Testing Local Realisim using optical TES detectors

Sae Woo Nam (saewoo.nam@nist.gov)

M. Giustina, A. Mech, S. Ramelow, B. Wittmann, J. Kofler, J. Beyer, A. Lita, B. Calkins, T. Gerrits, R. Ursiin, A. Zeilinger

M. Giustina et al, *Nature* 497, 227–230 (09 May 2013) doi:10.1038/nature12012

Outline

- What is Local Realism?
- Why should we care?
- Why is this hard?
- What have we done so far?
- What is next?

Einstein-Podolsky-Rosen (EPR)

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

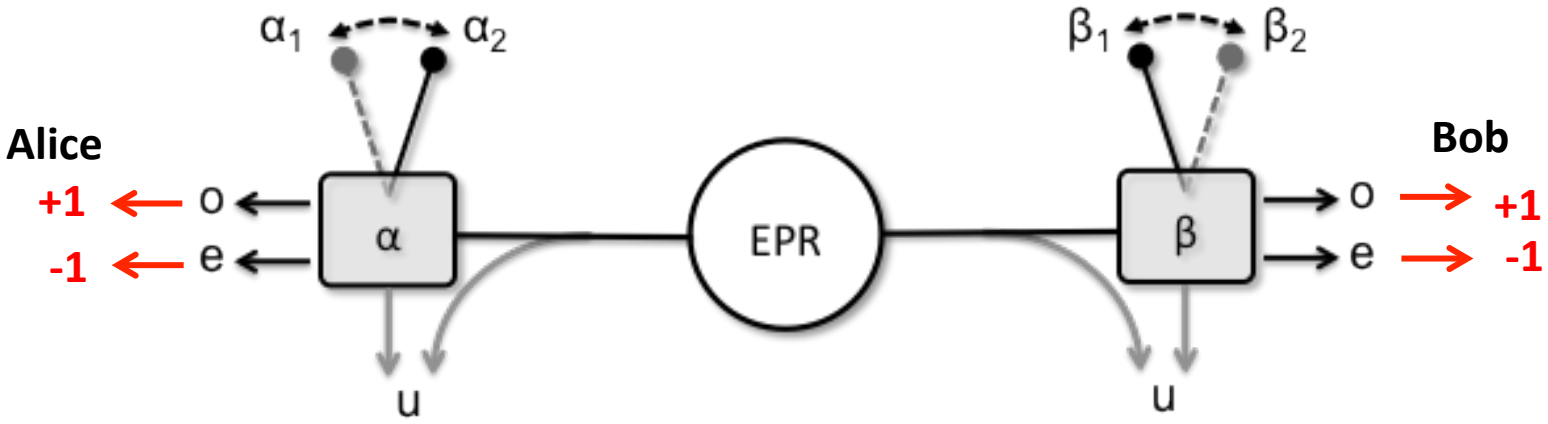
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality.

... *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*

EPR (Bell) pair



$$|\Psi\rangle = 1/\sqrt{2}\ \ (|HV\rangle - |VH\rangle\ )$$

Joint and single-sided probabilities

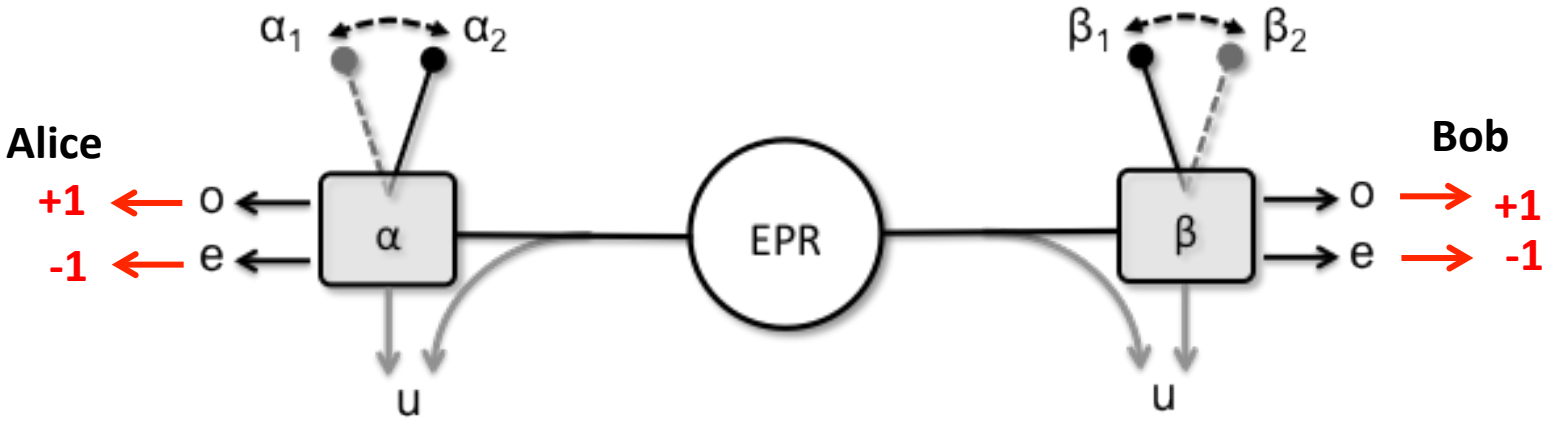
$$P{\downarrow}{+}{+}\ (\alpha,\beta),\ P{\downarrow}{+}{-}\ (\alpha,\beta),\ P{\downarrow}{-}{+}\ (\alpha,\beta),\ P{\downarrow}{-}{-}\ (\alpha,\beta)$$

$$P{\downarrow}{+}\ (\alpha),\ P{\downarrow}{-}\ (\alpha),\ P{\downarrow}{+}\ (\beta),\ P{\downarrow}{-}\ (\beta)$$

Is there a hidden variable?

John Bell (1964) – "Bell Test"

- No Local Hidden Variable Theory (LHV) can explain the results possible from Quantum Mechanics



$S = E(A_1 * B_1) + E(A_1 * B_2) + E(A_2 * B_1) - E(A_2 * B_2)$

$= A_1 * (B_1 + B_2) + A_2 * (B_1 - B_2)$

$S_{LR} \leq 2$

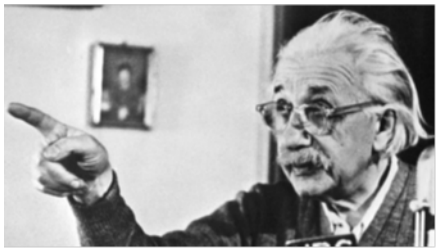
$S_{QM} = 2\sqrt{2}$ for "Bell States"

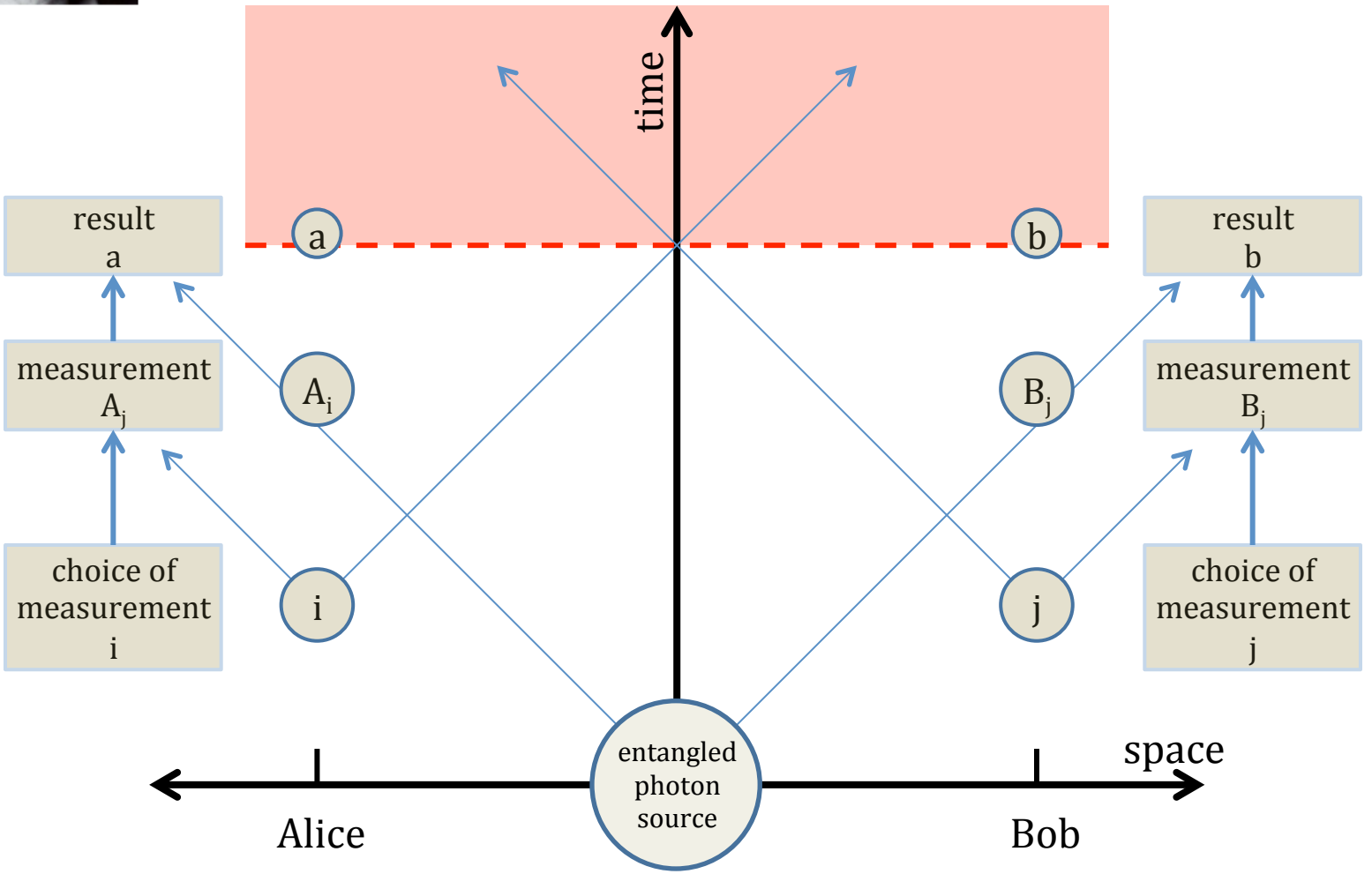
Significant Experimental challenges / loopholes

- Fair-sampling (very efficient detection)
- Locality (Alice and Bob are space-time separated)
- Free-choice (settings must be random)
- Memory loophole (statistical analysis)

- Trapped Ions, superconductors, and atom-photons have all closed the fair-sampling
- Photons have closed locality

Loophole-free Bell tests





Eberhard (1993)

- Use two detectors (one on each side)
- Using asymmetric entangled states requires less efficient detectors.
- Threshold is 2/3 detection efficiency
- Slightly different “Bell Inequality”

$$|\Psi\downarrow r\rangle = 1/\sqrt{1+r\uparrow 2}\ \ (|HV\rangle + r|VH\rangle)$$

$$J = -C(\alpha\downarrow 1, \beta\downarrow 1) - C(\alpha\downarrow 1, \beta\downarrow 2) - C(\alpha\downarrow 2, \beta\downarrow 1)$$
$$+ C(\alpha\downarrow 2, \beta\downarrow 2) + S\uparrow A(\alpha\downarrow 1) + S\uparrow B(\beta\downarrow 1)$$

$$\boldsymbol{J\downarrow LR > 0}$$

Why should we care?

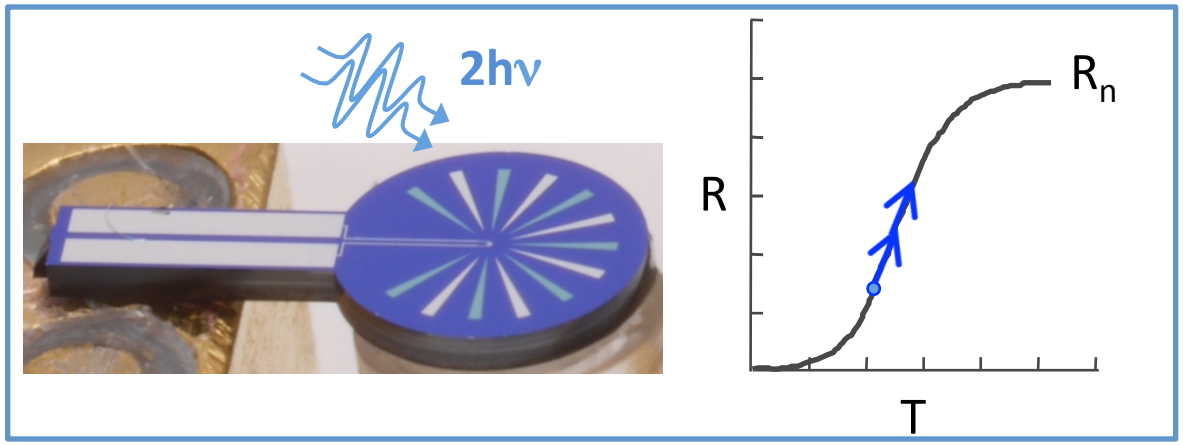
- Fundamental test of quantum mechanics and longtime goal in experimental physics
- Potential for secure communications: "Device Independent Quantum Key Distribution"
- Potential for "provable" random number generation
  - Enables fundamentally new cryptographic protocols

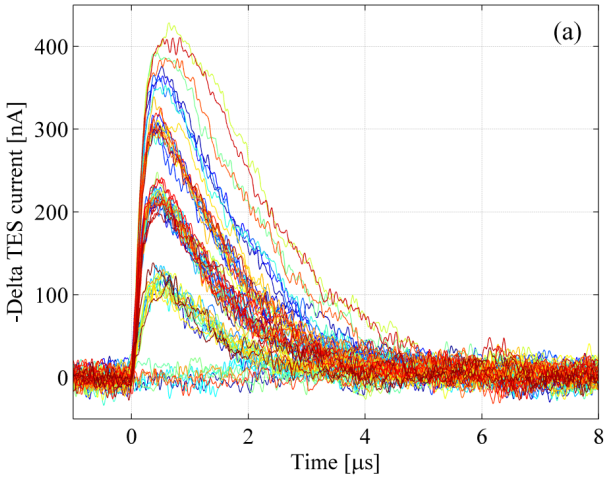
Why use LTD/TES detectors?

- Near 100% system detection efficiency is needed
- Need multiple detectors (accidents happen)
- Need reliable and robust packaging
- No background subtraction is permitted
- Use pulse height to discriminate against background photons

Tungsten (W) Transition Edge Sensor (TES)

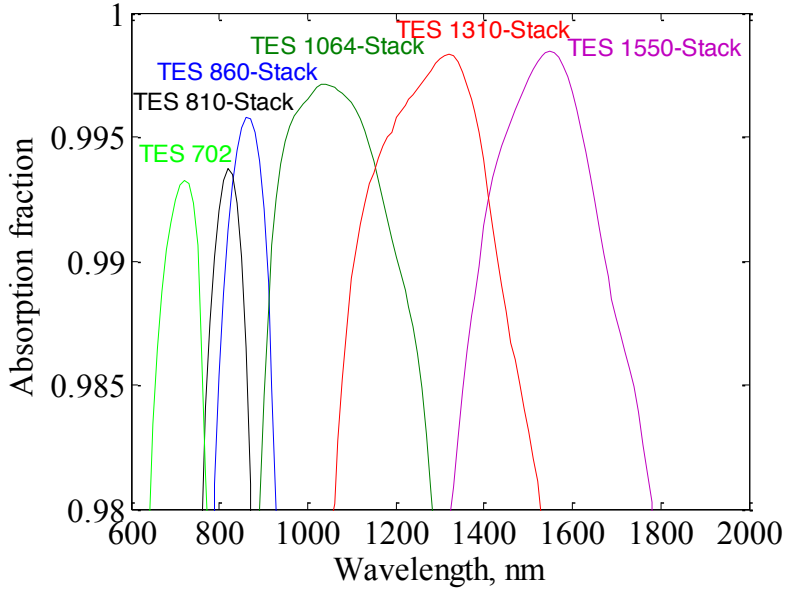
Calorimetric detection of UV/optical/IR photons



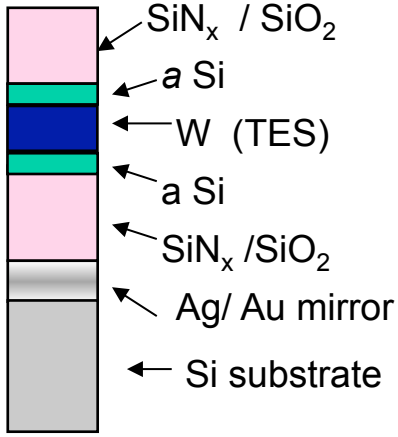


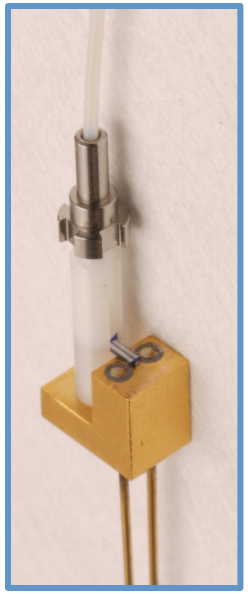
Fiber coupled self-aligned TES
< 1% coupling loss

TES Simulated Absorption



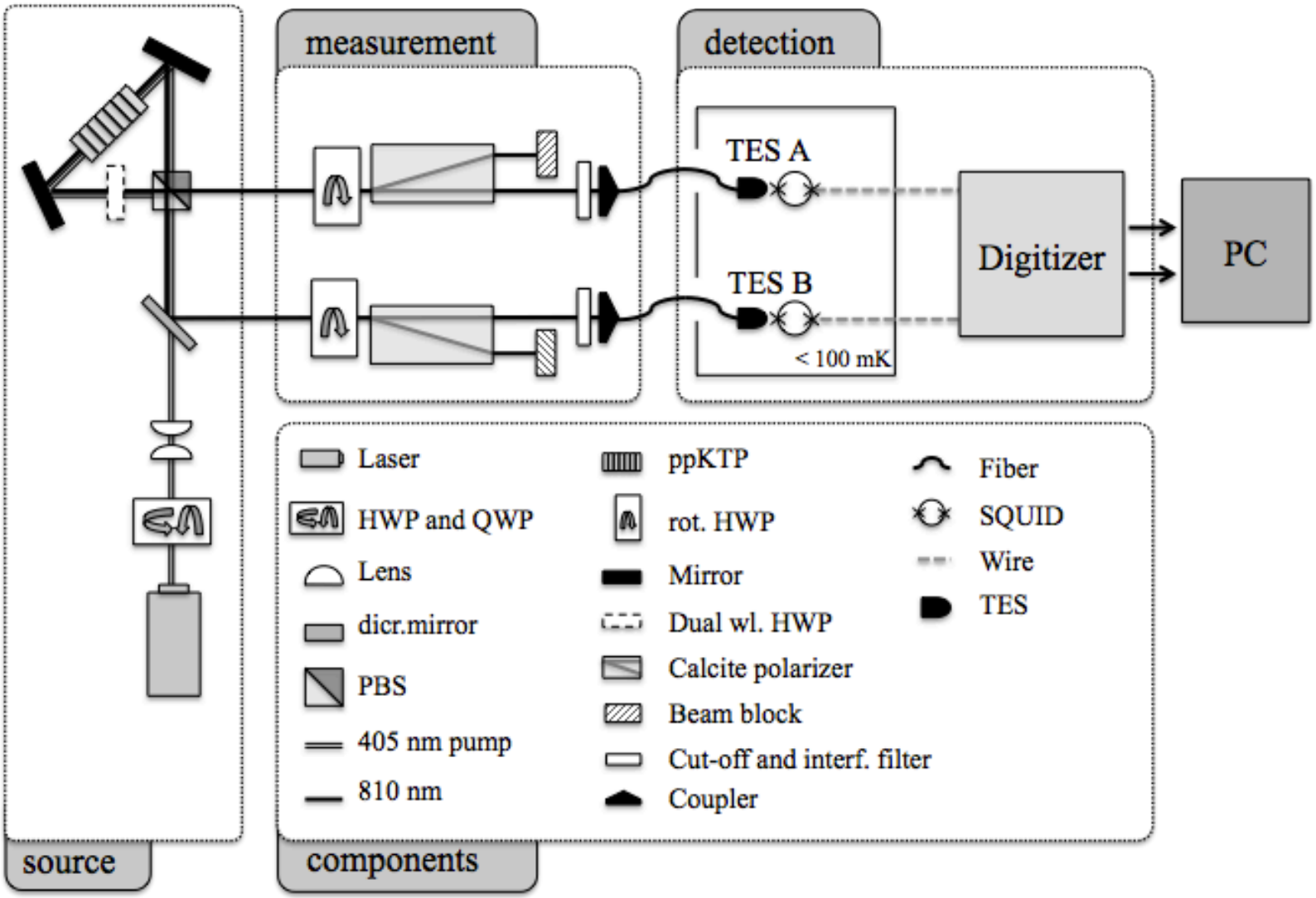
Optical stack





NIST

Optical Diagram



Results

$|\Psi_r\rangle = 1/\sqrt{1+r^2}\ (|HV\rangle + r|VH\rangle)$, where $r \sim 0.3$

$\alpha_1 = 85.6°$, $\alpha_2 = 118.0°$, $\beta_1 = -5.4°$, and $\beta_2 = 25.9°$

300s	Singles A	Singles B	Coincidence
α_1, β_1	1526617	1699881	**1069306**
α_1, β_2	**1522865**	4515782	**1152595**
α_2, β_1	4735046	**1693718**	**1191146**
α_2, β_2	4729369	4507497	**69749**
J			**-126715**

Summary

- Photons in separate experiments have closed all major loopholes
- Groups are actively trying to close all the loopholes simultaneously
- Other QI systems are also pursuing this goal… Expect results within a couple of years.
- Research into using this type of test for communications and RNG

Randomness Beacon

Transparency, verifiability, security

- Generate provable quantum randomness
- Time stamp
- Digitally sign
- Publish on internet

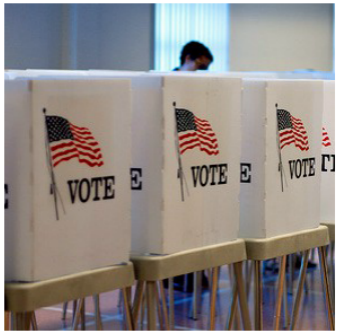
Beacon Applications

No-fly lists

- Input *private* name, *private* no-fly list

Auditing voting stations

- Cannot test all booths/machines
- need random numbers predictable by no one, verifiable by everyone



Selective disclosure

- Currently all or nothing (medical records)