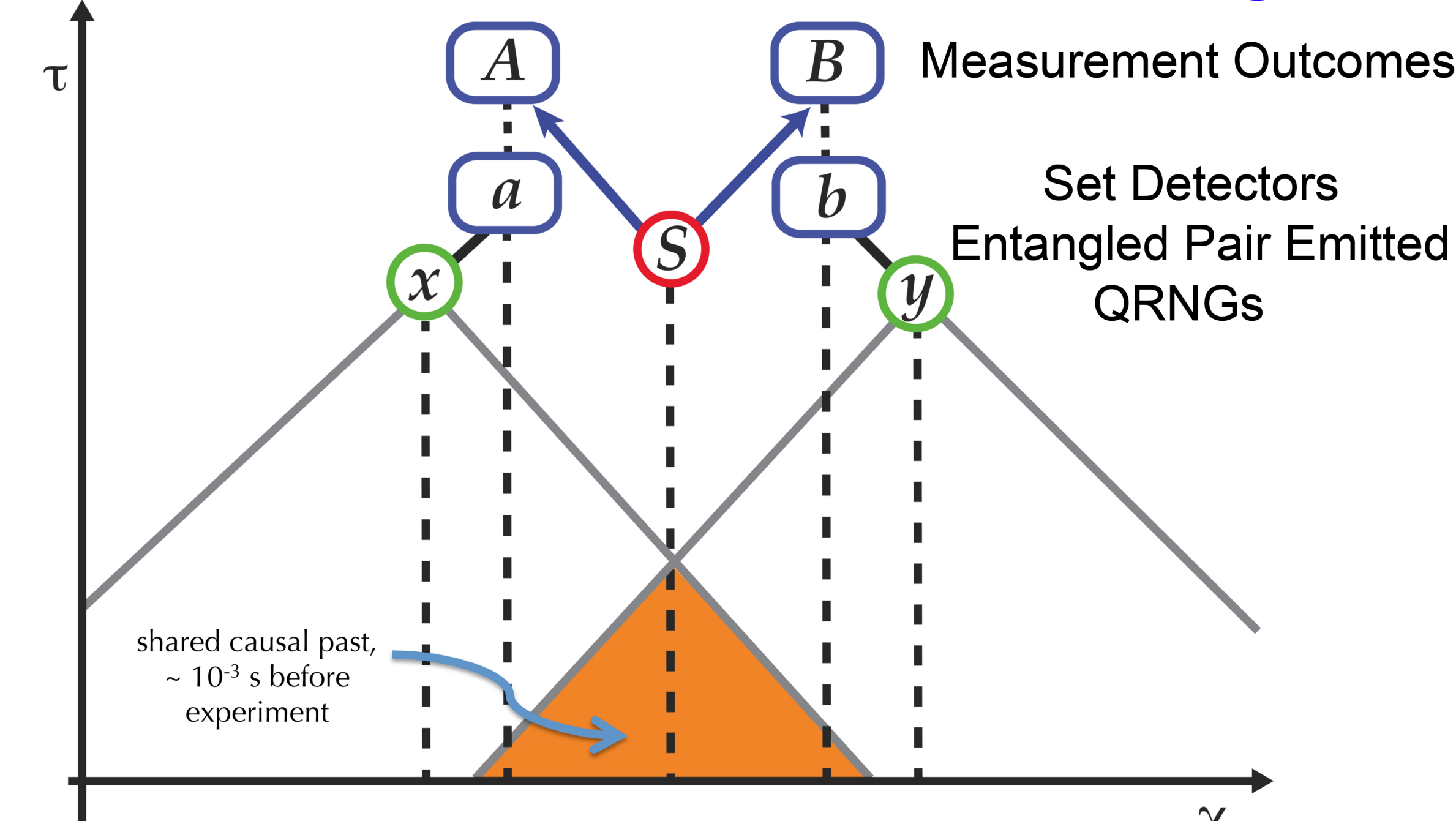


Quasar y



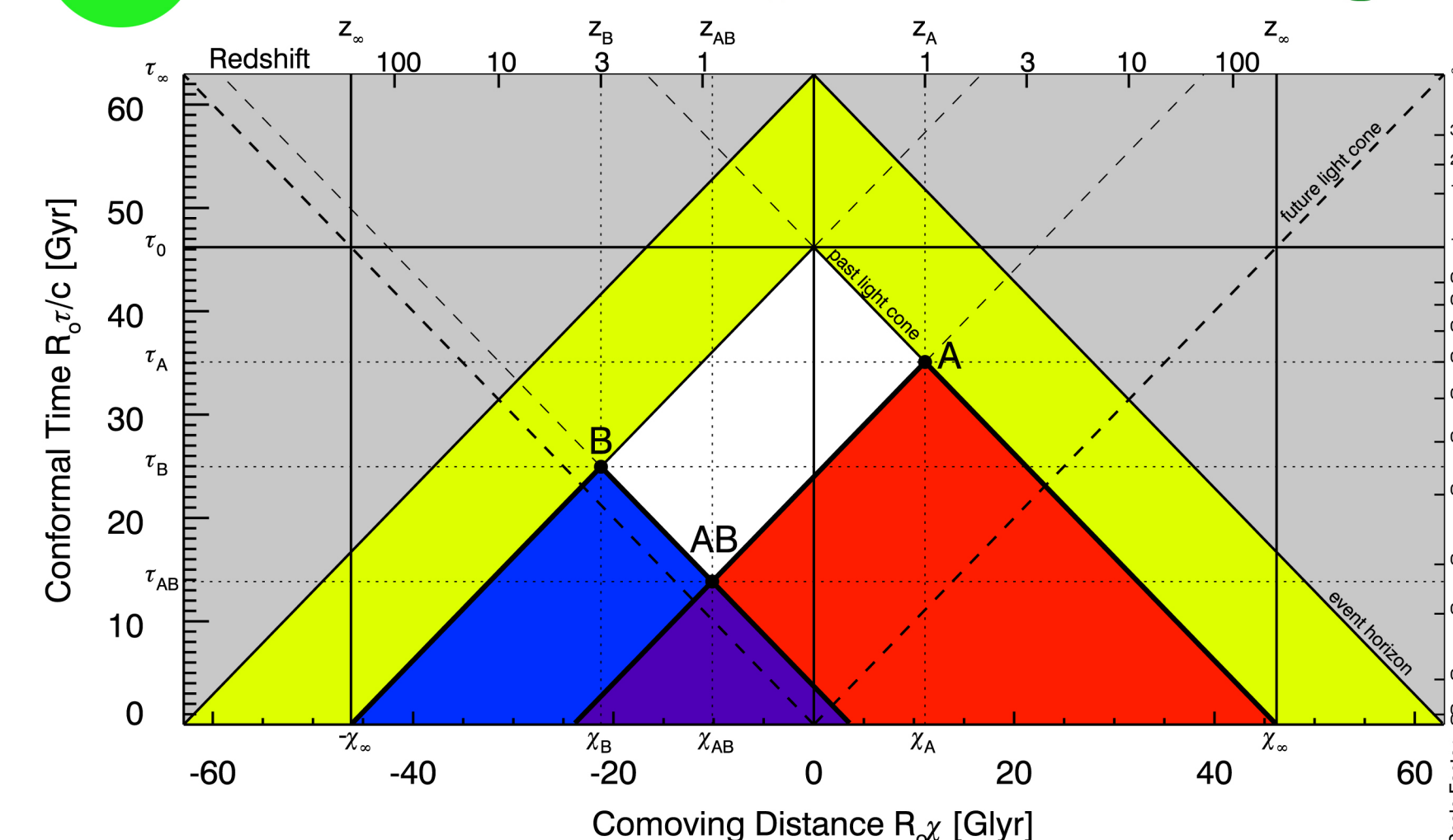
Choosing Settings

2 Standard Bell Test Spacetime Diagram

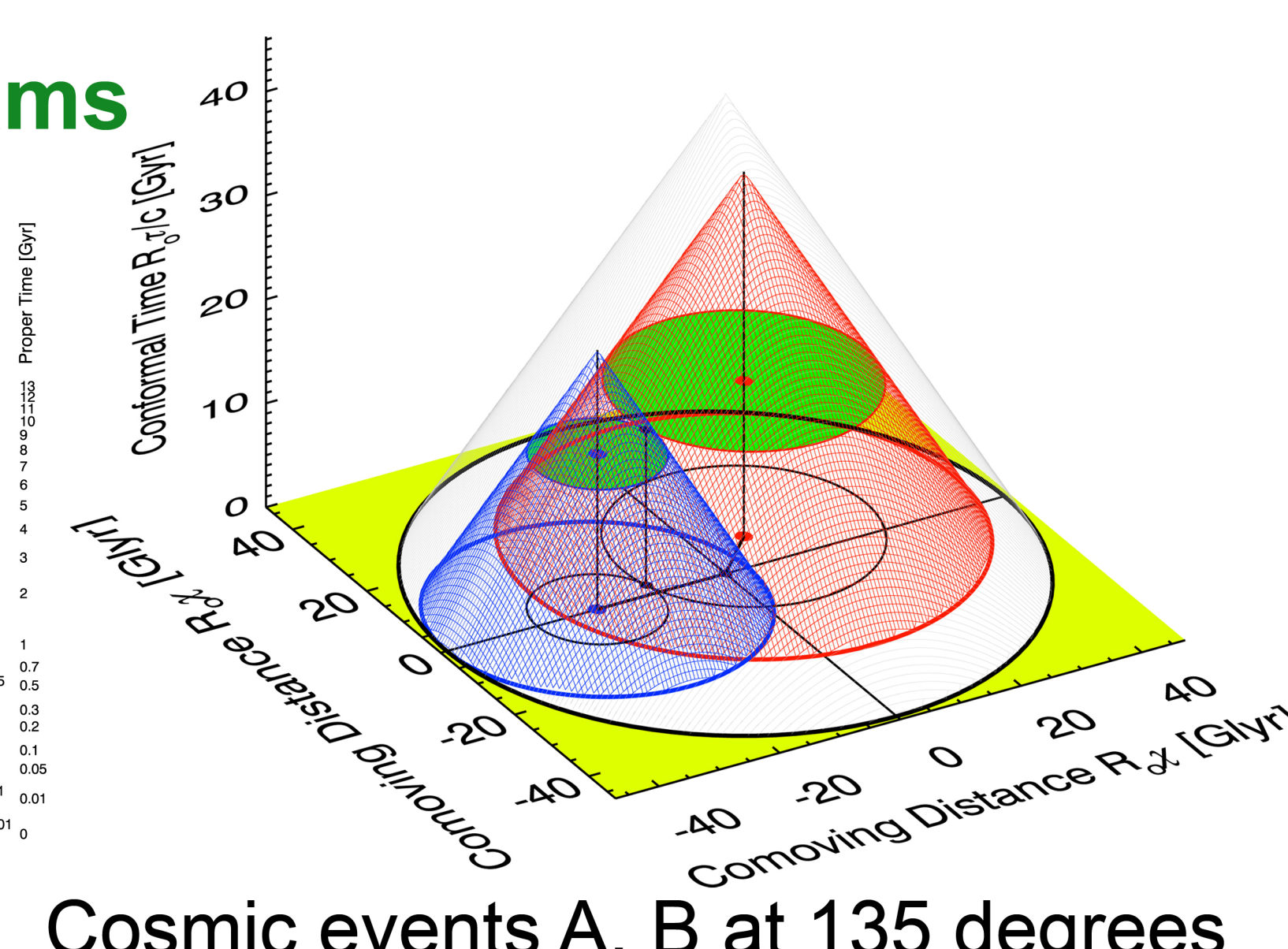


Why: Close last major Bell test loophole: "free will" or "setting independence". Alternative theory could mimic quantum predictions if experimental settings choices x, y shared even small correlations with some local "hidden variables" due to unknown causal influences a mere few milliseconds before experiment (orange region).

4 Conformal Spacetime Diagrams

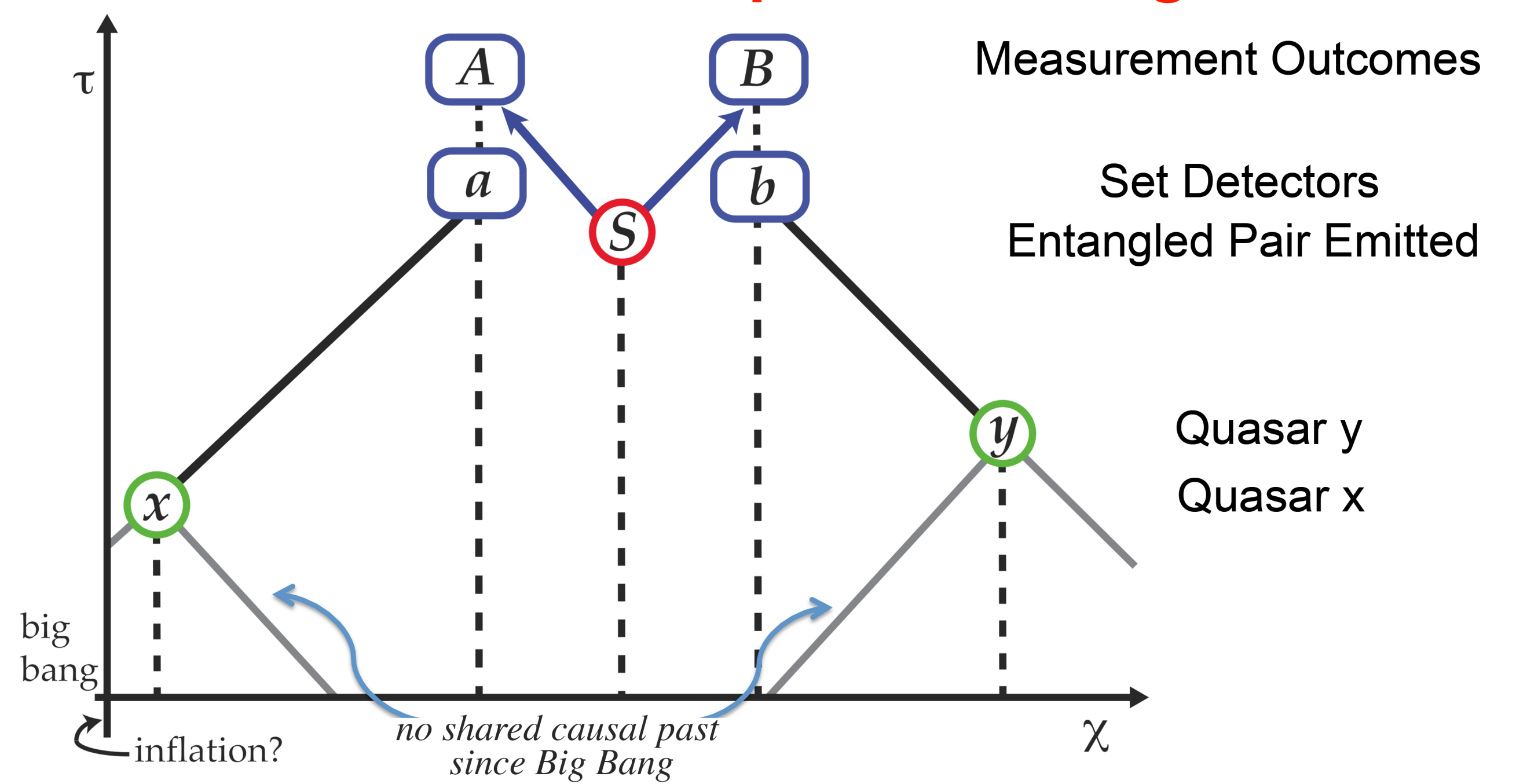


Cosmic events A, B on opposite sides of the sky with redshifts ($z_A=1, z_B=3$). Past light cones (red, blue) intersect at event AB at proper time 13.42 Gyr ago.



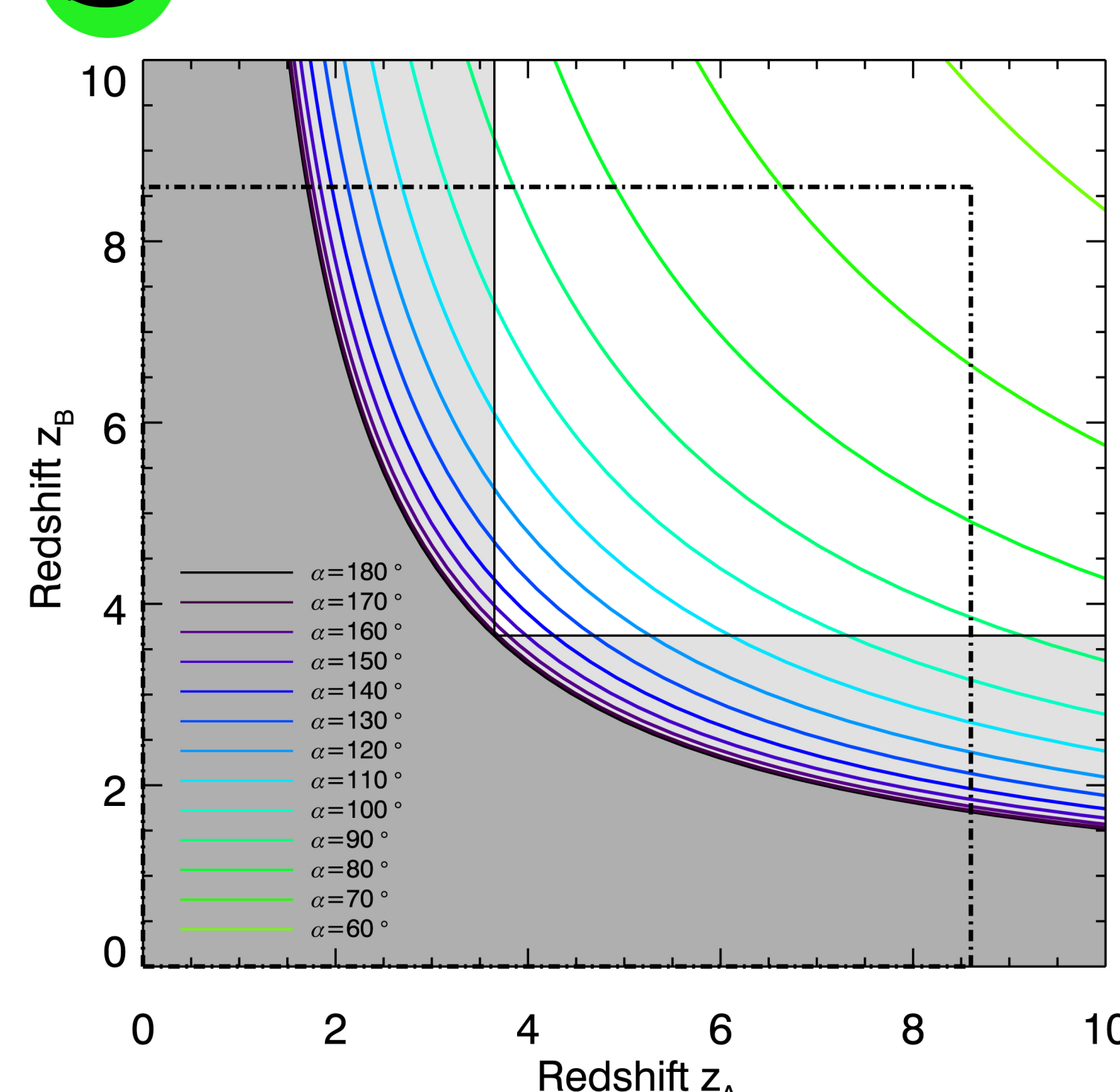
Cosmic events A, B at 135 degrees as seen from Earth (same redshifts). Past light cones (red, blue) intersect at event AB (green plane) at a proper time 13.32 Gyr ago.

3 Cosmic Bell Test Spacetime Diagram



Solution: Choose settings with cosmic events x, y with no causal overlap (past light cones don't intersect) since hot Big Bang 13.8 Gyr ago (after any inflationary expansion). Constrain any local hidden variable "conspiracy" to very early universe. Improvement of 20 orders of magnitude!

5 Causal Pasts of Cosmic Event Pairs



General conditions for cosmic event pairs with any redshifts, angular separations to have no shared causal pasts since hot big bang in flat, dark energy dominated, accelerating FLRW universes like our own. **White Box:** No shared causal past with Earth.

Applications: Security of quantum cryptography.
Can eavesdroppers exploit hidden variables?

6 Animations: Visualizing past light cone intersections:

http://web.mit.edu/asf/www/causal_past.shtml

Future: 3 or more entangled particles (GHZ)

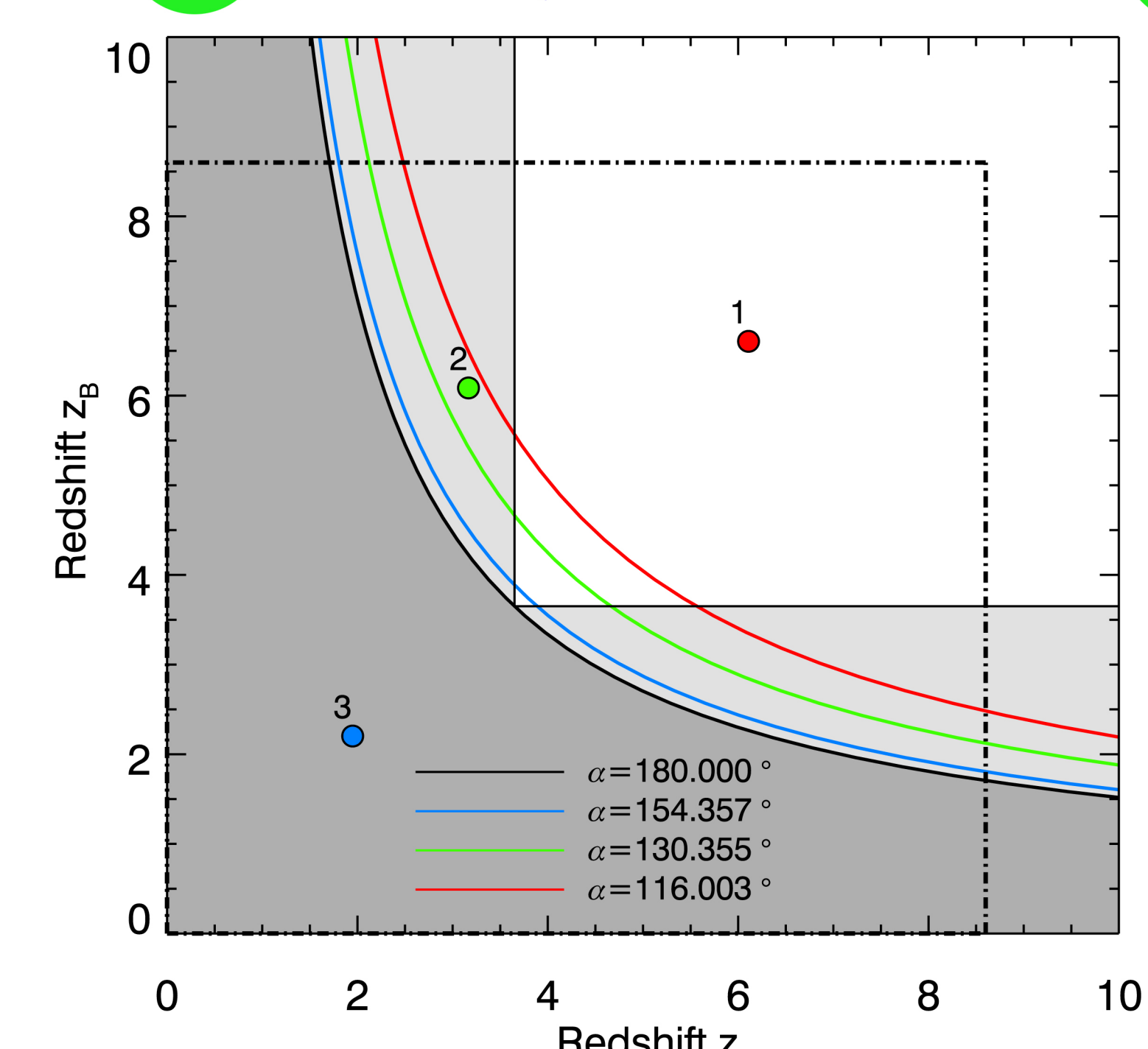
9 Conclusions, Possible Outcomes

Cosmic Bell experiment feasible with existing technology. $z > 3.65$ quasars at optical wavelengths are optimal candidate source pairs using present technology (but causally disjoint patches of cosmic microwave background radiation at redshift $z \sim 1090$ could also set detectors). Many known quasar pairs have no shared causal past since end inflation, 13.8 Gyr ago.

Expected: Strengthen confidence in quantum theory, non-locality.

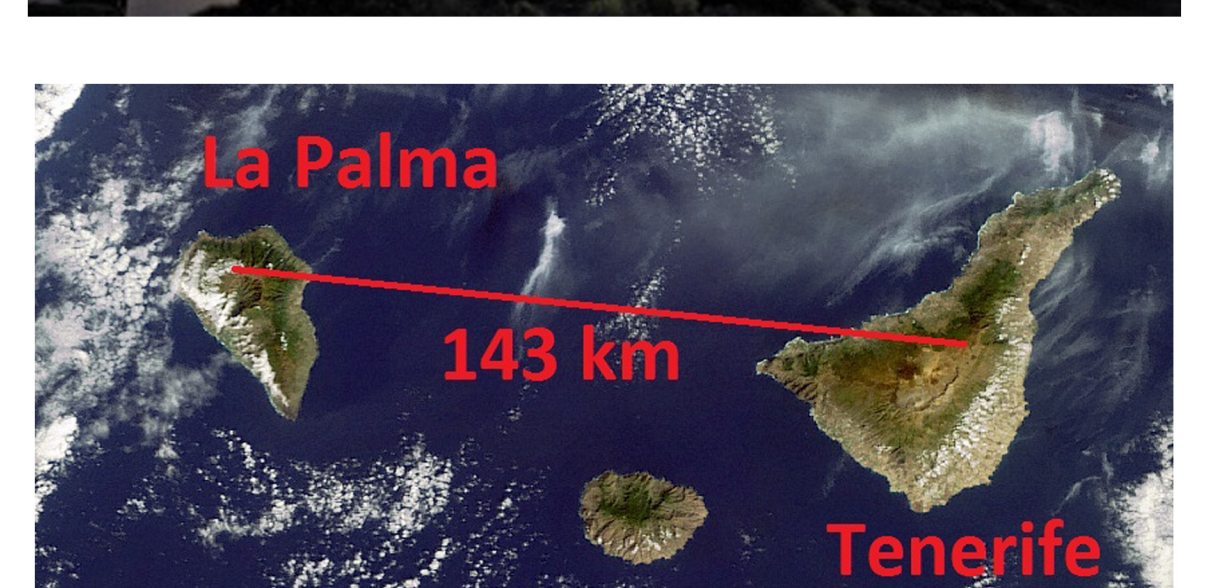
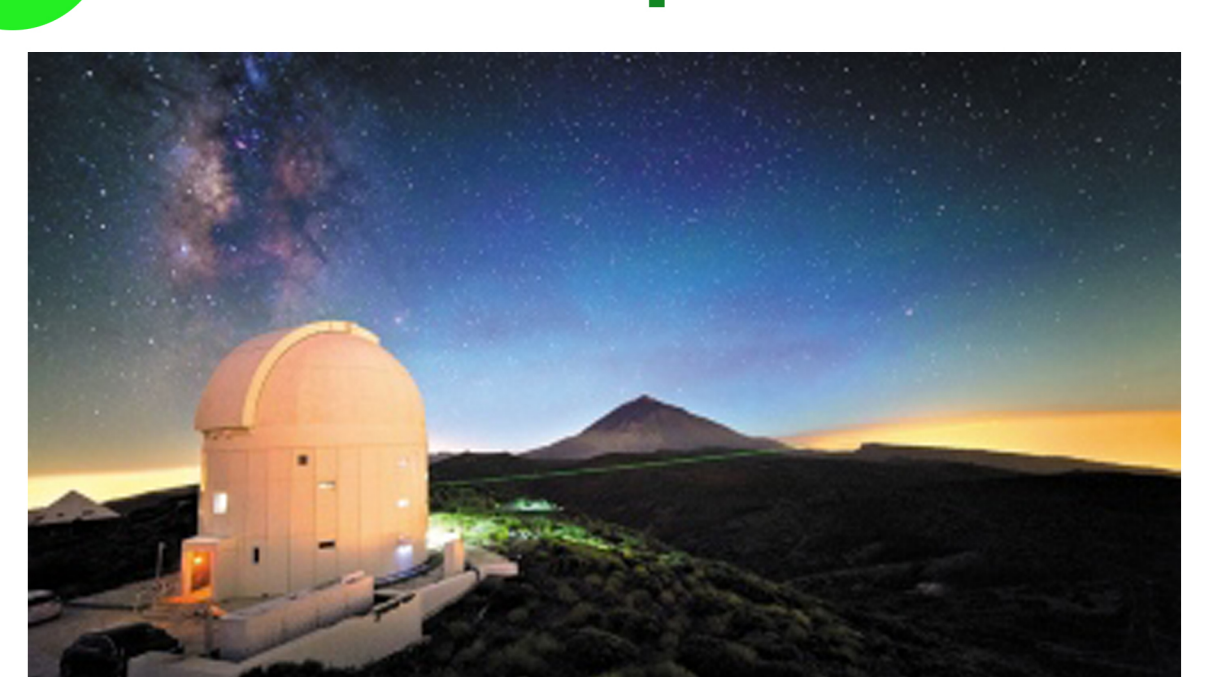
Unexpected: Test new physics, quantum gravity, early universe cosmology.

7 Real Quasar Pairs



Search database of > 1 million quasars for optimal pairs with no shared past since some epoch.

8 Actual Experiment?



Collaborators: Zeilinger group (Vienna). World record open air Bell test with photons (143km) in Canary Islands.