

Title: Measurement without "measurement": Experimental violation of Complementarity and its aftermath

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Abstract: Bohr's Principle of Complementarity of wave and particle aspects of quantum systems has been a cornerstone of quantum mechanics since its inception. Einstein, Schrödinger and deBroglie vehemently disagreed with Bohr for decades, but were unable to point out the error in Bohr's arguments. I will report three recent experiments in which Complementarity fails, and argue that the results call for an upgrade of the Quantum Measurement theory. Finally, I will introduce the novel concept of Contextual Null Measurement (CNM) and discuss some of its surprising applications.

Web-page: <http://users.rowan.edu/~afshar/> Preprint (published in Proc. SPIE 5866, 229-244, 2005): <http://www.irims.org/quant-ph/030503/>

Measurement without “measurement”: Violation of Complementarity & its aftermath

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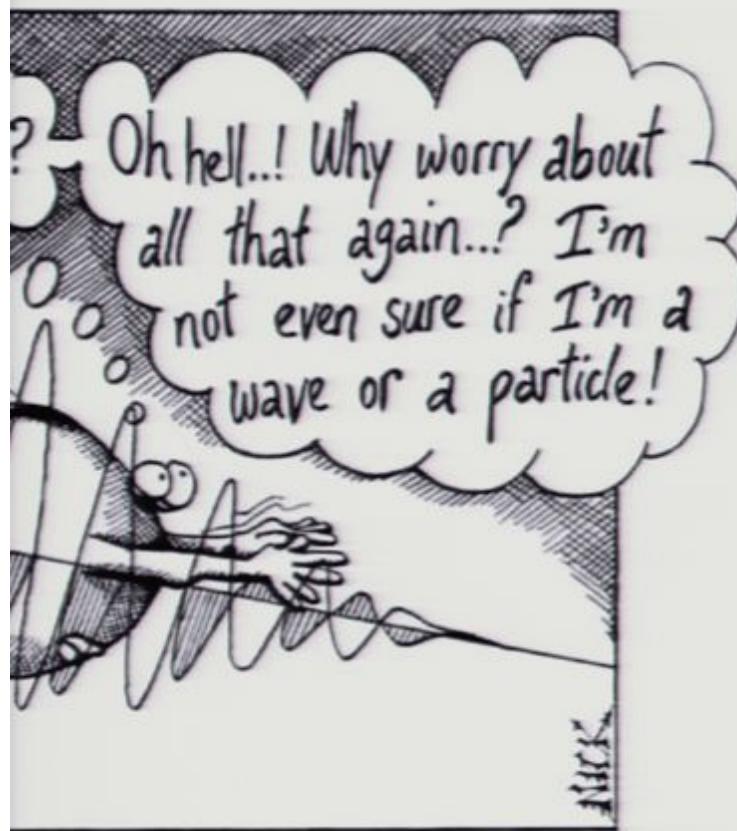


(Drawing by Chas. Addams; © 1940 The New Yorker Magazine, Inc.)

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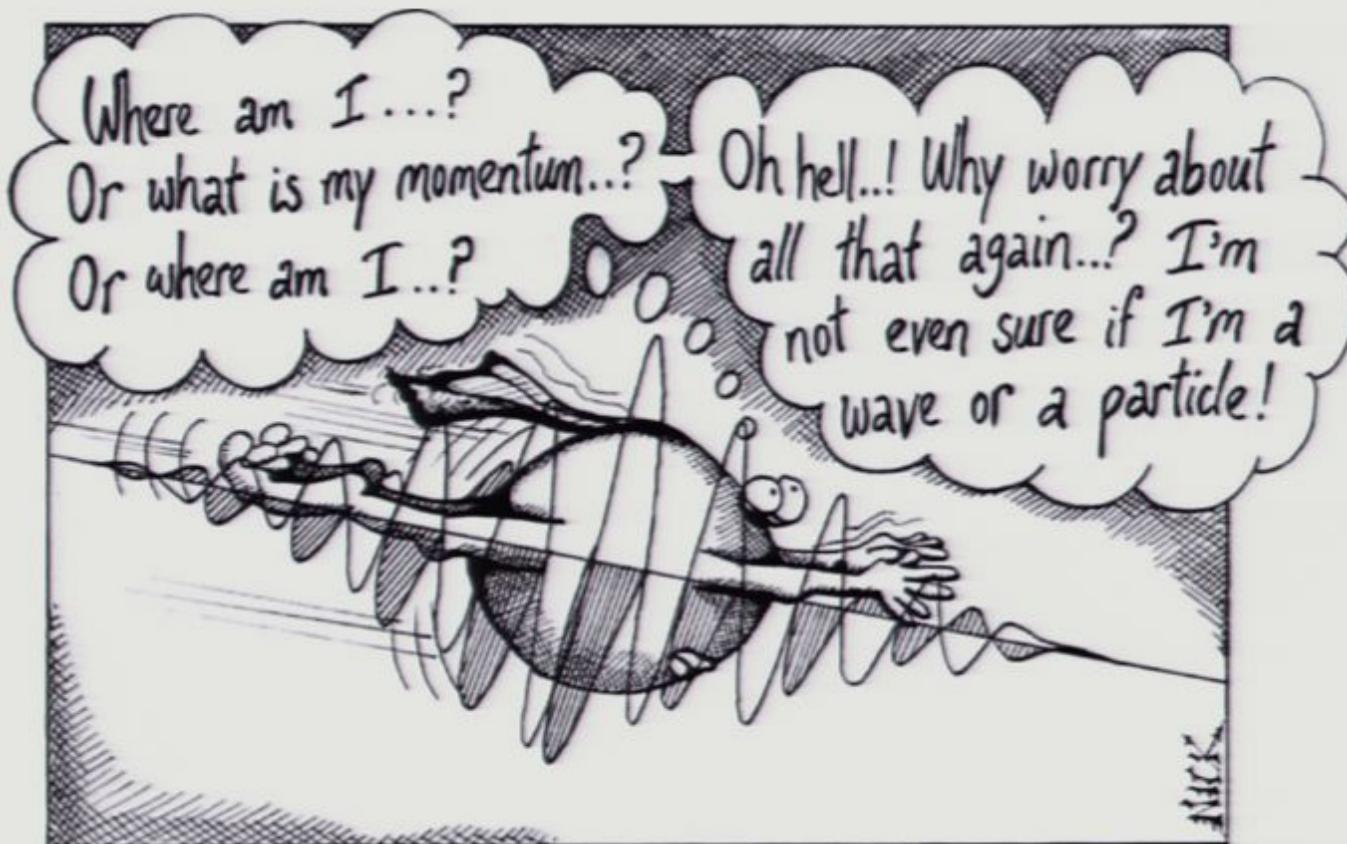


Quotations on the Wave-Particle duality and Complementarity



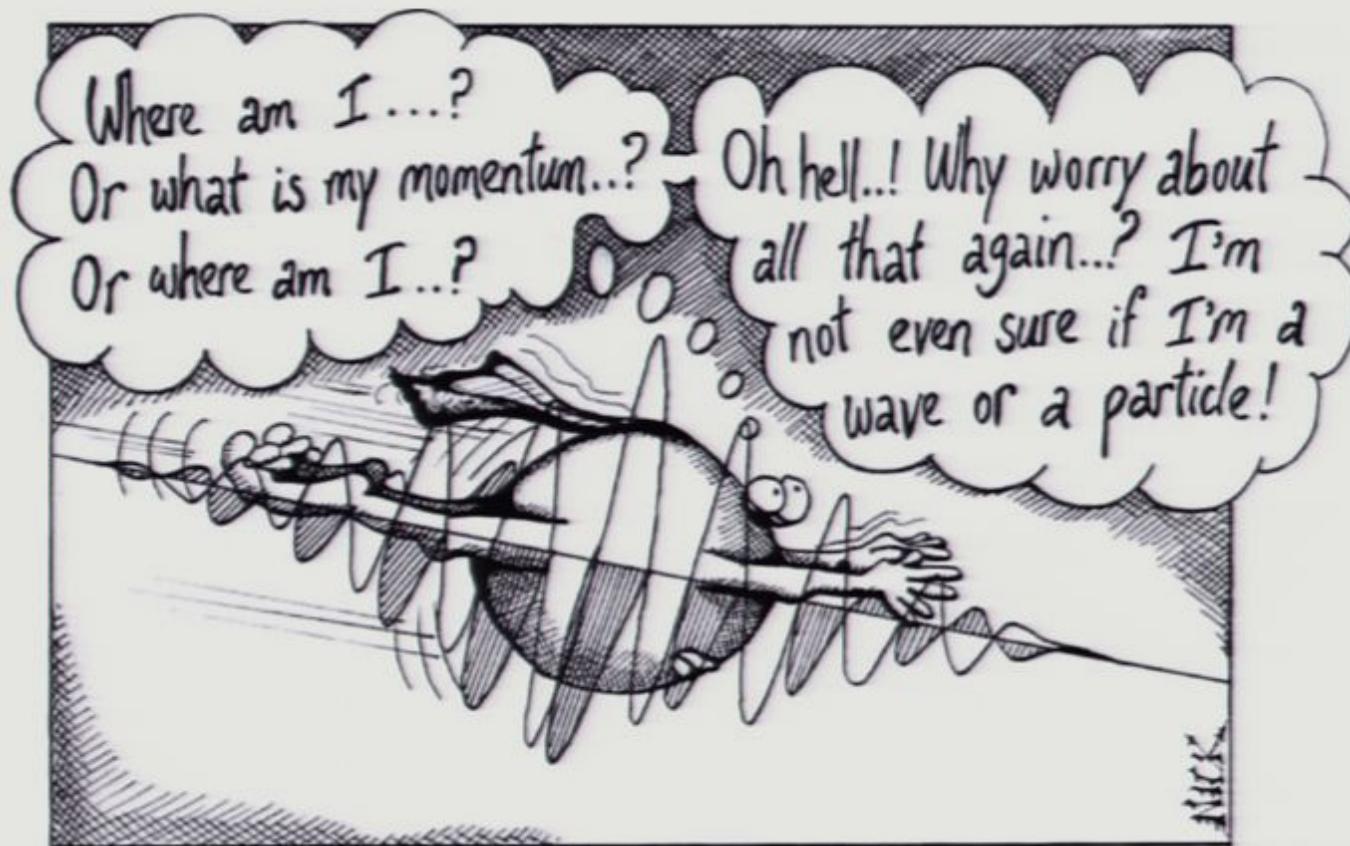
entity problems.

Quotations on the Wave-Particle duality and Complementarity



Photon self-identity problems.

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Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken." -- **Albert Einstein** in 1951. (Stuewer)

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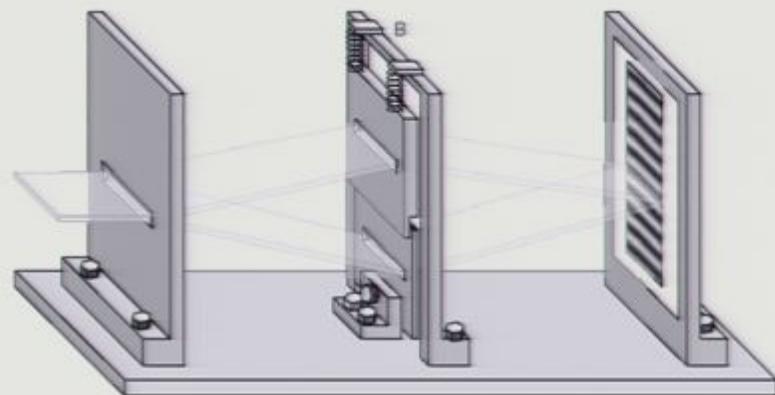
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"But for quantum theory to say in one breath 'through which slit' and in another 'through both' [for the same quanta] is logically inconsistent." **John A. Wheeler** in 1979. (Woolf)

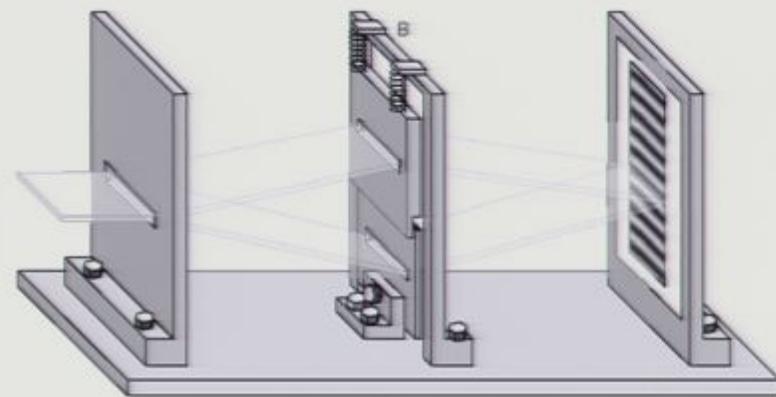
"In the two-slit setup, if we discover by any means whatsoever through which slit each one of the photons traveled (thus acquiring "which-way" information), we lose the interference pattern..." -- **Marlan O. Scully** in 1994.

Welcher-Weg (Which-Way) Experiments

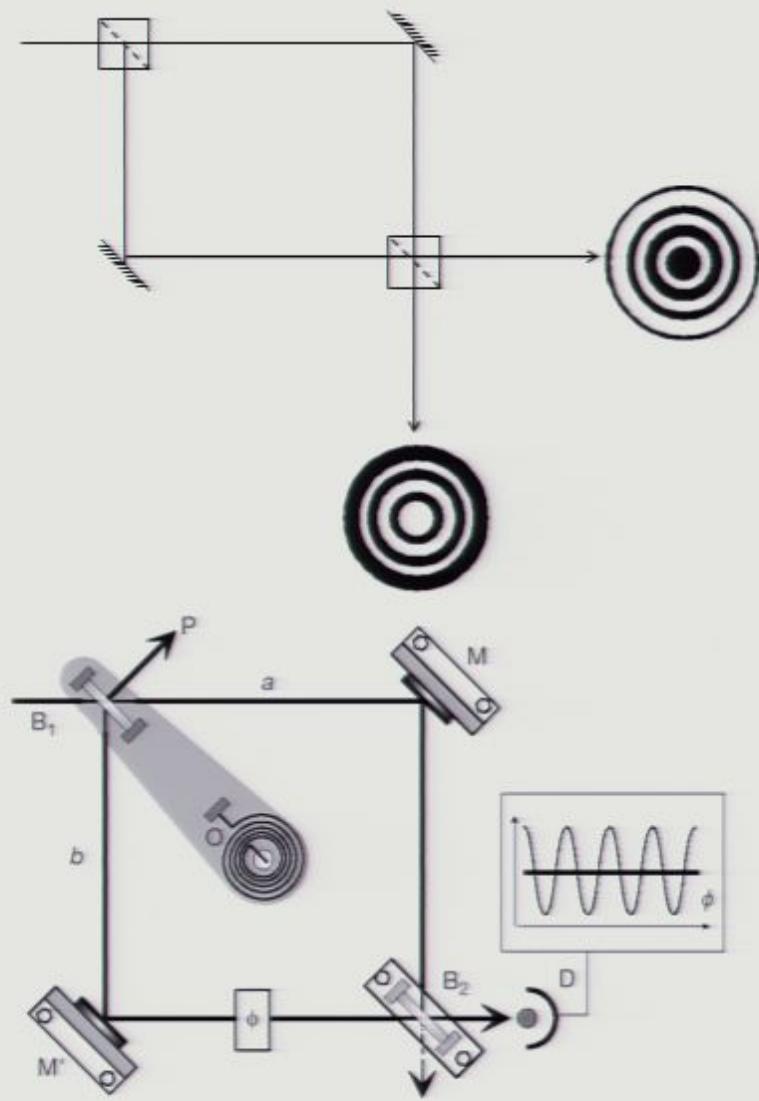
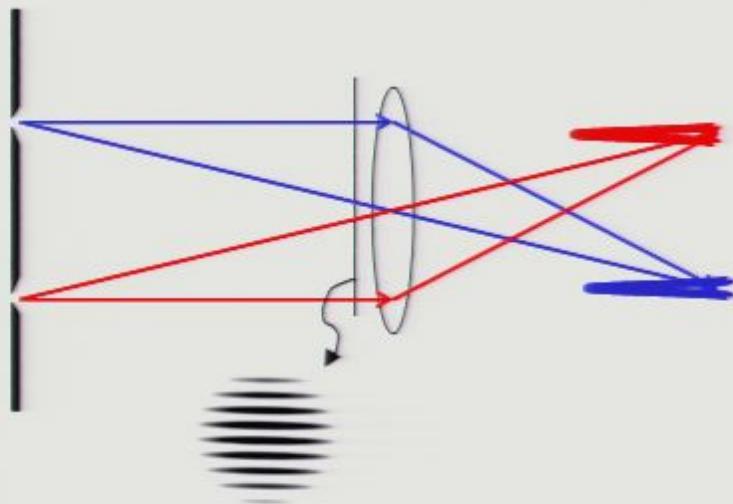


Bohr-Einstein Debate, 1927

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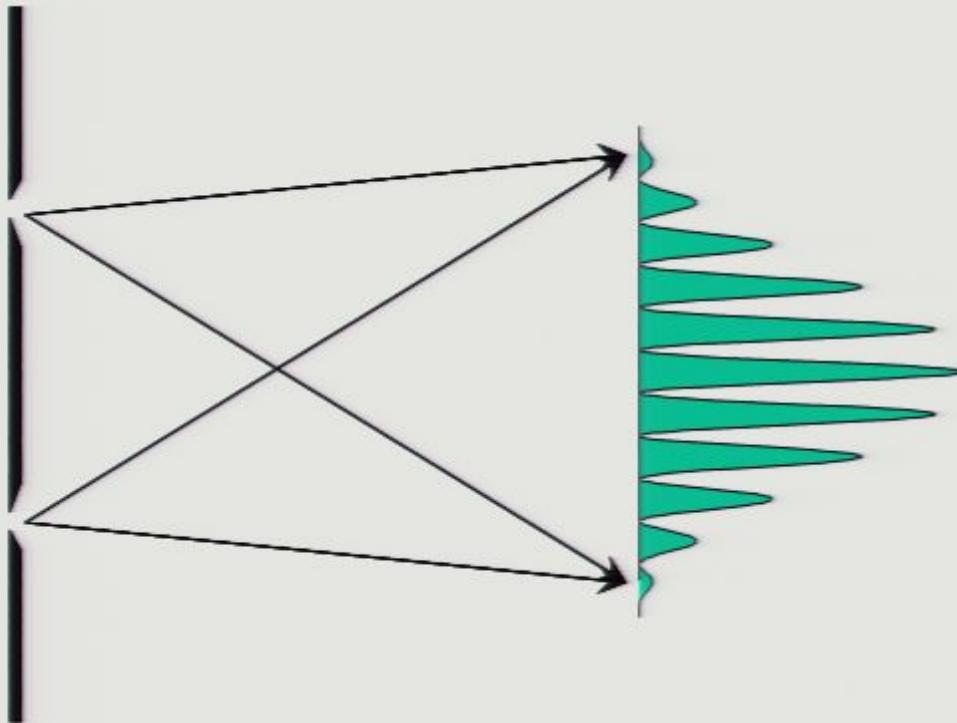


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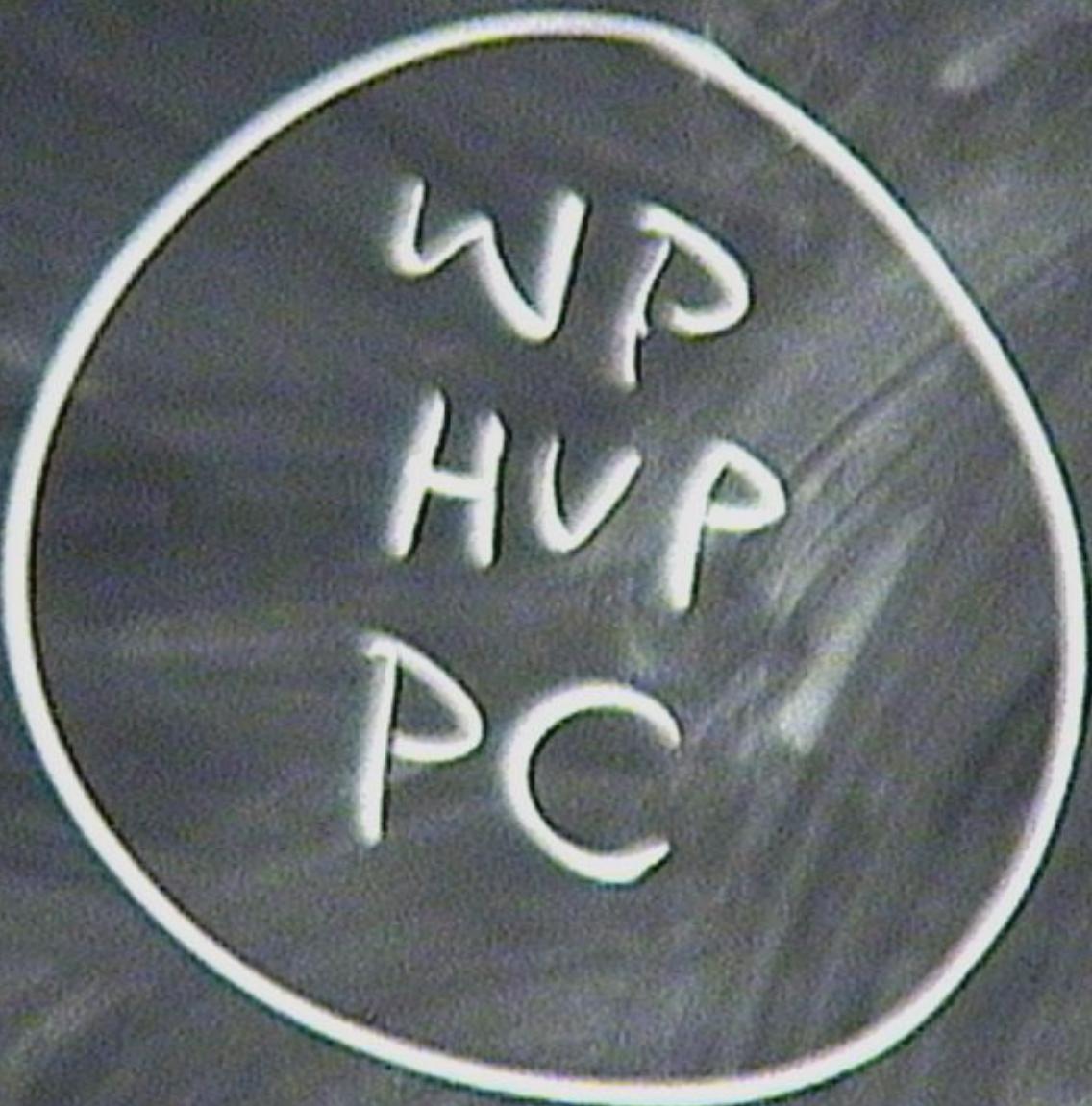


Feynman treats “the only mystery in quantum mechanics.”

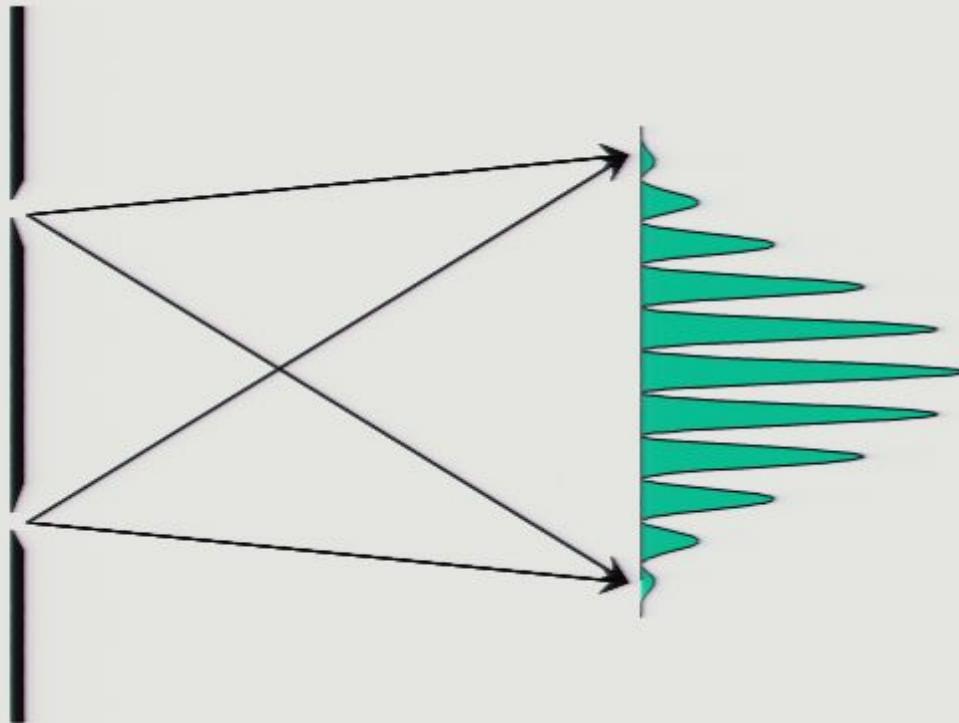
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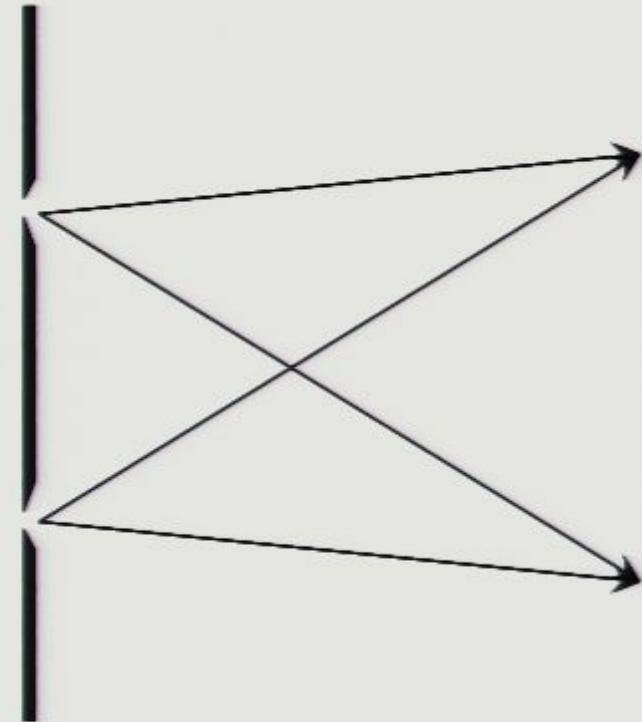
Interference Pattern



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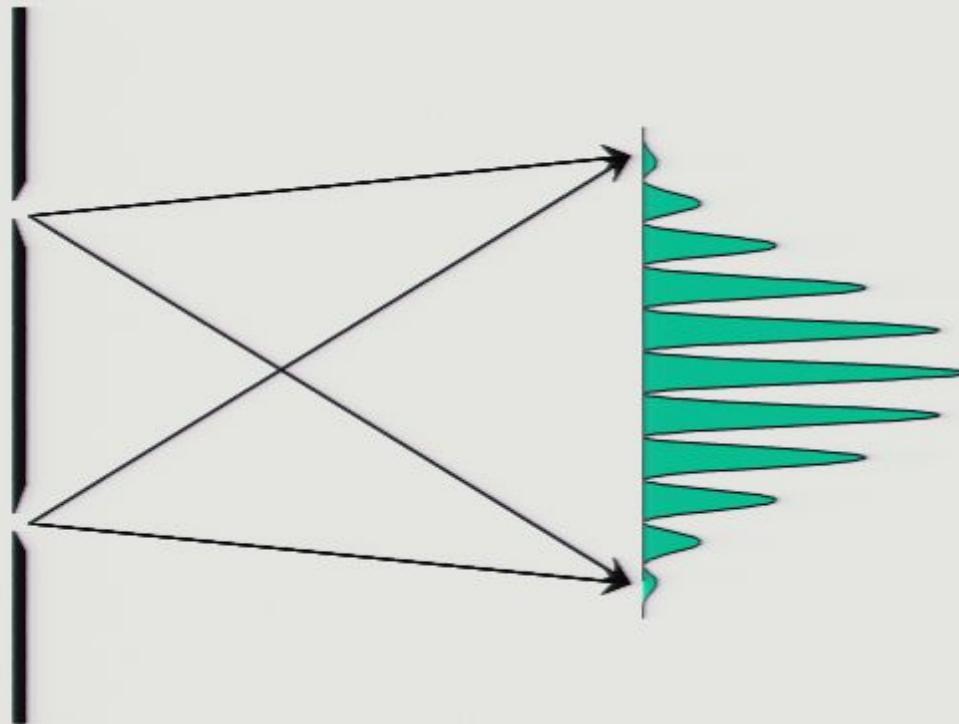


Interference Pattern

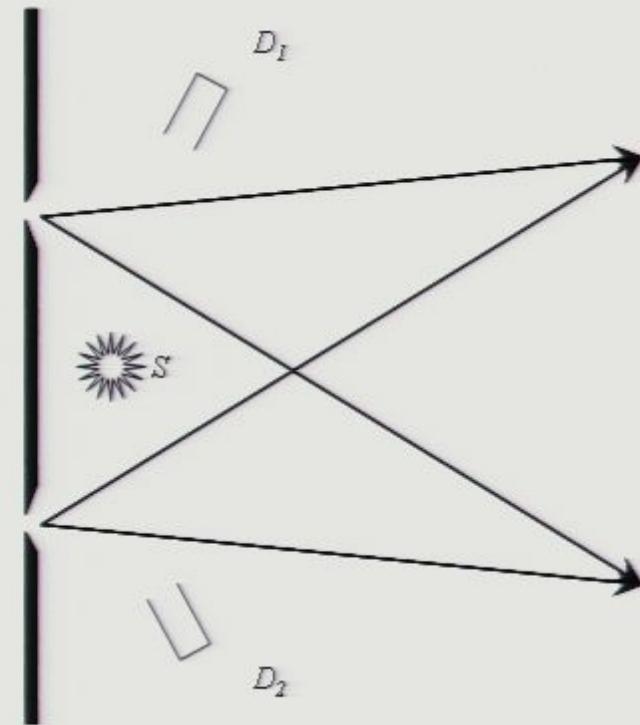


Which-Way Information

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Interference Pattern



Which-Way Information

Complementarity is not always enforced by the Uncertainty Principle

articles

Origin of quantum-mechanical complementarity probed by a 'which-way' experiment in an atom interferometer

S. Dürr, T. Nonn & G. Rempe
Institut für Physik, Universität Ulm, 7900 Ulm, Germany

The principle of complementarity refers to the ability of quantum-mechanical entities to behave as particles or waves under different experimental conditions. For example, in the famous double-slit experiment, a single electron can apparently pass through both apertures simultaneously, forming an interference pattern. But if a "which-way" detector is employed to determine the particle's path, the interference pattern is destroyed. This is usually explained in terms of Heisenberg's uncertainty principle, in which the acquisition of spatial information increases the uncertainty in the particle's momentum, thus destroying the interference. Here we report a which-way experiment in an atom interferometer in which the "back-action" of path detection on the atom's momentum is too small to explain the disappearance of the interference pattern. We attribute it instead to correlations between the which-way detector and the atomic motion, rather than to the uncertainty principle.

In classical physics, a particle moves along a well-defined trajectory. A quantum object, however, reveals its wave character in interference experiments in which the object seems to move from one place to another along several different paths simultaneously. It is essential that these ways are indistinguishable, because any attempt to observe which way the object actually took unavoidably destroys the interference pattern.

The usual explanation for the loss of interference in a which-way experiment is based on Heisenberg's position-momentum uncertainty relation. This has been illustrated in famous gedanken experiments like Einstein's "renouncing slit" or Feynman's light microscope. In the light microscope, electrons are illuminated with light immediately after they have passed through a double slit with separation d . A scattered photon locates the electron with a position uncertainty of the order of the light wavelength, $\Delta x \sim \lambda_{\text{light}}$. Owing to Heisenberg's position-momentum uncertainty relation, this localization must produce a momentum uncertainty of the order of $\Delta p \sim \hbar/\lambda_{\text{light}}$. This momentum uncertainty arises from the momentum kick transferred by the scattered photons. For $\lambda_{\text{light}} < d$, no which-way information is obtained, but the momentum kick is so large that it completely washes out the spatial interference pattern.

However, Scully *et al.*¹ have recently proposed a new gedanken experiment, where the loss of the interference pattern in an atomic beam is not related to Heisenberg's position-momentum uncertainty relation. Instead, the correlations between the which-way detector and the atomic beams are responsible for the loss of interference fringes.

Such correlations had already been studied experimentally. They are, for example, responsible for the lack of ground-state quantum beats in time-resolved fluorescence spectroscopy². Other examples are neutron interferometers, where which-way information can be stored by selectively flipping the neutron spin in one arm of the interferometer³.

Nevertheless, the gedanken experiment of Scully *et al.* was criticized by Stoen *et al.*⁴, who argued that the uncertainty relation allows inference rules like sufficient to wash out the fringes. This started a controversial discussion^{5,6} about the following question: Is complementarity more fundamental than the uncertainty principle?

The atom interferometer

Figure 1 shows a scheme of our atom interferometer. An incoming beam of atoms passes through two separated standing wave light beams. The detuning of the light frequency from the atomic resonance, $\Delta = \omega_{\text{trap}} - \omega_{\text{resonance}}$, is large so that spontaneous emission can be neglected. The light fields each create a conservative potential U for the atoms, the so-called light shift, with $U \propto \Omega^2$, where Ω is the light intensity (see, for example, ref. 7). Interactions between the light intensity and the wavevector of the light, $\Omega \partial_x = U_{\text{ext}}(\partial_x \Omega)/\hbar$, where $U_{\text{ext}} = \hbar^2 k^2/2m$, with $k = 2\pi/\lambda$.

NATURE VOL 351 SEPTEMBER 1991 Nature © Macmillan Publishers Ltd 1991 33

Scully, Englert and Walther suggested a test of the origin of Complementarity in 1991
(Nature 351, 111-116)



Complementarity is not always enforced by the Uncertainty Principle

articles

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The usual explanation for the loss of interference in a which-way experiment is based on Heisenberg's position-momentum uncertainty relation. This has been illustrated in famous gedanken experiments like Einstein's "measuring slit" or Feynman's light microscope.¹ In the light microscope, electrons are illuminated with light immediately after they have passed through a double slit with separation d . A scattered photon locates the electron with a position uncertainty of the order of the light wavelength, $\Delta x \sim \lambda_{\text{light}}$. Owing to Heisenberg's position-momentum uncertainty relation, this localization must produce a momentum uncertainty of the order of $\Delta p \sim \hbar/\lambda_{\text{light}}$. This momentum uncertainty arises from the momentum kick transferred by the scattered photons. As this way information is obtained, but the momentum kick is so large that it completely washes out the spatial interference pattern.

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Nevertheless, the gedanken experiment of Scully et al.² was criticized by Stein et al.⁵, who argued that the uncertainty relation allows infinite read kicks sufficient to wash out the fringes. This started a controversial discussion⁶⁻¹⁰ about the following question:

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Figure 1 shows a scheme of our atom interferometer. An incoming beam of atoms passes through two separated standing wave light beams. The detuning of the light frequency from the atomic resonance, $\Delta = \omega_{\text{Rabi}} - \omega_{\text{atom}}$, is large so that spontaneous emission can be neglected. The light fields each create a conservative potential U for the atoms, the so-called light shift, with $U \propto \Omega^2$, where Ω is the light intensity (see, for example, ref. 11). Interacting with the light intensity in a fixed position, $R(t) = L_1(t)/L_2(t)$, where $L_{1,2}$ is the wavevector of the light, hence the light shift potential takes the form $U(t) = U_{\text{ext}}(\theta(t))t$, with $U_{\text{ext}} = \Omega^2/L$.

letters to nature

strong constraints on different missing processes (such as gravitational settling or meridional circulation).

Cosmic-ray-moderation models¹² and observations of interstellar clouds¹³ indicate that the primordial ratio, $f^*(t)$, in the protoplanetary matter could have been as high as 0.3–0.5, which in turn would allow either the possibility of some ^{12}Li depletion in the star or the ingestion of planets with even smaller mass. In this scenario we have assumed that the planet(s) was (were) ingested after the stellar convective envelope had shrunk, 10–20 Myr after stellar birth¹⁴, and had reached its current mass and depth. The timescale is comparable to the lifetime of protoplanetary disks¹⁵ (10–20 Myr) and planetary migration. Our results favour a scenario in which a planet was engulfed owing to the multi-body interactions in the system that can take place over a timescale of 100–500 Myr¹⁶. This is strongly supported by the highly eccentric orbit of the planetary companion of HD20945 (about 0.06). However, we hesitate to generalize it to explain the metal-rich nature¹⁷ of other stars hosting planets. Further Li isotopic ratio studies of a large sample of planet-bearing stars can help to put additional constraints on this scenario.

Note added in proof: A second planet with a minimum mass of 0.08 M_J has been discovered orbiting HD20945, with a period of 220 days (M. Mayor, personal communication). This detection has been done with the CORALIE spectrograph at the ESO La Silla Observatory.

ACKNOWLEDGEMENTS: These observations were made possible through the EITI Research in the Interest of the Earth programme of the European Commission and the French Space Agency. We thank the referee for his valuable support for this paper. Support from the French Agence pour l'Aménagement du territoire and the Région Ile-de-France is acknowledged.

Correspondence and requests for materials should be addressed to G.R.; e-mail: gr@mpa-garching.mpg.de.

A complementarity experiment with an interferometer at the quantum-classical boundary

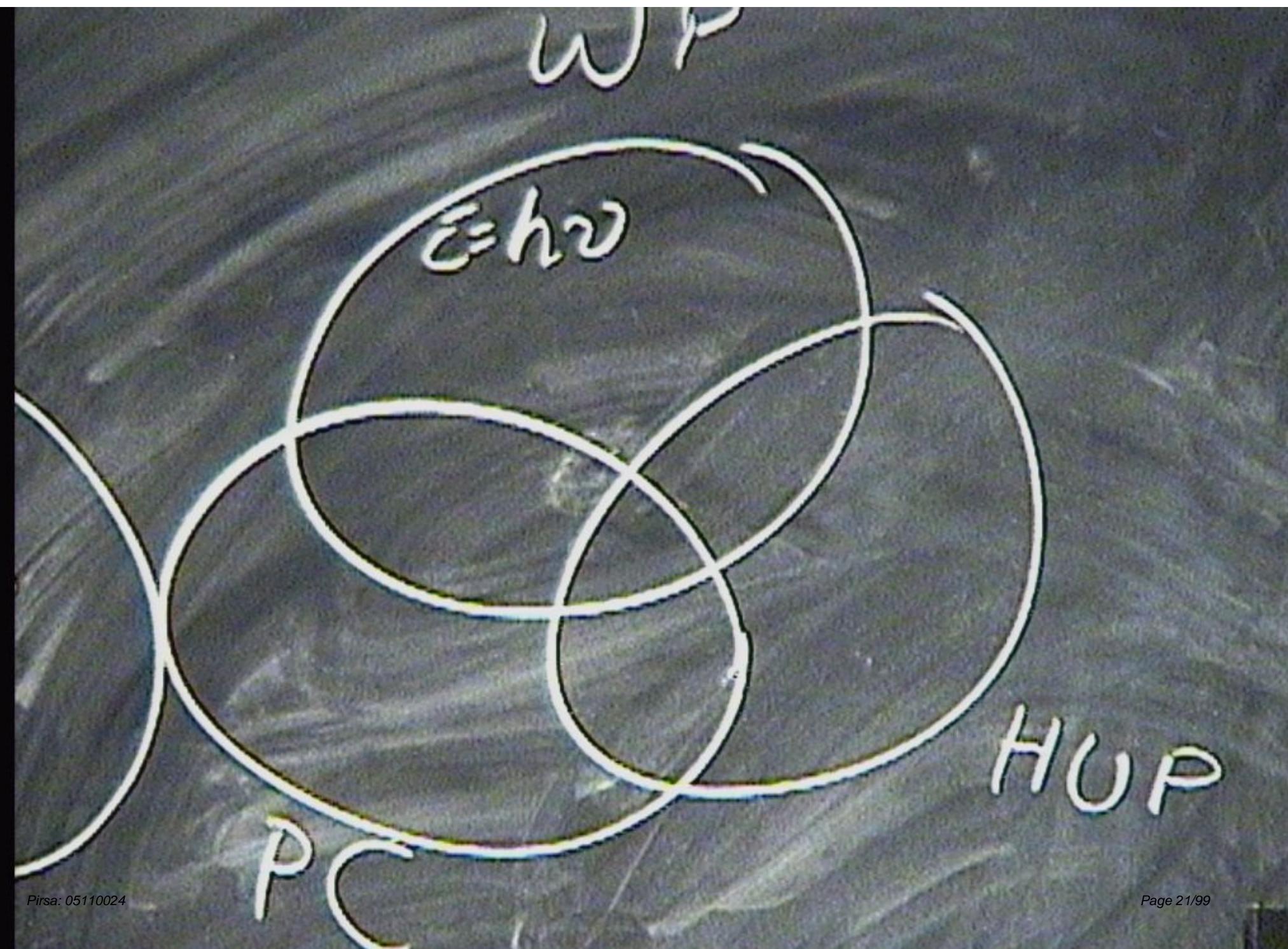
P. Dotter, S. Nonn, A. Schneebeli, G. Rempe, A. Jauress, M. Braun, J. H. Künneth & S. Hensel

Laboratoire Kastler Brossel, Département de Physique, Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France

To illustrate the quantum mechanical principle of complementarity, Bohr described an interferometer with a microscopic slit that records the particle's path. Recall of the quantum slit causes it to become entangled with the particle, resulting in a kind of Einstein-Podolsky-Rosen pair.¹ As the motion of the slit can be observed, the ambiguity of the particle's trajectory is lifted, suppressing interference effects. In contrast, the state of a sufficiently massive slit does not depend on the particle's path; hence, interference fringes are visible. Although many experiments illustrating various aspects of complementarity have been proposed²⁻¹⁰ and realized¹¹⁻¹⁴, none has addressed the quantum-classical limit in the design of the interferometer. Here we report an experimental investigation of complementarity using an interferometer in which the properties of one of the beam-splitting elements can be tuned continuously from being effectively microscopic to macroscopic. Following a recent proposal¹⁵, we use an atomic double-pulse Ramsey interferometer¹⁶, in which microwave pulses act as beam-splitters for the quantum states of the atoms. One of the pulses is a coherent field stored in a cavity, comprising a small, adjustable mass photon number. The visibility of the interference fringes in the final atomic state probability increases with this photon number, illustrating the quantum-to-classical transition.

Interferences in ordinary space are easier to understand than those in the abstract space of quantum states, so it is illuminating to make the analogy between the Ramsey design¹⁶ and a standard optical interferometer. Instead of Bohr's original design (Fig. 1), we describe here a Mach-Zehnder interferometer¹⁷ which provides a closer analogy with our Ramsey experiment (Fig. 2a). A photon beam is split into two paths α and β and recombined by two beam splitters B_1 and B_2 . The quantum amplitudes associated with these paths present a phase difference ϕ , swept by a retarding element. If B_1 and B_2 are macroscopic, the probability for detecting the particle in detector D exhibits a sinusoidal modulation as a function of ϕ . Suppose now that B_2 is a massive classical object, and B_1 is a light plate rotating around an axis perpendicular to the interferometer

Scully, Englert and Walther suggested a test of the origin of Complementarity in 1991
(Nature 351, 111-116)



WP

$$E = h\nu$$

HUP

$$[x, p] \neq 0$$

PC

SCIENCE AND TECHNOLOGY NEWS

THE WEEK'S BEST IDEAS

US JOBS IN SCIENCE

NewScientist

July 24-30, 2004

Rule 1 Nothing exists until it is measured

Niels Bohr 1930

RULE 2
IGNORE RULE 1

The Quantum Rebellion

Pirsa: 05110024

MASTER BLASTER
THE MAN WHO MAKES

Turning off
unruly regions

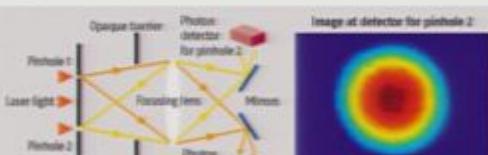


ASHAR'S QUANTUM BOMBSHELL

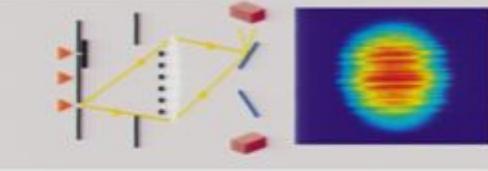
Shantanu Ashar's version of the double-slit experiment does what was thought to be impossible: it shows light behaving as both particles and waves at the same time

● Maximum intensity ● Minimum intensity

Laser light coming through each of the two pinholes is focused by a lens onto two mirrors, and then sent to two photon detectors, each of which responds to particles of light coming from one of the pinholes.



Ashar closes one pinhole and carefully places thin vertical wires at particular places in front of the lens. Some of the light now scatters off the wires, degrading the image and slightly reducing the number of photons reaching the detector from the open pinhole.



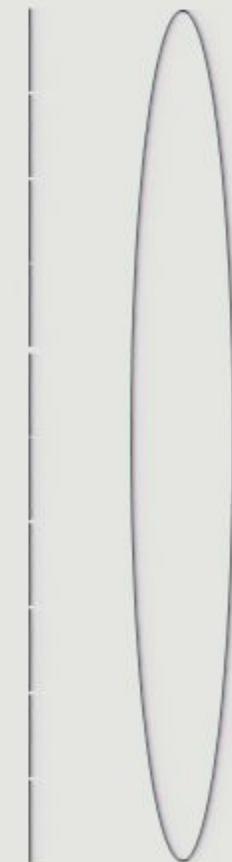
Ashar opens up the slit again and the image is restored. The wires no longer deflect any light and the number of photons reaching detector 2 returns to its original value. This seems to be because the wires are in the dark bands of an interference pattern so no light hits them. Only light behaving as a wave can create an interference pattern – so this experiment is strong evidence of light behaving as a wave and a particle at the same time.



Complementarity: Full WW information must lead to full decoherence.

1

2

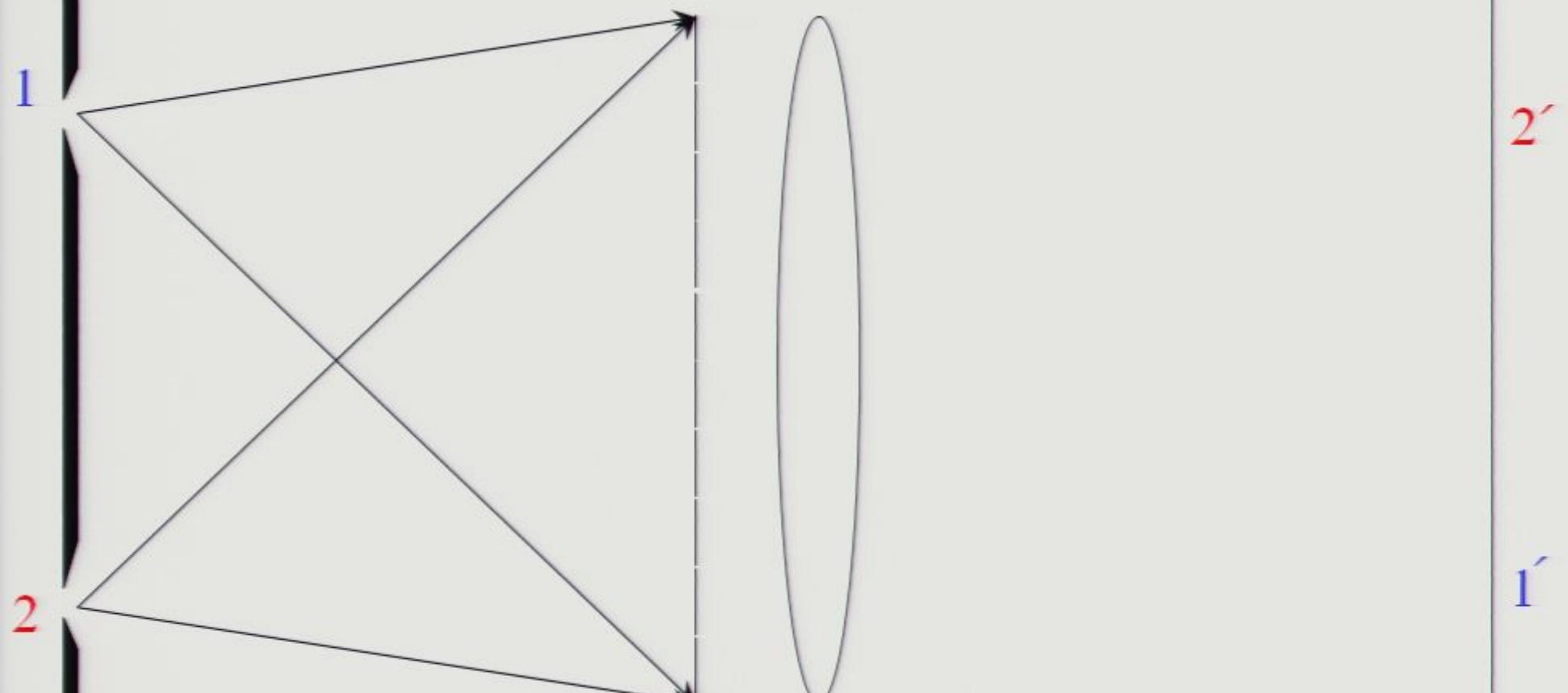


2'

1'

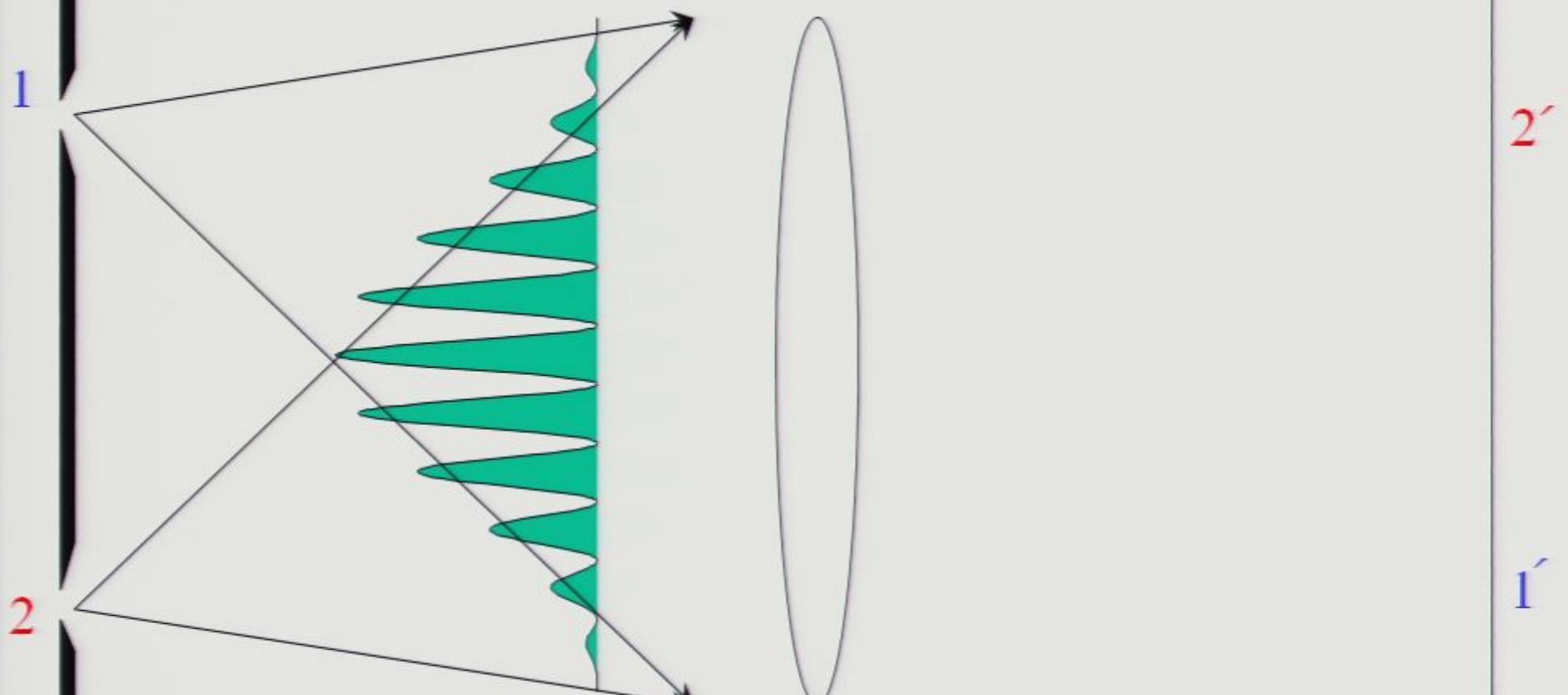
Wheeler's Delayed-Choice Experiment

Complementarity: Full WW information must lead to full decoherence.



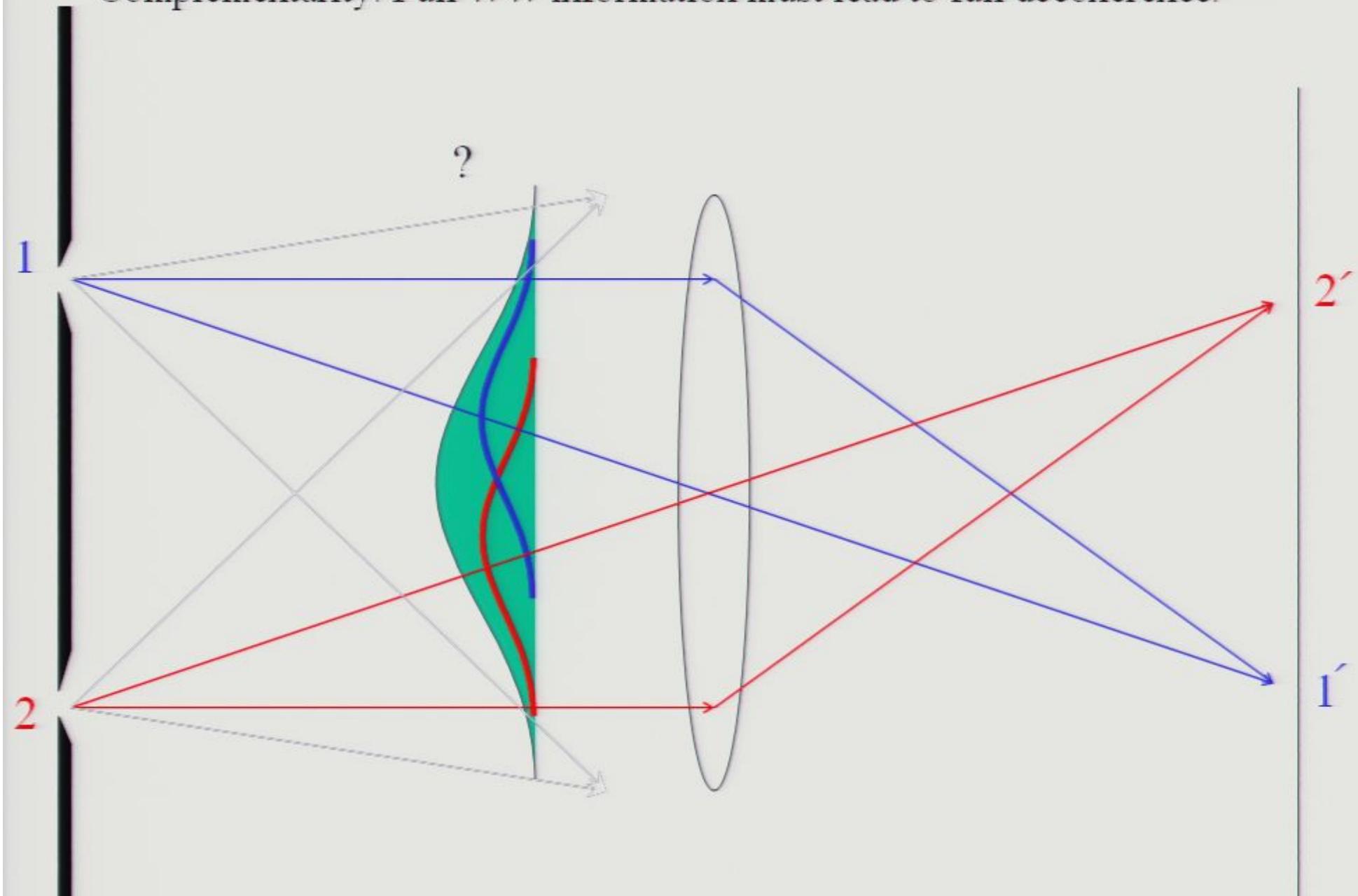
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Complementarity: Full WW information must lead to full decoherence.



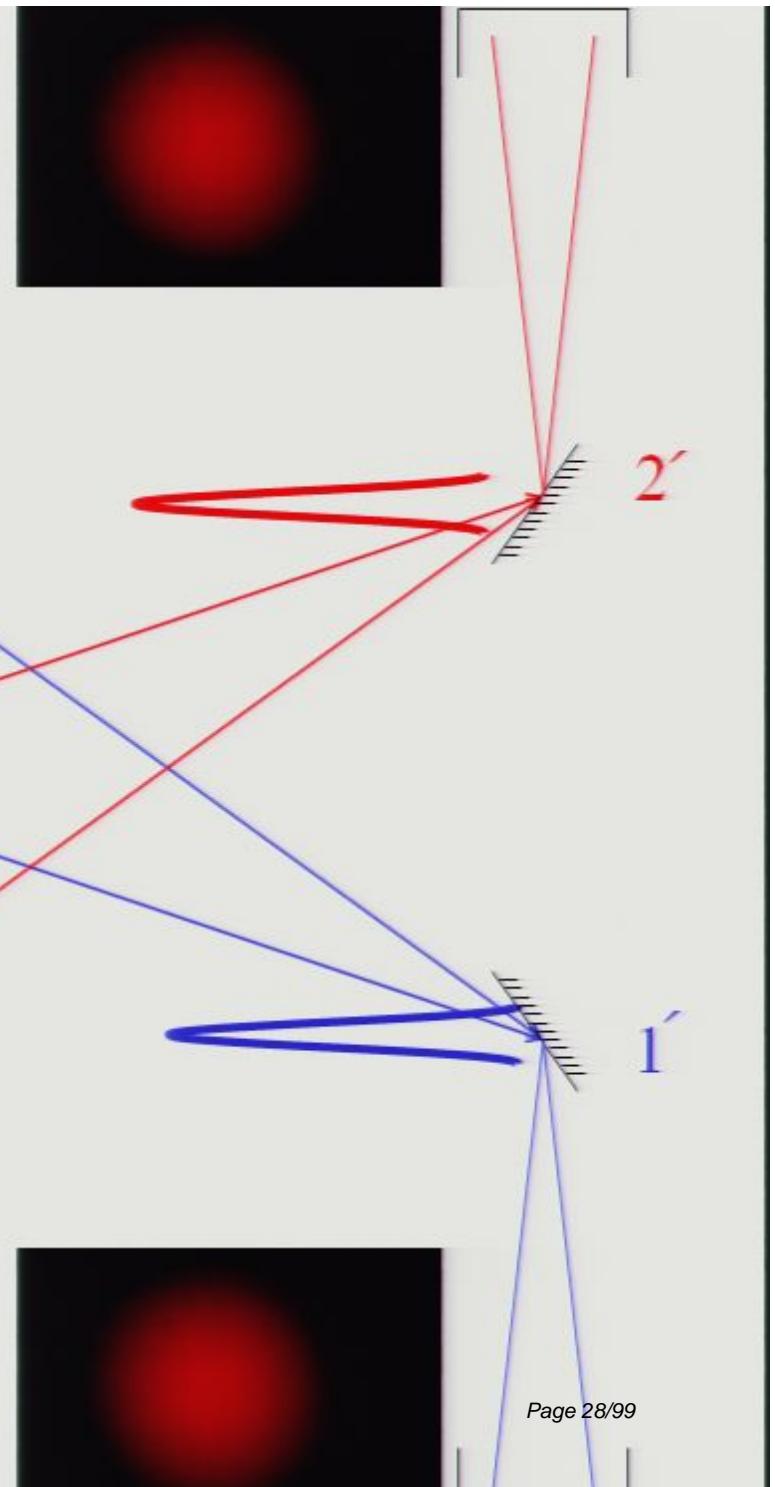
Wheeler's Delayed-Choice Experiment

Complementarity: Full WW information must lead to full decoherence.



Wheeler's Delayed-Choice Experiment

No Wire Grid



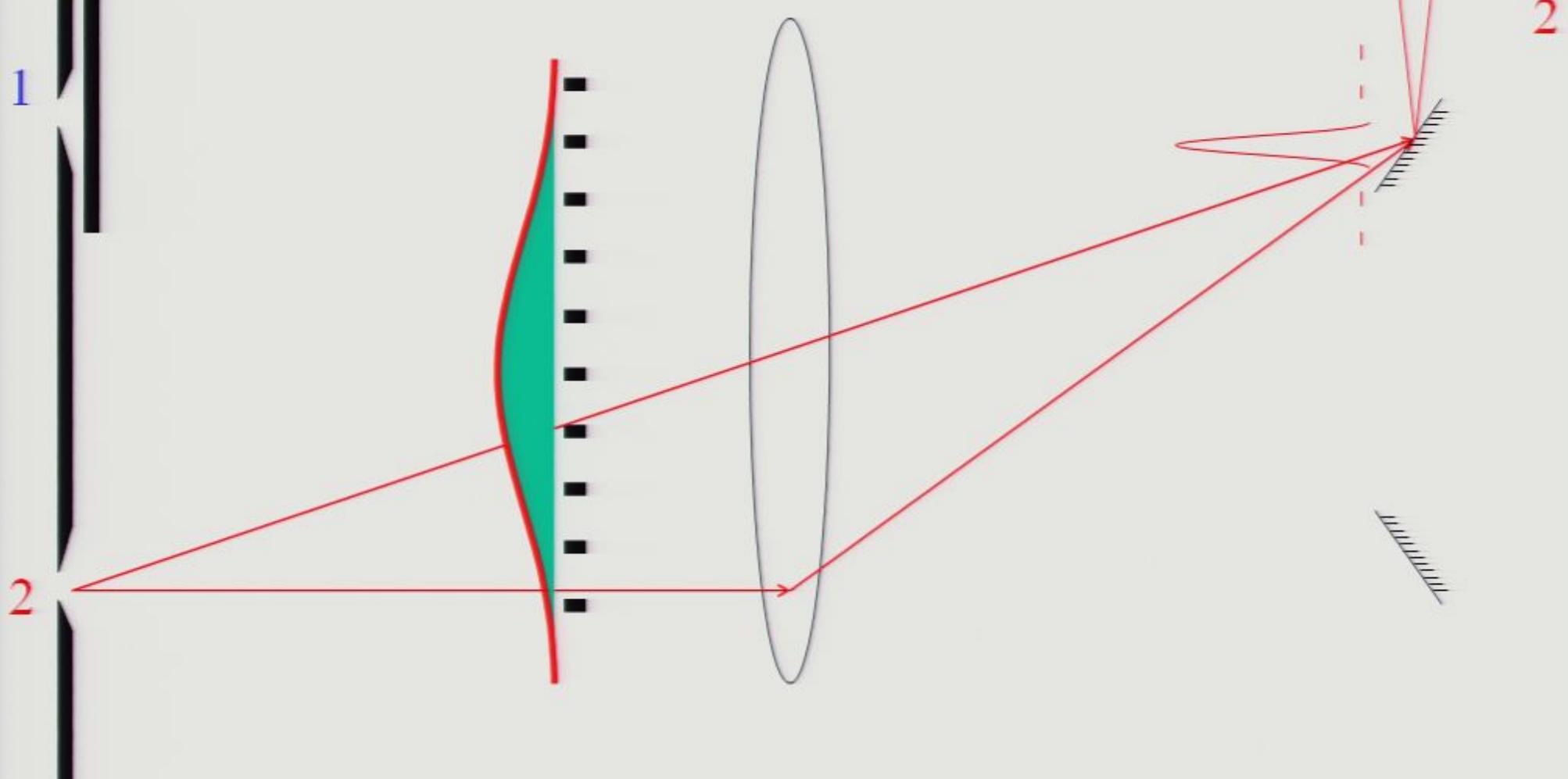
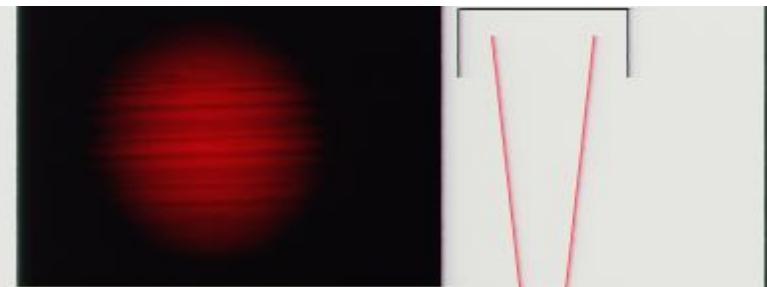
1

2

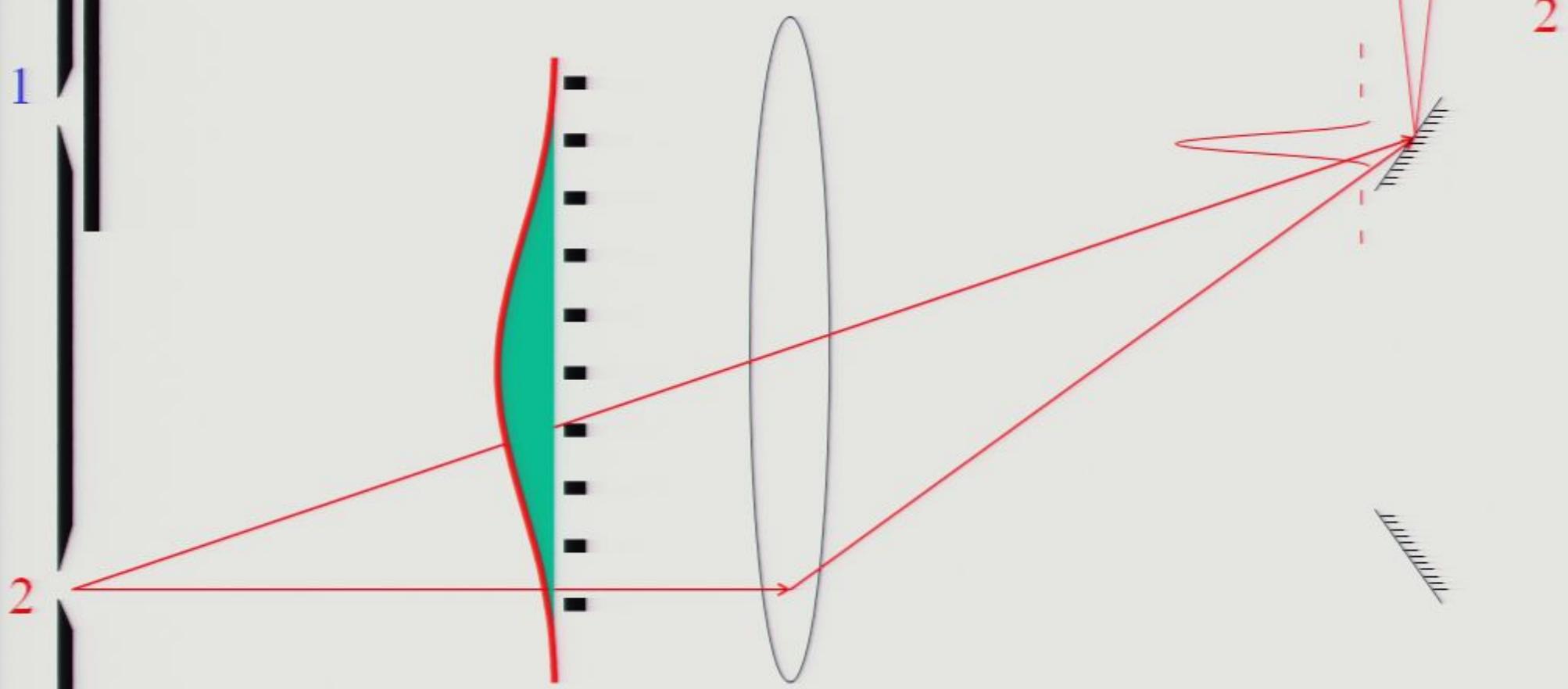
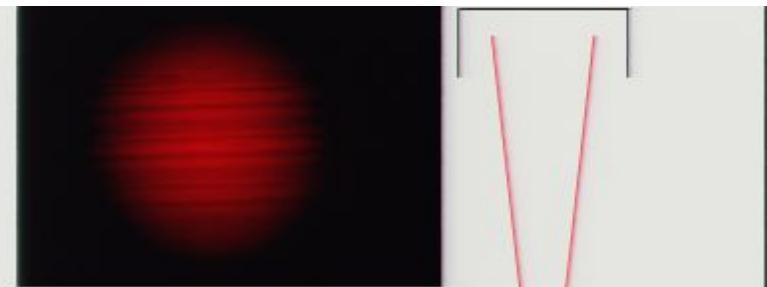
2'

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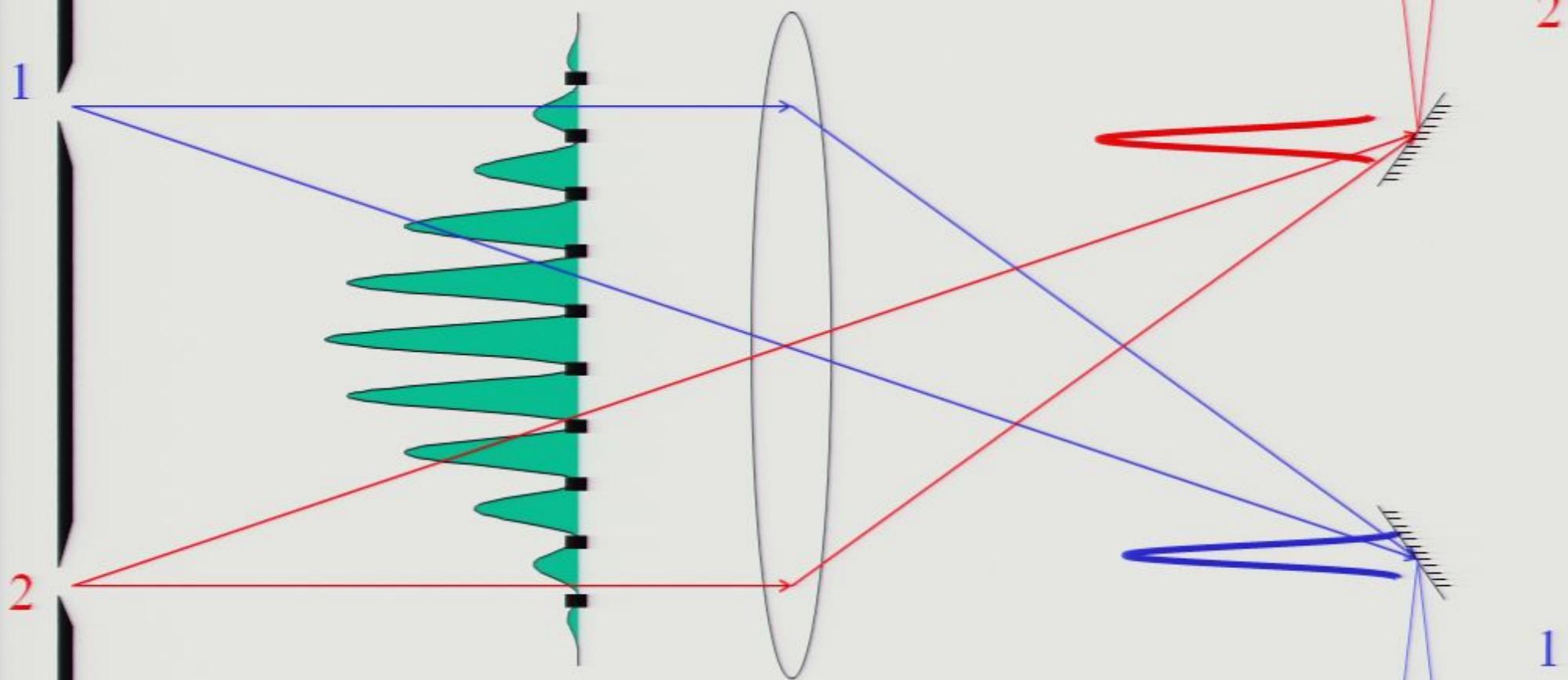
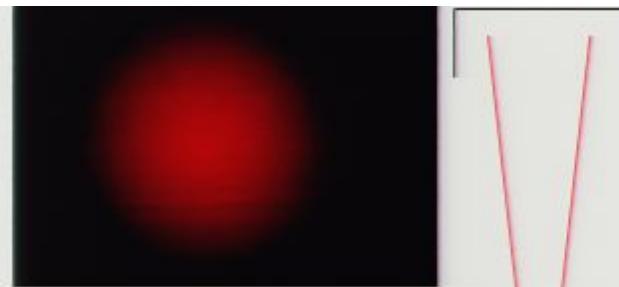
With Wire Grid (6 Wires)
Only 2 Open



With Wire Grid (6 Wires)
Only 2 Open



With Wire Grid (6 Wires)
Both Open



If Complementarity is correct, then we expect to observe
when the Wire Grid is present and Both Pinholes are Open



With WG (6 Wires)
Only 2 Open

If Complementarity is correct, then we expect to observe
when the Wire Grid is present and Both Pinholes are Open



With WG (6 Wires)
Only 2 Open

If Complementarity is correct, then we expect to observe
when the Wire Grid is present and Both Pinholes are Open

But we observe



With WG (6 Wires)
Both Open



With WG (6 Wires)
Only 2 Open

If Complementarity is correct, then we expect to observe
when the Wire Grid is present and Both Pinholes are Open

But we observe



With WG (6 Wires)
Both Open

And ideally



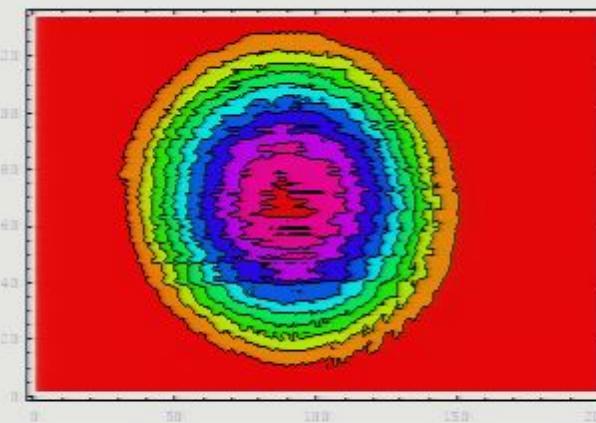
No WG (Control)



With WG (6 Wires)
Only 2 Open



Wires at minima, both open



$$\iint P_2 dA dt$$

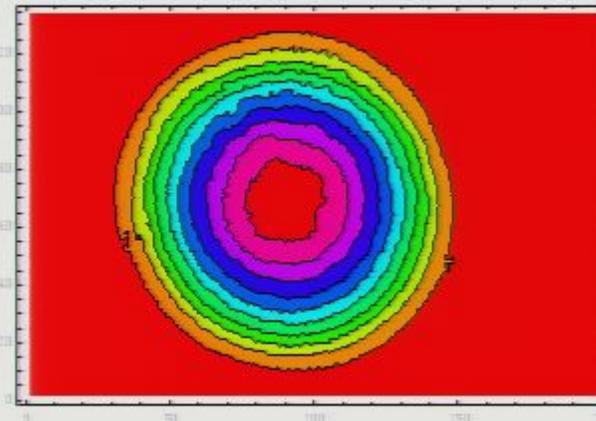
Throughput Ratio
relative to Control

1010643

$100.1\% \pm 0.5\%$

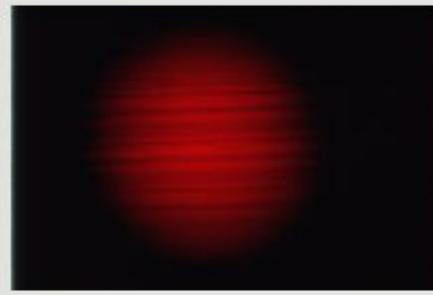


Control

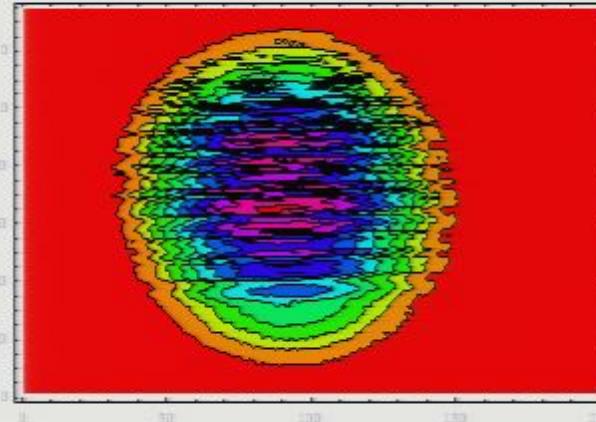


1009851

100%

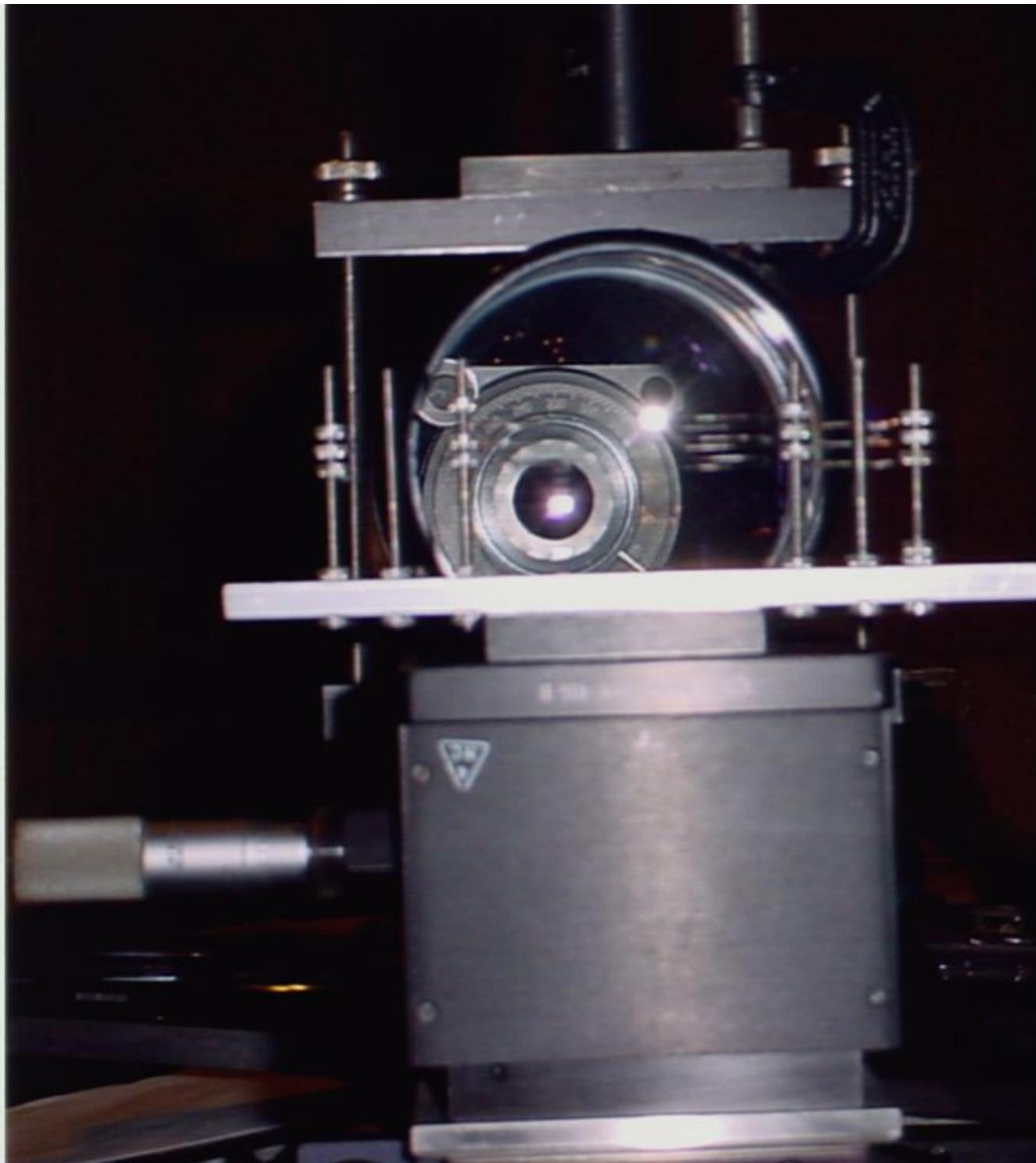


Wires at minima, one open

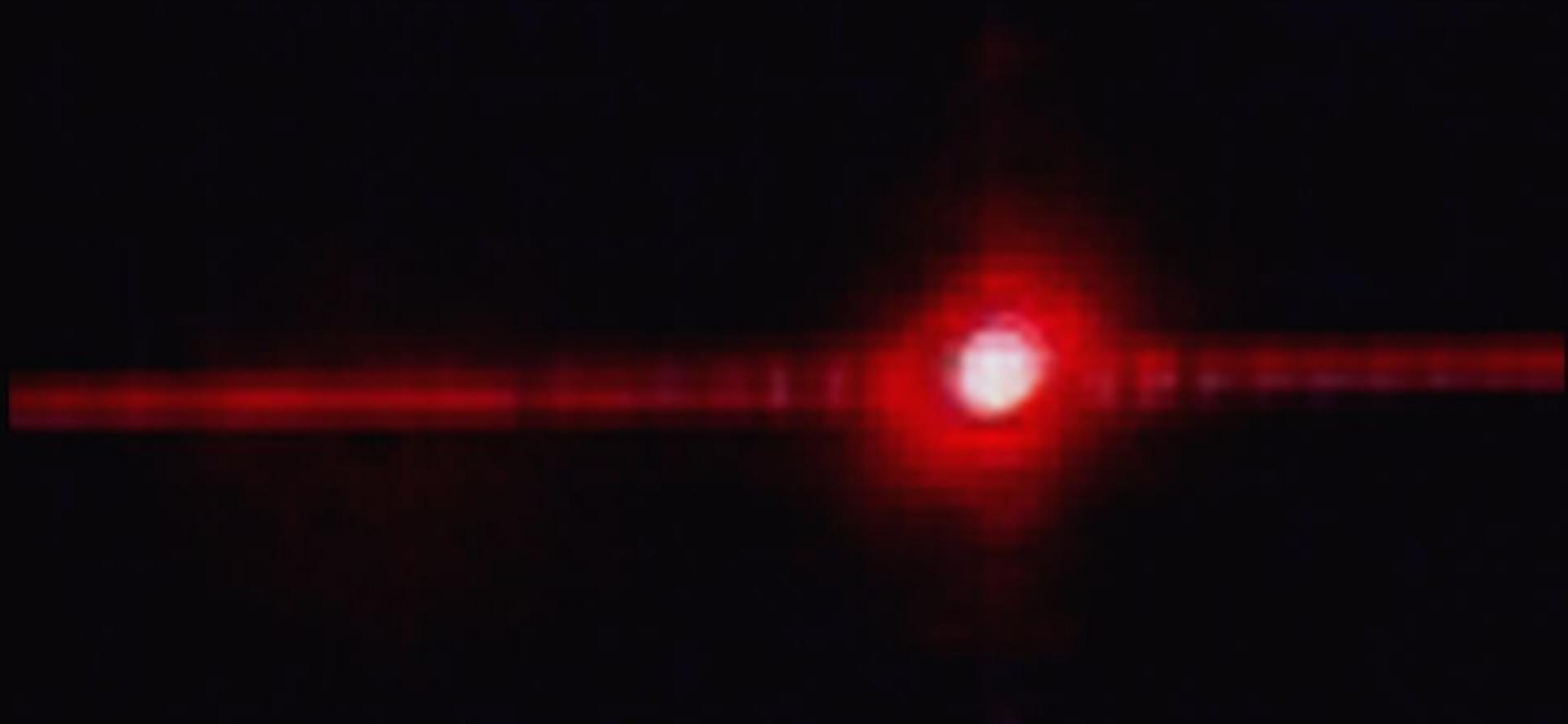


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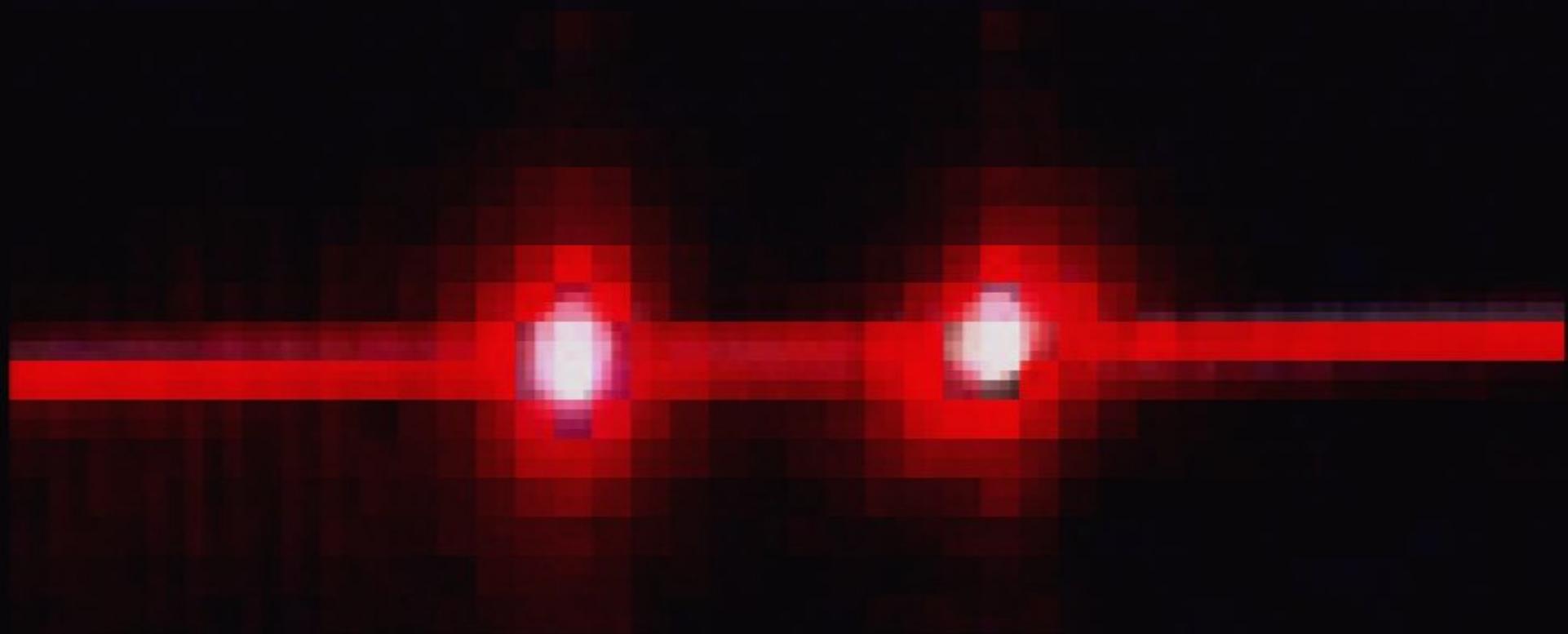
$93.4\% \pm 0.5\%$



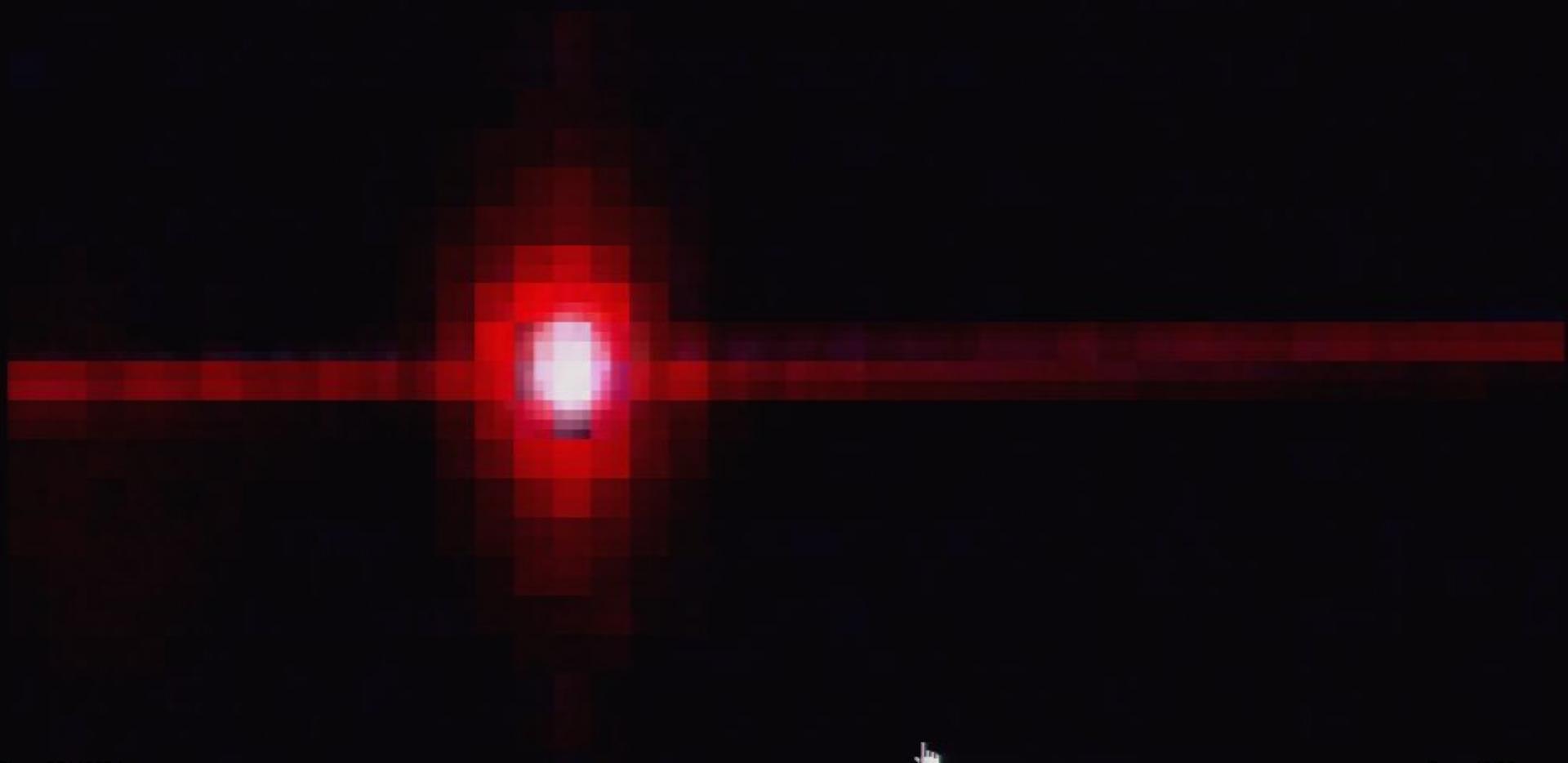
One Closed, then Both Open, Wire at Central Maximum



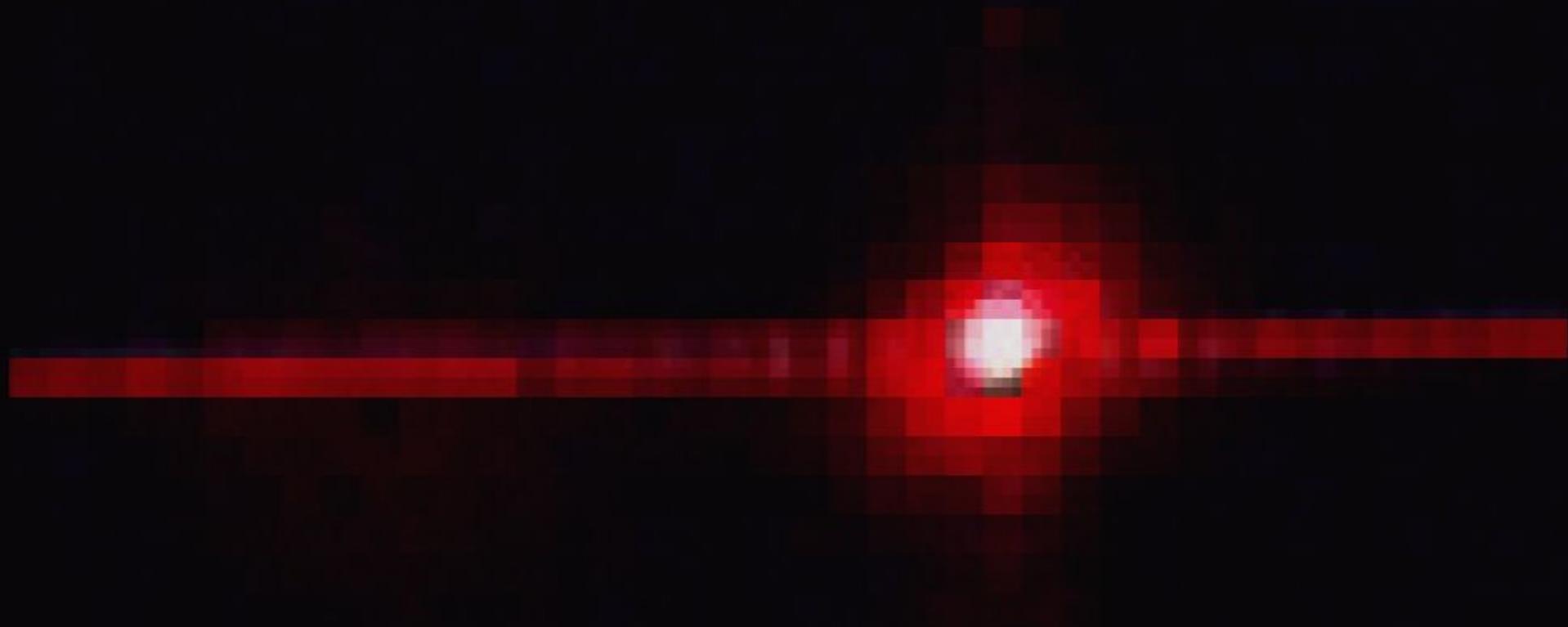
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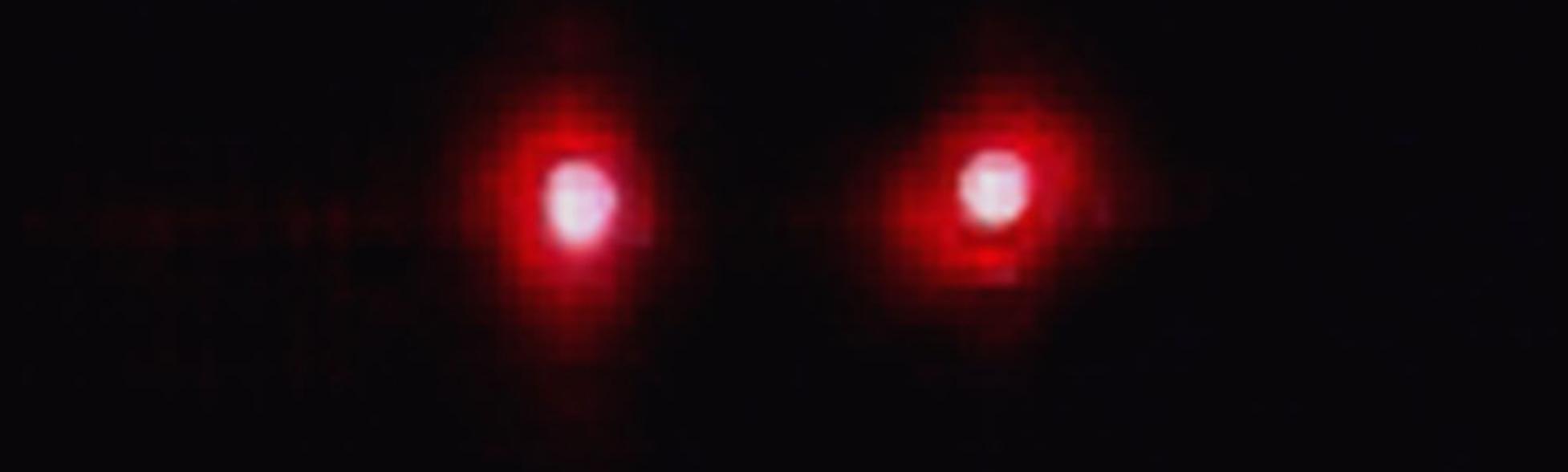
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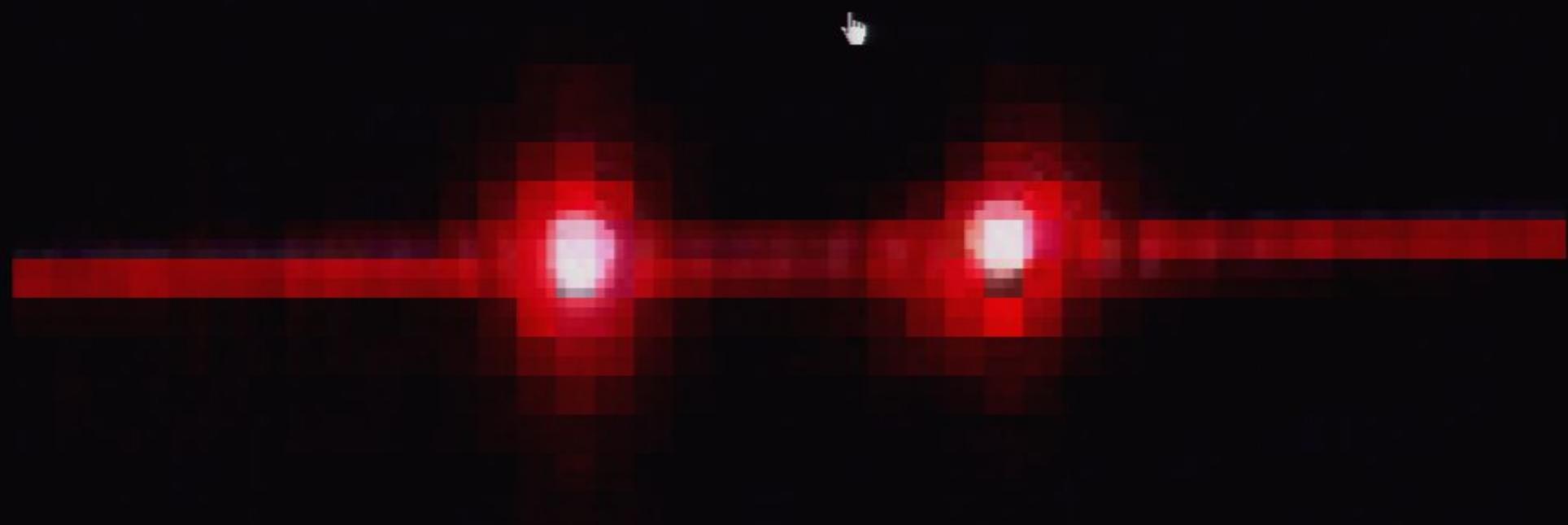
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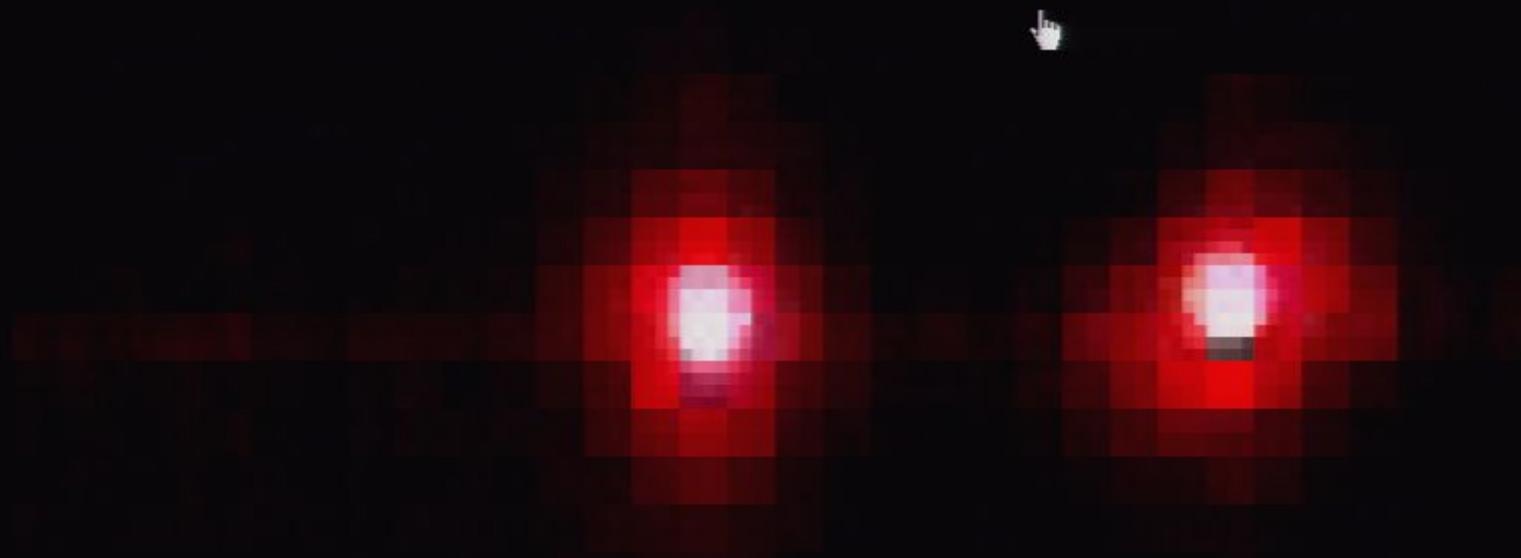
Both Open, Wire Moving from Central Minimum to Maximum



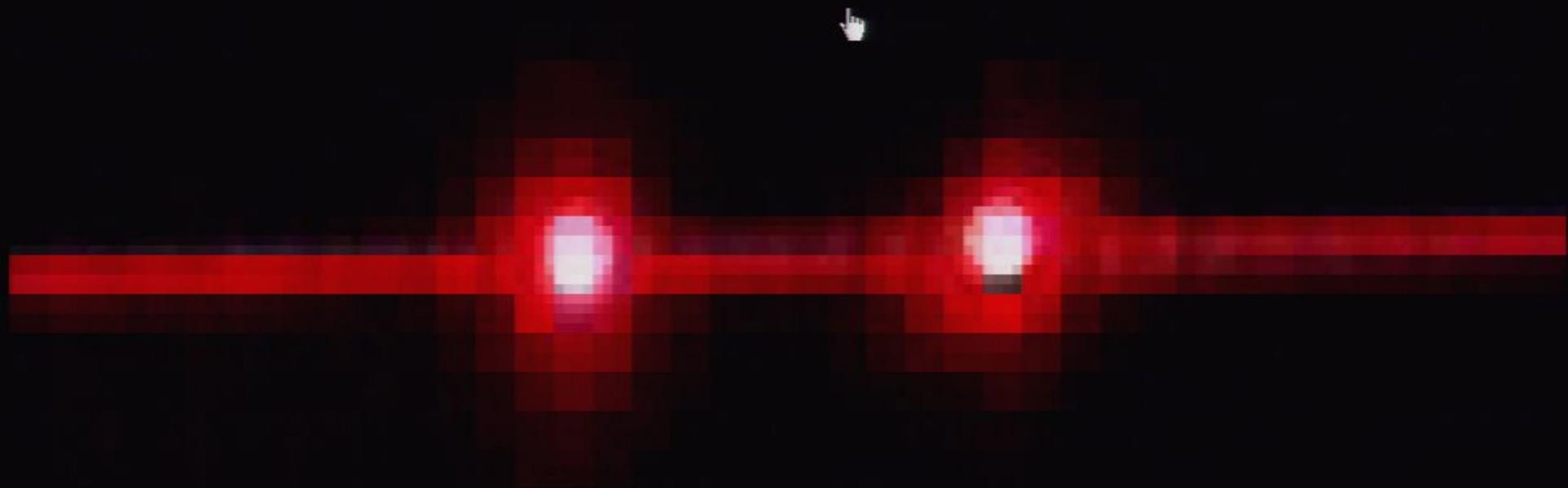
Both Open, Wire Moving from Central Minimum to Maximum



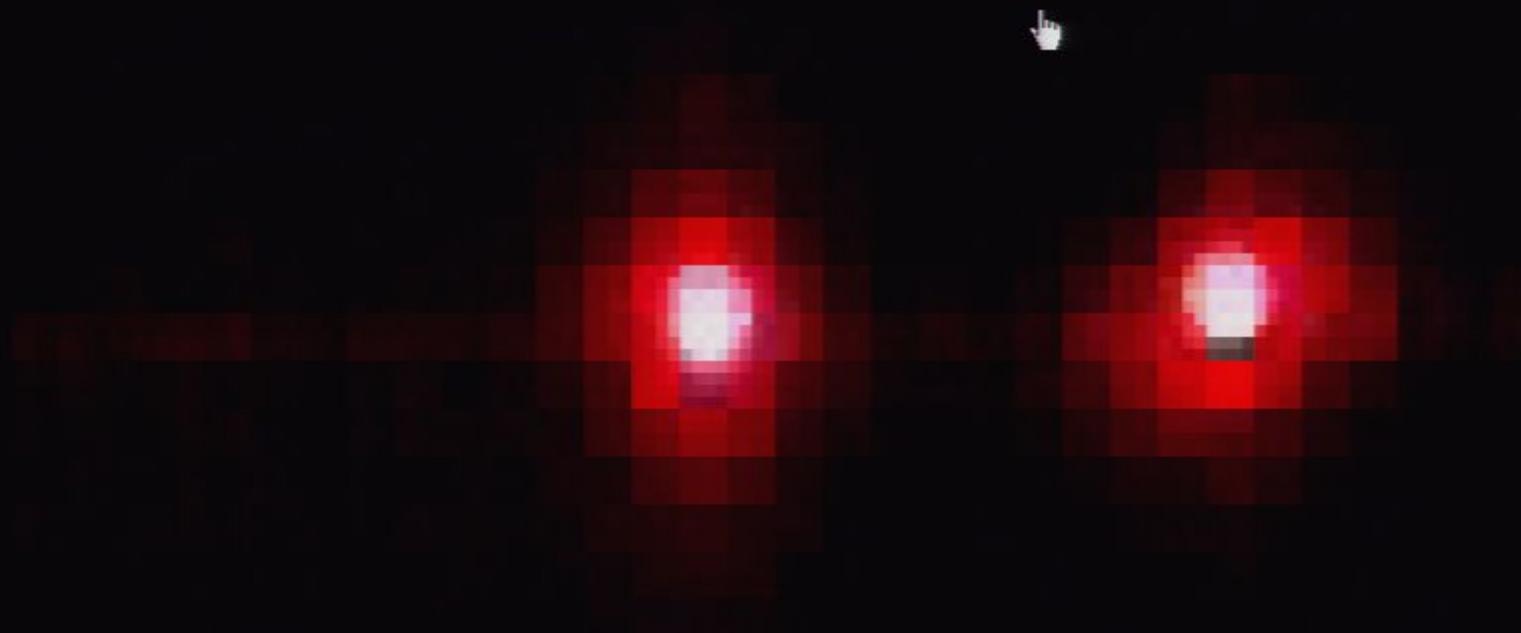
Both Open, Wire Moving from Central Minimum to Maximum



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Both Open, Wire Moving from Central Minimum to Maximum



Both Open, then One Open, Wire at Central Minimum



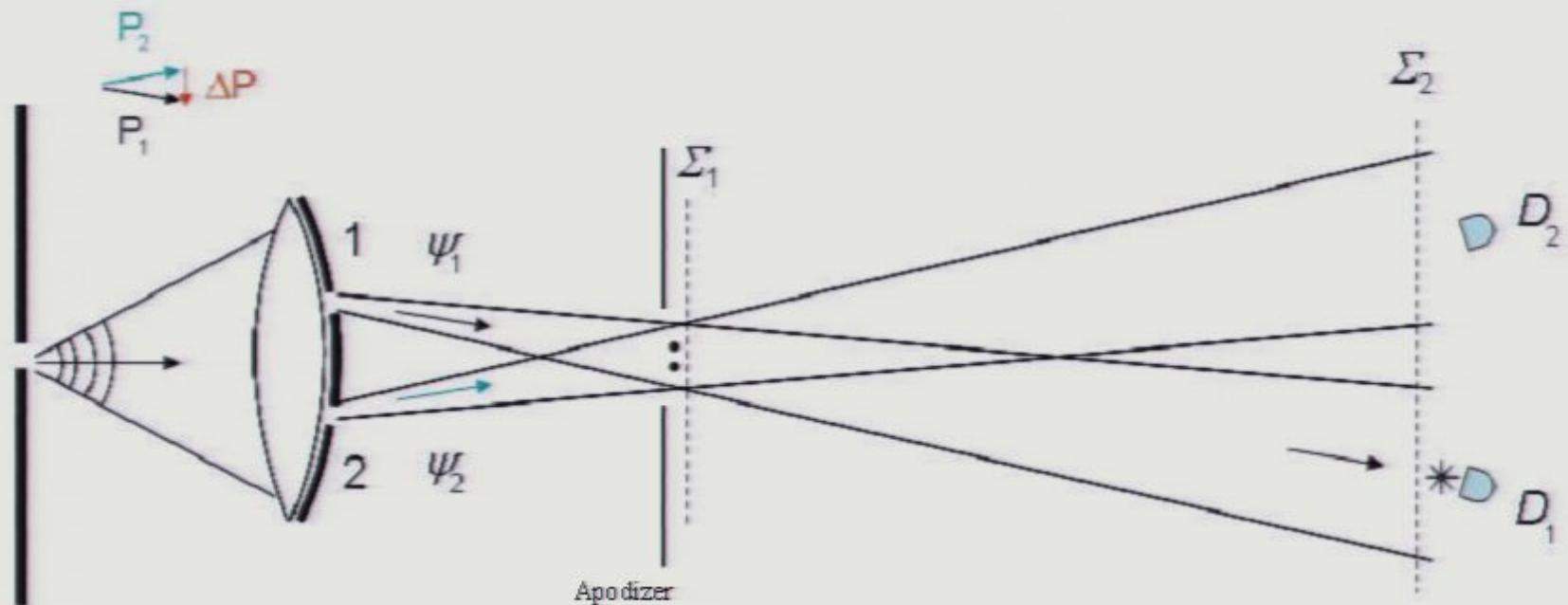
Both Open, then One Open, Wire at Central Minimum



Both Open, then One Open, Wire at Central Minimum



Experiment without the imaging lens.



Rowan Exp. May 2005

Quantitative Definition of Complementarity in “Which-Way” Experiments.

In the past 25 years a quantitative version of the PC has emerged, in which the Visibility of the interference pattern (V) and reliability of Which-Way Information (K) has the following form:

$$V^2 + K^2 \leq 1 \quad (1)$$

where

$$V = (I_{max} - I_{min}) / (I_{max} + I_{min}) \quad (2)$$

and

$$K_I = (I_1 - I_2) / (I_1 + I_2) \quad (3)$$



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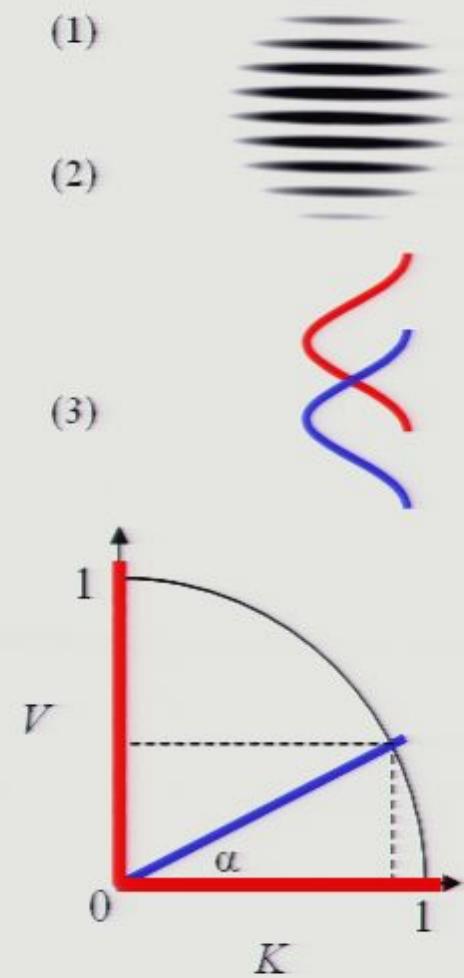
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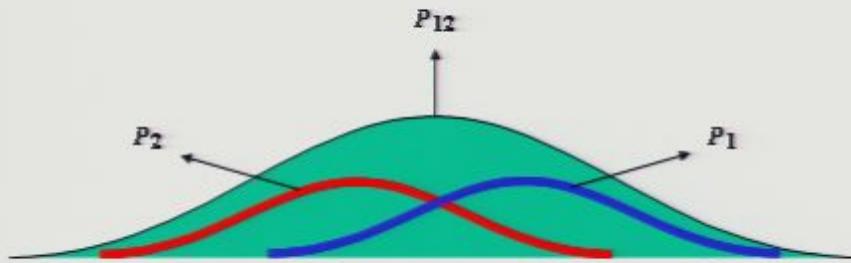
It is clear that $0 \leq V \leq 1$ and $0 \leq K \leq 1$ cannot both be equal to 1, and their relationship is exactly that of the Sin and Cos of an angle $0 \leq \alpha \leq \pi/2$

As we can see, there are intermediate conditions allowed by PC e.g. $\alpha = \pi/4$.

So, to be safe, we must choose the extreme cases i.e. $\alpha = 0$ and $\alpha = \pi/2$.

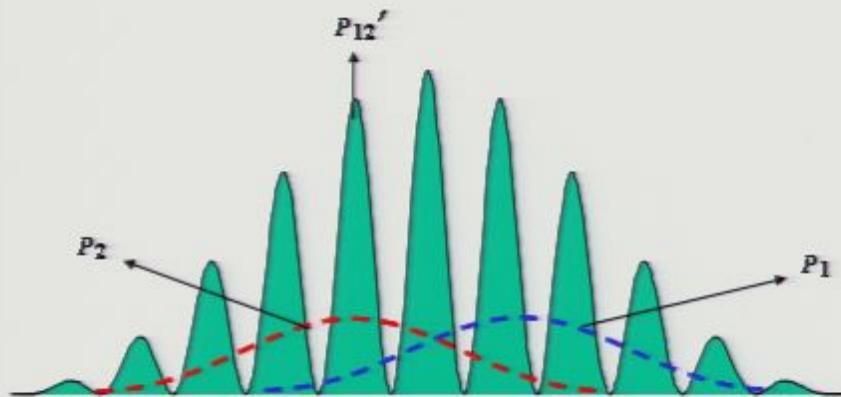


In the case of *decoherence*, (in orthogonal states), where WW information is known 100%, we have:



$$\begin{aligned}P_1 &= |\psi_1|^2, \\P_2 &= |\psi_2|^2, \\P_{12} &= P_1 + P_2, \\ \therefore \int \int P_{12} dx dt &= \int \int (P_1 + P_2) dx dt\end{aligned}$$

In the Interference plane we have:



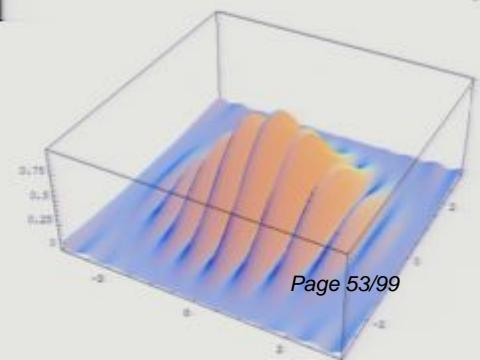
$$\begin{aligned}P_1 &= |\psi_1|^2, \\P_2 &= |\psi_2|^2, \\P_{12}' &= |\psi_1 + \psi_2|^2 = P_1 + P_2 + 2\sqrt{P_1 P_2} \cos \delta, \\ \Gamma &= 2\sqrt{P_1 P_2} \cos \delta, \\ \therefore P_{12}' &\neq P_1 + P_2 \\ \int \int P_{12}' dx dt &= \int \int (P_1 + P_2 + \Gamma) dx dt\end{aligned}$$

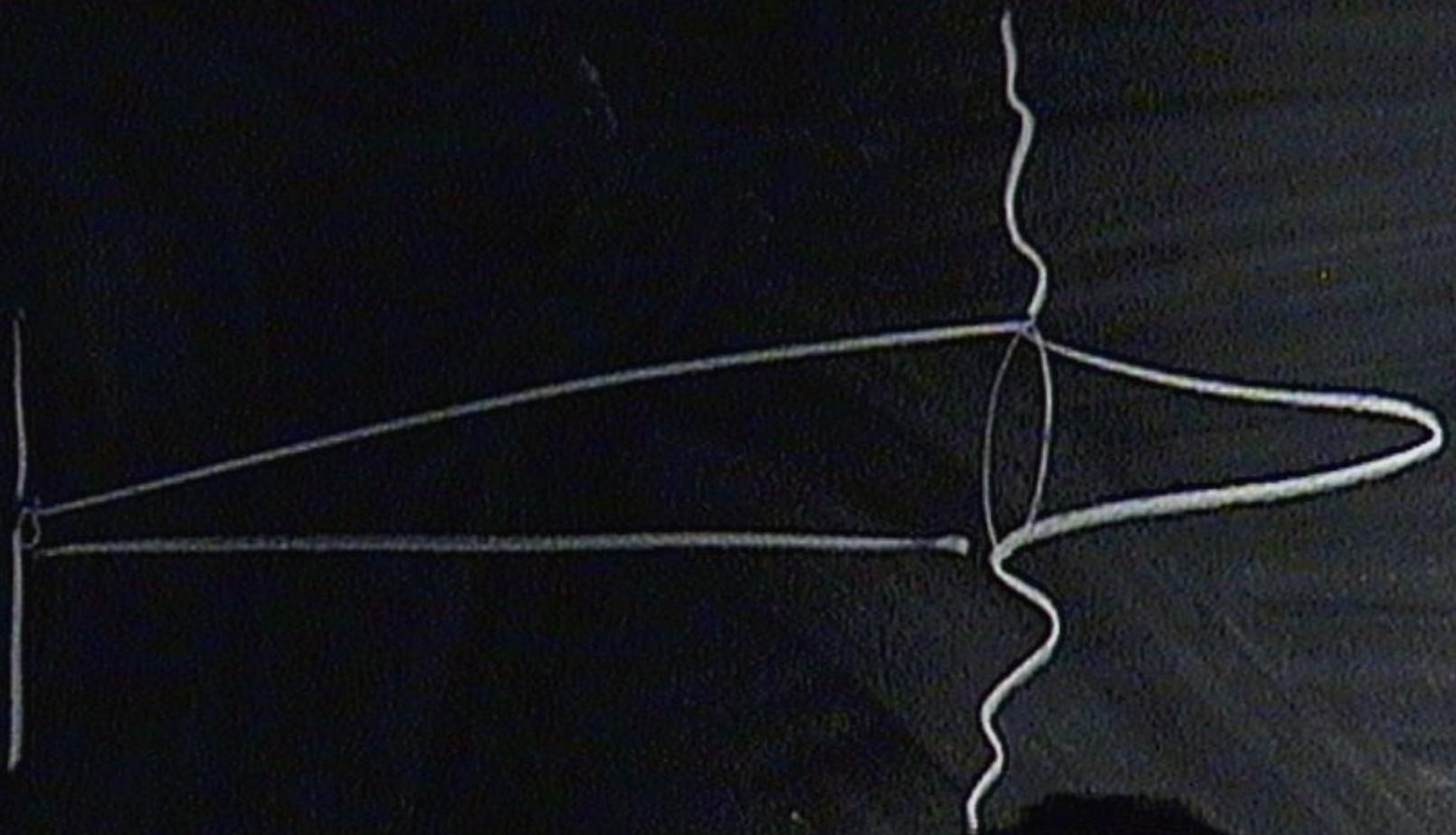
Remarkably, although $P_{12}' \neq P_{12}$,
however, due to the boundary conditions we have:

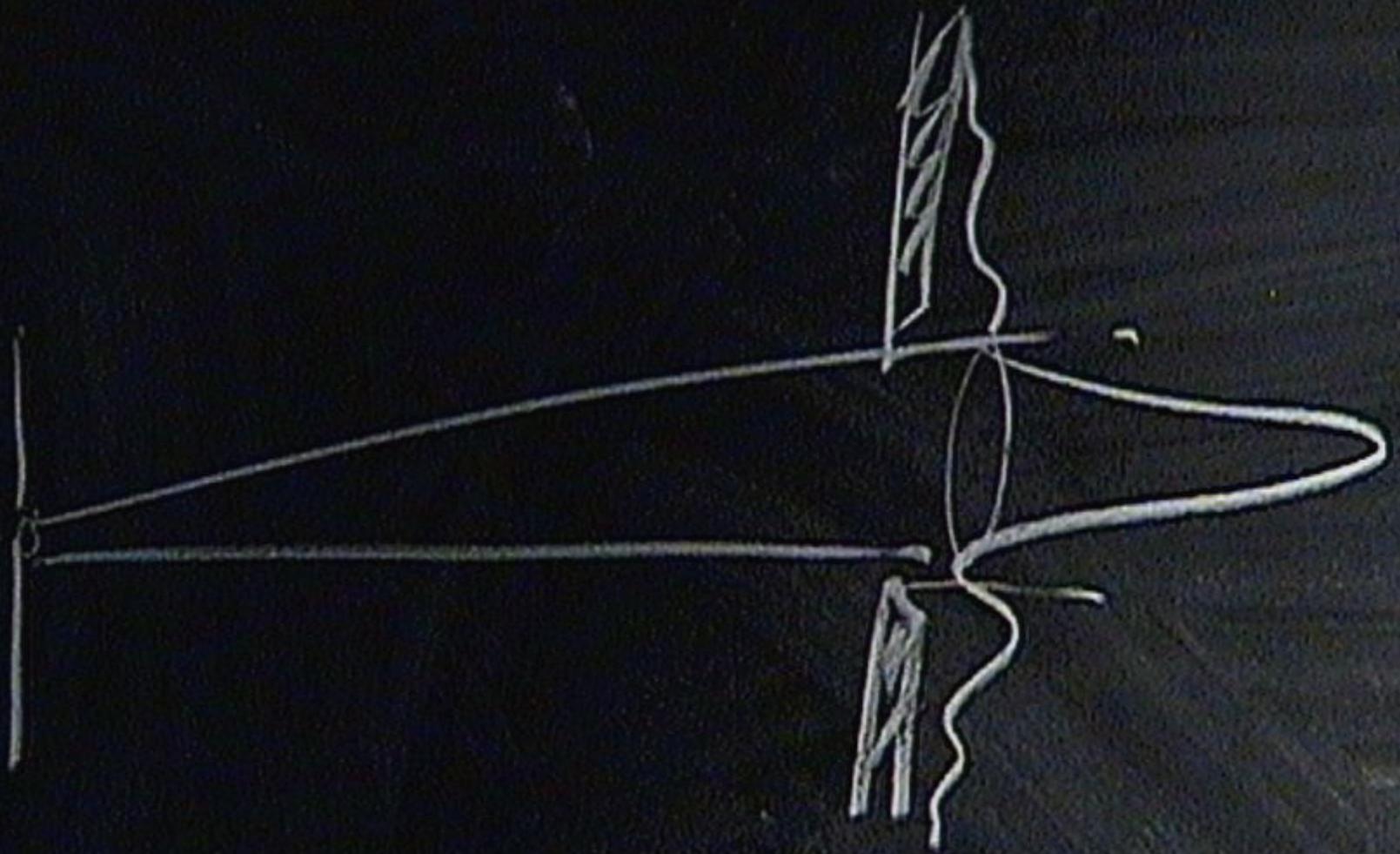
$$\int \int P_{12}' dx dt = \int \int P_{12} dx dt$$

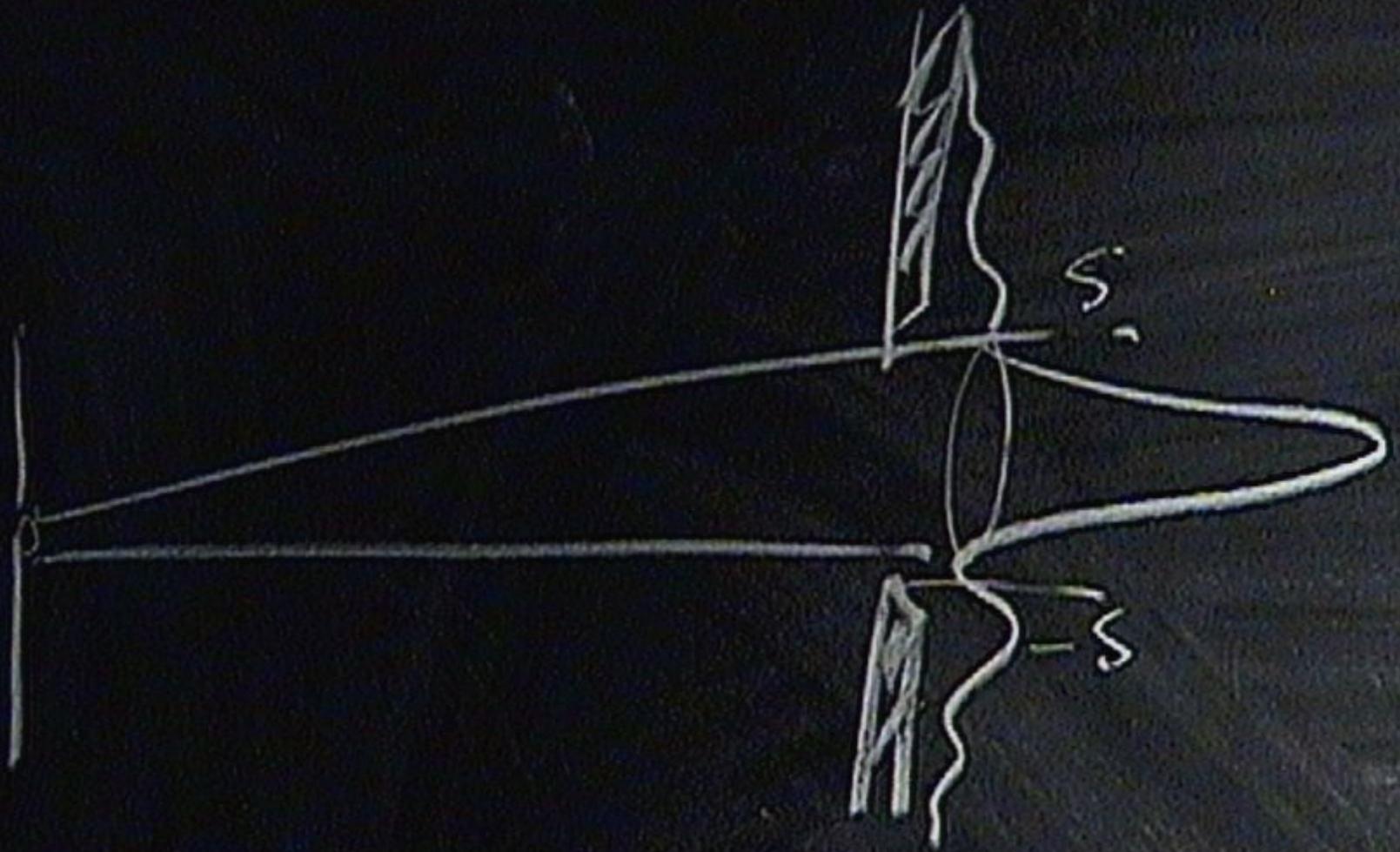
Which can be generalized for the 2D case of our experiment to:

$$\int \int \int P_{12}' dx dy dt = \int \int \int P_{12} dx dy dt$$



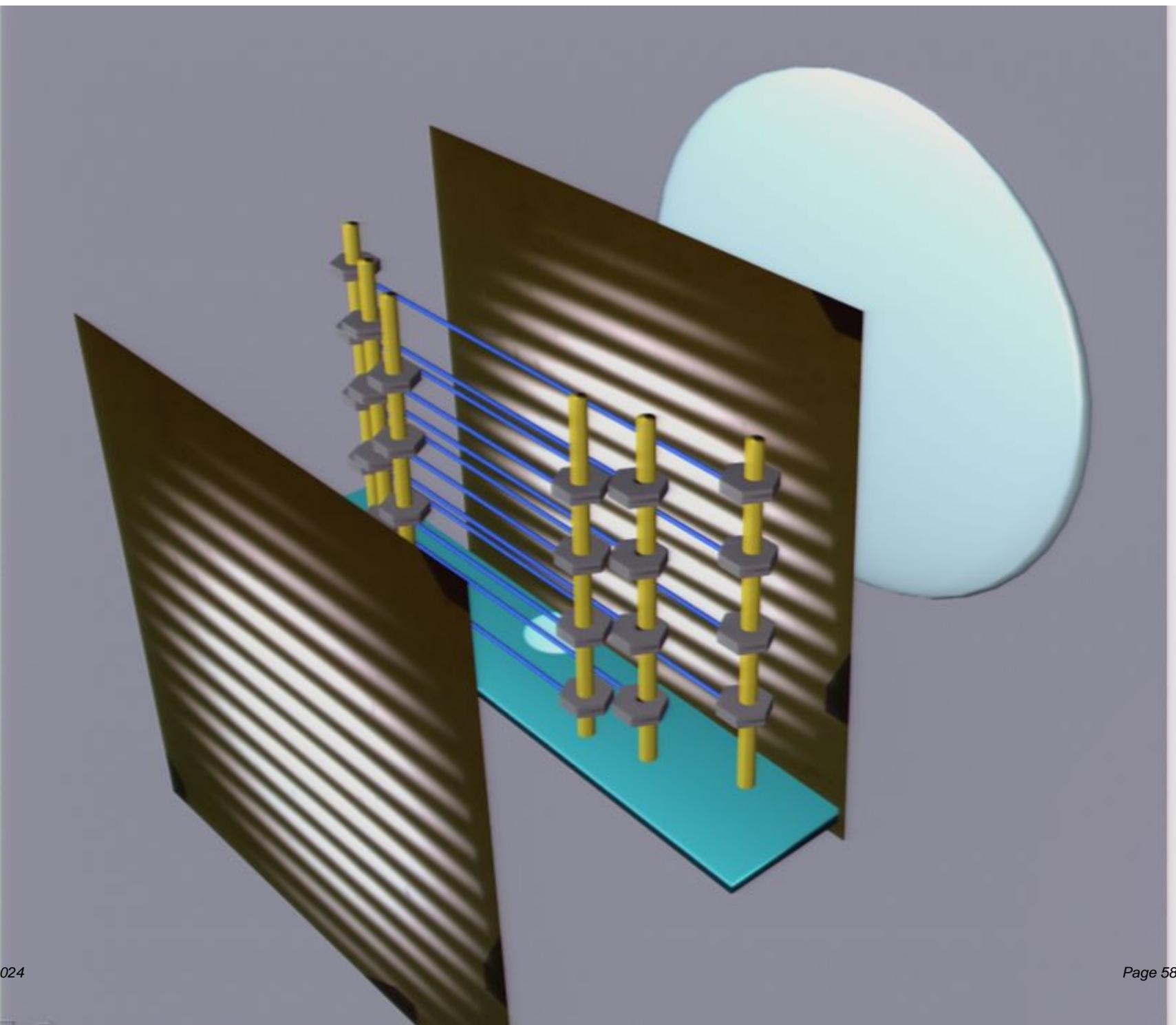




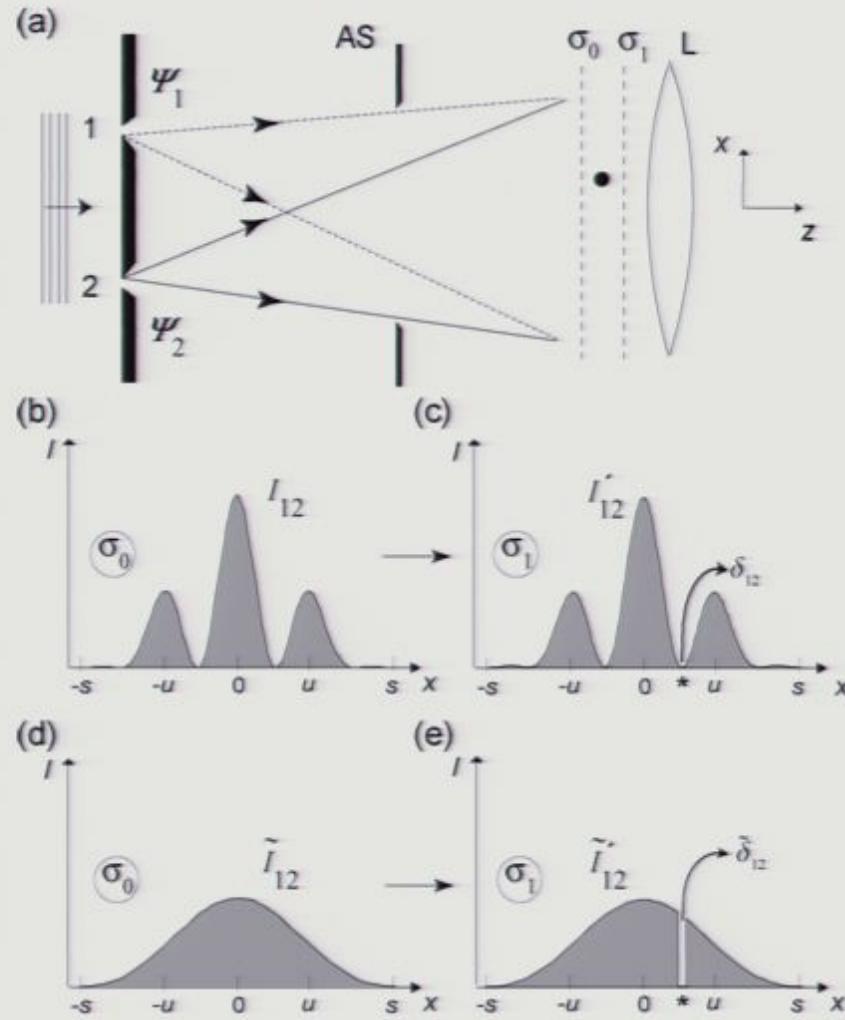


Where did Bohr go wrong?: Measurement without a “measurement”

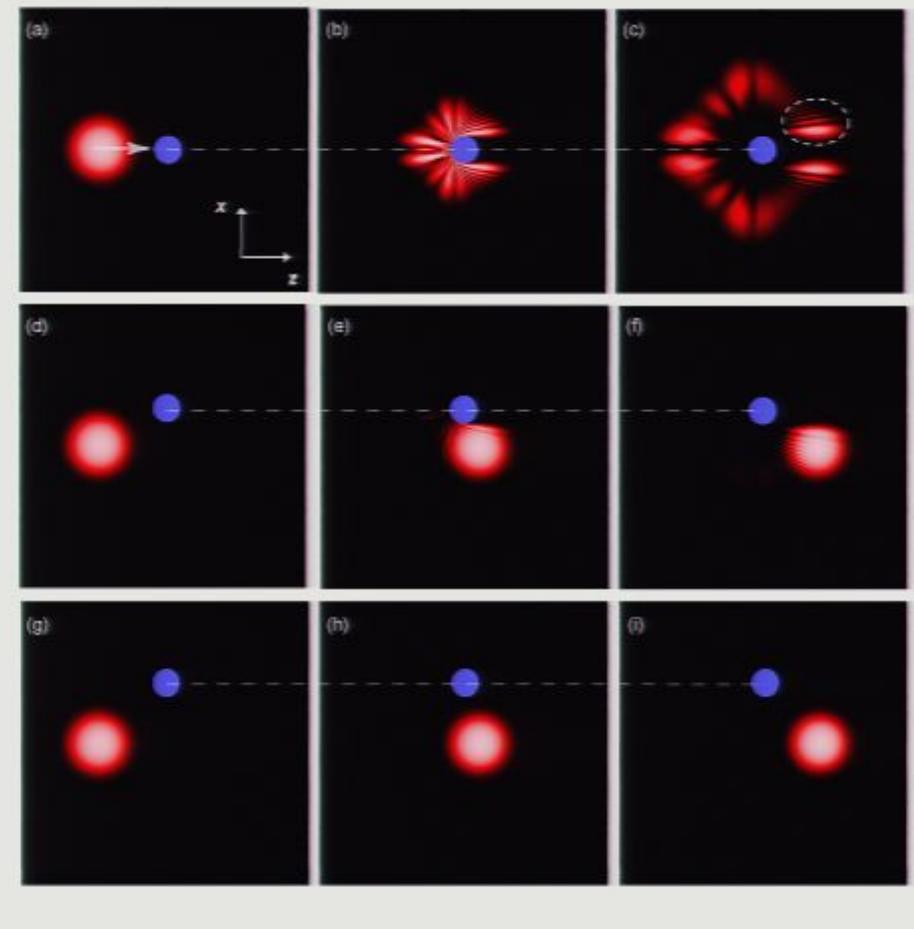
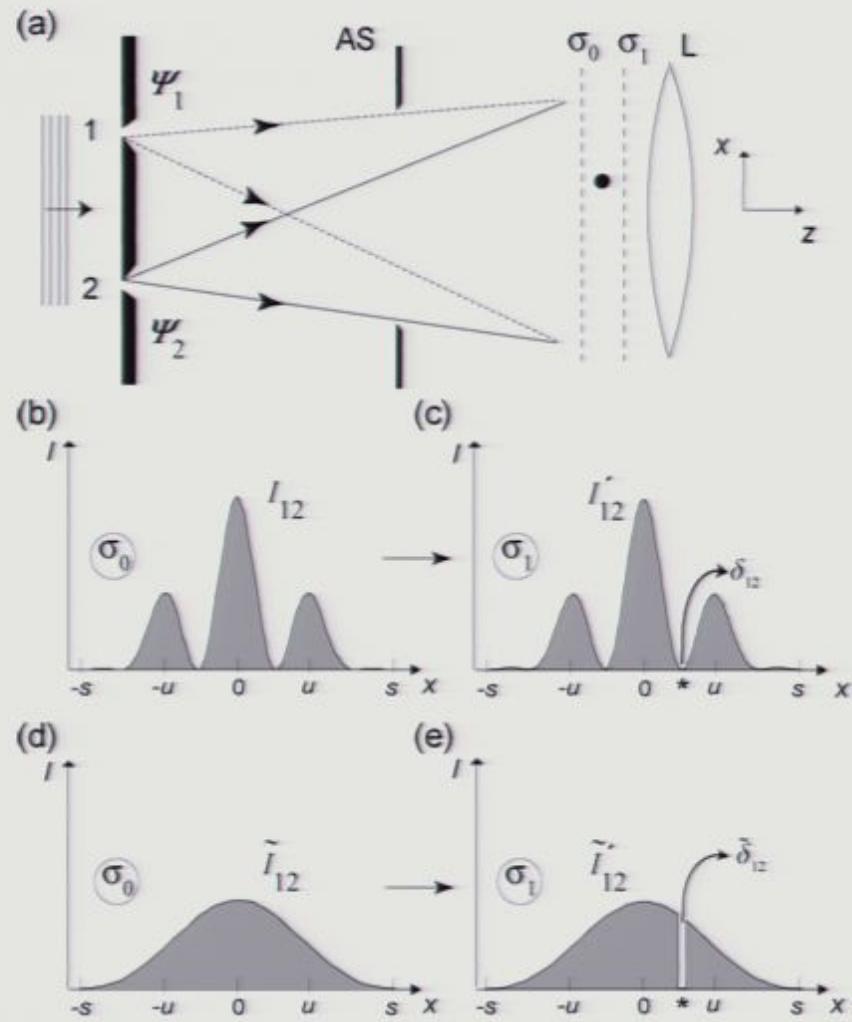
The measurement theory of ensemble properties (e.g. coherence) needs an upgrade!



Difference Between Coherent and “Decoherent” prob. distributions.



Difference Between Coherent and “Decoherent” prob. distributions.



Introducing: *Contextual Null Measurement* (CNM)

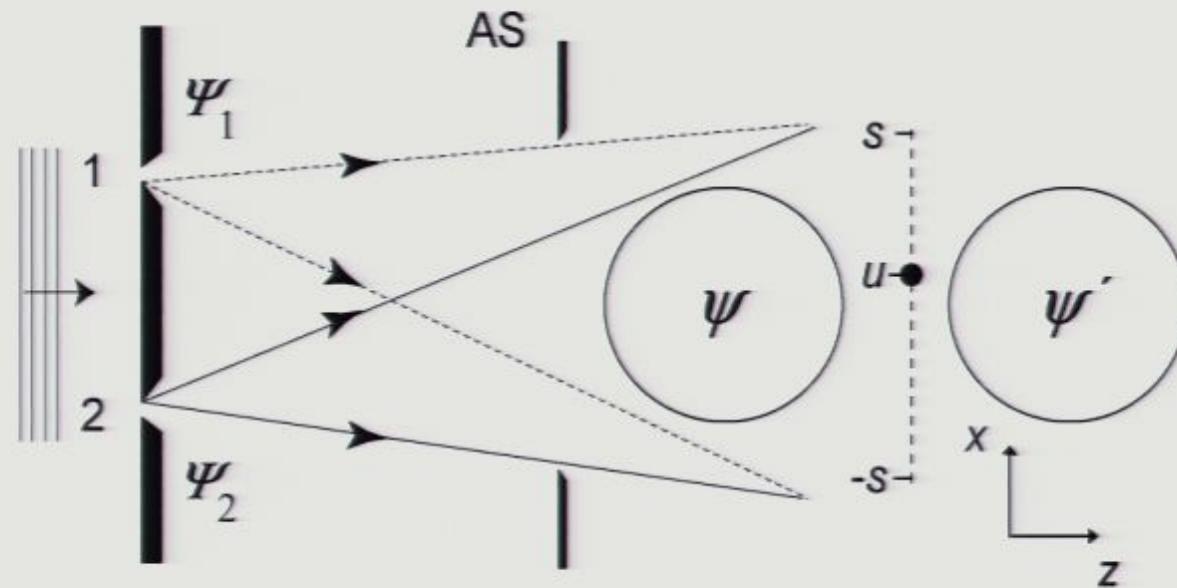
The nulls of a wavefunction can be verified non-perturbatively.

i.e.: The unitary evolution of the wavefunctions continues as though there were no detector in its path.

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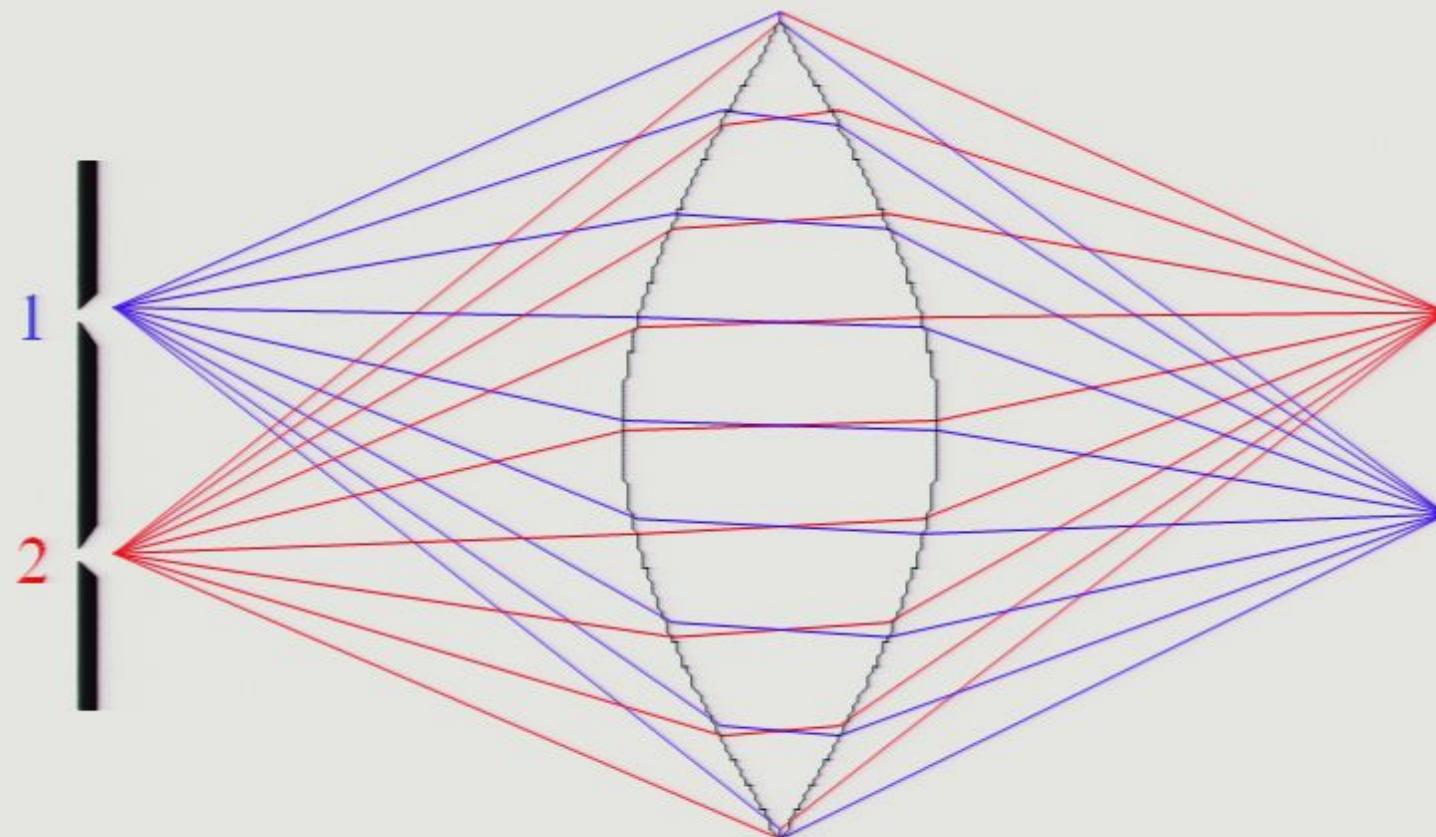
$$1) \|\psi\|^2 = \|\psi'\|^2 \neq 0 \Rightarrow \delta = \int_{x_1}^{x_2} |\psi|^2 dx = 0$$

$$2) |\psi(u)| = 0 \Leftrightarrow \psi(u) = 0$$

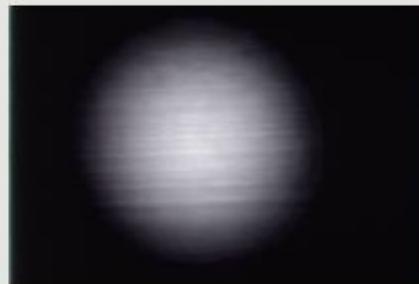
$$3) \|\psi(x, y)\|^2 > 0 \wedge \psi(u, v) = 0 \Rightarrow \psi(u, v) = \psi_1(u, v) + \psi_2(u, v) = 0$$

QED analysis of the lens with coherent radiation.

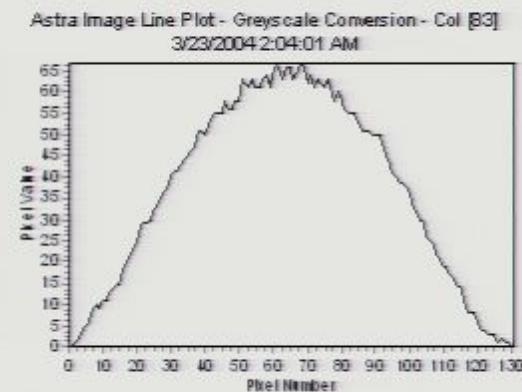
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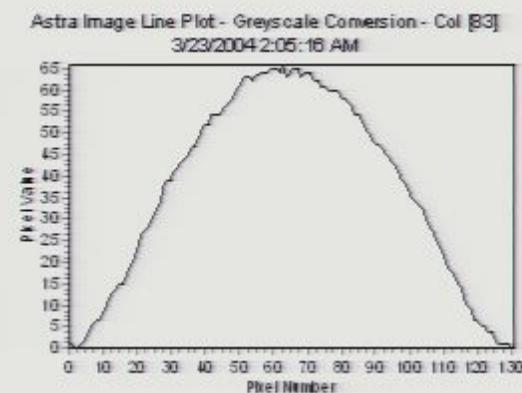
Some Results from Original Experiment at IRIMS



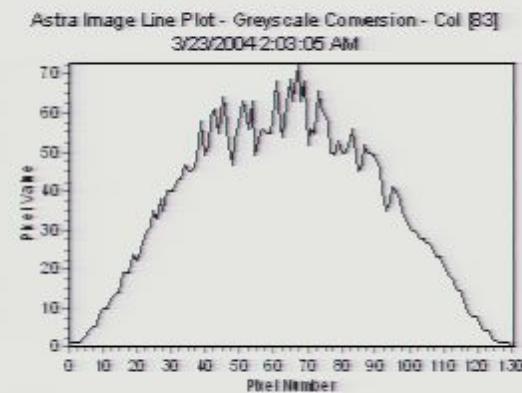
Wires at minima, both open



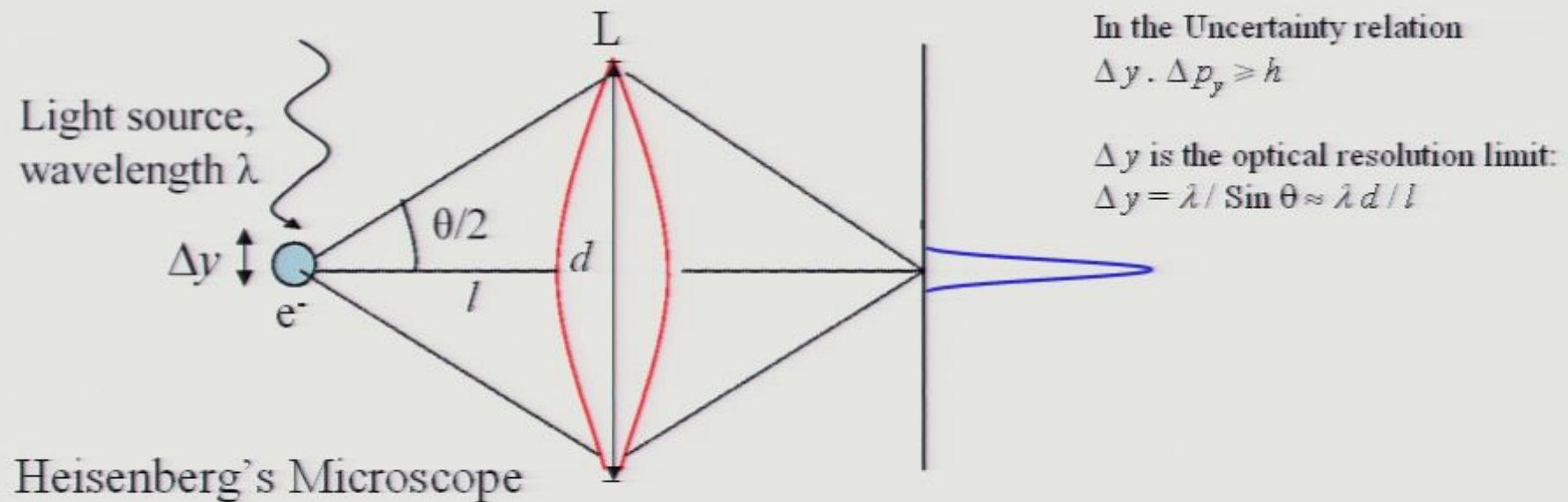
Control

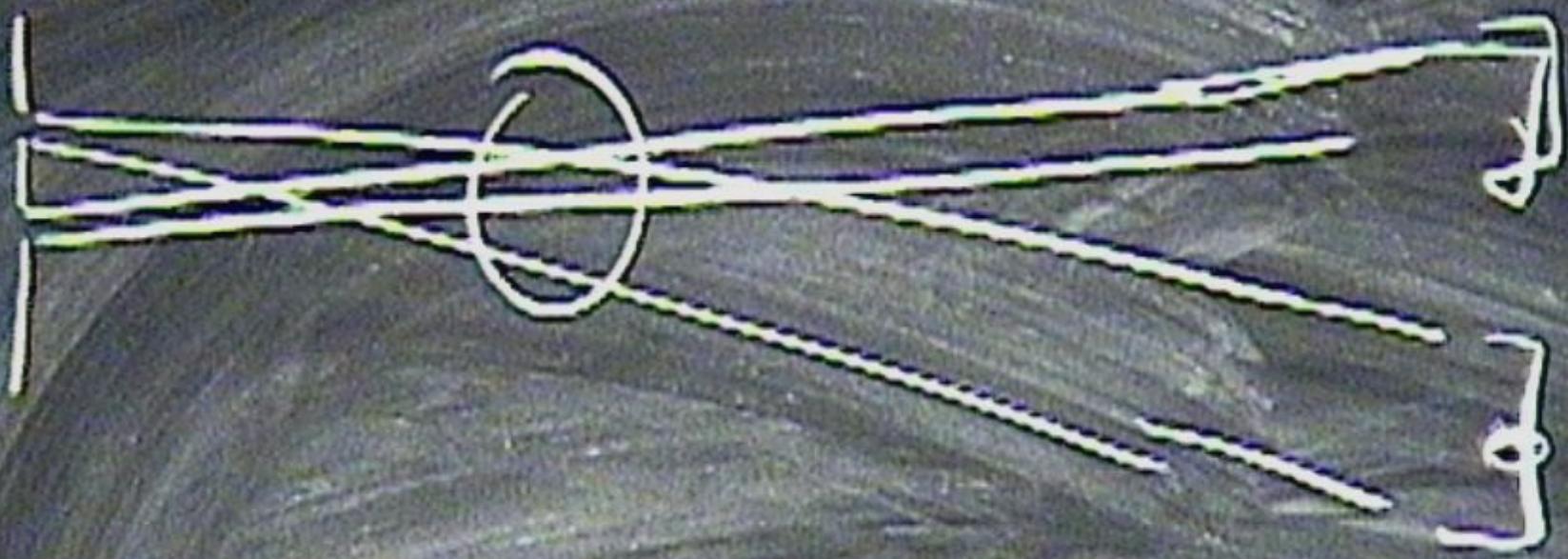


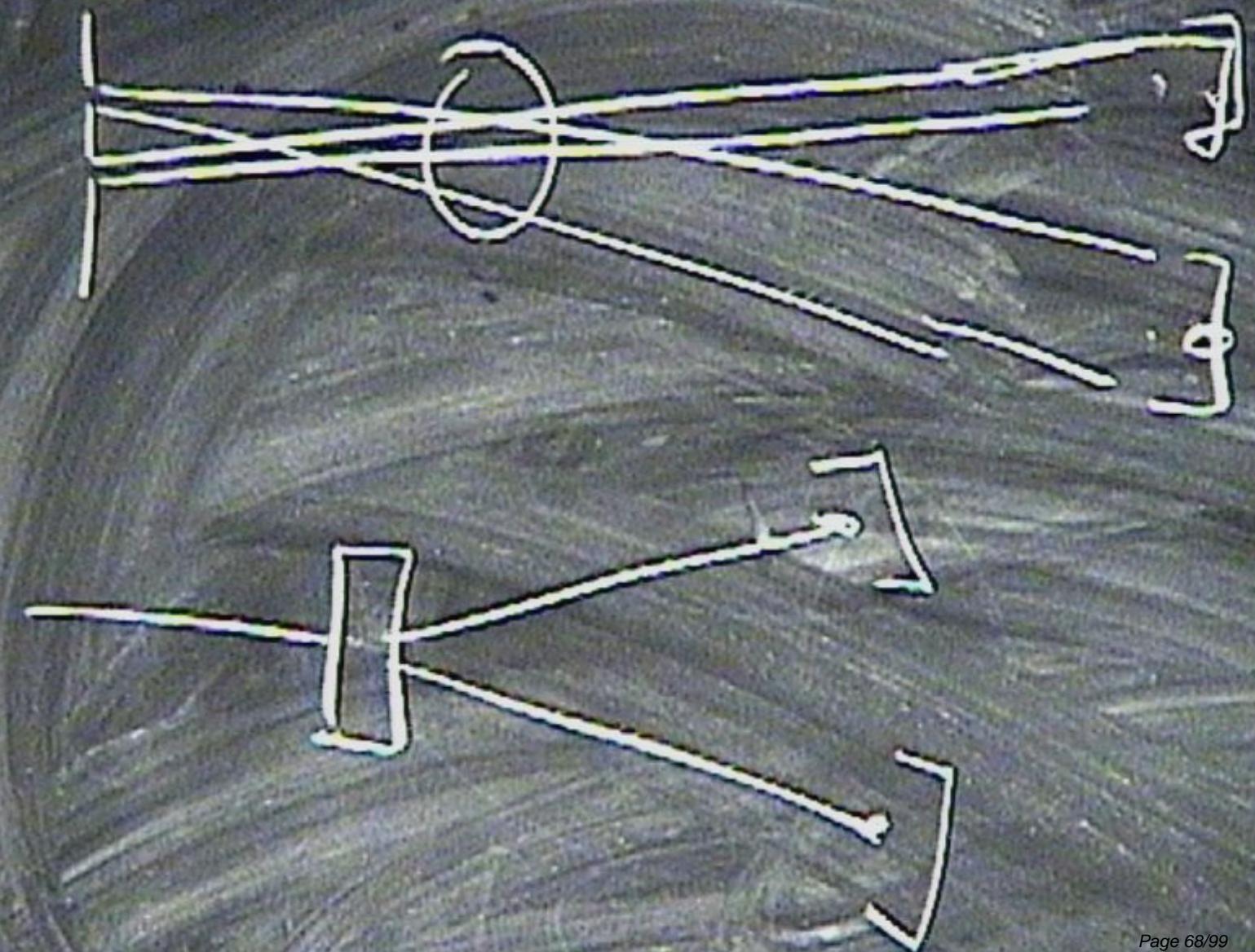
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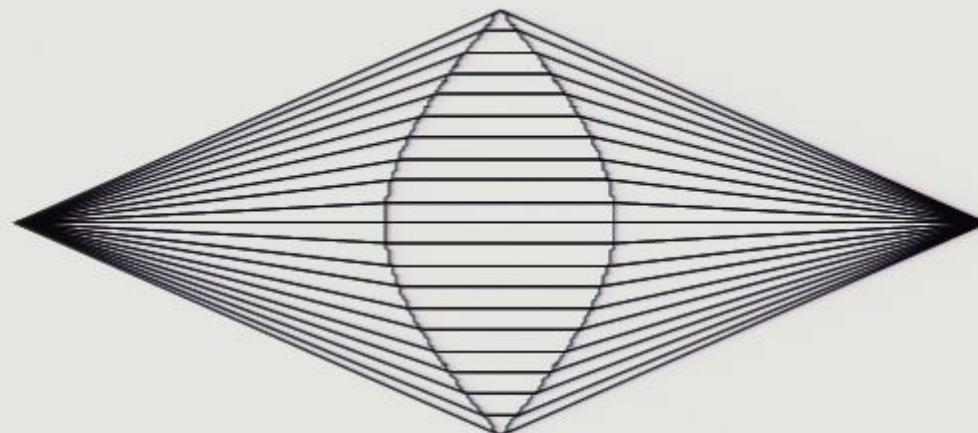
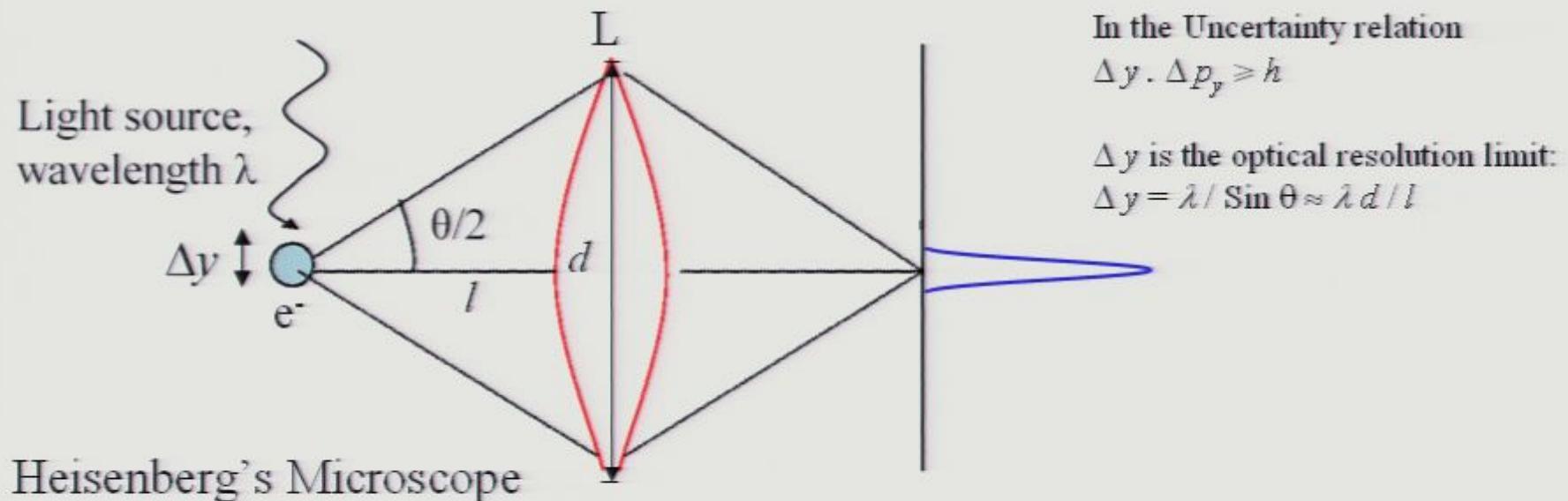
Using a Lens as a Position (Which-Way) Detector







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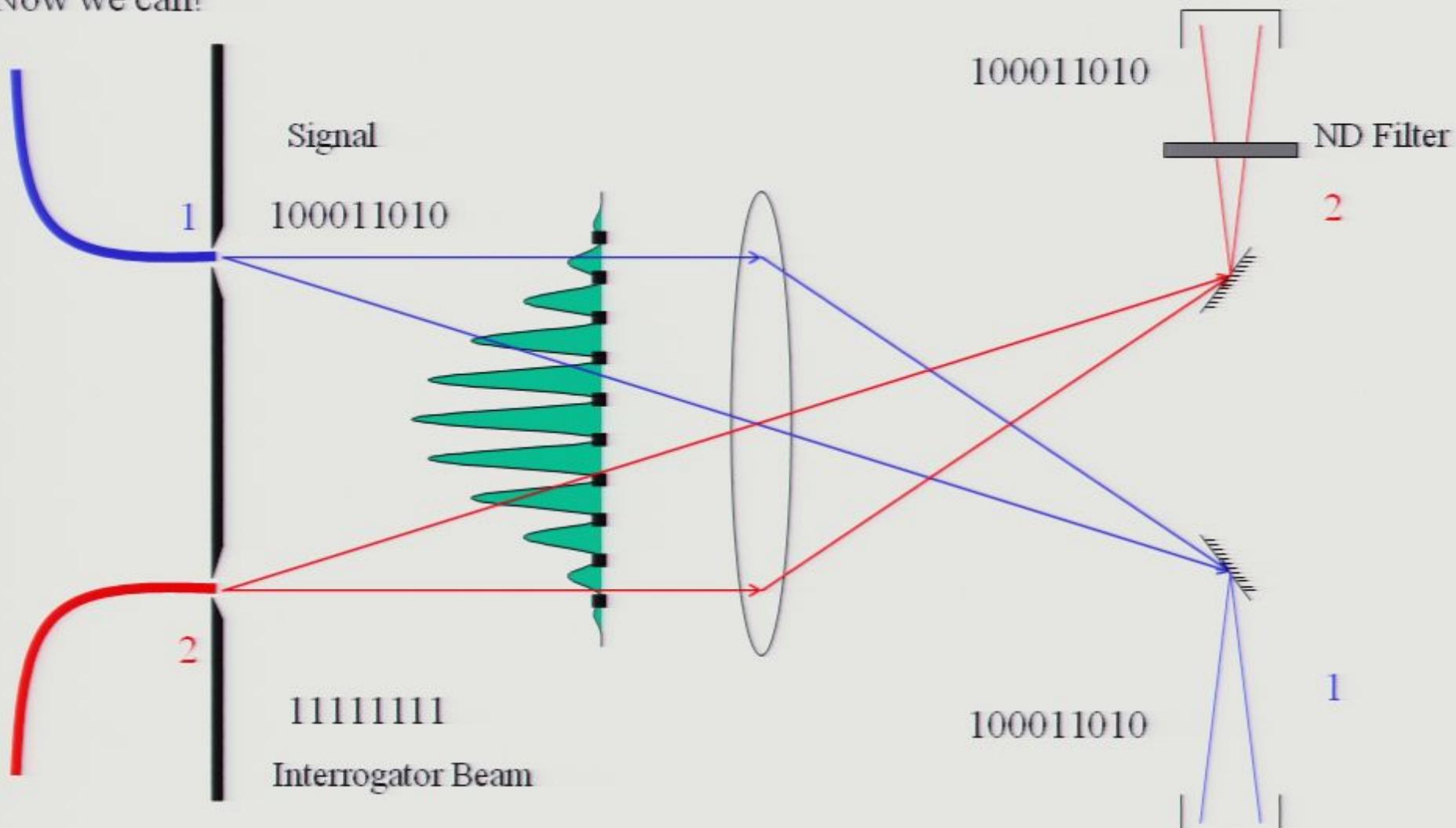


Feynman's QED Sum Over Paths (Phasors) Treatment of a Lens

Application of CNM

Can we read/copy binary optical data without causing any loss in intensity, dephasing or any other contamination in the signal?

Now we can!



What does it mean?

- Falsification of Bohr's Principle of Complementarity?
- Falsification of Copenhagen Interpretation (physical reality of unmeasured properties)?
- Falsification of the Many World Interpretation?
- New theory of measurement?
- Possible new technology (nonperturbative measurement of quantum flux)...

What next?

Theoretical expansion of CNM.

Analogue experiment with electrons.

Experimental probe of the wavefunction collapse process.

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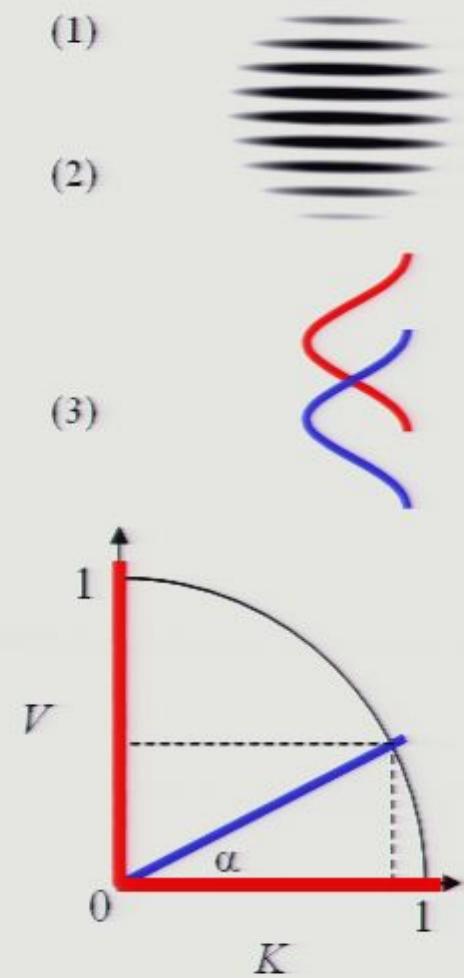
and

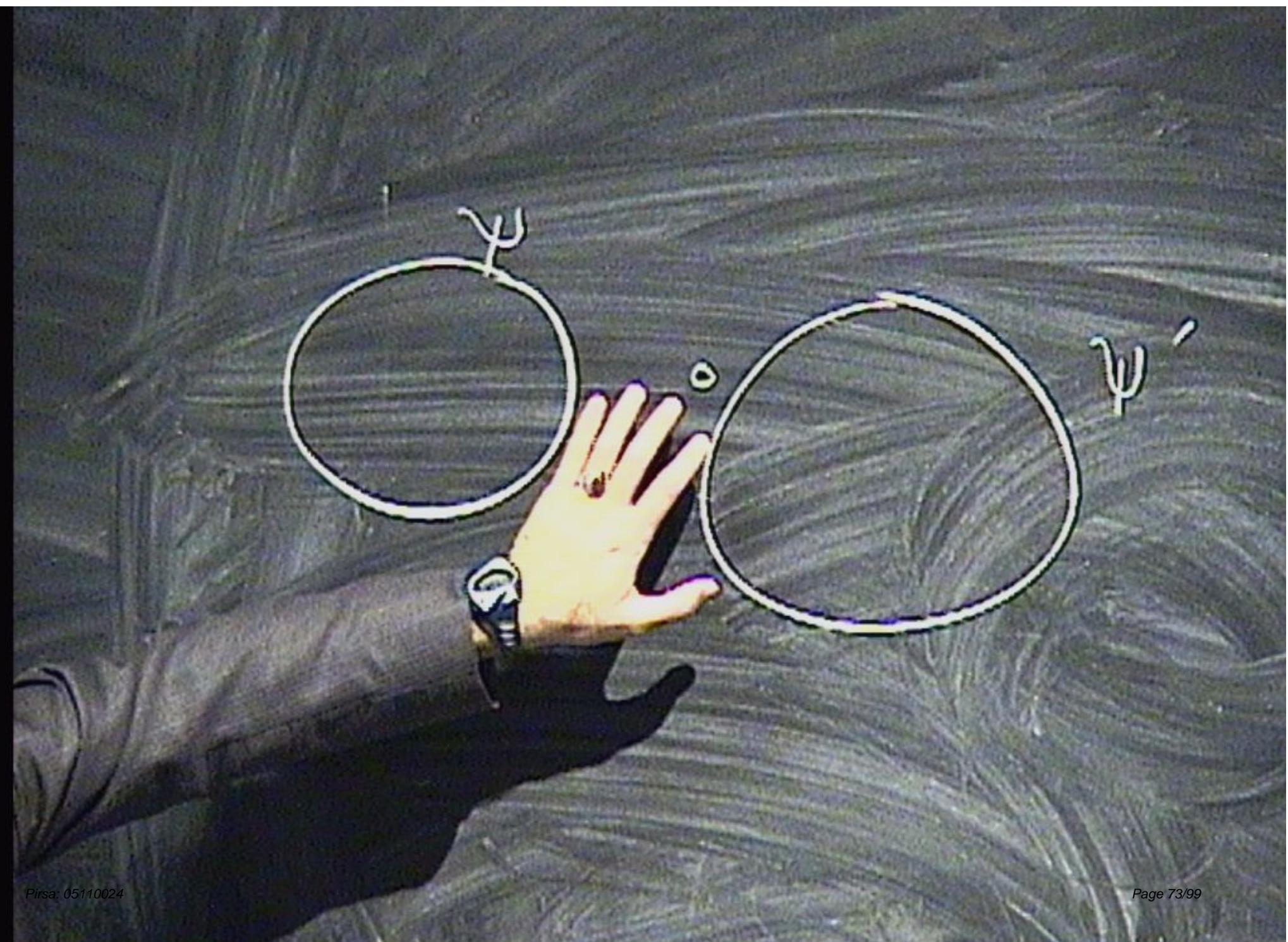
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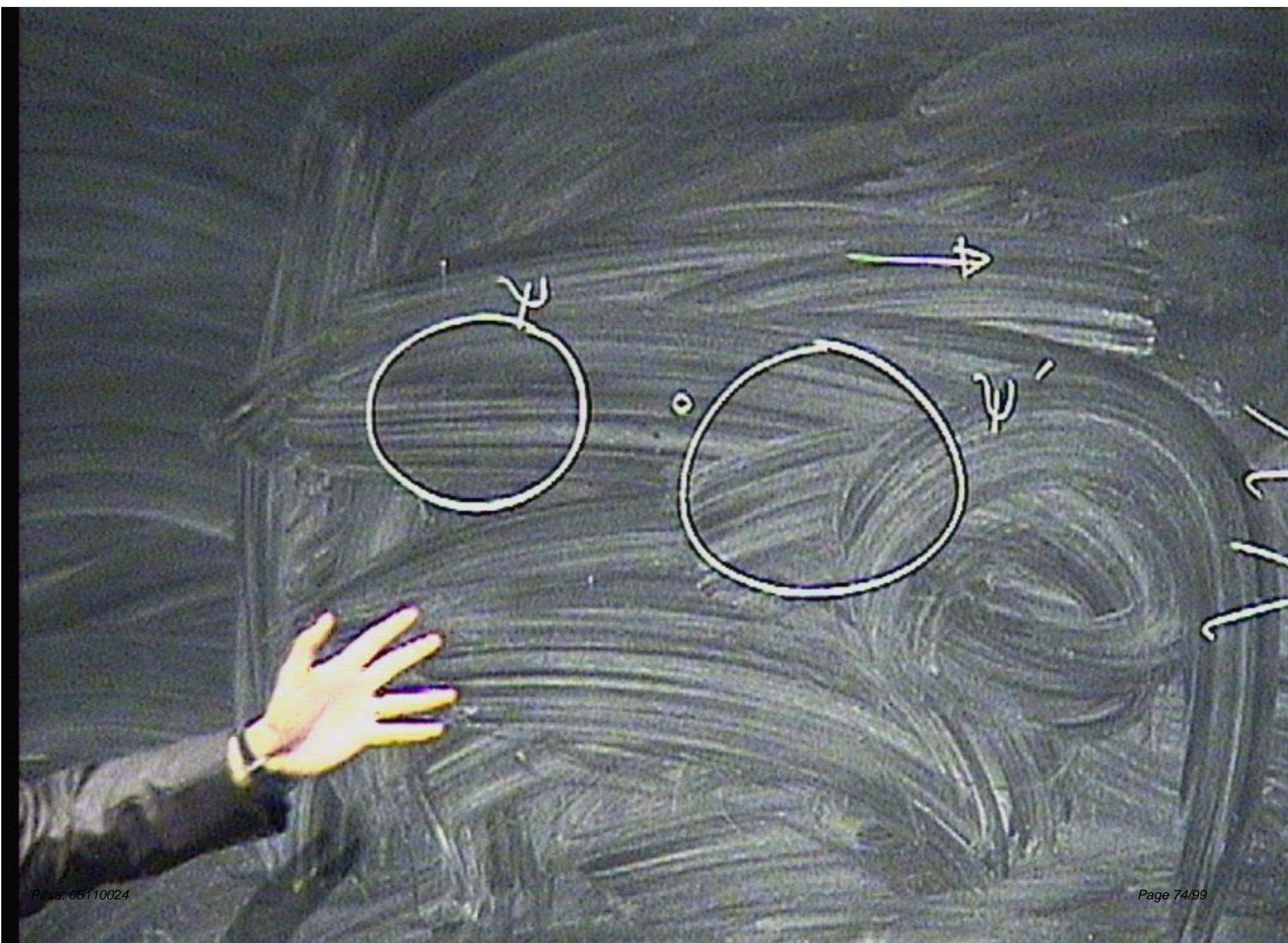
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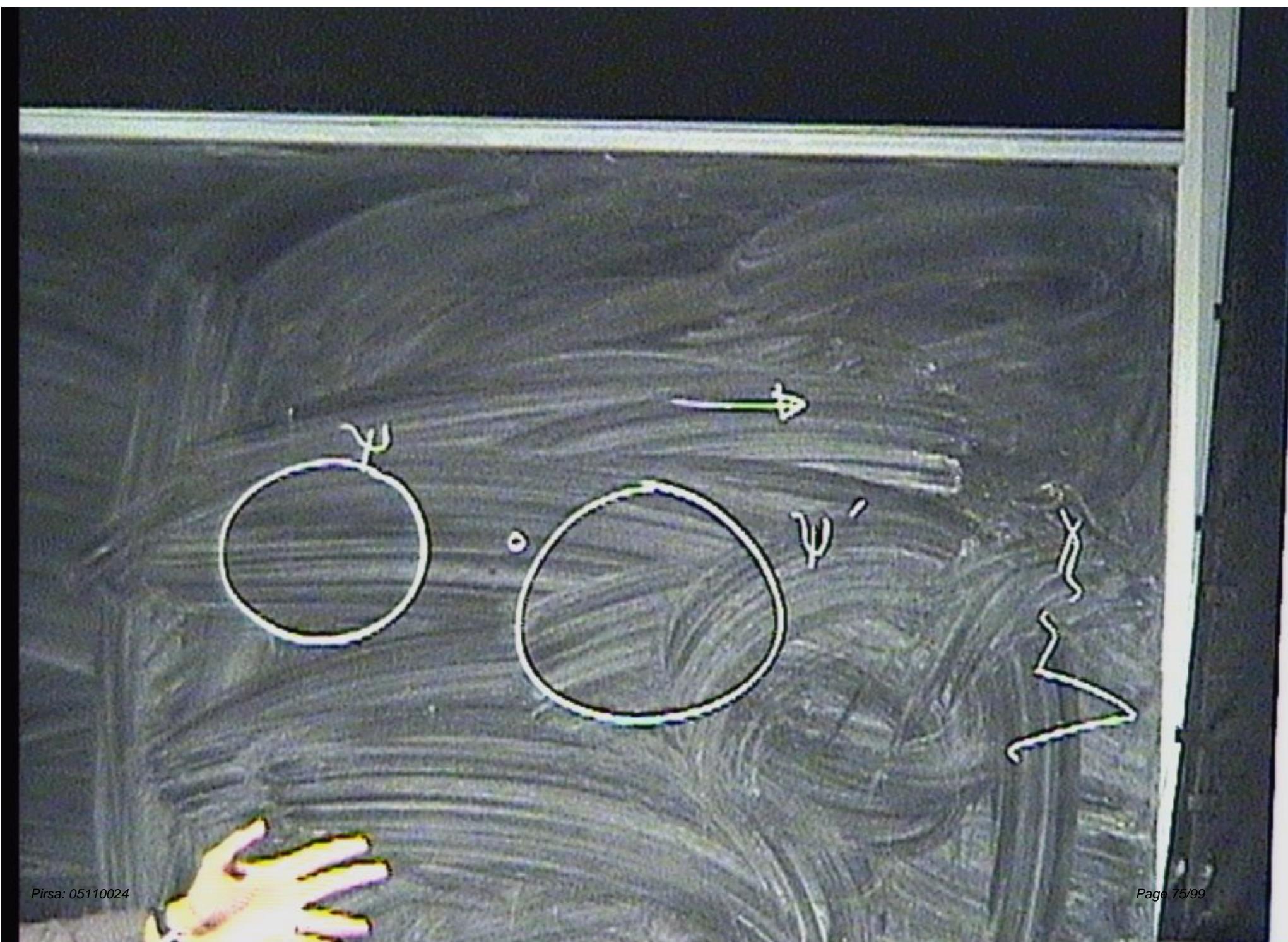
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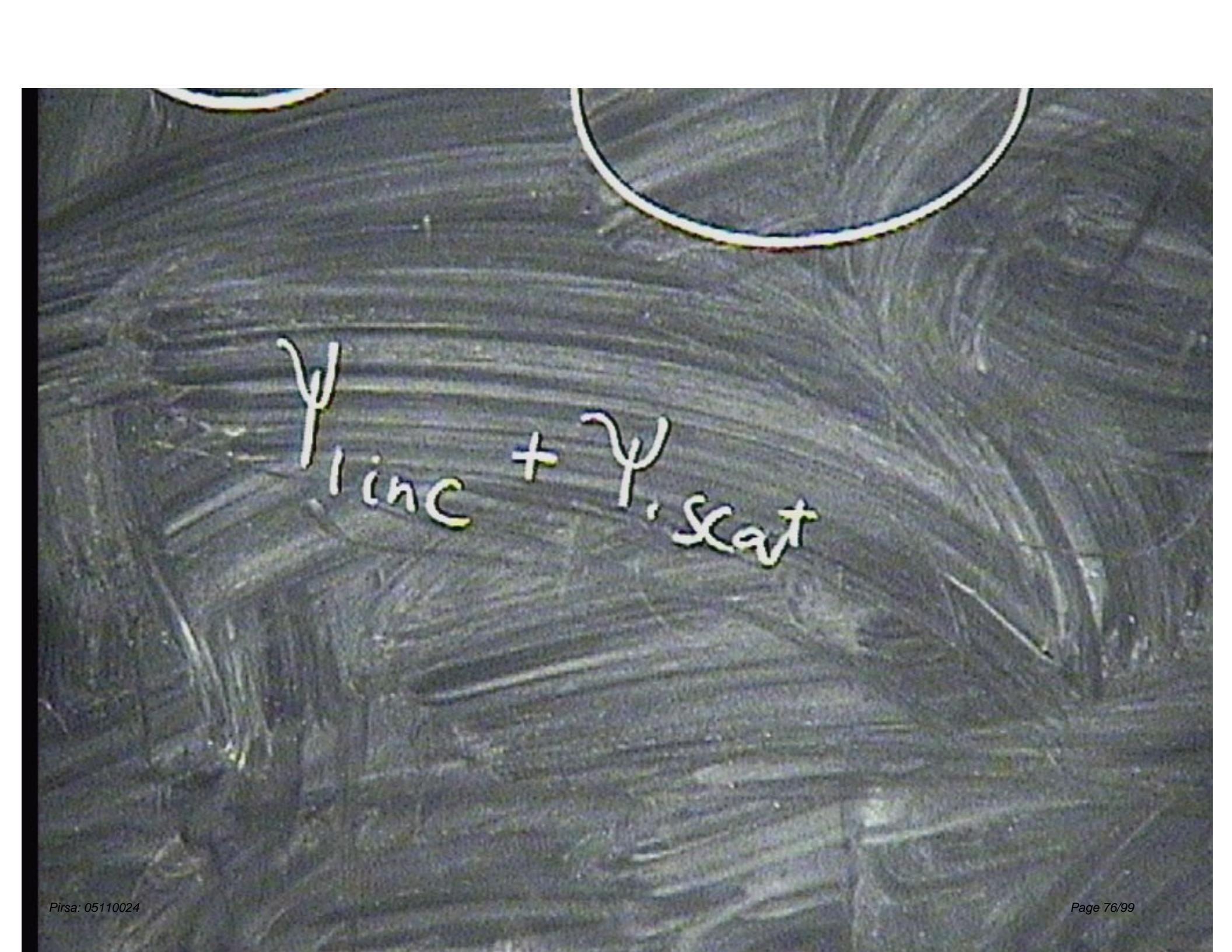
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 $\psi_{\text{inc}} + \psi_{\text{scat}}$

$$|\gamma_{\text{inc}} + \gamma_{\text{scat}}|^2$$



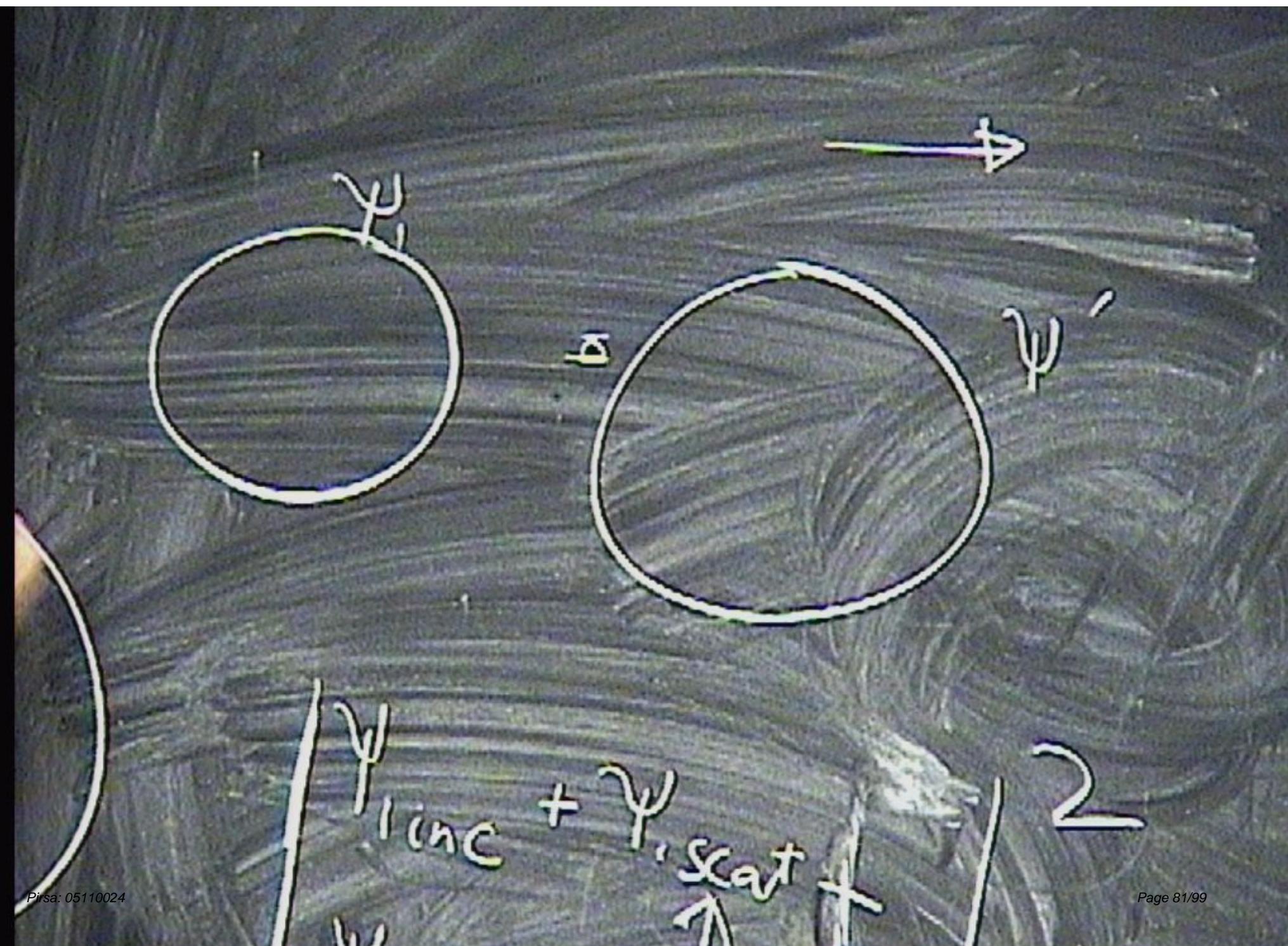
$$\psi_{1\text{inc}} + \psi_{1\text{scat}}$$

$$\psi_{2\text{inc}} + \psi_{2\text{scat}}$$

2

$$\frac{\psi_{1 \text{ inc}} + \psi_{1 \text{ scat}}}{\psi_{2 \text{ inc}} + \psi_{2 \text{ scat}}} = 2$$

$$\left| \psi_{1\text{inc}} + \psi_{1\text{scat}} \right|^2$$
$$\left| \psi_{2\text{inc}} + \psi_{2\text{scat}} \right|^2$$
$$|\psi_1 + \psi_2|^2$$



2

γ

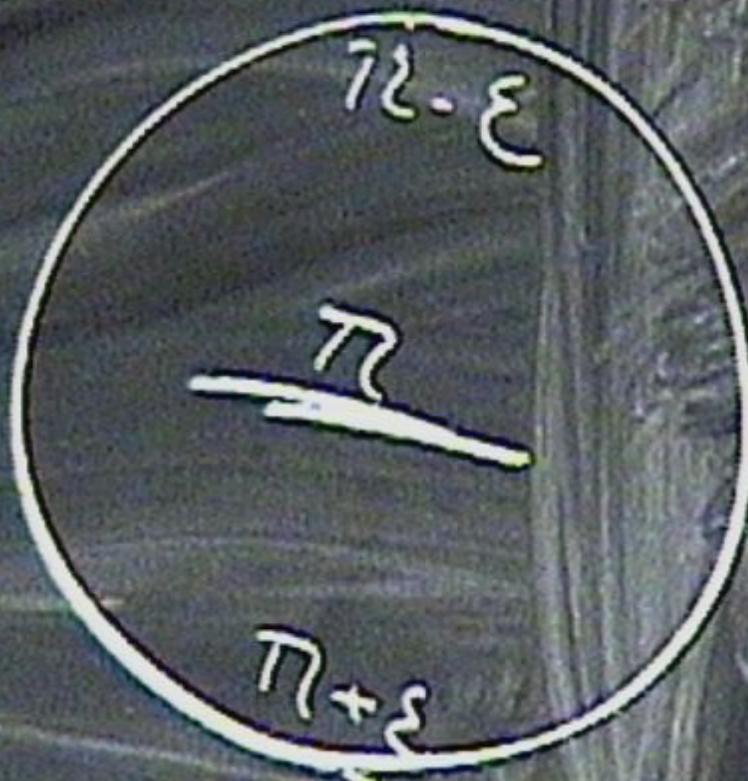
γ

$\gamma_{line} + \gamma$

γ

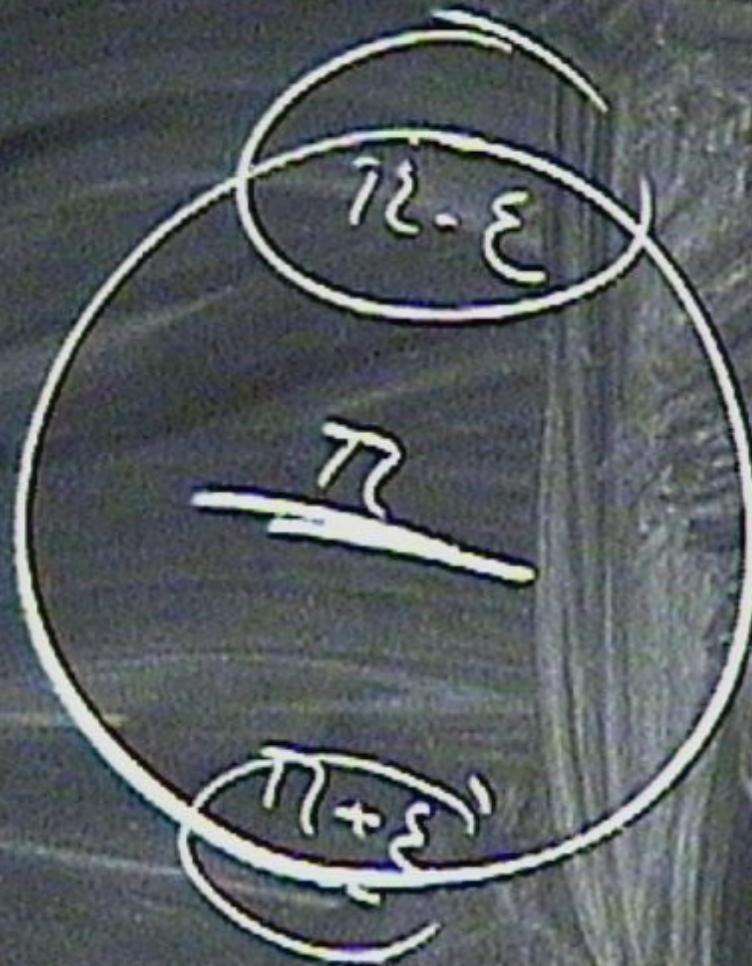
$\gamma_{line} - \gamma$

2



$$\begin{aligned} & \gamma_{1\text{inc}} + \gamma_1 \\ & \gamma_{2\text{inc}} + \gamma_2 \end{aligned}$$

2H



$$\gamma_{\text{inc}} + \gamma_{\text{out}}$$
$$\gamma_{\text{inc}} + \gamma_{\text{out}}$$



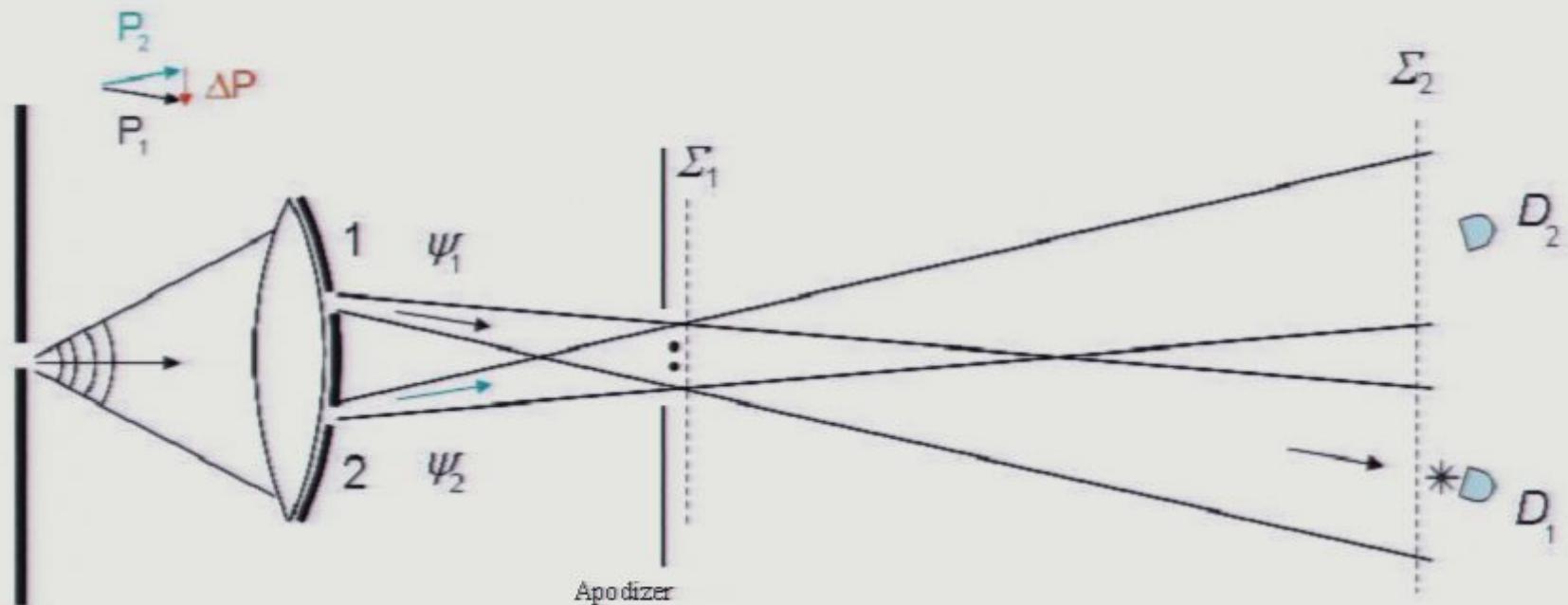
$\Psi_{1\text{inc}} + \Psi_{1\text{scat}}$

$\Psi_{2\text{inc}} + \Psi_{2\text{scat}}$

$\Psi_1 + \Psi_2$

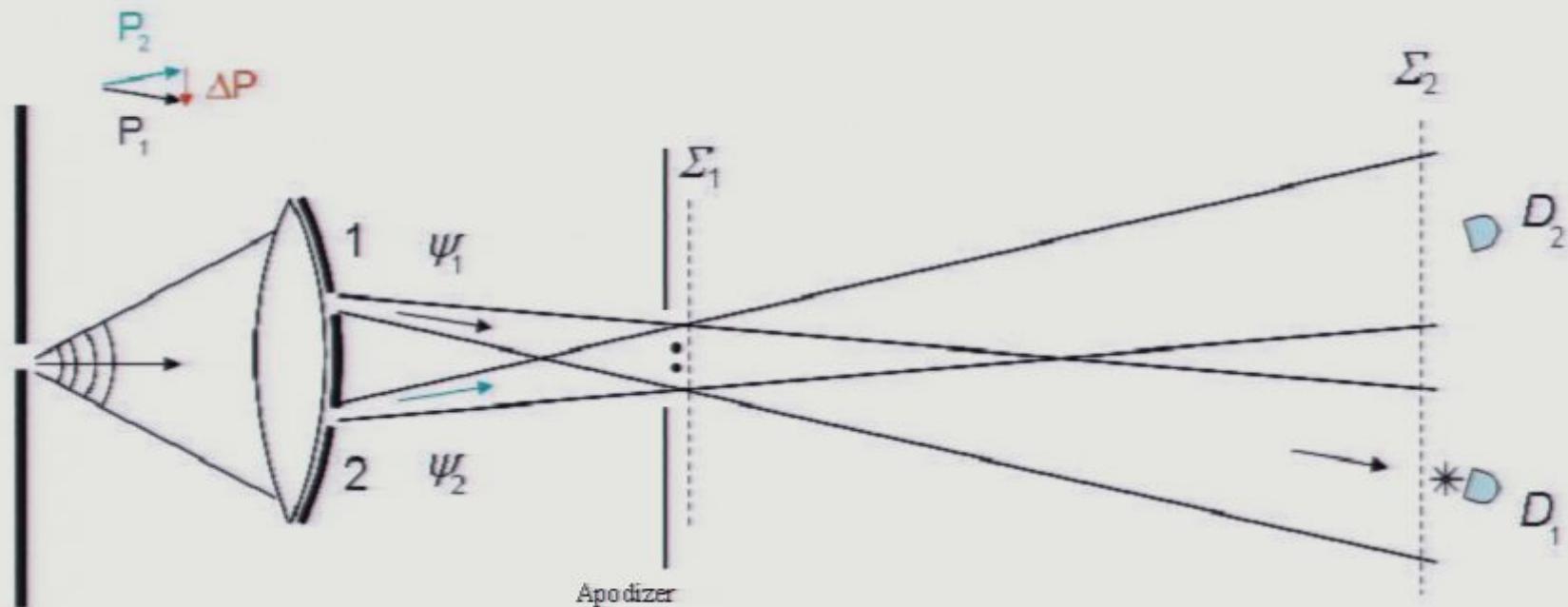
2

Experiment without the imaging lens.

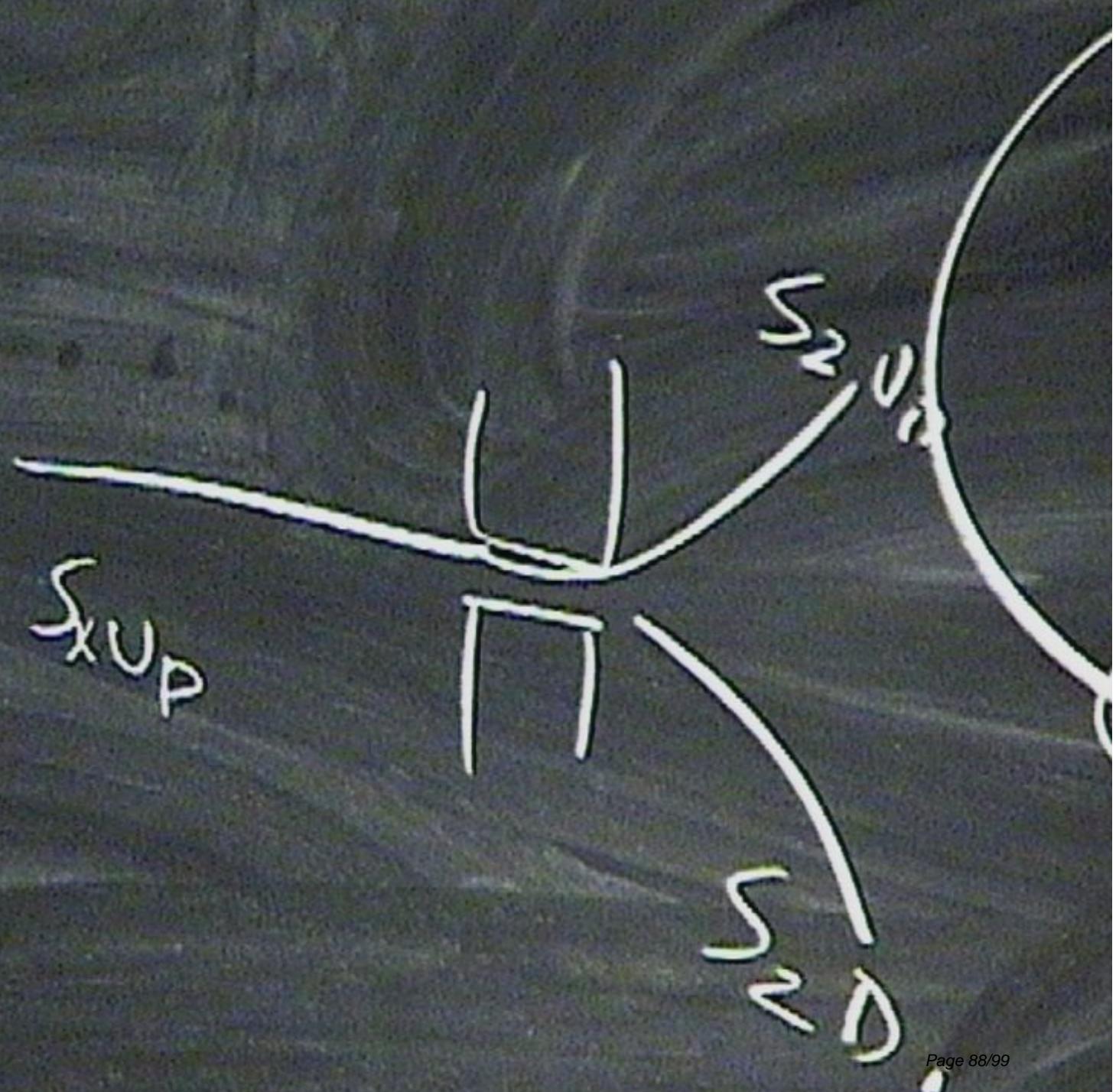


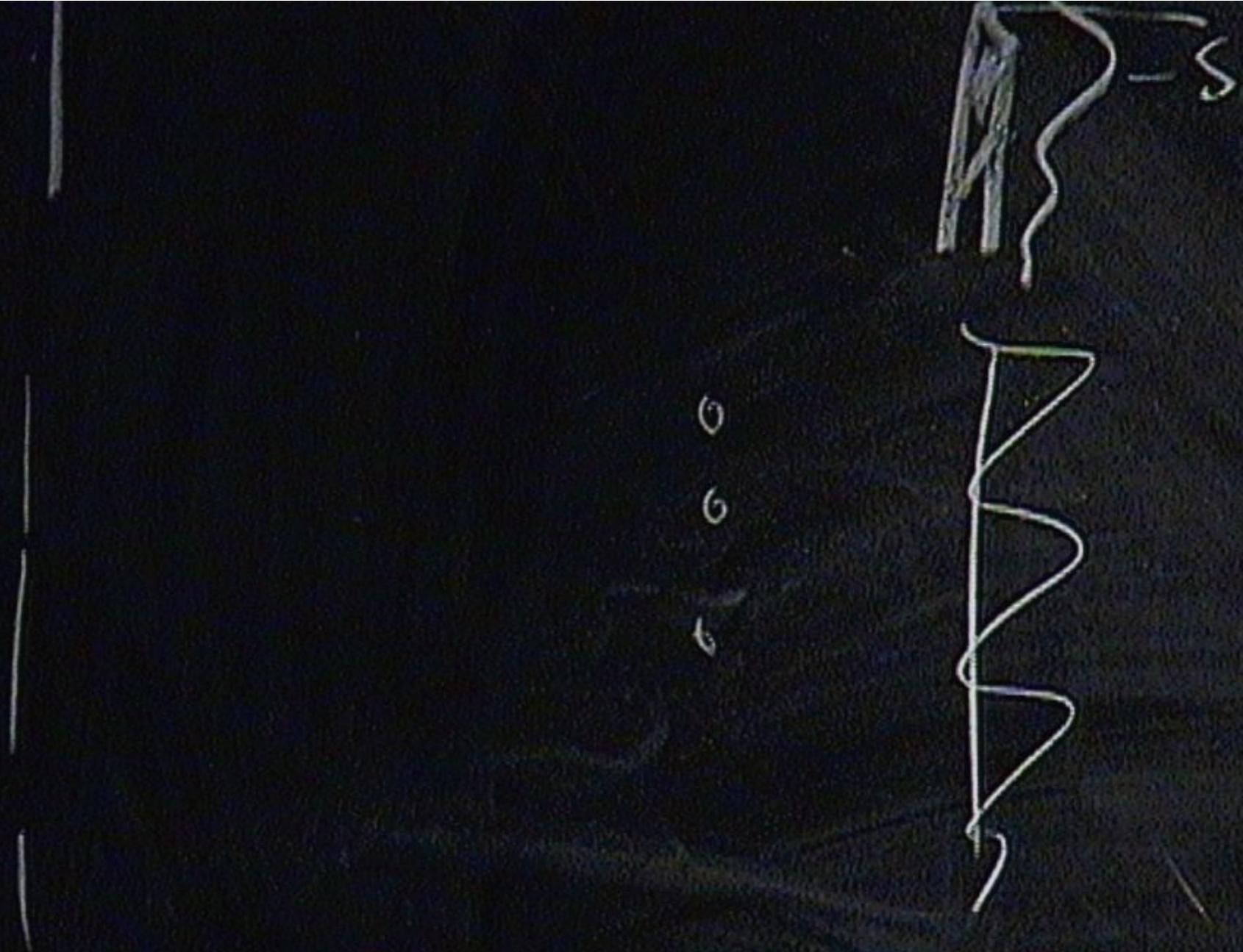
Rowan Exp. May 2005

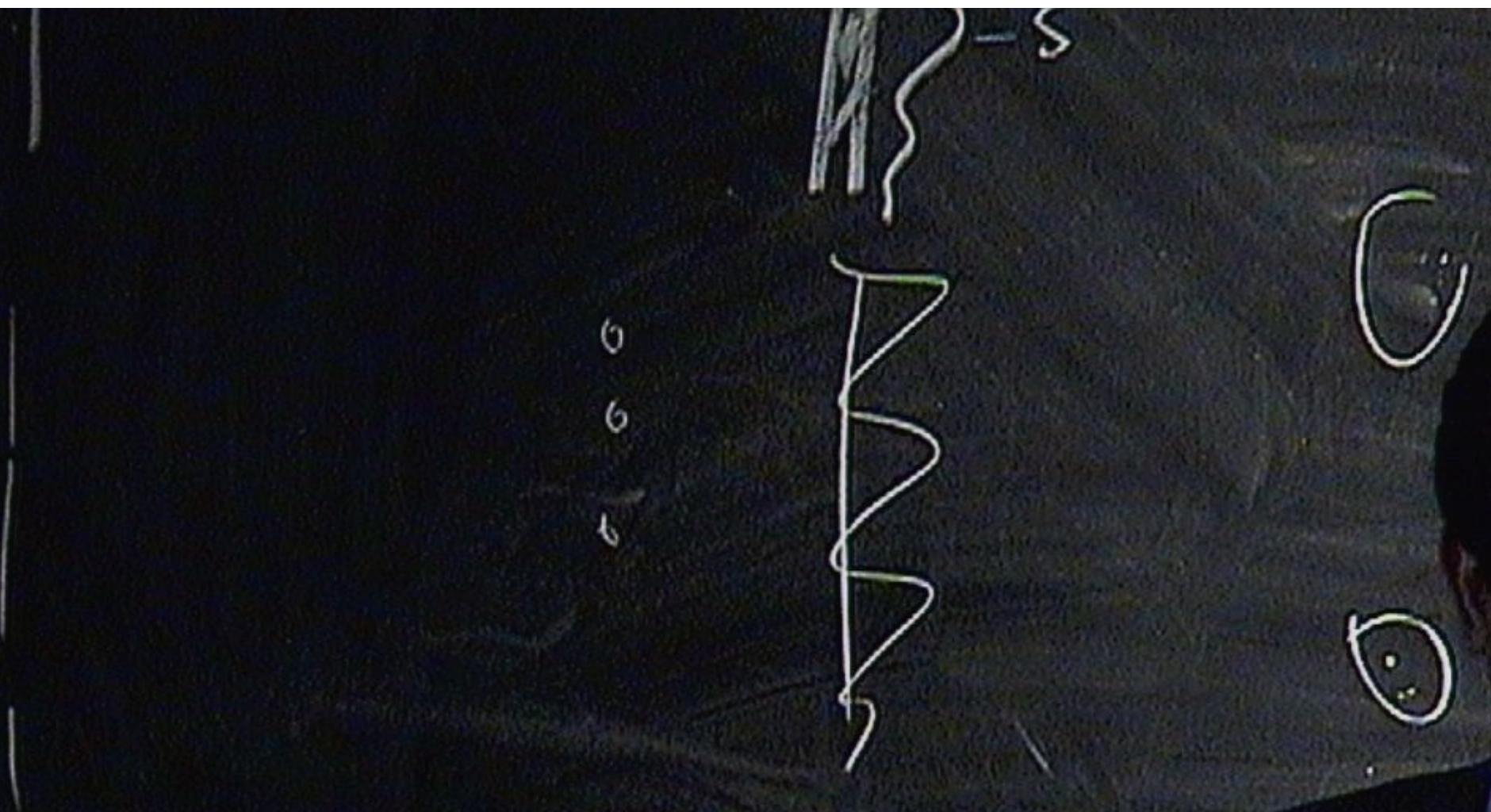
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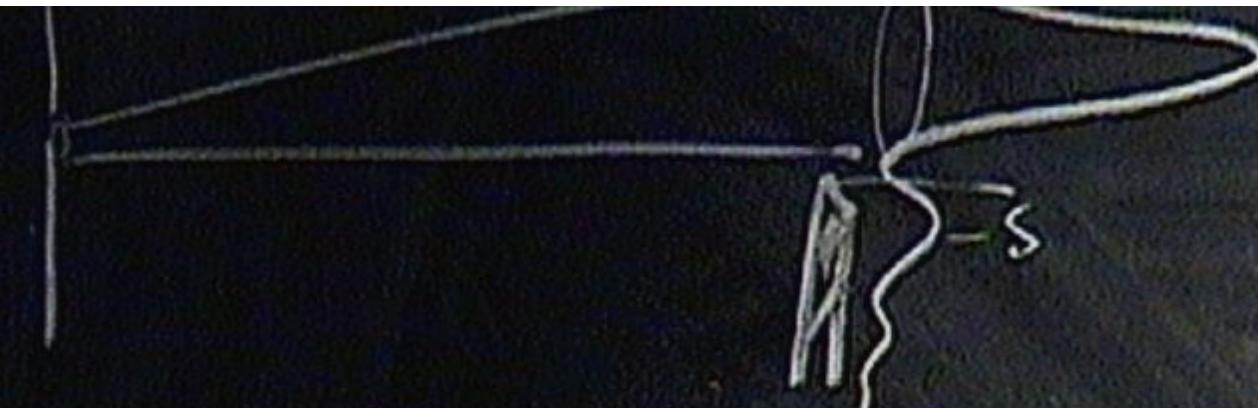


Rowan Exp. May 2005





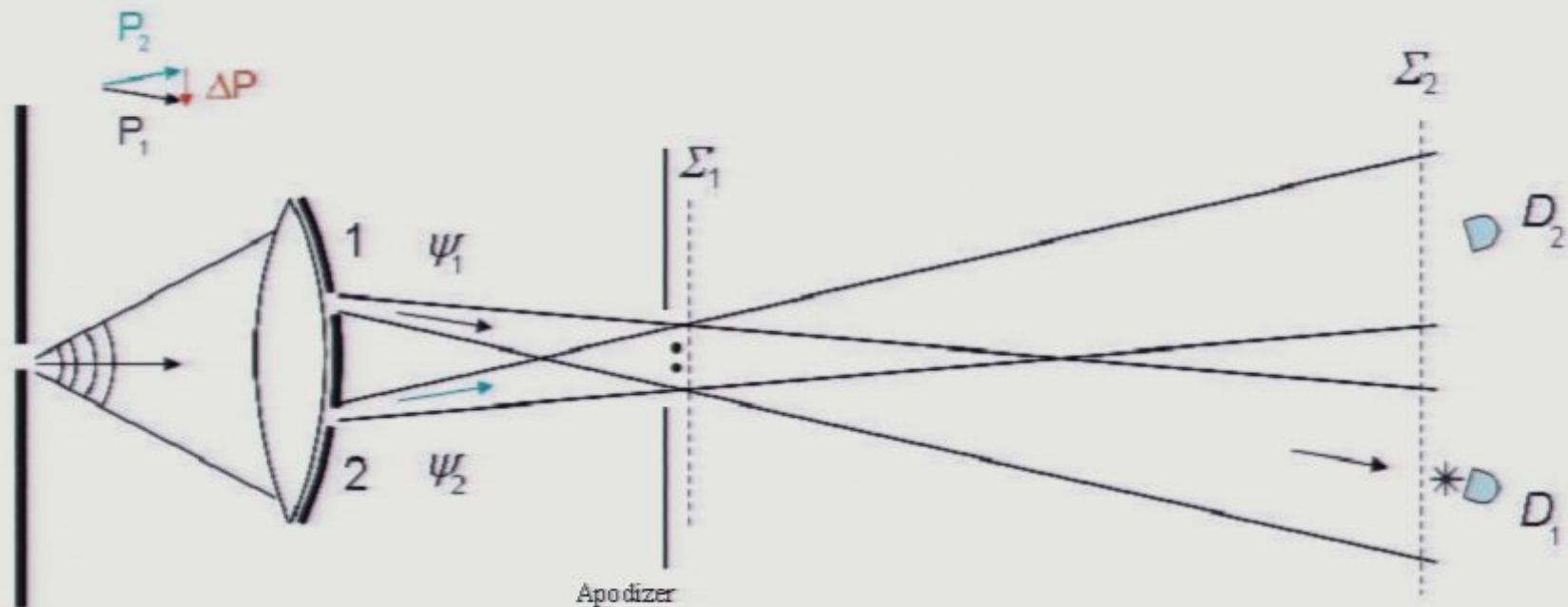




6
6
6



Experiment without the imaging lens.



Rowan Exp. May 2005

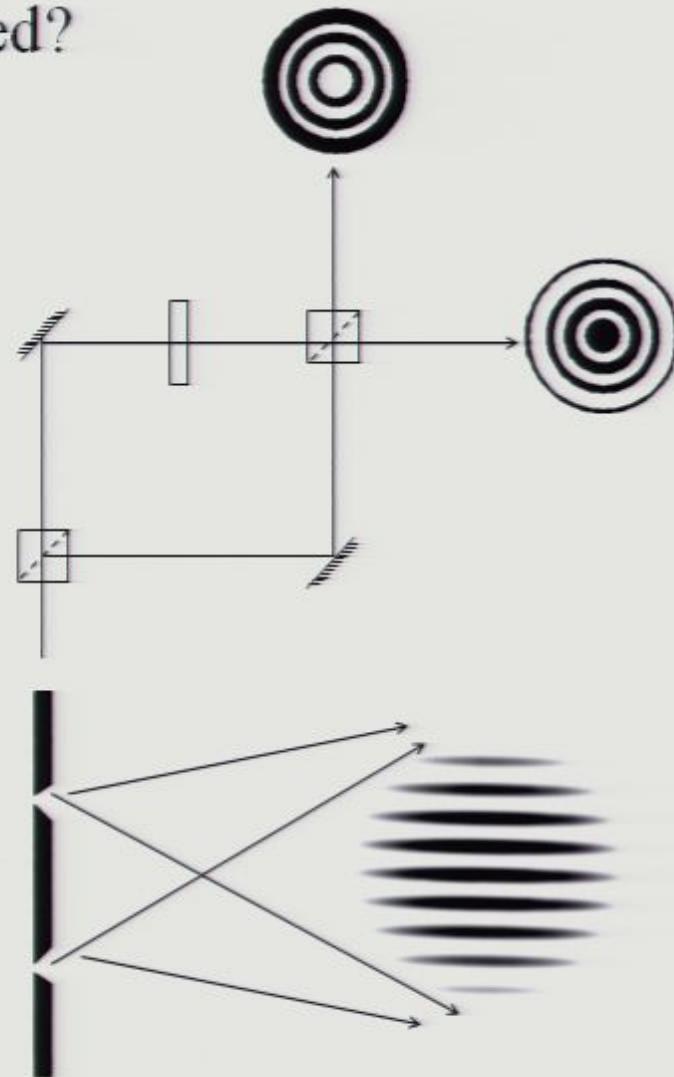
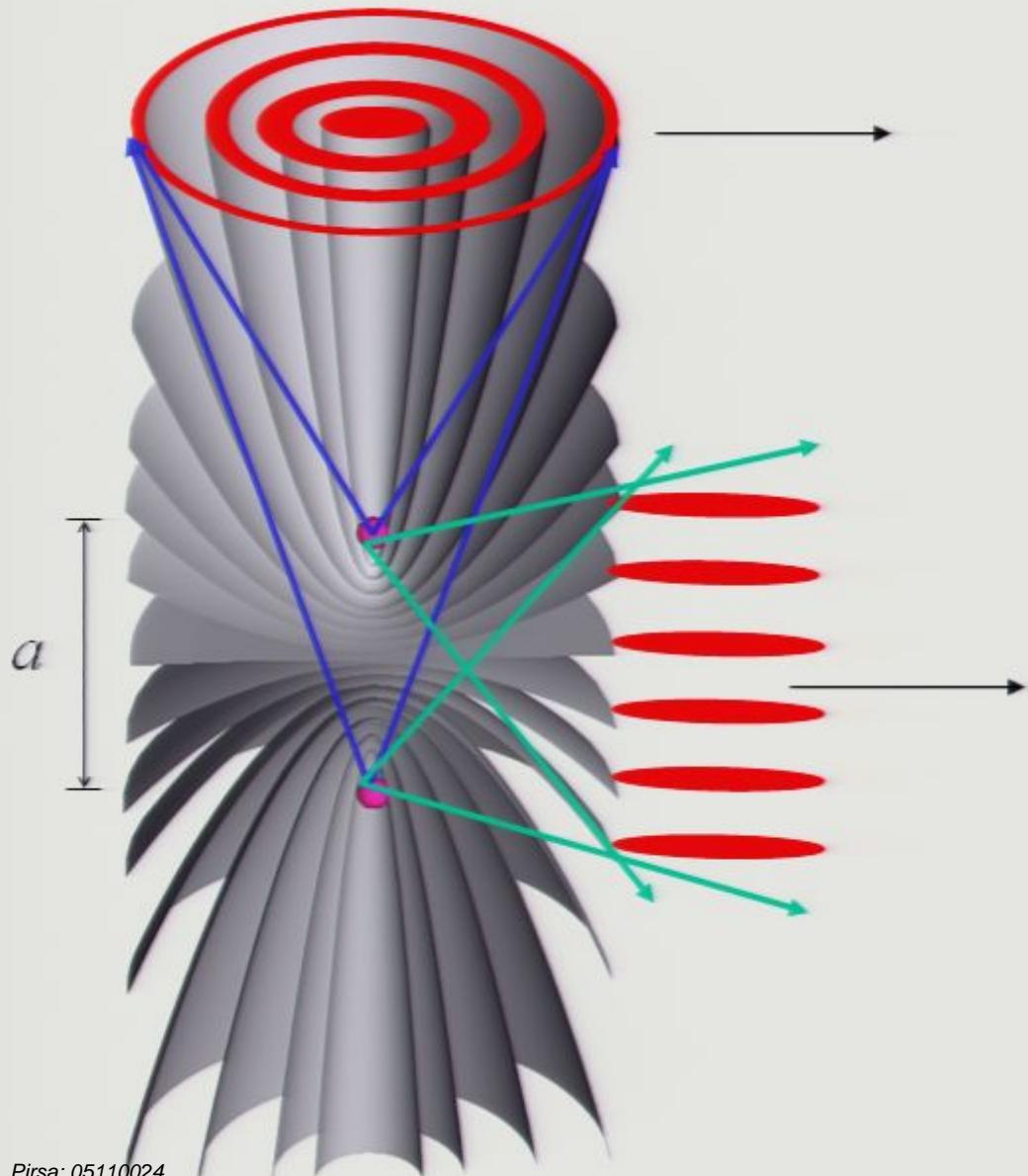
γ
lines + ν

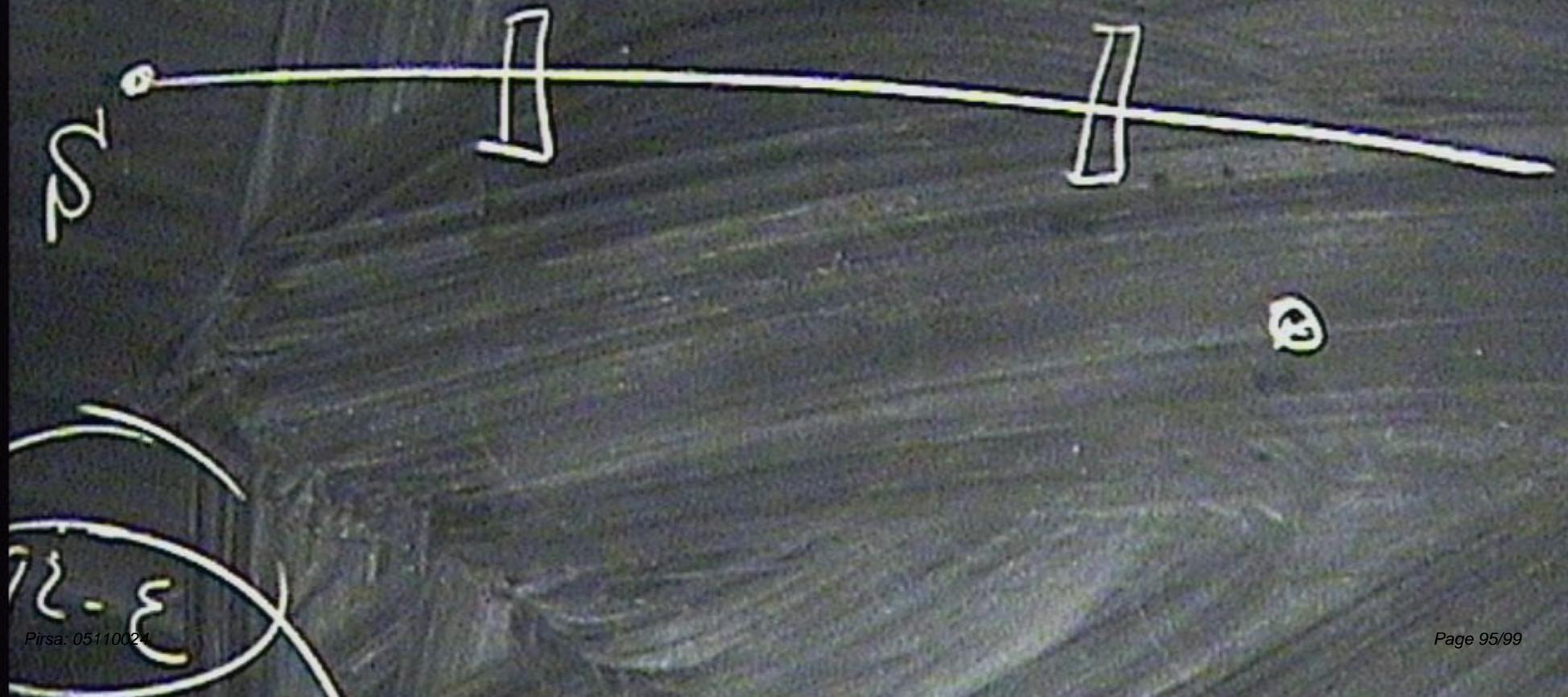
A

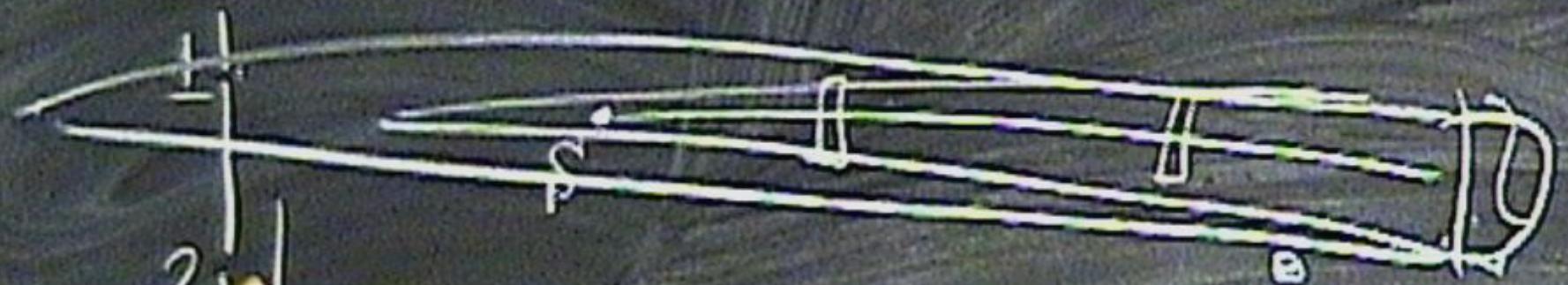


B

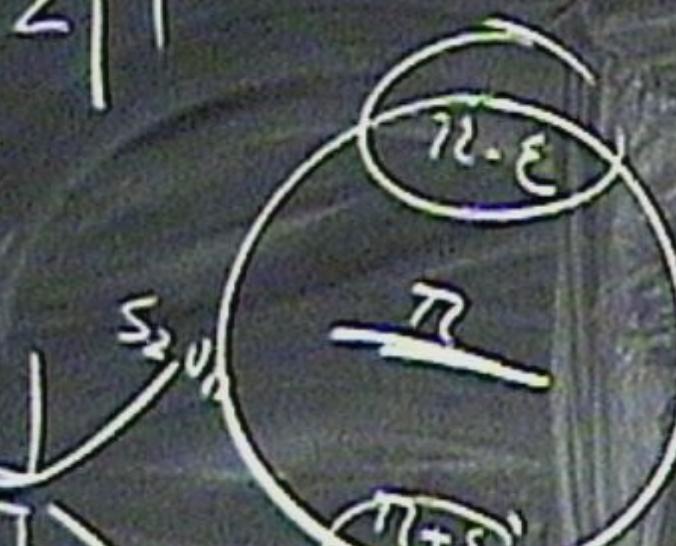
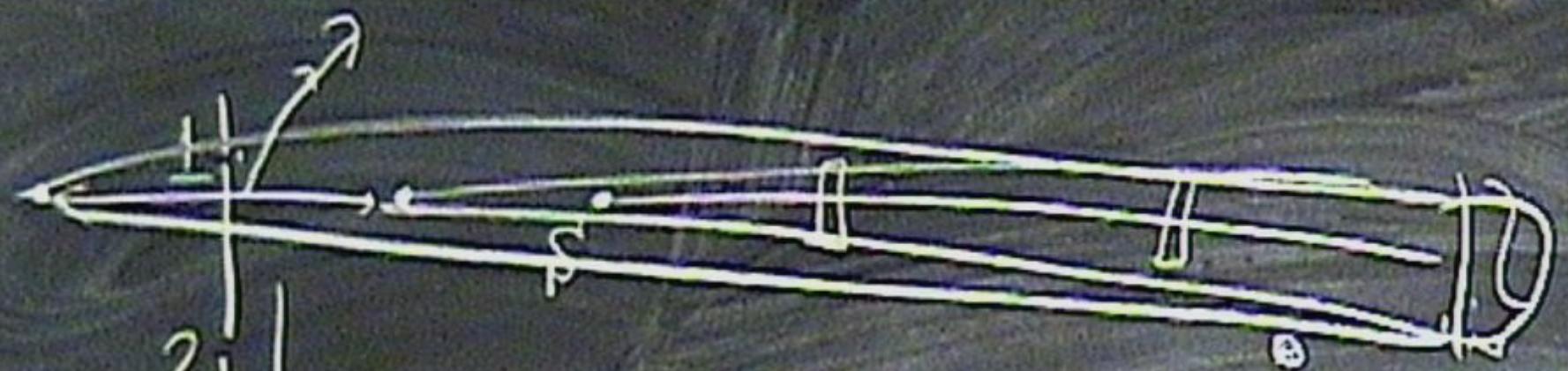
Why have previous experiments failed?







A
 $\gamma_{line} + \gamma_{Scat}$



$\gamma_{\text{line}} + \gamma_{\text{scat}} +$

Why have previous experiments failed?

