INTERFERENCYJNY ŚWIADEK SPLATANIA

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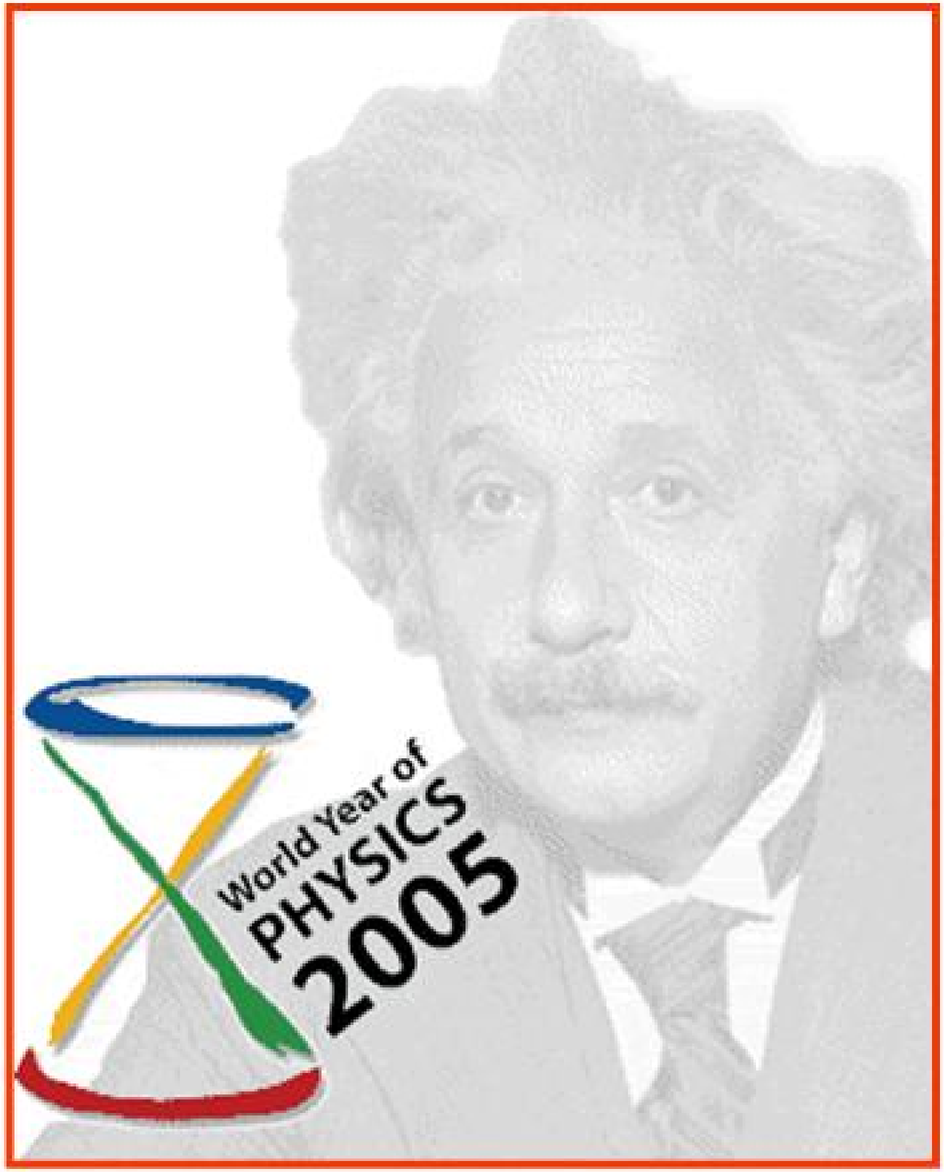
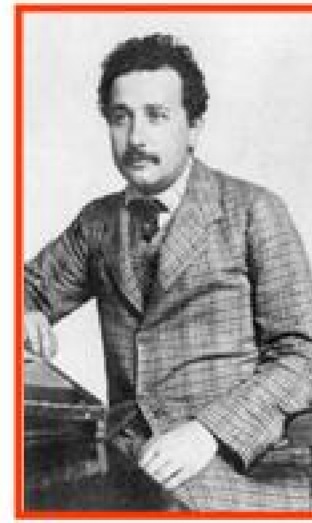
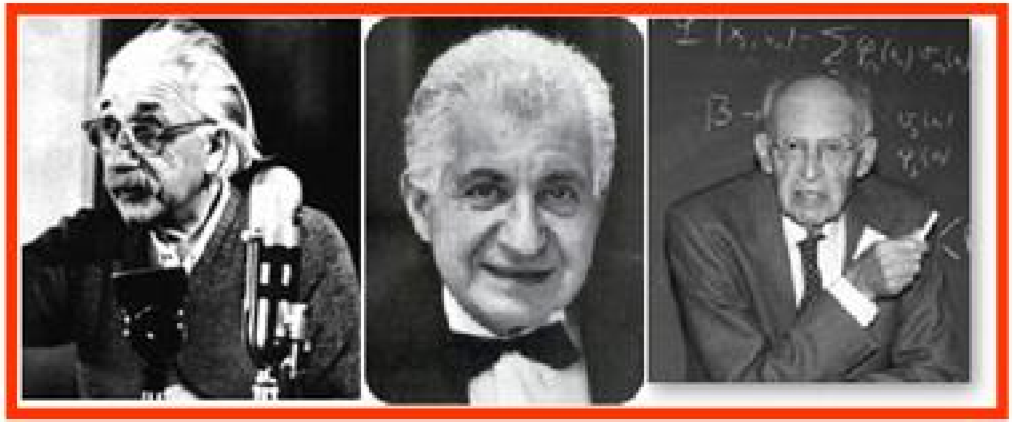




- 1905
  Kwant światła

- 1935
  Kwantowe korelacje



1935

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. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

$$\Psi(x_1, x_2) = \sum_{n=1}^{\infty} \psi_n(x_2) u_n(x_1), \qquad (7)$$

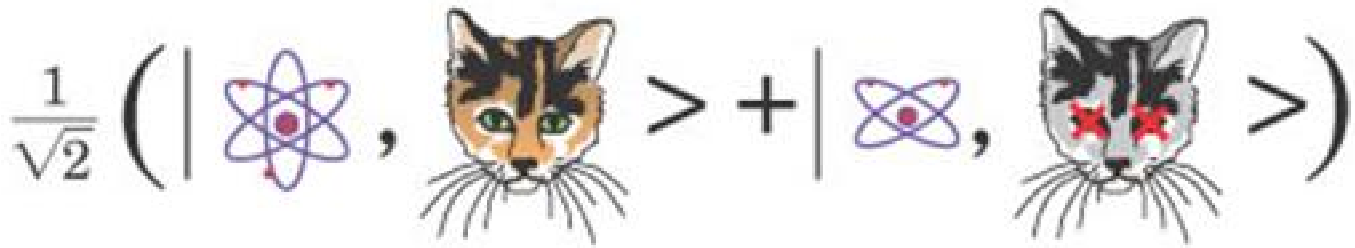
Rozkład Schmidta

$$\Psi(x_1, x_2) = \int_{-\infty}^{\infty} e^{(2\pi i/h)(x_1 - x_2 + x_0)p} dp, \qquad (9)$$

$$\psi_{EPR} \sim \delta(q_a - q_b) \quad \tilde{\psi}_{EPR} \sim \delta(p_a + p_b)$$

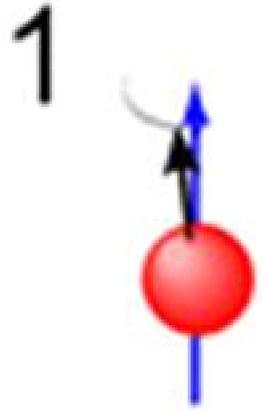
Stan spleciony (1935)

Schrödinger



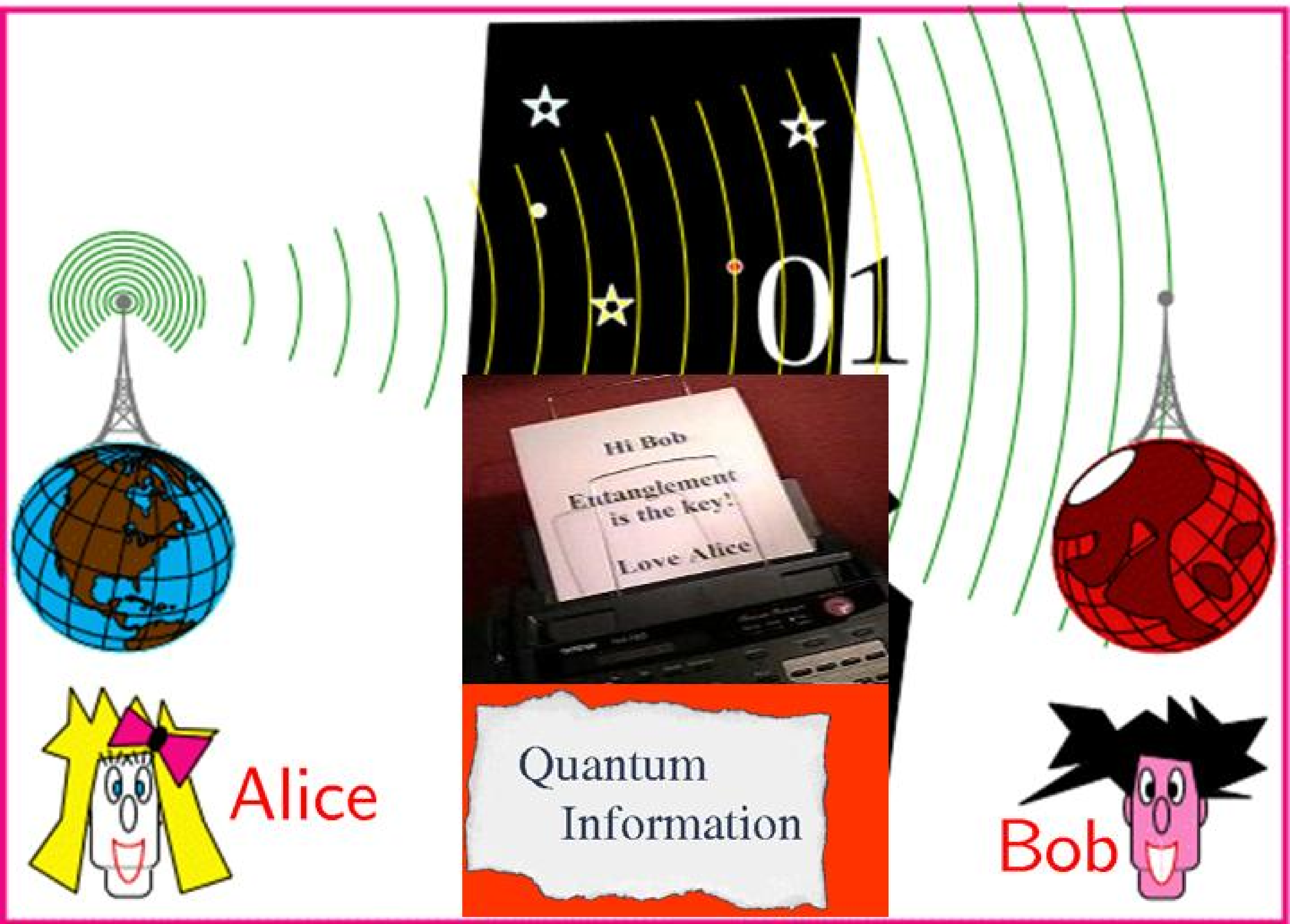
$$|\Psi\rangle \neq |\psi_a\rangle \otimes |\psi_b\rangle$$

Qubit



Stan Bella
Maksymalnie spleciony

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\mathbf{H},\mathbf{V}\rangle + |\mathbf{V},\mathbf{H}\rangle)$$



01
Hi Bob
Entanglement is the key!
Love Alice
Quantum Information
Alice
Bob

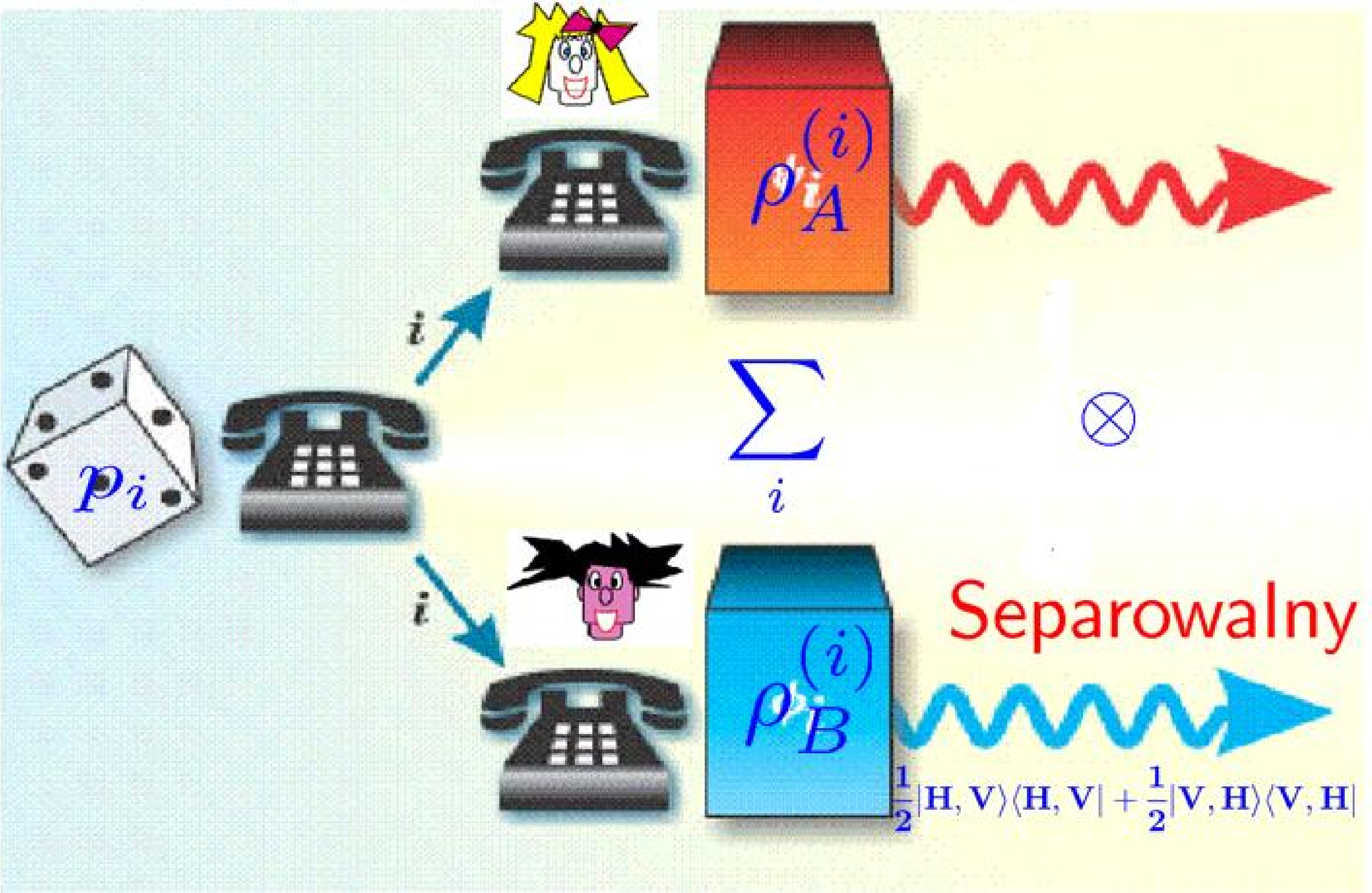
SPLATANIE
10% SALE

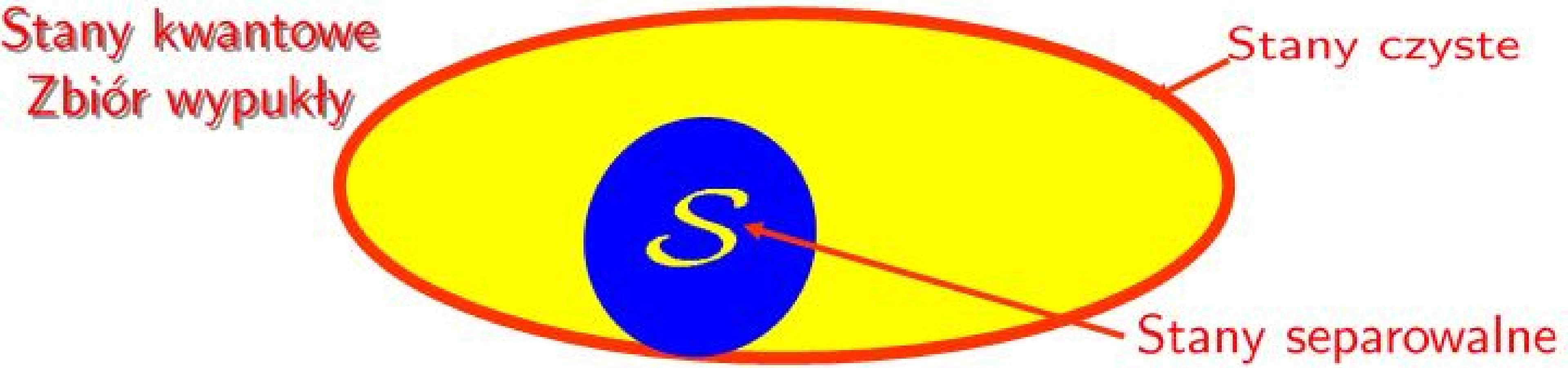
$$\frac{1}{2}|\mathbf{H},\mathbf{V}\rangle\langle\mathbf{H},\mathbf{V}| + \frac{1}{2}|\mathbf{V},\mathbf{H}\rangle\langle\mathbf{V},\mathbf{H}|$$

?

$$\frac{1}{\sqrt{2}}\left(|\mathbf{H},\mathbf{V}\rangle + |\mathbf{V},\mathbf{H}\rangle\right)$$

Kwantowa separowalność, Werner (1989)
Lokalne operacje na stanie i klasyczna komunikacja





$$\rho = p\rho_1 + (1-p)\rho_2, \quad 0 \le p \le 1$$

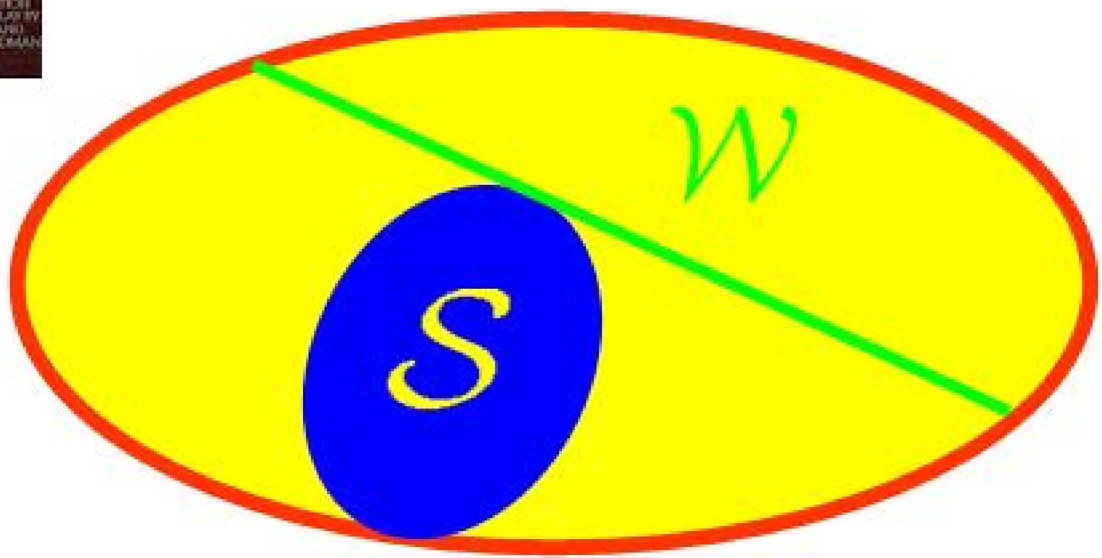
Stany nieseparowalne. Kwantowe.

Stany separowalne. Klasyczne.

$$\rho = \sum p_i \, \rho_A^{(i)} \otimes \rho_B^{(i)}$$

Świadek splatania

$$\langle \hat{\mathcal{W}} \rangle = \begin{cases} \geq 0, & \rho \in \mathcal{S} \\ < 0, & \rho \notin \mathcal{S} \end{cases}$$

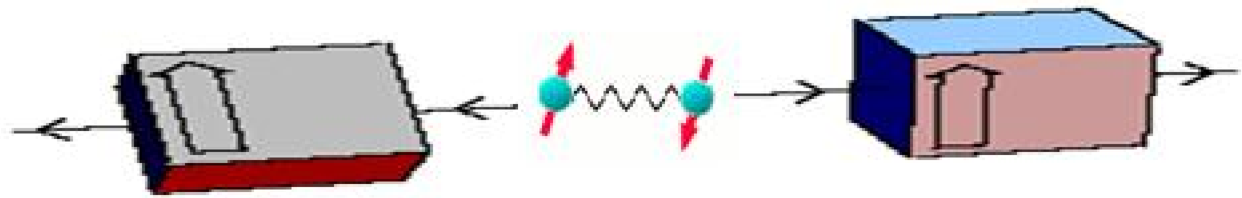


Twierdzenie Hahna Banach

Świadek Bella dla qubitów

J. Bell

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\mathbf{H},\mathbf{V}\rangle + |\mathbf{V},\mathbf{H}\rangle)$$



Nierówność Bella $\mathcal{B} = \langle \hat{B} \rangle \leq 2$

$\hat{\mathcal{W}} = 2 - \hat{B}$ $\langle \hat{\mathcal{W}} \rangle < 0$ jest spleciony

$$\langle \psi | \hat{\mathcal{W}} | \psi \rangle = 2(1 - \sqrt{2}) = -0.8284\ldots$$

Stan Wernera

Wypukła kombinacja separowalnego i nieseparowalnego

$$\rho_{\mathrm{W}} = p\,|\Psi\rangle\langle\Psi| + (1-p)\,\frac{I_a \otimes I_b}{4}$$

$$\rho_W = \sum p_i\,\rho_A^{(i)} \otimes \rho_B^{(i)} \quad \Leftrightarrow \quad 0 \leq p \leq \frac{1}{3}$$

$$\mathrm{Tr}\{\hat{\mathcal{W}}\rho_W\} > 0 \quad \Leftrightarrow \quad 0 \leq p \leq \frac{1}{\sqrt{2}} = 0.7071\ldots$$

nie jest spleciony

Zły świadek

Świadek Bella kłamie

Splecione struktury w NATURZE

?

Splecione struktury gaussowskie

Splatanie fotonów

$$\vec{\mathbf{E}} \sim \vec{\mathbf{e}}(\mathbf{a}\mathbf{e}^{-\mathbf{i}\omega\mathbf{t}} + \mathbf{a}^{\dagger}\mathbf{e}^{\mathbf{i}\omega\mathbf{t}})$$

$$\vec{\mathbf{E}} = \vec{\mathbf{e}}(\mathbf{q}\cos\omega\mathbf{t} + \mathbf{p}\sin\omega\mathbf{t})$$

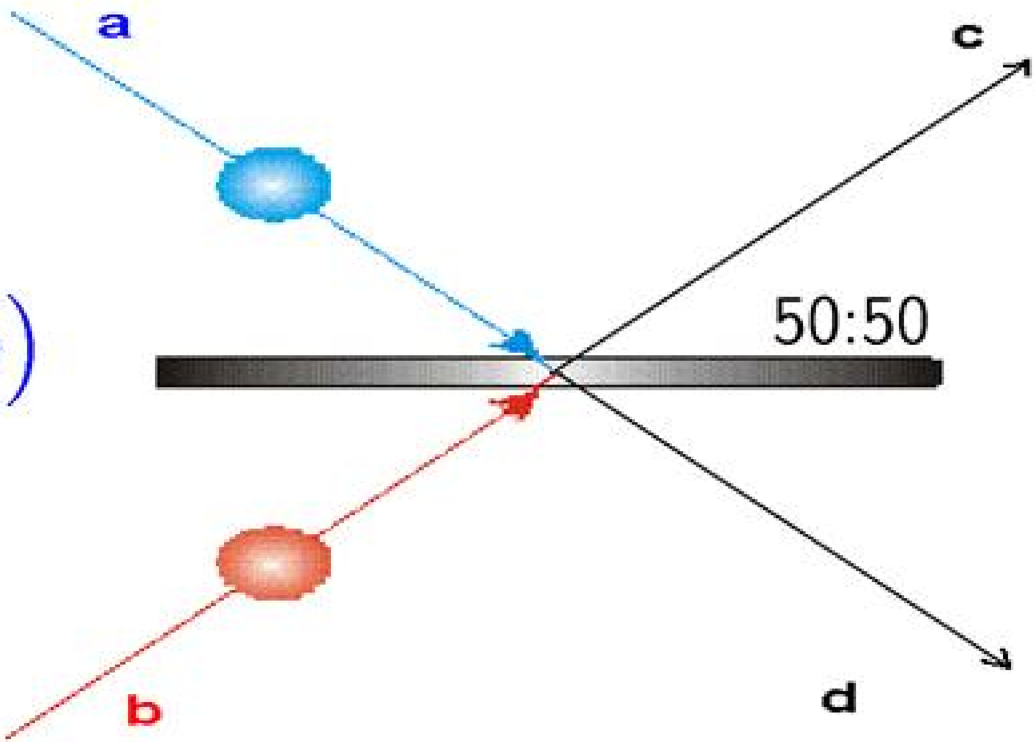
polaryzacja $\vec{e} = (H, V)$

$$[\mathrm{q}, \mathrm{p}] = \mathbf{i}$$

Kwadratury pola

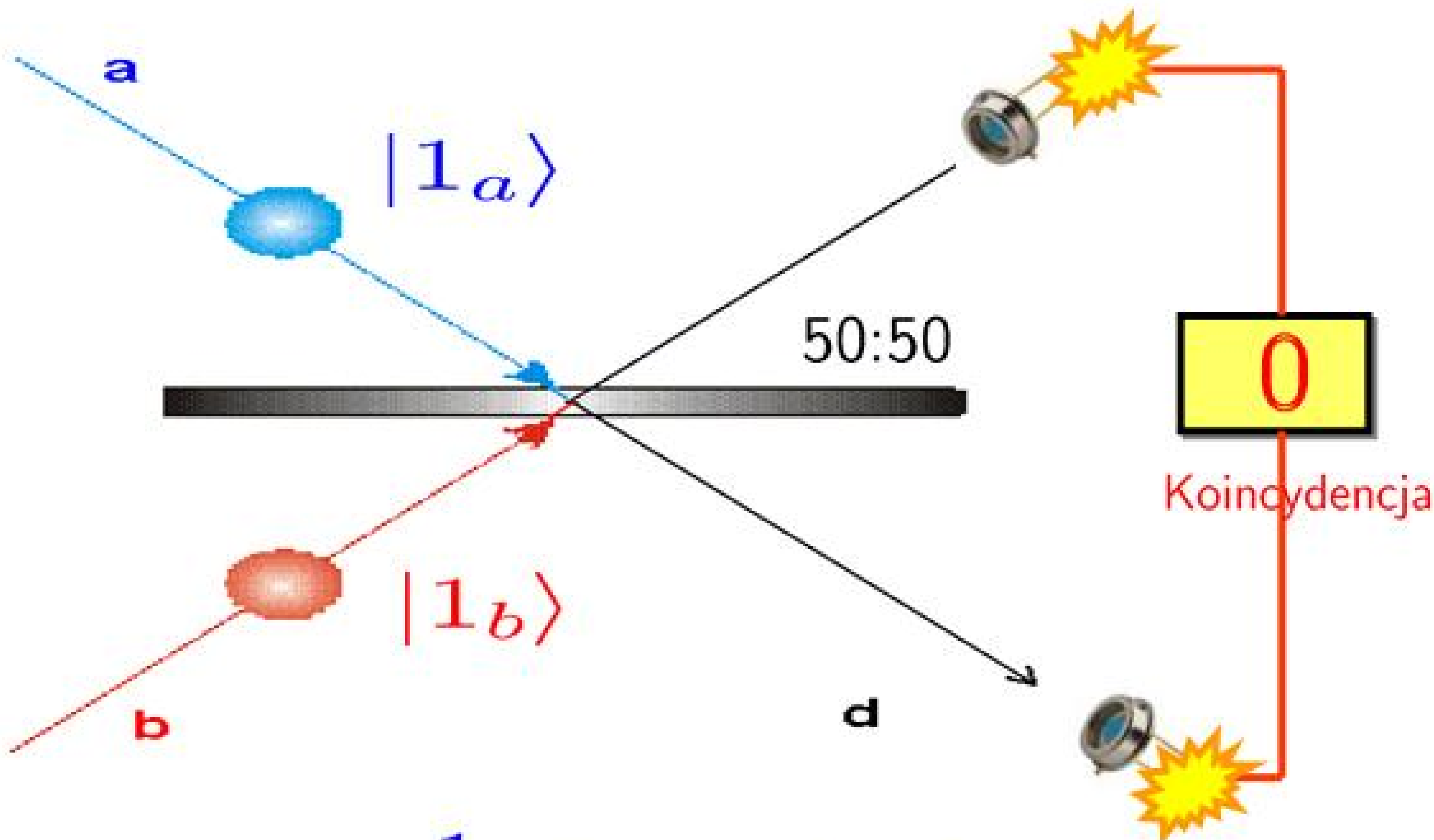
Splatanie fotonów

$\rho_{in}(a,b)$



$\rho_{out}(c,d)$

$$c = \frac{1}{\sqrt{2}}(a+b) \qquad d = \frac{1}{\sqrt{2}}(a-b)$$



$$a^\dagger b^\dagger|0;0\rangle \quad \Rightarrow \quad \frac{1}{2}(c^\dagger + d^\dagger)(c^\dagger - d^\dagger)|0;0\rangle$$

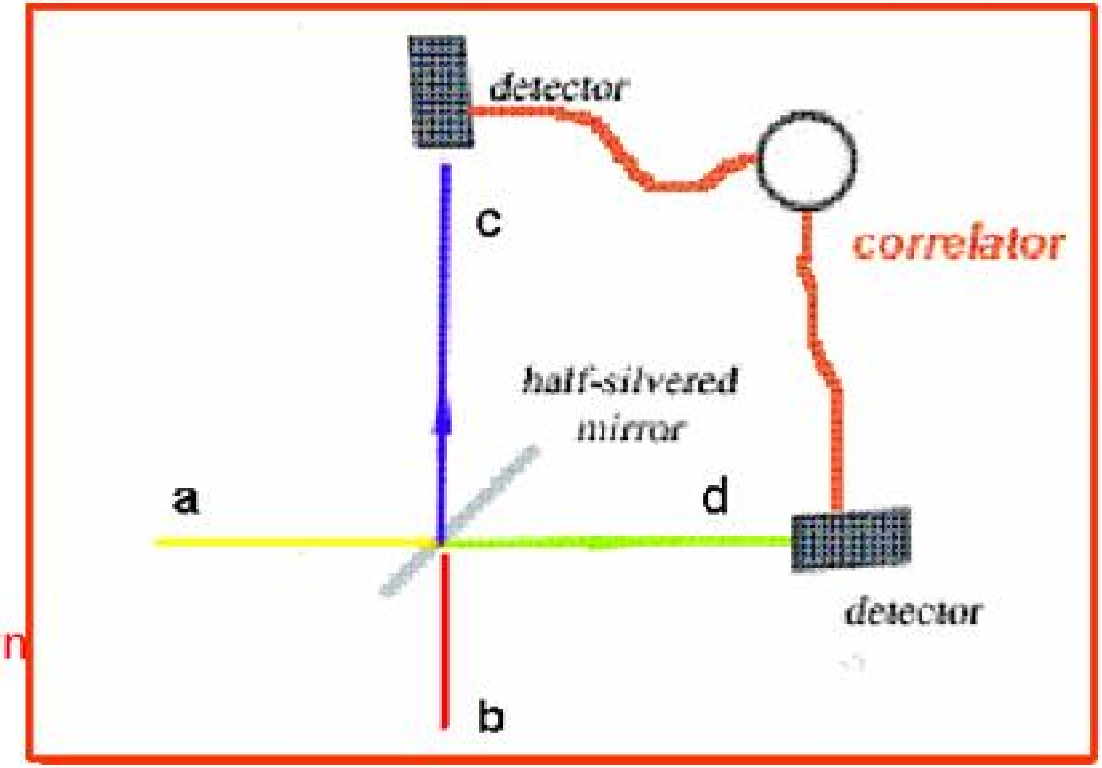
$$\frac{1}{\sqrt{2}}\left(|2,0\rangle - |0,2\rangle\right)$$

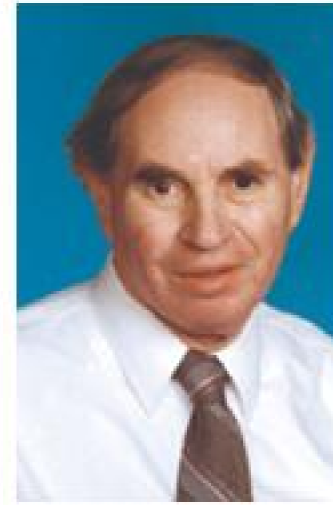
$$\langle \hat{W} \rangle = ?$$

- Interferencja

Świadek interferencyjny

G. Hanbury-Brown
R. Twiss



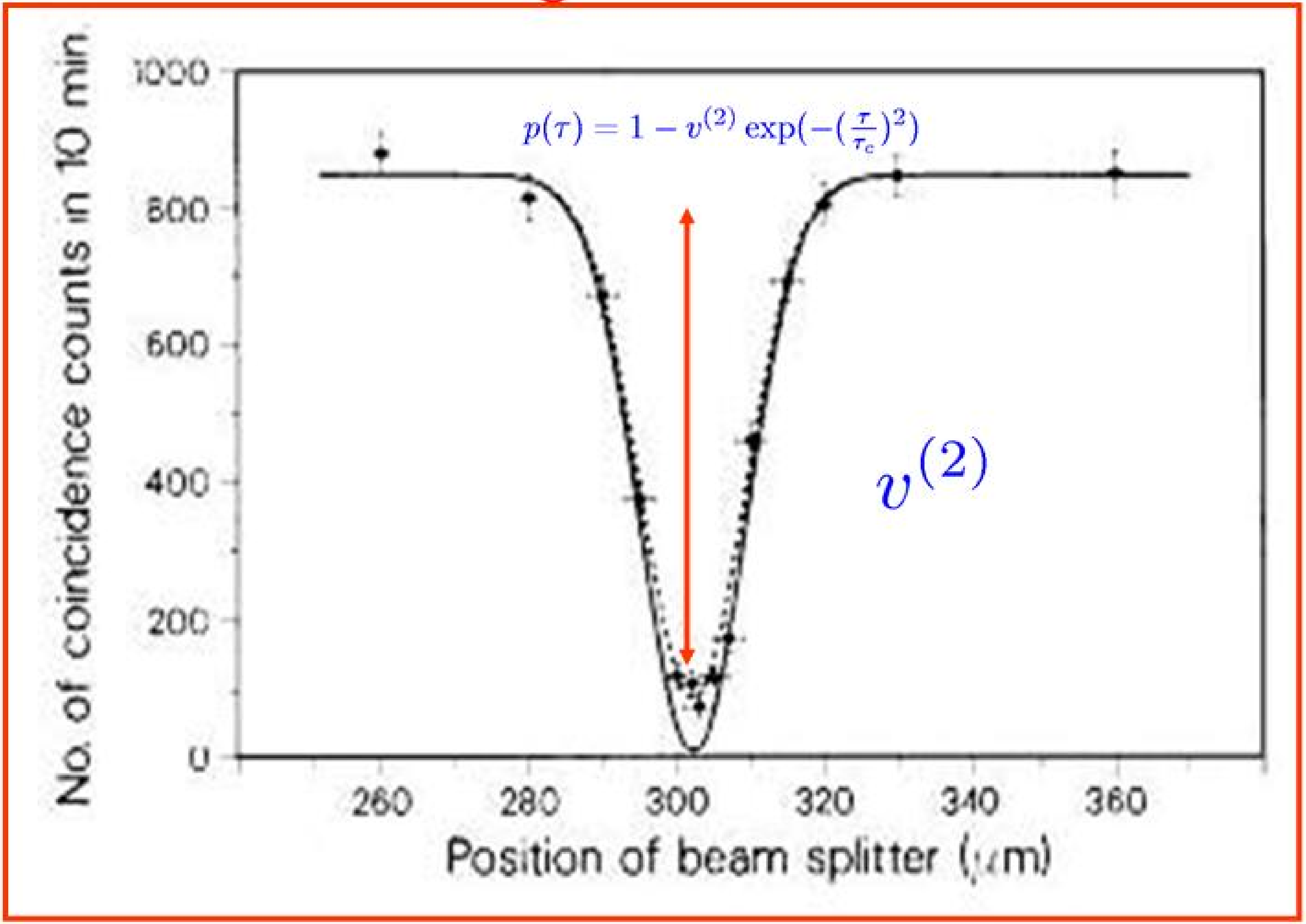


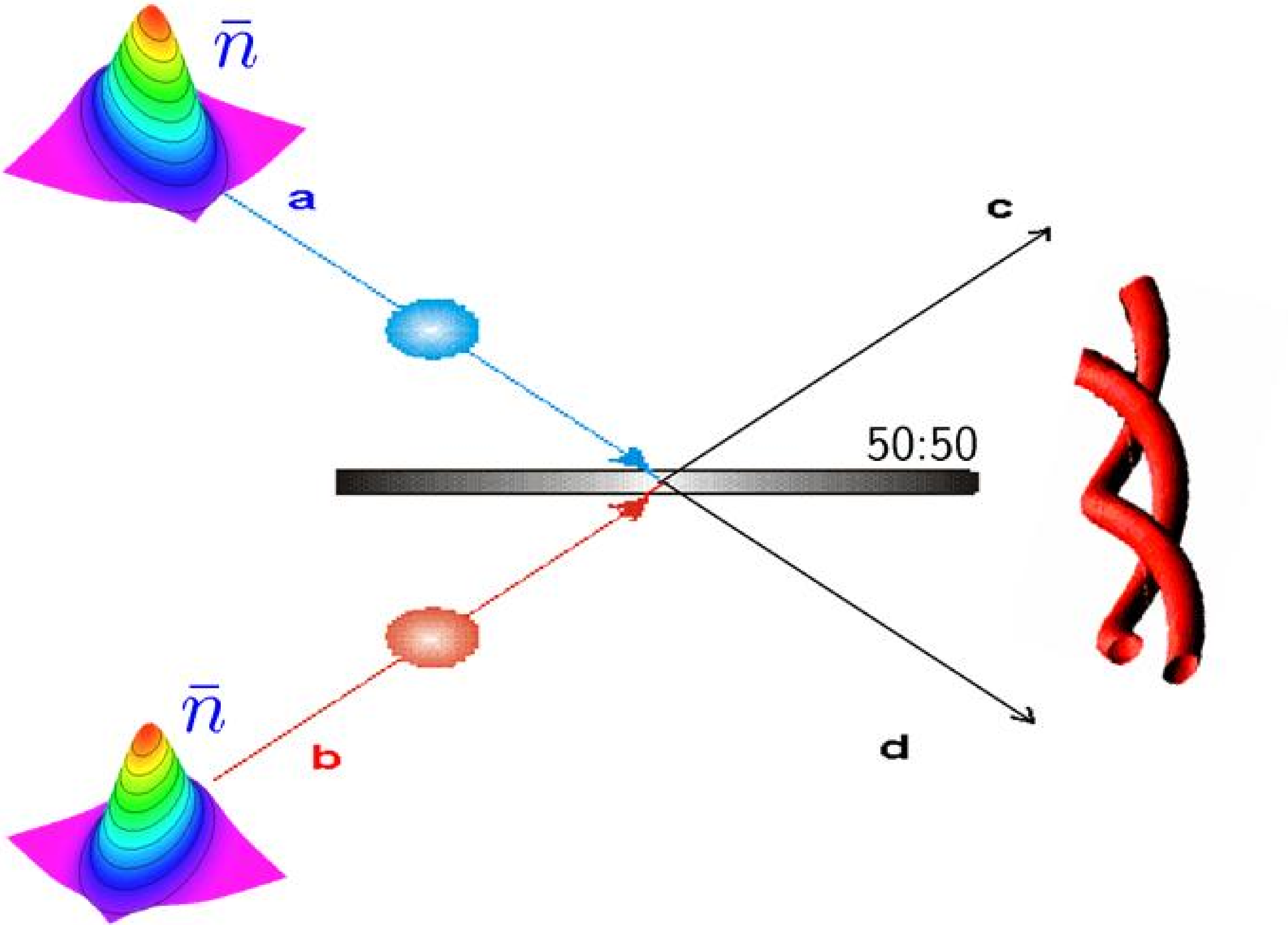
L. Mandel

$$\langle E_d^{(-)}(t)E_c^{(-)}(t+\tau)E_c^{(+)}(t+\tau)E_d^{(+)}(t)\rangle$$

$$p(\tau) = 1 - v^{(2)} \exp(-(\frac{\tau}{\tau_c})^2)$$

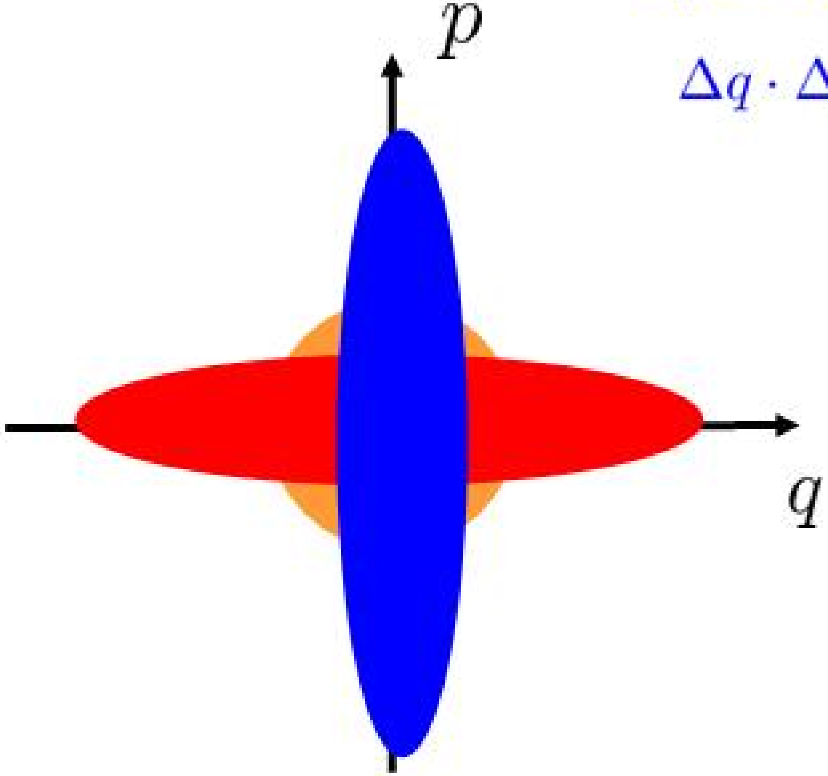
Hong Ou Mandel





$\bar{n}$
a
c
50:50
$\bar{n}$
b
d

Termiczne stany ściśnięte



Stan termiczny

$$\Delta p = \Delta q = \sqrt{\bar{n} + \tfrac{1}{2}}$$

$$\Delta q \cdot \Delta p = \bar{n} + \tfrac{1}{2}$$

Termiczny ściśnięty

$$\Delta q = \sqrt{\bar{n} + \tfrac{1}{2} - m}$$

$$\Delta p = \sqrt{\bar{n} + \tfrac{1}{2} + m}$$

$$\Delta q \cdot \Delta p = \sqrt{(\bar{n} + \tfrac{1}{2})^2 - m^2}$$

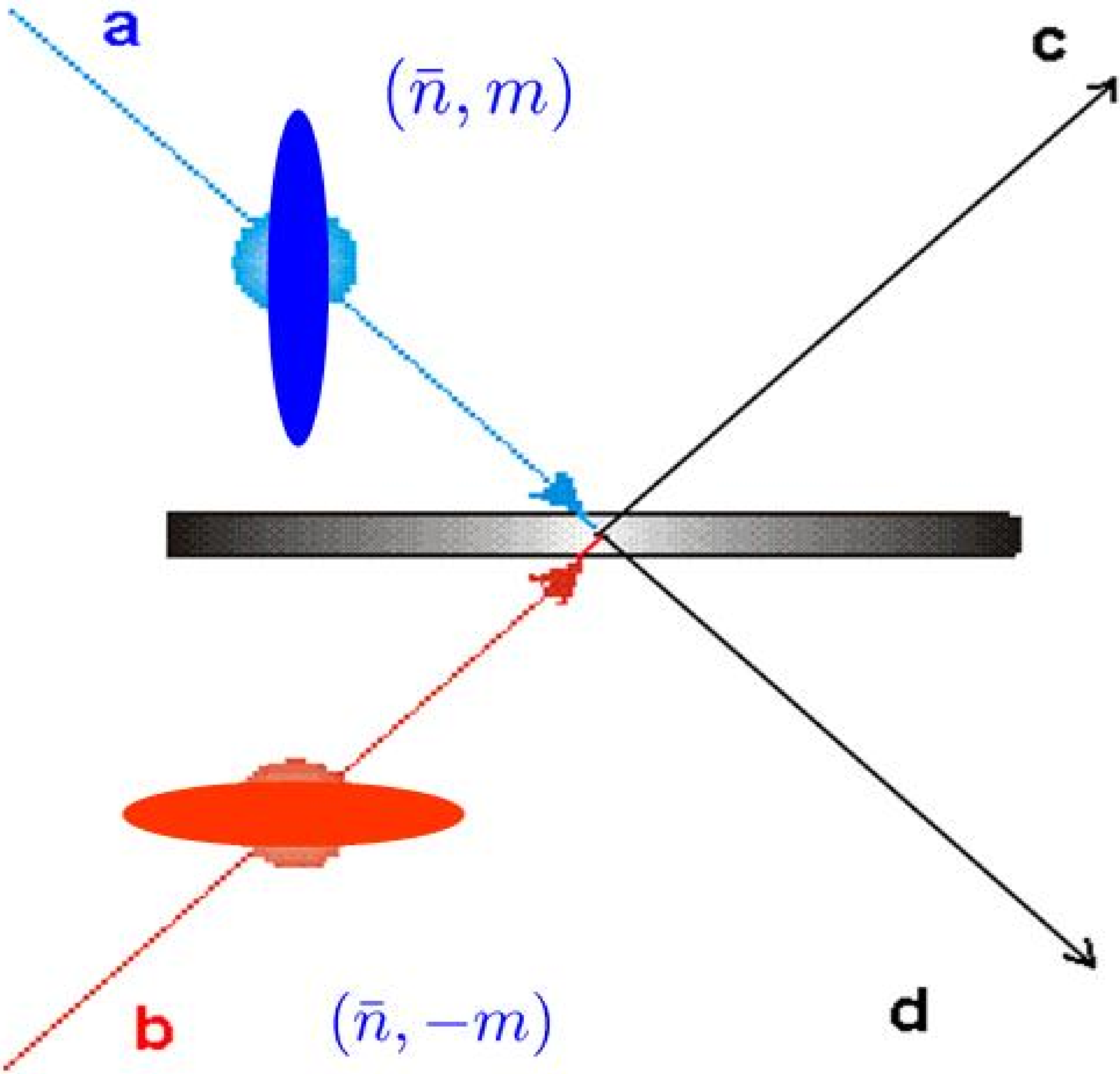
$$0 \leq m \leq \bar{n}(\bar{n}+1)$$

Najbardziej ogólny stan Gaussa

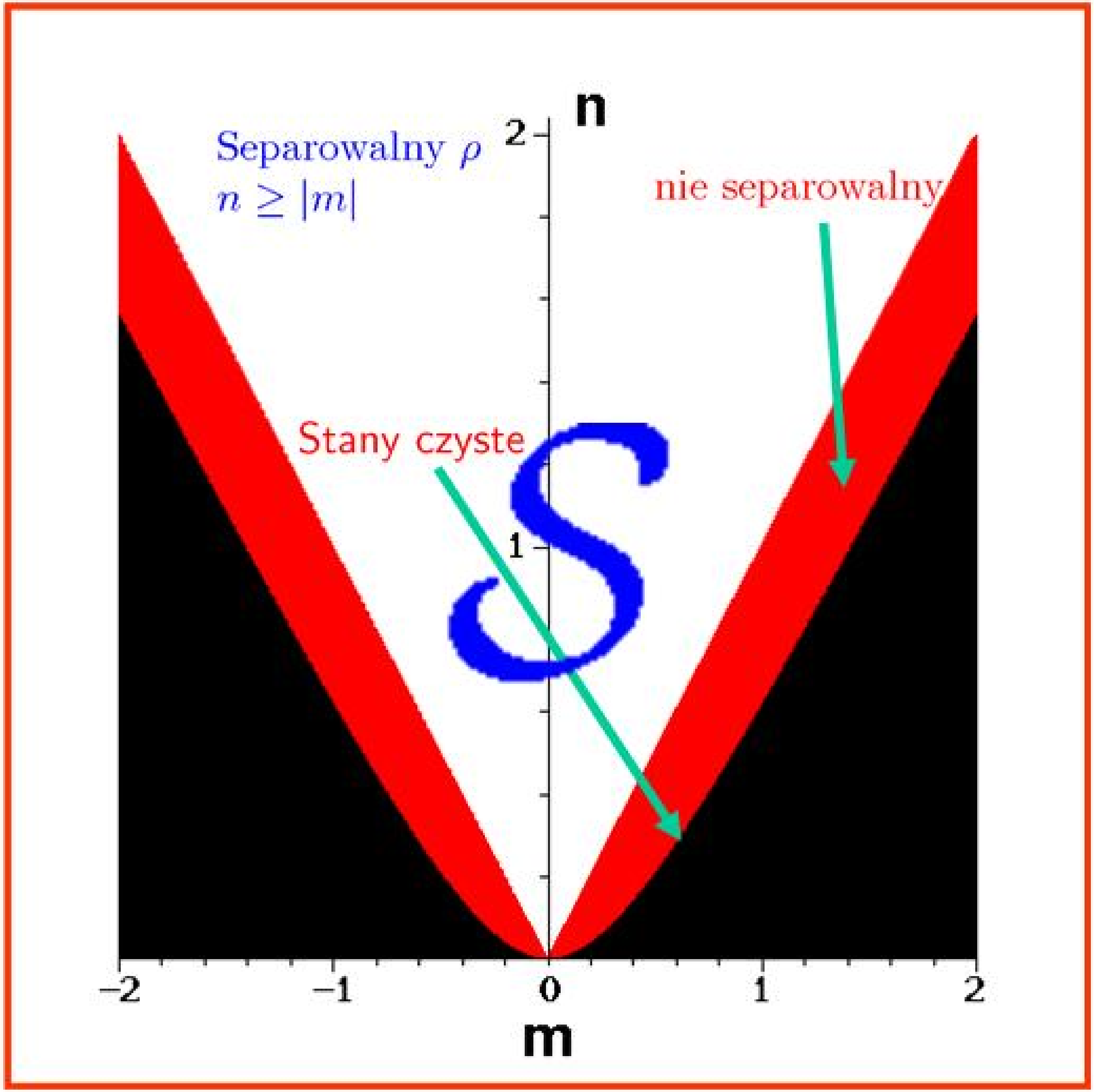
$$\rho_S = \frac{e^{-(\bar{n})a^\dagger a - (m^*)a^2 - (m)a^{\dagger\,2}}}{Z}$$

Splatanie stanów ściśniętych

M. Stobińska, K.W.
G. Leuchs

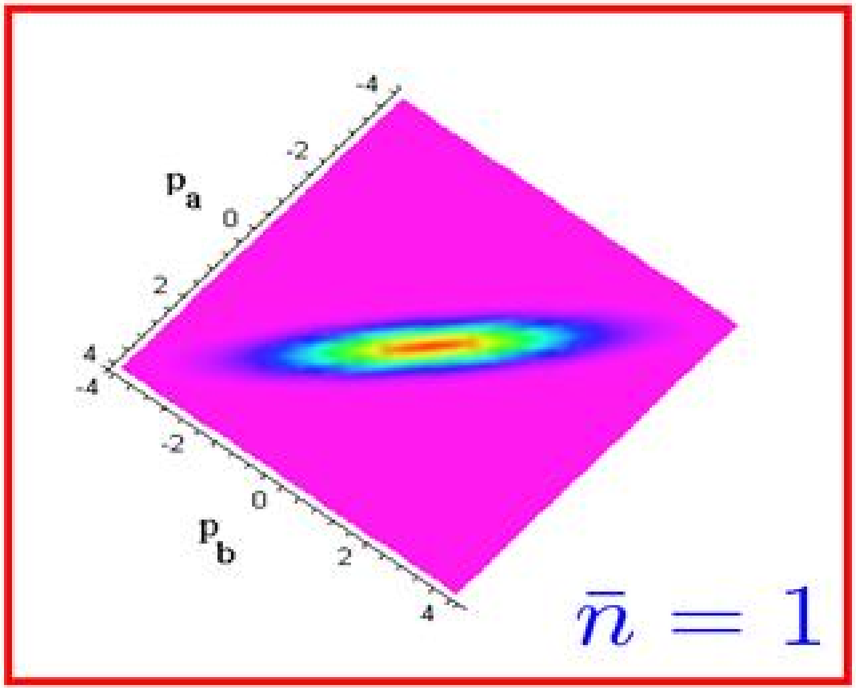


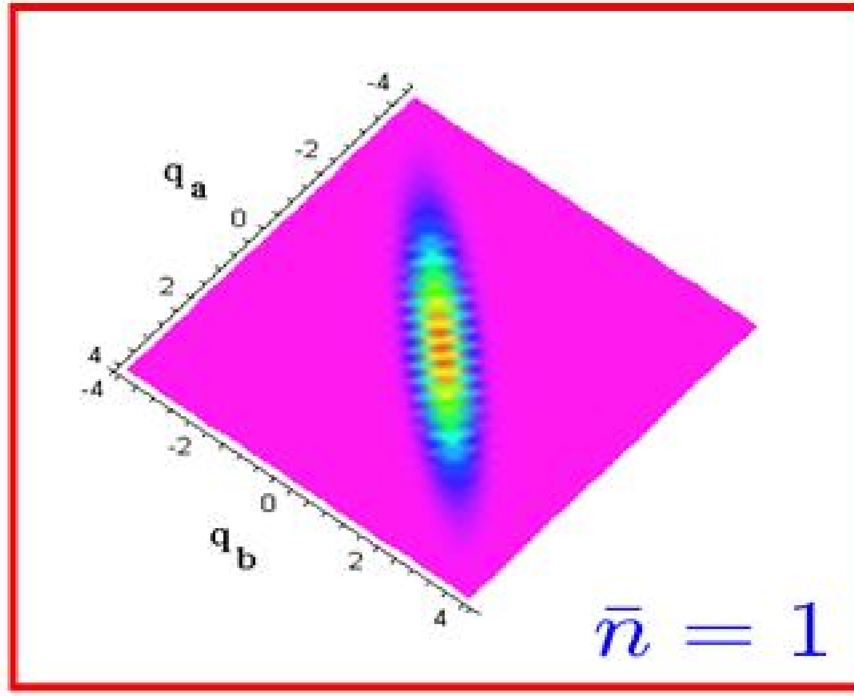
$$\rho_{AB}(\bar{n}, m)$$



Separowalny ρ
$n \geq |m|$
nie separowalny
Stany czyste
S
n
m
2
1
0
−2
−1
0
1
2

Stan czysty



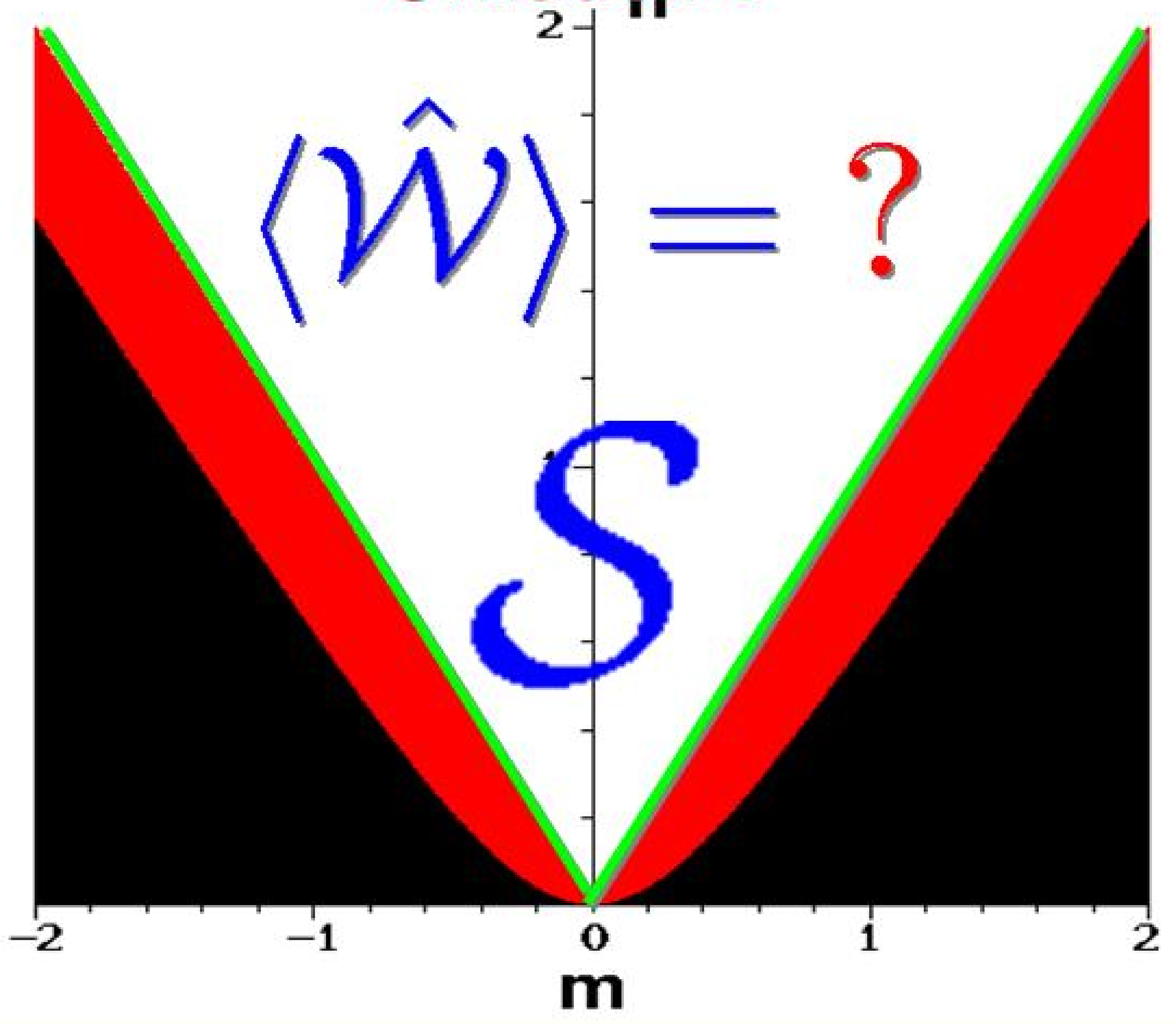


$$\bar{n} \to \infty$$

$$\Psi_{\mathrm{EPR}} \sim |0,0\rangle + |1,1\rangle + |2,2\rangle \cdots$$

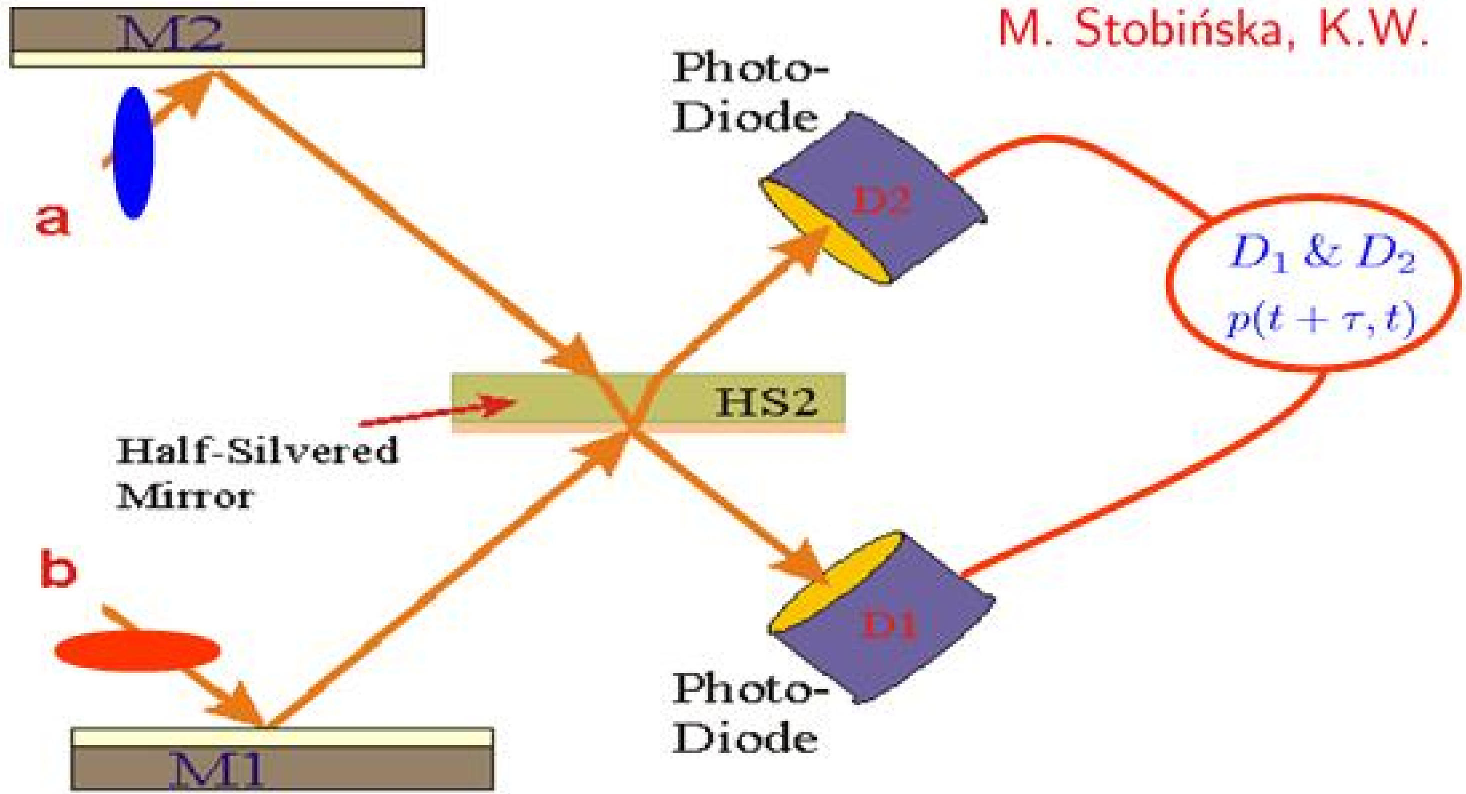
$$\Psi_{\mathrm{EPR}}(q_a, q_b) \sim \delta(q_a - q_b) \quad \tilde{\Psi}_{\mathrm{EPR}}(p_a, p_b) \sim \delta(p_a + p_b)$$

Świadek ?



Interferencyjny Świadek

M. Stobińska, K.W.



$$\mathcal{W}^{(HBT)} = \frac{1}{2} - \frac{2a^\dagger b^\dagger ab + {b^\dagger}^2 a^2 + {a^\dagger}^2 b^2}{\langle : (a^\dagger a + b^\dagger b)^2 : \rangle}$$

$$\mathrm{Tr}\{\mathcal{W}^{(HBT)}\rho\} = \frac{n^2 - |m|^2}{2(3n^2 + |m|^2)} = \begin{cases} \geq 0, & \text{separowalny} \\ < 0, & \text{nieseparowalny} \end{cases}$$

Interferencja HBT
Dołek Hong-Ou-Mandela

$$\langle E_d^{(-)}(t)E_c^{(-)}(t+\tau)E_c^{(+)}(t+\tau)E_d^{(+)}(t)\rangle \Longleftrightarrow \langle\hat{\mathcal{W}}\rangle$$

$$p(\tau) = 1 - v^{(2)}\exp(-(\frac{\tau}{\tau_c})^2)$$

$$\boxed{v^{(2)} = \frac{n^2+|m|^2}{3n^2+|m|^2}}$$

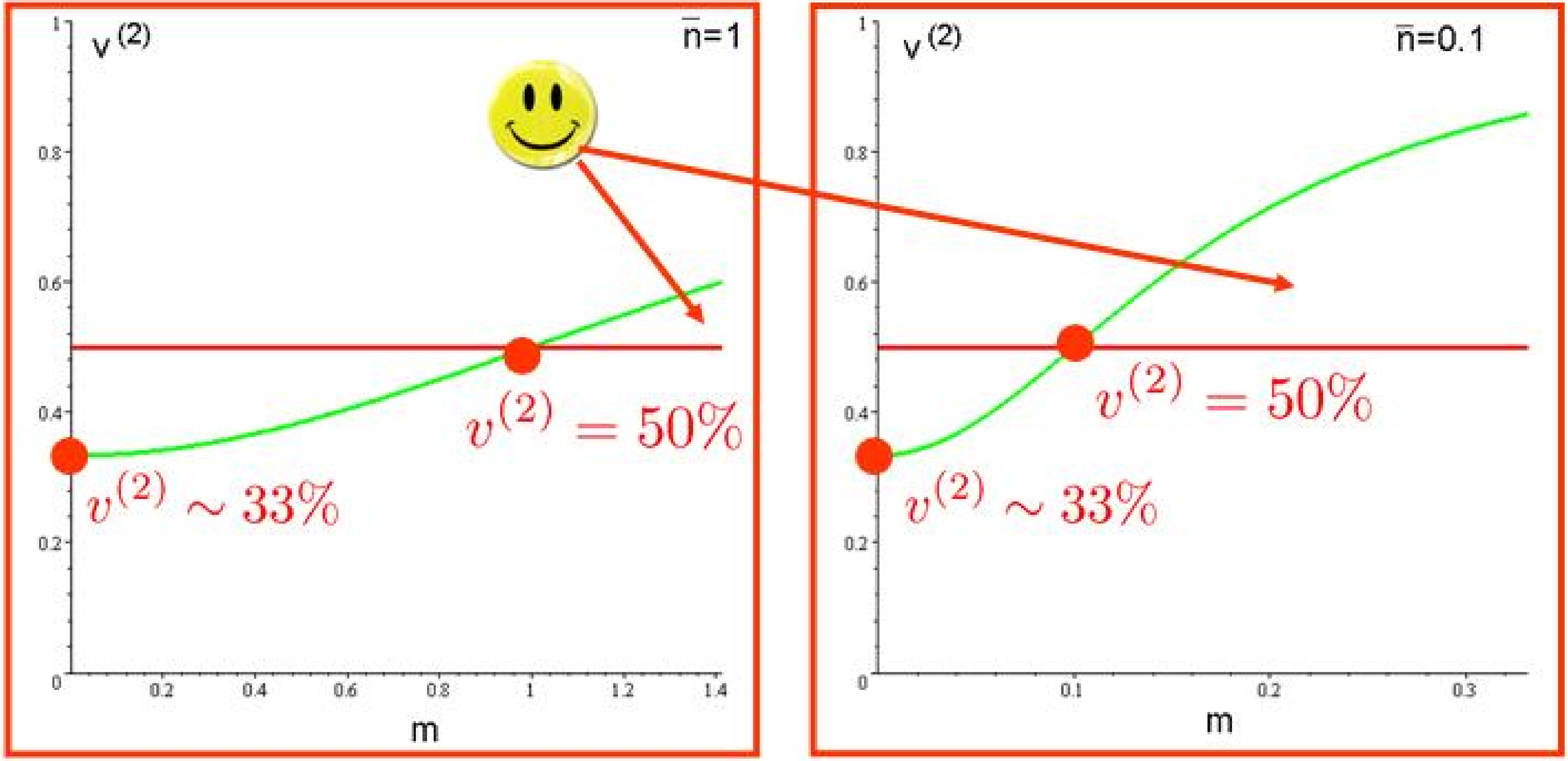
$$\langle\hat{\mathcal{W}}\rangle = \frac{1}{2} - v^{(2)}$$

Widzialność

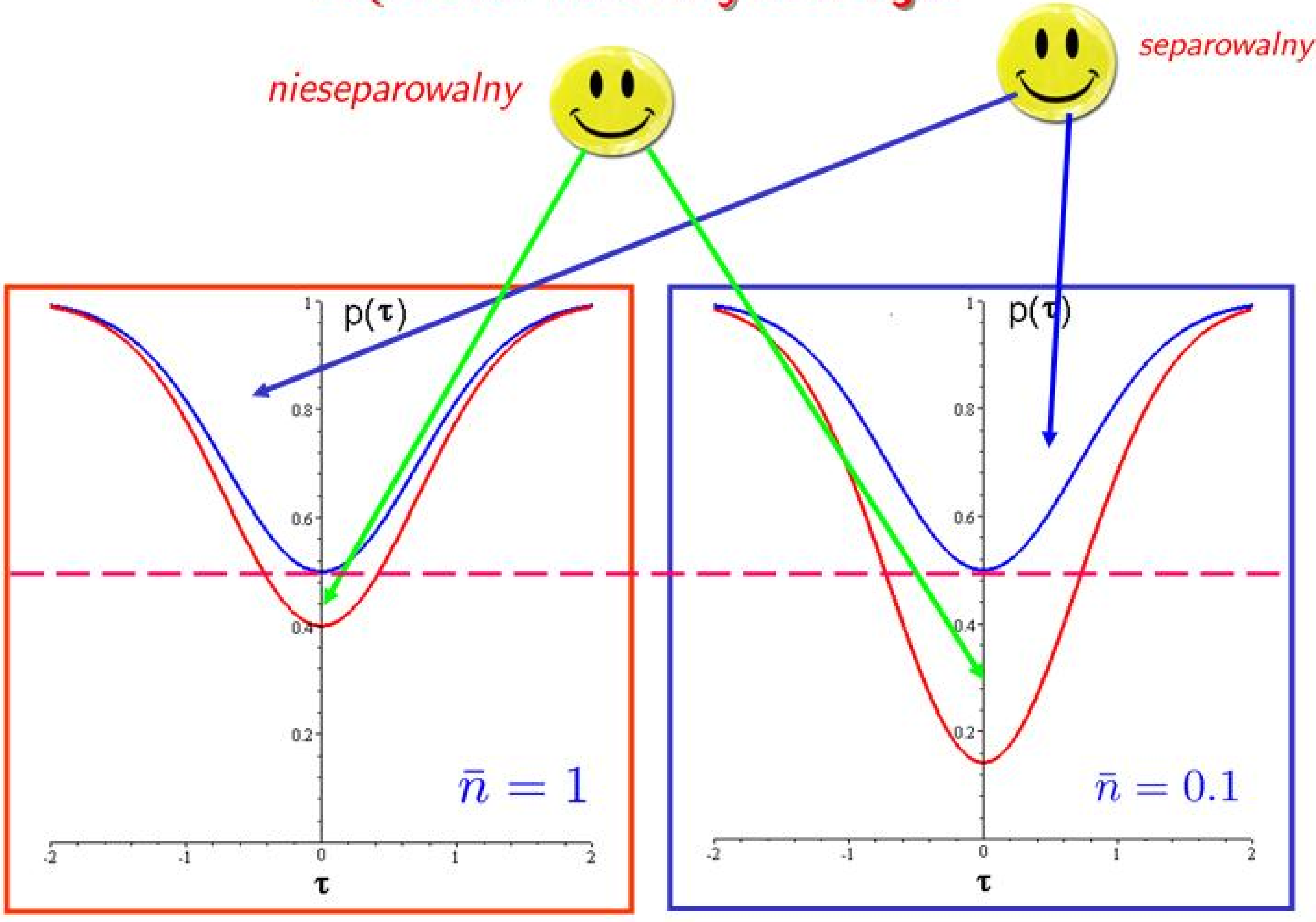
$$v^{(2)} = \frac{n^2 + |m|^2}{3n^2 + |m|^2}$$

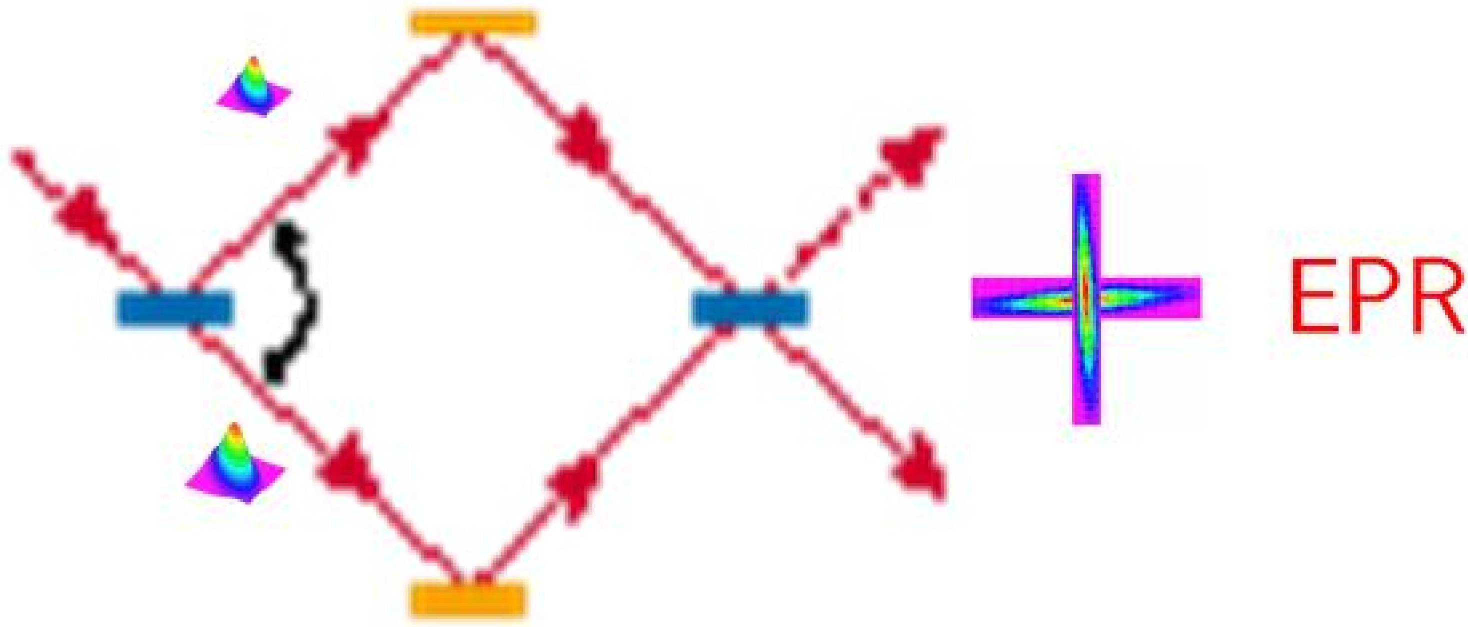
separowalny $\bar{n} = m \rightarrow v^{(2)} = 50\%$

nieseparowalny $\rightarrow v^{(2)} \geq 50\%$



Łączna koincydencja





$$\mathcal{W}^{(HBT)} = \frac{1}{2} - \frac{2a^\dagger b^\dagger ab + b^{\dagger 2} a^2 + a^{\dagger 2} b^2}{\langle : (a^\dagger a + b^\dagger b)^2 : \rangle}$$

$\mathrm{Tr}\{\mathcal{W}^{(HBT)} \rho_{EPR}\} =< 0$ nieseparowalny