Title: Measurement without Â“measurementÂ”: Experimental violation of Complementarity and its aftermath

Date: Nov 30, 2005 04:00 PM

URL: http://pirsa.org/05110024

Abstract: BohrÂ’s Principle of Complementarity of wave and particle aspects of quantum systems has been a cornerstone of quantum mechanics since its inception. Einstein, SchrÃ¶dinger and deBroglie vehemently disagreed with Bohr for decades, but were unable to point out the error in BohrÂ’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: 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.)

Quotations on the Wave-Particle duality and Complementarity

ntity problems.

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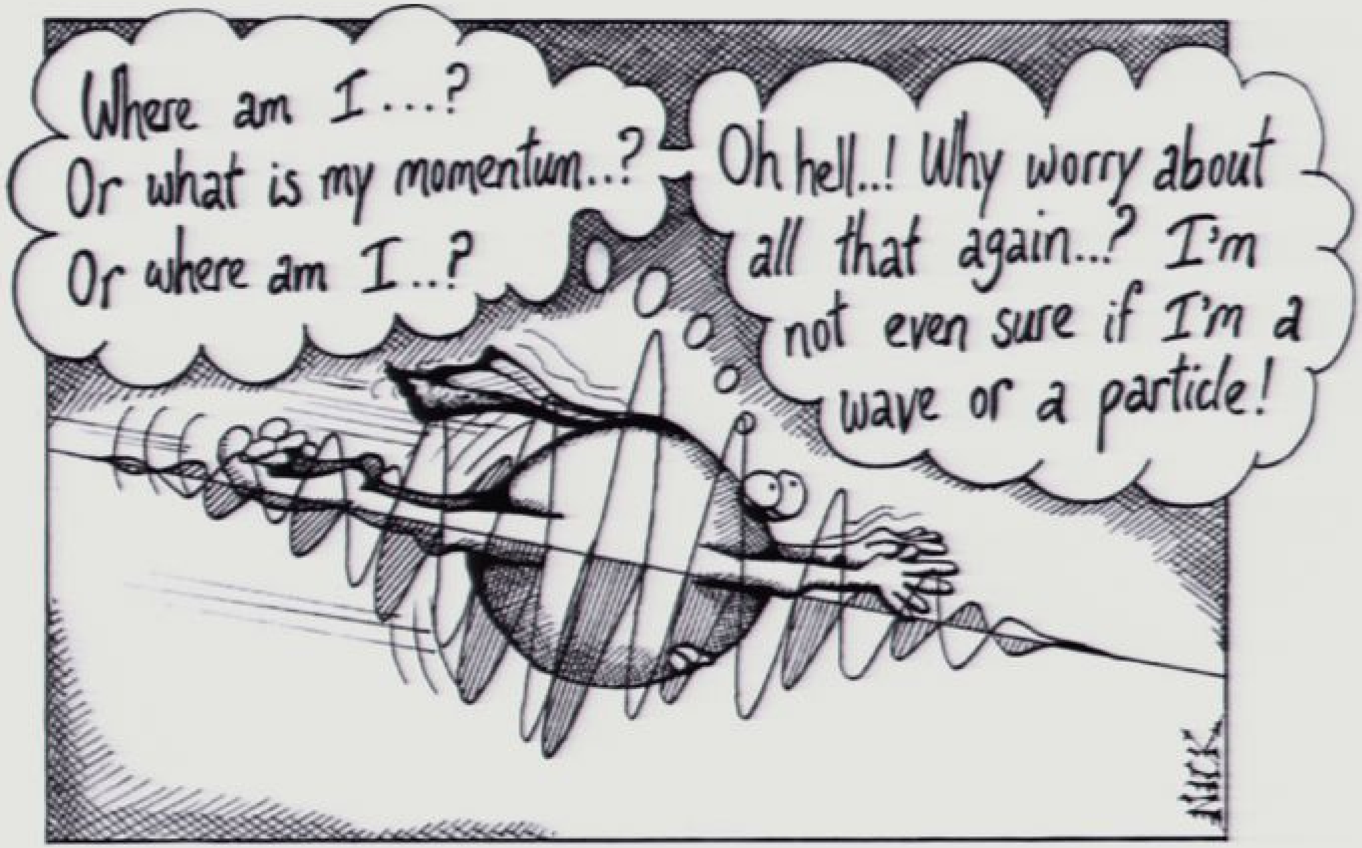

Photon self-identity problems.

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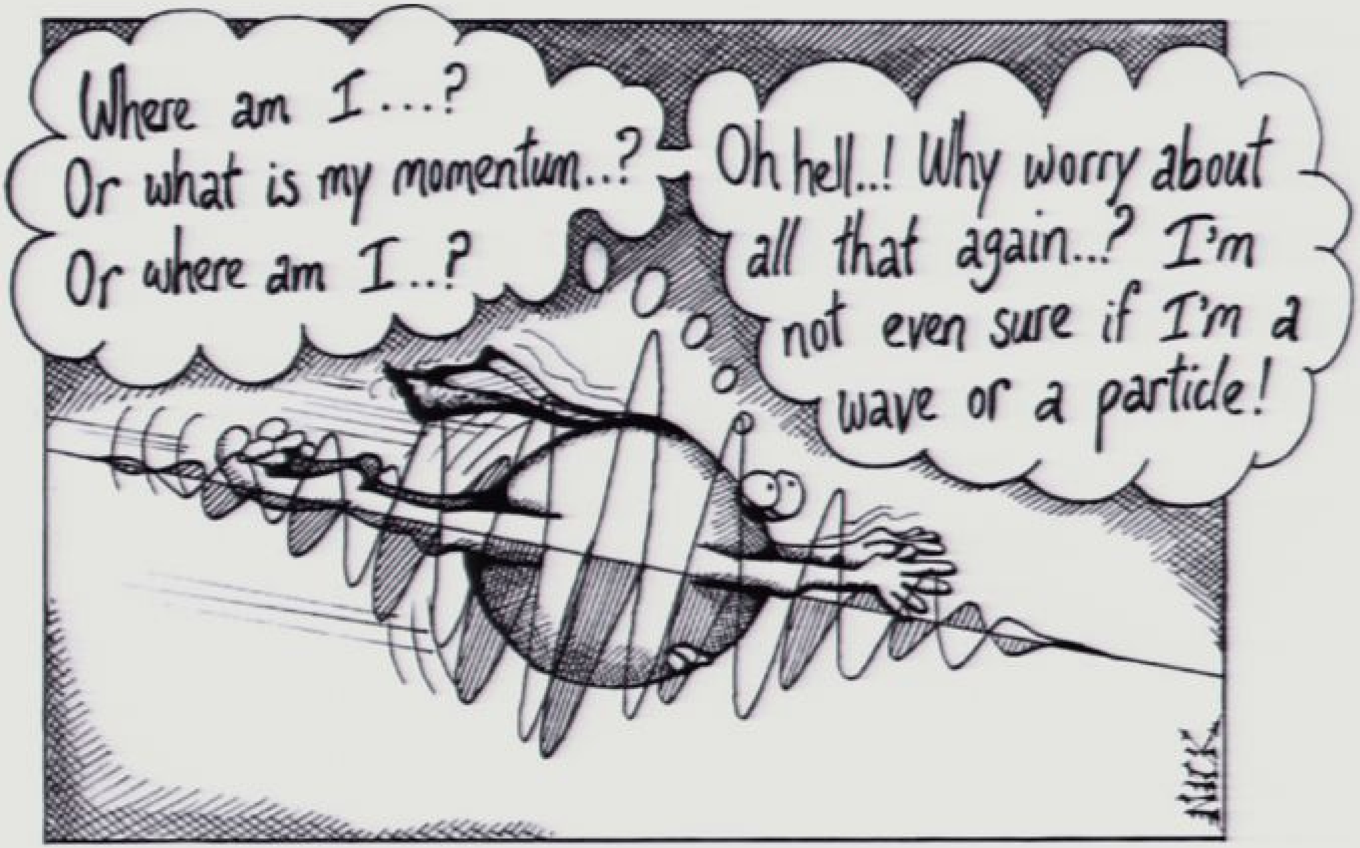

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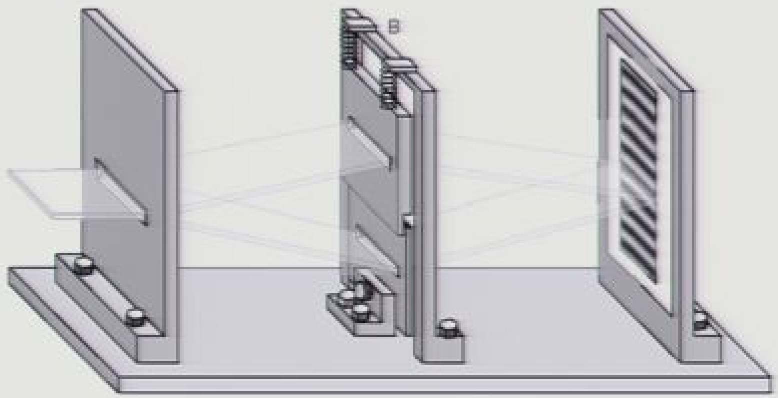
"But for quantum theory to say in one breath 'through which slit' and in another 'through both' [for the same quanta] is logically inconsistent." **John A. Wheeler** in 1979. (Woolf)

"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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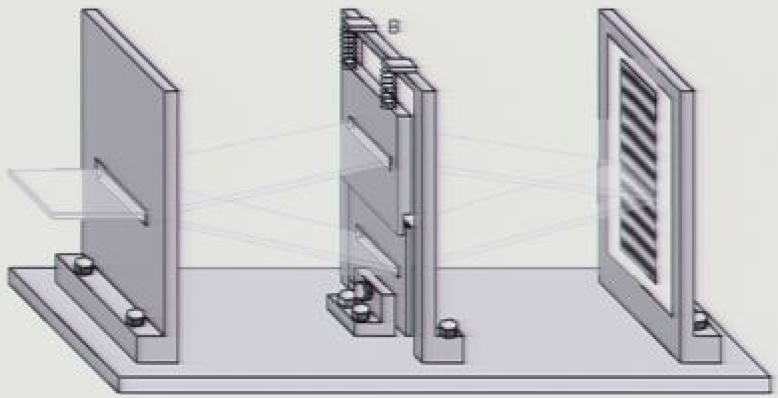
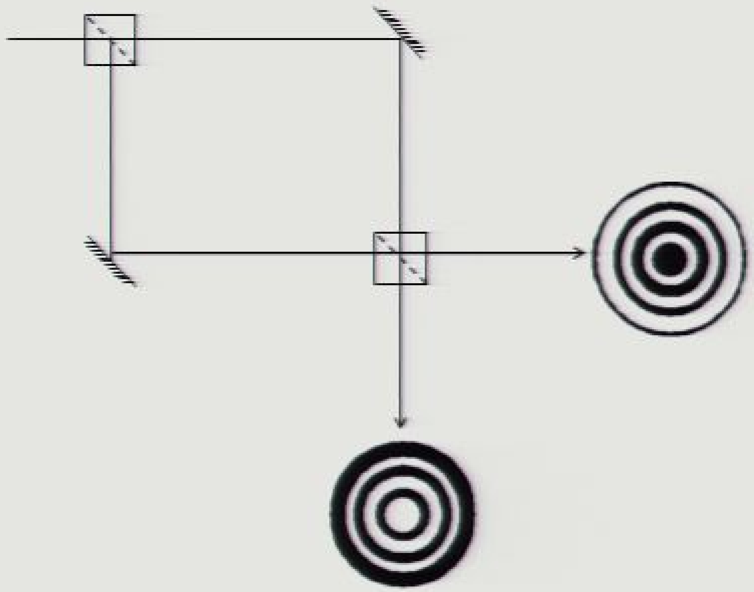
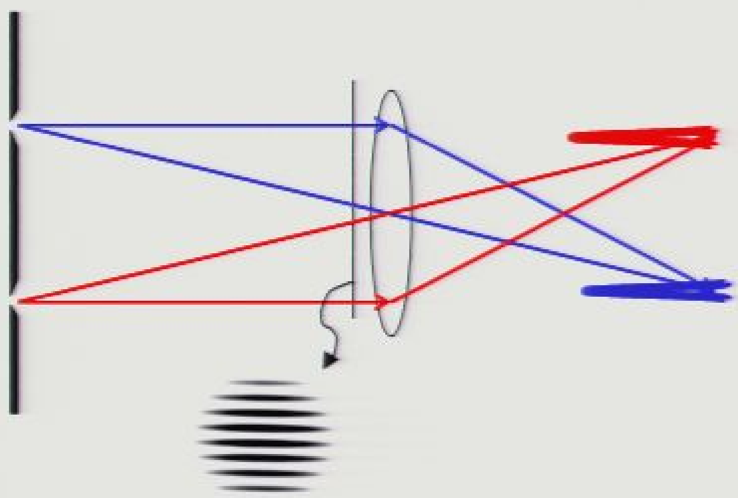
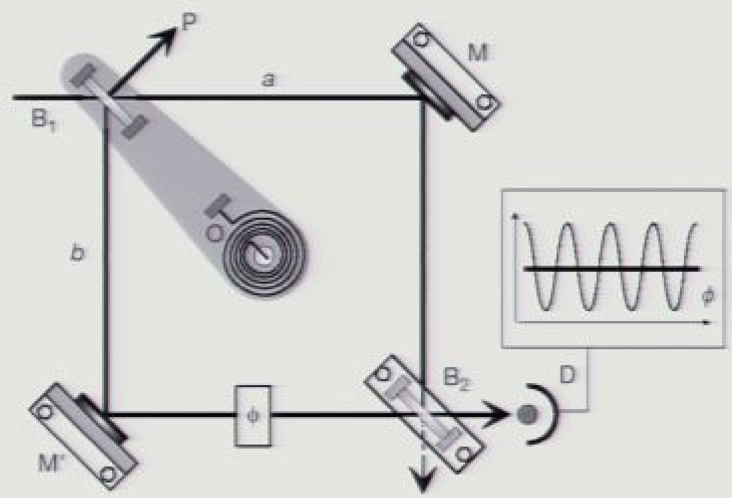


Bohr-Einstein Debate, 1927





Wheeler & Bartell, 1979



Bertet et al., 2001

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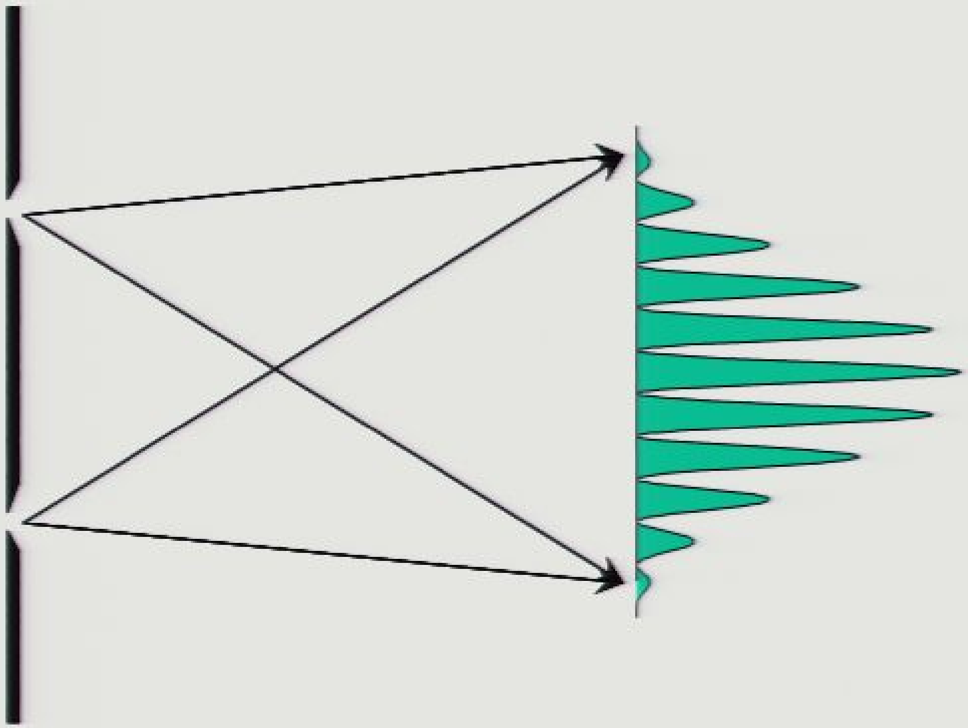
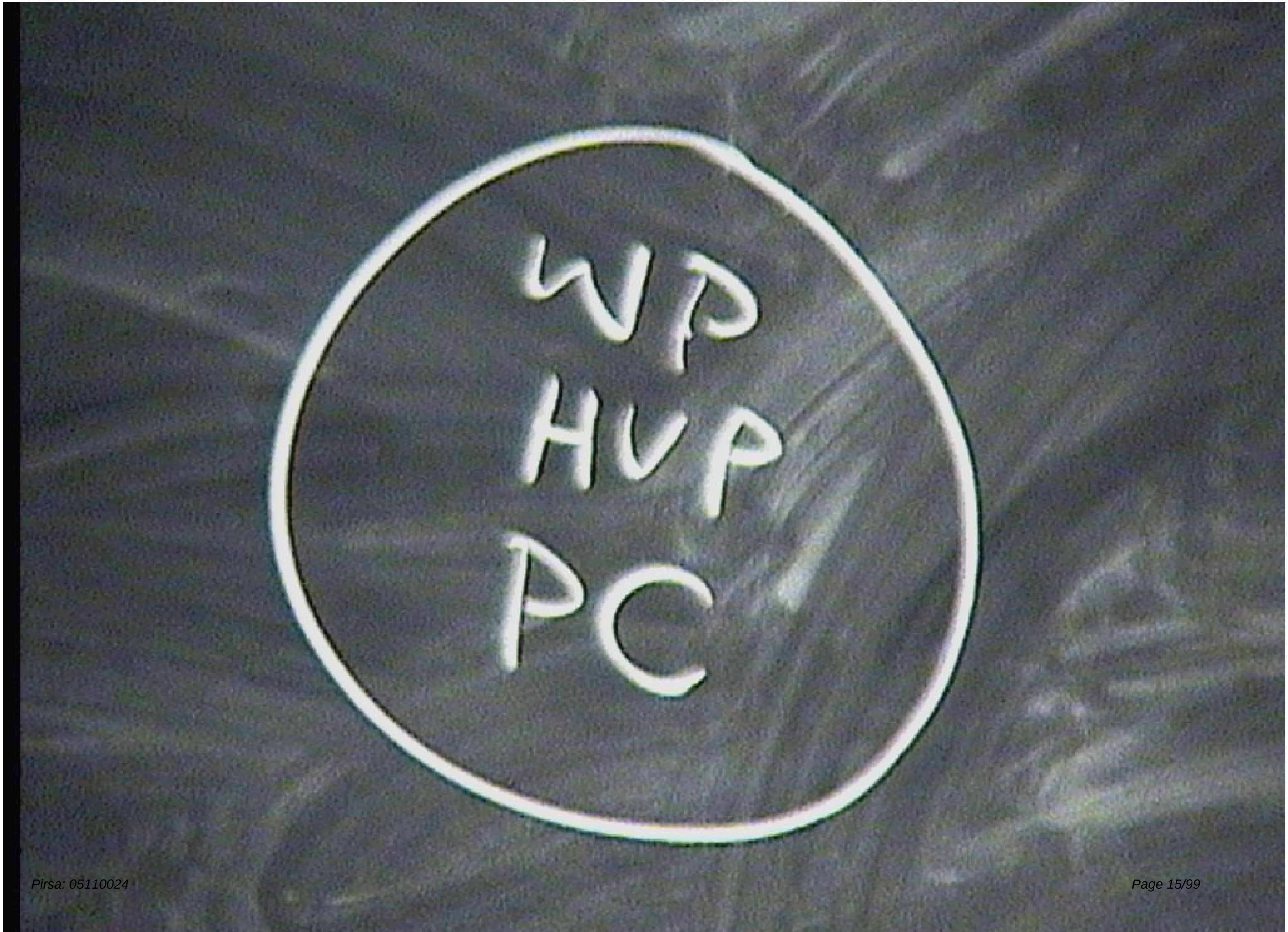


Interference Pattern


WP
HUP
PC

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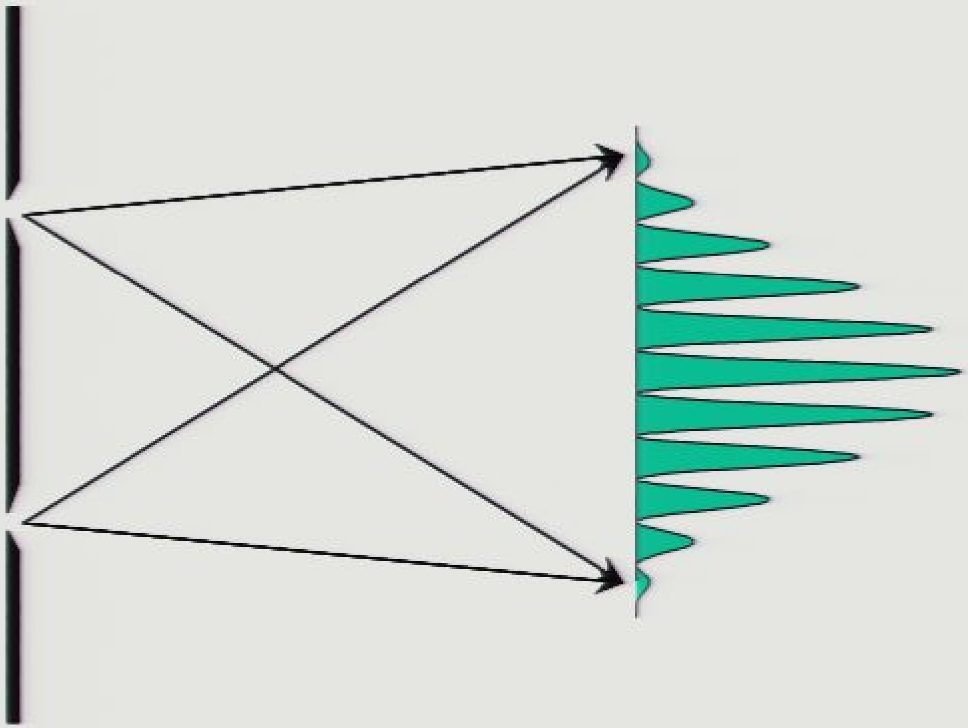

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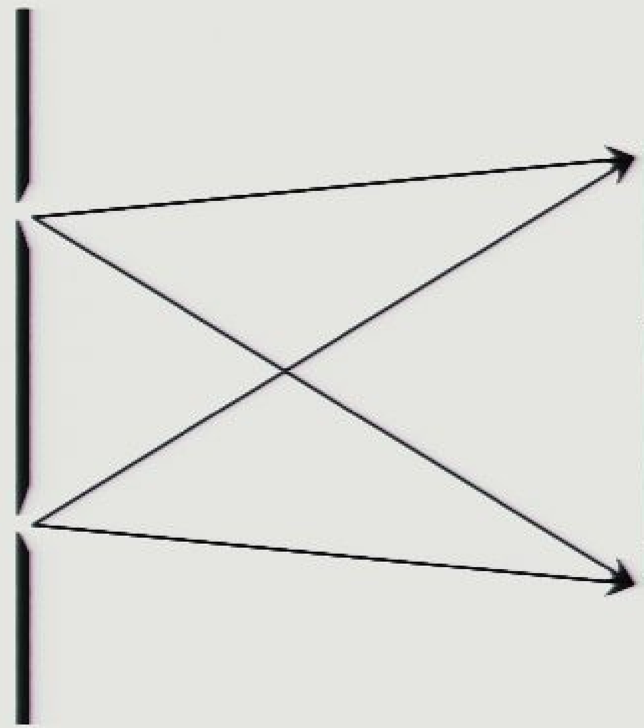
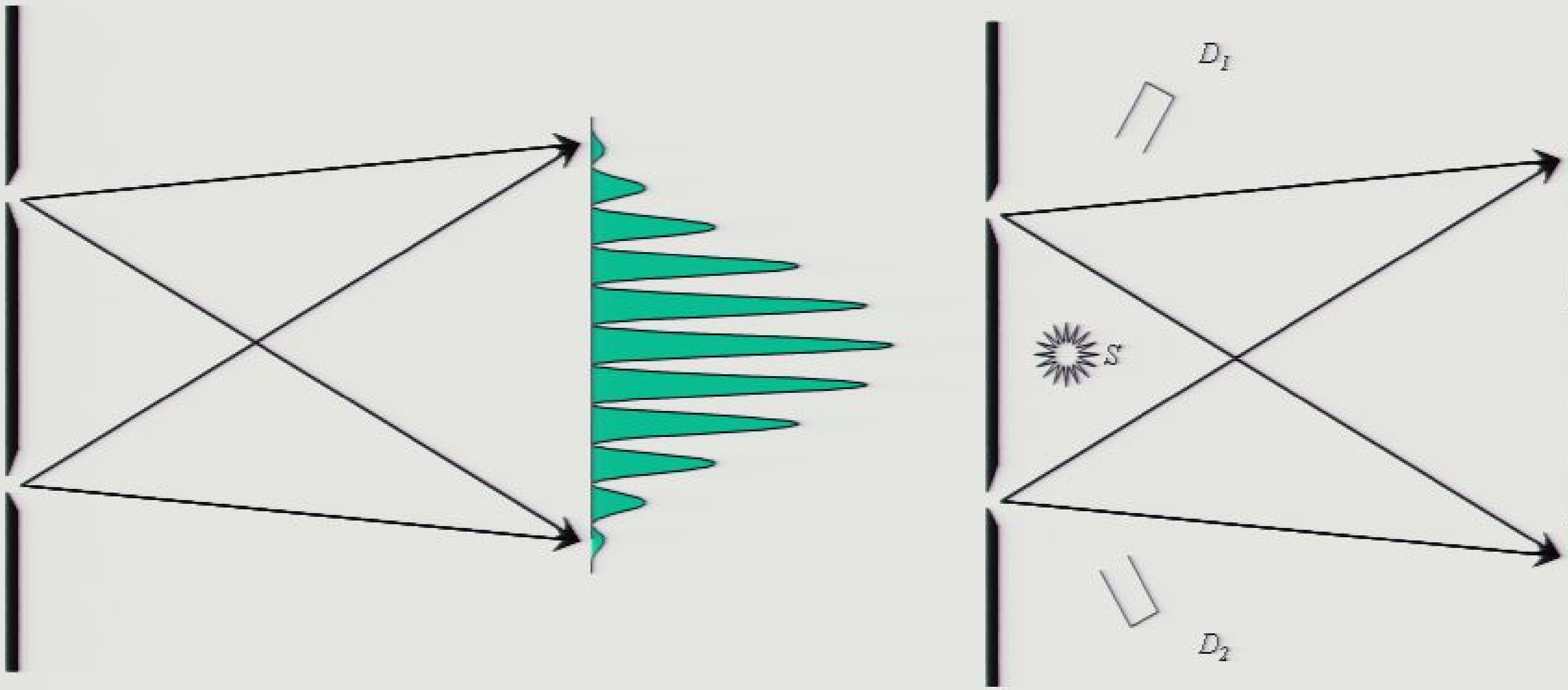


Which-Way Information

Feynman treats "the only mystery in quantum mechanics."



Interference Pattern

Which-Way Information

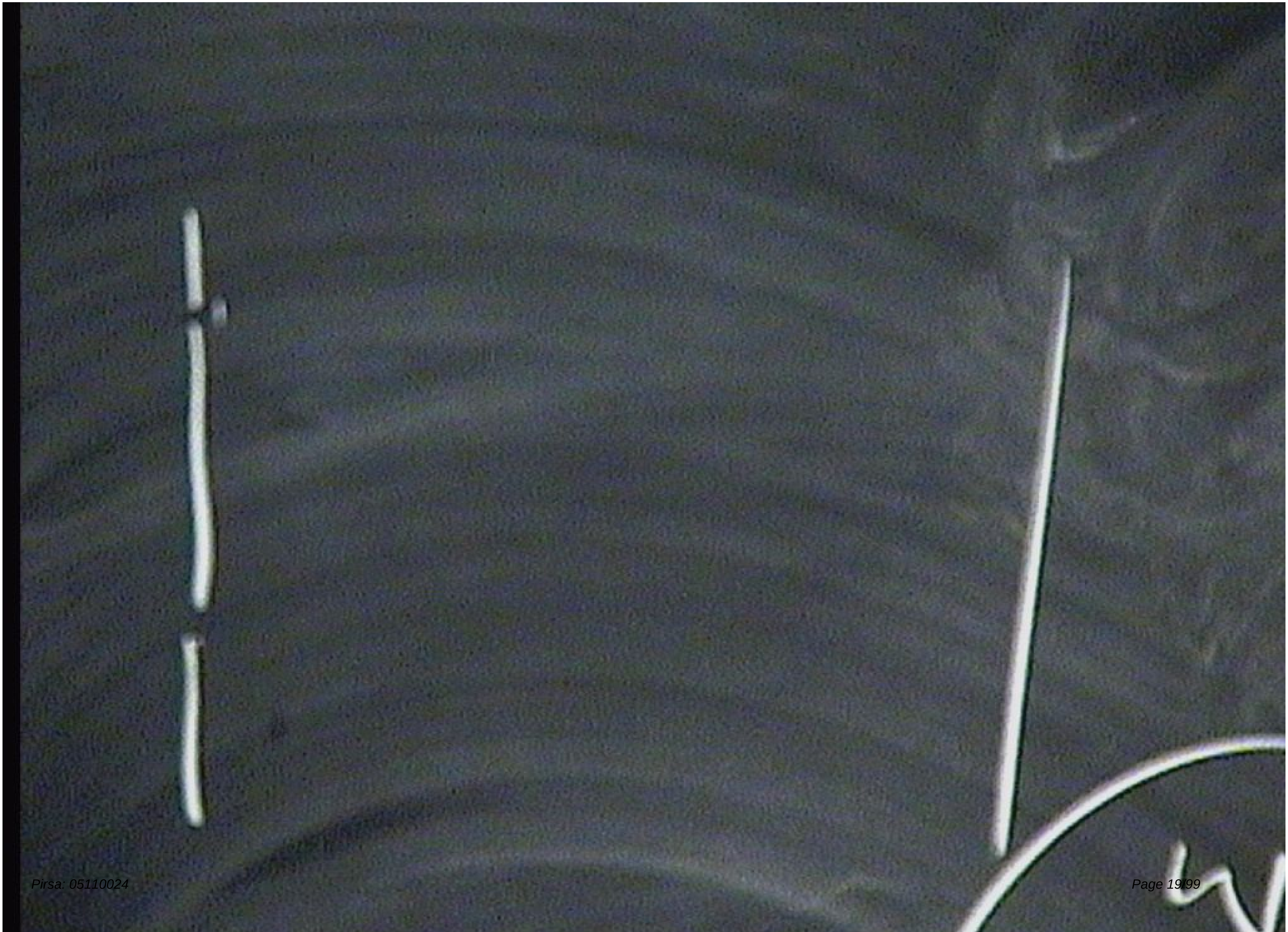
Complementarity is not always enforced by the Uncertainty Principle


articles

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

S. Dürr, T. Nonn & G. Rempe

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



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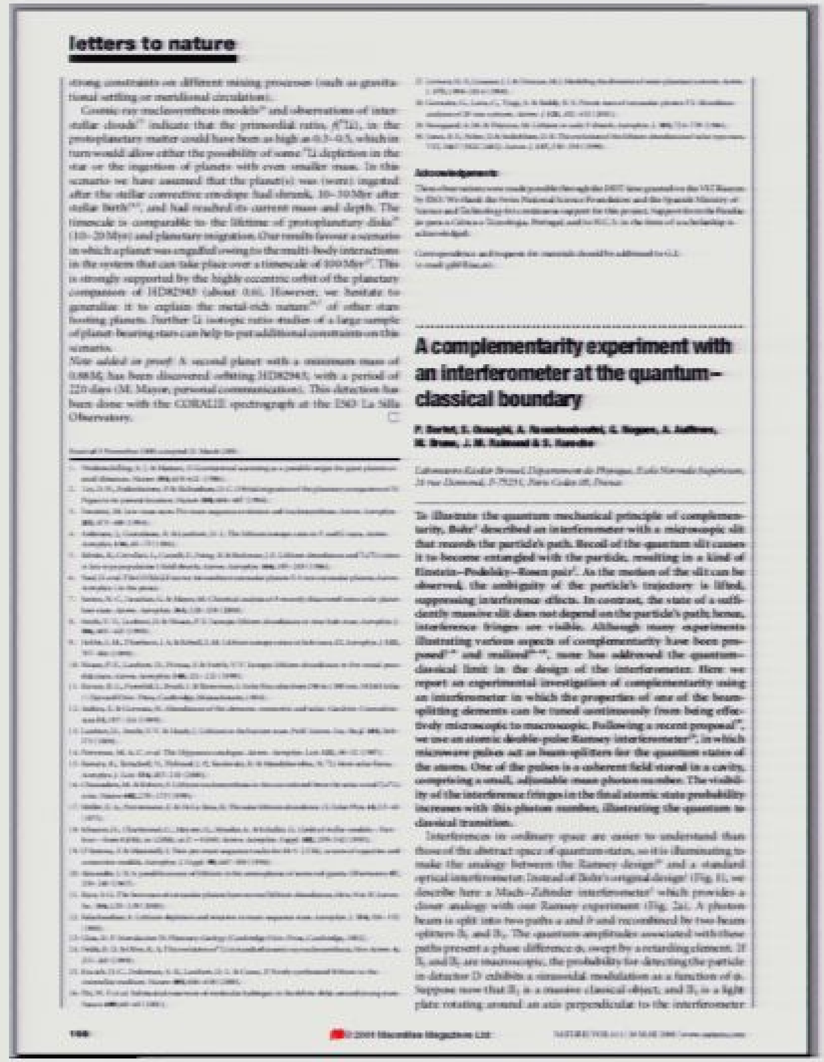
The principle of complementarity refers to the ability of quantum-mechanical entities to behave as particles or waves under different experimental conditions. For example, in the famous double-slit experiment, a single electron can apparently pass through both apertures simultaneously, forming an interference 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.


letters to nature

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

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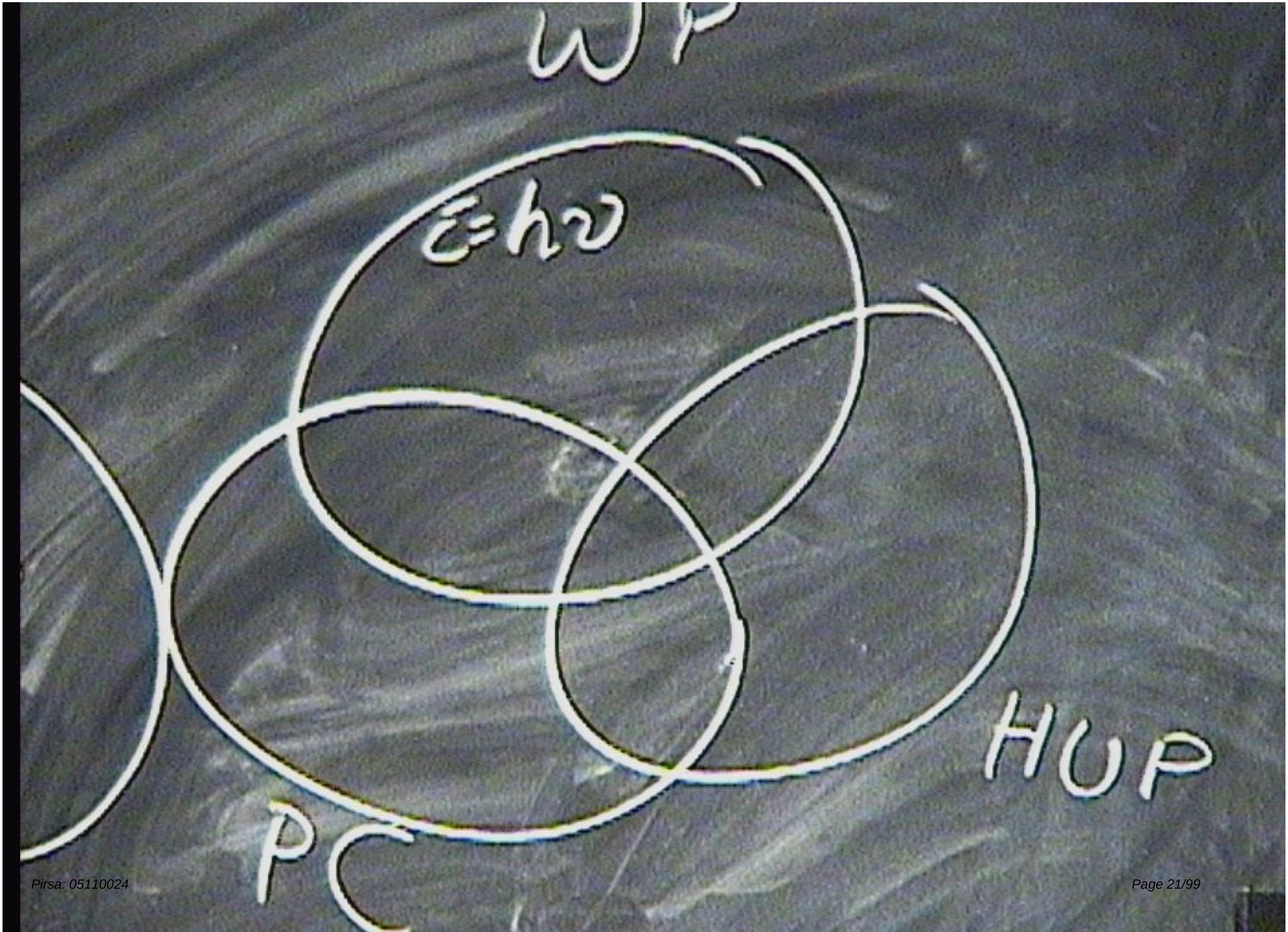
WP
E=hν
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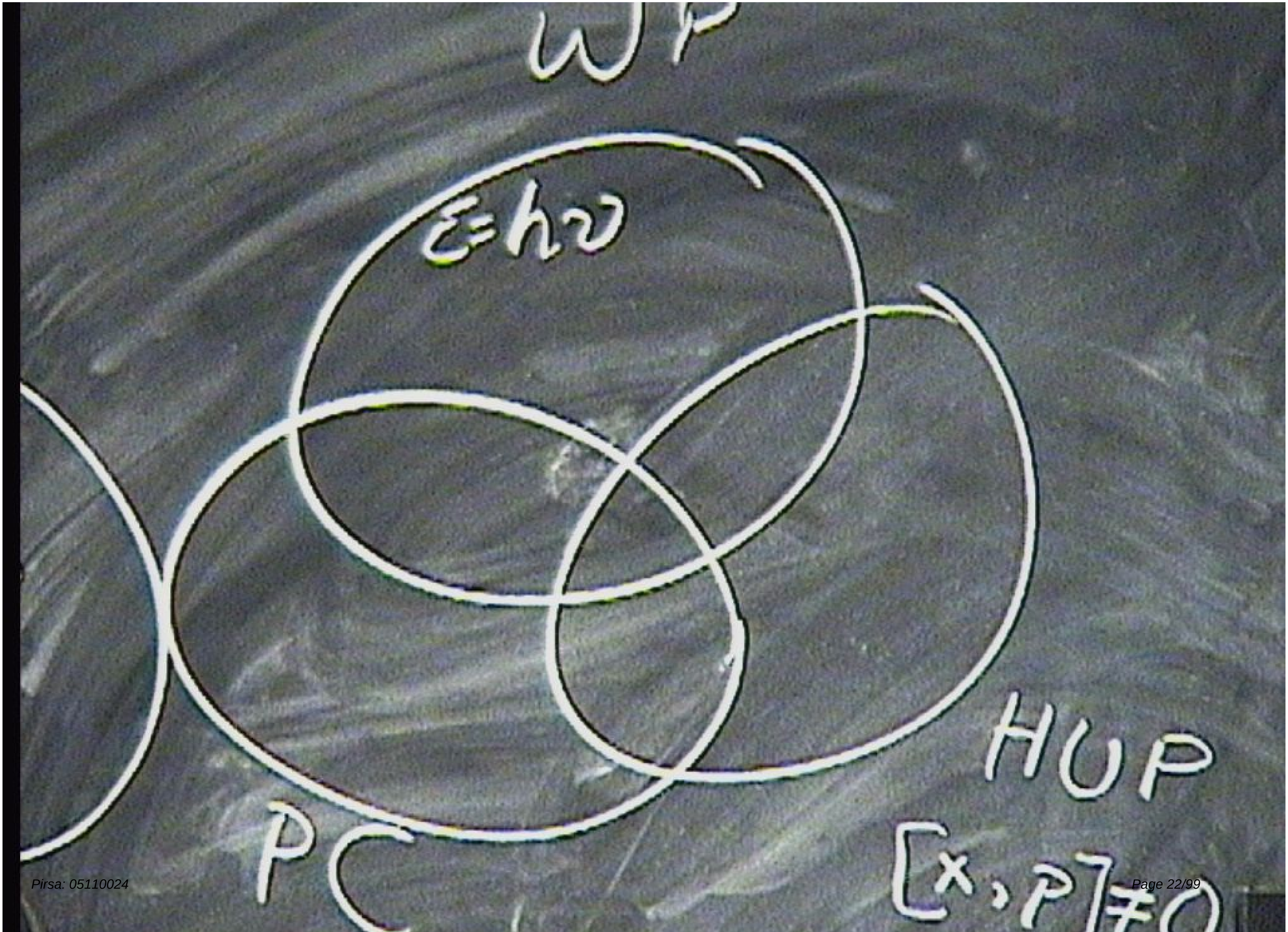
WP
E=hν
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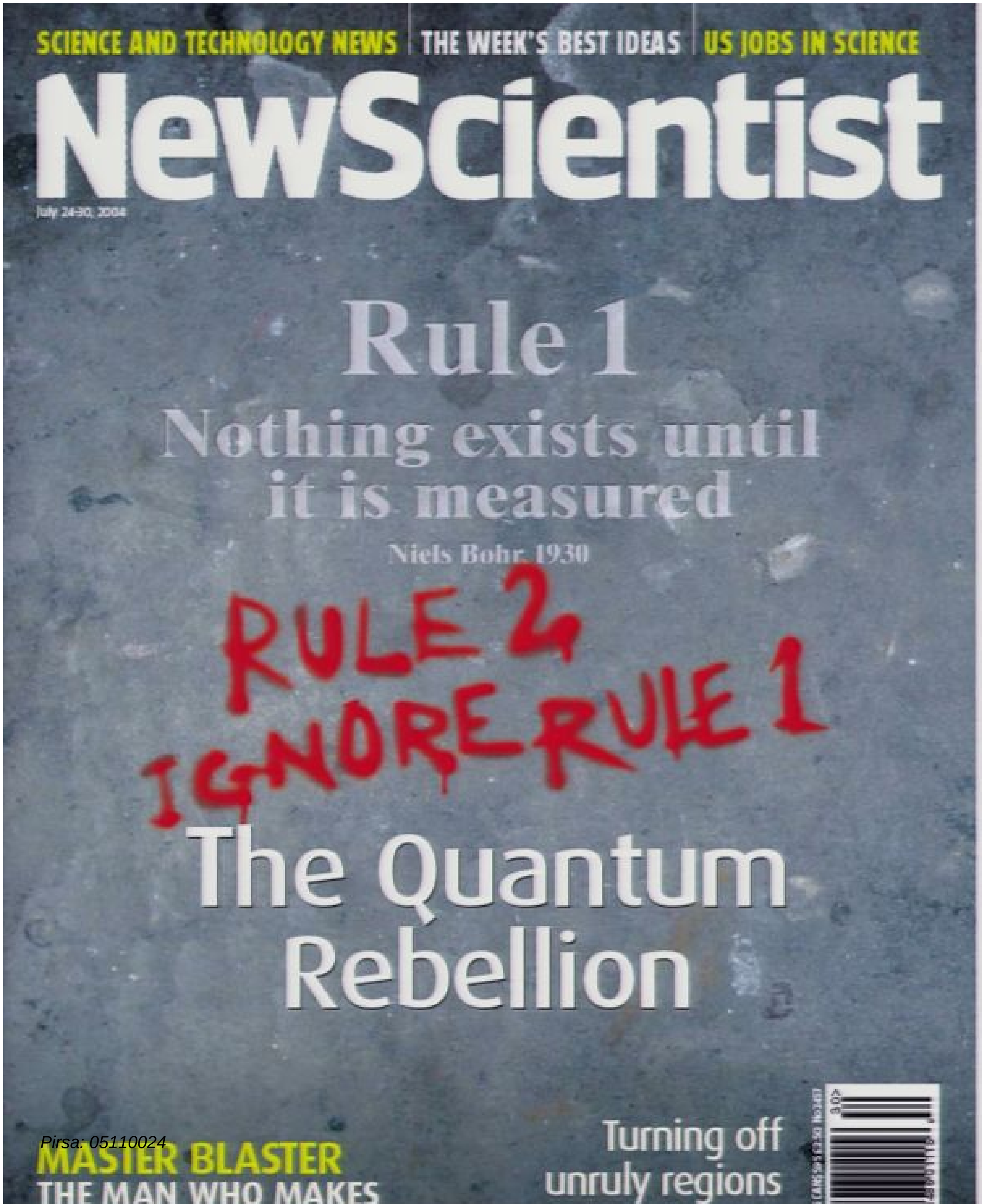
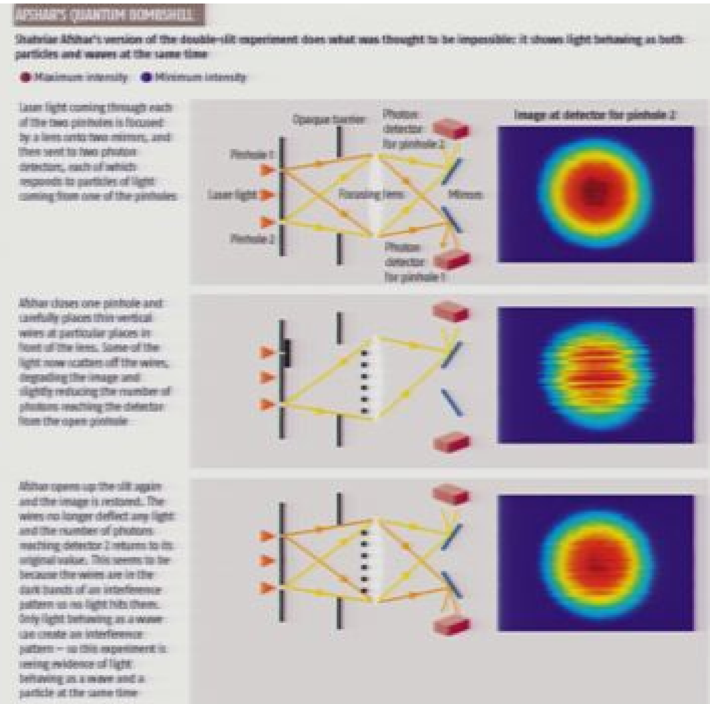
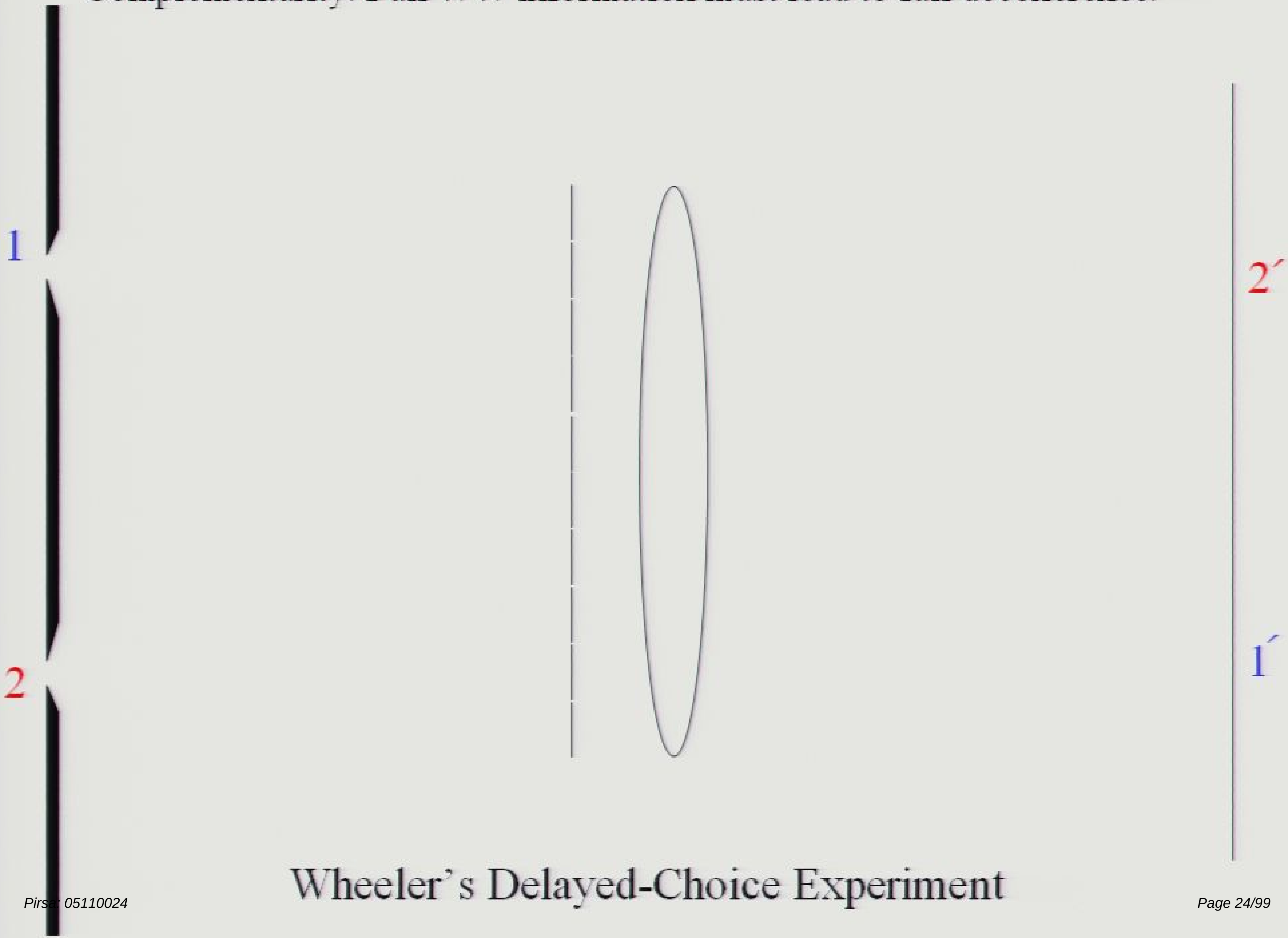
[x,p]≠0
PC


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
MASTER BLASTER
THE MAN WHO MAKES
Turning off unruly regions


AFSHAR'S QUANTUM BOMBSHELL
Shahriar Afshar'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
Opaque barrier
Photon detector for pinhole 2
Image at detector for pinhole 2
Pinhole 1
Laser light
Focusing lens
Mirrors
Pinhole 2
Photon detector for pinhole 1
Afshar 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
Afshar 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 seeing evidence of light behaving as a wave and a particle at the same time

Complementarity: Full WW information must lead to full decoherence.



Wheeler's Delayed-Choice Experiment

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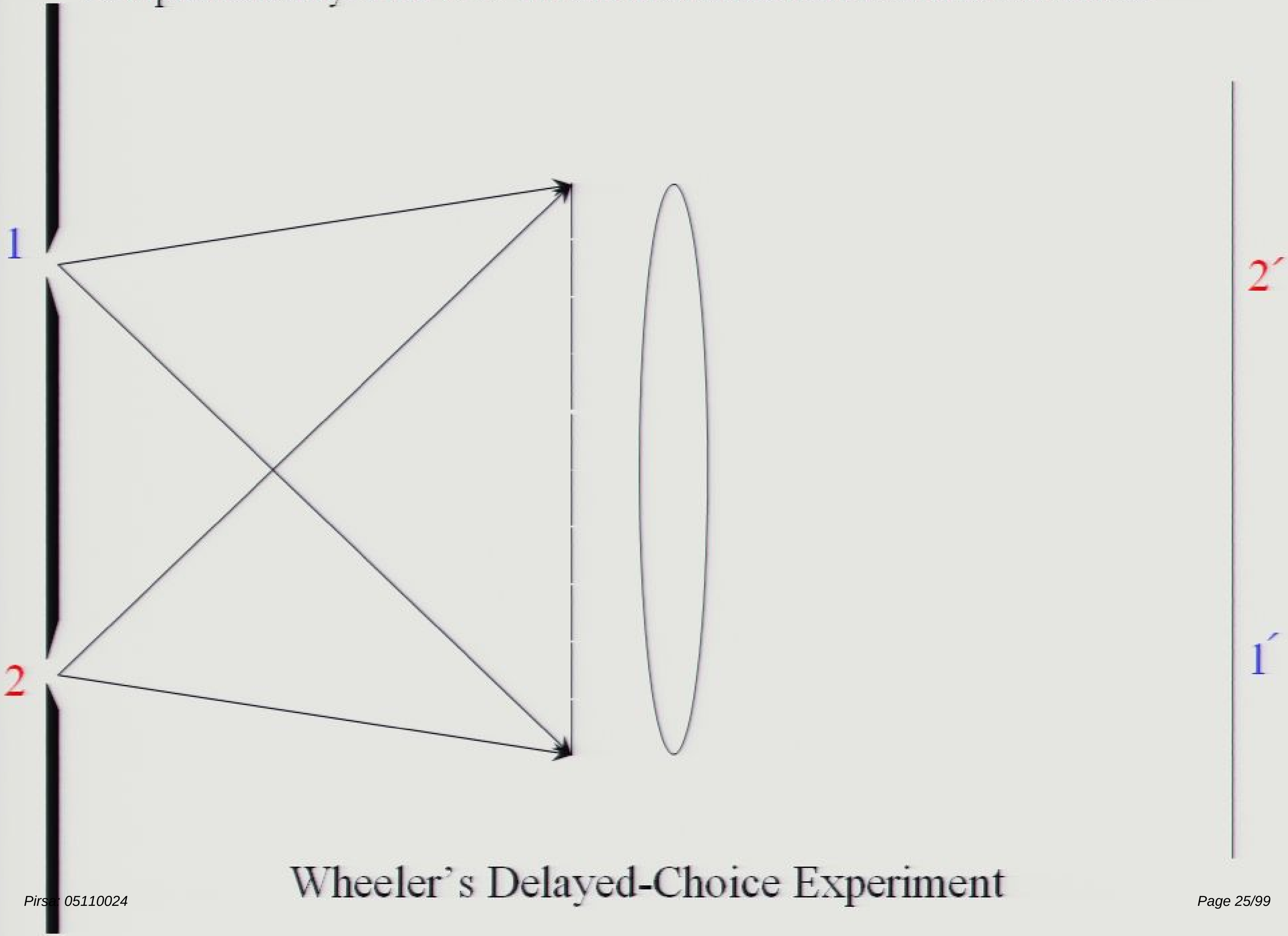

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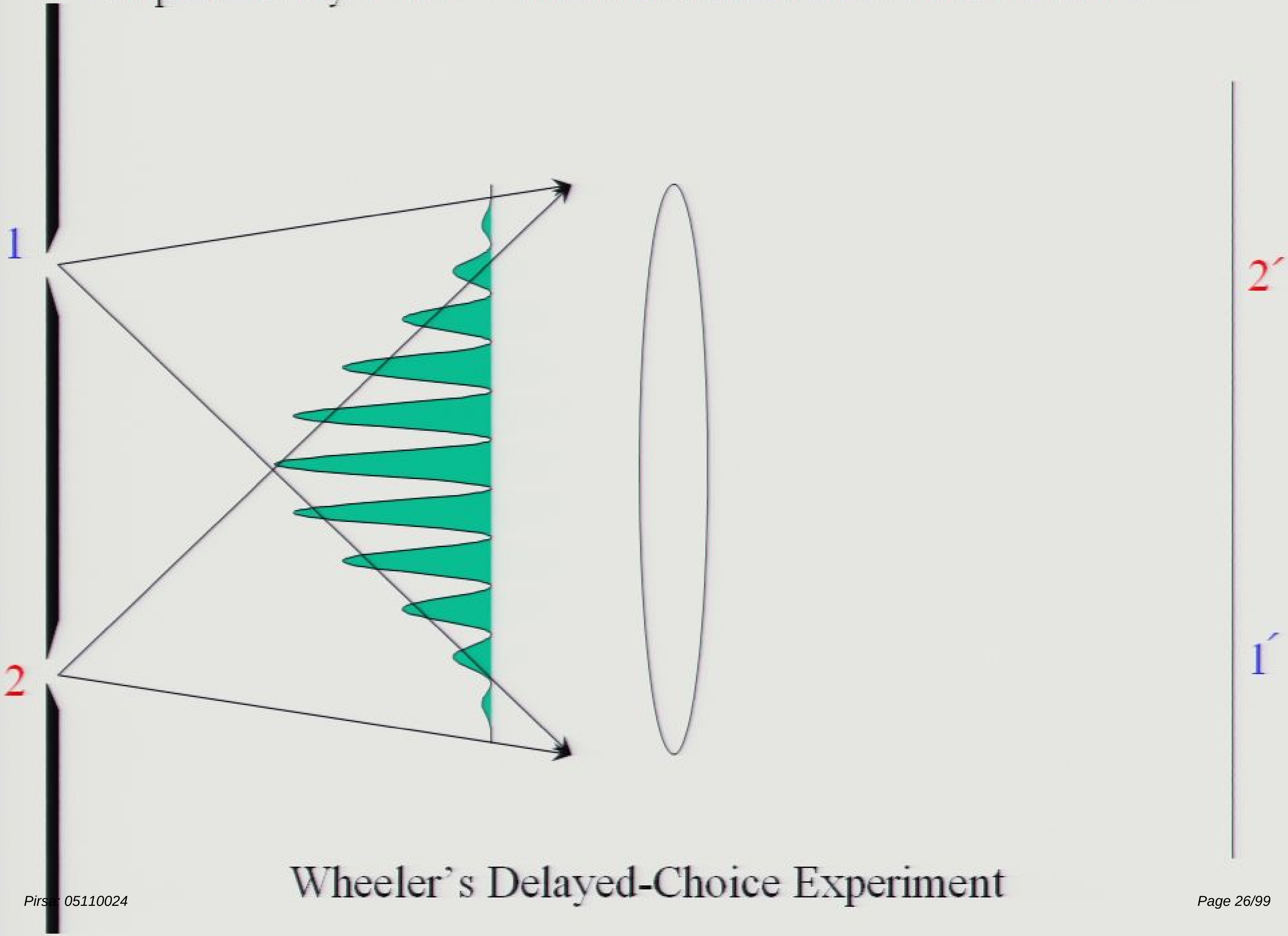

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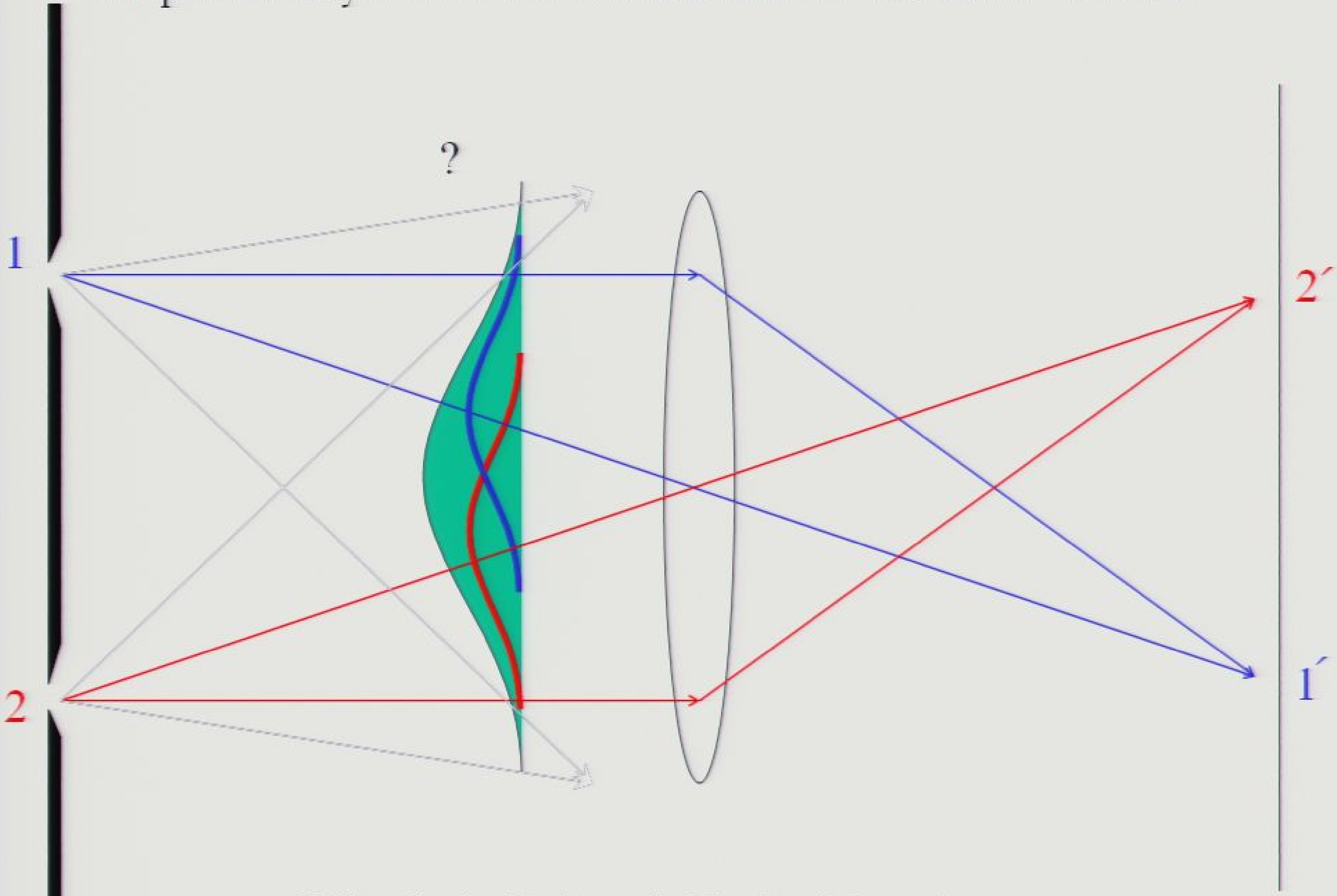
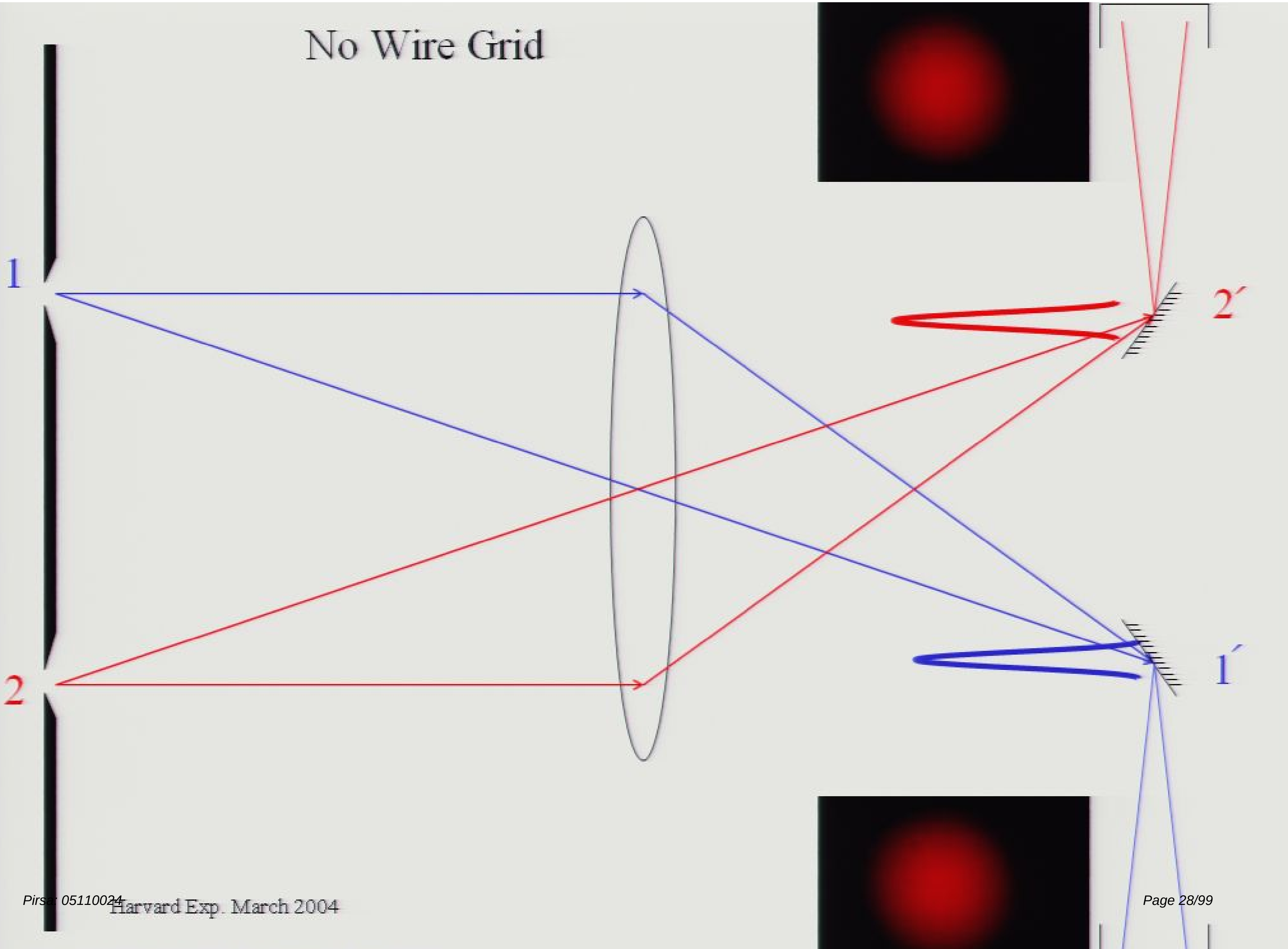


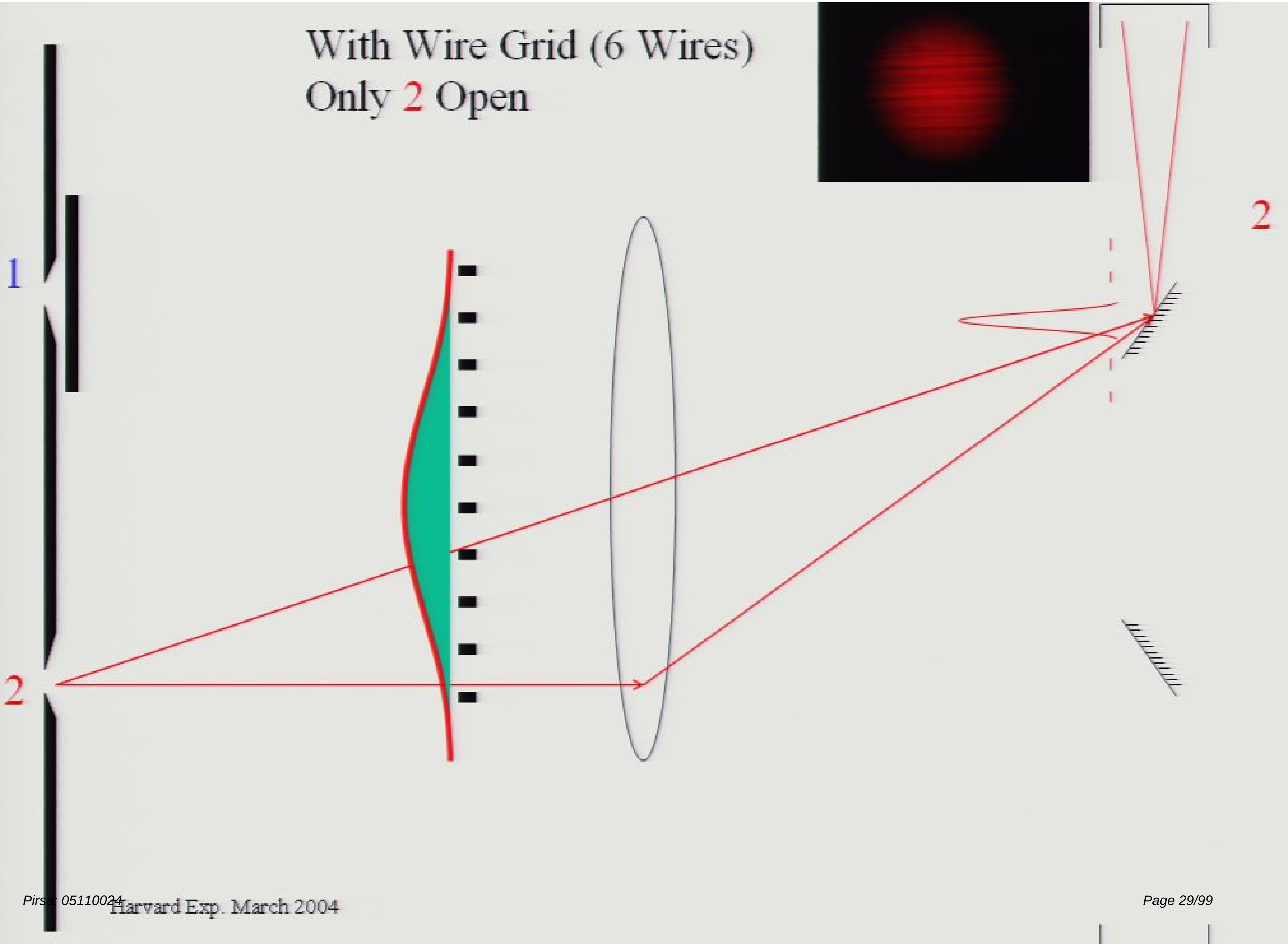
Wheeler's Delayed-Choice Experiment

No Wire Grid



Harvard Exp. March 2004

With Wire Grid (6 Wires)
Only 2 Open



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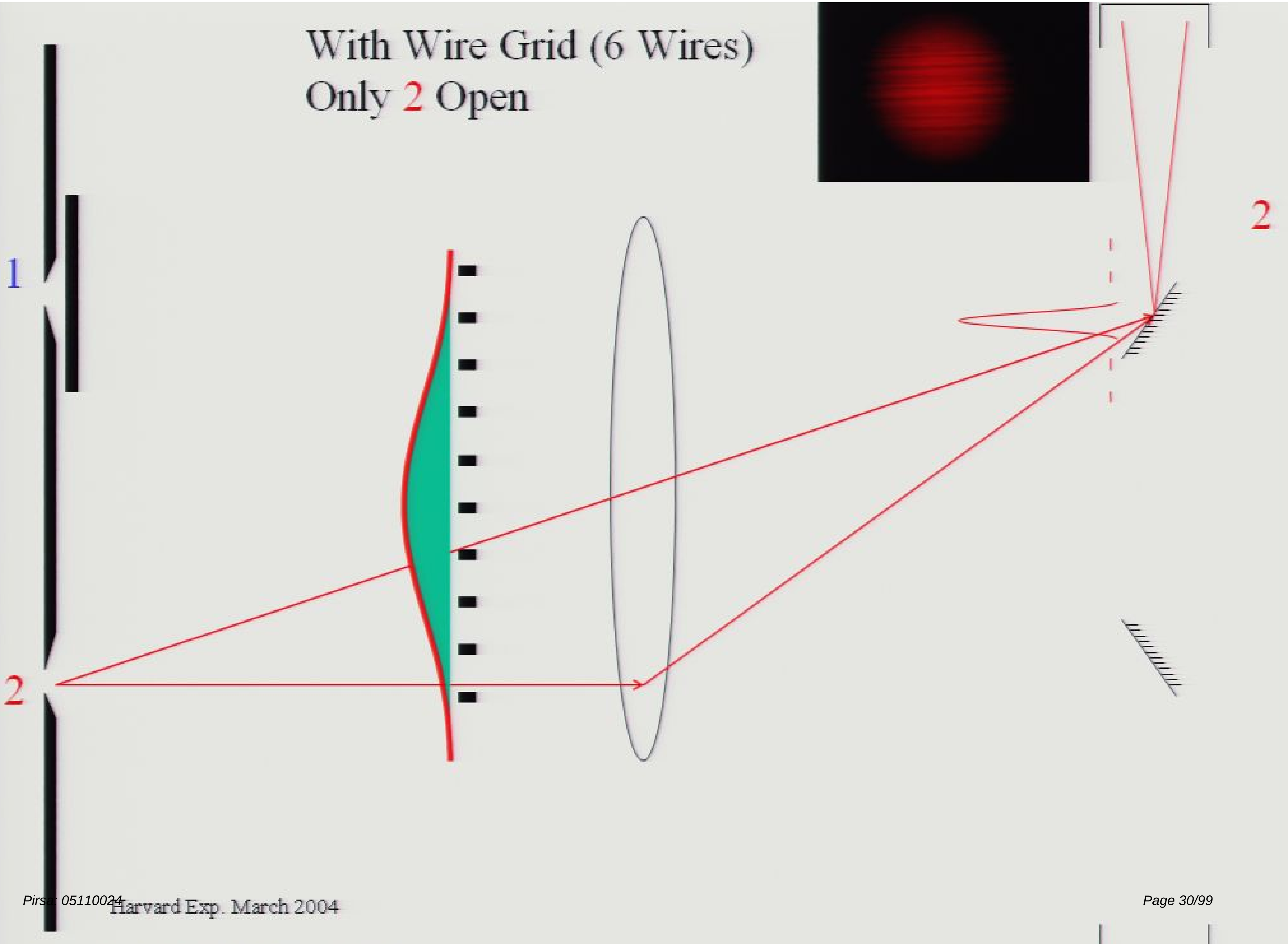

Harvard Exp. March 2004

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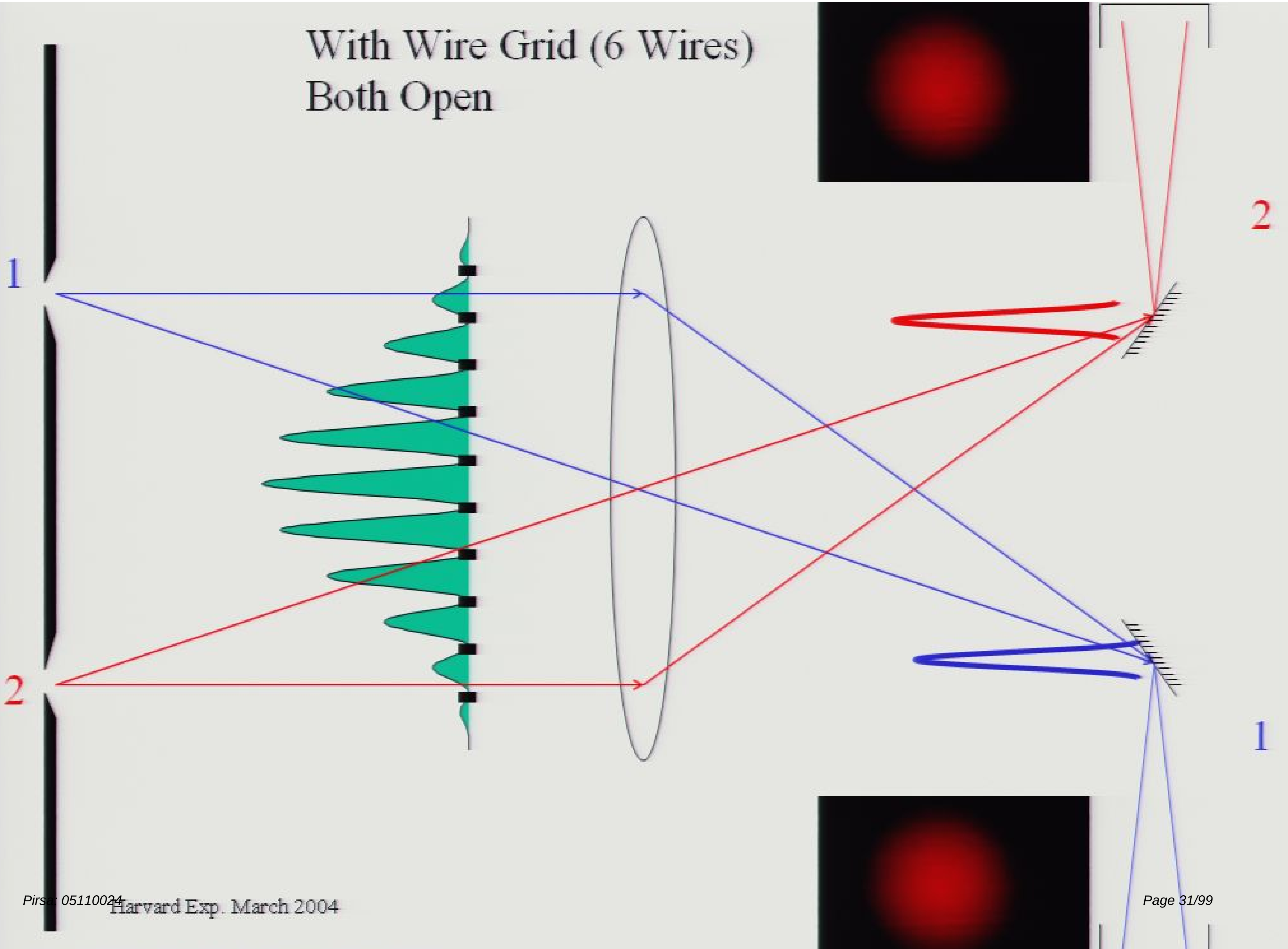
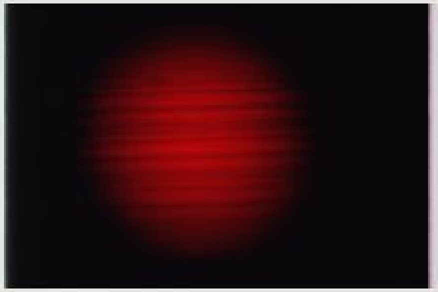


Harvard Exp. March 2004

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



With WG (6 Wires)
Only 2 Open

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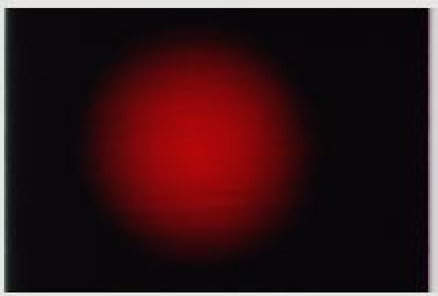
With WG (6 Wires)
Only 2 Open

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

Harvard Exp. March 2004

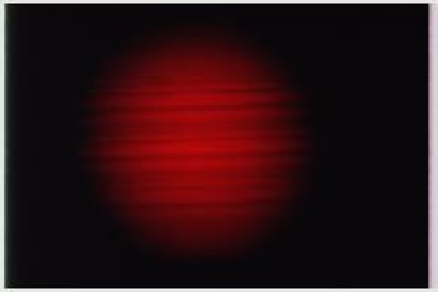
If Complementarity is correct, then we expect to observe when the Wire Grid is present and Both Pinholes are Open

But we observe

And ideally

With WG (6 Wires)
Both Open

No WG (Control)

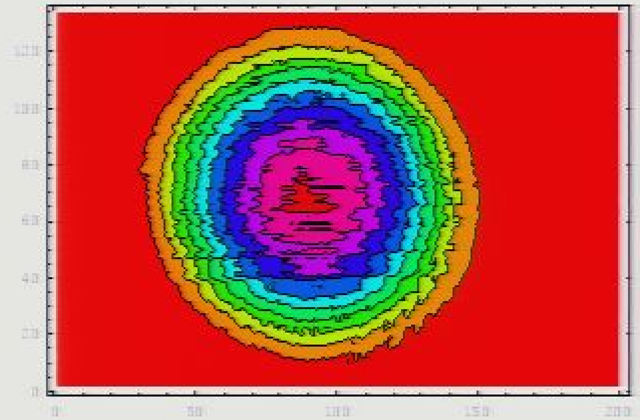


With WG (6 Wires)
Only 2 Open

Harvard Exp. March 2004

$\int\int P_2\, dA\, dt$ | Throughput Ratio relative to Control

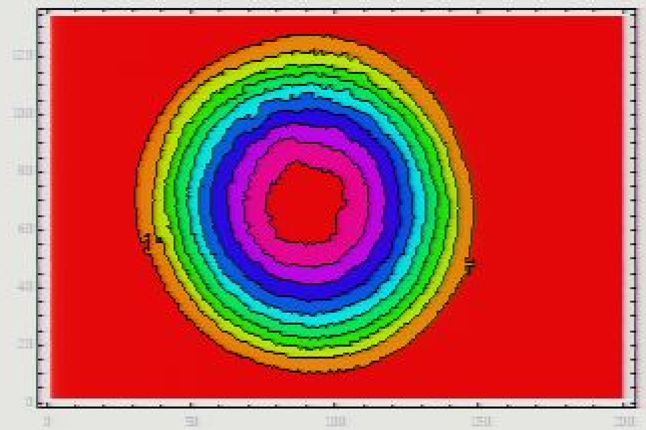
Wires at minima, both open



1010643

100.1% ± 0.5%

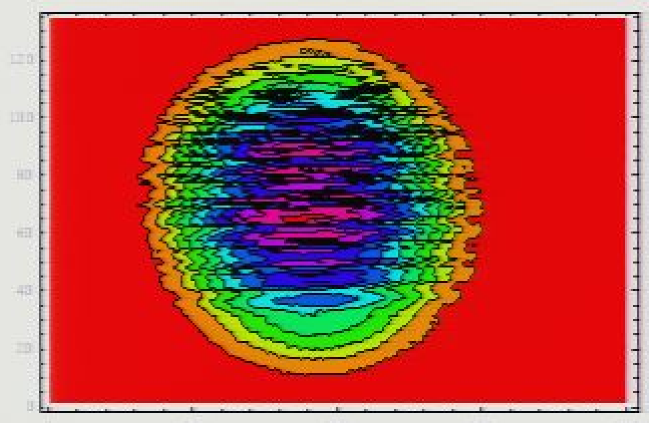
Control



1009851

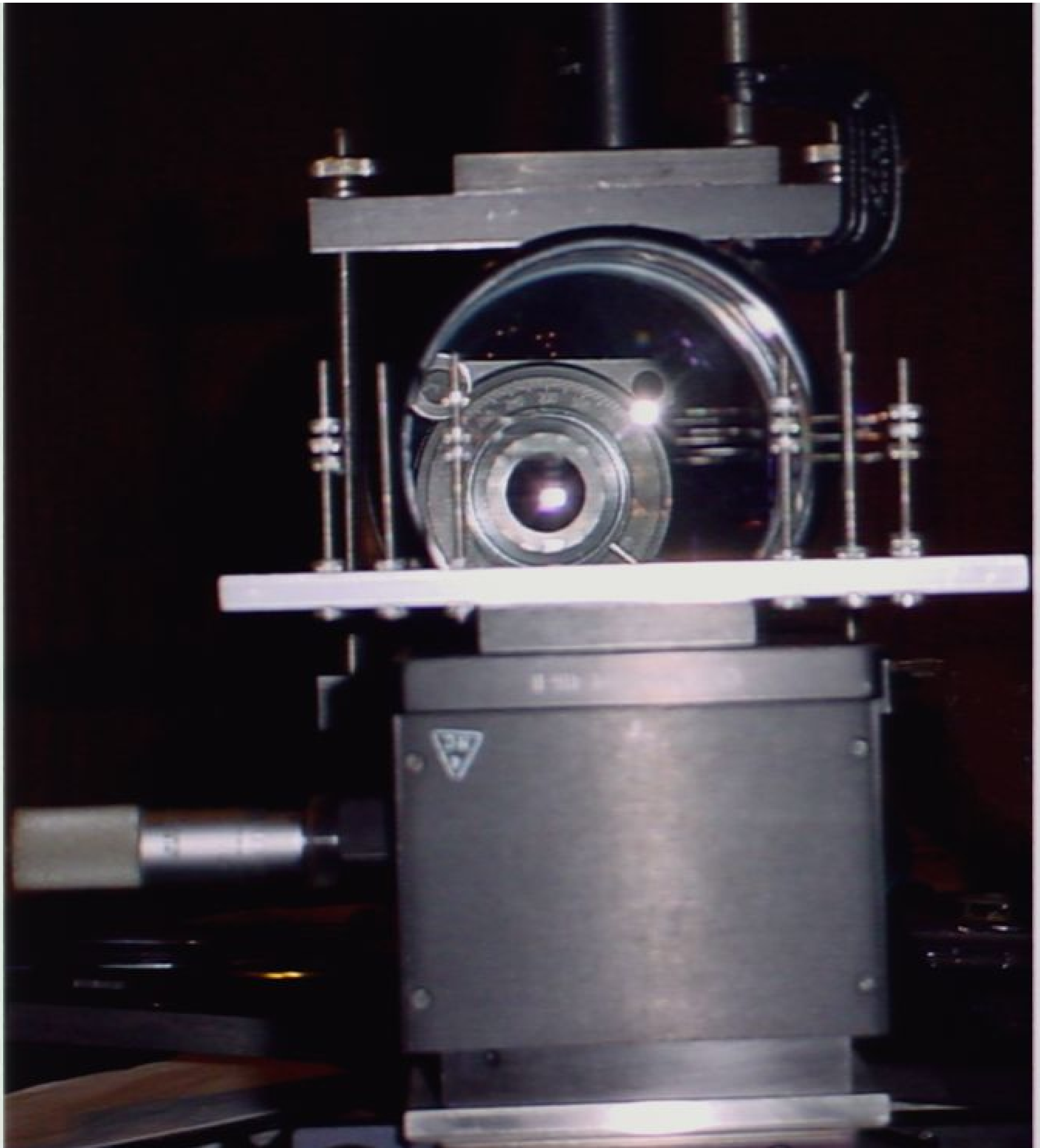
100%

Wires at minima, one open

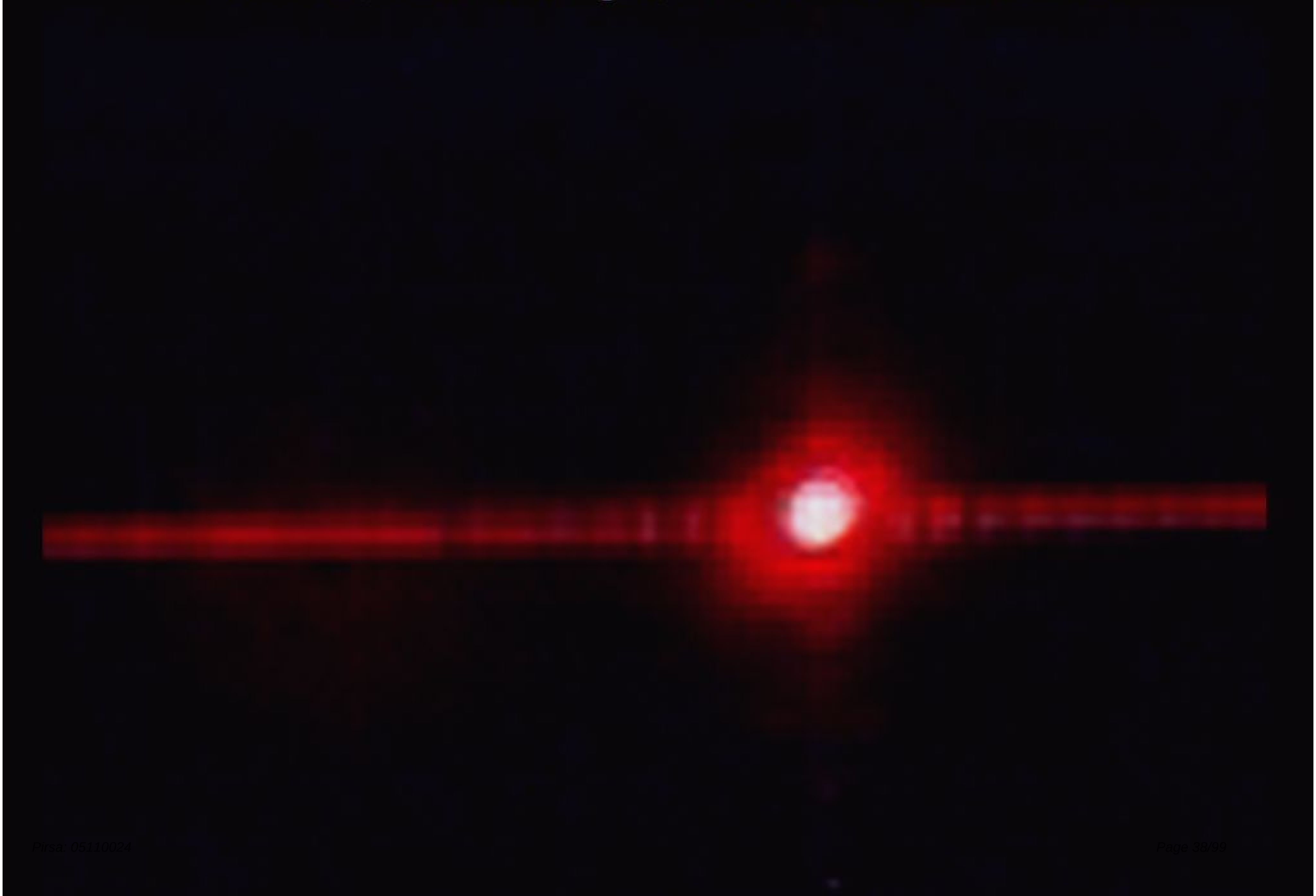


942724

93.4% ± 0.5%



One Closed, then Both Open, Wire at Central Maximum



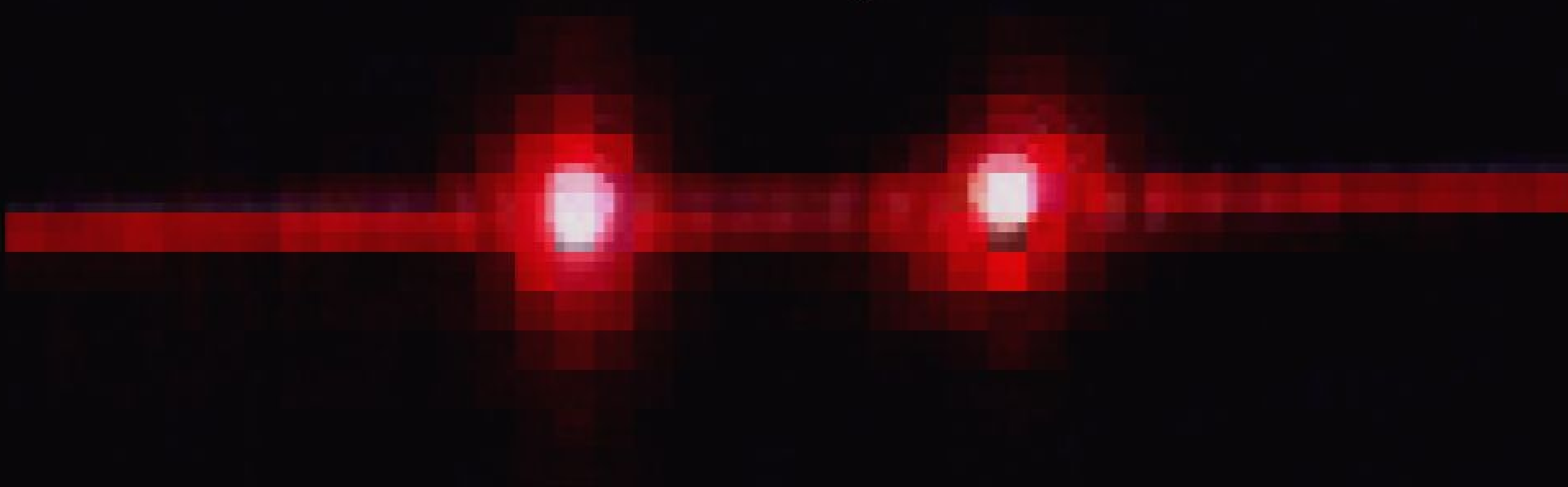
One Closed, then Both Open, Wire at Central Maximum

One Closed, then Both Open, Wire at Central Maximum

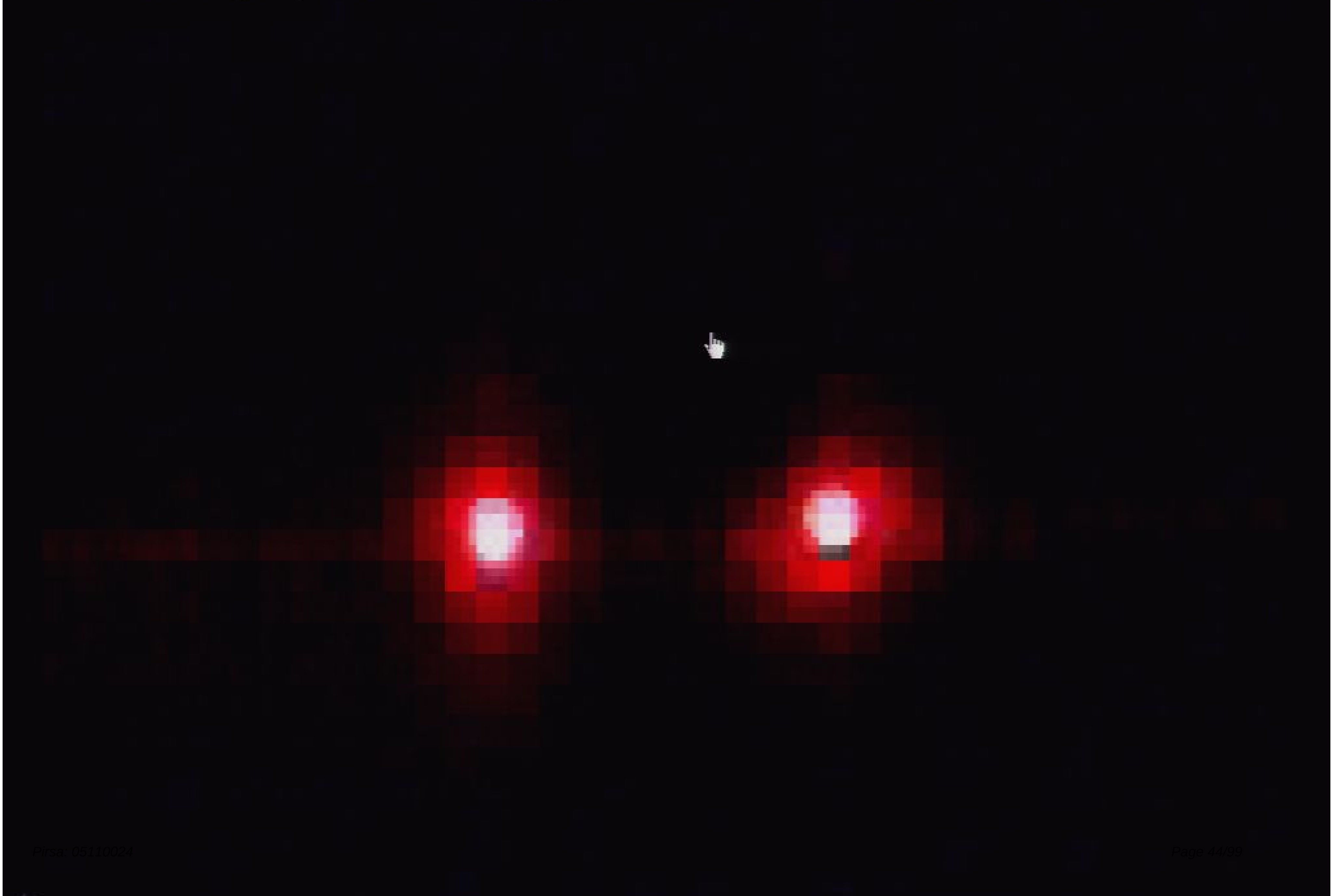
One Closed, then Both Open, Wire at Central Maximum

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



Both Open, Wire Moving from Central Minimum to Maximum

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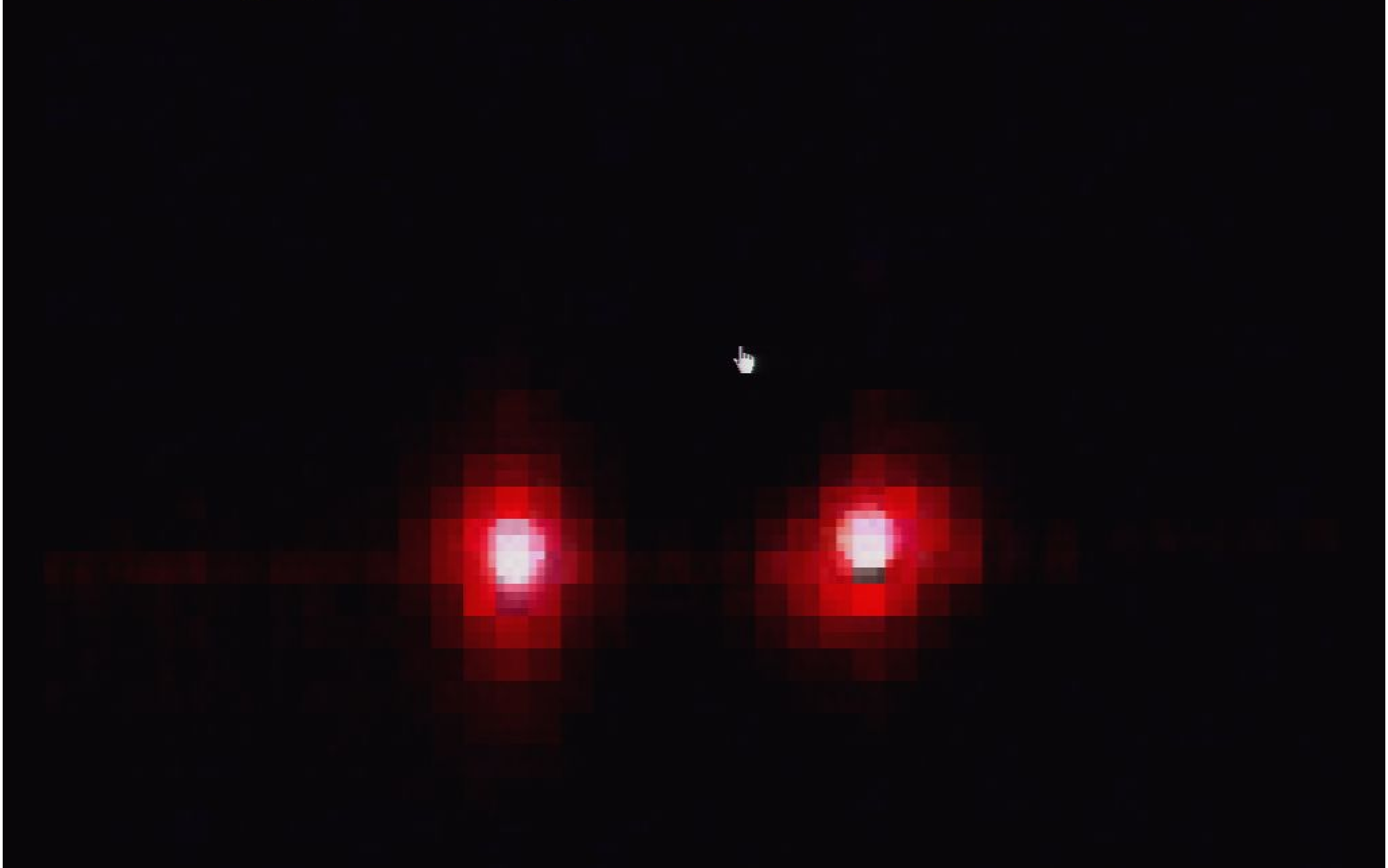
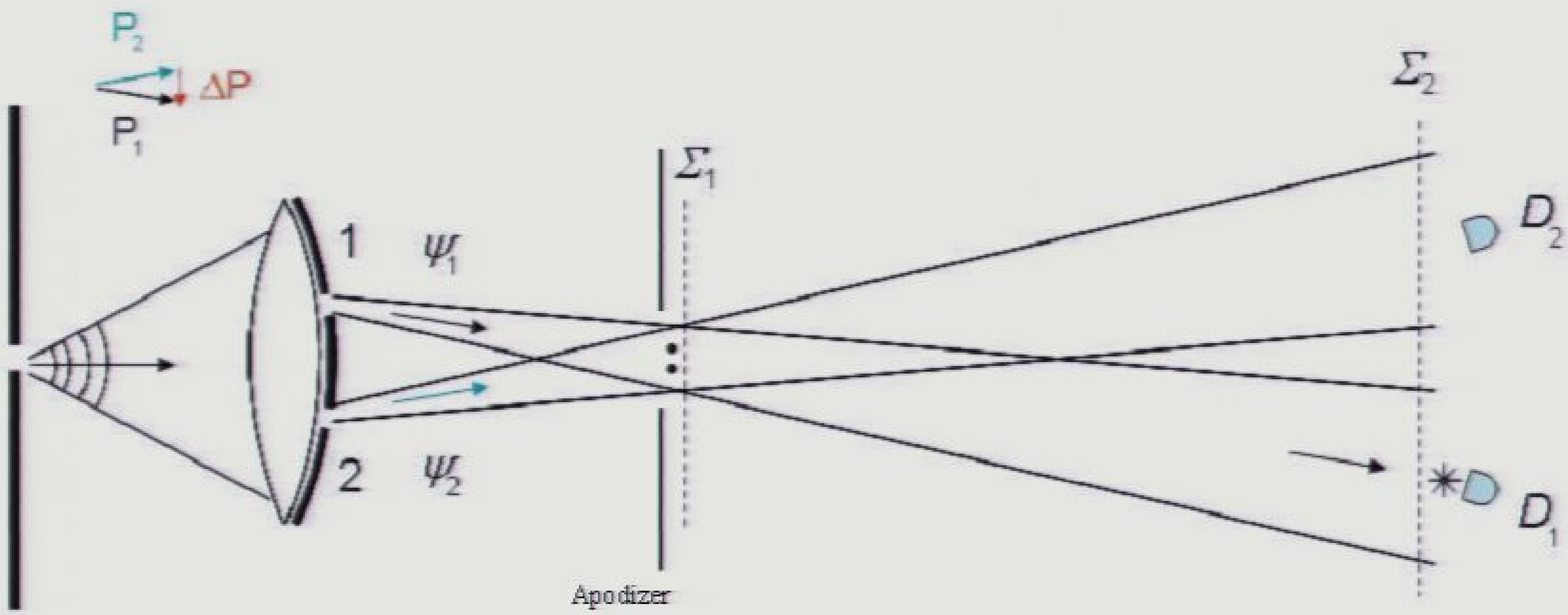


Both Open, then One Open, Wire at Central Minimum

Both Open, then One Open, Wire at Central Minimum

Both Open, then One Open, Wire at Central Minimum

Experiment without the imaging lens.



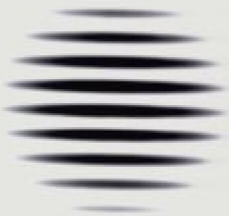
Rowan Exp. May 2005

AIP Conf. Proc. **810**, 2006

Quantitative Definition of Complementarity in "Which-Way" Experiments.

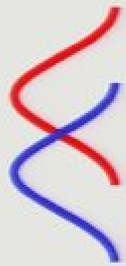
In the past 25 years a quantitative version of the PC has emerged, in which the Visibility of the interference pattern (V) and reliability of Which-Way Information (K) has the following form:

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



where

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



and

$$K_1 = (I_1 - I_2) / (I_1 + I_2) \quad (3)$$

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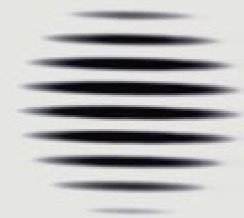

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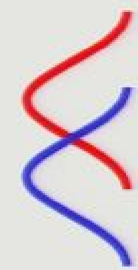

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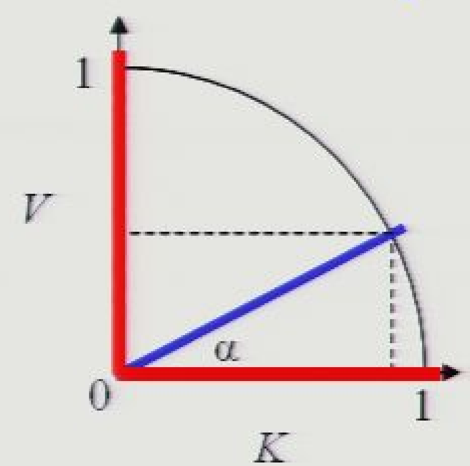
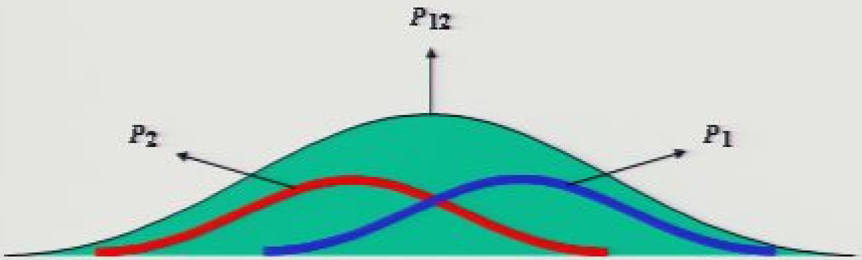


It is clear that $0 \leq V \leq 1$ and $0 \leq K \leq 1$ cannot both be equal to 1, and their relationship is exactly that of the Sin and Cos of an angle $0 \leq \alpha \leq \pi/2$

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

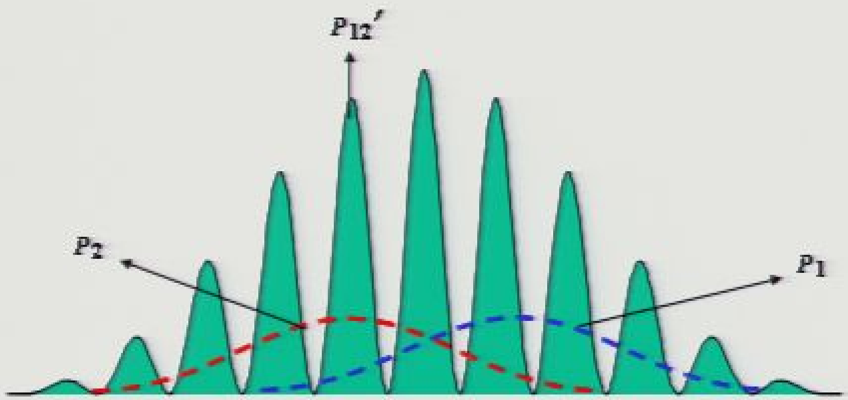
So, to be safe, we must choose the extreme cases i.e. $\alpha = 0$ and $\alpha = \pi/2$.

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



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

In the Interference plane we have:



$$P_1 = |\psi_1|^2,$$
$$P_2 = |\psi_2|^2,$$
$$P_{12}' = |\psi_1 + \psi_2|^2 = P_1 + P_2 + 2\sqrt{P_1 P_2}\, \mathrm{Cos}\,\delta,$$
$$\Gamma = 2\sqrt{P_1 P_2}\, \mathrm{Cos}\,\delta,$$
$$\therefore\ P_{12}' \neq P_1 + P_2$$
$$\int\int P_{12}'\, dx\, dt = \int\int (P_1 + P_2 + \Gamma)\, dx\, dt$$

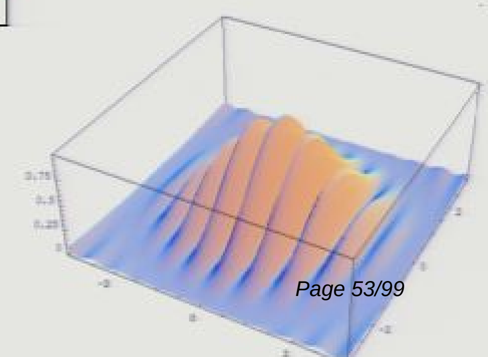
Remarkably, although $P_{12}' \neq P_{12}$,

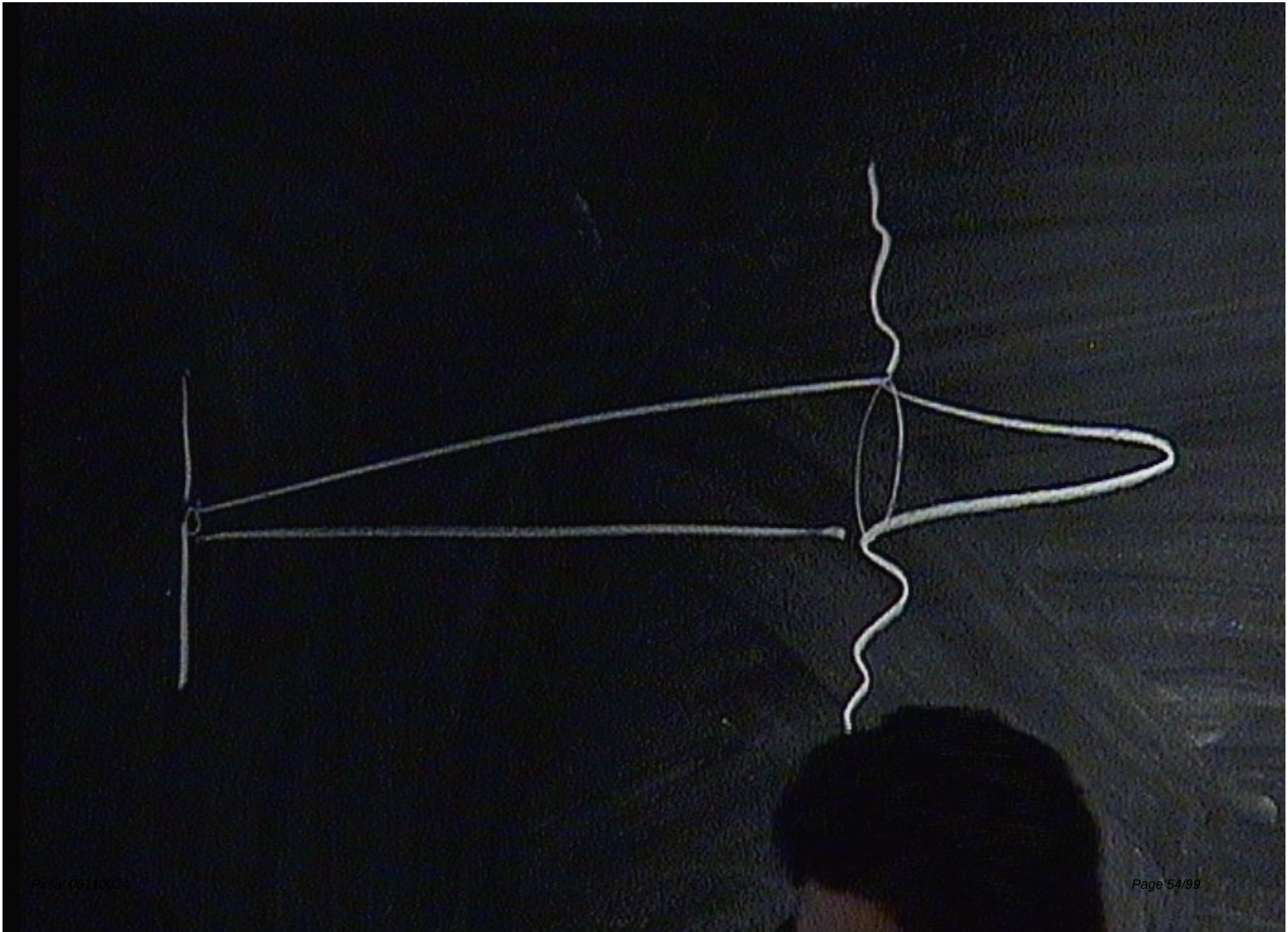
however, due to the boundary conditions we have:

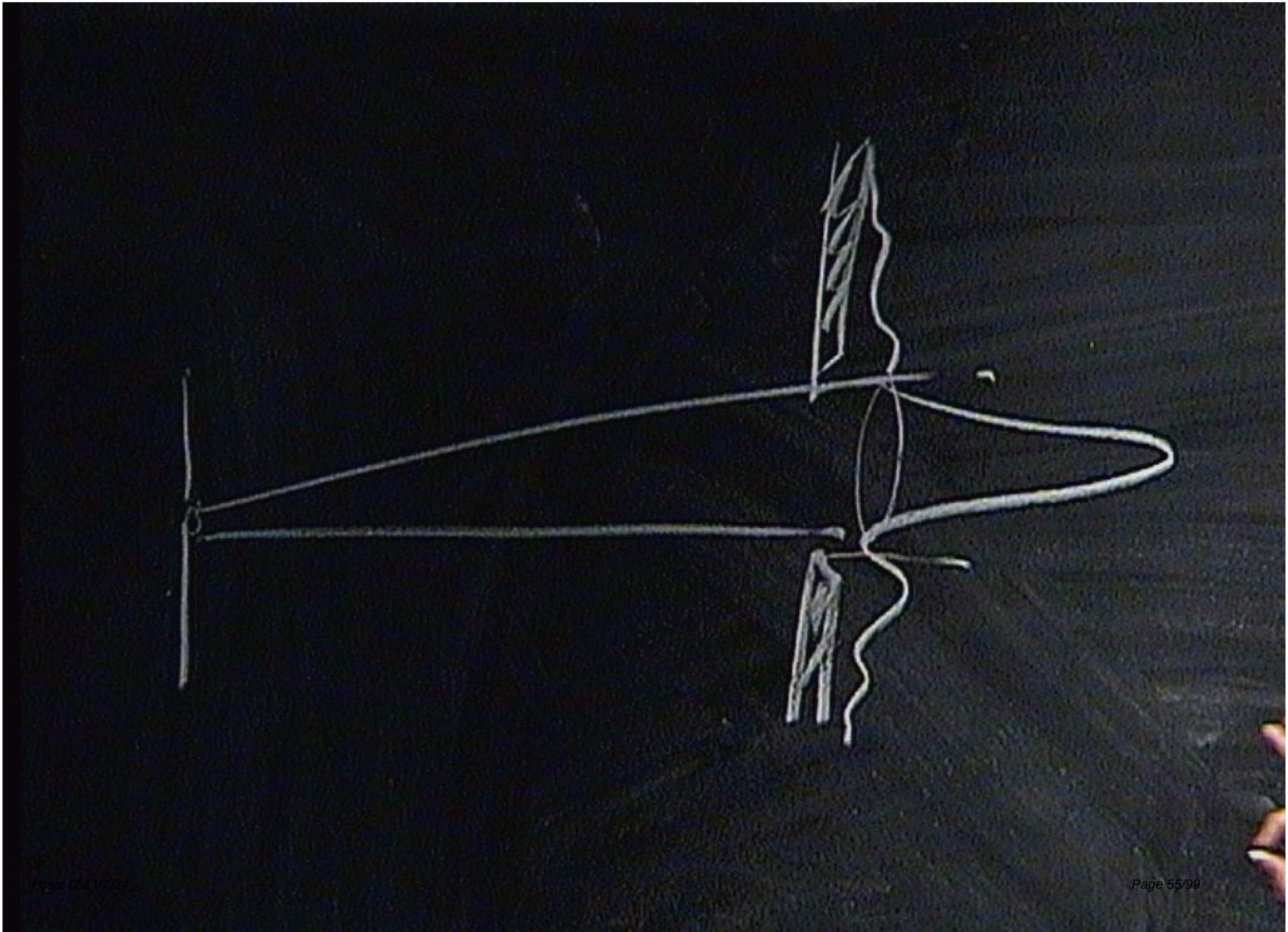
$$\int\int P_{12}'\, dx\, dt = \int\int P_{12}\, dx\, dt$$

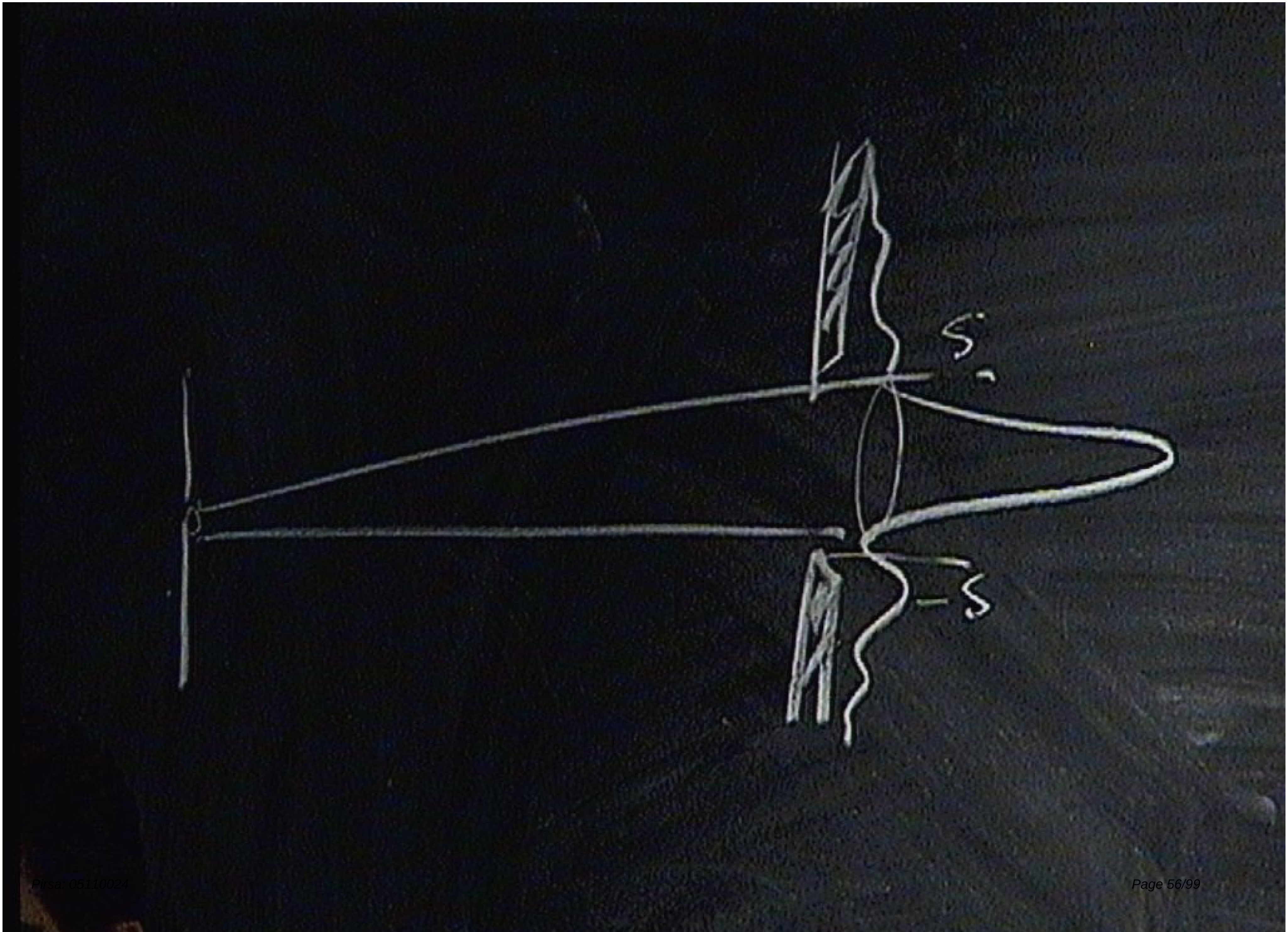
Which can be generalized for the 2D case of our experiment to:

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



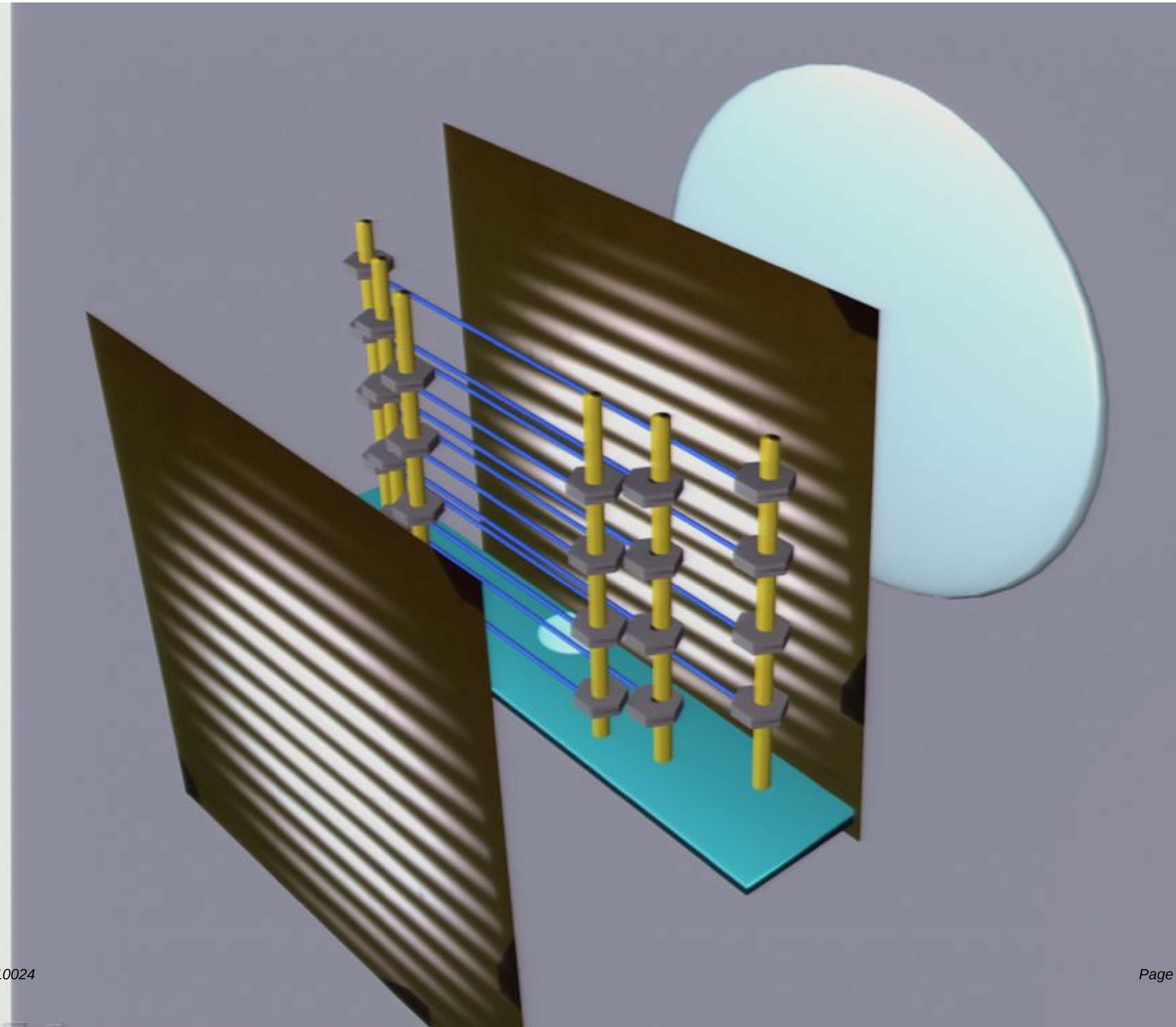




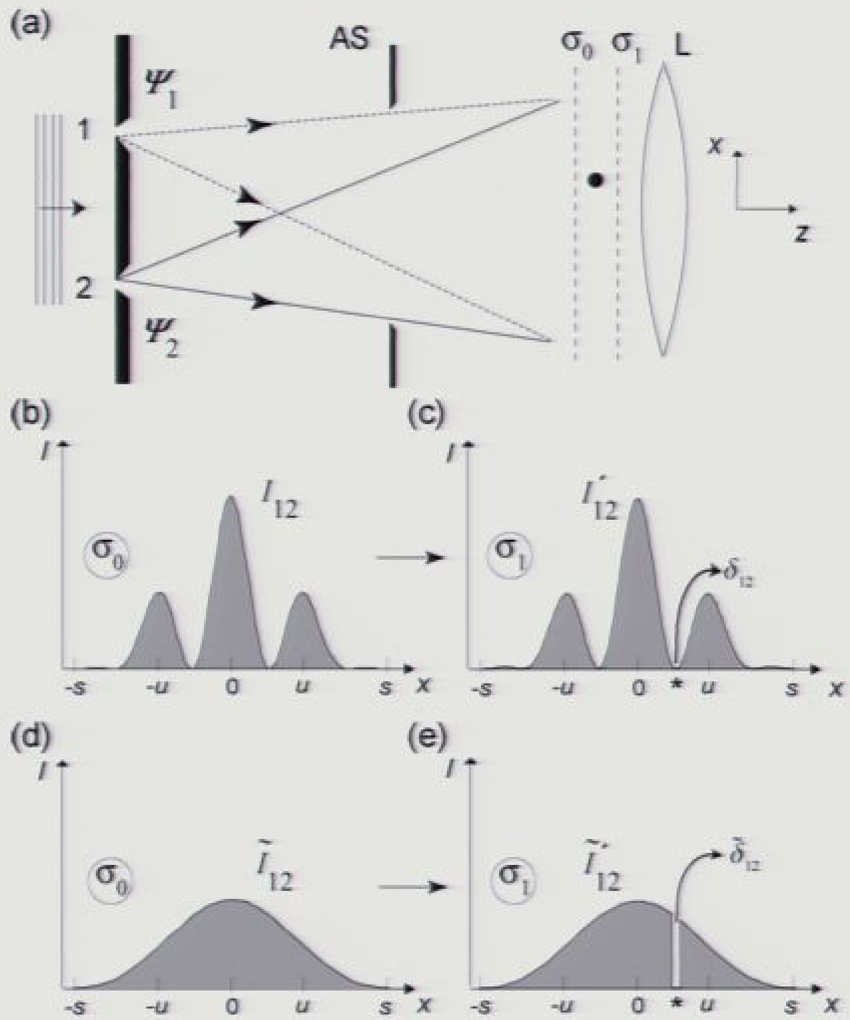


Where did Bohr go wrong?: Measurement without a "measurement"

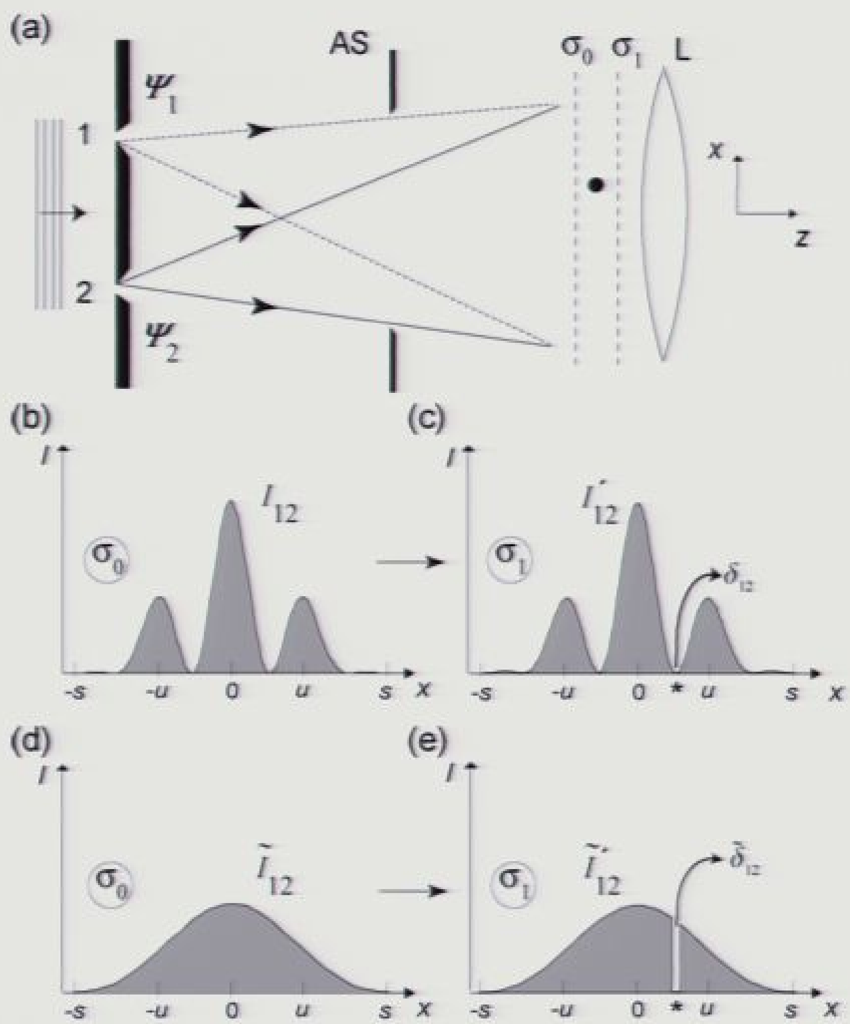
The measurement theory of ensemble properties (e.g. coherence) needs an upgrade!

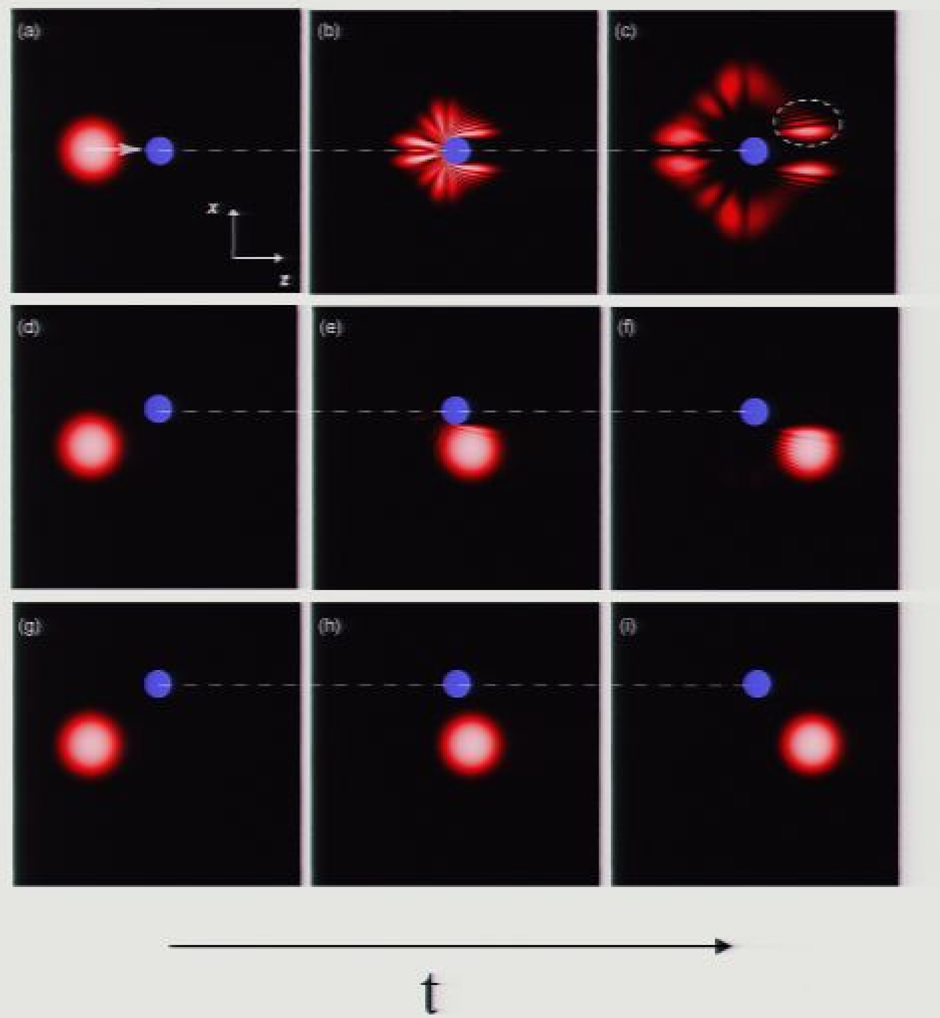


Difference Between Coherent and "Decoherent" porb. distributions.



Difference Between Coherent and “Decoherent” porb. distributions.





Introducing: *Contextual Null Measurement* (CNM)

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

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

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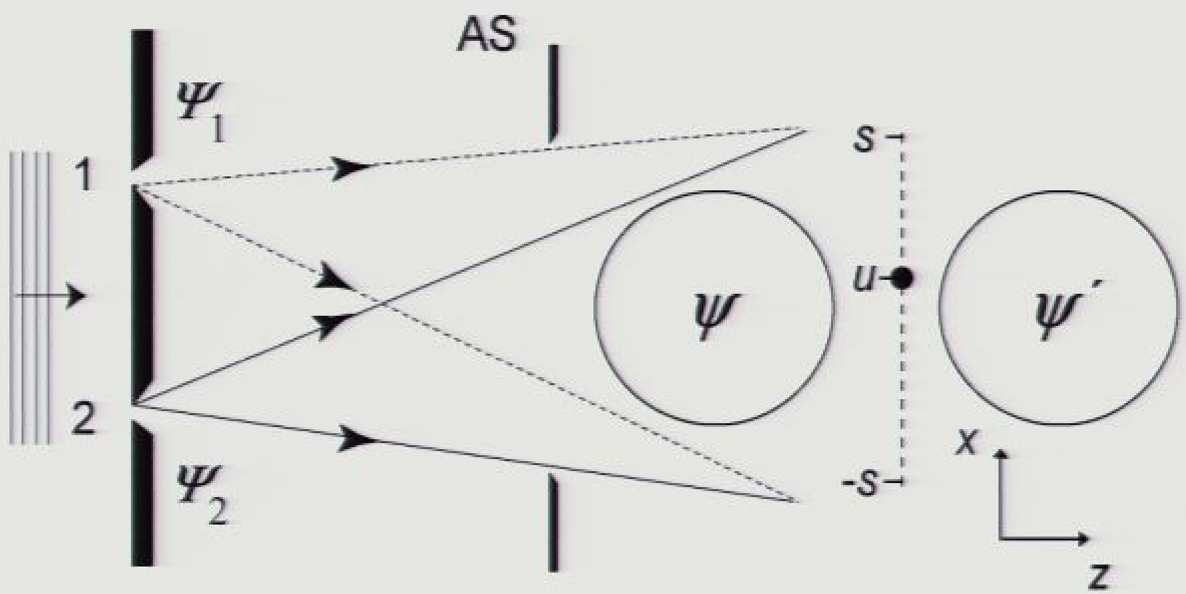

1) $\|\psi\|^2 = \|\psi'\|^2 \neq 0 \Rightarrow \delta = \int_{x_1}^{x_2} |\psi|^2 dx = 0$

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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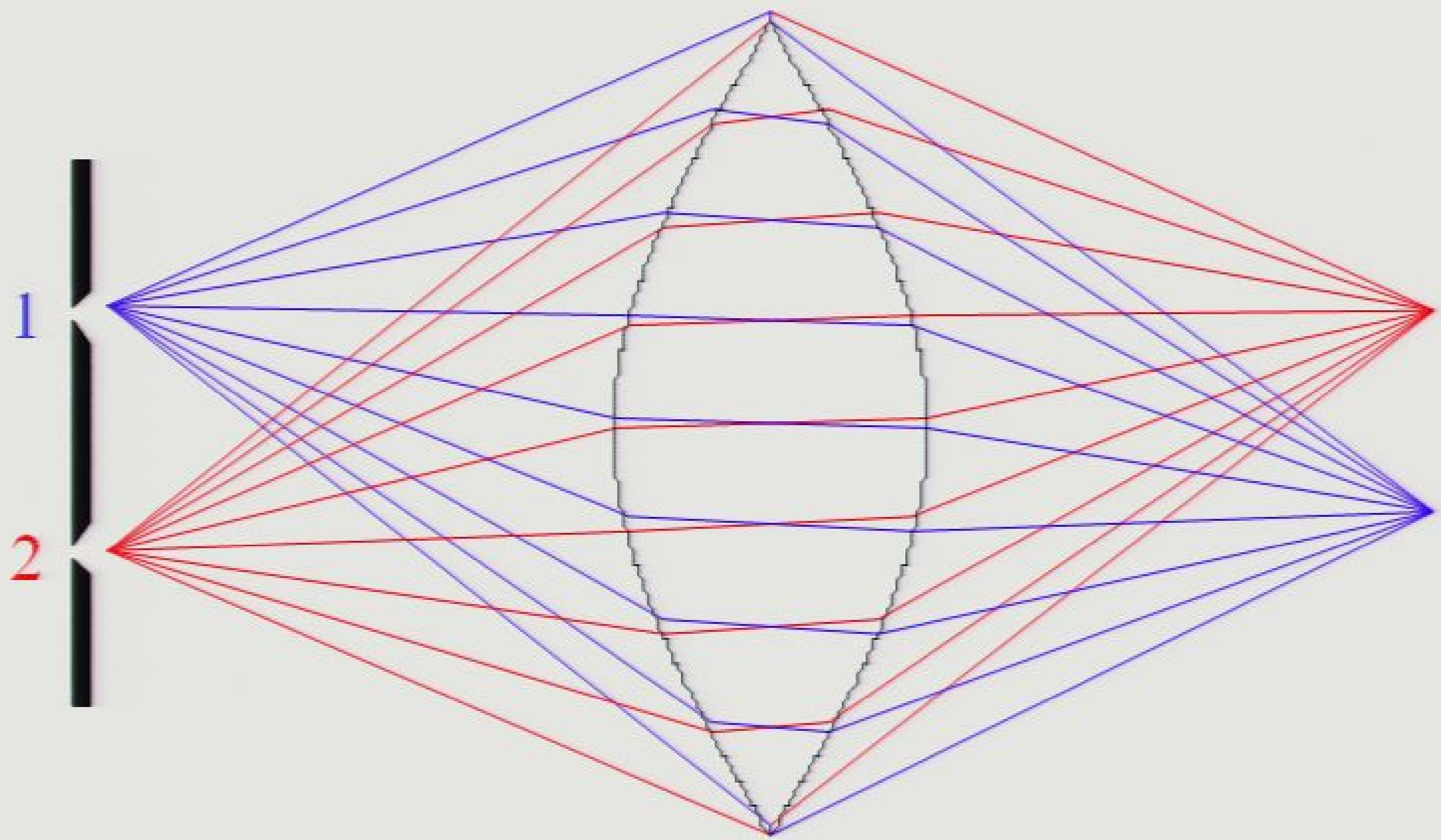
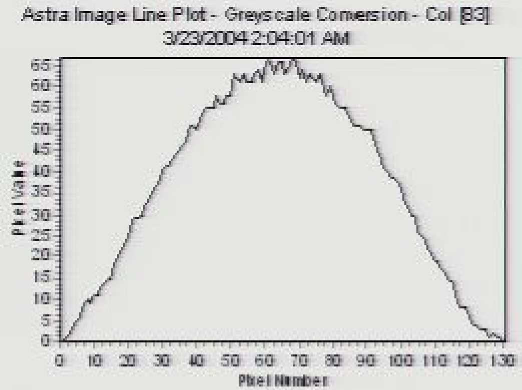
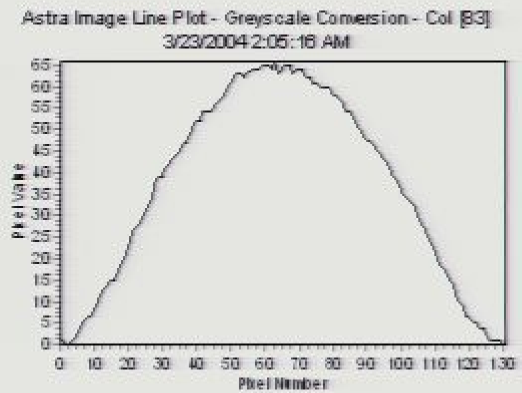


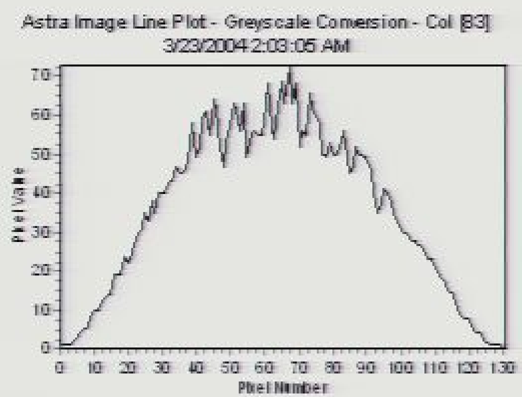
Some Results from Original Experiment at IRIMS



Wires at minima, both open

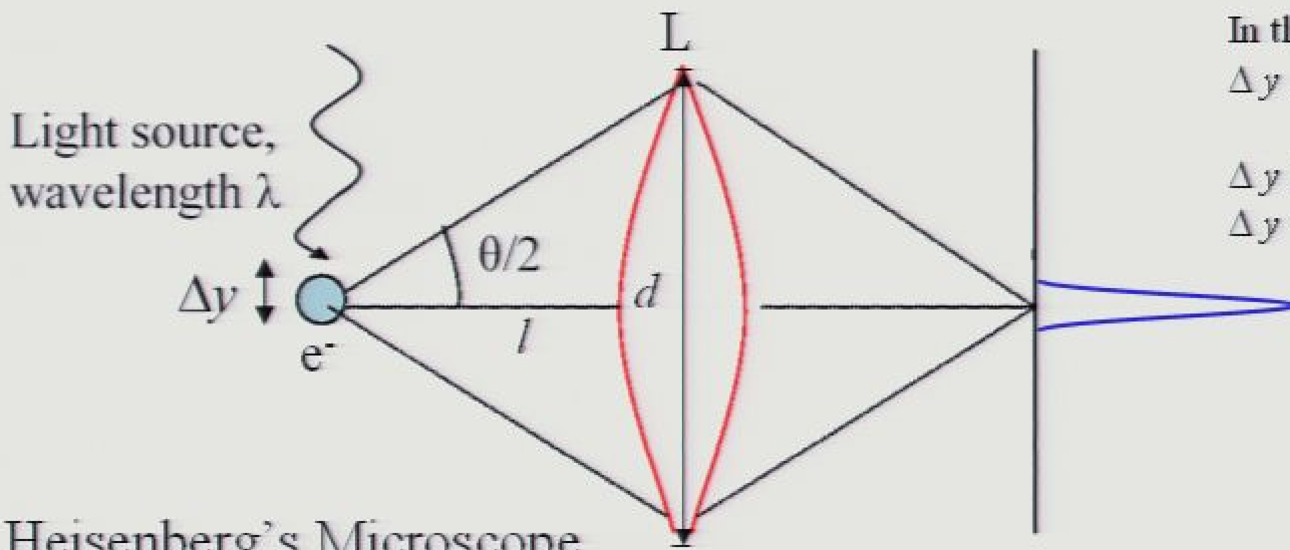


Control



Wires at minima, one open

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



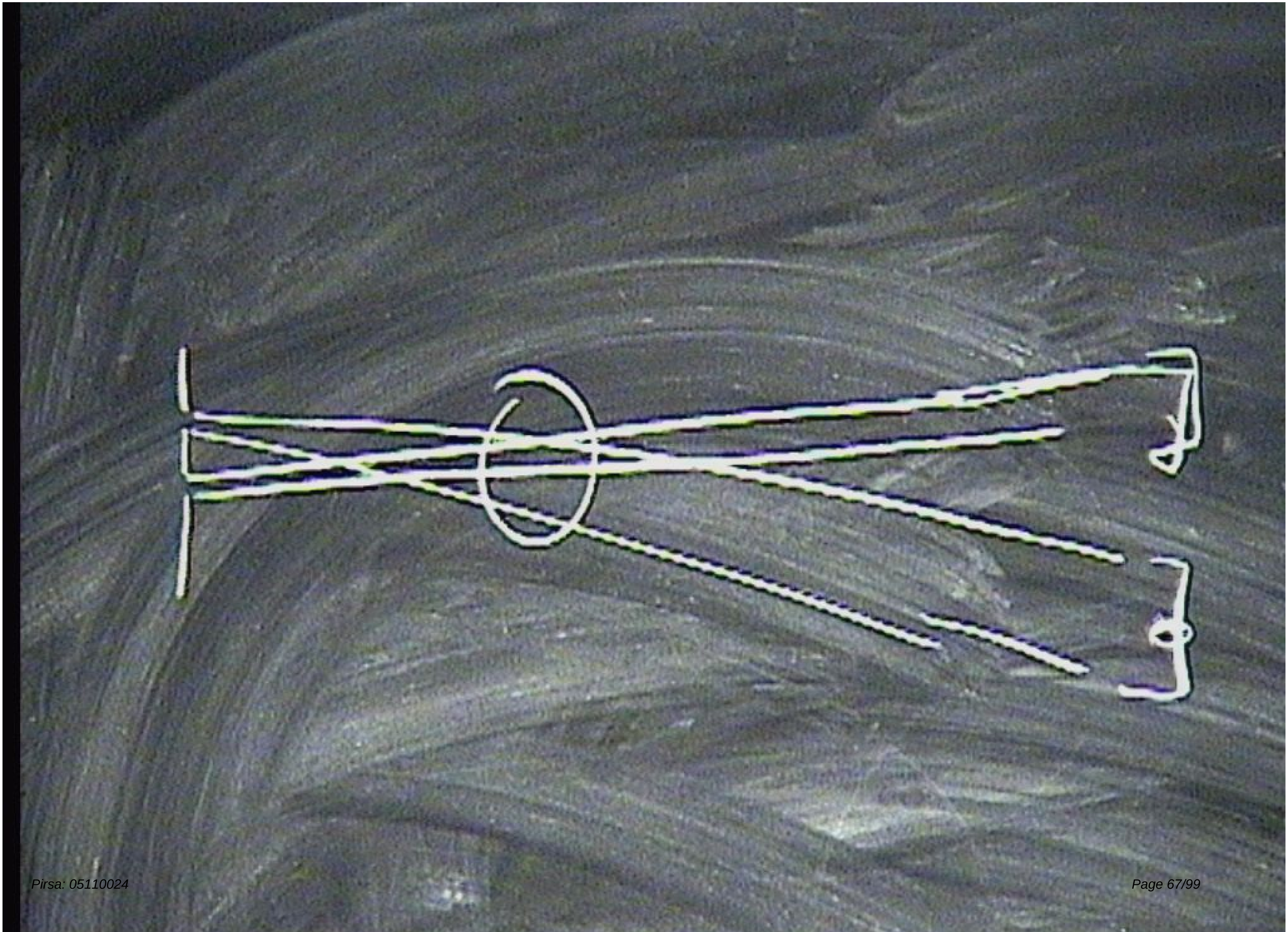
Heisenberg's Microscope

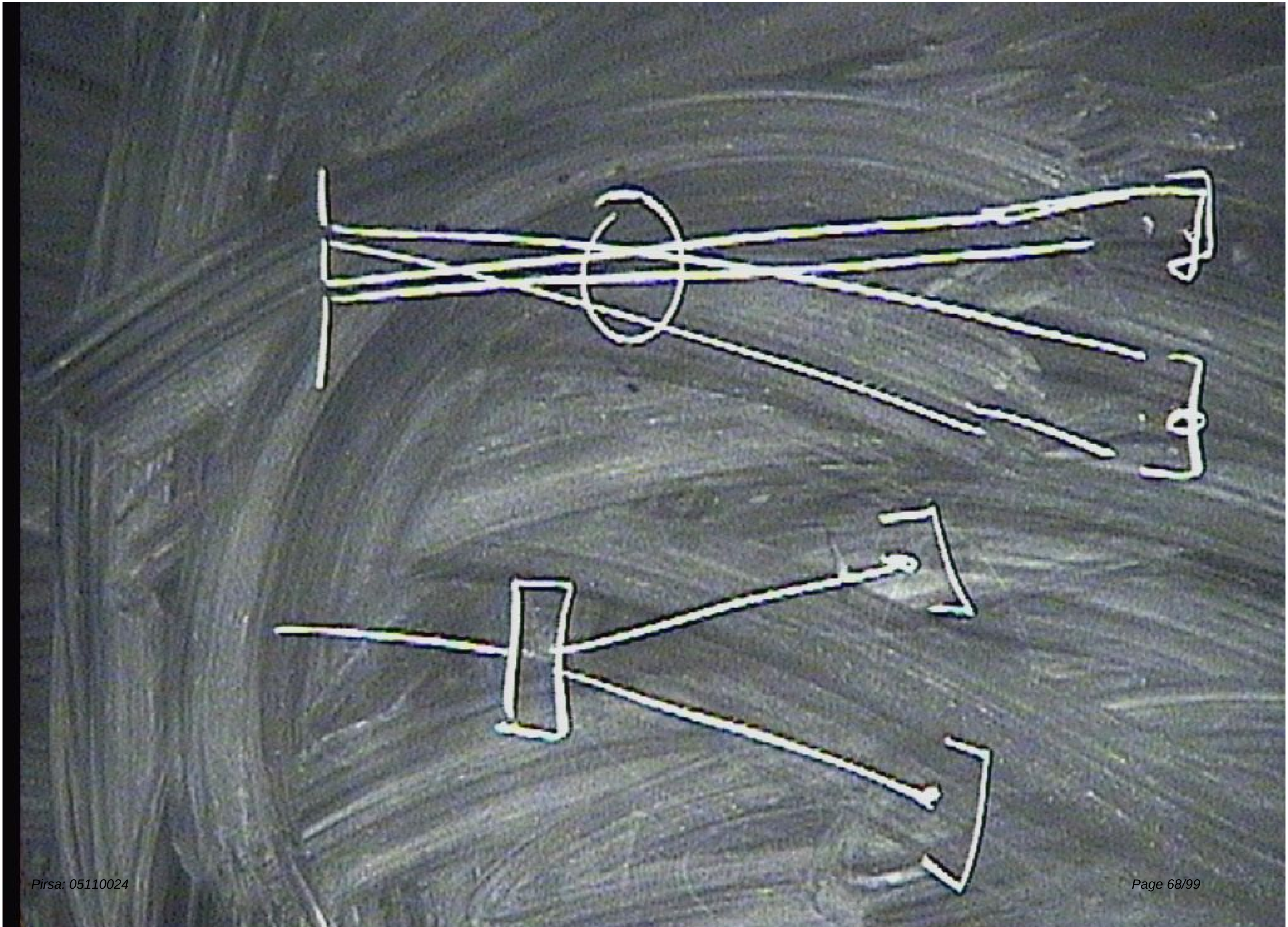
In the Uncertainty relation

$\Delta y \, . \, \Delta p_y \geq h$

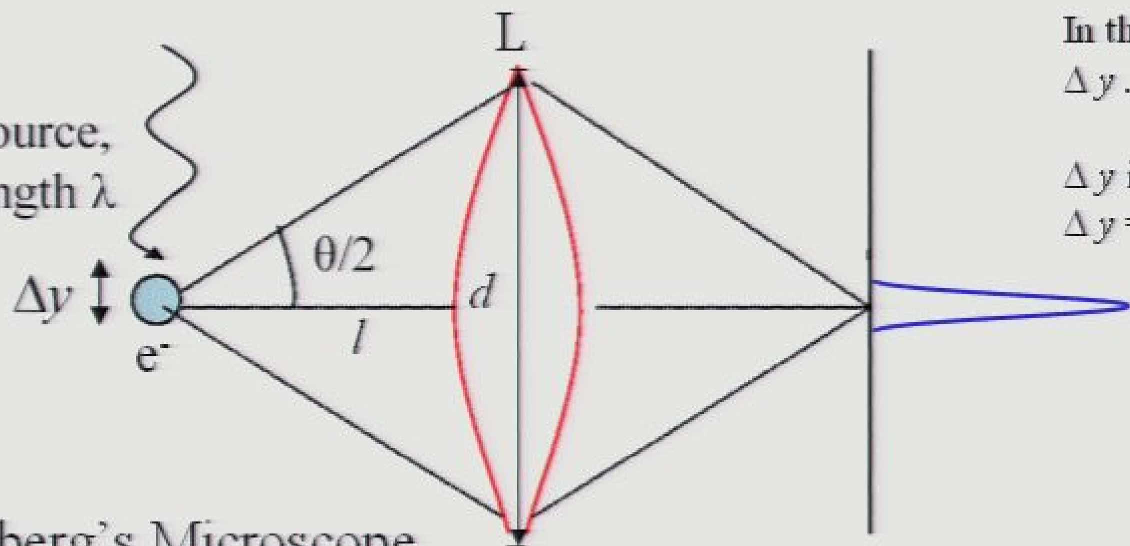
Δy is the optical resolution limit:

$\Delta y = \lambda / \text{Sin}\,\theta \approx \lambda\, d / l$





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



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In the Uncertainty relation
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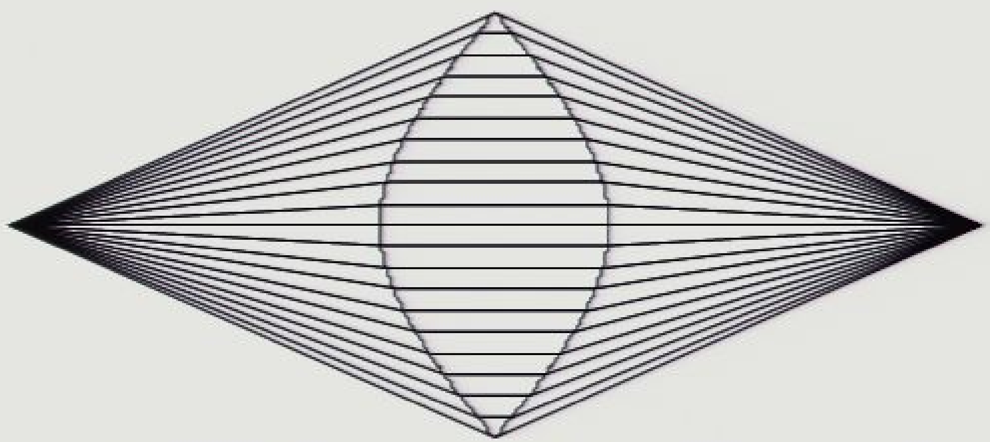
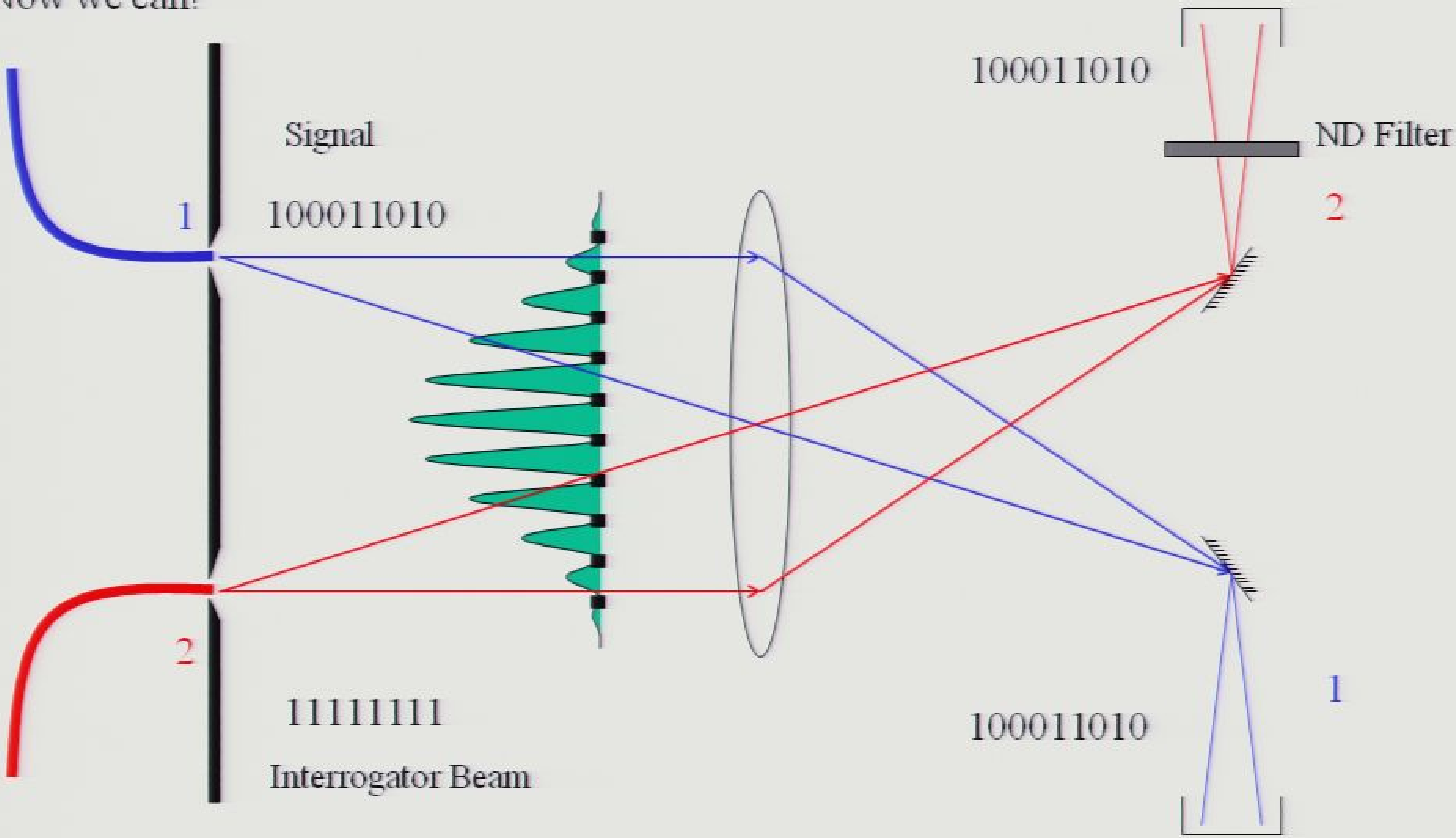


Feynman's QED Sum Over Paths (Phasors) Treatment of a Lens

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?

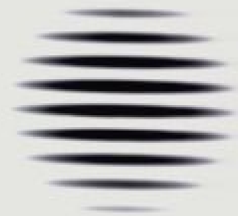
-Falsification of Bohr's Principle of Complementarity?
-Falsification of Copenhagen Interpretation (physical reality of unmeasured properties)?
-Falsification of the Many World Interpretation?
-New theory of measurement?
-Possible new technology (nonperturbative measurement of quantum flux)...

What next?
Theoretical expansion of CNM.
Analogue experiment with electrons.
Experimental probe of the wavefunction collapse process.

Quantitative Definition of Complementarity in "Which-Way" Experiments.

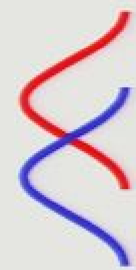
In the past 25 years a quantitative version of the PC has emerged, in which the Visibility of the interference pattern (V) and reliability of Which-Way Information (K) has the following form:

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



where

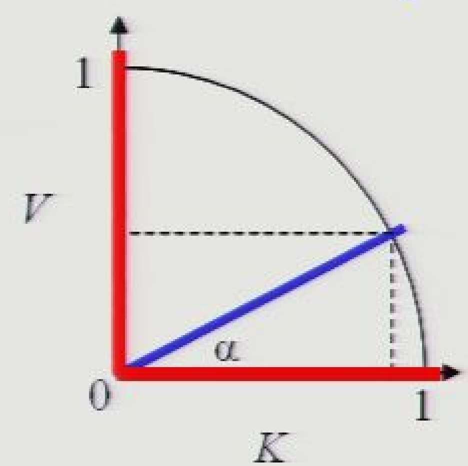
$$V = (I_{max} - I_{min}) / (I_{max} + I_{min}) \qquad (2)$$



and

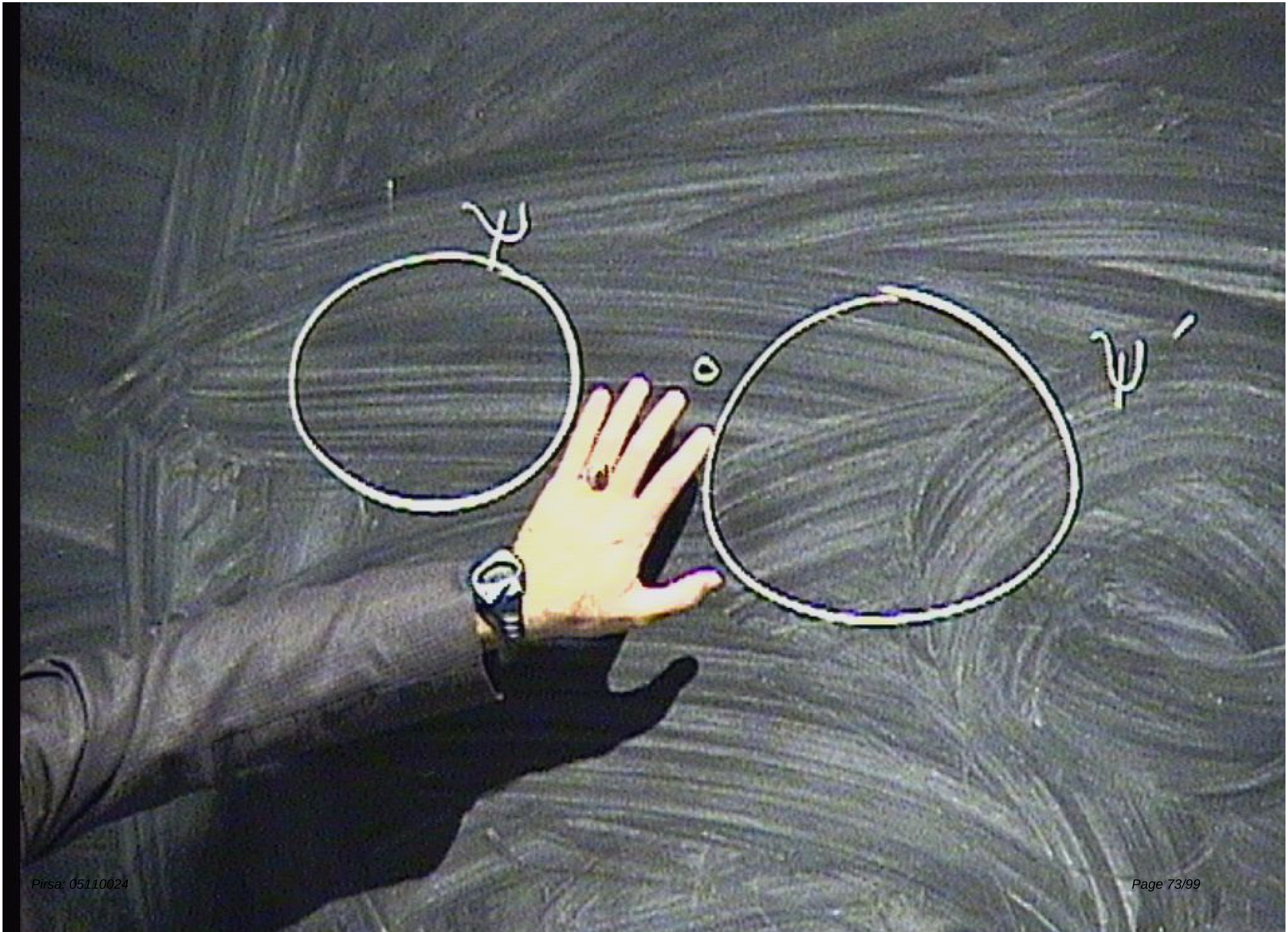
$$K_1 = (I_1 - I_2) / (I_1 + I_2) \qquad (3)$$

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 $0 \leq \alpha \leq \pi/2$

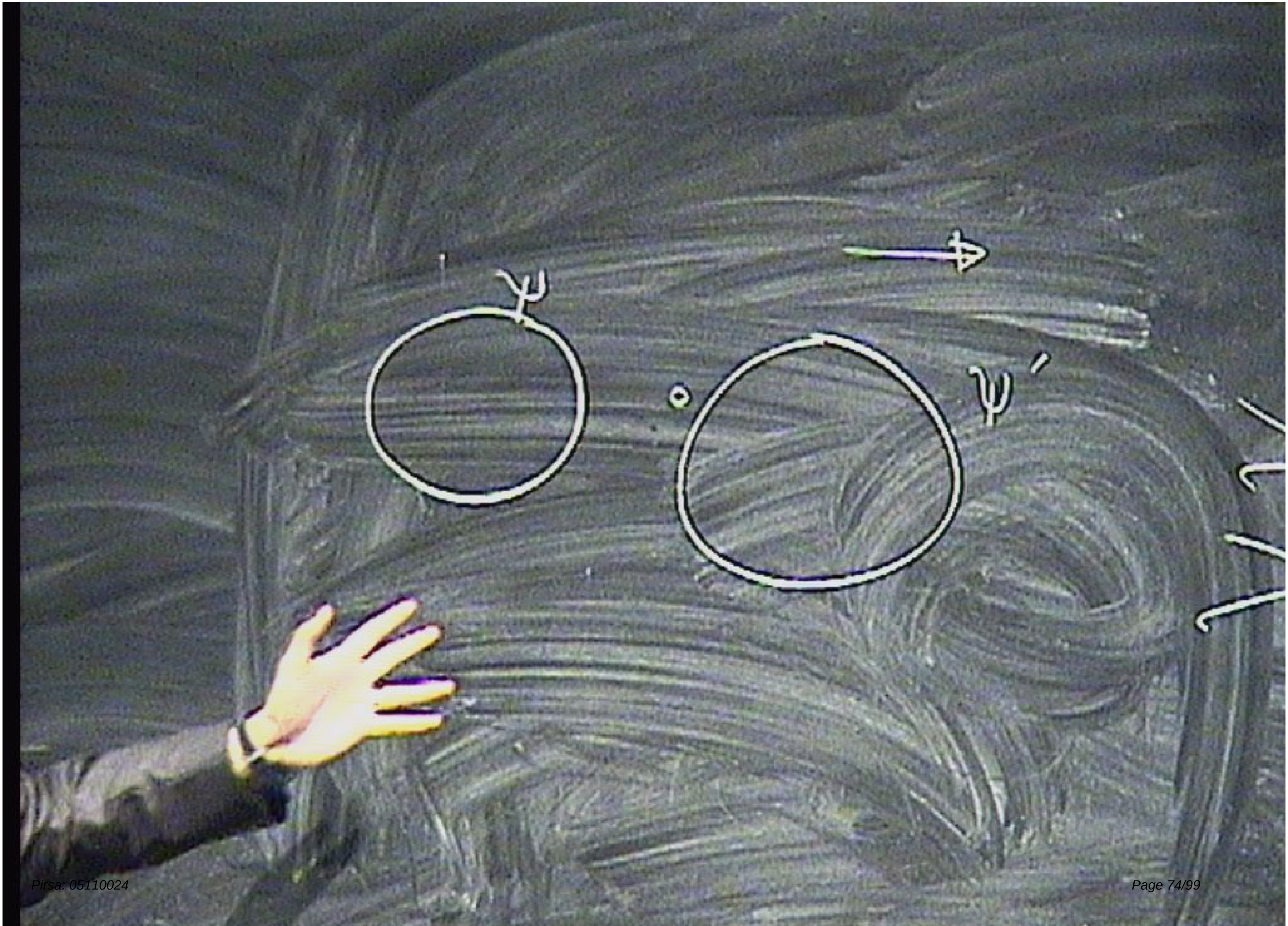


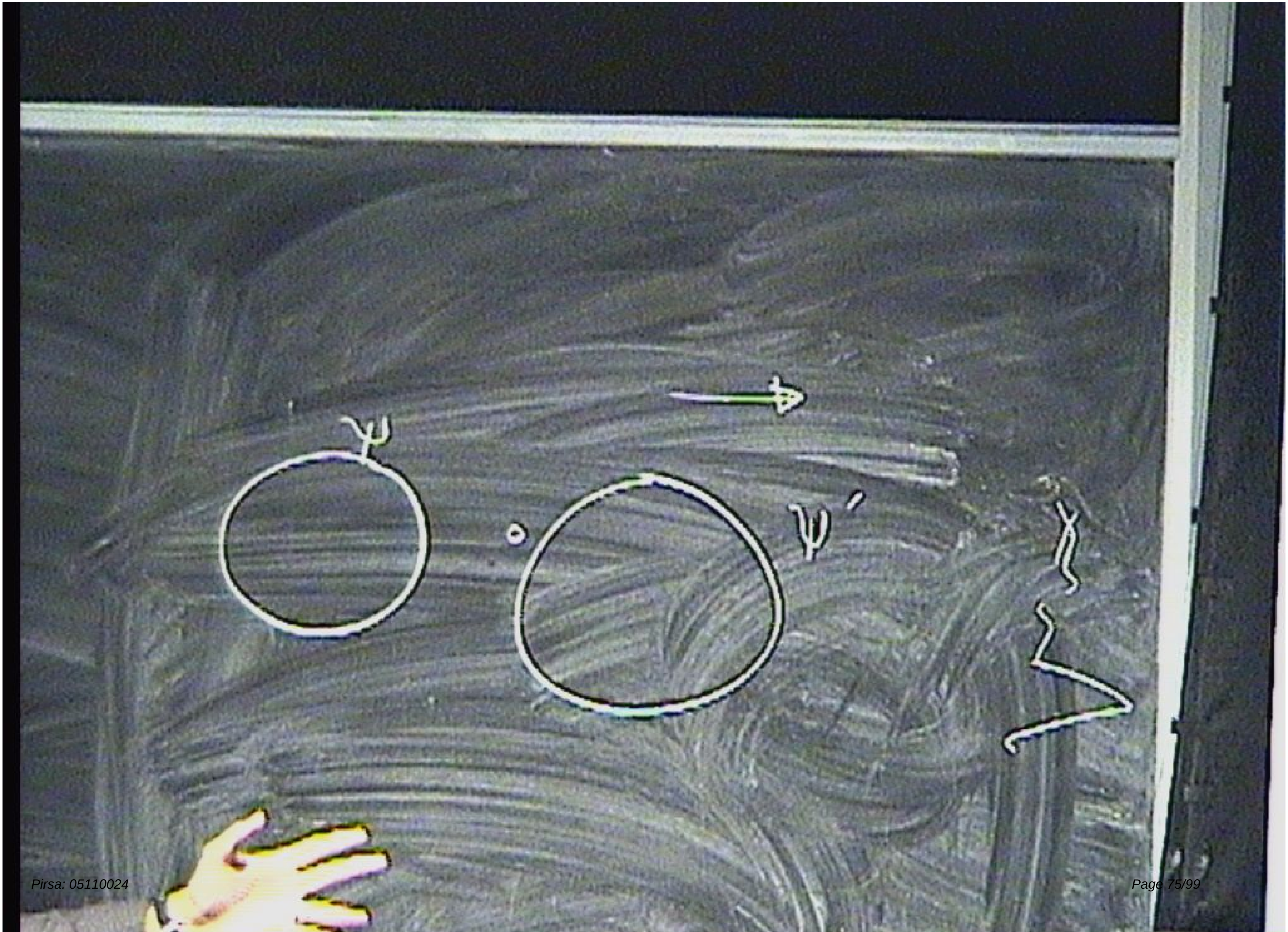
As we can see, there are intermediate conditions allowed by PC e.g. $\alpha = \pi/4$.

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

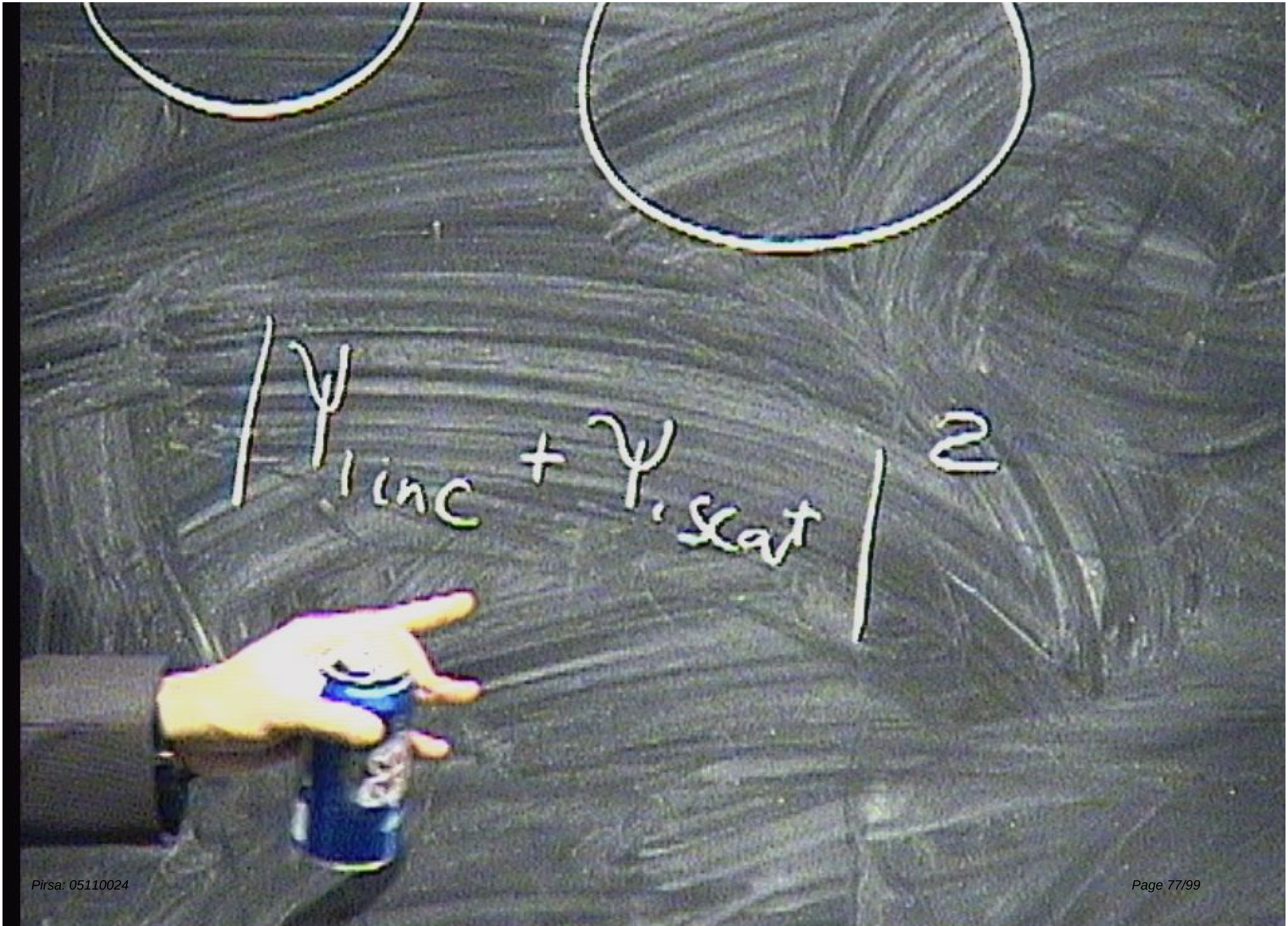


ψ
ψ'


ψ
ψ′


ψ
ψ'

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

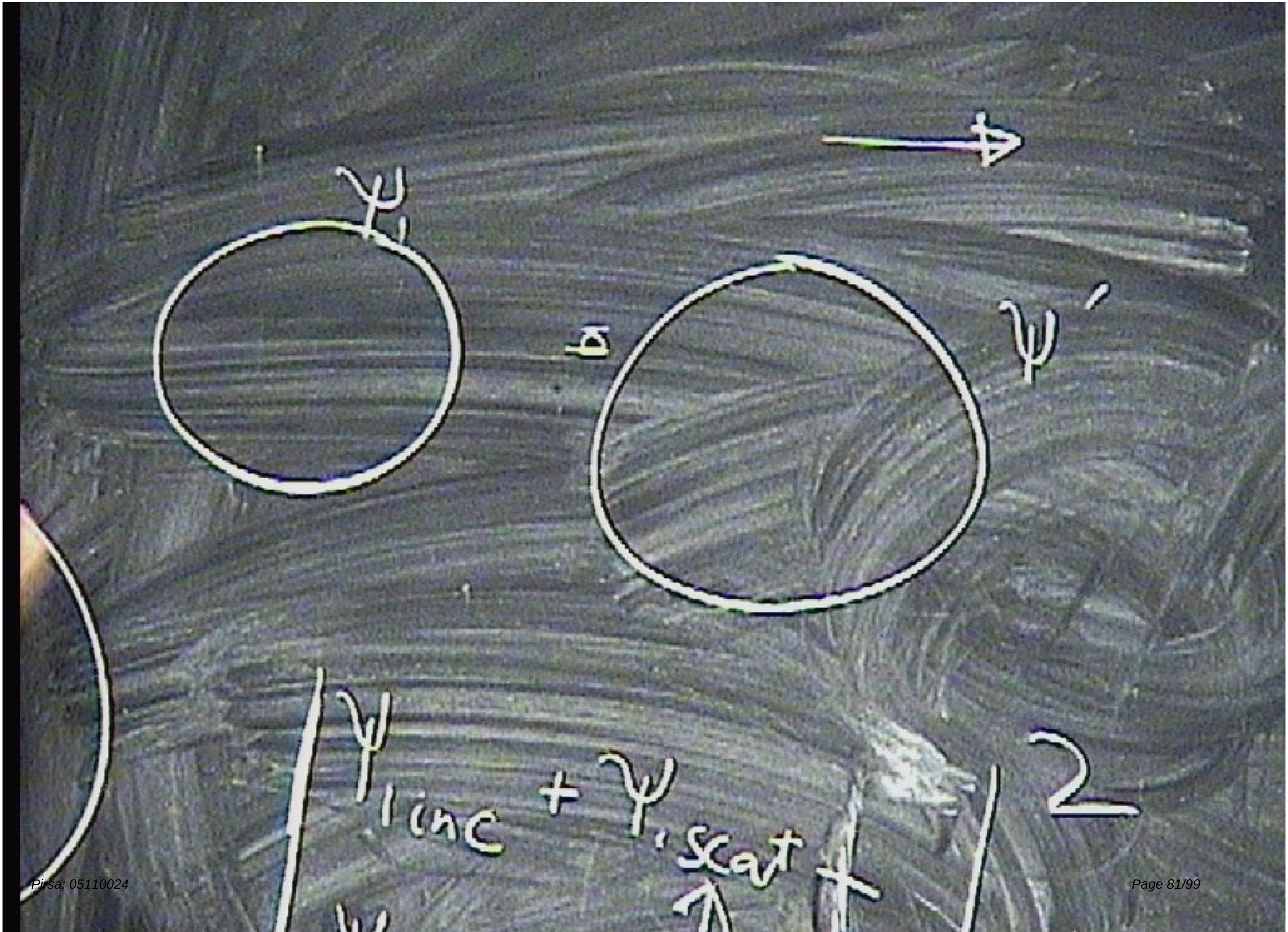

$|\psi_{inc} + \psi_{scat}|^2$

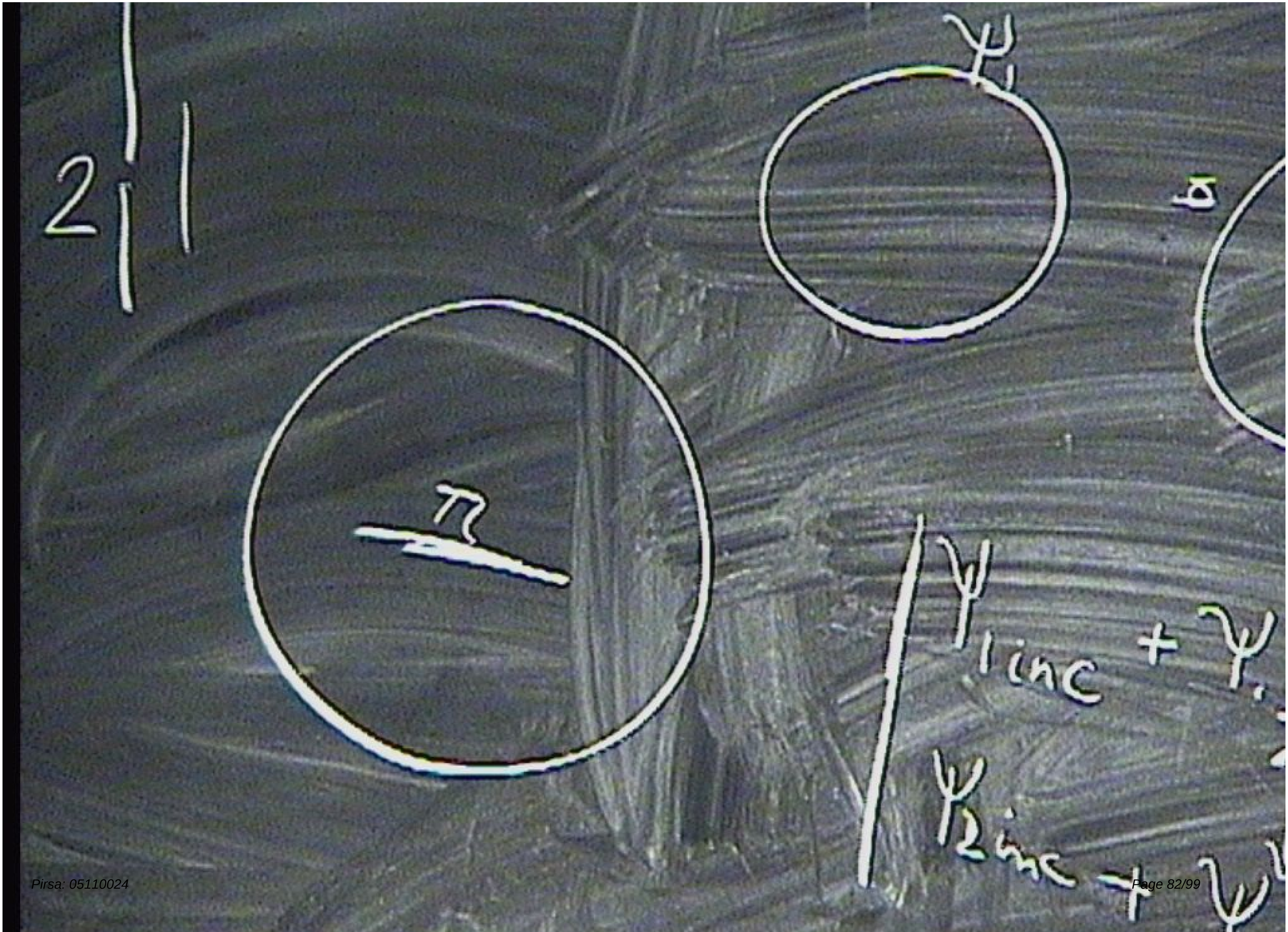
$$\left| \psi_{1\,inc} + \psi_{1\,scat} + \psi_{2\,inc} + \psi_{2\,scat} \right|^2$$

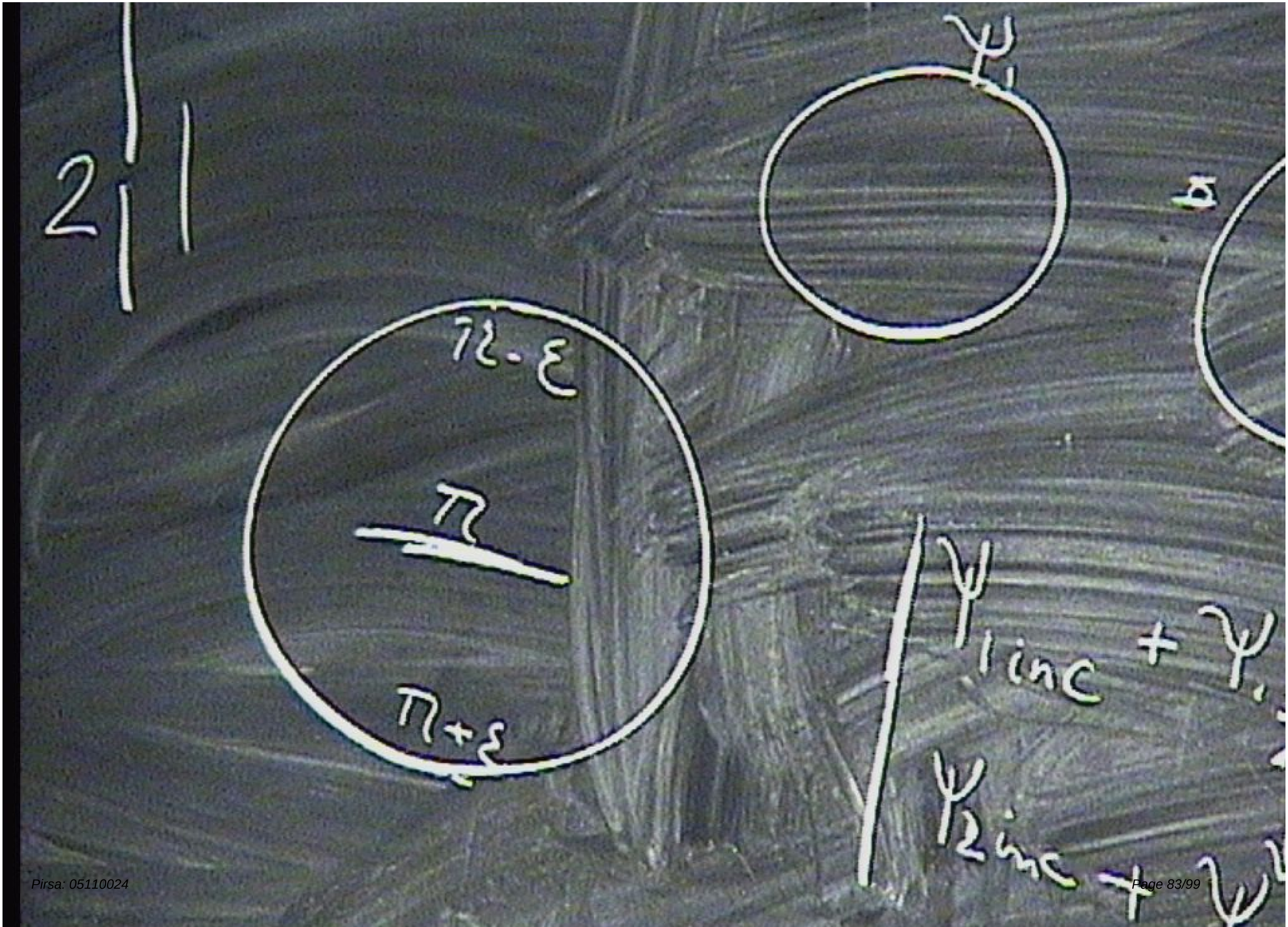
$$\left| \psi_{1\,inc} + \psi_{1\,scat} + \psi_{2\,inc} + \psi_{2\,scat} \right|^2$$

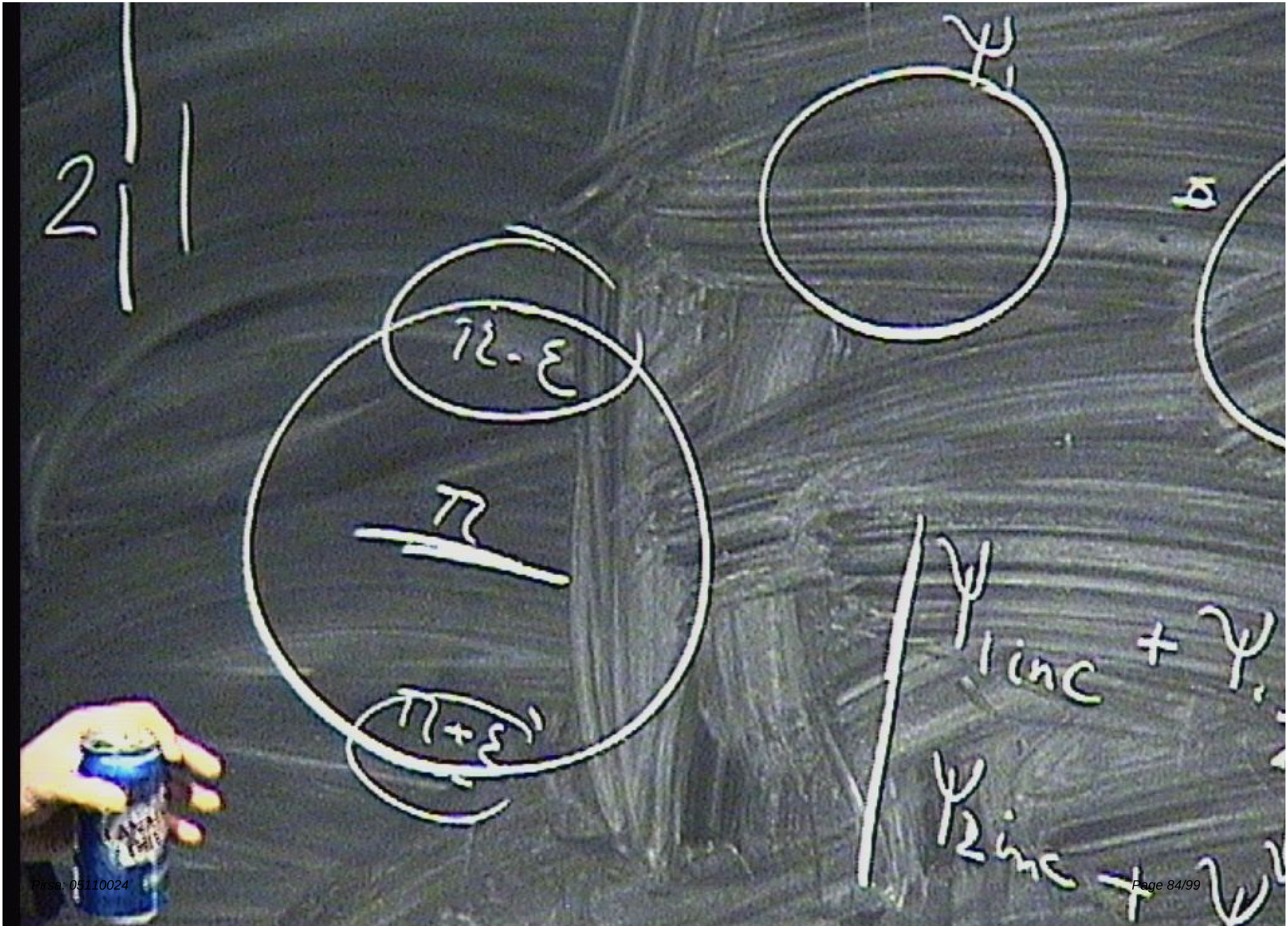
$$\left| \psi_{1\,inc} + \psi_{1\,scat} + \psi_{2\,inc} + \psi_{2\,scat} \right|^2$$

$$|\psi_1 + \psi_2|^2$$


ψ1
ψ'
|ψ1 inc + ψ1 scat|2


2
r
ψ1inc + ψ
ψ2inc + ψ

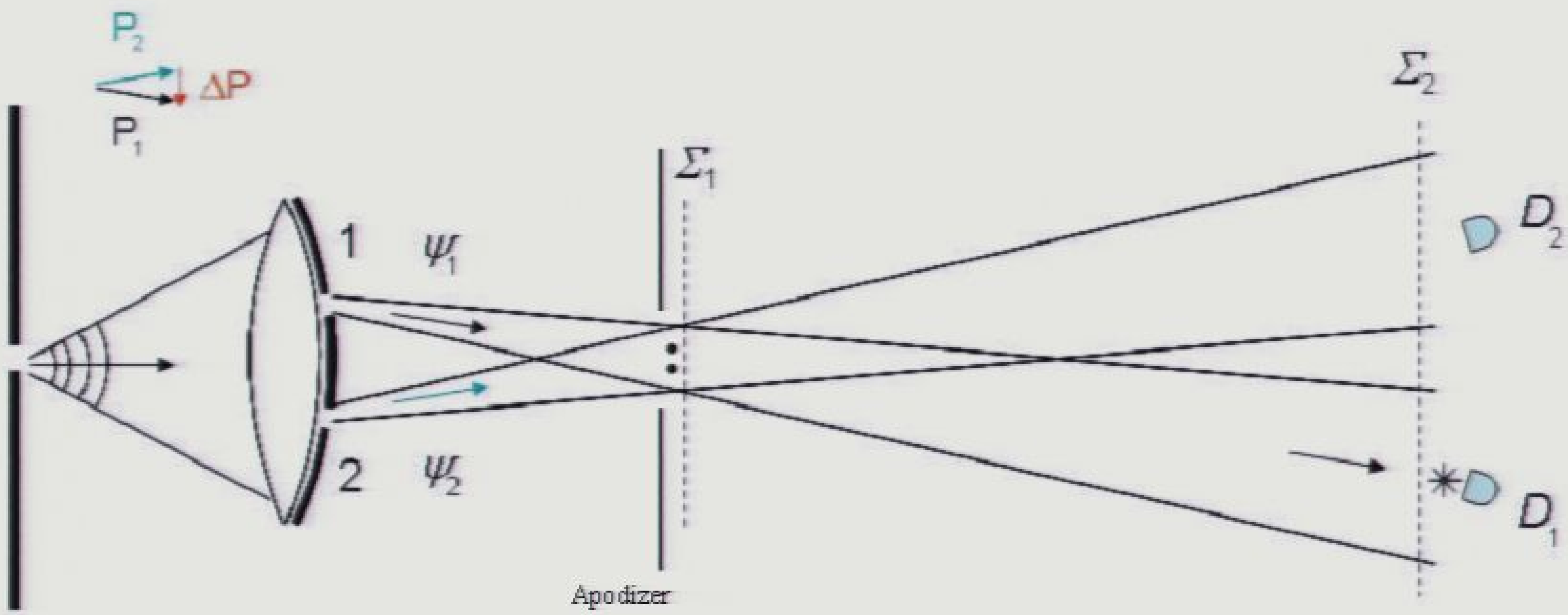

2
π-ε
π
π+ε
ψ1
ψ1 inc + ψ
ψ2 inc + ψ


2
π - ε
π
π + ε'
ψ₁inc +
ψ₂inc +

$$\left|\psi_{1\,inc} + \psi_{1\,scat}\right|^2 + \left|\psi_{2\,inc} + \psi_{2\,scat}\right|^2$$

$$|\psi_1 + \psi_2|^2$$

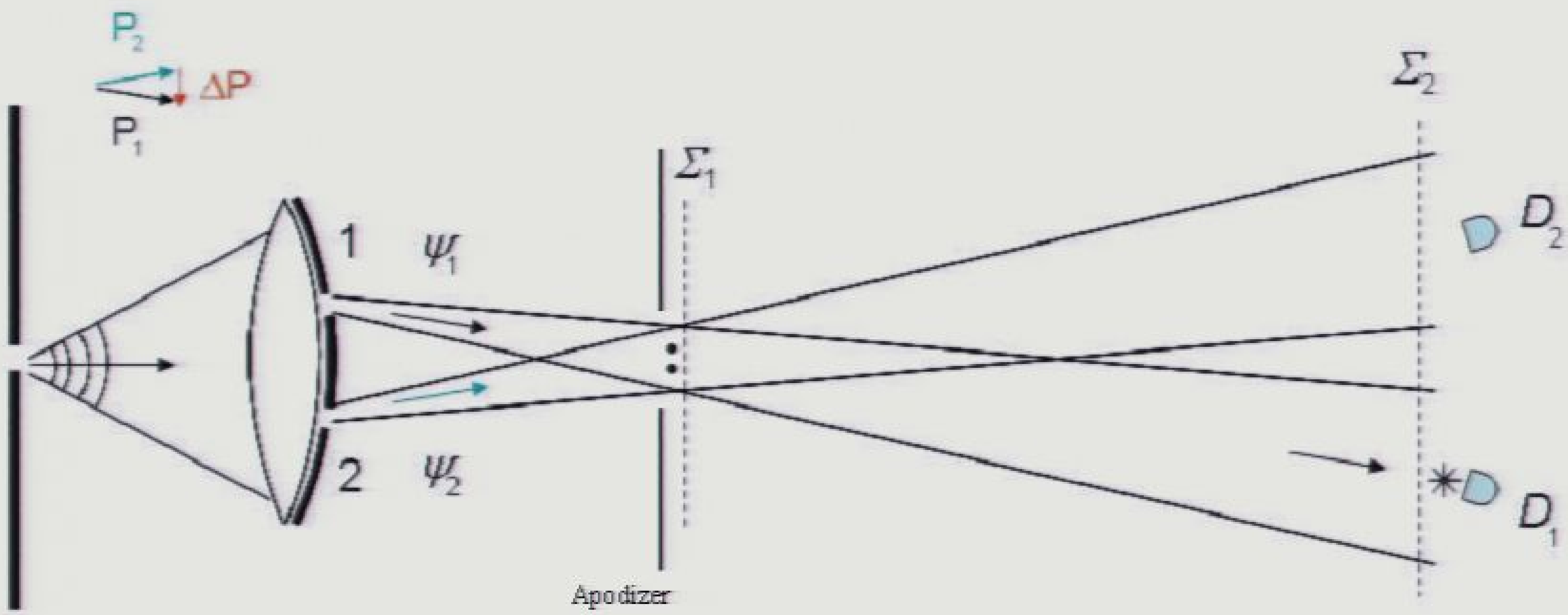
Experiment without the imaging lens.



Rowan Exp. May 2005

AIP Conf. Proc. **810**, 2006

Experiment without the imaging lens.



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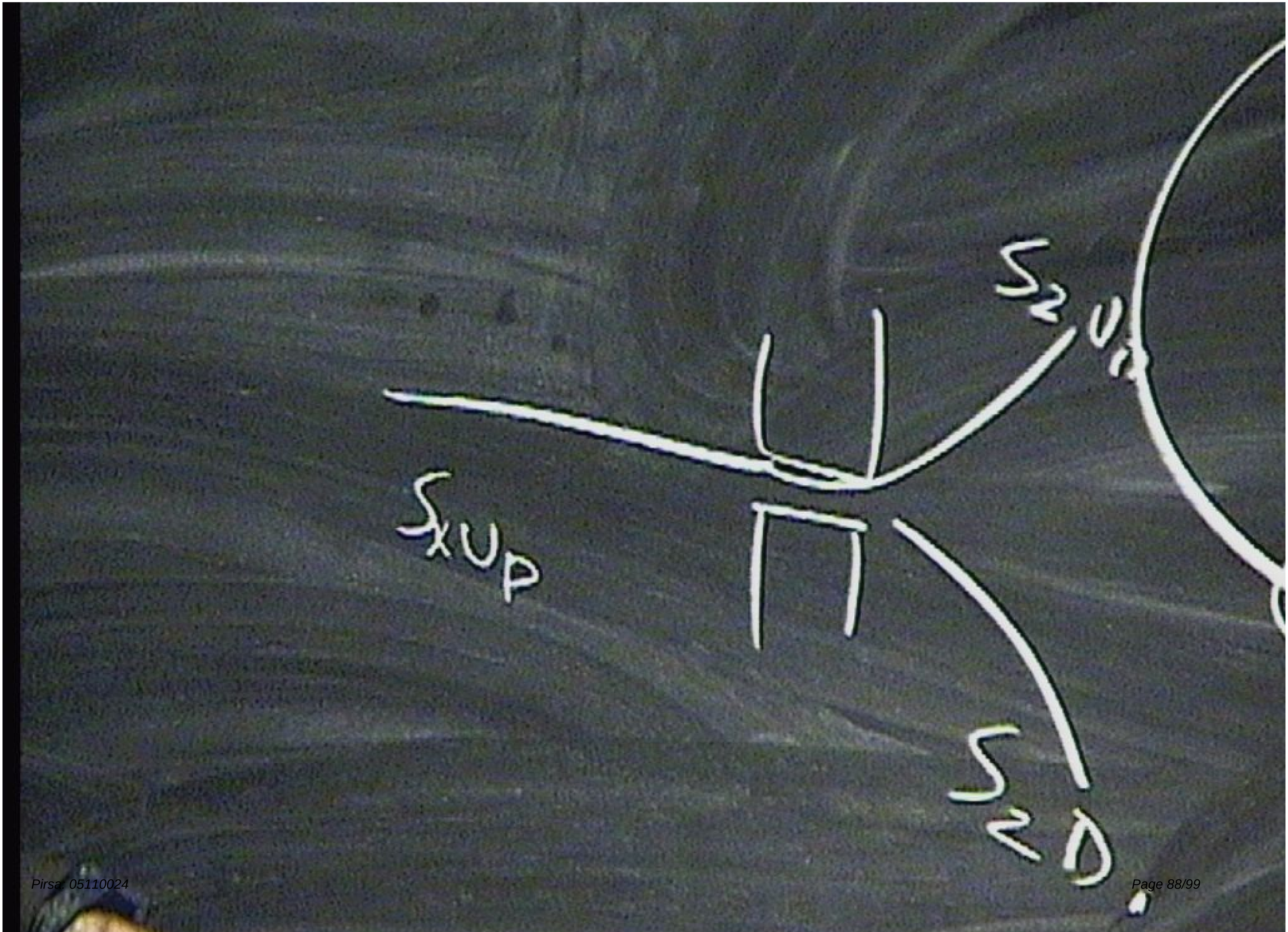
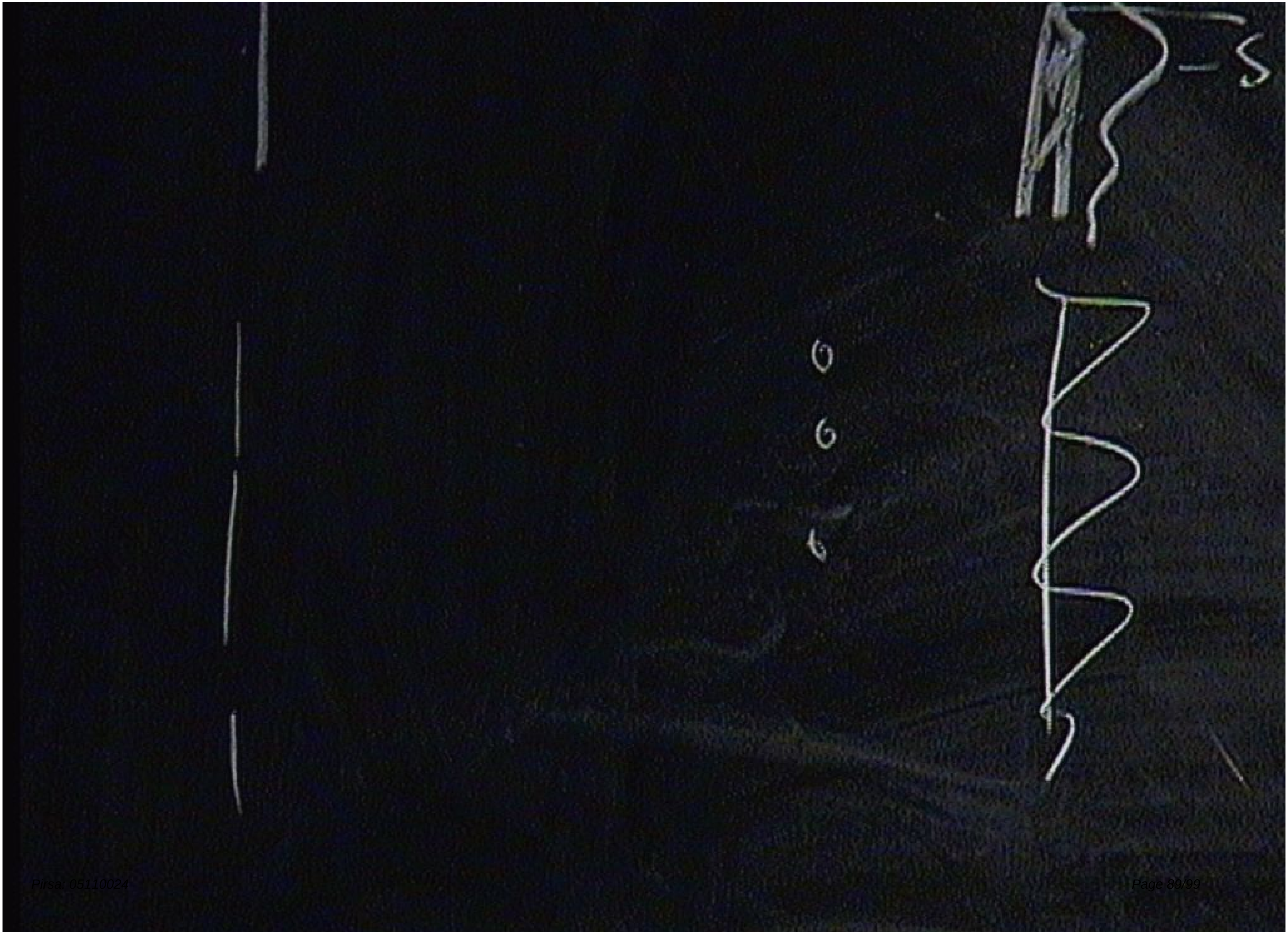
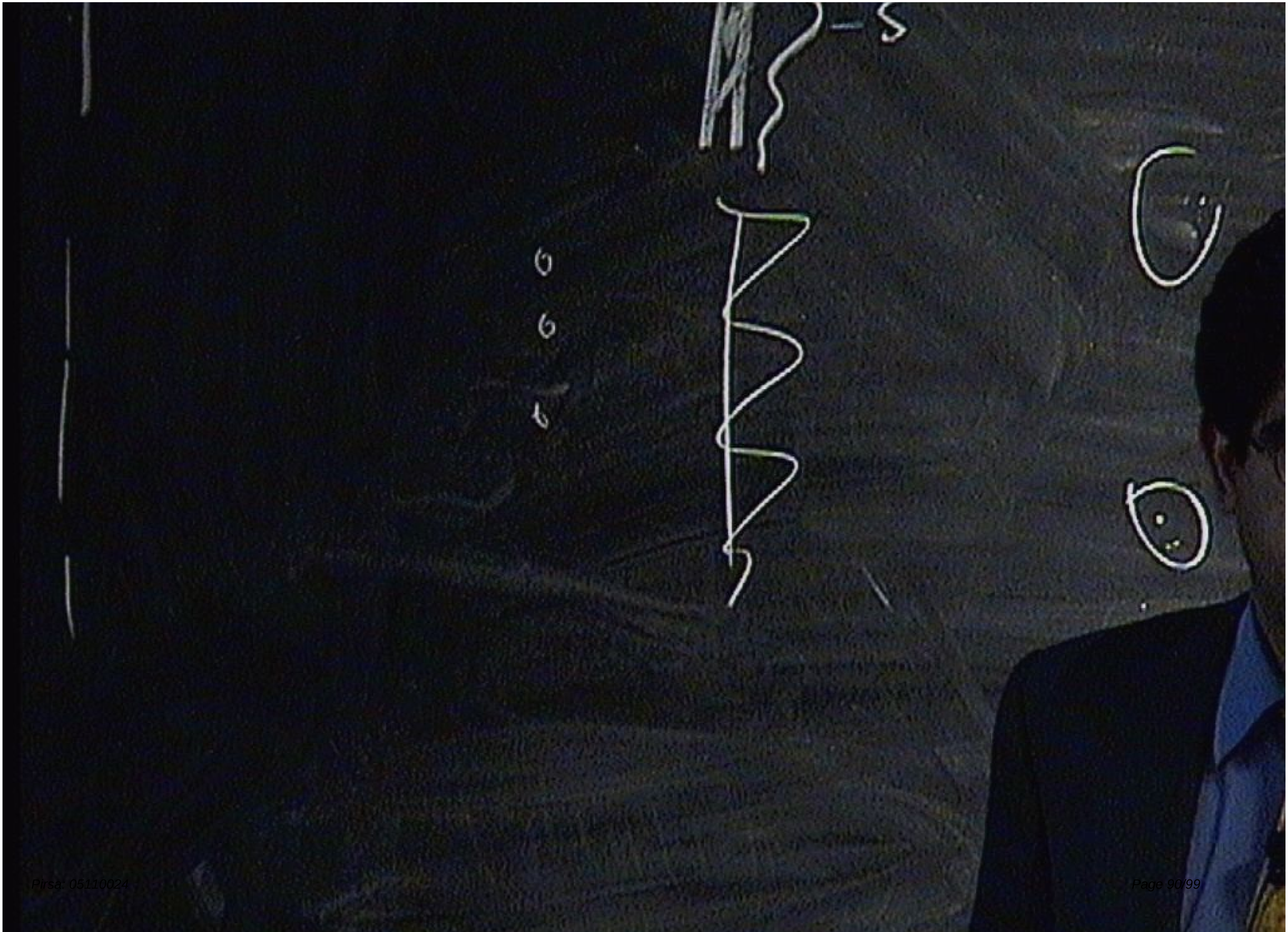
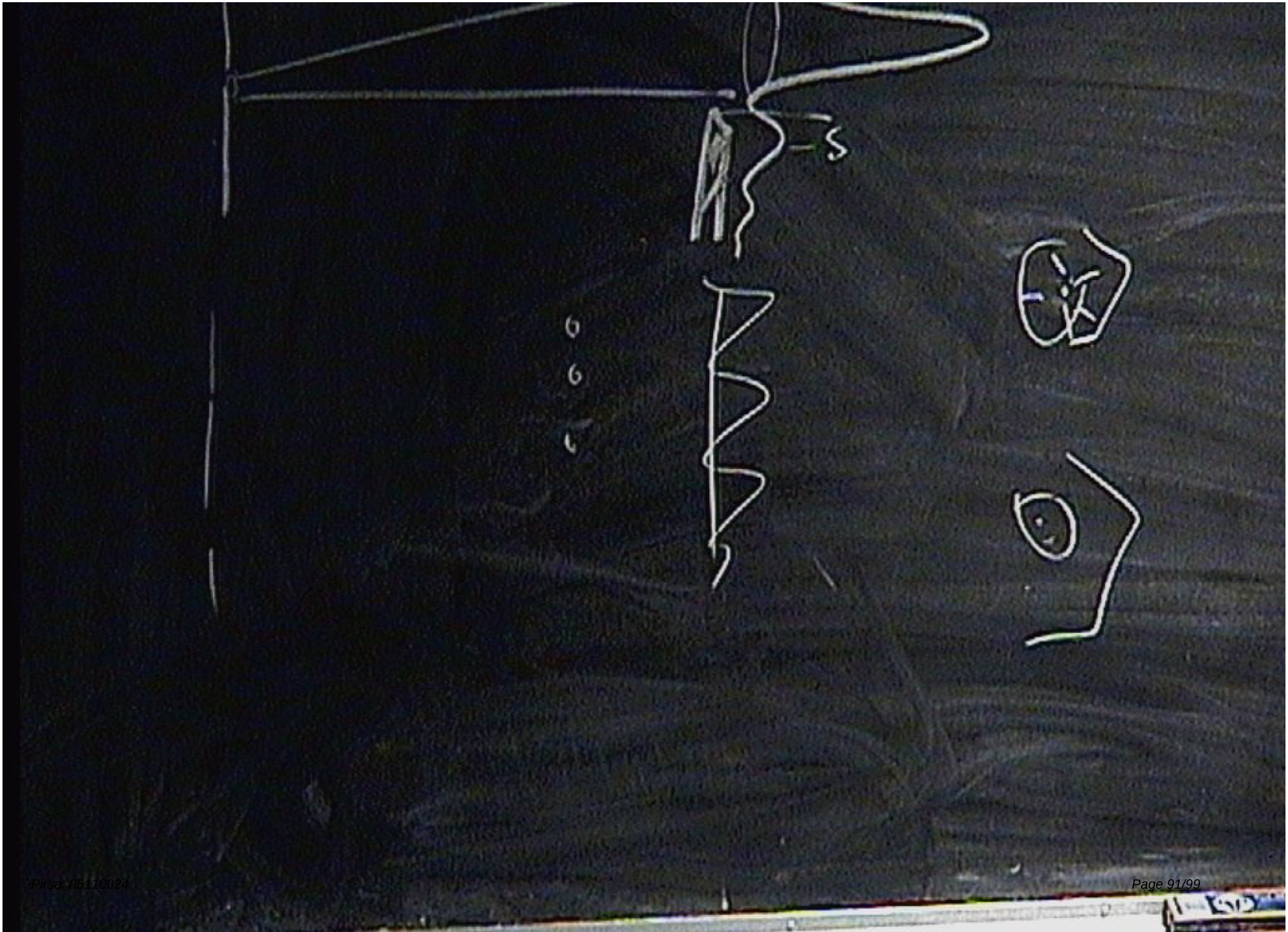

S2 U
S X Up
S2 D







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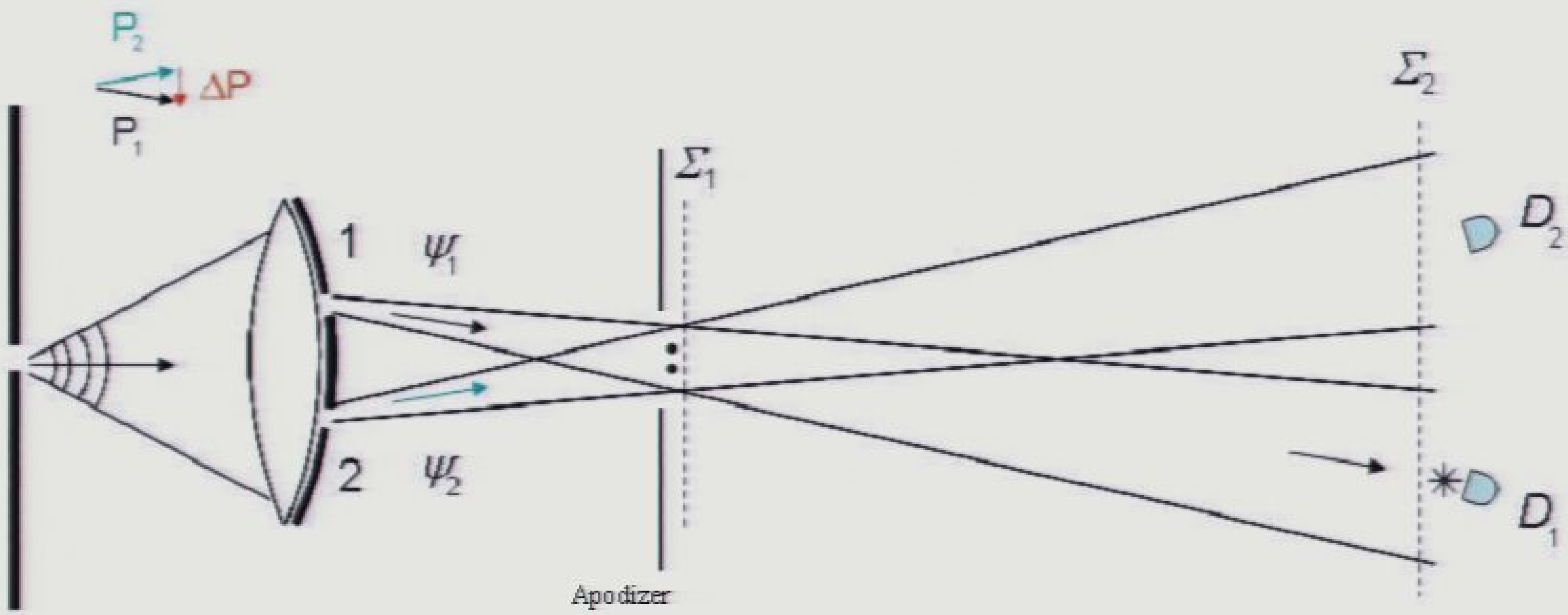

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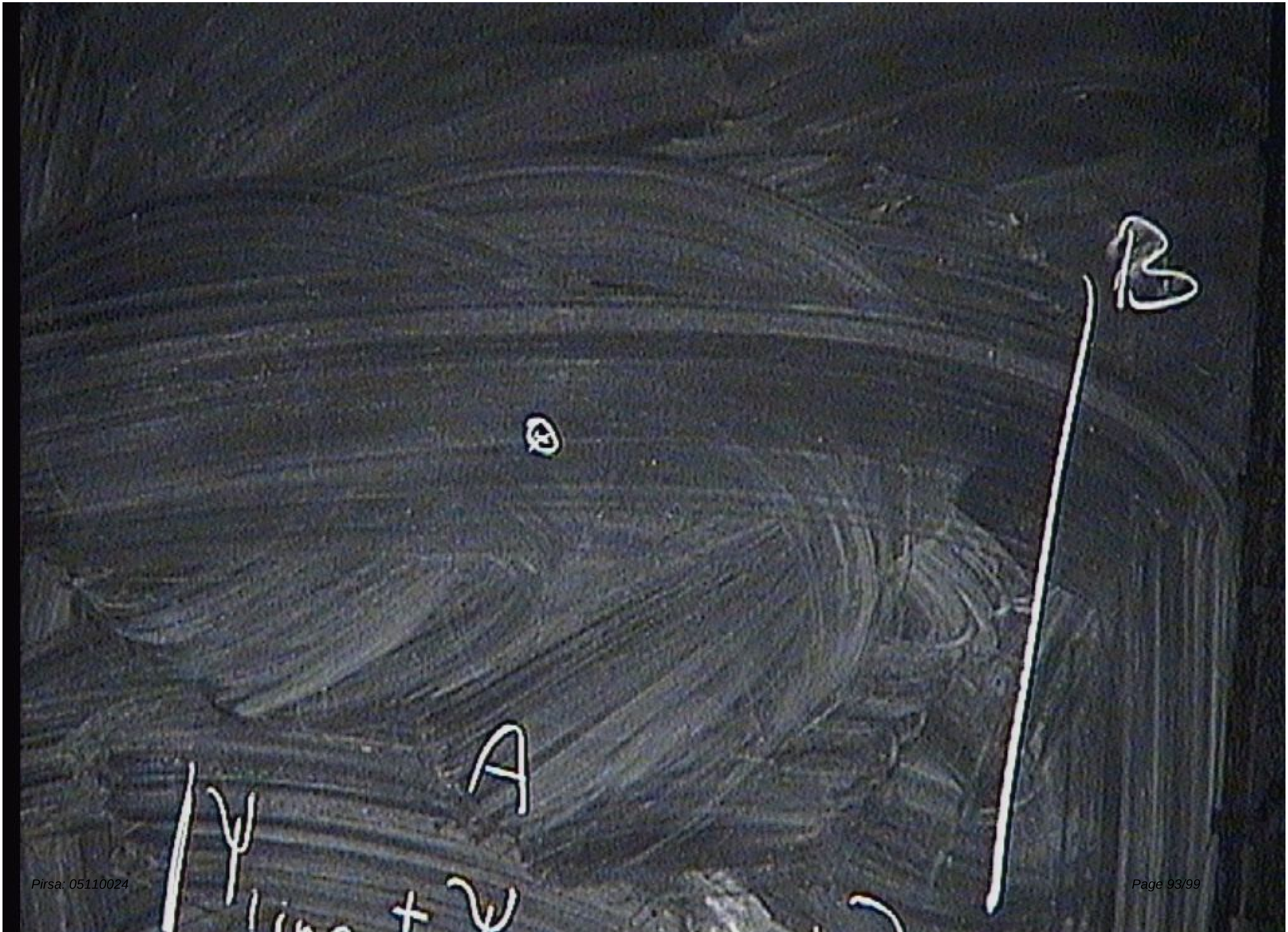
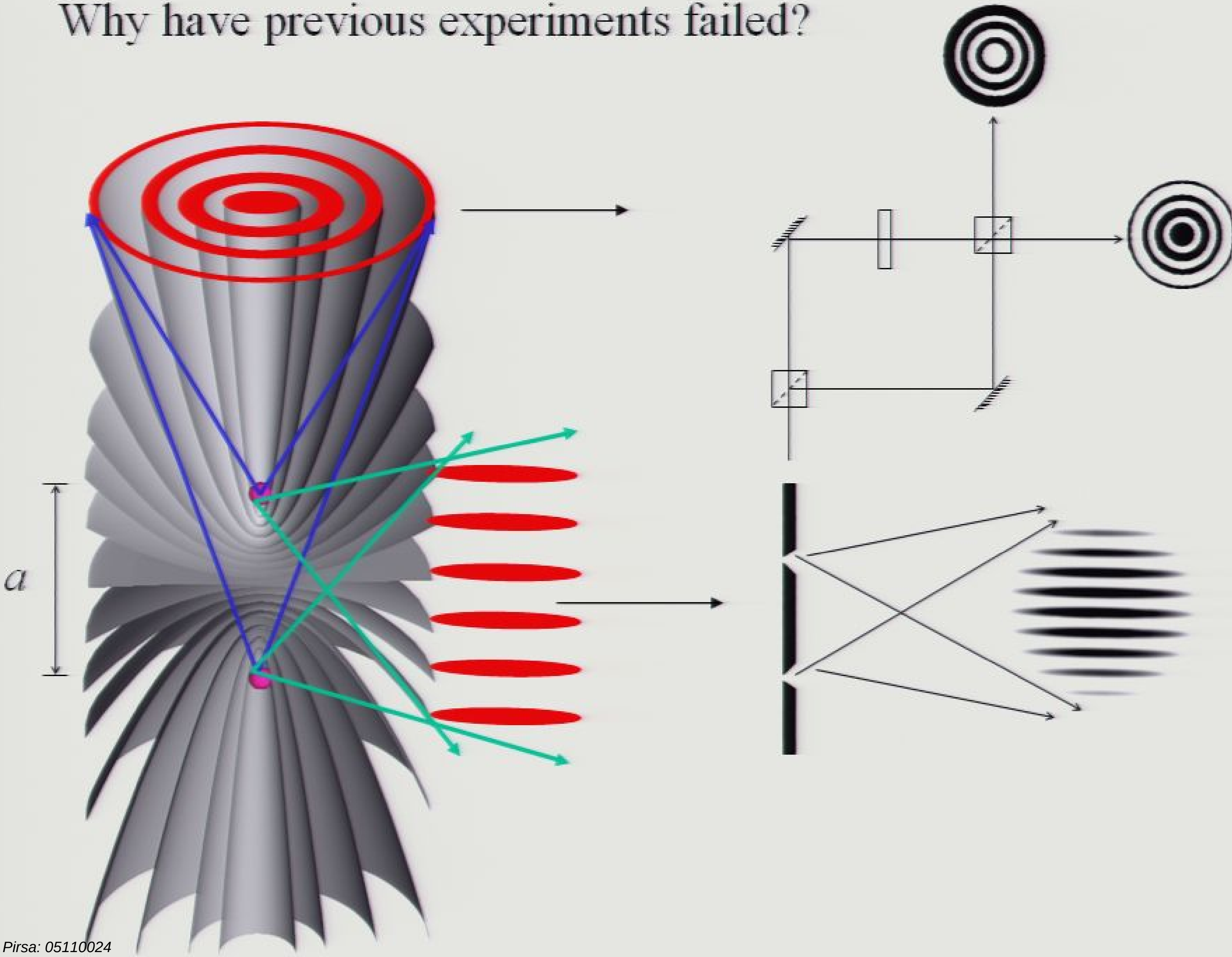
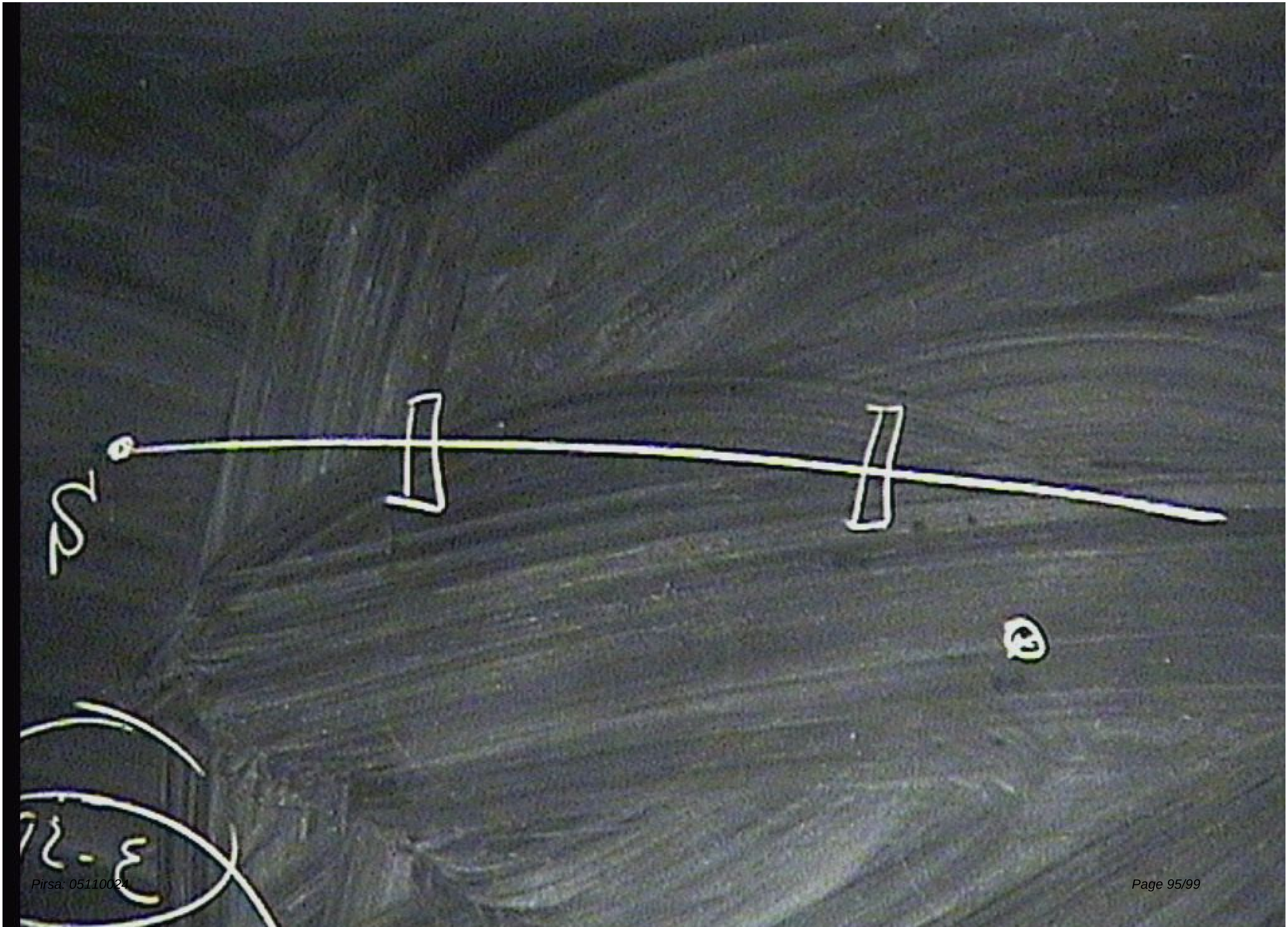
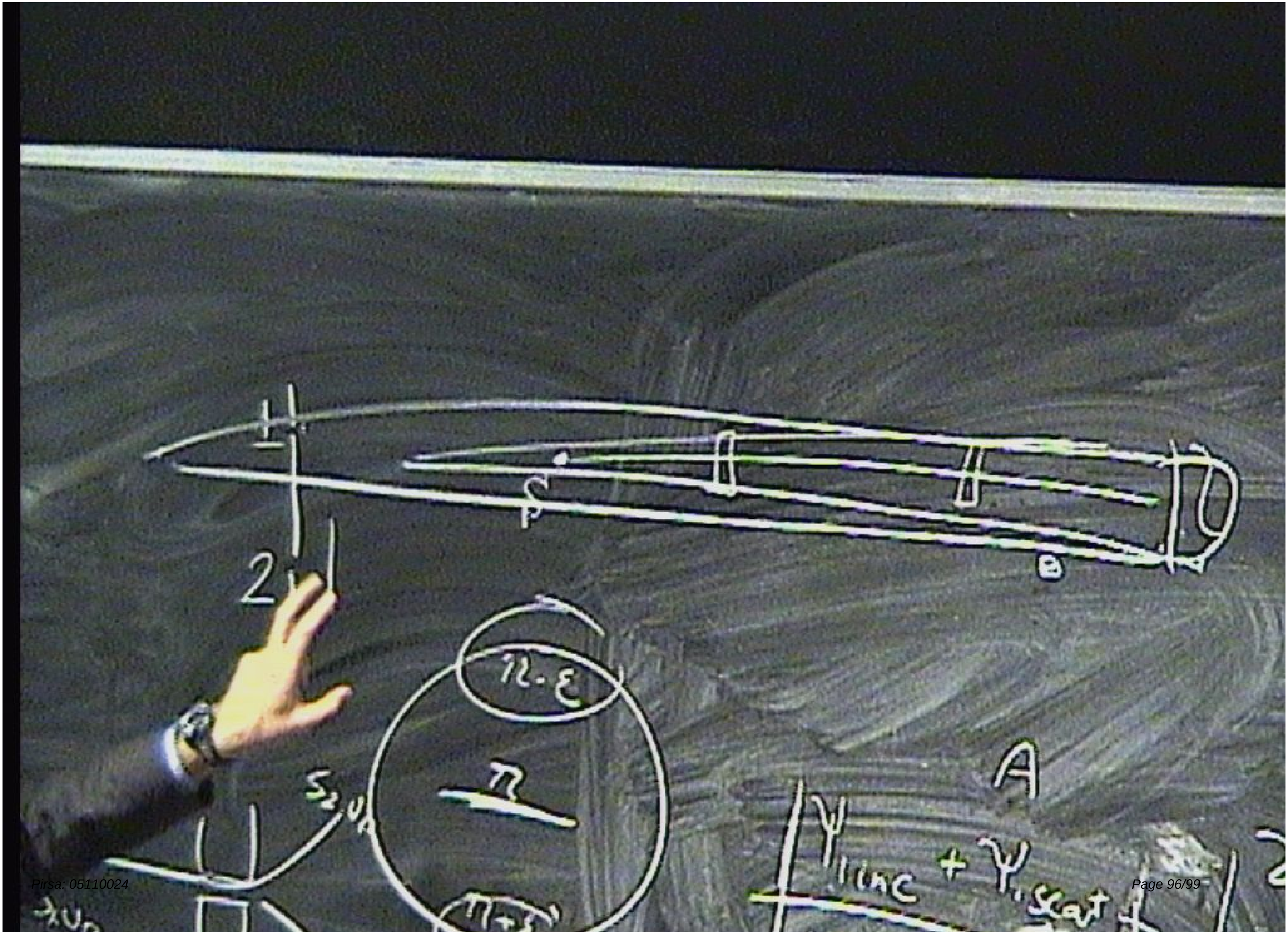
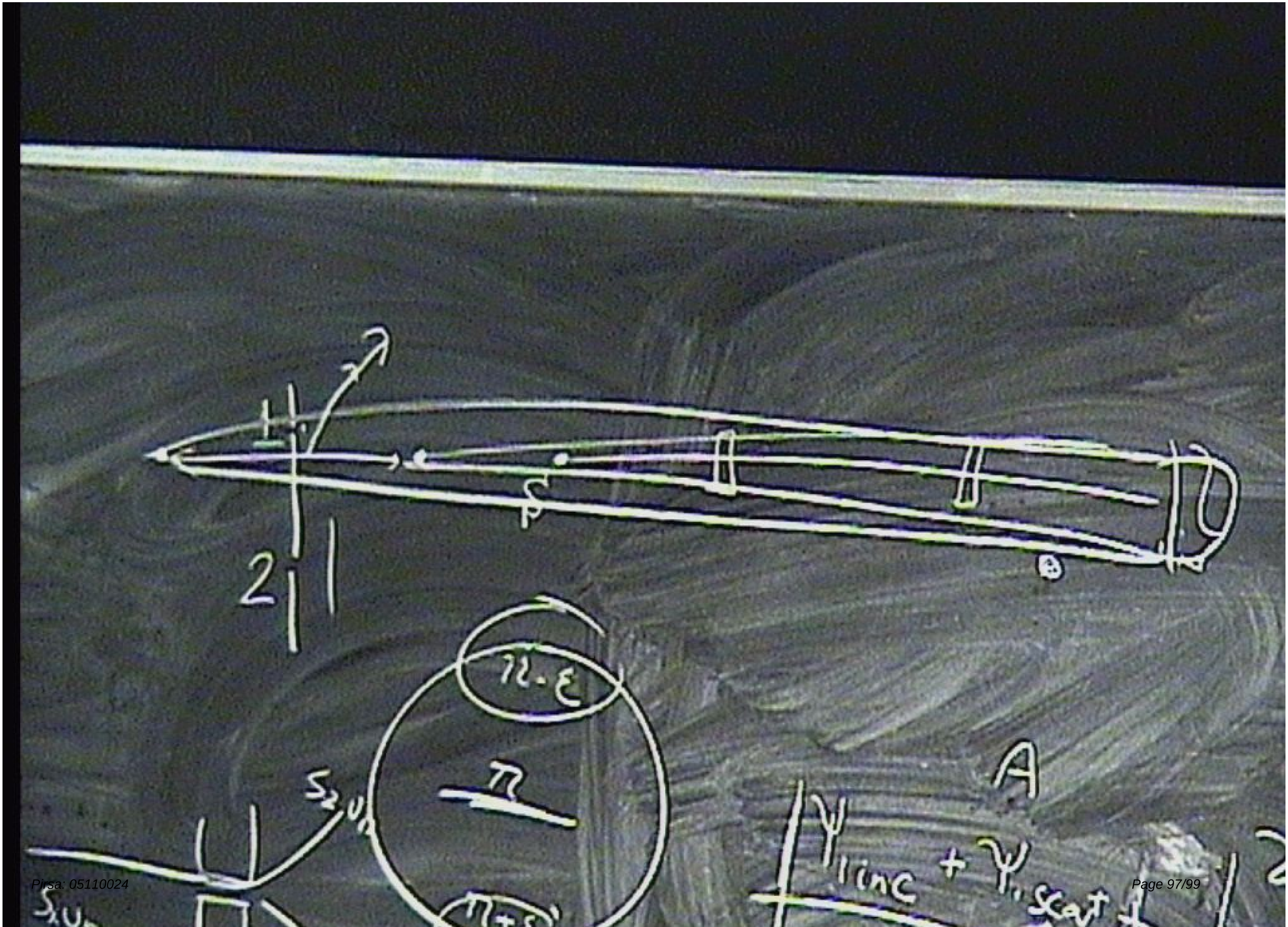

B
A

Why have previous experiments failed?









2
π-ε
π
π+ε
A

Why have previous experiments failed?