Entanglement on the dot

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classical correlations

qubits

$$|0\rangle = |\uparrow\rangle\,, \quad |1\rangle = |\downarrow\rangle$$

Classical correlations

$$\rho = \frac{1}{2}\Big(|01\rangle\langle 01| + |10\rangle\langle 10|\Big)$$

$$Tr(\rho\sigma_z \otimes \sigma_z) = -1$$

$$Tr(\rho\sigma_x \otimes \sigma_x) = 0$$

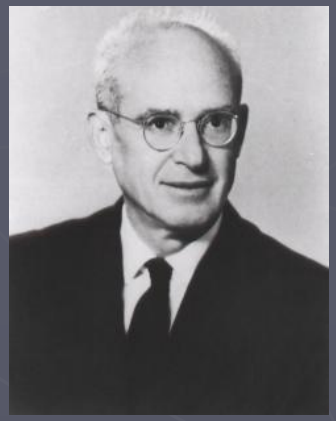
Alice & Bob

$$|A\rangle \otimes |B\rangle$$

$$P_{A\otimes B}(i,j) = |\langle A|i\rangle|^2 \, |\langle B|j\rangle|^2 = P_A(i) P_B(j)$$

Statistical independence

Entangled Alice & Bob



+

$$|A_1\rangle \otimes |B_1\rangle + |A_2\rangle \otimes |B_2\rangle$$

Spooky action at a distance

Entangled Bell states

$$\sqrt{2}\,|S\rangle = |01\rangle - |10\rangle$$

$$\rho = |S\rangle\langle S| = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$Tr(\rho\,\sigma_x \otimes \sigma_x) = -1$$

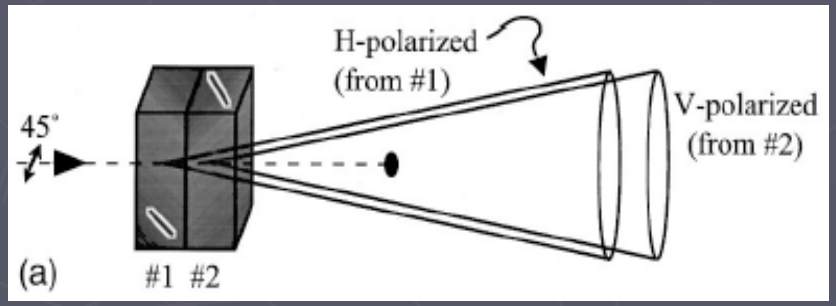
Peres test

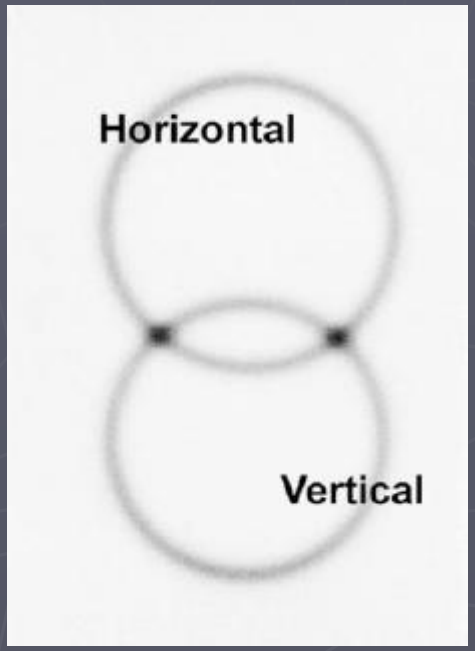
$$\rho = \begin{pmatrix} A & B \\ B^* & C \end{pmatrix}, \quad \rho^P = \begin{pmatrix} A & B^* \\ B & C \end{pmatrix}$$

If transform has negative eigenvalue state is entangled

$$\rho = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \rho^P = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

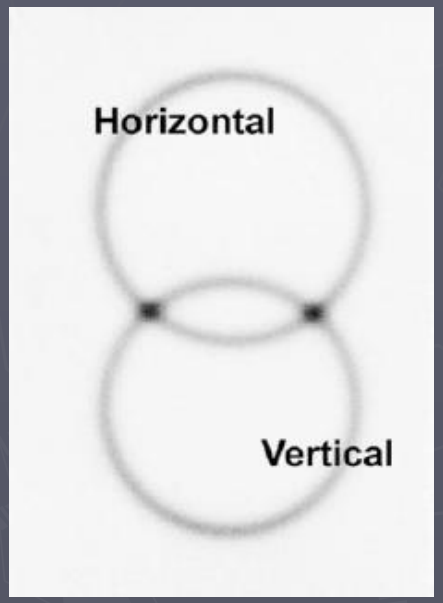
Down Conversion





Which path or Welcher weg

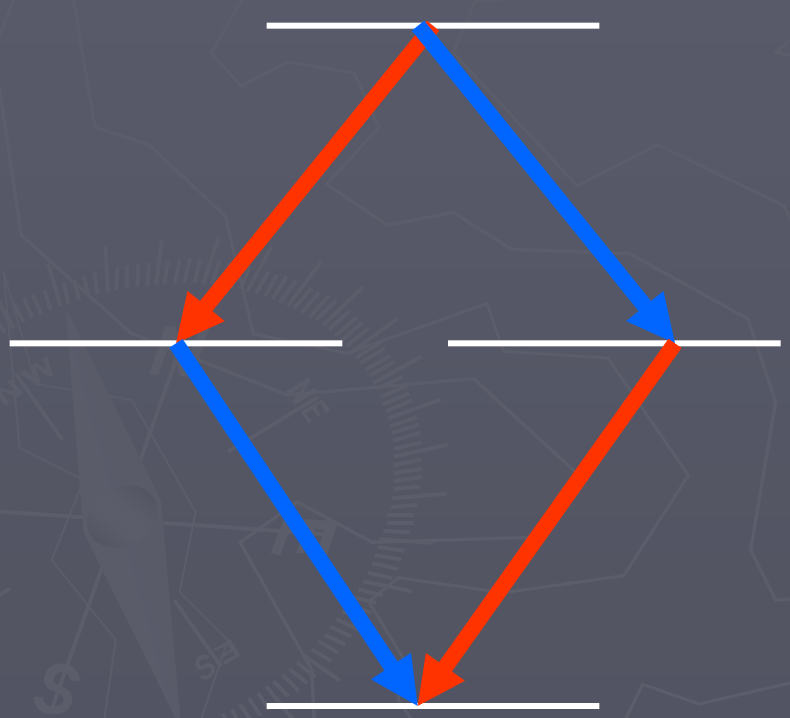
On Demand

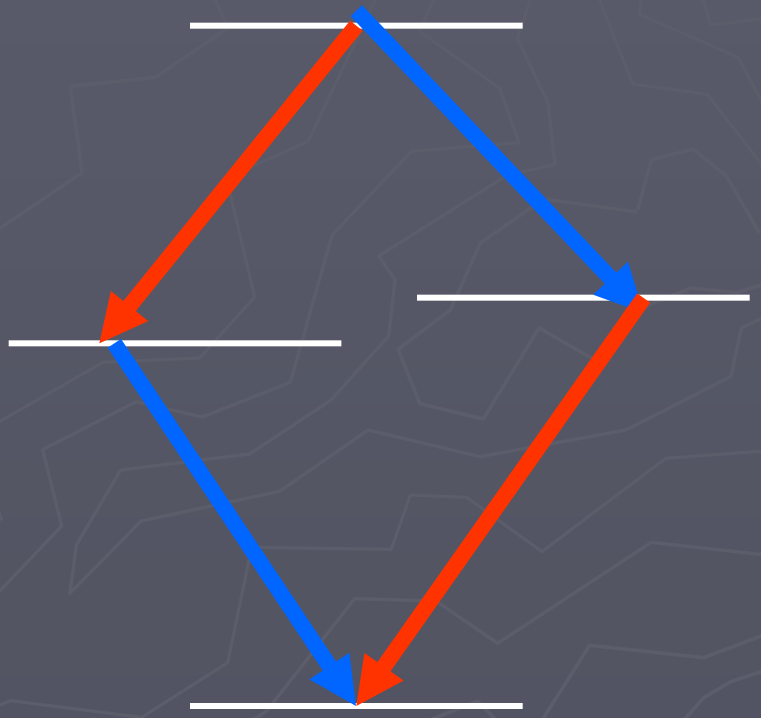


$$
\begin{aligned}
|\Psi\rangle &= |0\rangle \otimes |0\rangle \\
&+ \varepsilon\Big(|0\rangle \otimes |H\rangle + other\ \ junk \Big) \\
&+ \varepsilon^2 \underbrace{(|H\rangle \otimes |V\rangle + |V\rangle \otimes |H\rangle)}_{Bell} \\
&+ \varepsilon^2\Big(|HV\rangle \otimes |0\rangle + other\ \ junk \Big)
\end{aligned}
$$

Need: quantum non-demolition 2 photon counter

Which path?





Color as witness

Photons wave packet

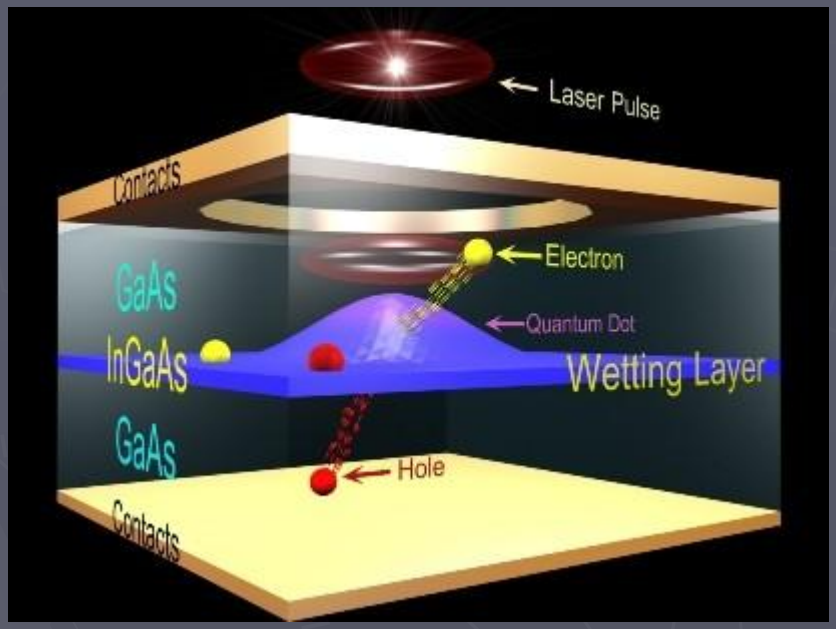
$$|\psi\rangle = \alpha\,|HH\rangle \otimes \overbrace{|p_H\rangle} + \beta\,|VV\rangle \otimes |p_V\rangle$$

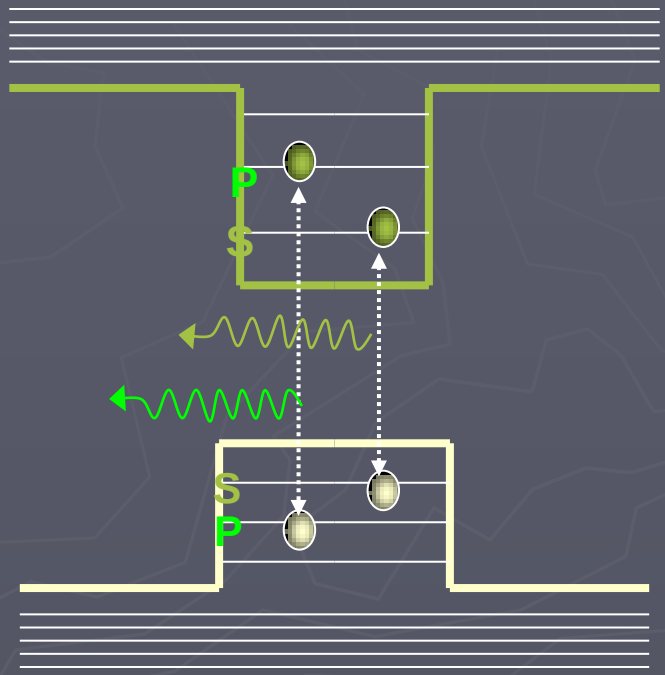
$$\rho = \begin{pmatrix} |\alpha|^2 & 0 & 0 & \gamma \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \gamma & 0 & 0 & |\beta|^2 \end{pmatrix}$$

$$\gamma = \alpha\bar{\beta}\langle p_H|p_V\rangle$$

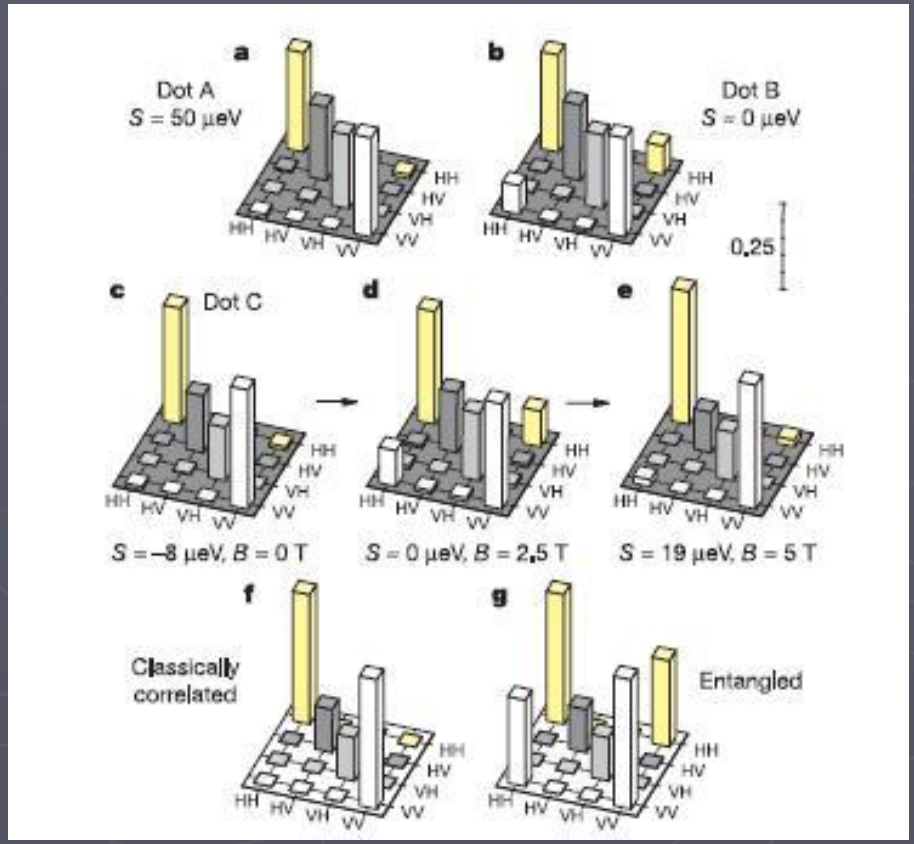
Reliable witnesses to the decay path kill the entanglement

Quantum dots





Naturally unentangled



Shields et. sl. Nature 439 (2006)

Choosing a base

Off diagonal no classical interpretation

$$\sqrt{2}\,|X\pm\rangle = |0\rangle \pm |1\rangle$$

$$2\rho = |X+, X+\rangle\langle X+, X+| + |X-, X-\rangle\langle X- X-| = \frac{1}{4}\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

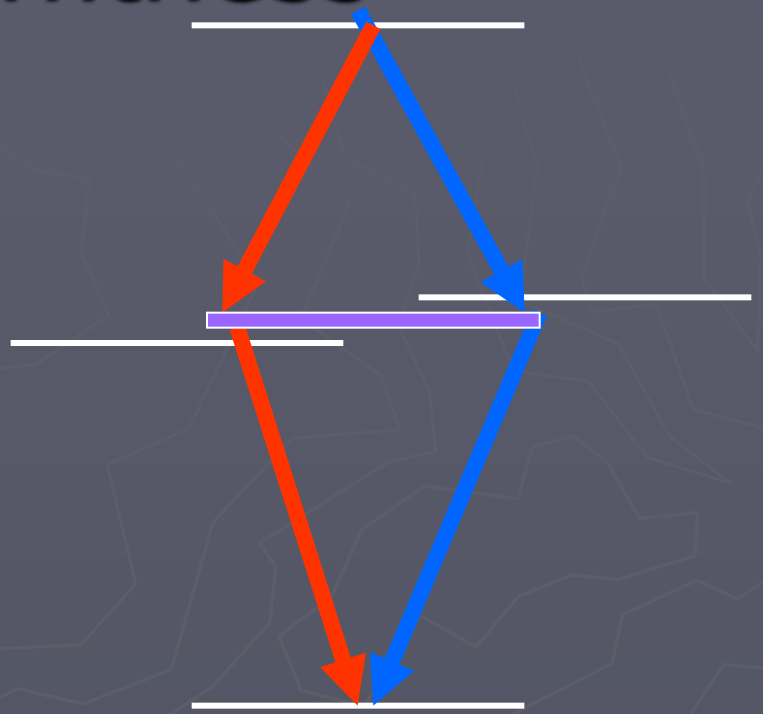
Shields et. sl. Nature 439 (2006)

Eliminating the witness

$$|\psi\rangle$$

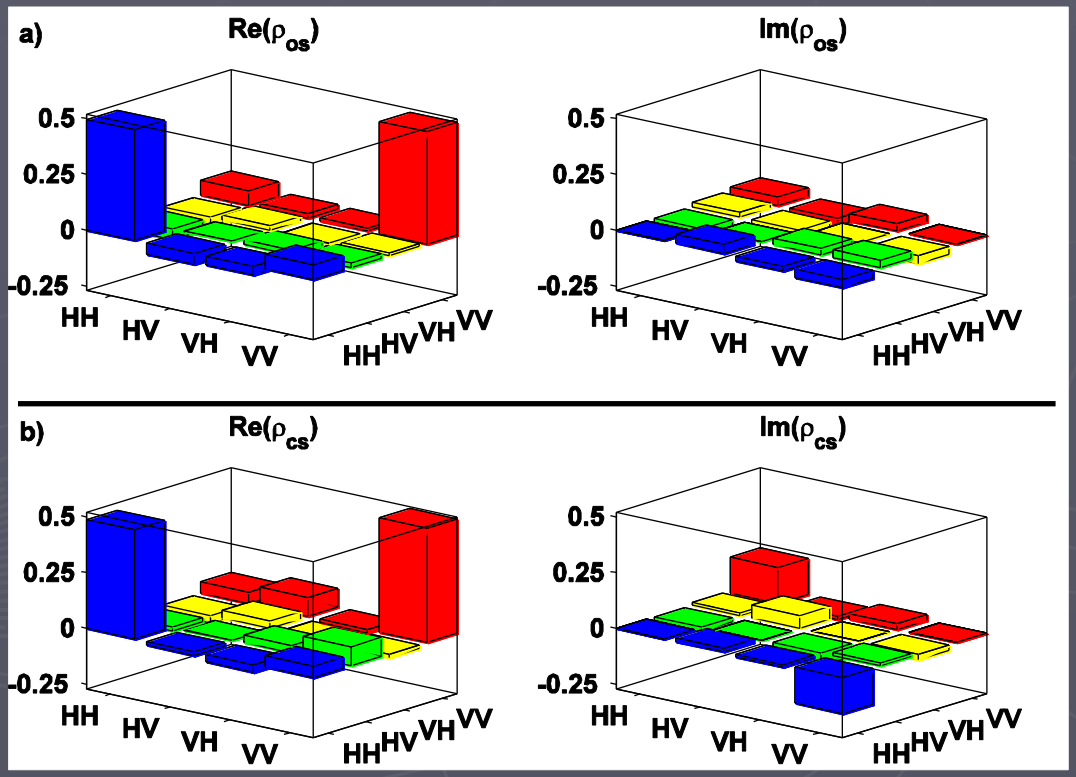
$$\rightarrow \Big(|HH\rangle + |VV\rangle \Big) \otimes |p\rangle$$

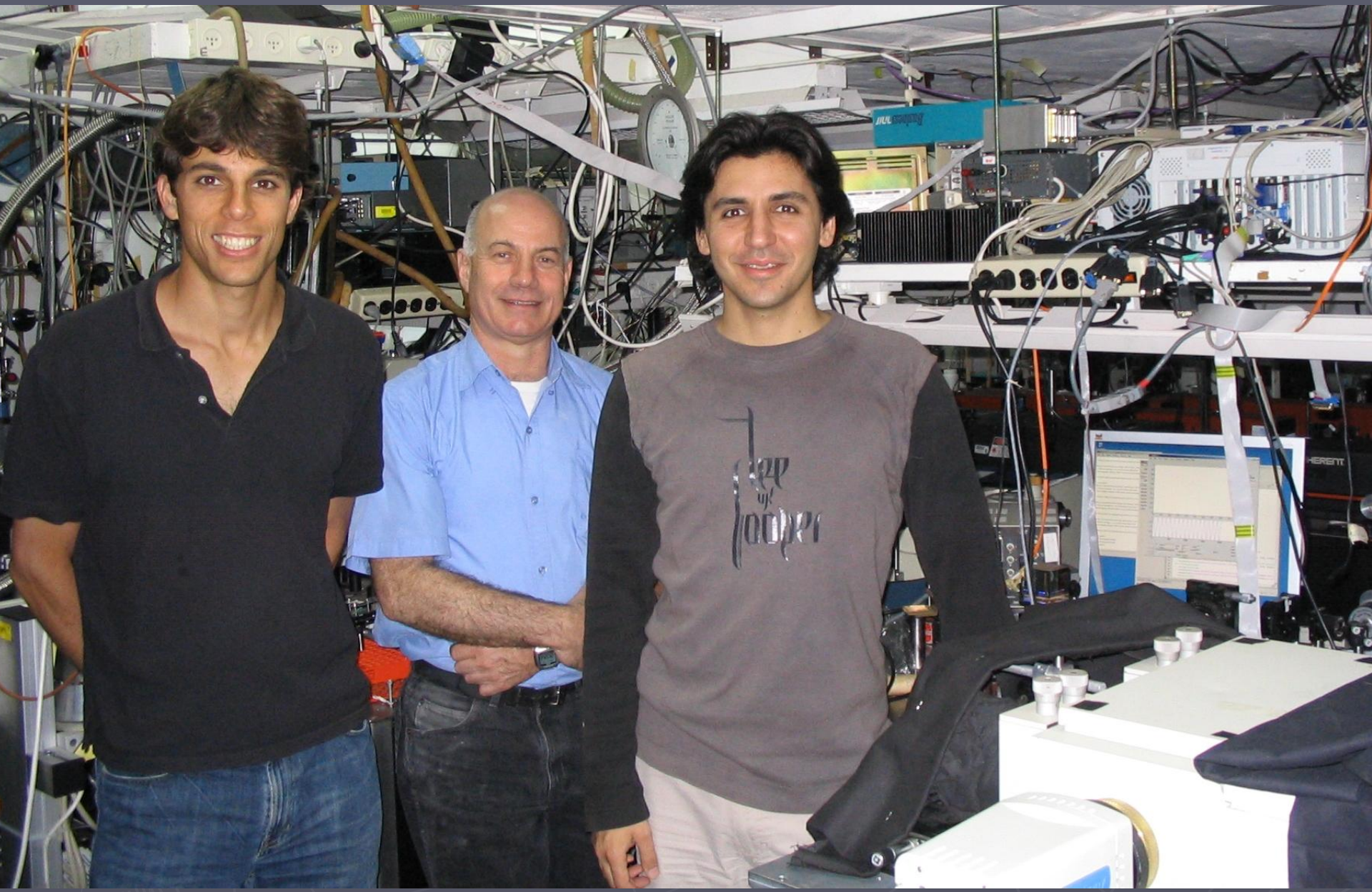
$$\rho = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}$$



Entanglement at a price

Tomography





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with Prof. Dudi Gershoni