Entanglement & wave-particle duality

Mostly a review

(in a slightly different way of seeing it)

Thiago Guerreiro

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"Nobody understands quantum mechanics"

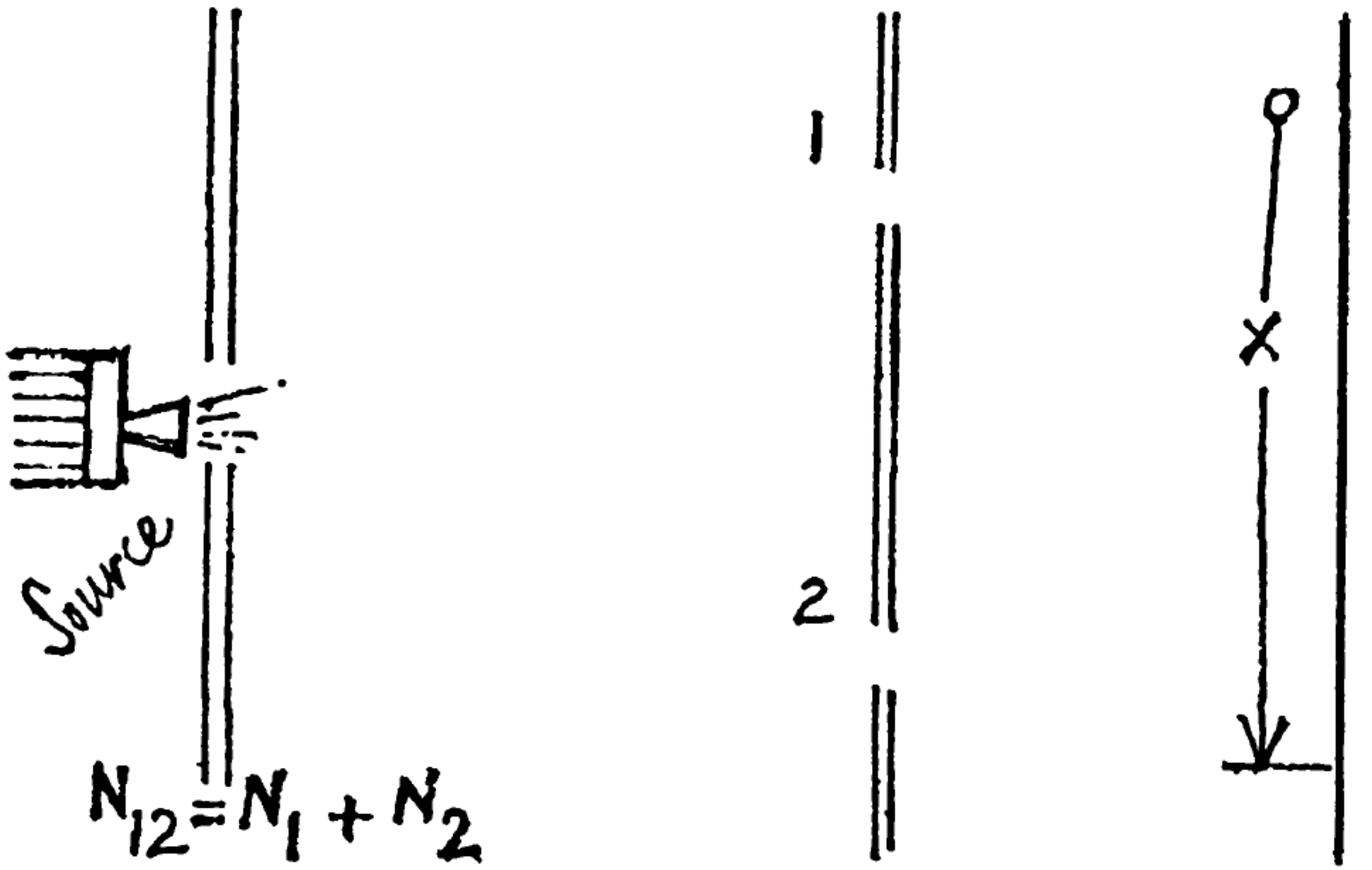


Figure 28

Figure: R. P. Feynman. The character of Physical law

"Nobody understands quantum mechanics"

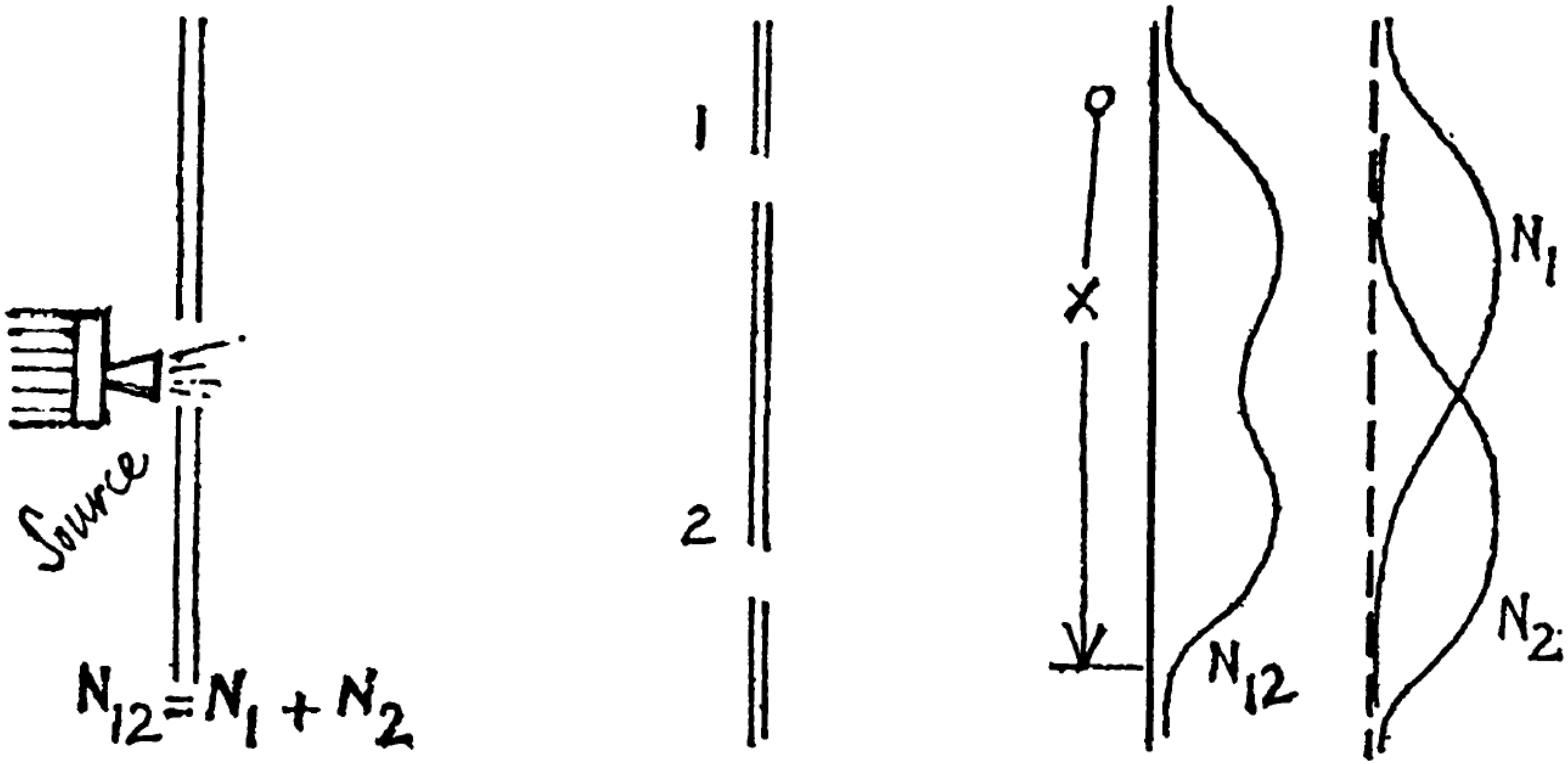
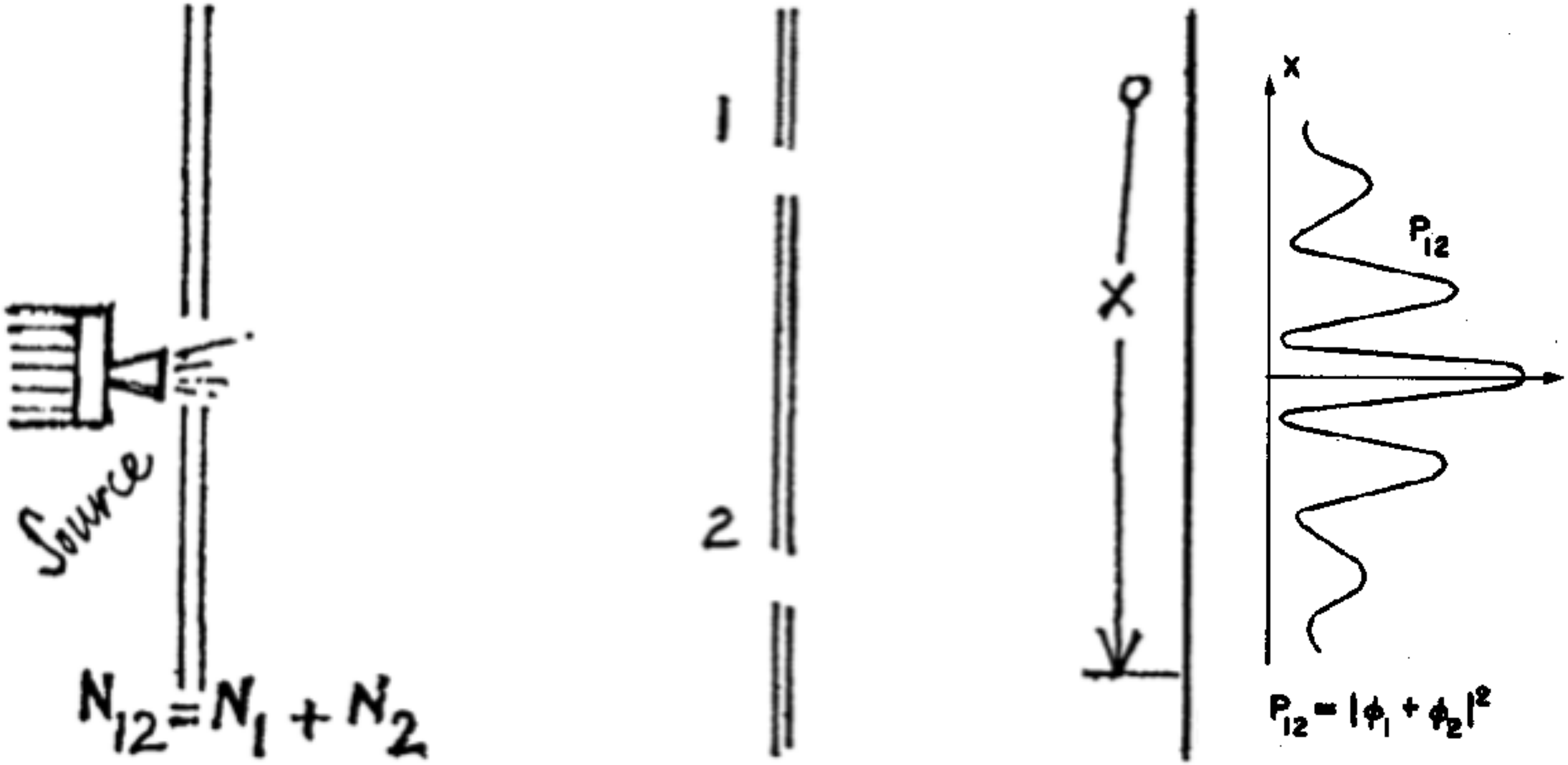


Figure 28

Expectation

Figure: R. P. Feynman. The character of Physical law

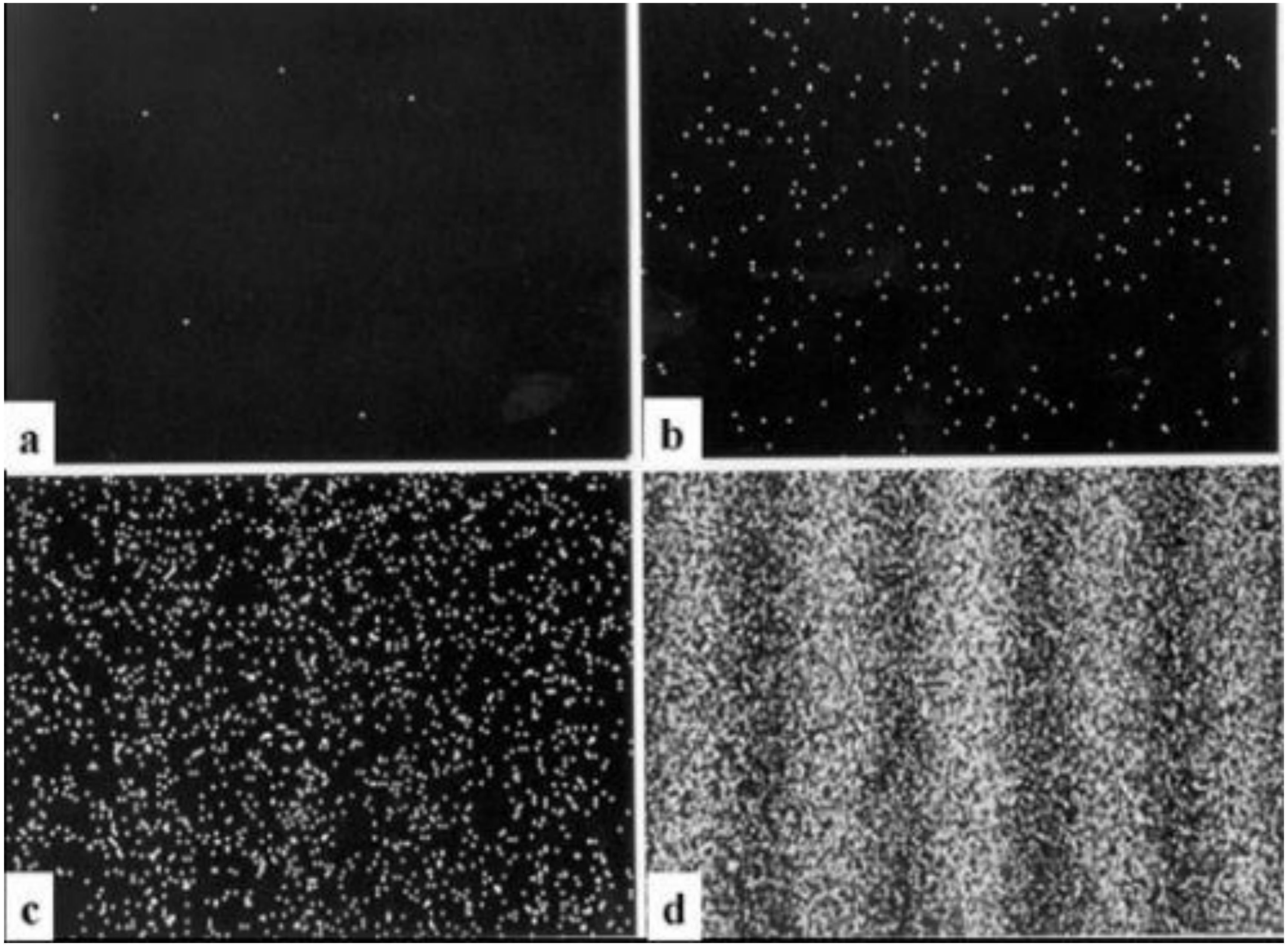
“Nobody understands quantum mechanics”



Result

Figure: R. P. Feynman. The character of Physical law

"Nobody understands quantum mechanics"



Result

Figure: Akira Tonomura

“Nobody understands quantum mechanics“

(not quite true.)

Individual “particles“ seem to exhibit wave-behavior.

Not a wave in some medium, but a wave of ‘information’

Why do we call'em particles?

* Energy comes in discrete packets

* Spin comes in discrete packets

* Charge comes in discrete packets

Why do we call'em waves?

* Essentially interference

Particle or wave?

But it's neither!

A monk asked, "Does a dog have a Buddha-nature or not?"

The master said, "Mu!"

Green, James. "The recorded sayings of Zen master Zhau Zhou"

Particle or wave?

But it's neither!

We spend a lot of time trying to understand the "Mu" category

Particle or wave?

But it's neither!

In fact, it's just a point in projective Hilbert space.

Particle or wave?

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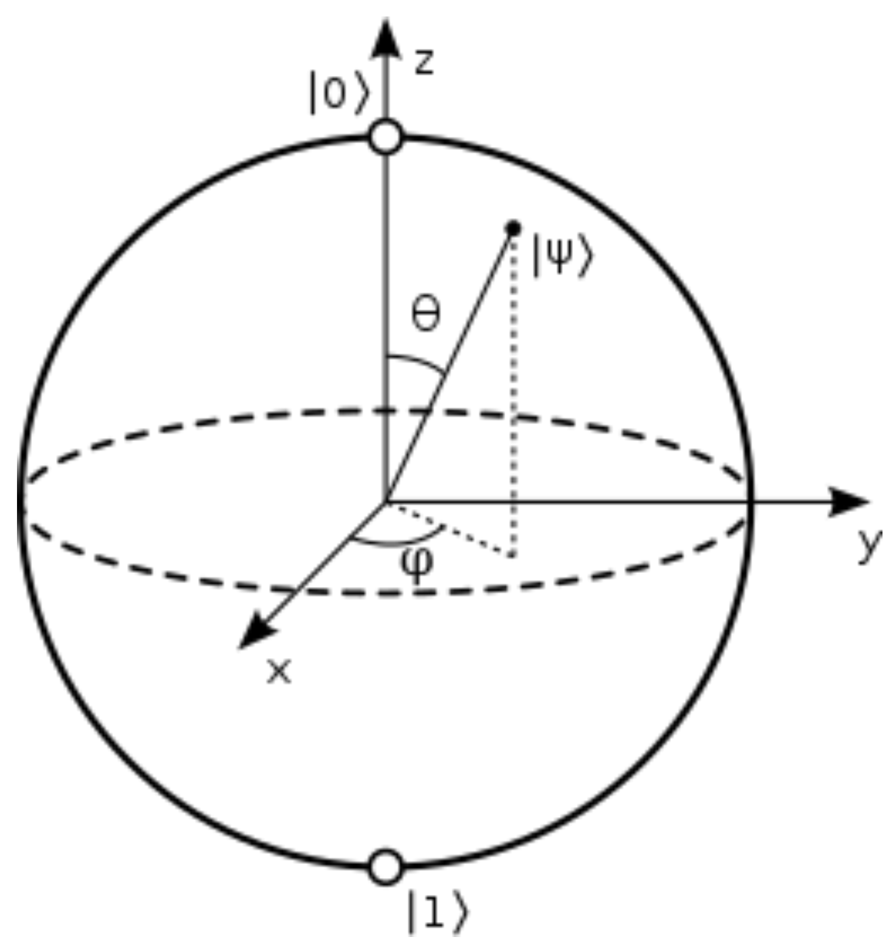
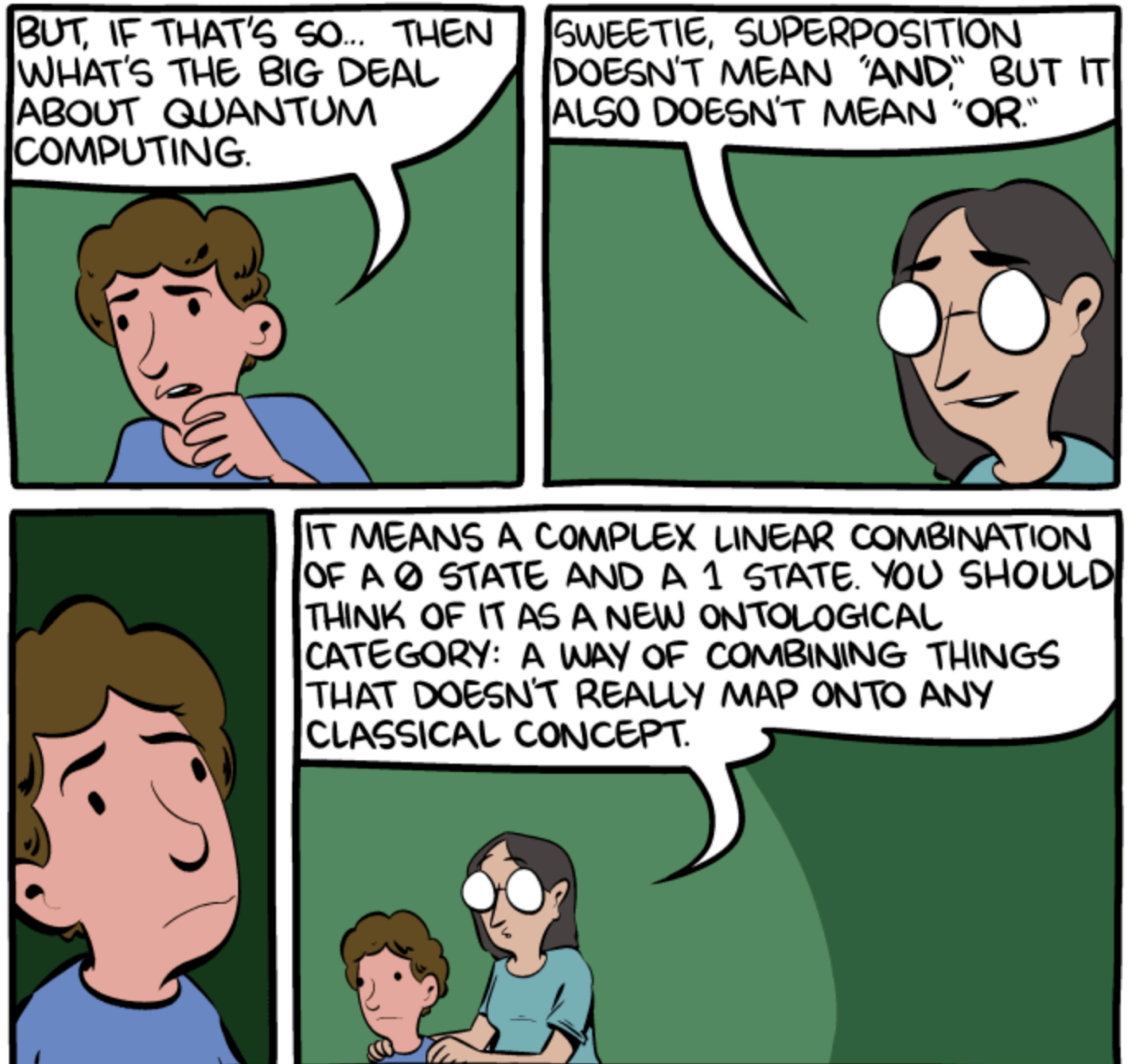
In fact, it's just a point in projective Hilbert space.

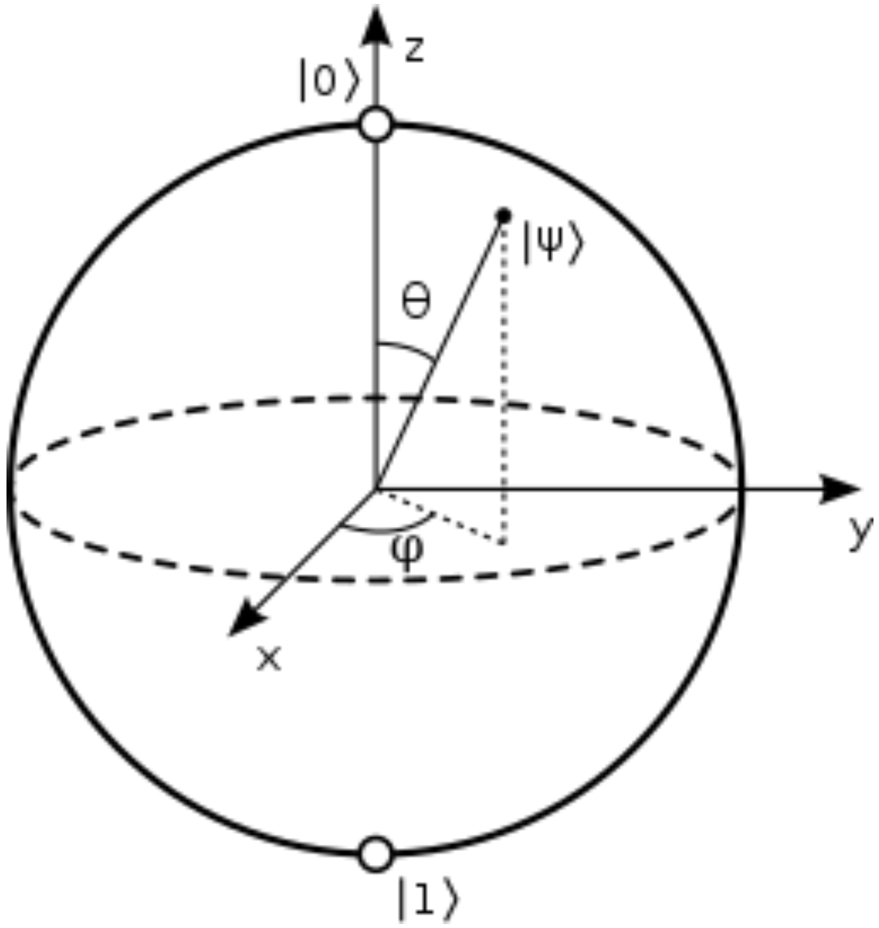


Spin 1/2

“The Talk” by Scott Aaronson & Zach Weinersmith

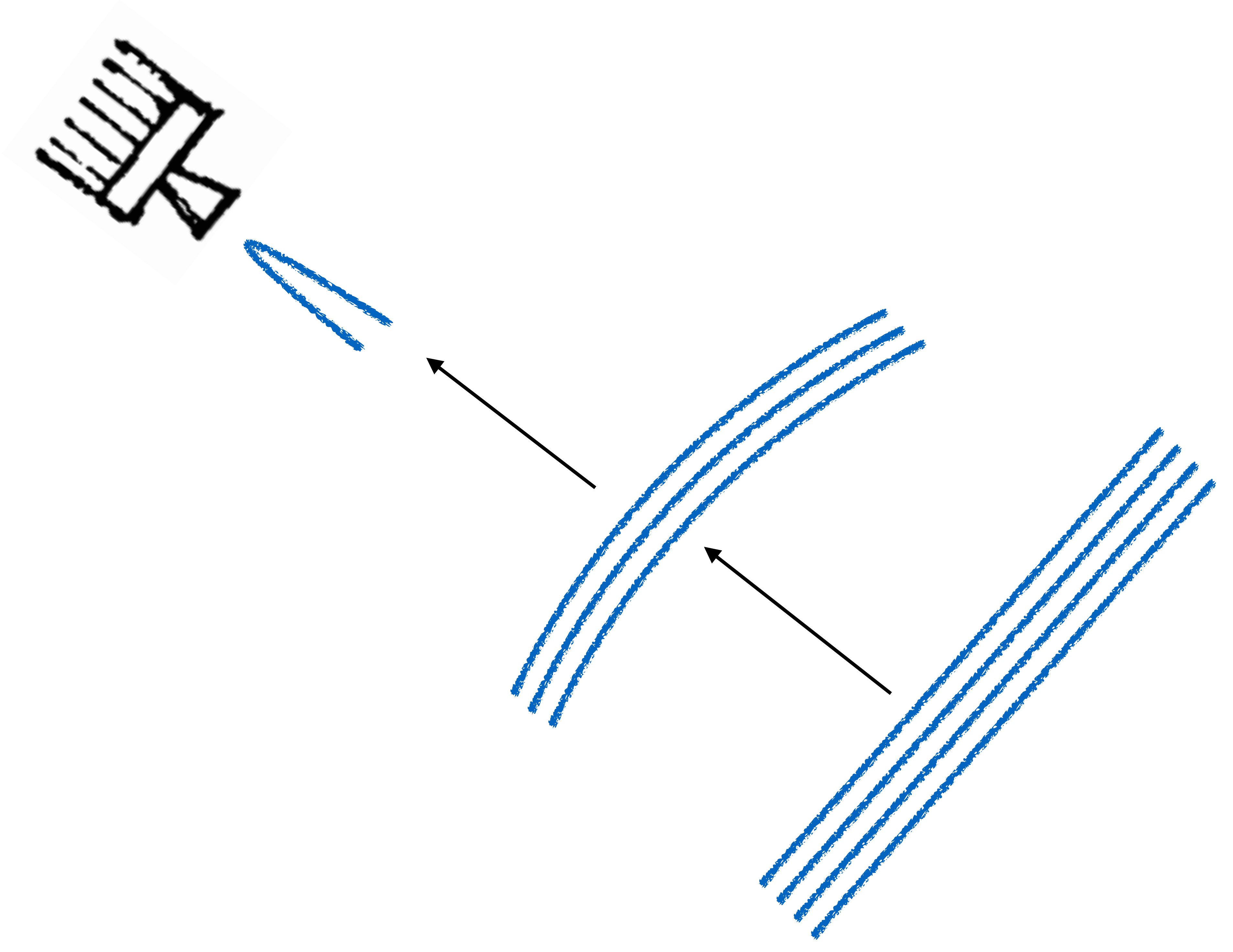


http://www.smbc-comics.com/comic/the-talk-3



Points cannot be "two points" at the same time

Similar considerations hold for X & P. Just different commutation relations.



Wave suddenly get's localized as particle.

A comment about waves and particles

$$\Box D(x-y) = \delta(x-y)$$

(a wave equation)

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$$\Box D(x-y) = \delta(x-y)$$

(a wave equation)

$$\begin{aligned} D(x-y) &= \int \frac{d^4p}{(2\pi)^4} e^{ip(x-y)} \frac{1}{p^2 - m^2 + i\varepsilon} \\ &= \int \frac{d^4p}{(2\pi)^4} e^{ip(x-y)} \int_0^\infty ds e^{is(p^2 - m^2 + i\varepsilon)} \end{aligned}$$

A comment about waves and particles

$$\langle p|x\rangle = e^{ipx}$$

(standard quantum mechanics)

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A comment about waves and particles

$$\langle p|x\rangle = e^{ipx}$$

(standard quantum mechanics)

$$D(x-y) = \int \frac{d^4p}{(2\pi)^4} \langle y|p\rangle \int_0^\infty ds e^{is(p^2-m^2+i\varepsilon)} \langle p|x\rangle$$

A comment about waves and particles

$$H = -p^2$$

(standard quantum mechanics)

$$D(x-y) = \int \frac{d^4p}{(2\pi)^4} \langle y|p\rangle \int_0^\infty ds e^{is(p^2-m^2+i\varepsilon)} \langle p|x\rangle$$

A comment about waves and particles

$$H = -p^2$$

Wave

$$D(x-y) = \int_0^\infty ds e^{-s\varepsilon} e^{-ism^2} \langle y | e^{-isH} | x \rangle$$

Particle

End of comment.

Englert-Greenberger-Yasin relation

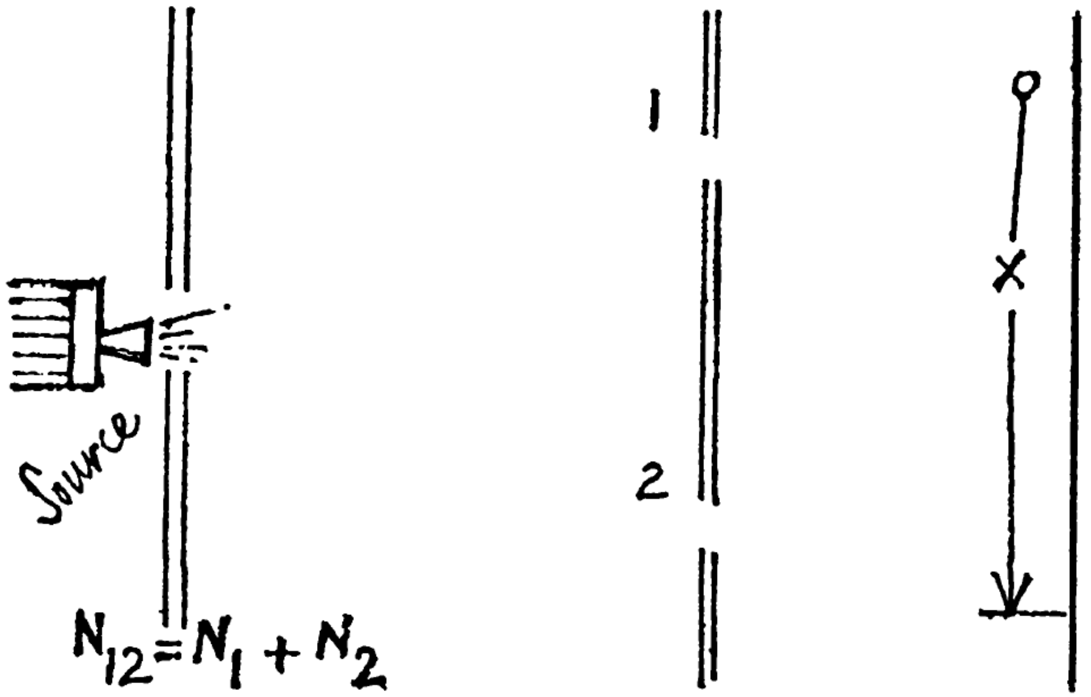


Figure 28

$$W = |P(1) - P(2)|^2 = \frac{|\mathcal{A}|^2 - |\mathcal{B}|^2}{|\mathcal{A}|^2 + |\mathcal{B}|^2}$$

$$V = \frac{2|\mathcal{A}||\mathcal{B}|}{|\mathcal{A}|^2 + |\mathcal{B}|^2}$$

$$V^2 + W^2 = 1$$

(pure states)

Figure: R. P. Feynman. The character of Physical law

Englert-Greenberger-Yasin relation

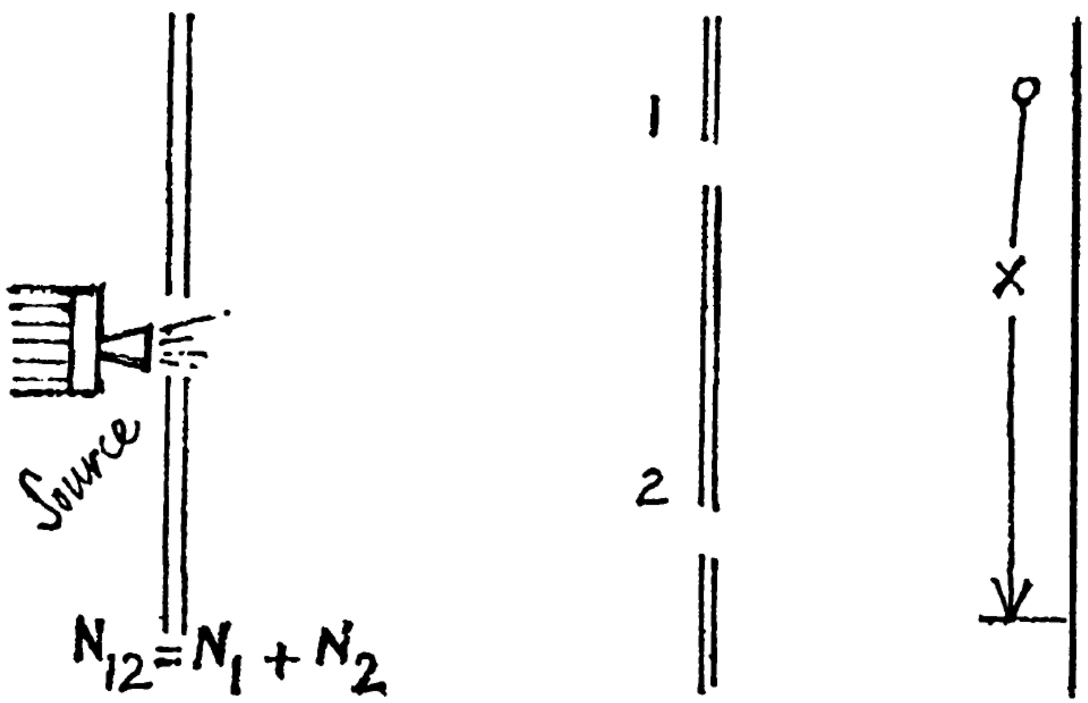


Figure 28

$$W = |P(1) - P(2)|^2 = \frac{|\mathcal{A}|^2 - |\mathcal{B}|^2}{|\mathcal{A}|^2 + |\mathcal{B}|^2}$$

$$V = \frac{2|\mathcal{A}||\mathcal{B}|}{|\mathcal{A}|^2 + |\mathcal{B}|^2}$$

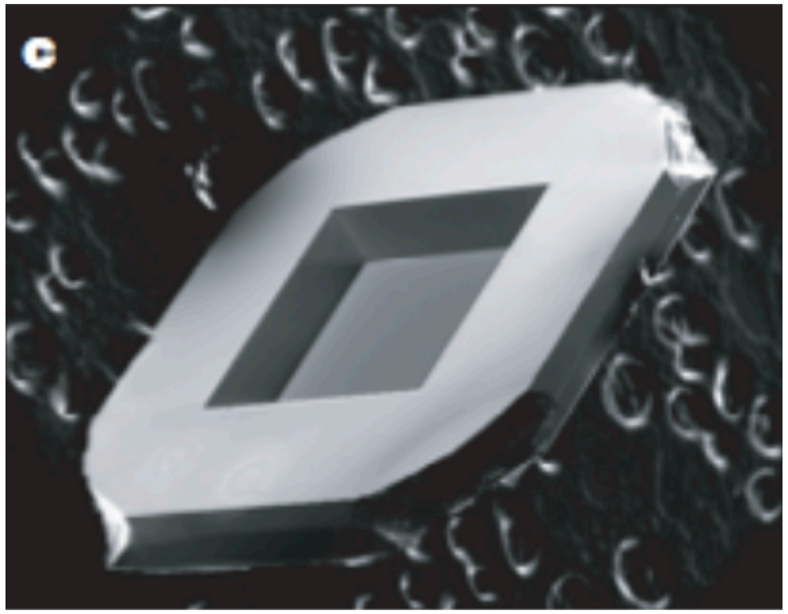
$$V^2 + W^2 \leq 1$$

(mixed states)

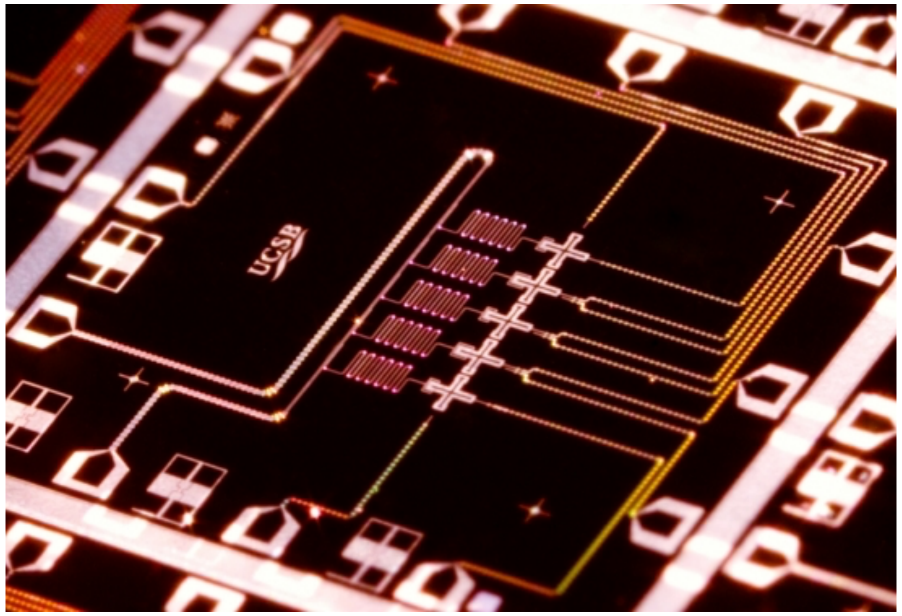
Figure: R. P. Feynman. The character of Physical law

Englert-Greenberger-Yasin relation

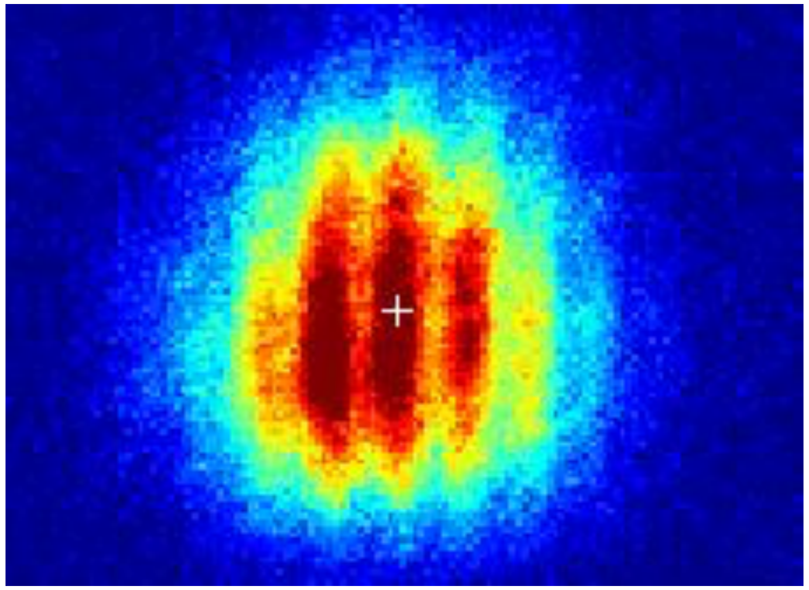
Not only true of particles.



Yale



UCSB



TU Wien

$$V^2 + W^2 \leq 1$$

Duality true of any quantum system, really.

Quantum mechanics is 'more' than a physical theory.

It is a sort of generalized probability theory (for amplitudes).

Like a 'machine' to calculate probabilities.

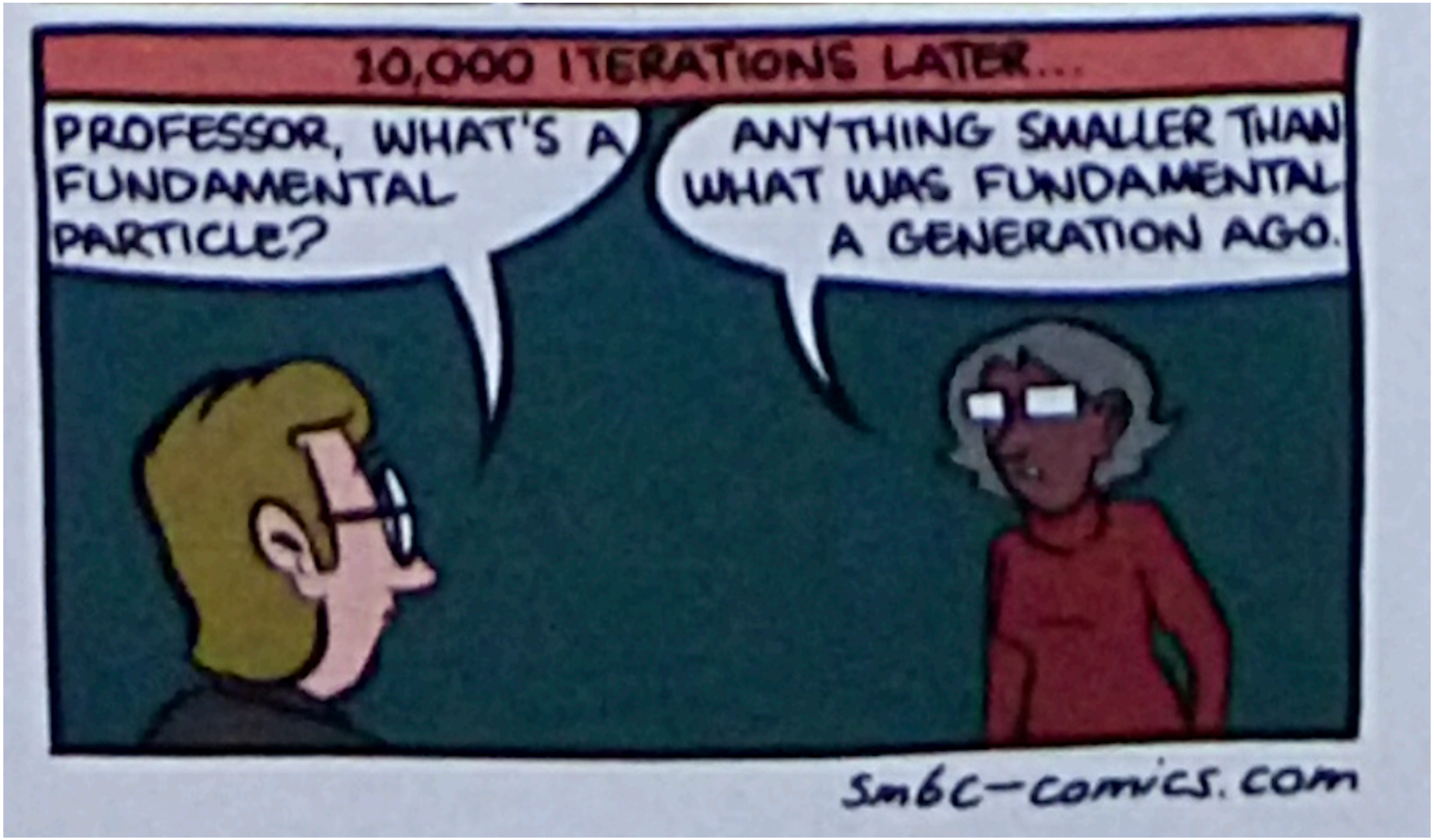
What is a particle?

Somewhere in CERN…

What is a particle?

Somewhere in CERN…

What is a particle?



Somewhere in CERN...

What is a particle?

I would even go further and say that particles are our current understanding of the building blocks of nature.

* Identical objects.

* Universal properties (mass, spin, charge)

* Follow relativity and quantum mechanics.

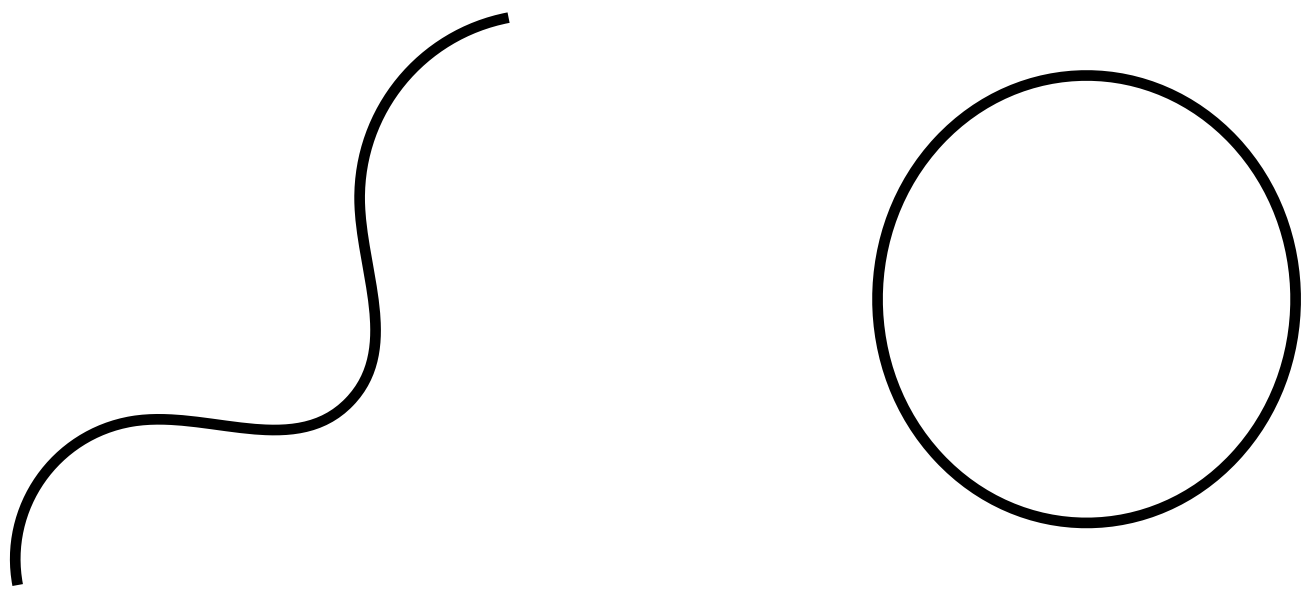
What is a particle?

In fact, what an electron is (for e.g.) depends on other fields (e.g. a Higgs field with a different v.e.v)

Particle identity is given by their behavior under spacetime symmetries (Wigner).

What is a particle?

We even have clues on how to get rid of the particle concept...



(What about string-wave duality?!)

Entanglement

$$\mathcal{H} = \mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \ldots \otimes \mathbb{C}^2$$

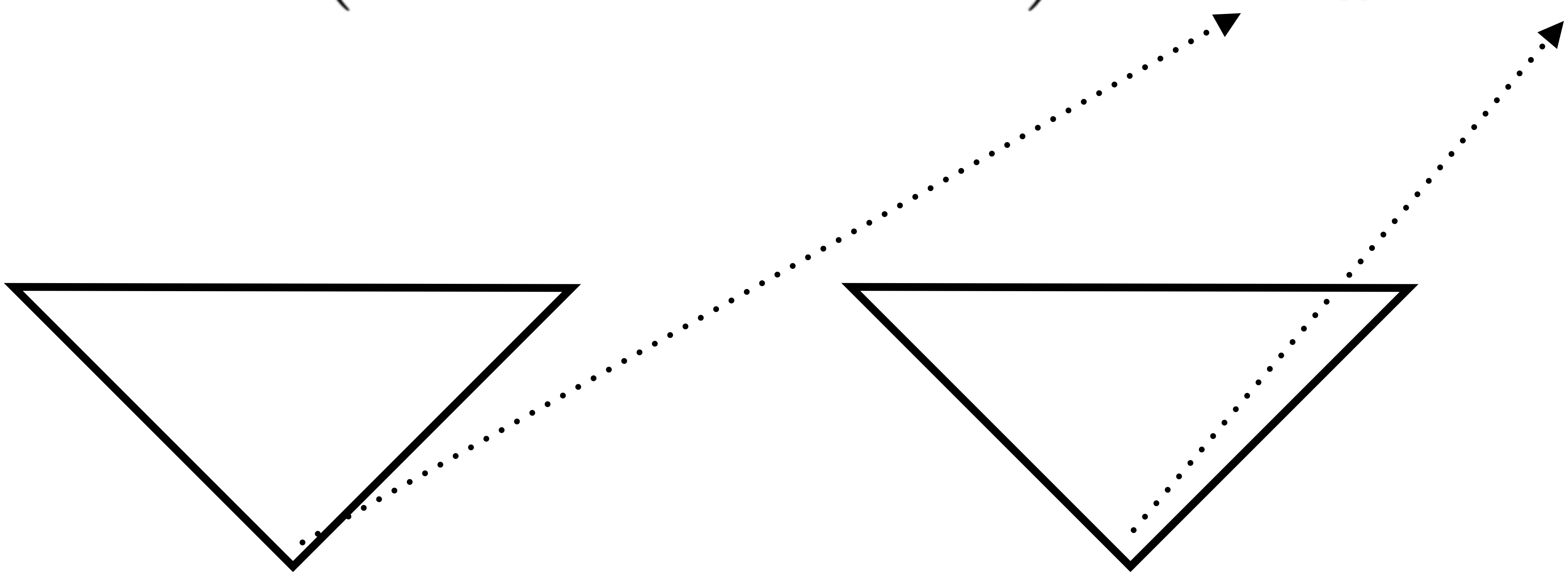
Entanglement

$$\mathcal{H} = \mathbb{C}^2 \otimes (\mathbb{C}^2 \otimes \ldots \otimes \mathbb{C}^2) = \mathcal{H}_a \otimes \mathcal{H}_b$$

We place the ‘cut’ wherever we want.

Entanglement

$$\mathcal{H} = \mathbb{C}^2 \otimes (\mathbb{C}^2 \otimes \ldots \otimes \mathbb{C}^2) = \mathcal{H}_a \otimes \mathcal{H}_b$$



But it's only really interesting when 'a' and 'b' are space-like separated.

Entanglement

$$\mathcal{H} = \mathbb{C}^2 \otimes \mathbb{C}^2$$

$$\Psi = \frac{|0\rangle|1\rangle - |1\rangle|0\rangle}{\sqrt{2}} \neq |\phi\rangle|\varphi\rangle$$

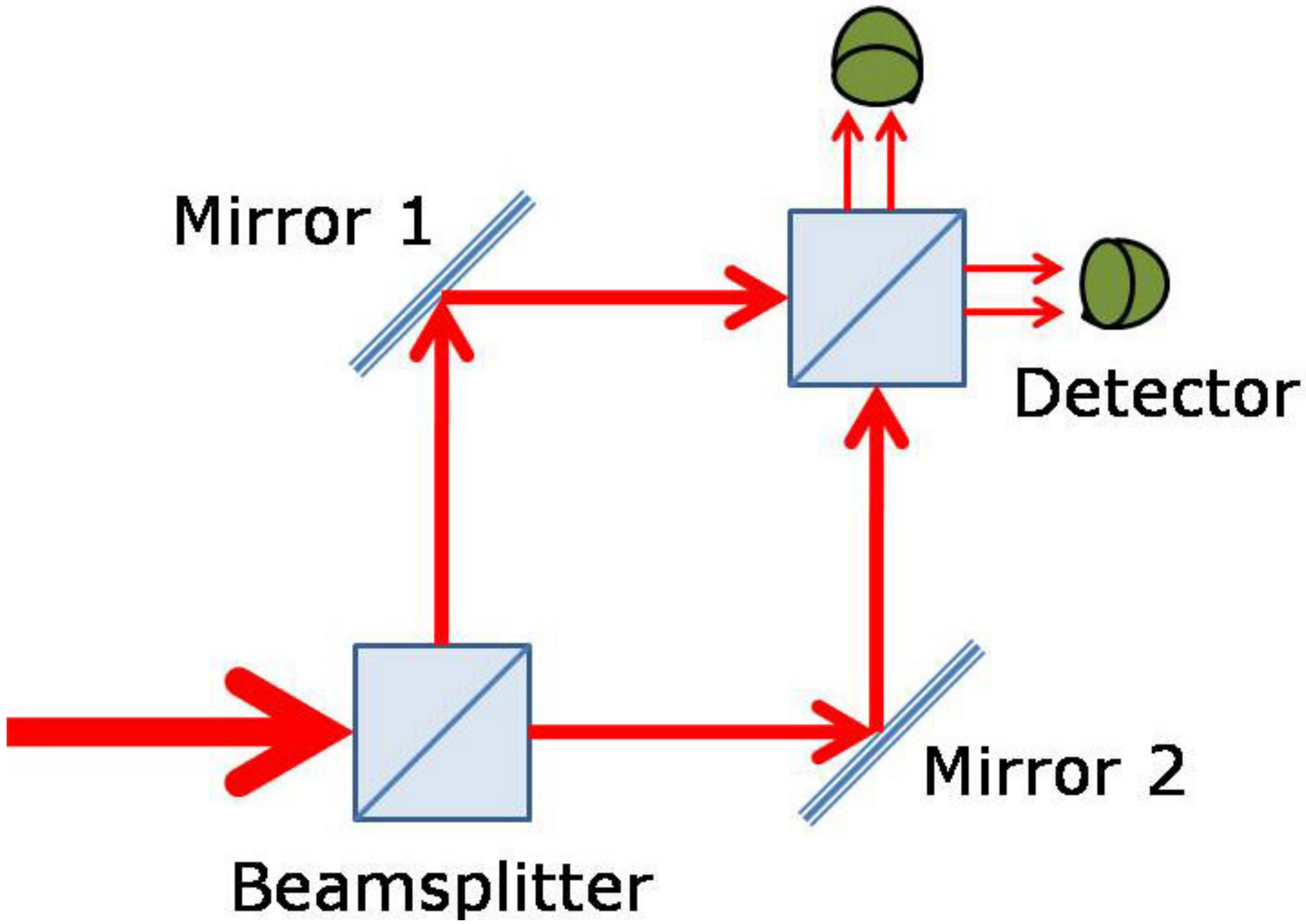
* Quantum correlations

* Incompatible with local hidden variables

Entanglement

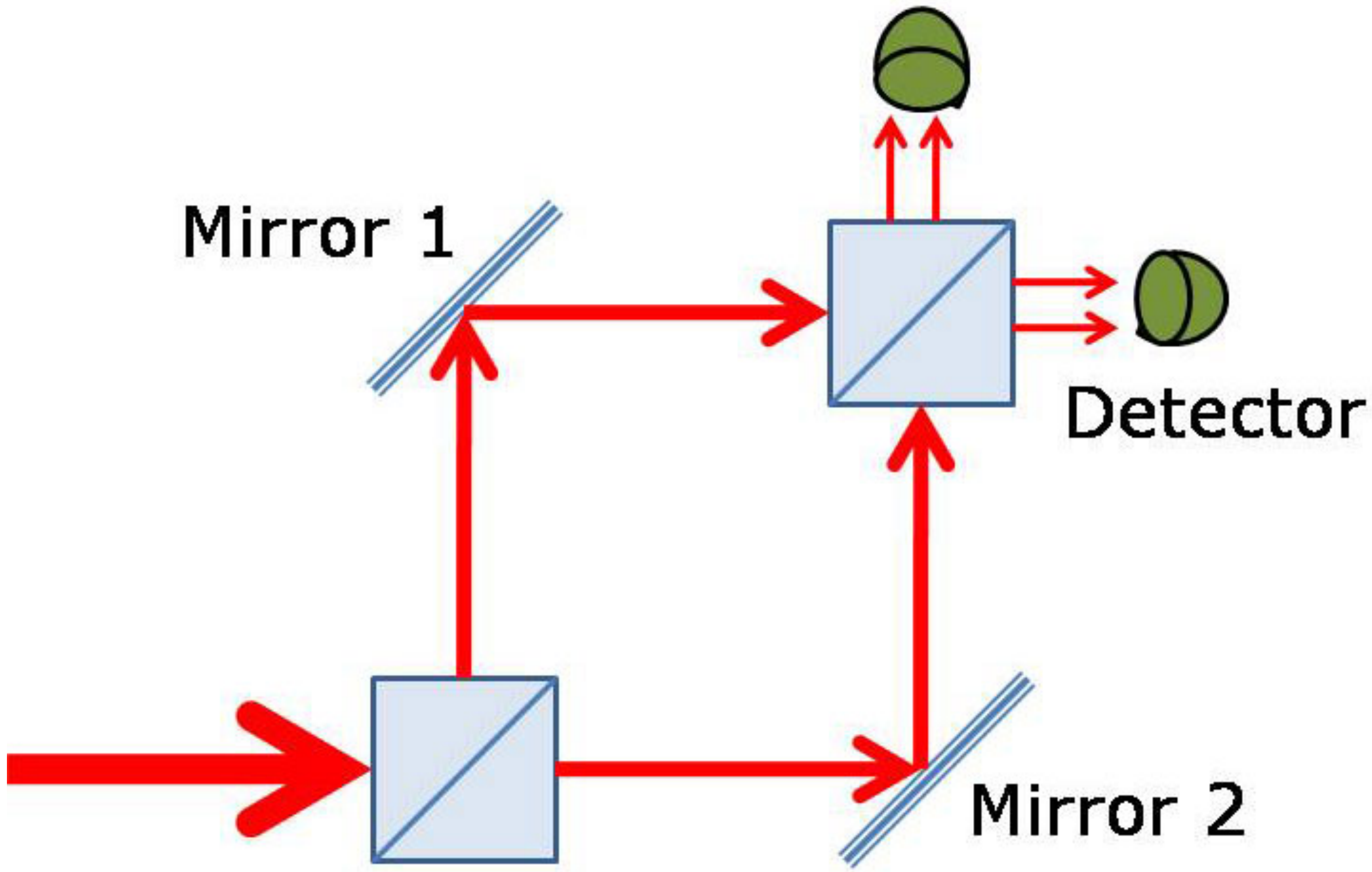
I'd like to focus on a particular story about waves, particles and entanglement

Entanglement



$$V^2 + W^2 \leq 1$$

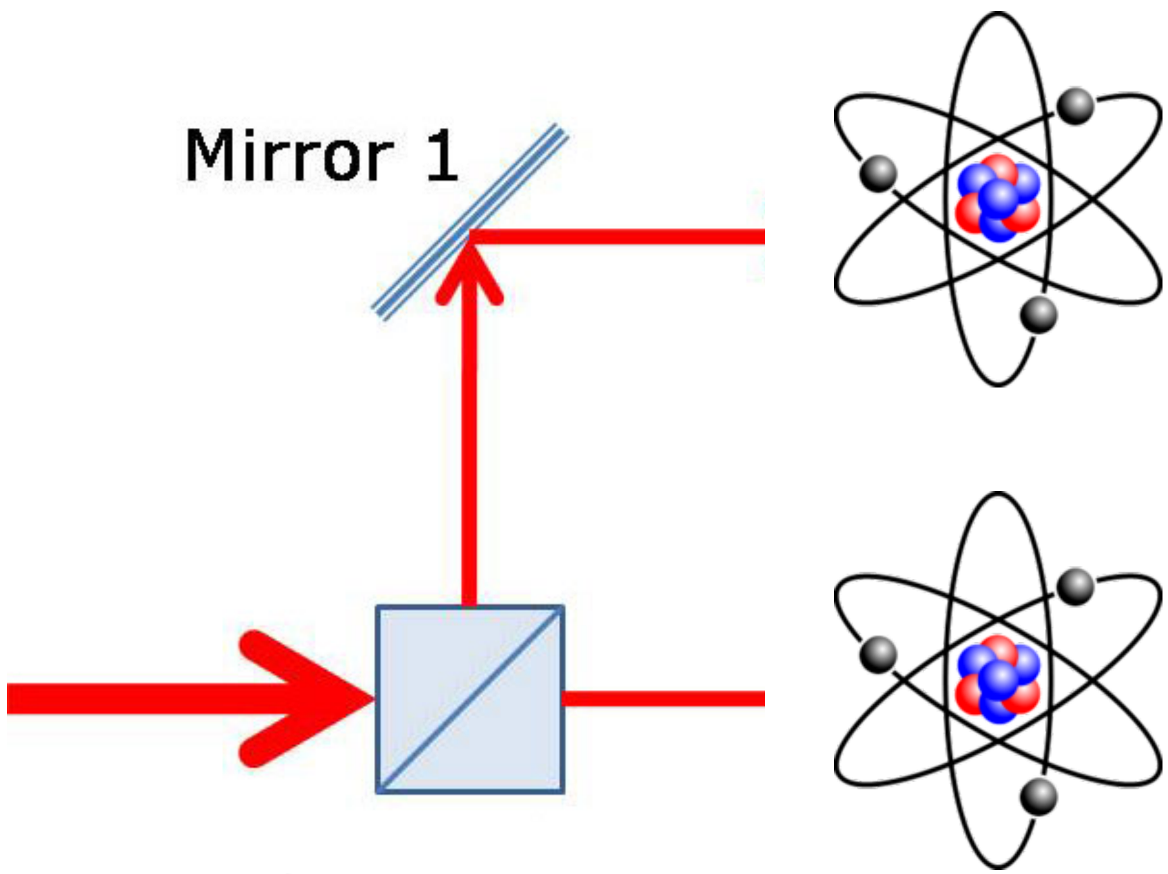
Entanglement



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_a|0\rangle_b - |0\rangle_a|1\rangle_b)$$

$$= \frac{1}{\sqrt{2}}(a^\dagger - b^\dagger)|0\rangle$$

Entanglement



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_a|0\rangle_b - |0\rangle_a|1\rangle_b)$$

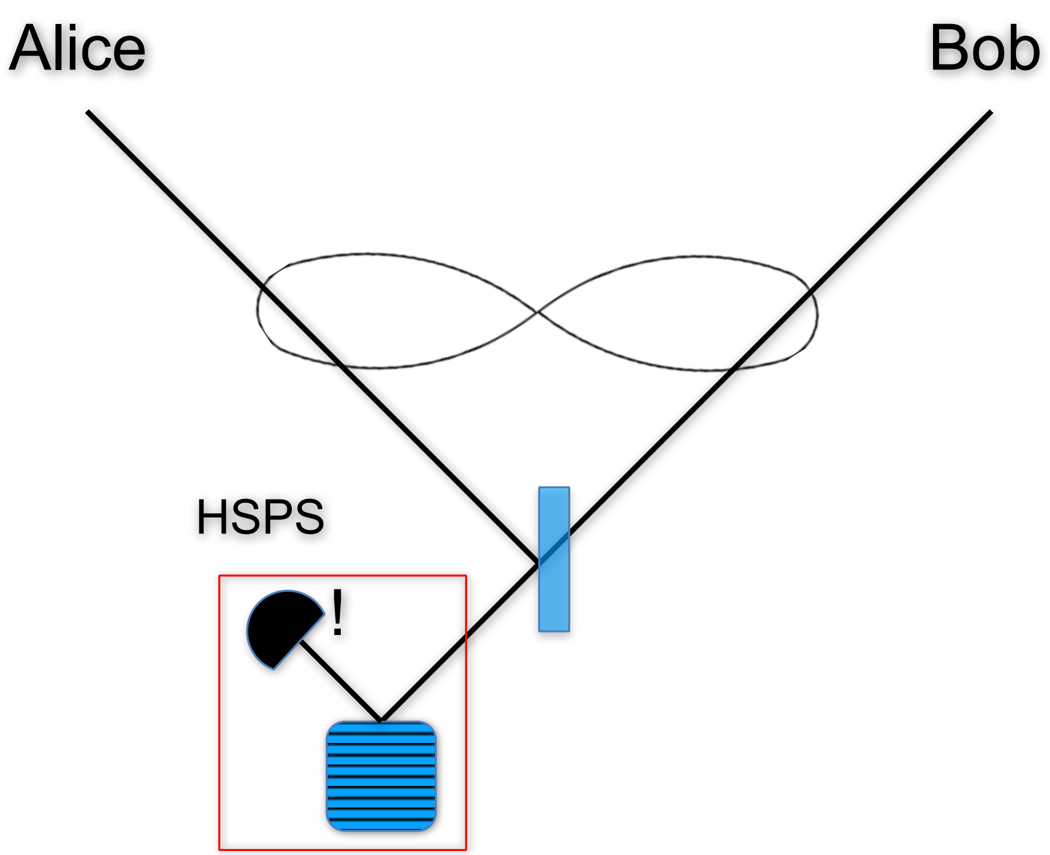
$$= \frac{1}{\sqrt{2}}(a^\dagger - b^\dagger)|0\rangle$$

Entanglement

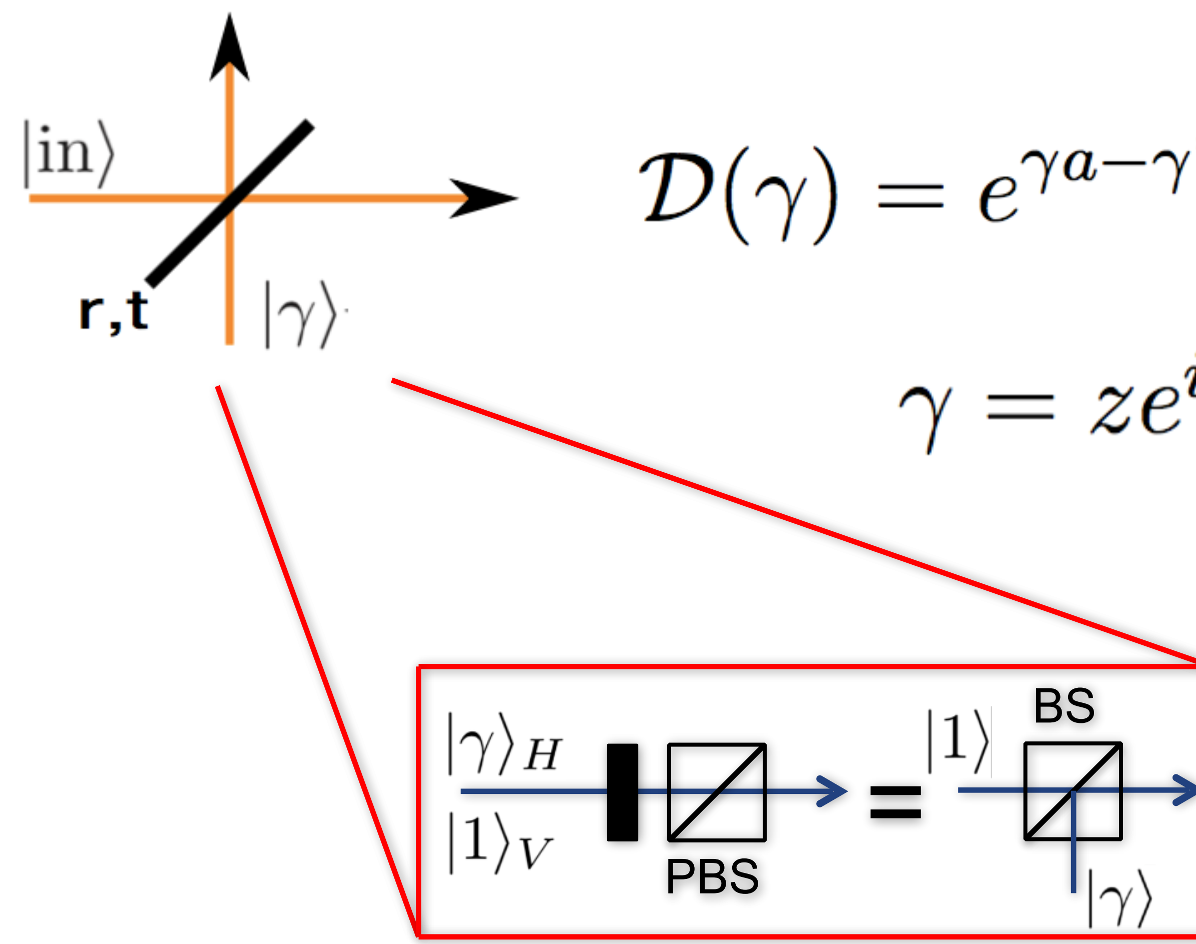
Entanglement between modes of the quantum field: can we verify it at space-like separations?

$$
\begin{aligned}
|\Psi\rangle &= \frac{1}{\sqrt{2}}(|1\rangle_a|0\rangle_b - |0\rangle_a|1\rangle_b) \\
&= \frac{1}{\sqrt{2}}(a^\dagger - b^\dagger)|0\rangle
\end{aligned}
$$

Entanglement



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A |1\rangle_B + |1\rangle_A |0\rangle_B)$$



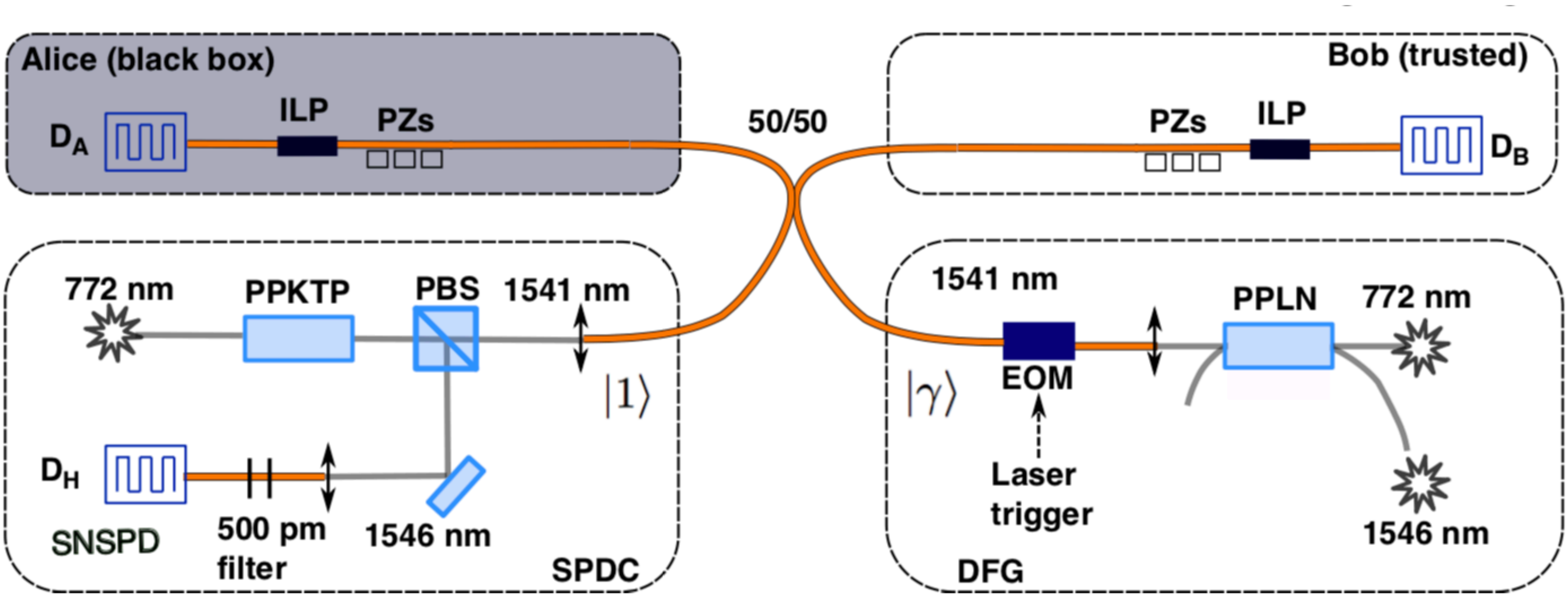
$$\mathcal{D}(\gamma) = e^{\gamma a - \gamma^* a^\dagger}$$

$$\gamma = z e^{i\theta}$$

"Weak field homodyne"

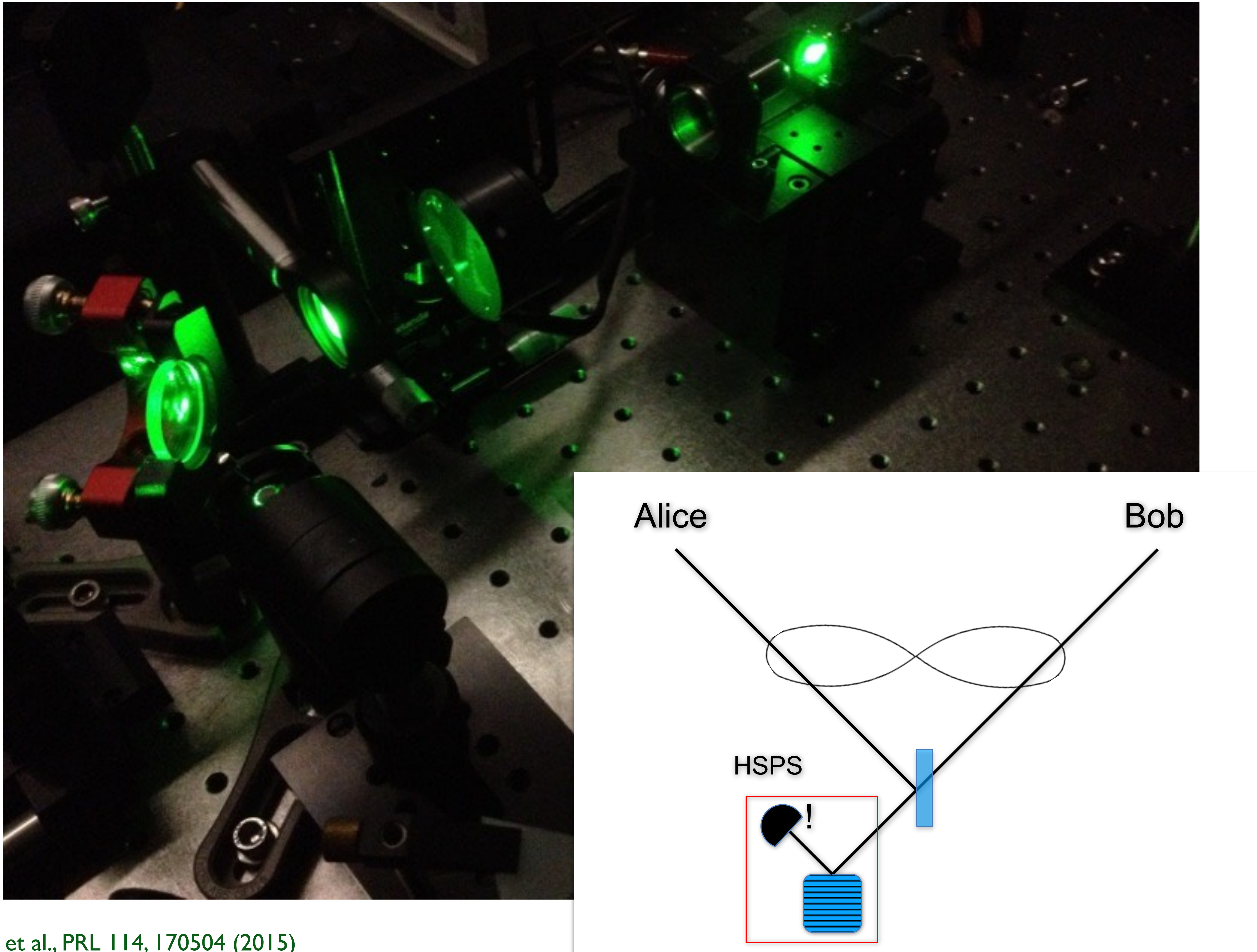
F. Monteiro et al., PRL 114, 170504 (2015)
T. Guerreiro et al., arXiv:1603.03589 (2016)

Entanglement



Setup

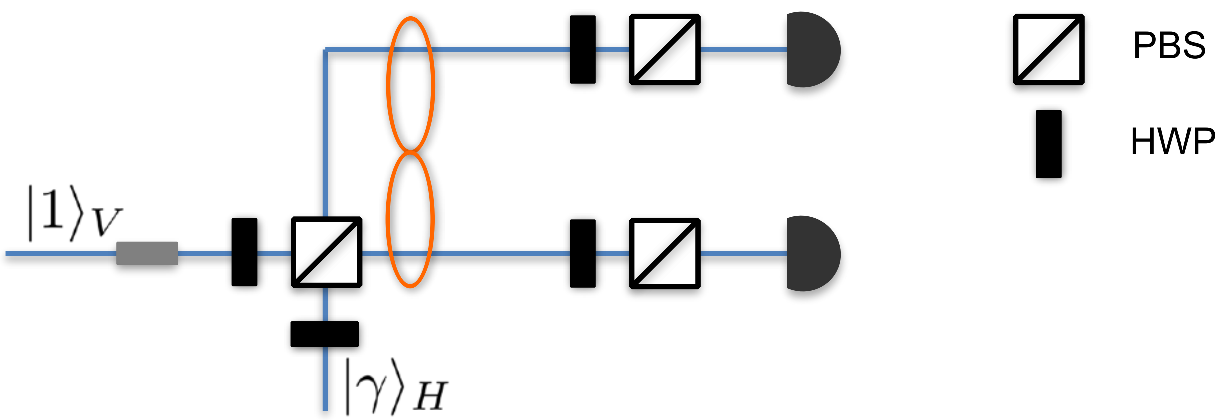
F. Monteiro et al., PRL 114, 170504 (2015)
T. Guerreiro et al., arXiv:1603.03589 (2016)

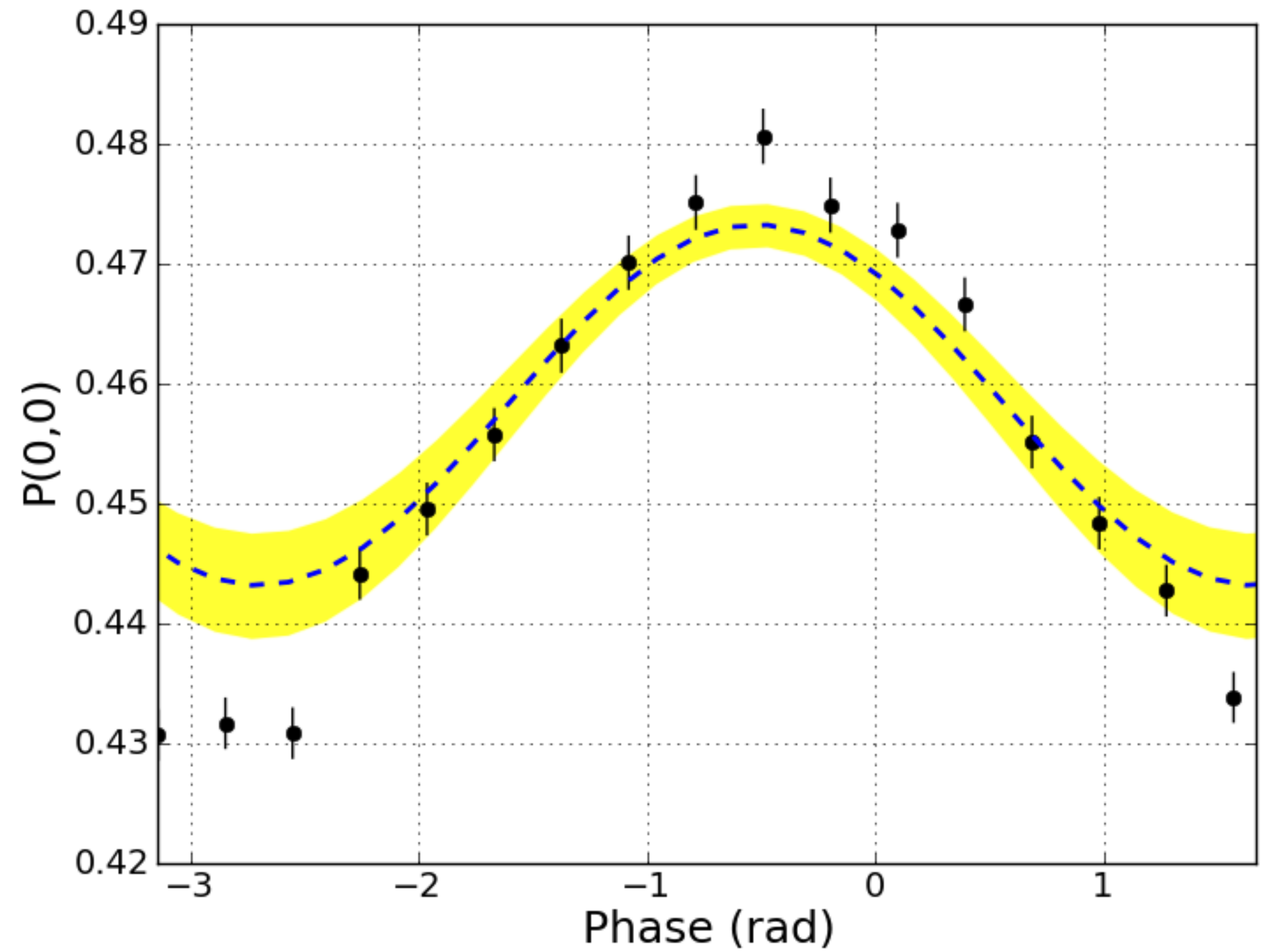


F. Monteiro et al., PRL 114, 170504 (2015)

T. Guerreiro et al., arXiv:1603.03589 (2016)

Displaced entanglement + single photon counting ~ oscillations!





Oscillations!

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$$p(00|\gamma_a,\gamma_b) = e^{-2z^2}(1-\eta_a-\eta_b) + e^{-2z^2}(\eta_a+\eta_b)z^2$$

$$+ \sqrt{\eta_a\eta_b}z^2e^{-2z^2}\cos\theta \quad .$$

F. Monteiro et al., PRL 114, 170504 (2015)
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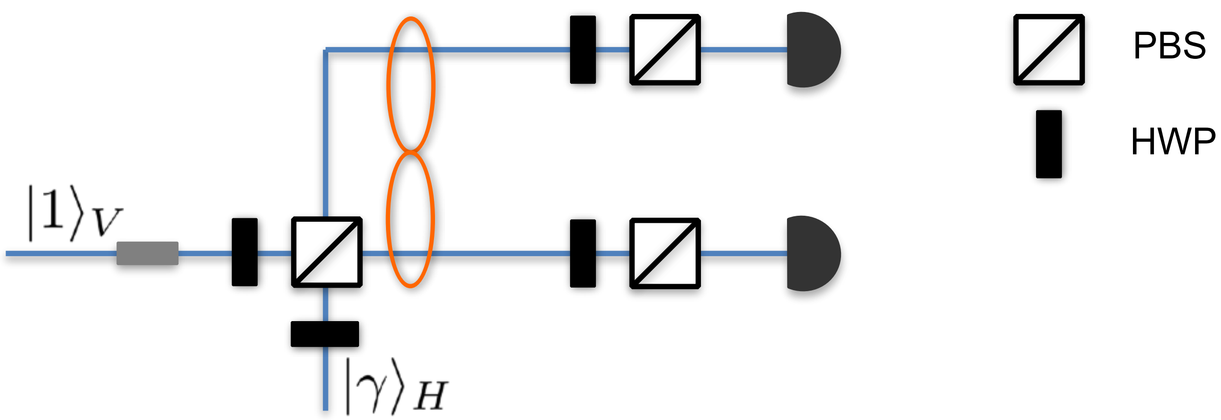
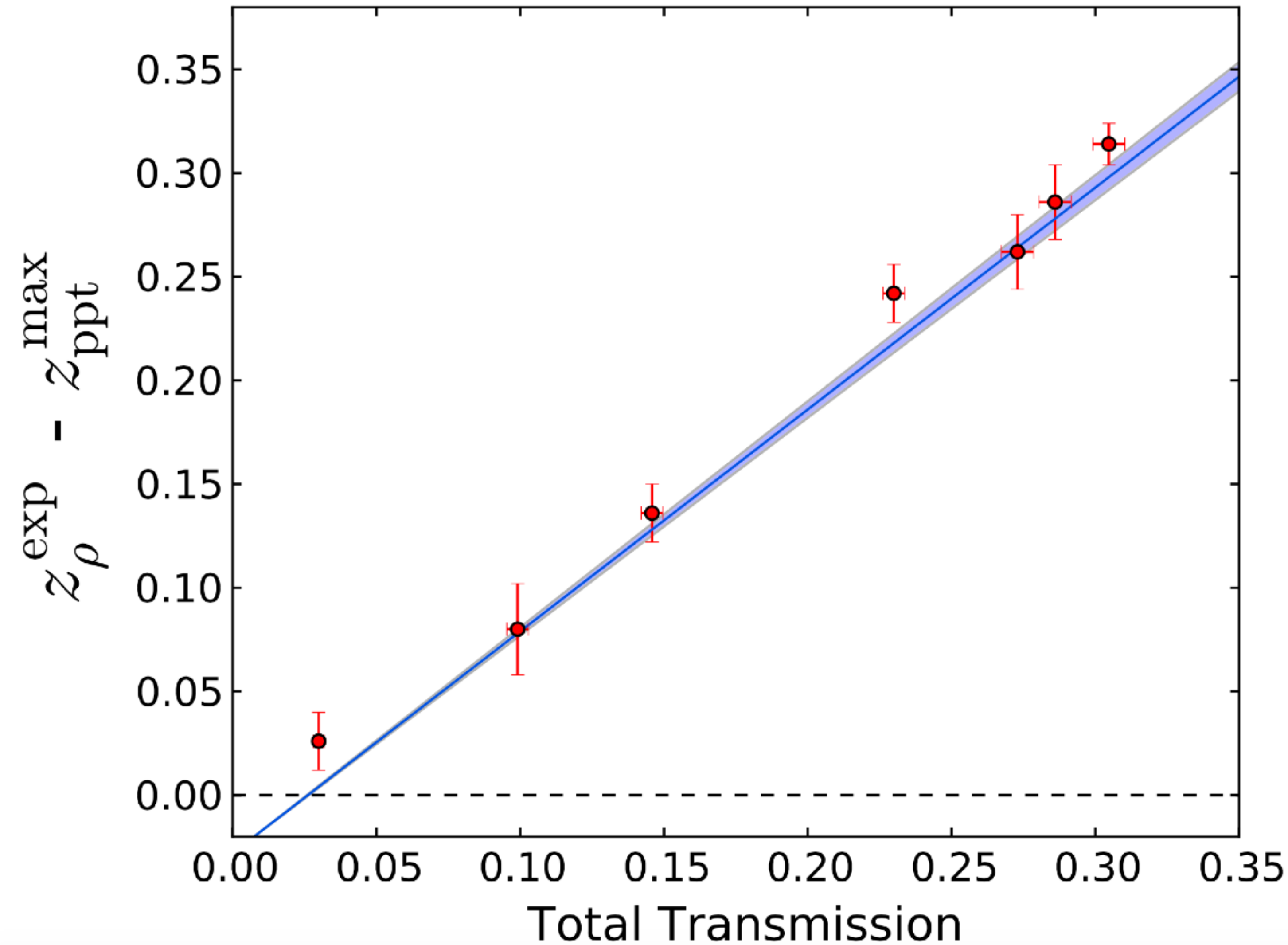
Displaced entanglement + single photon counting ~ oscillations!



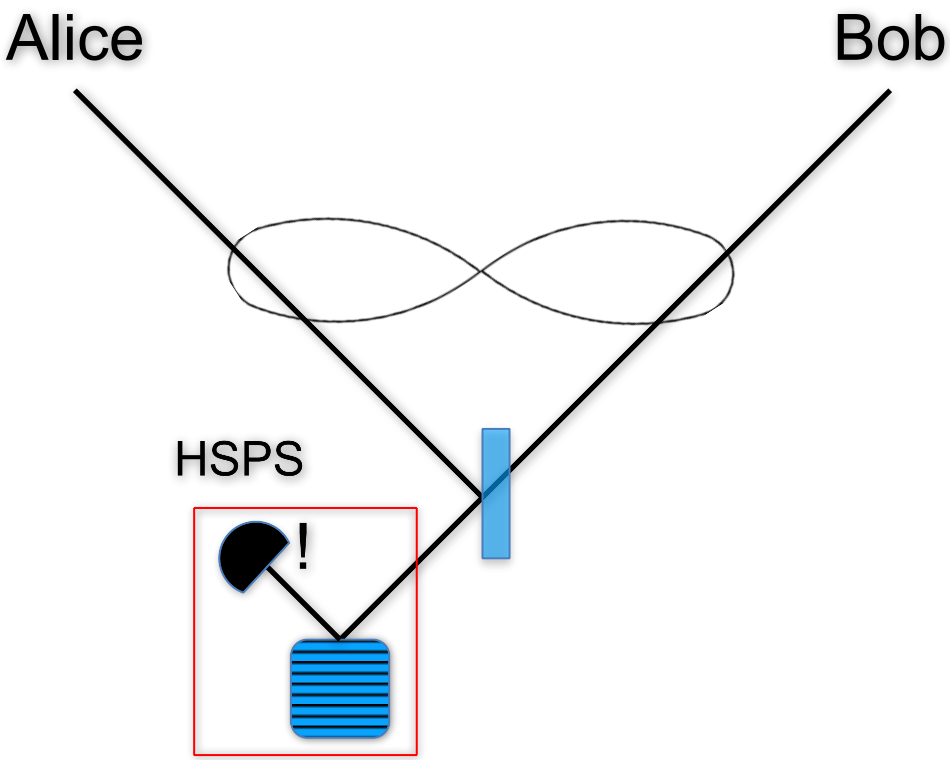


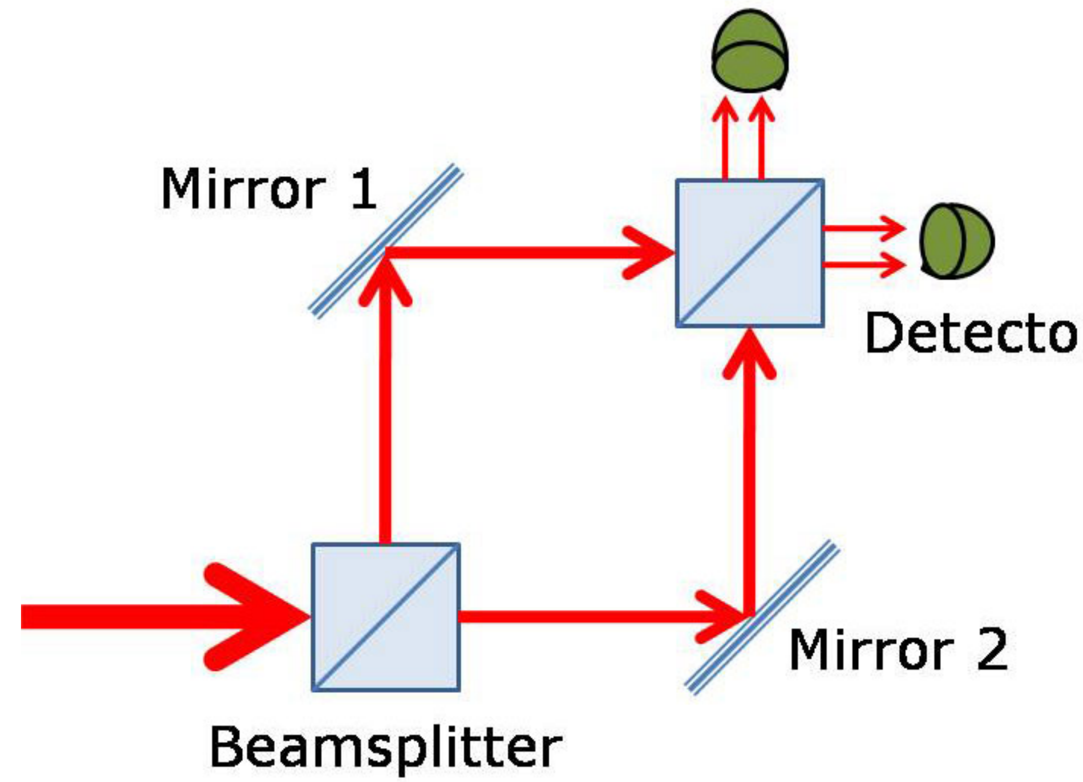
Linear with loss

UNIVERSITÉ DE GENÈVE

$$p(00|\gamma_a,\gamma_b) = e^{-2z^2}(1-\eta_a-\eta_b) + e^{-2z^2}(\eta_a+\eta_b)z^2 + \boxed{\sqrt{\eta_a\eta_b}z^2e^{-2z^2}\cos\theta} .$$

F. Monteiro et al., PRL 114, 170504 (2015)
T. Guerreiro et al., arXiv:1603.03589 (2016)





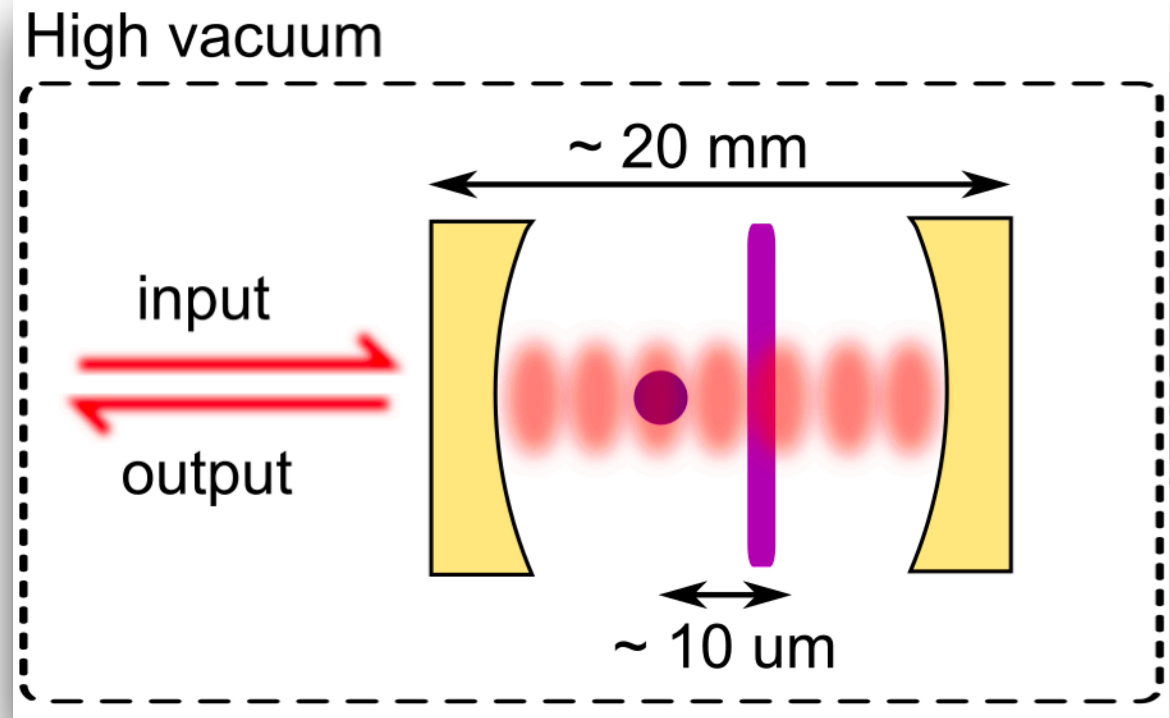
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A |1\rangle_B + |1\rangle_A |0\rangle_B)$$

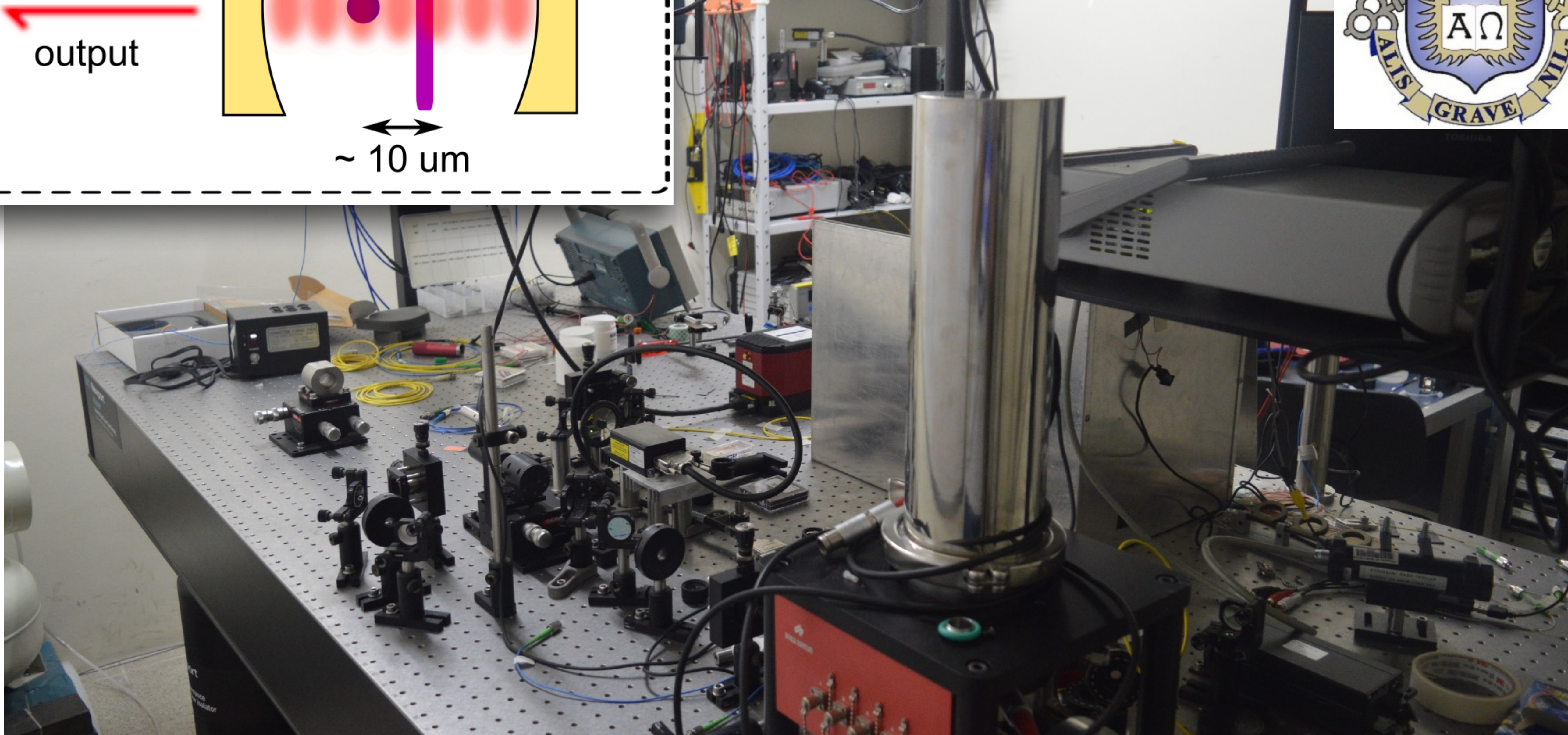
$$V^2 + W^2 \leq 1$$

$$\mathcal{H} = \mathbb{C}^2 \otimes (\mathbb{C}^2 \otimes \ldots \otimes \mathbb{C}^2) = \mathcal{H}_a \otimes \mathcal{H}_b$$

Superposition ~ entanglement

(just need space-time + measurements)





Come hear me on the 11th!

Room 4 (~16:30)

Thank you!

If you're interested, come talk to me (theory and exp)!

CETUC

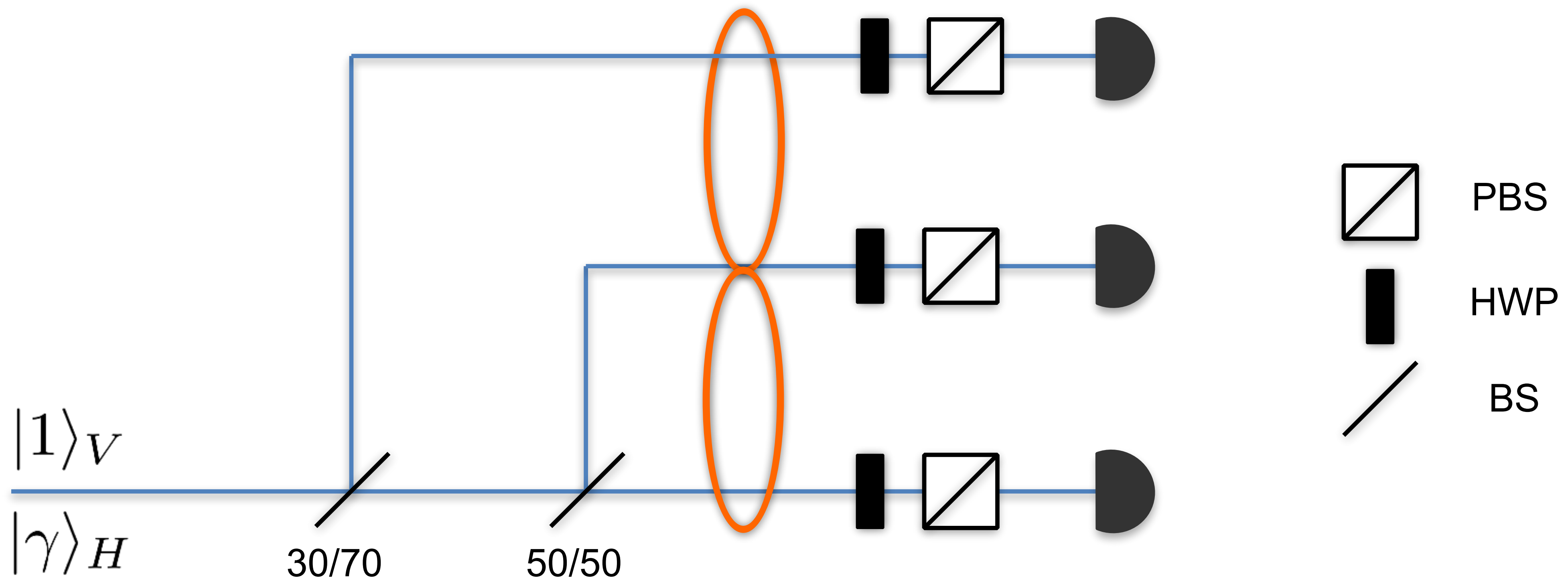
serrapilheira

Collaborators and friends:

Bruno Melo (PUC), George Svetlichny (PUC), Fernando Monteiro (Yale), Welles Morgado (PUC), Valerio Euculpi (CERN), Vieri Candelise (CERN), Enrico Schioppa (CERN), Francesco Corardesci (Cambridge)

Backup

Tripartite entanglement



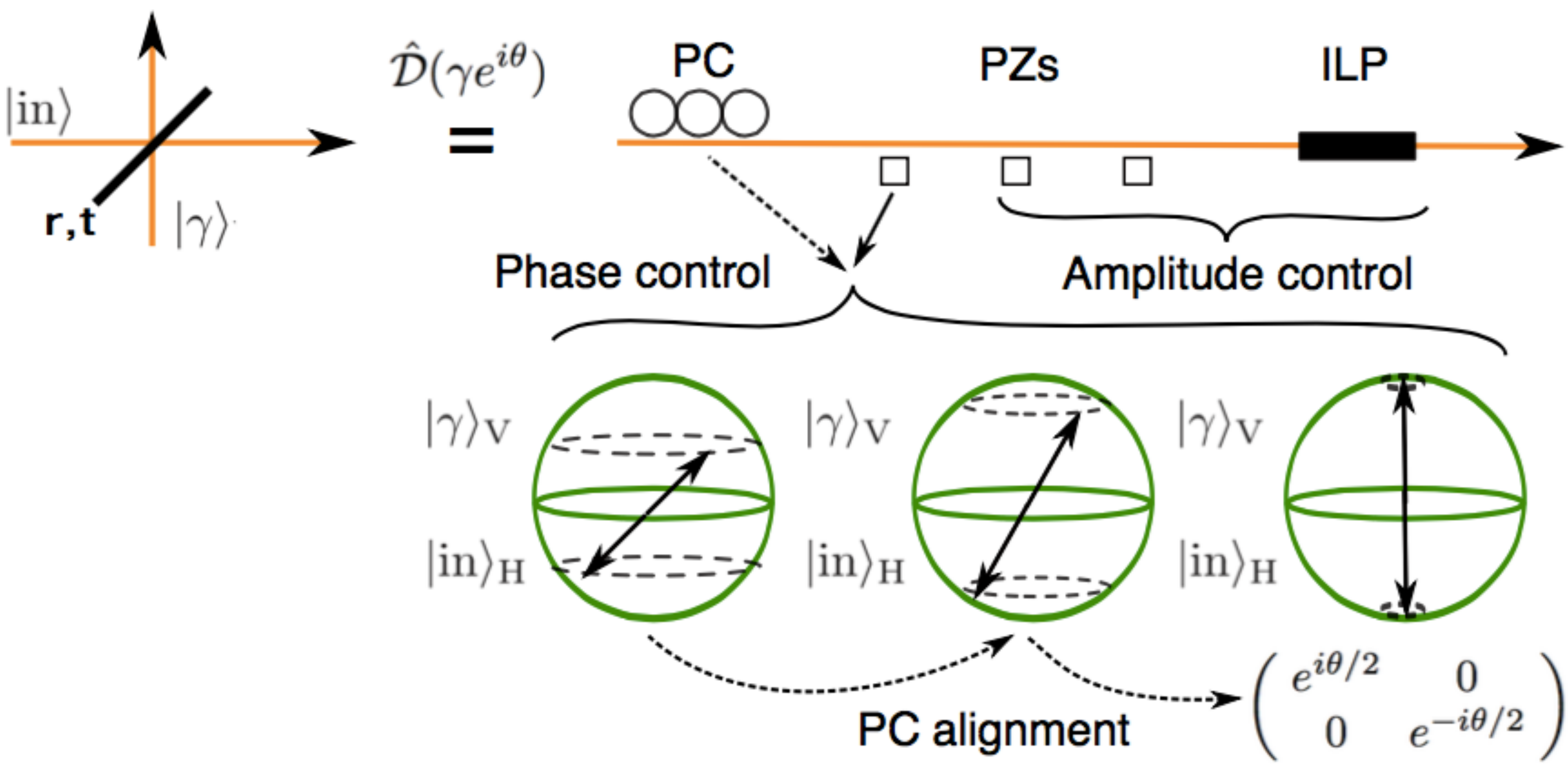
$$|1\rangle_A|0\rangle_B|0\rangle_C + |0\rangle_A|1\rangle_B|0\rangle_C + |0\rangle_A|0\rangle_B|1\rangle_C$$

$$z_3^{exp} - z_{ppt}^{max} = 0.99 \pm 0.10 > 0$$

F. Monteiro et al., Phys. Rev. Lett. 114, 170504 (2015)

Experiment: oscillations

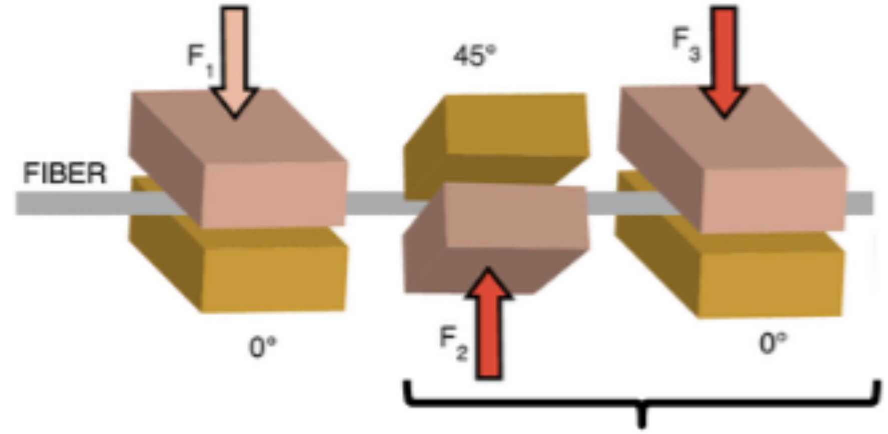
Phase and amplitude control of displacement



Review: Stress-induced birefringence

Photon: Right

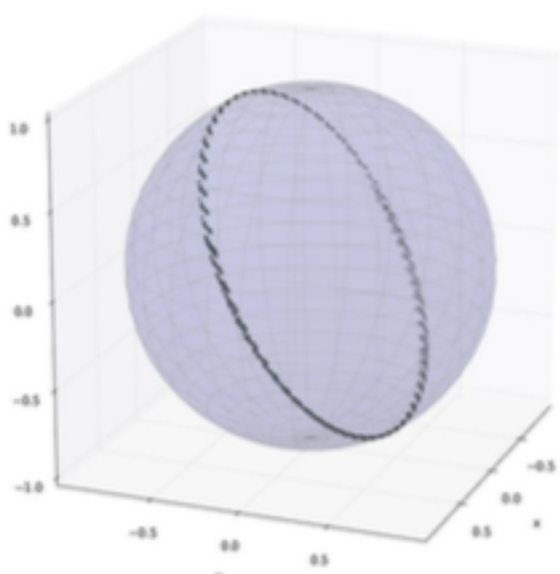
Coherent state: Left

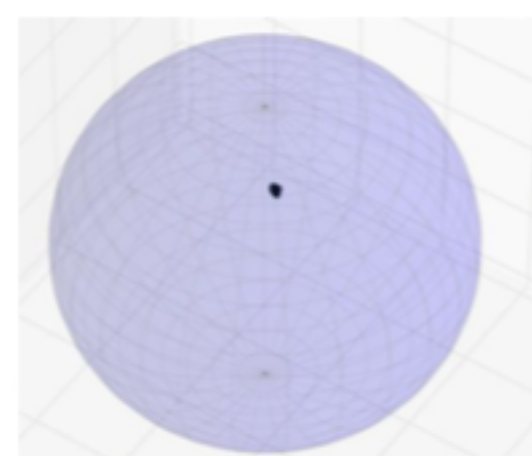


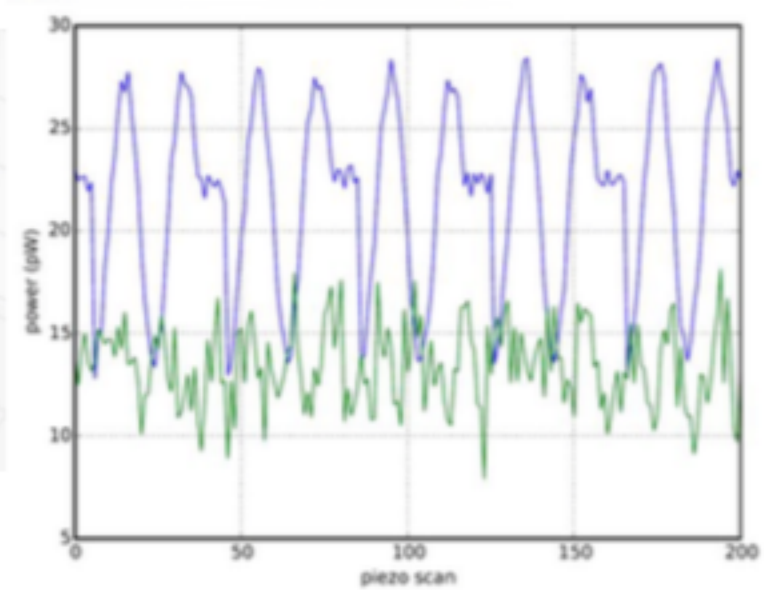
To PBS…

Displacement intensity

$$R_z(\theta) \equiv e^{-i\frac{\theta}{2}Z} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Z = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$







$$\text{Transmission} = \underbrace{0.98}_{\text{connector}} \times \underbrace{0.98}_{\text{BS}} \times \underbrace{0.98}_{\text{3 piezos}} \times \underbrace{0.98}_{\text{connector}} = 0.93$$

Experiment: oscillations

The single photon entangled state under loss:

$$\begin{pmatrix} 1-\eta_a-\eta_b & 0 & 0 & 0 \\ 0 & \eta_a & \sqrt{\eta_a\eta_b} & 0 \\ 0 & \sqrt{\eta_a\eta_b} & \eta_b & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Undergoes oscillations as a function of relative displacement phase

$$p(00|\gamma_a,\gamma_b) \;=\; e^{-2z^2}(1-\eta_a-\eta_b)+e^{-2z^2}(\eta_a+\eta_b)z^2$$

$$+\;\boxed{\sqrt{\eta_a\eta_b}z^2e^{-2z^2}\cos\theta}\;.$$

oscillations scales linear with losses!

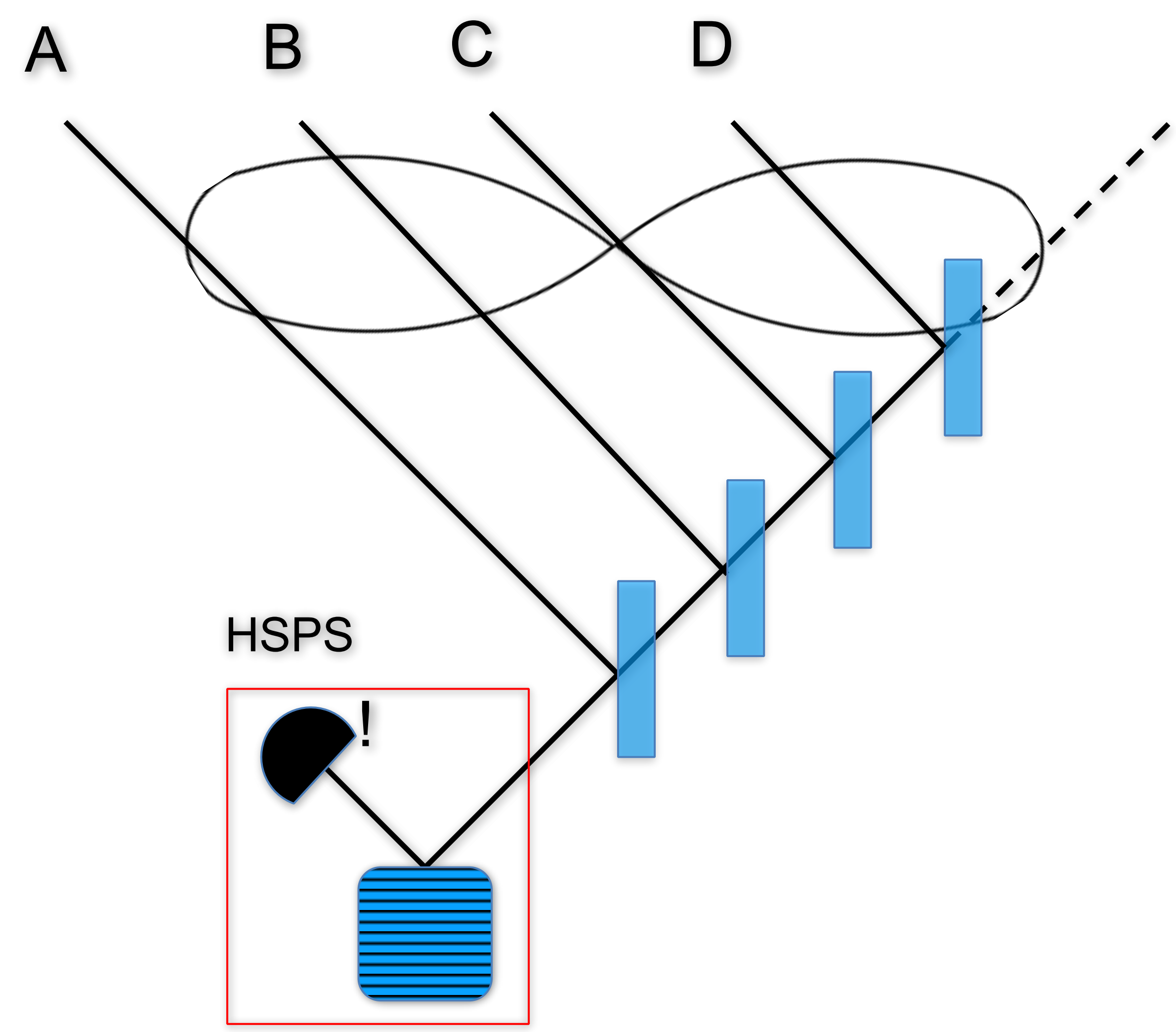
We cannot know whether "vacuum" came from loss or from the original entangled state:
NO WAY TO POSTSELECT DATA

Heralded entanglement

How many photons do we REALLY need to herald entanglement?

Path entanglement

$$|1\rangle_A|0\rangle_B|0\rangle_C|0\rangle_D... + ... + |0\rangle_A|0\rangle_B|0\rangle_C|1\rangle_D...$$



It's scalable!

F. Monteiro et al., Phys. Rev. Lett. 114, 170504 (2015)

Experiment: entanglement witness

A bipartite entanglement witness:

$$Z_\rho = 2(\sigma_\gamma \otimes \sigma_\gamma) - \sigma_0 \otimes \sigma_0$$

$$z_\rho = 2(P_{00} + P_{cc} - P_{0c} - P_{c0})|_\gamma - (P_{00} + P_{cc} - P_{0c} - P_{c0})|_{\gamma=0}$$

If $z_\rho - z_{ppt}^{max} > 0$, we have entanglement.

Where z_{ppt}^{max} is a function of measured local probabilities.

F. Monteiro et al., Phys. Rev. Lett. 114, 170504 (2015)

Experiment: entanglement witness

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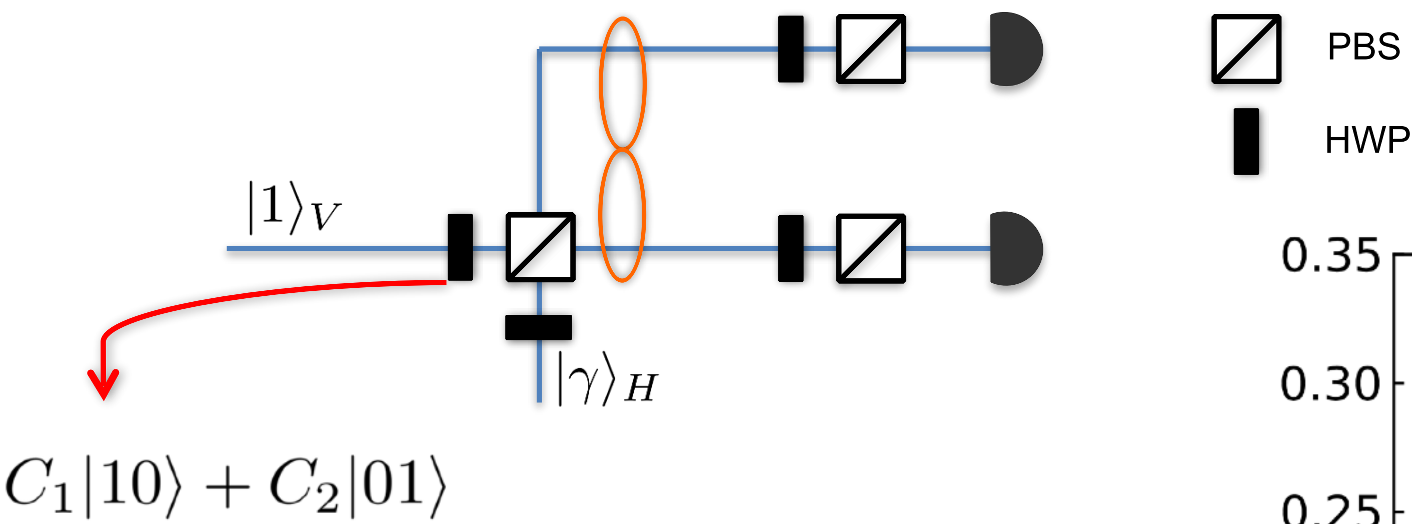
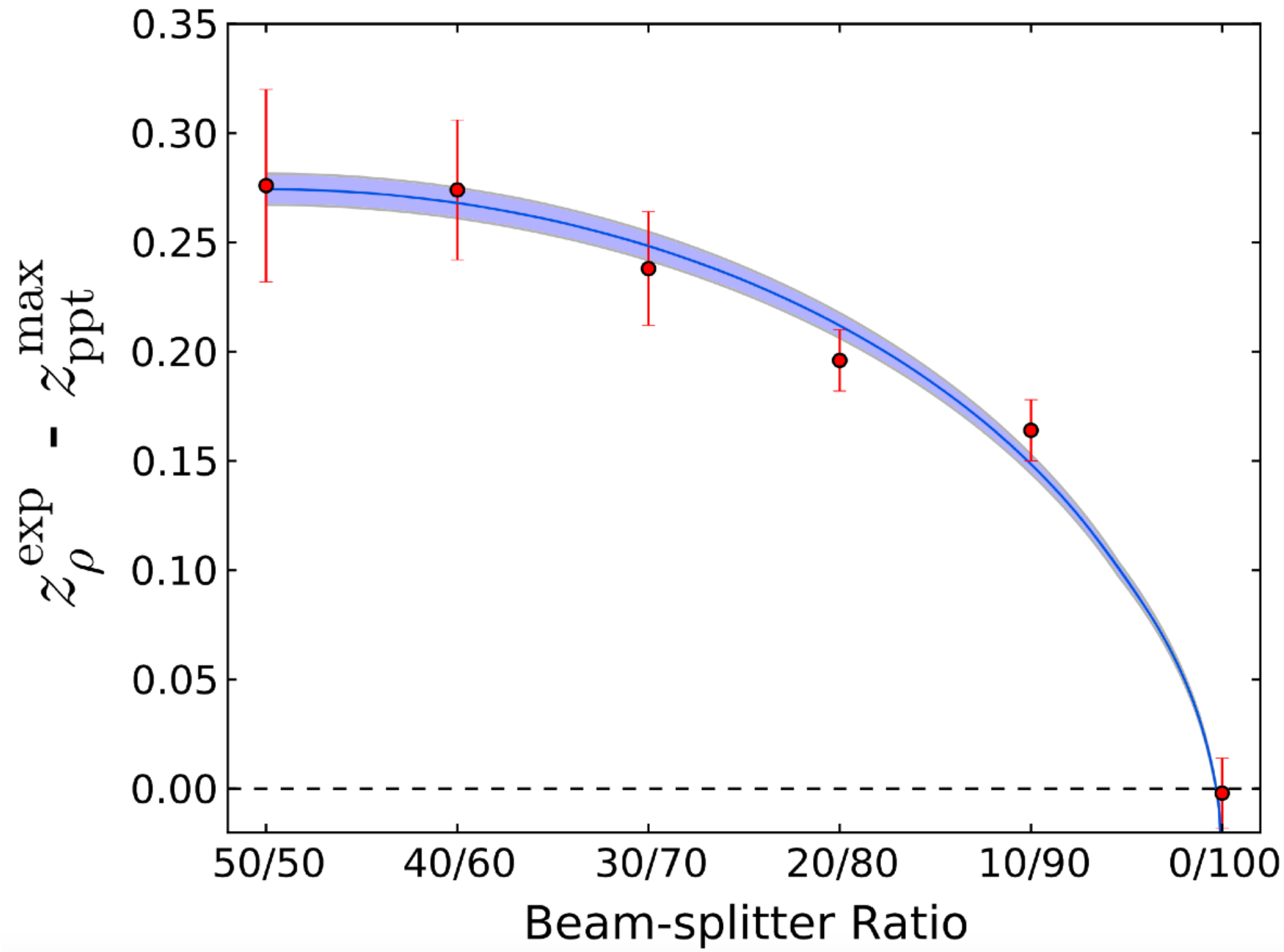


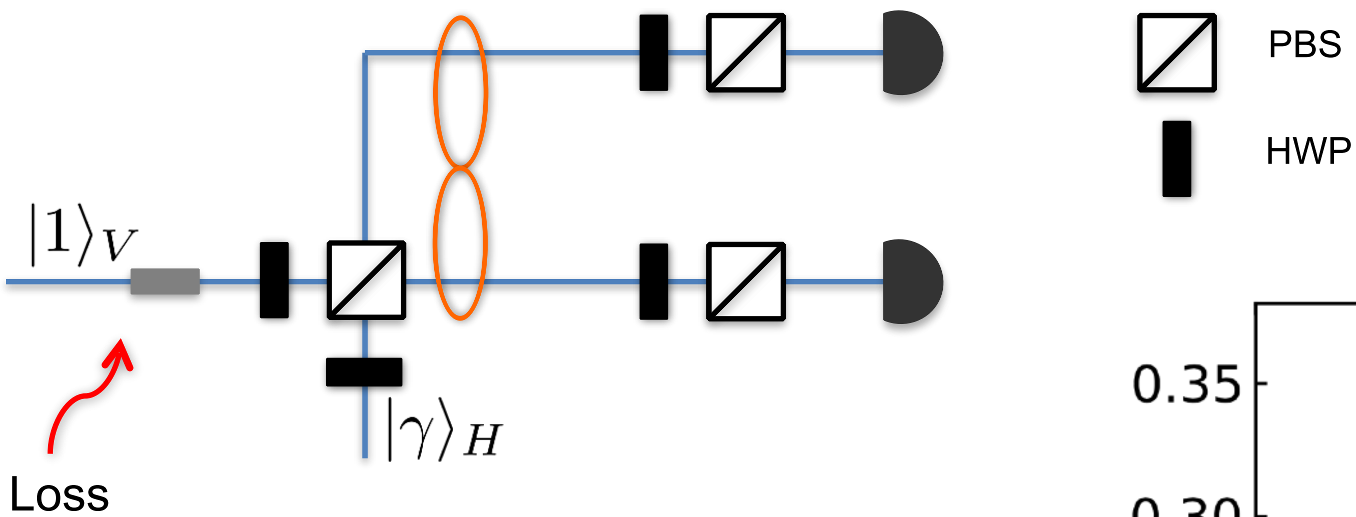


Unbalanced states

~ 8 kHz heralded entanglement (two and three partite)

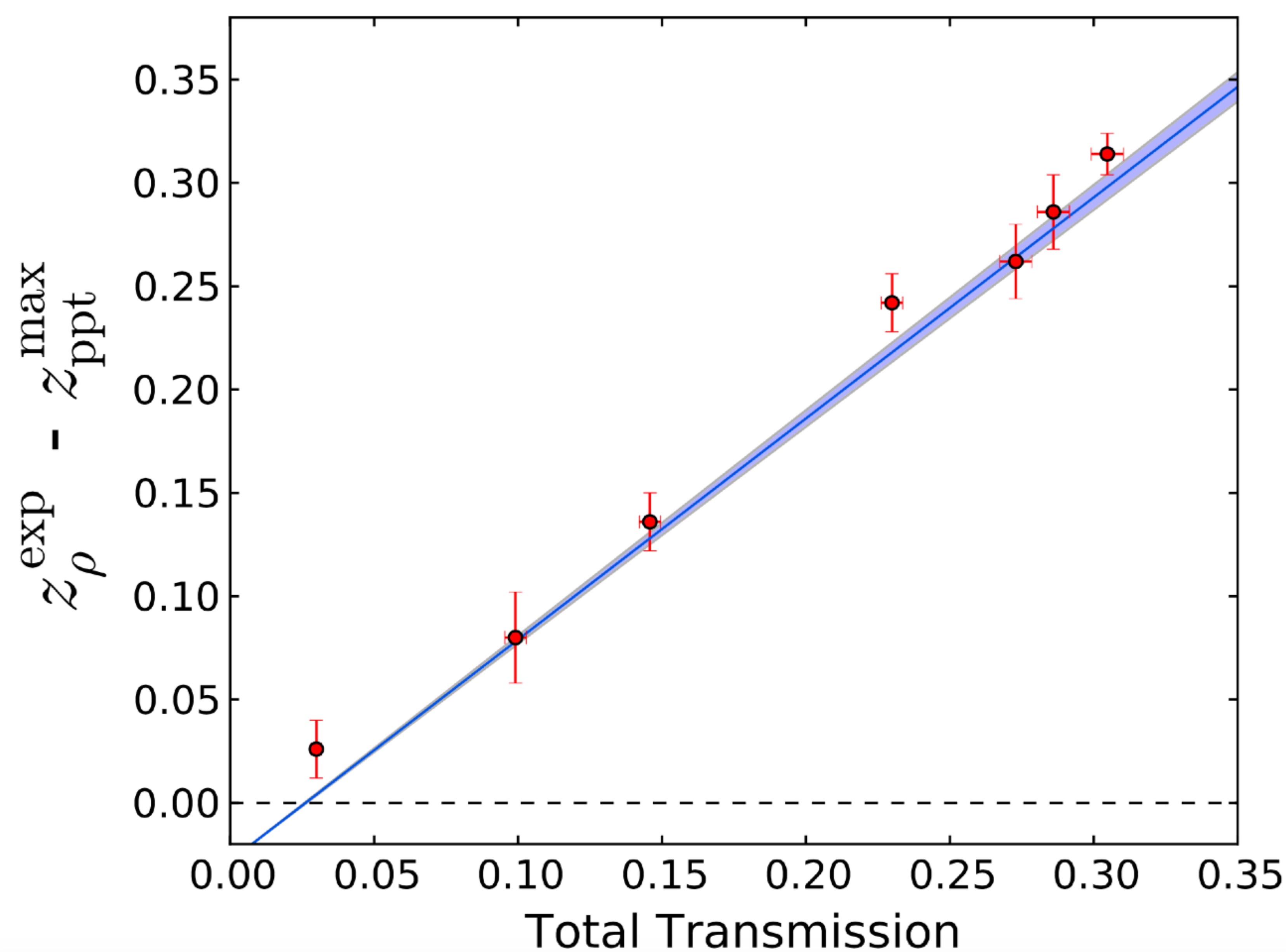
F. Monteiro et al., Phys. Rev. Lett. 114, 170504 (2015)

Experiment: entanglement witness



The effect of loss:

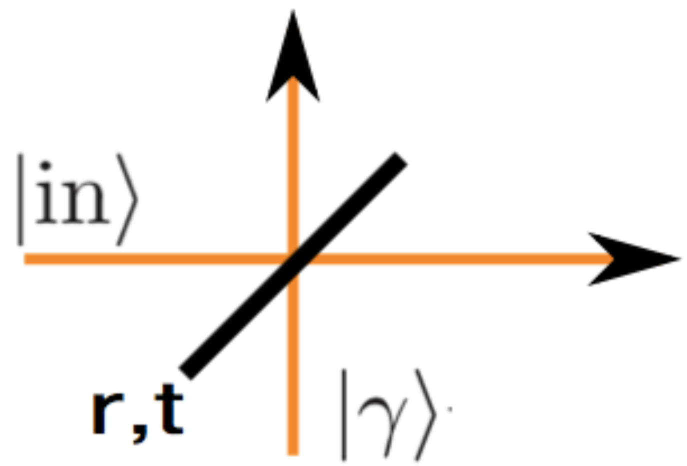
linearity



F. Monteiro et al., Phys. Rev. Lett. 114, 170504 (2015)

Measuring single photon entanglement

The answer is simple: Displacement operations!



$$\mathcal{D}(\gamma) = e^{\gamma a - \gamma^* a^\dagger}$$

Probability of "no click": given by the trace of the projection of the state onto coherent state

$$\mathcal{D}(\gamma)|0\rangle\langle 0|\mathcal{D}(\gamma^*) = |\gamma\rangle\langle\gamma|$$ **outcome +1**

Probability of "click": the complement

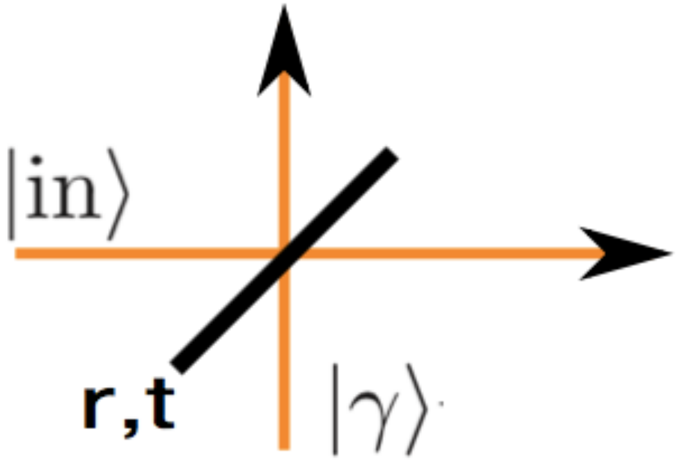
$$\mathbb{1} - |\gamma\rangle\langle\gamma|$$ **outcome -1**

B. Hessmo et. al., PRL, 92:180401, 2004.

V. C. Vivoli et. al. NJP, 17, 2015

Measuring single photon entanglement

$$M(\gamma) = 2|\gamma\rangle\langle\gamma| - \mathbb{1} = \begin{pmatrix} 2e^{-z^2} - 1 & 2e^{-z^2 - i\theta} z \\ 2e^{-z^2 + i\theta} z & 2e^{-z^2} z^2 - 1 \end{pmatrix}$$



$$\gamma = z e^{i\theta}$$

(vacuum-1 photon subspace)

Displacement allows you to access complementary basis.

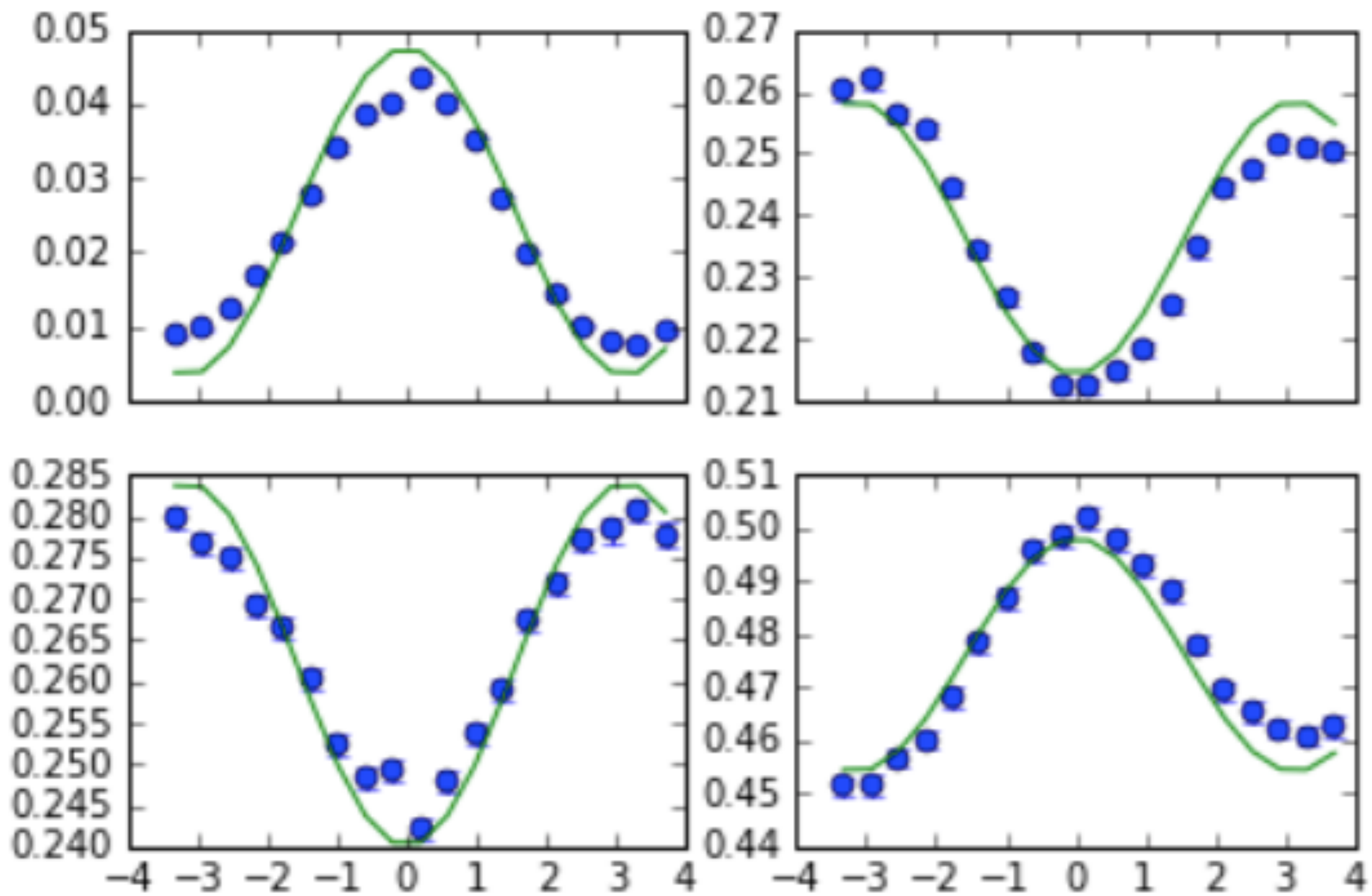
$$\sigma_{\gamma=0} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Approximates Pauli matrices.

$$\sigma_{\gamma=1} \approx - \begin{pmatrix} 0.3 & 0.7 \\ 0.7 & 0.3 \end{pmatrix}$$

Experiment: oscillations

Quantum mechanical prediction:



Model: fixed coherent state value, no double-pairs

V_exp = 0.053 V_th = 0.050