Recent Bell Tests

Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars
J, Handsteiner, A.Zeilinger et al, Phys.Rev.Lett. 121, 080403 (2018)
(Vienna Center for Quantum Science and Technology, Univ. of Vienna)

Test of Local Realism into the Past without Detection and Locality Loopholes
J. Wei Pan, et al, Phys.Rev.Lett. 121, 080404 (2018)
(University of Science and Technology of China, Shanghai)

cf. Event-Ready Bell Test Using Entangled Atoms Simultaneously
Closing Detection and Locality Loopholes
W. Rosenfeld et.al., Phys. Rev. Lett. 119, 010402 (2017),

T. Yoshie,

Journal Club May 17, 2019

- EPR paradox on QM and LHV theory
- Bell’s inequality and Bell Tests
- Loopholes
- Recent works to close “freedom of choice” LH

EPR paradox on QM and LHV theory

- basic concepts of Quantum Mechanics
  - wave function: probability interpretation
  - measurement: wave function contraction
  - entangled state

Alice ↑ (↓)

Entangled state

$$\psi = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$$

Bob ↓ (↑)

  - If Alice and Bob observe spin in the same direction, results are 100% anti-correlated, even if they are space-likely separated

- Einstein, Podolsky, Rosen (EPR) (1936) claim
  - any physics theory should be local and realistic
  - local means …, realistic means …
  - local hidden variable (LHV) theory for QM
  - e.g. $\psi = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow) \otimes \lambda_1\ \lambda_2,\ \lambda_i \in [0,1]$uniform, and $\lambda_1 + \lambda_2$=1 when a spin 0 state is created, travels with spin, and $\uparrow$ is observed when $\lambda \le$0.5, $\downarrow$ others
- Bell (1964)
  - derives an inequality valid for any LHV theory
  - and showed that a QM situation violates it
  - enables us to distinguish LHV theory and QM

- CHSH inequality (1969), a variant of Bell's ineq.

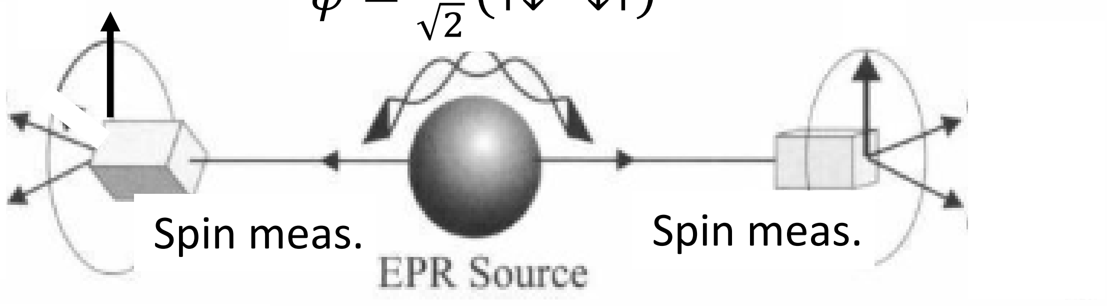
Clauser, Horne, Shimony, Holt

Entangled state

Alice ↑ (↓)

$\psi = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$

Bob ↓ (↑)



For spin meas direction, choose θ_a or θ_b *at random*

For spin meas direction, choose θ_c or θ_d *at random*

– Record angle θ and result (1 or -1 for $\uparrow$ *or* $\downarrow$)

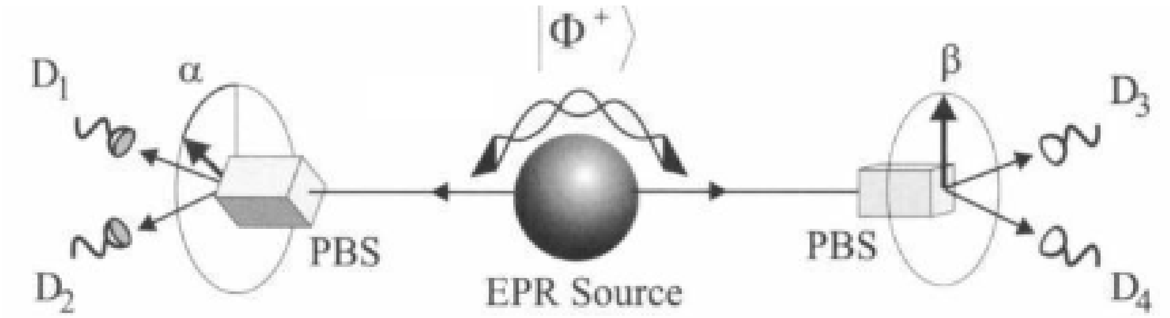
– correlation between Alice and Bob's results.

$$S = \langle ac \rangle + \langle bc \rangle - \langle ad \rangle + \langle bd \rangle$$

$$|S| \leq 2 \text{ for LHV}, \quad |S| \leq 2\sqrt{2} \text{ for QM}$$

$|S| = 2\sqrt{2}$ for $\theta_a - \theta_c = \frac{\pi}{4}$...

- Note: recent experiments examine photon pair for entangled state
  spin -> polarization, two orientations of PBS changed at random



- Derivation of CHSH inequality for LHV theory
  - ✓ $|ac + bc - ad + bd| \leq 2$ for $|a|, |b|, |c|, |d| \leq 1$ (proof: triangle inequality)
  - ✓ $P(\lambda_1, \lambda_2 \ldots, \lambda_n)$: distribution prob. of HV's
  - ✓ $\langle ac \rangle = \int d\,\lambda_1 \ldots d\lambda_n\, a(\theta_a, \lambda_1,.., \lambda_n)\, c(\theta_c, \lambda_1,.., \lambda_n)$ x $P(\lambda_1, \lambda_2 \ldots, \lambda_n)$:

- Pioneering experiments 1972-1976
  – observed violation of Bell's (CHSH's) inequality
  – but far from ideal
  – referred to as loopholes

- Loopholes
  - locality loophole
    - Alice and Bob measurements should be separated space-likely
    - from the start of measurement setup (random choice of angles) to the end of recording result
    - closed in 1998
  - detection loophole
    - device loophole/ fair-sampling loopholes
    - measure spins with more than 78% efficiency
    - closed in 2001
  - exp. closing the two loopholes simultaneously
    - three exp's. in 2015:
      Hanson[nl] (NVc), Zeilinger[at] (γ), Shalm[usa](γ)

- event ready type experiments

Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes

– entanglement swapping: (Żukowski 1993)

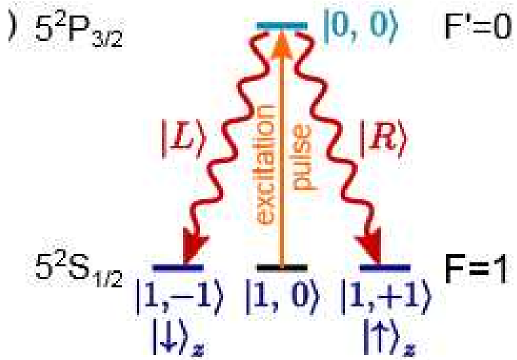
prepare two entangled states $\frac{1}{\sqrt{2}}(\uparrow_1 \downarrow_2 - \downarrow_1 \uparrow_2) \otimes \frac{1}{\sqrt{2}}(\uparrow_3 \downarrow_4 - \downarrow_3 \uparrow_4)$

entangle the 2nd and 4th particles $\frac{1}{\sqrt{2}}(\uparrow_2 \downarrow_4 - \downarrow_2 \uparrow_4)$ [idler]

[measure the total spin and select spin 0 state]

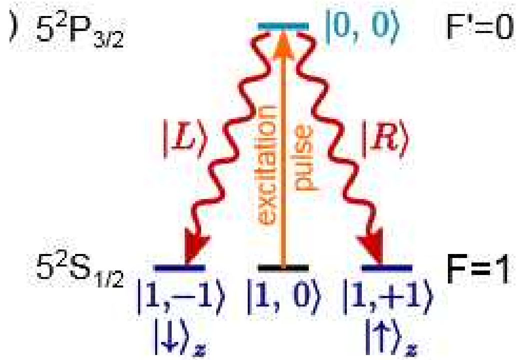
the 1st and 3rd particles entangle to spin 0 : $\frac{1}{\sqrt{2}}(\uparrow_1 \downarrow_3 - \downarrow_1 \uparrow_3)$ [signal]

particles for signal can be far separated



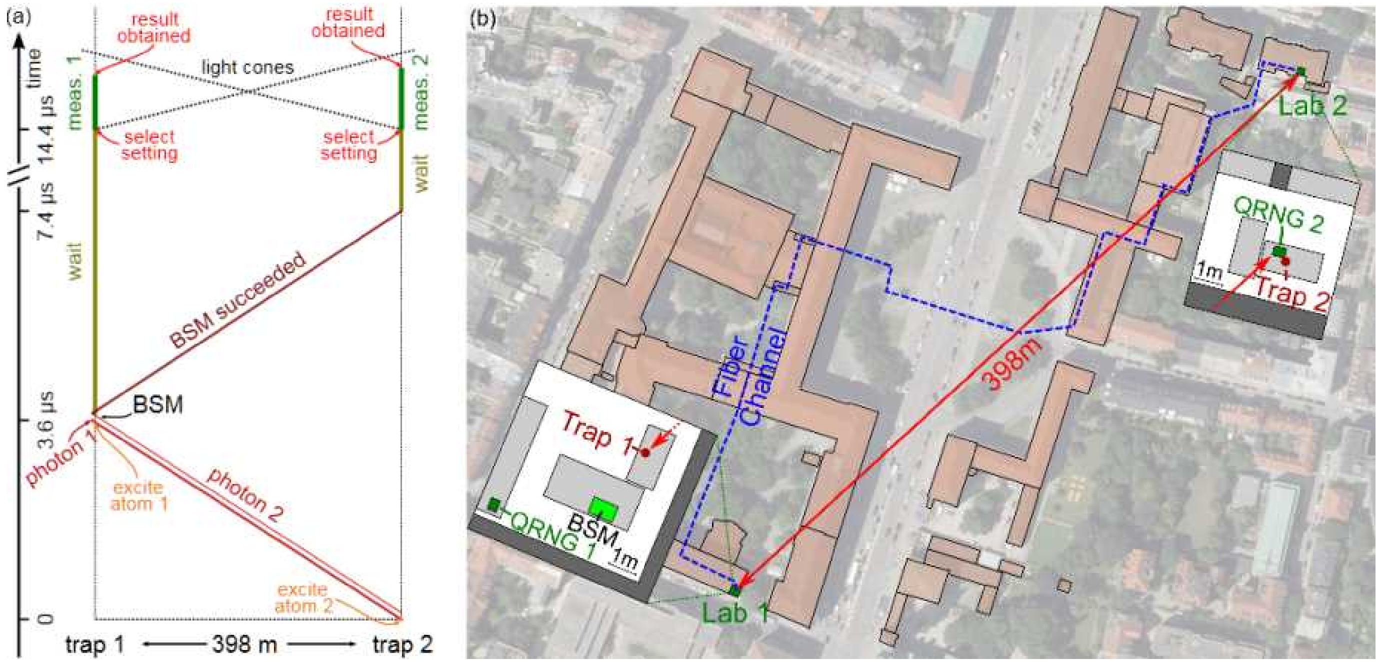
send photon

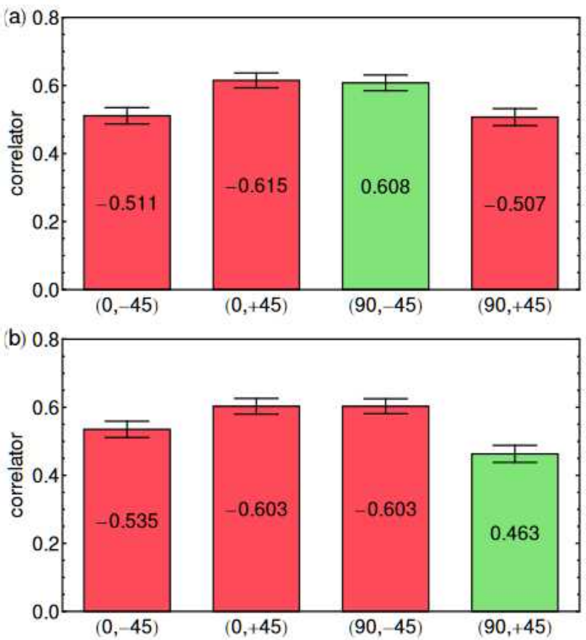
inform entnglement



Rb (signal)+γ(idler)
$\gamma\gamma$ entangled at BSM

Rb (signal)+γ(idler)





$$S = 2.221 \pm 0.033 \qquad P \leq 2.57 \cdot 10^{-9}$$

- Freedom of Choice (a.k.a Free-Will) Loophole
  - HV originates in the past may affects measurement setting
  - note (HV at entanglement generation is excluded)
  - HV in the (overlap of) backward light cones of Alice and Bob may mimic QM results
- Idea to close the loophole
  - use random number source generated as past as possible to choose measurement setup
  - past: random source (frequency of light) from stellar objects
  - violation of Bell's inequality rules out HV born after the time the light was emitted
    (assuming no intervention in between)

- several works in this direction

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(Vienna Center for Quantum Science and Technology, Univ. of Vienna)
Locality LH closed, Fair-Sampling LH open
HV excluded up up at least 7.8Gyr

Cosmic Bell Test: Measurement Settings from Milky Way Stars
authors: as above, Phys.Rev.Lett. 118,060401 (2017)
HV excluded up to several hundred years, Fair-sampling LH not closed

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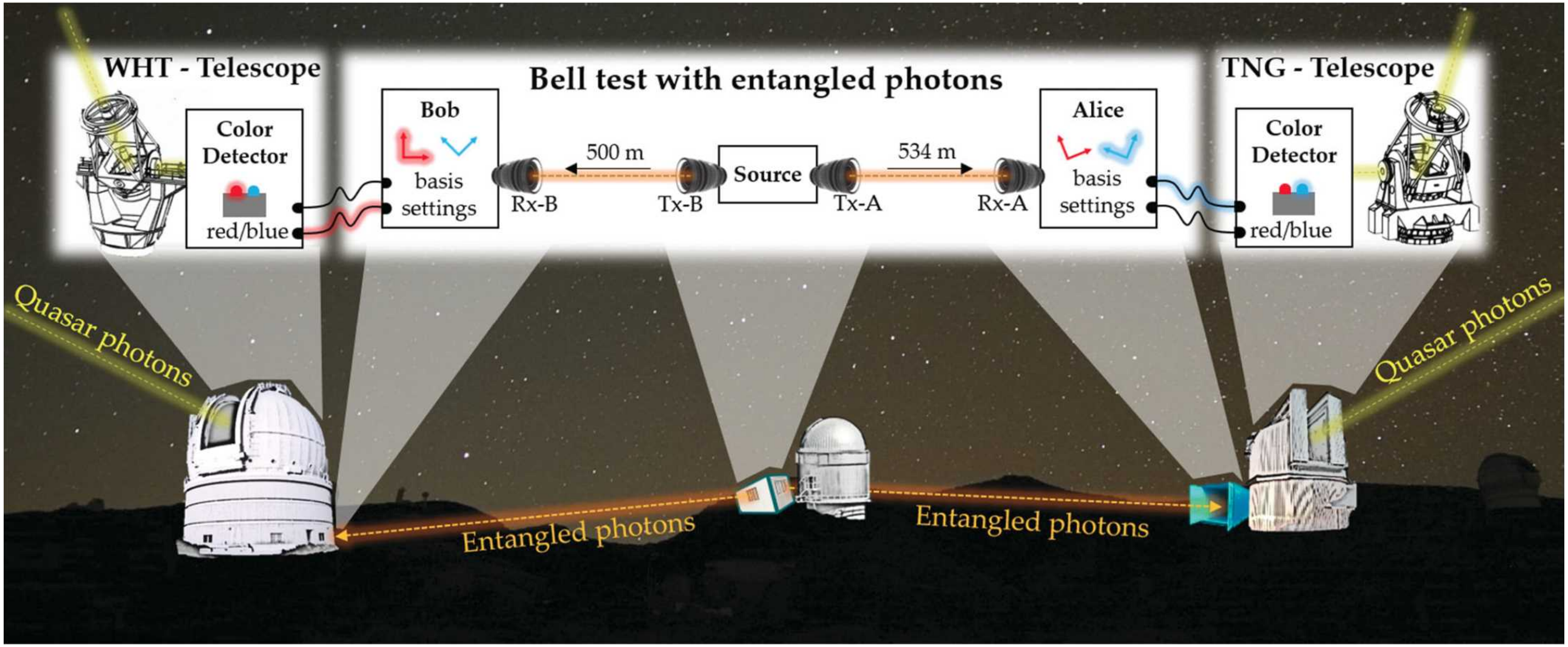
HV within 11years excluded

Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars



La Palma observatory, Canary Islands, Spain

violation of Bell's inequality by 9.3 sigma

LHV ($t < 7.8$Gyr) ruled out

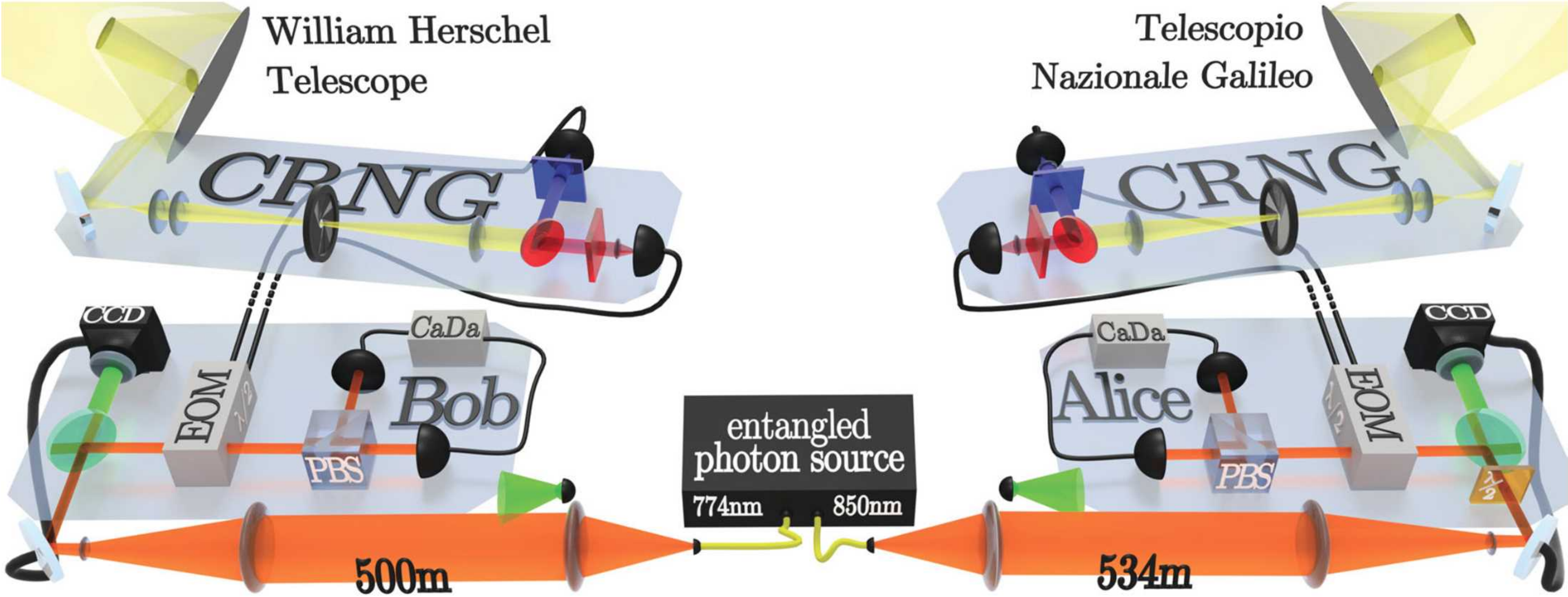


FIG. 2. A photon pair source located in the middle produced polarization-entangled photons at center wavelengths of 773.6 and 850 nm. The photons were separated into two spatial modes via a dichroic mirror and sent via free-space channels to the quantum receivers at Bob (773.6 nm) and Alice (850 nm). Fast steering mirrors guided the photons to the receivers using a green LED as a reference. Electro-optical modulators (EOM) rotate the measurement basis according to the input signals from the CRNGs. Polarization measurements are performed using a polarizing beam splitter (PBS) with avalanche photodiodes in each output path. Detection events are time stamped by the control and data acquisition unit (CaDa) and stored locally. Quasar light is collected by the astronomical telescopes and fed into an optical system that creates a magnified image with an iris to restrict the field of view. The quasar light is then split according to its wavelength into a "blue" and a "red" channel, whereby each channel contains additional filters to remove misdirected photons. The detector signals are used to trigger the implementation of the corresponding measurement basis at the EOM.