Title: The Entanglement Game and 21st-century applications of quantum theory including quantum computers

Date: Jul 12, 2006 10:45 AM

URL: http://pirsa.org/06070023

Abstract: This presentation will introduce the counter-intuitive quantum concept of entanglement and help to explain it via the Â‘entanglement gameÂ’, a hands-on interactive activity that has been successfully tested with a number of Grade 12 classes. It will also introduce the emerging field of quantum technology within which researchers are harnessing some of the strange features of quantum theory to build new powerful 21stÂ–century technologies such as quantum computers, quantum teleporters and quantum secret codes.

The Vega Science Trust - Electrons and their Interactions - Freeview Video - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.vega.org.uk/video/programme/47

Customize Links | Free Hotmail | Windows Marketplace | Windows Media | Windows

Home News Programmes Schools Order Video Search Vega Awards Media Links Help About Us

Home | Programmes | Vega Science Lectures | Richard Feynman | Electrons and their Interactions

Electrons and their Interactions

The Douglas Robb Memorial Lectures - Part 3

Feynman diagrams and the intricacies of particle interaction.

▶ Play | ? Help | ! Info

The Vega Science Trust is actively supported by:

FSU | hefce | Leverhulme | University of Sussex | real

Page Options

Programme Index

Useful Links:

Tell a friend
about this page

Join our newsletter
keep up to date and help Vega

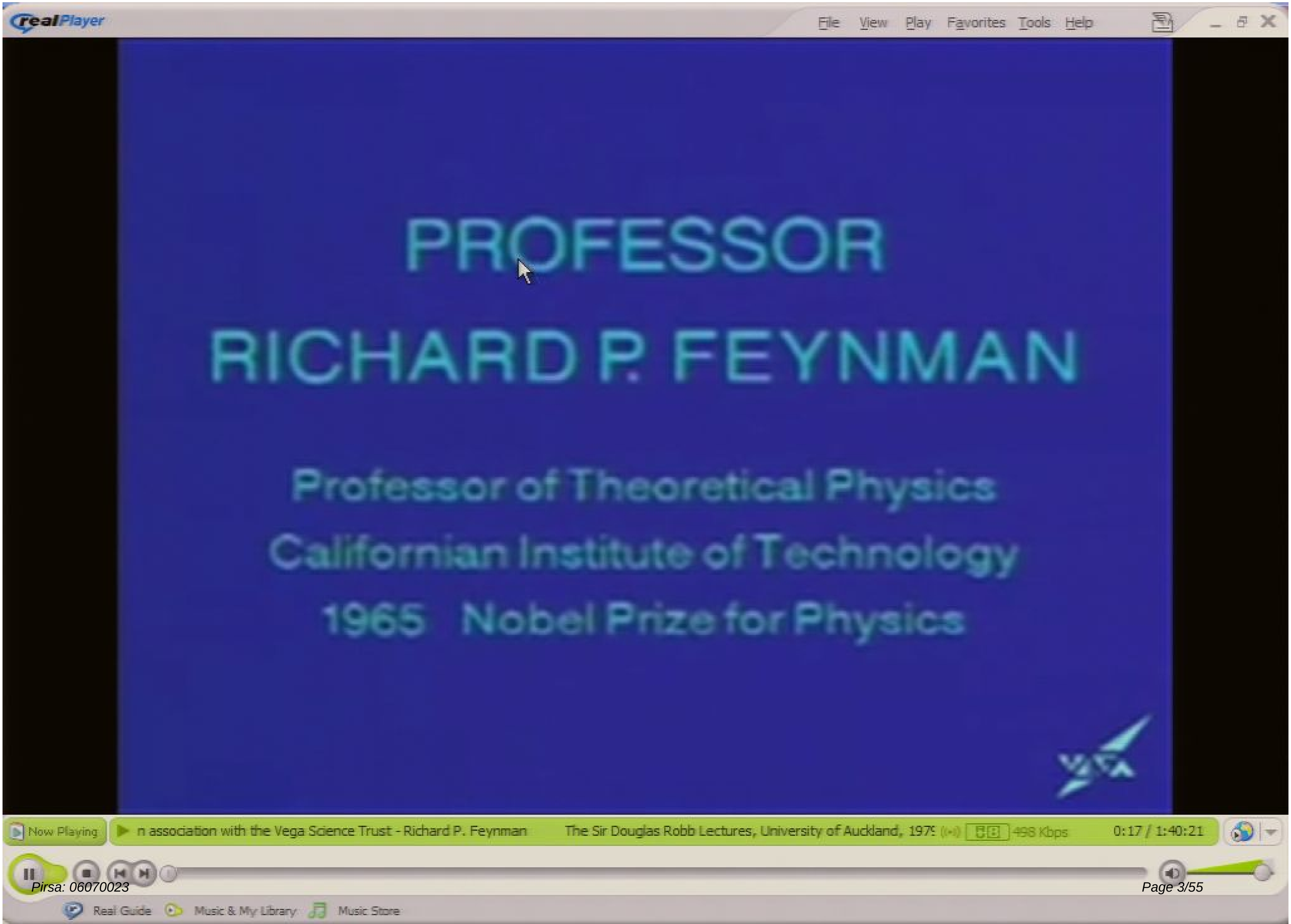
Donate to Vega
via cheque or credit card

Broken link
please let us know

Link to Vega
add us to your website

Contact us

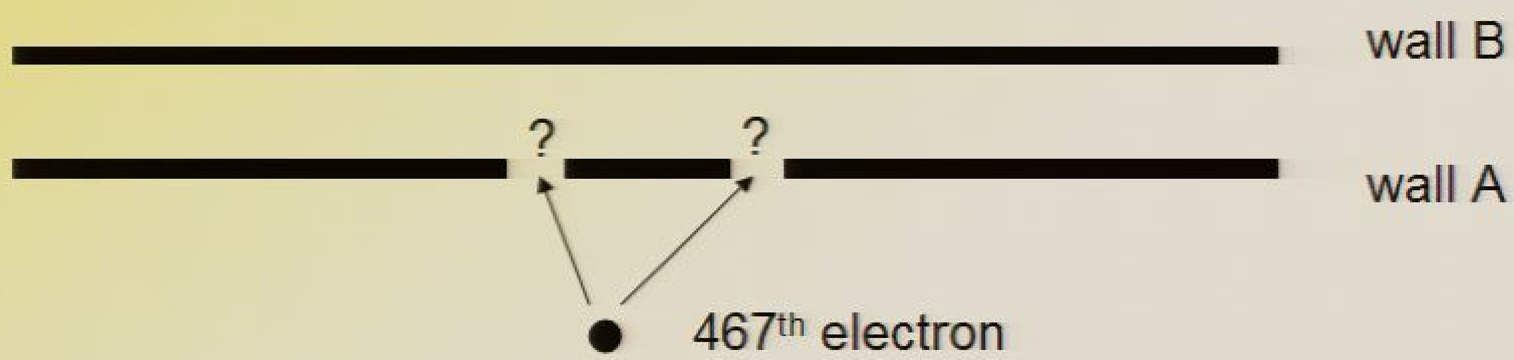
http://vegaserver1.hpc.susx.ac.uk:8080/ramgen/feynman/feynman3.rm

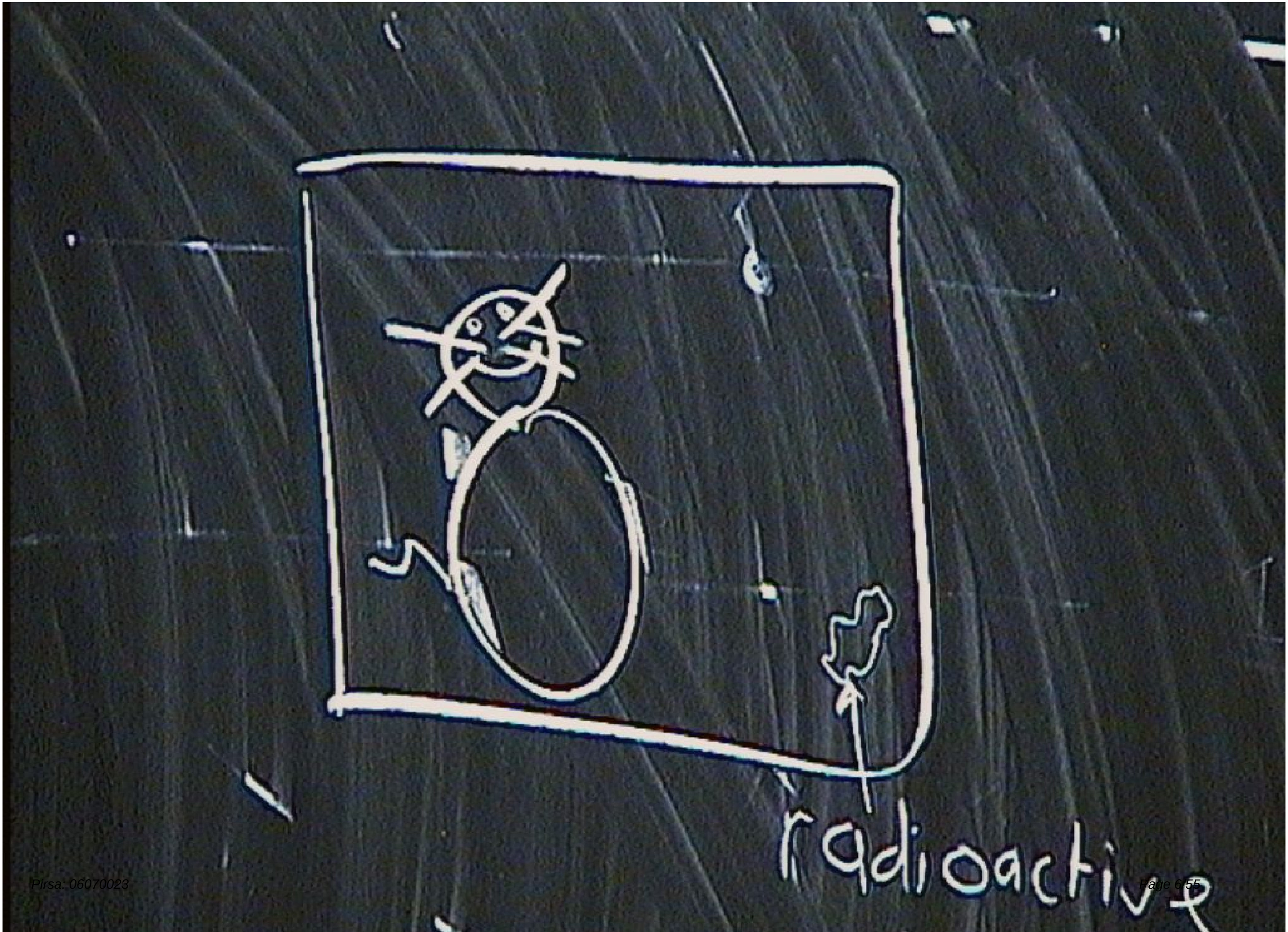

realPlayer
File View Play Favorites Tools Help
PROFESSOR
RICHARD P. FEYNMAN
Professor of Theoretical Physics
Californian Institute of Technology
1965 Nobel Prize for Physics
Now Playing
n association with the Vega Science Trust - Richard P. Feynman The Sir Douglas Robb Lectures, University of Auckland, 197
498 Kbps
0:17 / 1:40:21
Real Guide
Music & My Library
Music Store

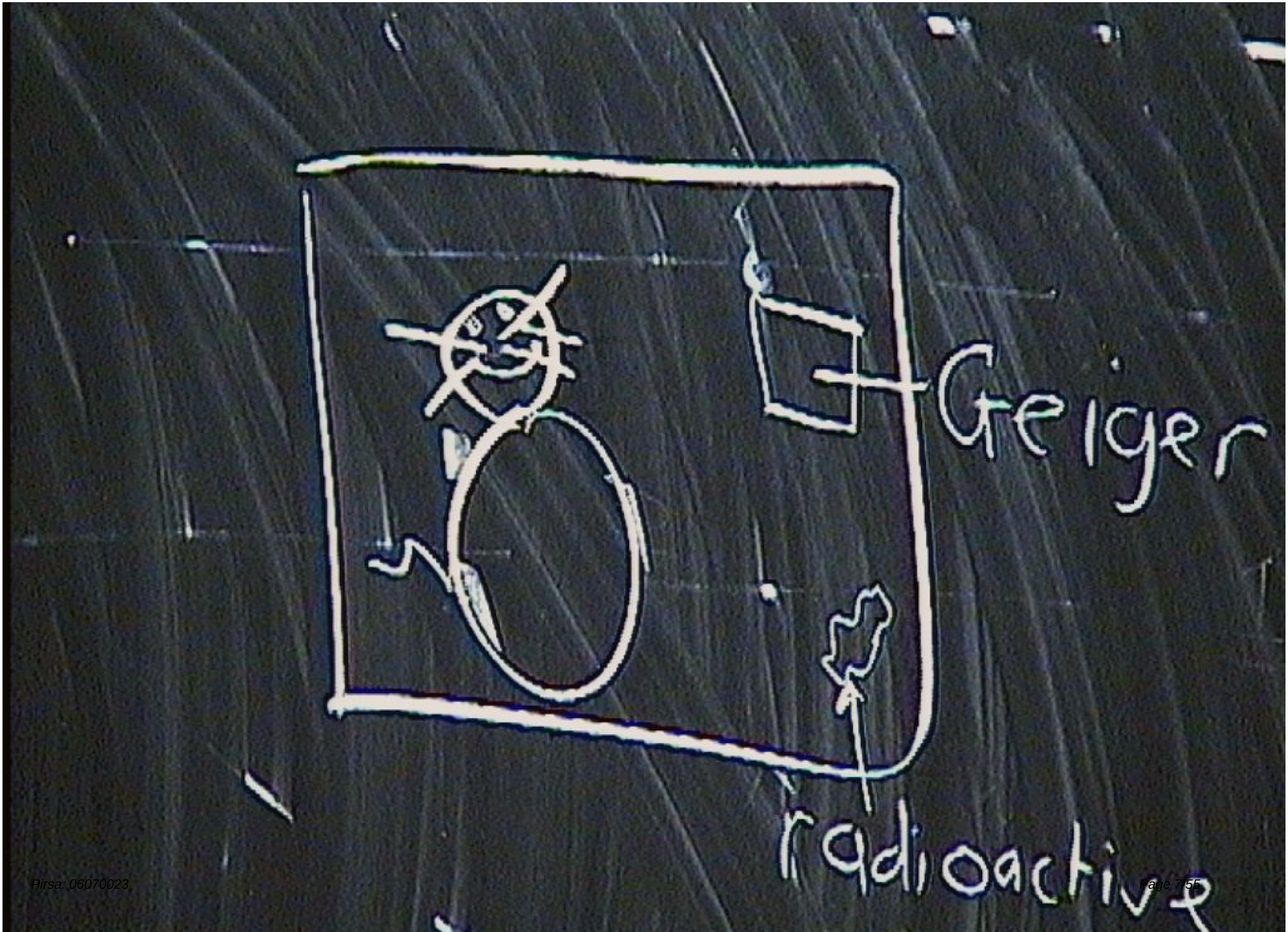
- Let us think about, say, the 467th electron to pass through wall A.
- Can we predict whether it will go through slit 1 or 2?

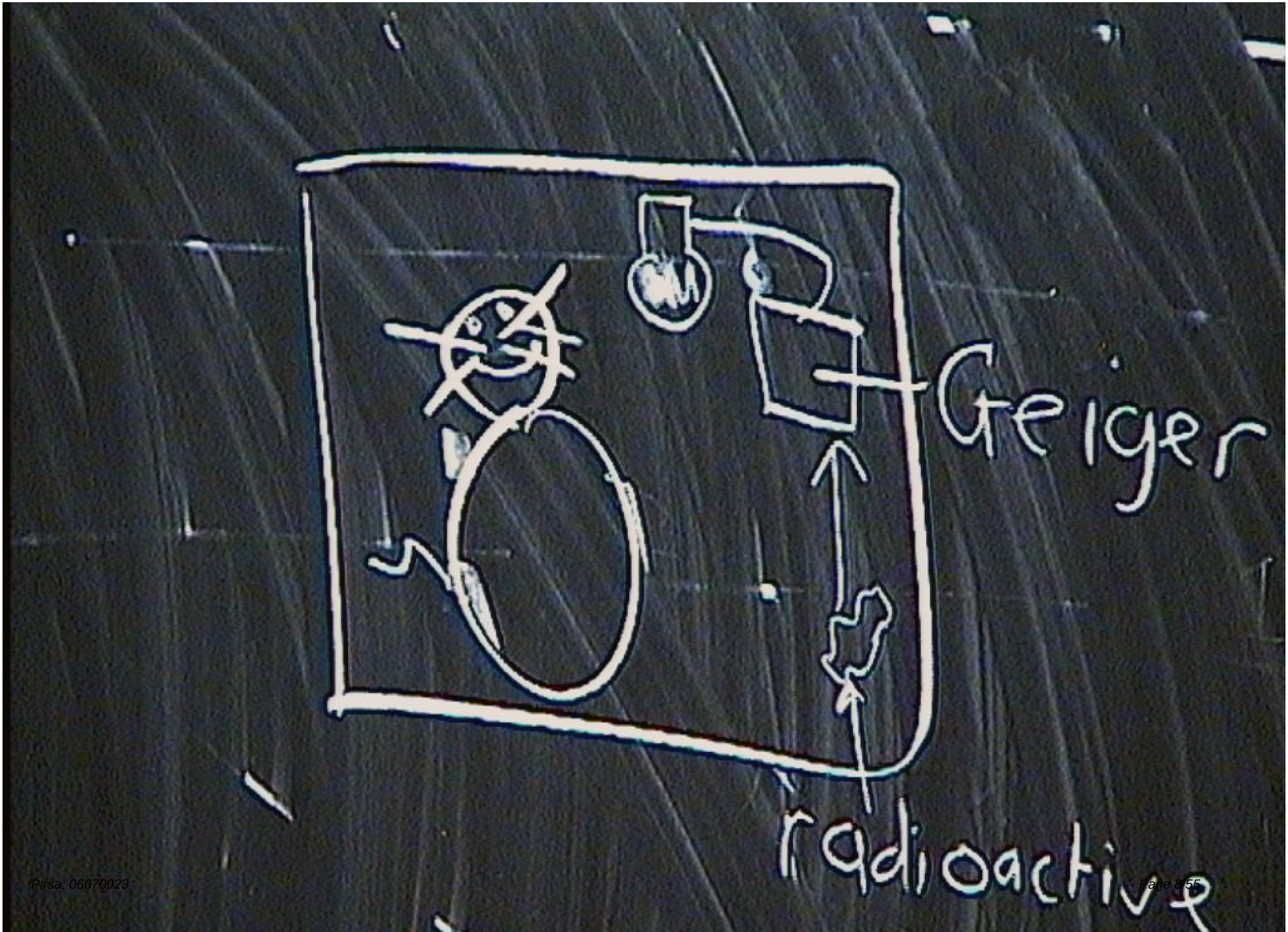
- Impossible to predict which slit the 467th electron (or any other) will pass through.
- 50-50 probability that it will pass through each slit. *Genuinely random event.*
- Another example of genuine randomness in quantum theory: We cannot predict with certainty whether we will see Schroedinger's cat as being dead or alive upon opening the box.

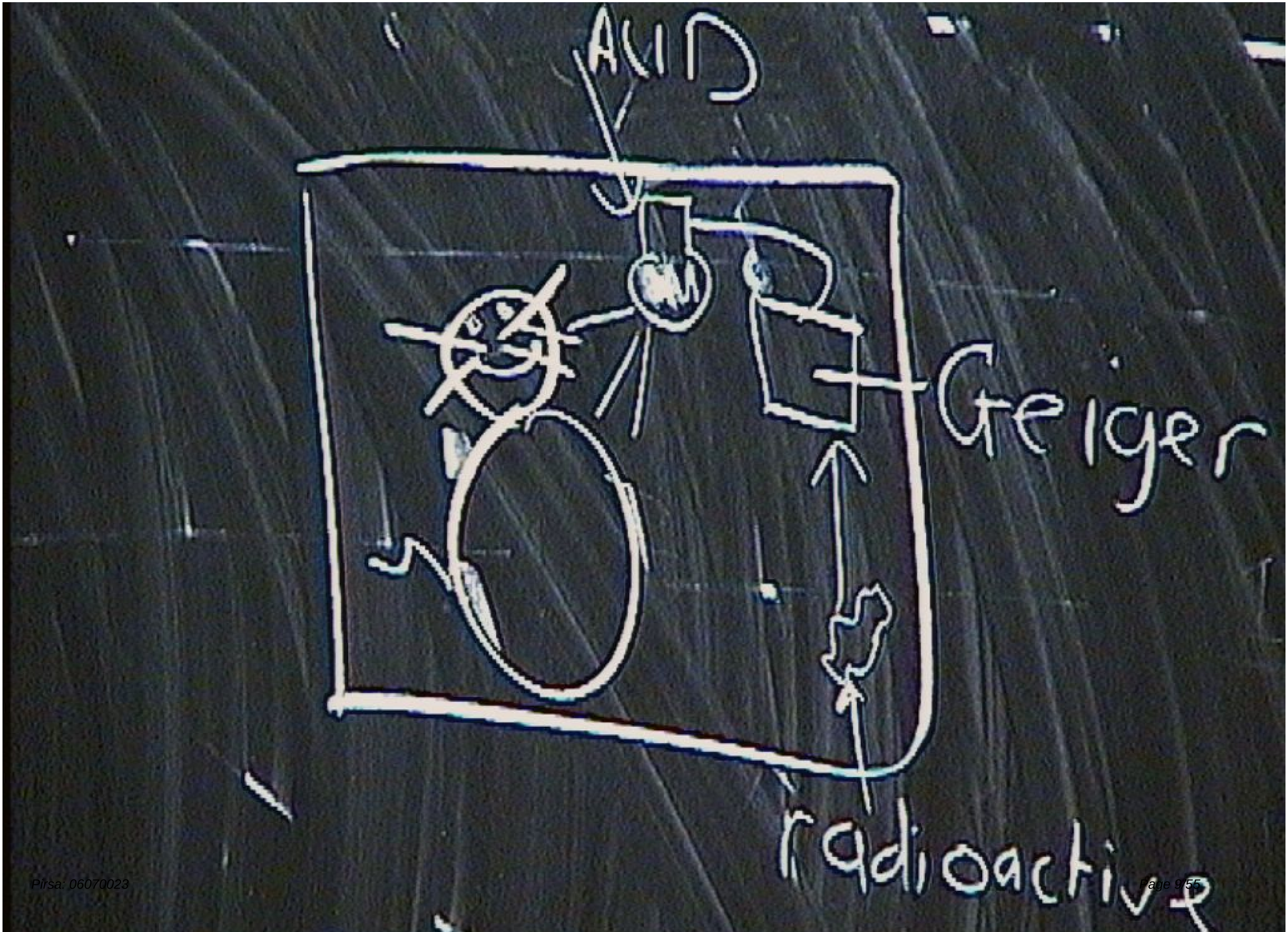
- A more familiar example: An individual radioactive decay event. Eg. inside your smoke detector
- Genuine randomness is core defining feature that runs throughout quantum theory.
- "The quantum casino."
- $|\psi|^2$ gives the probability (density)

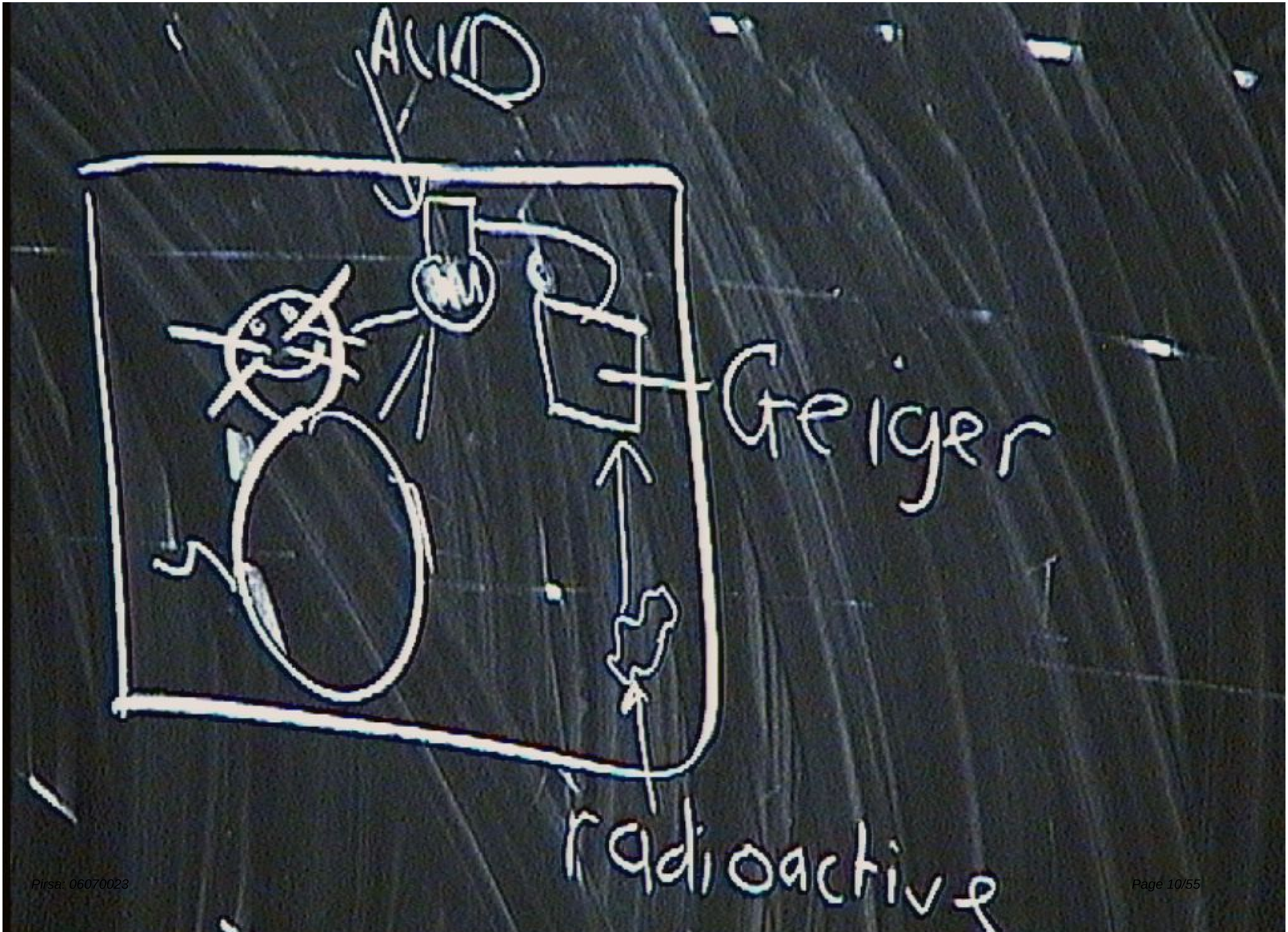



radioactive


Geiger
radioactive

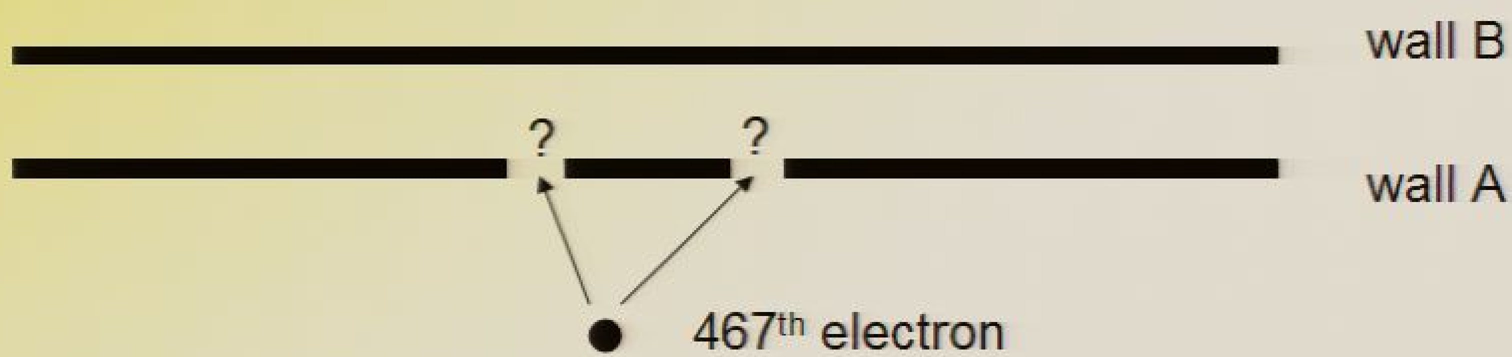

Geiger
radioactive


ACID
Geiger
radioactive


ACID
Geiger
radioactive

- Impossible to predict which slit the 467th electron (or any other) will pass through.
- 50-50 probability that it will pass through each slit. *Genuinely random event.*
- Another example of genuine randomness in quantum theory: We cannot predict with certainty whether we will see Schroedinger's cat as being dead or alive upon opening the box.

- A more familiar example: An individual radioactive decay event. Eg. inside your smoke detector
- Genuine randomness is core defining feature that runs throughout quantum theory.
- "The quantum casino."
- $|\psi|^2$ gives the probability (density)



Practical applications?

- Commerically available quantum random number generators. Genuinely random numbers.

- Idquantique, Geneva, Switzerland.
- http://www.idquantique.com
- "When random numbers cannot be left to chance!"
- Uses include "gambling, lotteries"
- Also quantum cryptography (tour of Institute for Quantum Computing on Wednesday)

image from http://www.idquantique.com

- Deep philosophical consequences.
  Is the world, fundamentally, one big casino?

- Hard to get one's head around the idea of things just happening for no reason whatsoever.

- Spontaneously occurrences (acausal)

- Is this really possible philosophically (metaphysically)?

Who do you think is right?

DAVID: "Physics must be deterministic as it's impossible for things to just happen for without any reason. There must be a deeper, hidden cause underlying why each electron goes through the slit that it does that we haven't yet discovered."

ANDREA: "We must take quantum theory at face value and trust what it seems to be telling us because it's been proven by experiment after experiment. Therefore, we should accept that electrons goes through the slit that it does in a fundamentally random fashion."

JOANNE: "Physics is just a collection of artificial models; a set of convenient fictions that we use. Thus, it can never tell us whether or not the world is really random or deterministic. Only philosophy or religion can answer such a question."

Who do you think is right?

DAVID: “Physics must be deterministic as it’s impossible for things to just happen for without any reason. There must be a deeper, hidden cause underlying why each electron goes through the slit that it does that we haven’t yet discovered.”

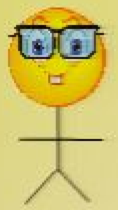
ANDREA: “We must take quantum theory at face value and trust what it seems to be telling us because it’s been proven by experiment after experiment. Therefore, we should accept that electrons goes through the slit that it does in a fundamentally random fashion.”

JOANNE: “Physics is just a collection of artificial models; a set of convenient fictions that we use. Thus, it can never tell us whether or not the world is really random or deterministic. Only philosophy or religion can answer such a question.”

Who do you think is right?

DAVID: "Physics must be deterministic as it's impossible for things to just happen for without any reason. There must be a deeper, hidden cause underlying why each electron goes through the slit that it does that we haven't yet discovered."

ANDREA: "We must take quantum theory at face value and trust what it seems to be telling us because it's been proven by experiment after experiment. Therefore, we should accept that electrons goes through the slit that it does in a fundamentally random fashion."



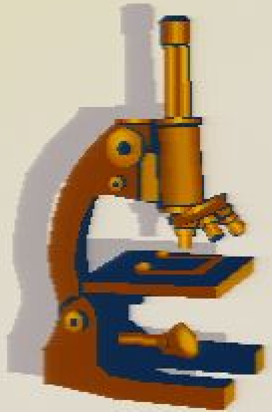
JOANNE: "Physics is just a collection of artificial models; a set of convenient fictions that we use. Thus, it can never tell us whether or not the world is really random or deterministic. Only philosophy or religion can answer such a question."

Core feature No. 4: Heisenberg's uncertainty principle

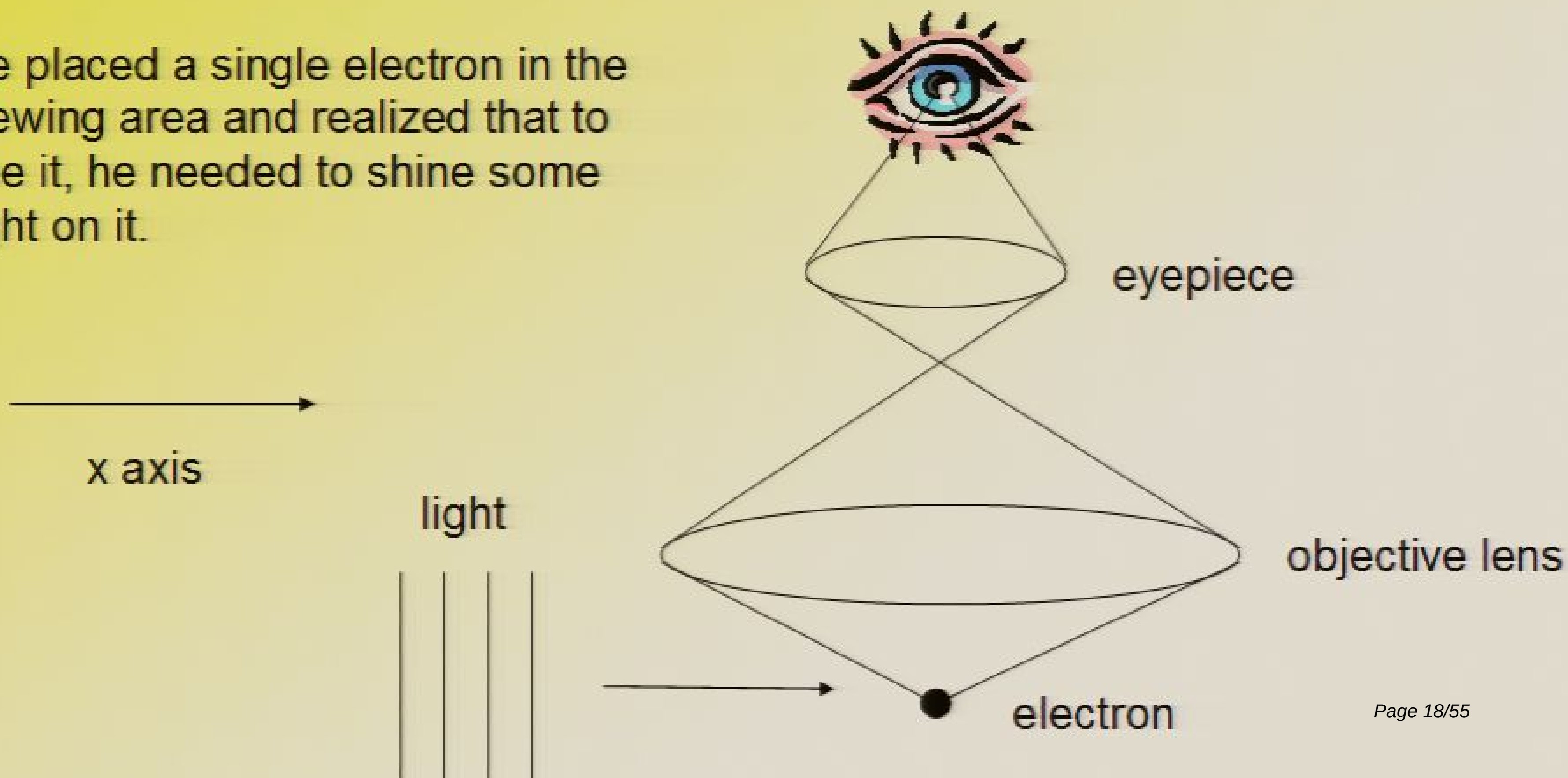
- In Newtonian physics, can we can measure both the position and the velocity of any object precisely. Eg. we can know exactly both the position and the velocity of a speck of dust drifting across a room.

- Not true for quantum entities. Heisenberg's uncertainty principle places a fundamental, 'hardwired' limit on what how much we can simultaneously know about these two properties.

- Let us consider the story of (Werner) Heisenberg trying to measure the position and the velocity of an electron using his 'gamma-ray microscope'



- Heisenberg walked into his lab one day and set up an idealized microscope.
- He placed a single electron in the viewing area and realized that to see it, he needed to shine some light on it.



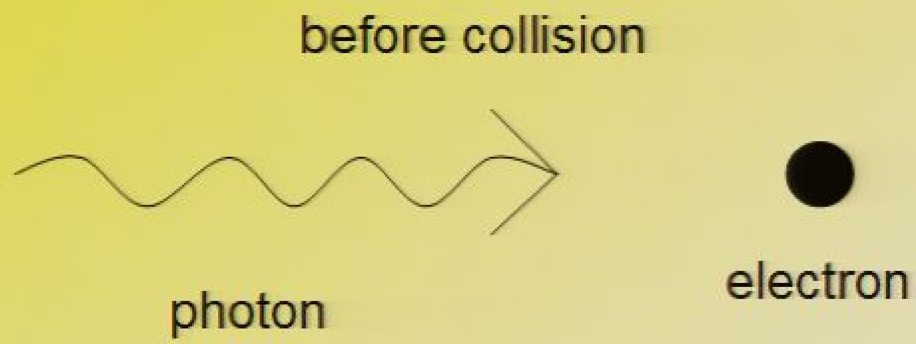
- As Heisenberg was intimately familiar with Einstein's photon hypothesis, he knew that he could think of the light as consisting of a large collection of particle-like photons.

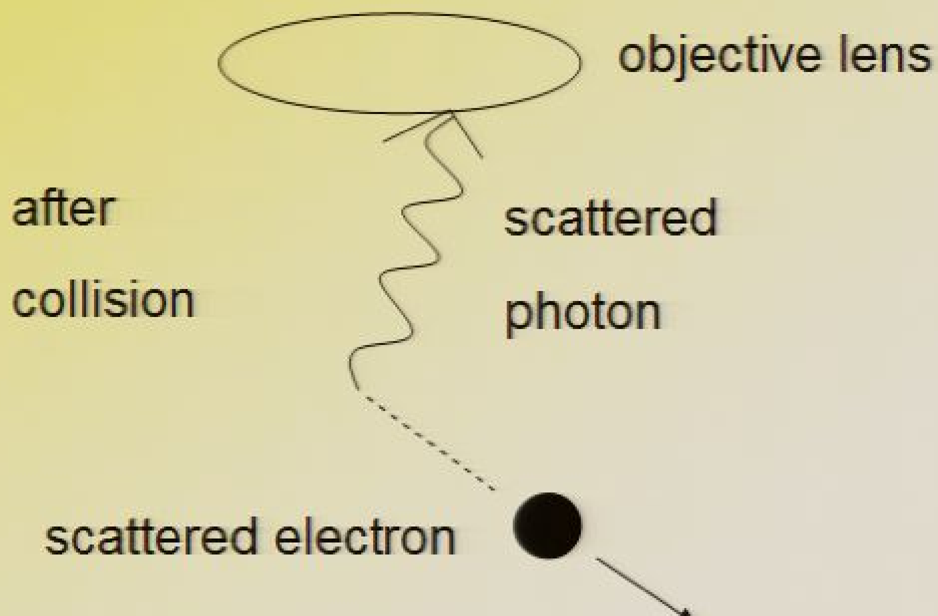
- He also knew that, as he had made sure that the light was travelling parallel to the x axis, the momentum in the x direction p_x of each photon was given by the equation $p_x = h/\lambda$, where h is Planck's constant (6.63×10^{-34} Js) and λ is the photon's wavelength.

- Of course, because he was good friends with Compton, he knew that the photons collided with the electron in particle-particle collisions modelled by the Compton effect

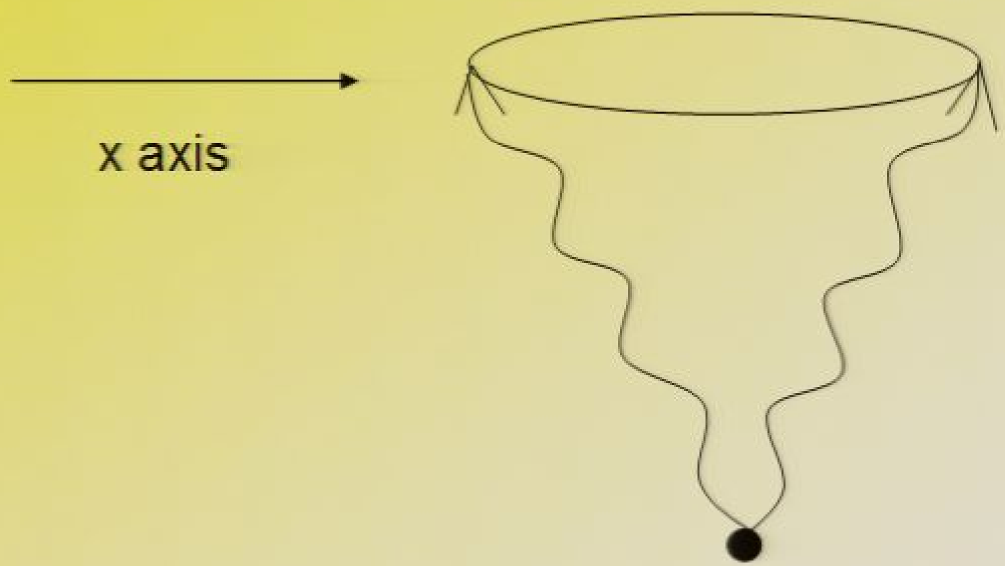
- While Heisenberg was fine-tuning his microscope, he suddenly thought "Aha! I must ensure that at least one photon collides with the electron if the microscope is to be of any use."

- He then begin to visualize what would happen during and after each collision.

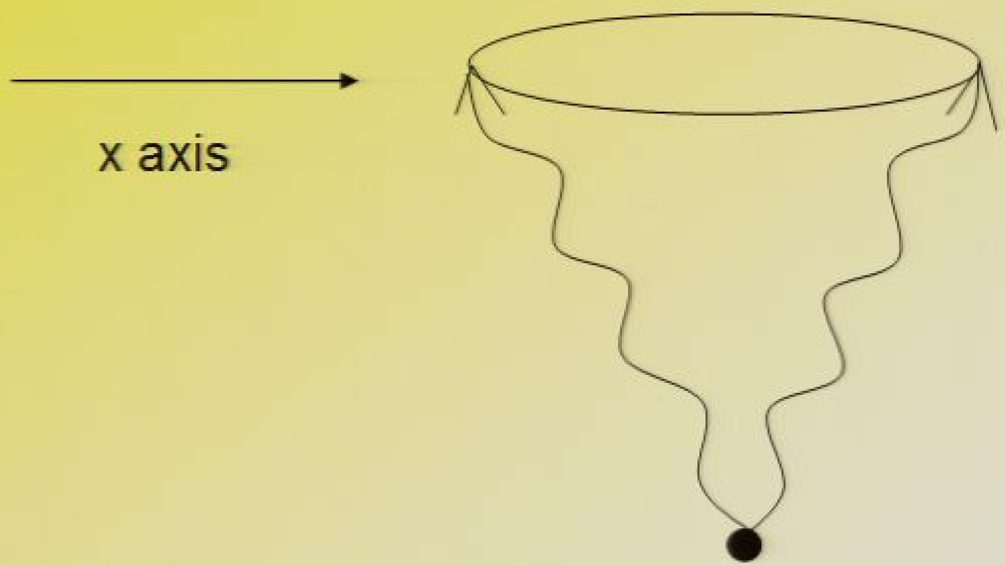




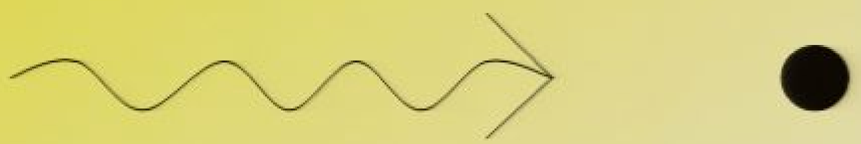
- He realized that each photon could enter the objective lens at any point along it but that, looking through his microscope, he could not tell where the entry point was or what the angle between the photon's path and the x axis was.

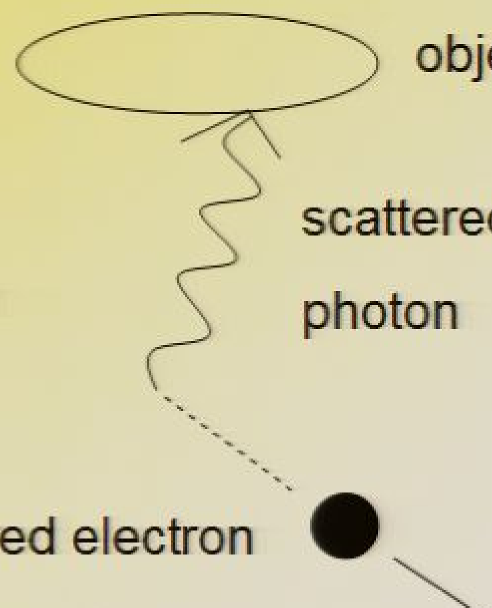


- He realized that each photon could enter the objective lens at any point along it but that, looking through his microscope, he could not tell where the entry point was or what the angle between the photon's path and the x axis was.



- He then begin to visualize what would happen during and after each collision.



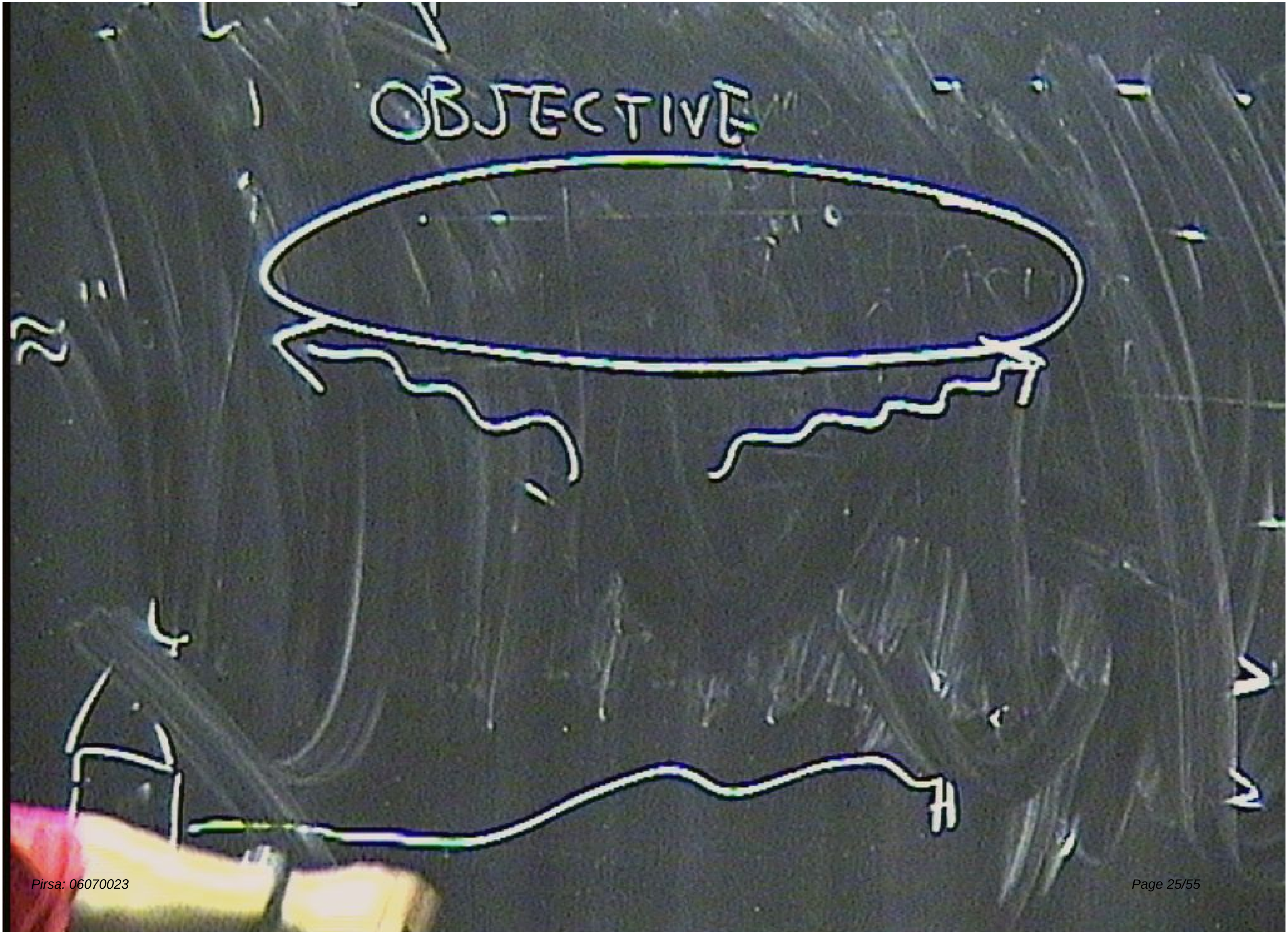


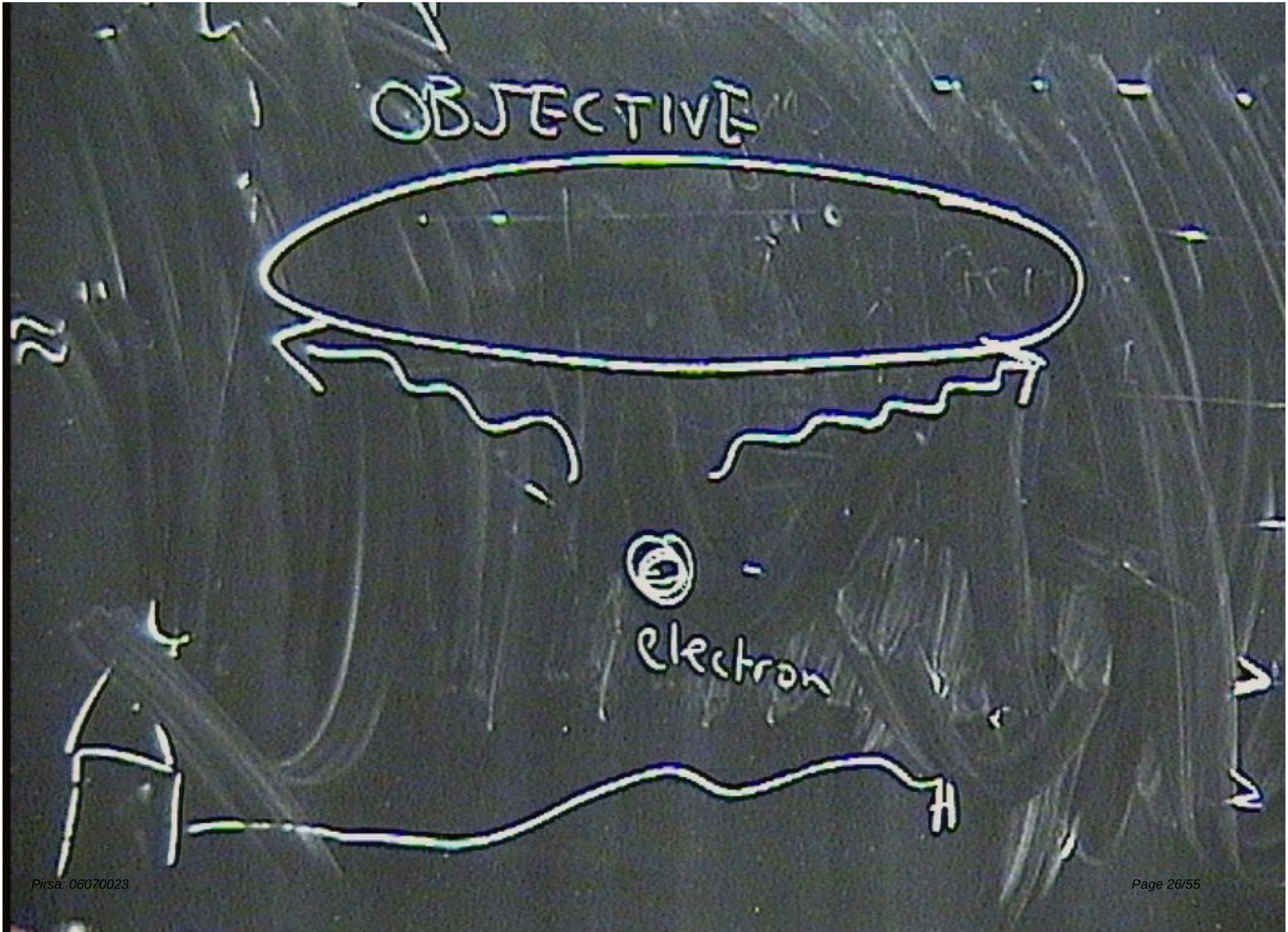
- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum $p_x=-h/\lambda$ (head-on collision) and one travelling in the positive x direction with momentum $p_x=h/\lambda$ (glancing collision).

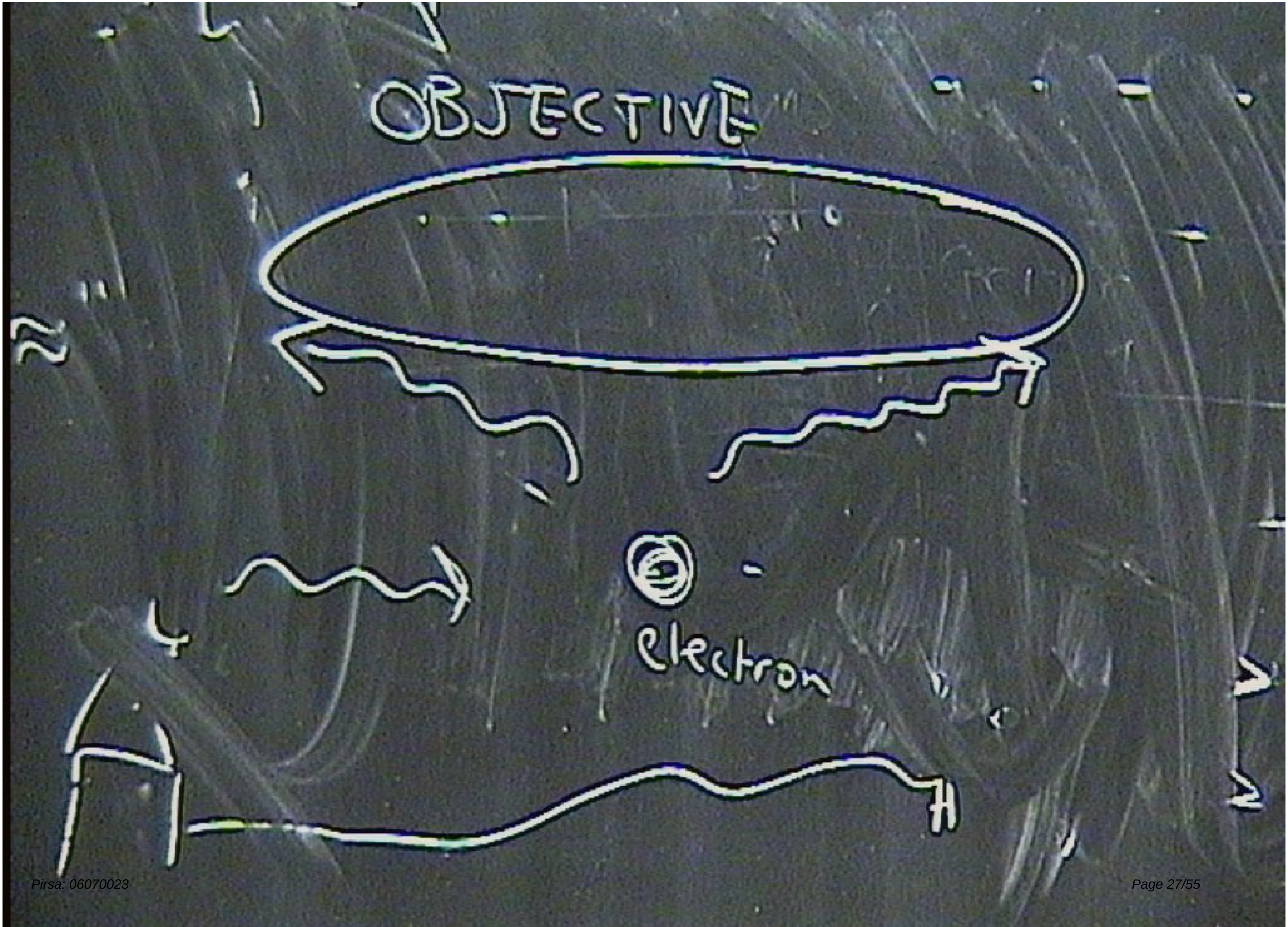
- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x=p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

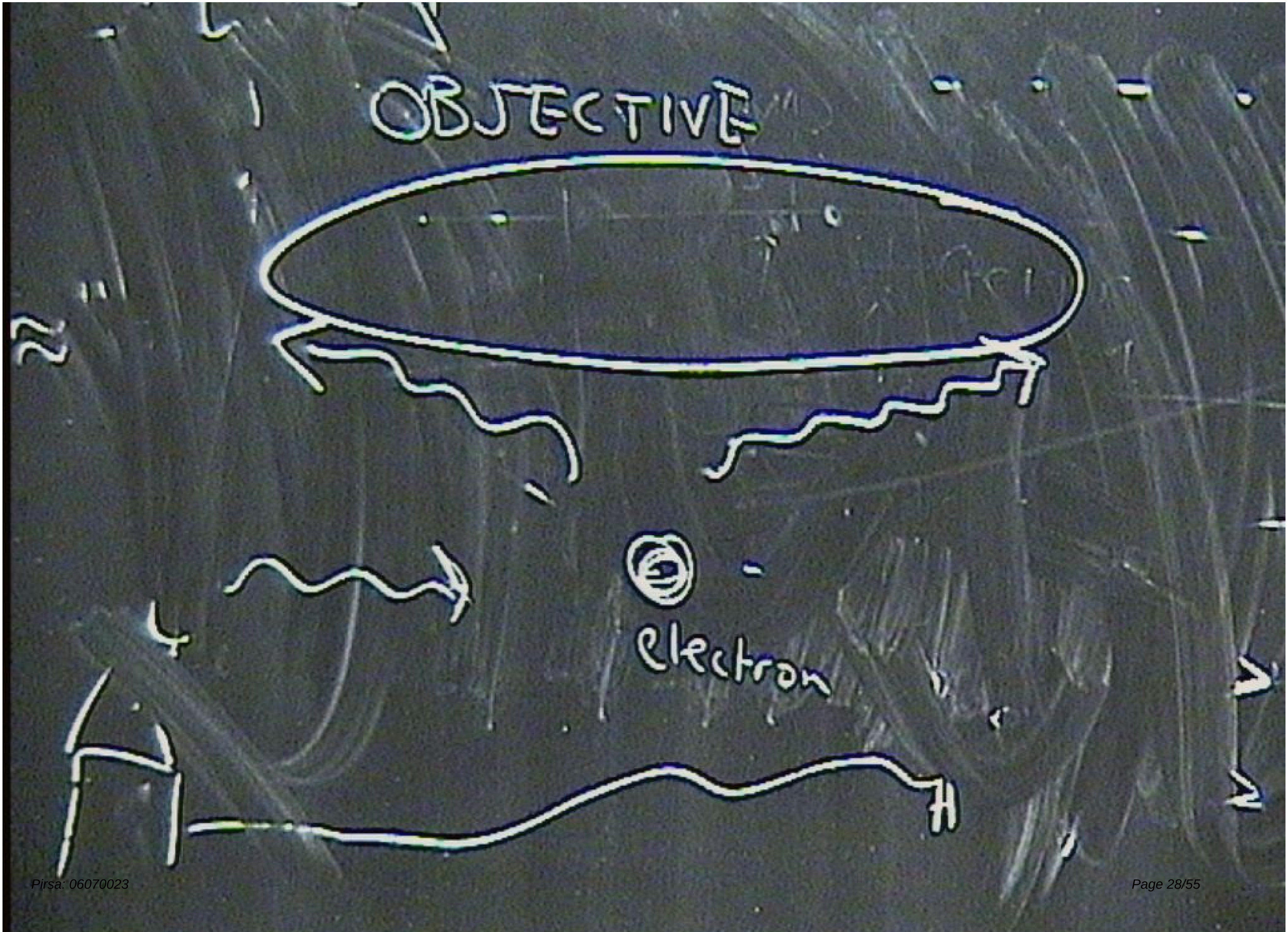
- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.


OBJECTIVE


OBJECTIVE
electron


OBJECTIVE
electron

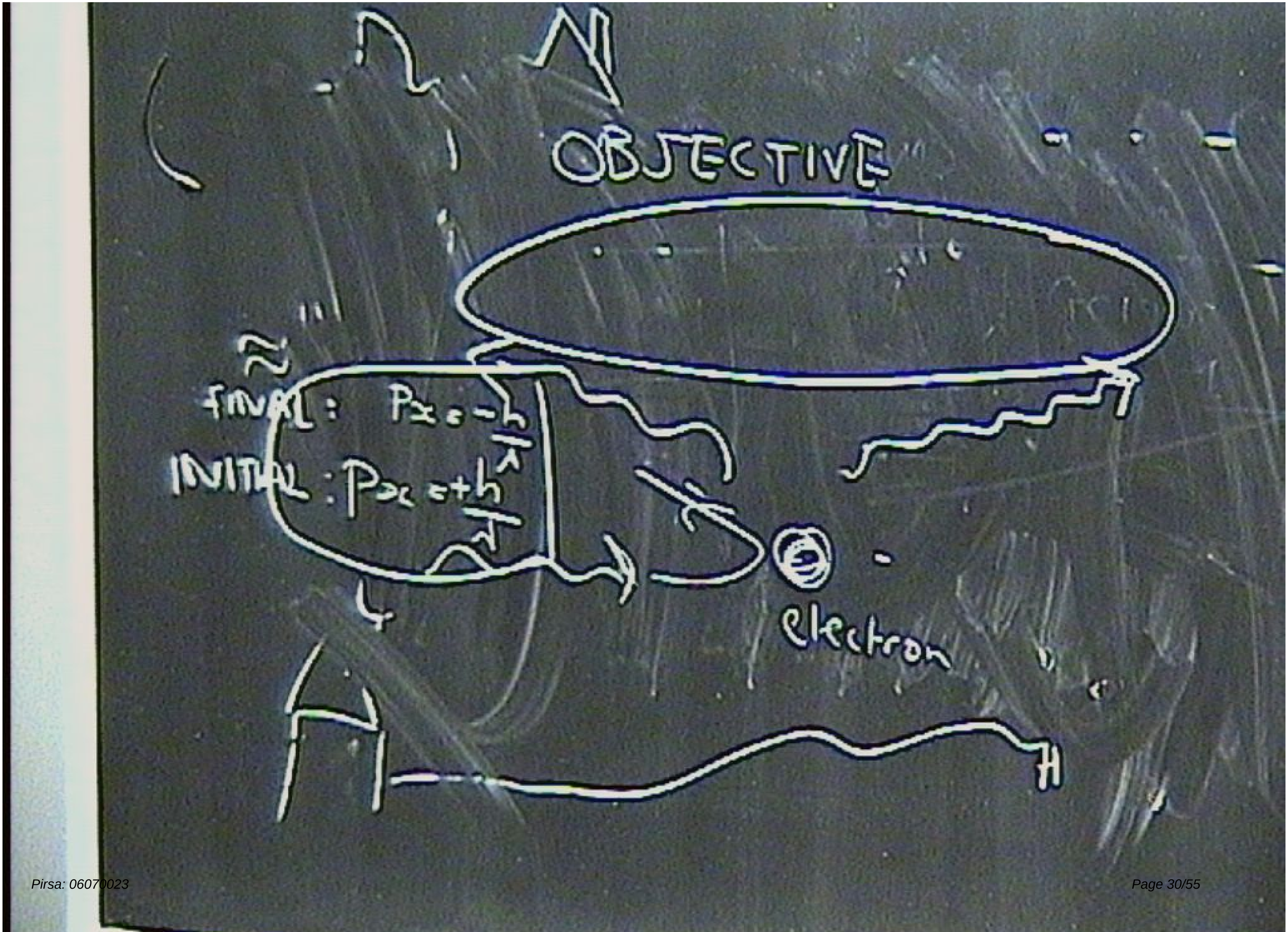

OBJECTIVE
electron

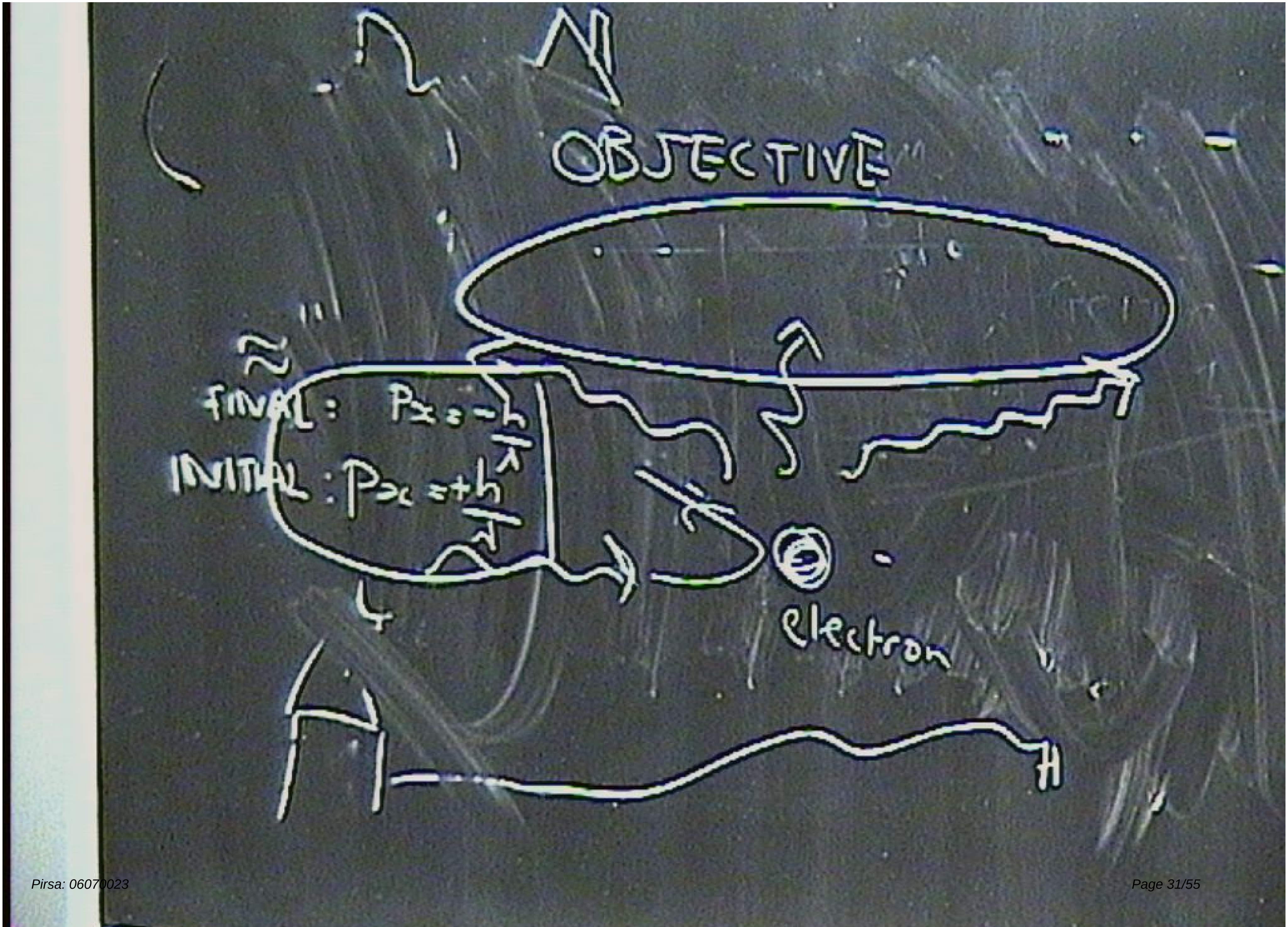
- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum $p_x=-h/\lambda$ (head-on collision) and one travelling in the positive x direction with momentum $p_x=h/\lambda$ (glancing collision).

- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x=p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.


OBJECTIVE
FINAL : Px = -h/λ
INITIAL : Px = +h/λ
electron

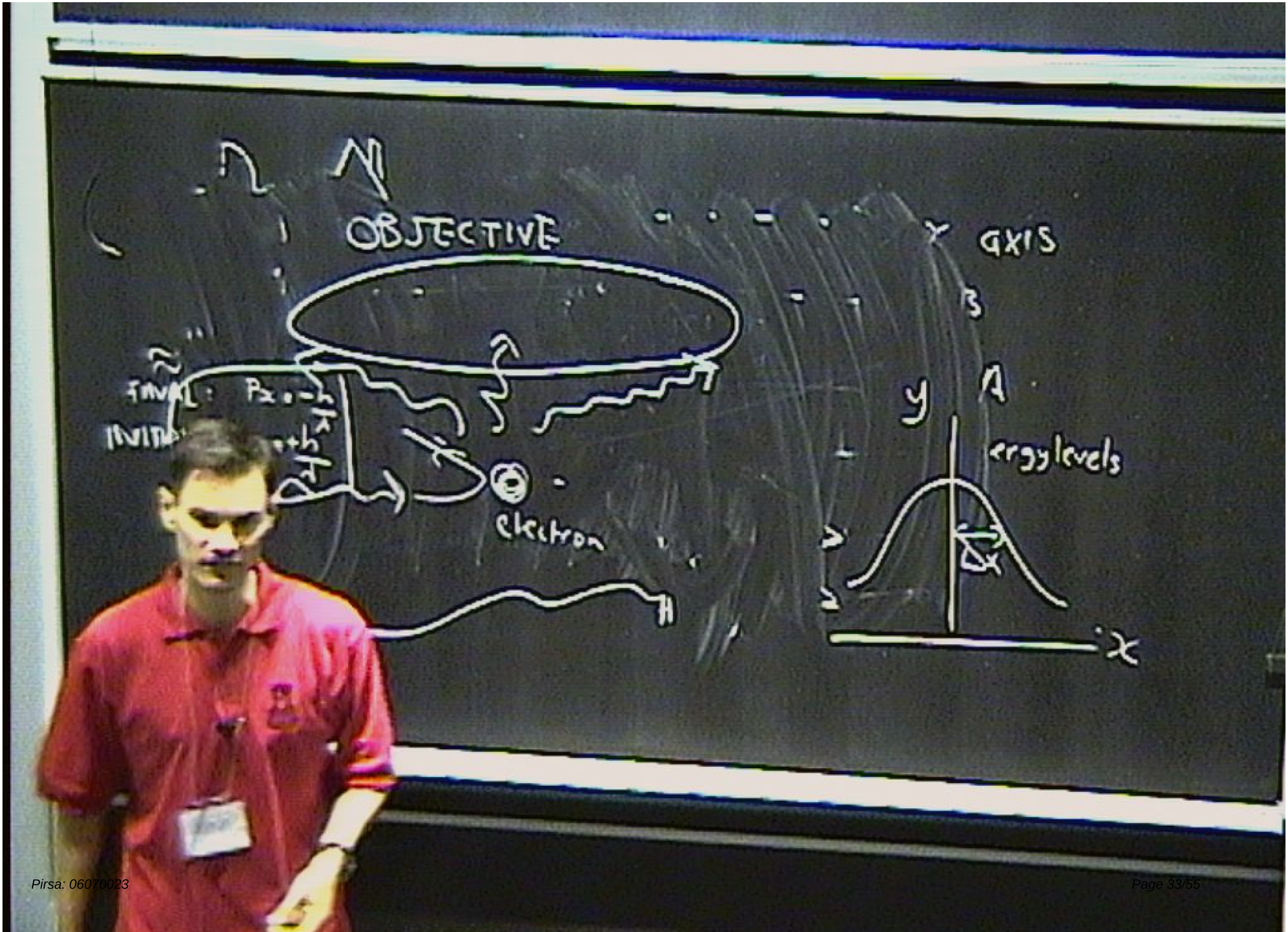

OBJECTIVE
FINAL : Px = -h/λ
INITIAL : Px = +h/λ
electron

- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum p_x=-h/λ (head-on collision) and one travelling in the positive x direction with momentum p_x=h/λ (glancing collision).

- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x = p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.


OBJECTIVE
B
A
y
ergylevels
electron
H
x

- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum $p_x=-h/\lambda$ (head-on collision) and one travelling in the positive x direction with momentum $p_x=h/\lambda$ (glancing collision).

- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x=p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.

- There are two ways to minimize (the electron's) Δp_x, he thought:
- 1. decrease intensity of the incident light so that just one photon hits the electron.
- 2. decrease the electron's momentum "kick" by increasing λ
- But, increasing λ has flow-on implications …

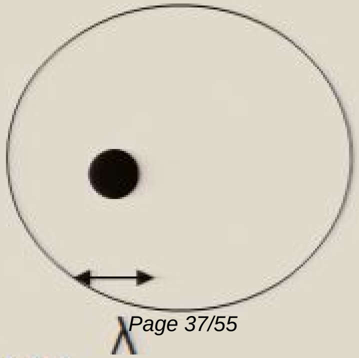
- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum p_x=-h/λ (head-on collision) and one travelling in the positive x direction with momentum p_x=h/λ (glancing collision).

- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x = p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.

- From his undergraduate days, Heisenberg knew that, as far as we know, electrons are point particles.
- But, he also recalled from Optics 101, we do not see them (or other objects) as point-like dots through a microscope.
- Rather (assuming a large number of photons are incident on the electron), we see an electron as a smeared-out circle (Airy disk) due to the diffraction of the light as it travels from the electron to the (circular) objective lens.
- Diameter of disk roughly equal to λ (given certain assumptions)
- Electron located at its centre (ignoring the effect of the collisions)

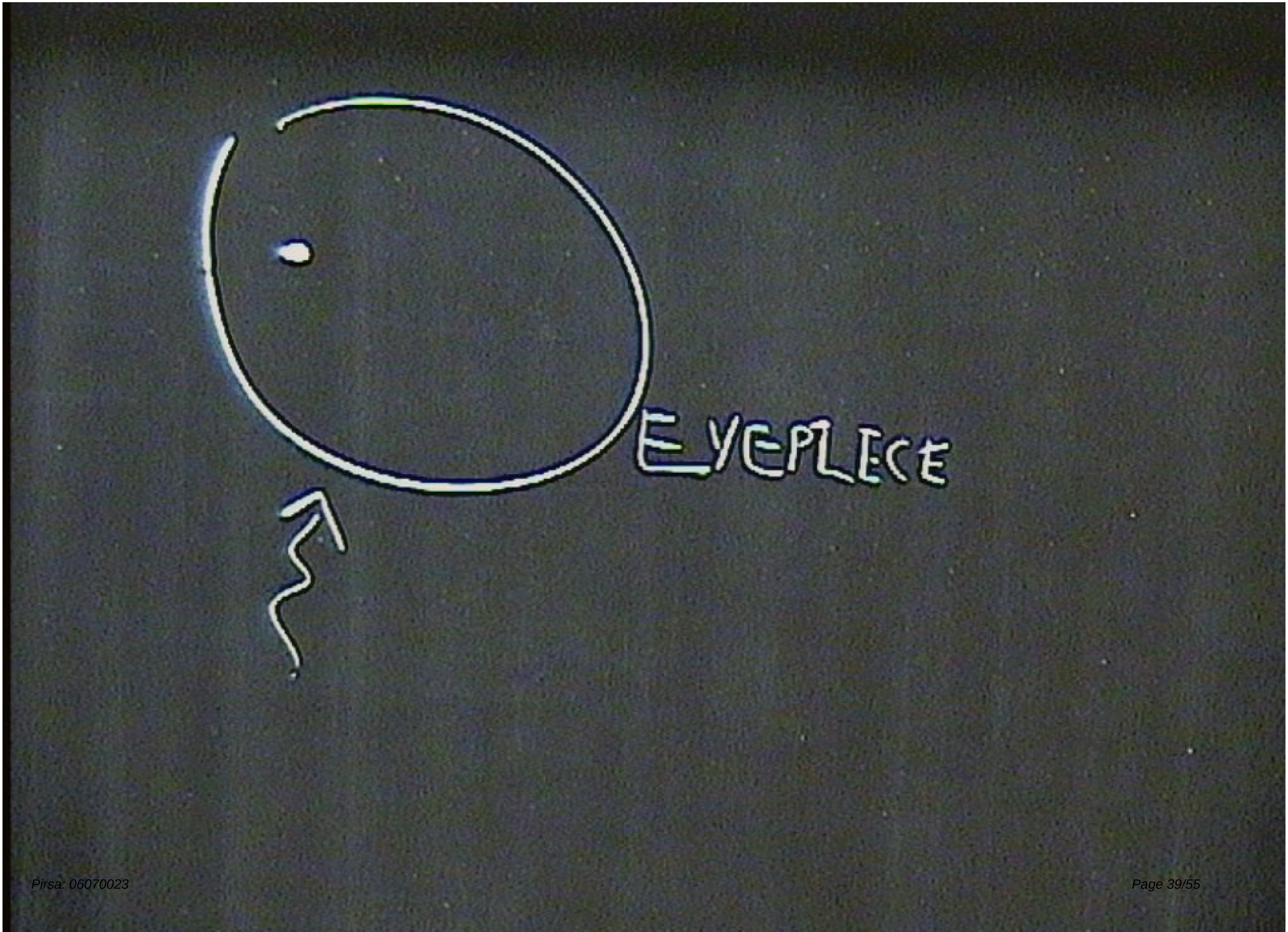


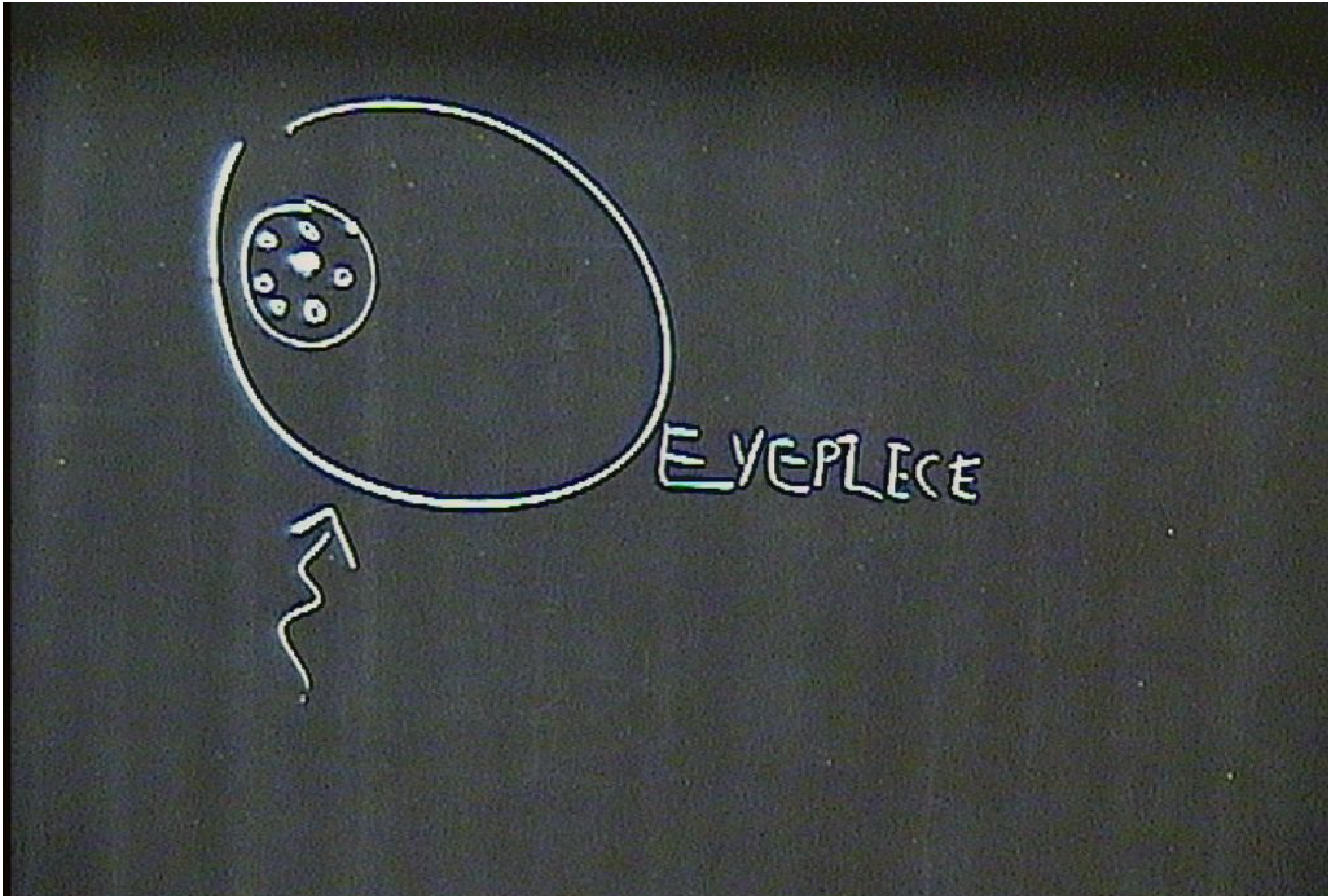
view through eyepiece

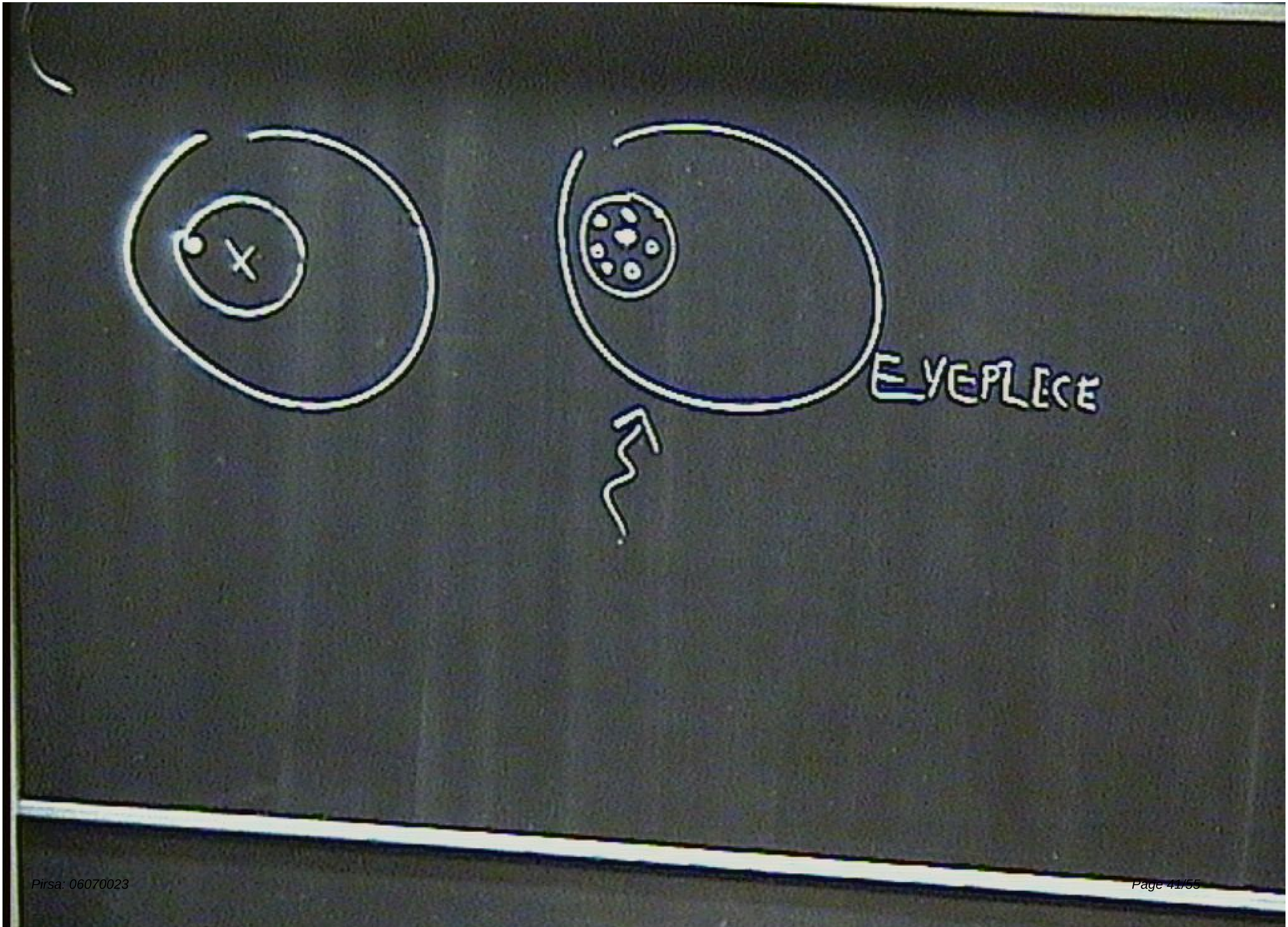
- He also vaguely seemed to remember the professor telling him that for each individual photon reaching the eyepiece, we detect it at a *random* location within the circle

- There is no strict correlation between the photon's position and electron's

- Therefore, Heisenberg surmised, if we try to find out electron's location using just one photon, we will always have an uncertainty of at least $\Delta x = \lambda$.


EYEPIECE


EYEPIECE


EYEPIECE

- Combining this limit with $\Delta p_x = h/\lambda$, he arrived at:

$\Delta x \, \Delta p \geq h$

HEISENBERG'S UNCERTAINTY PRINCIPLE

- More detailed arguments lead to $\Delta x \Delta p \geq \frac{\hbar}{2}$

$$\hbar = \frac{h}{2\pi}$$

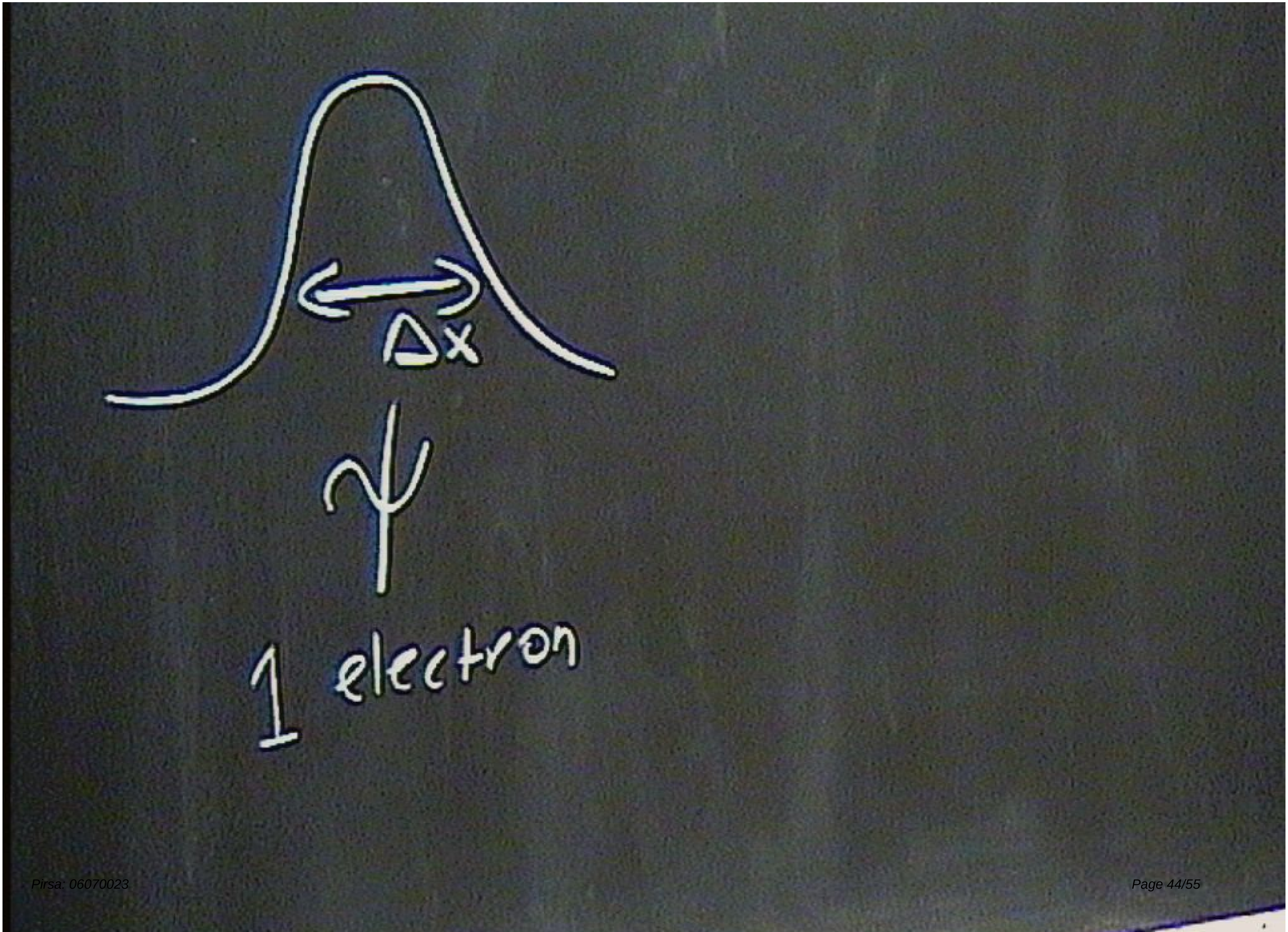
- Hardwired limit within nature (assuming quantum theory is true). Cannot measure both x and p with arbitrary accuracy

(Note: The modern (statistical) account of

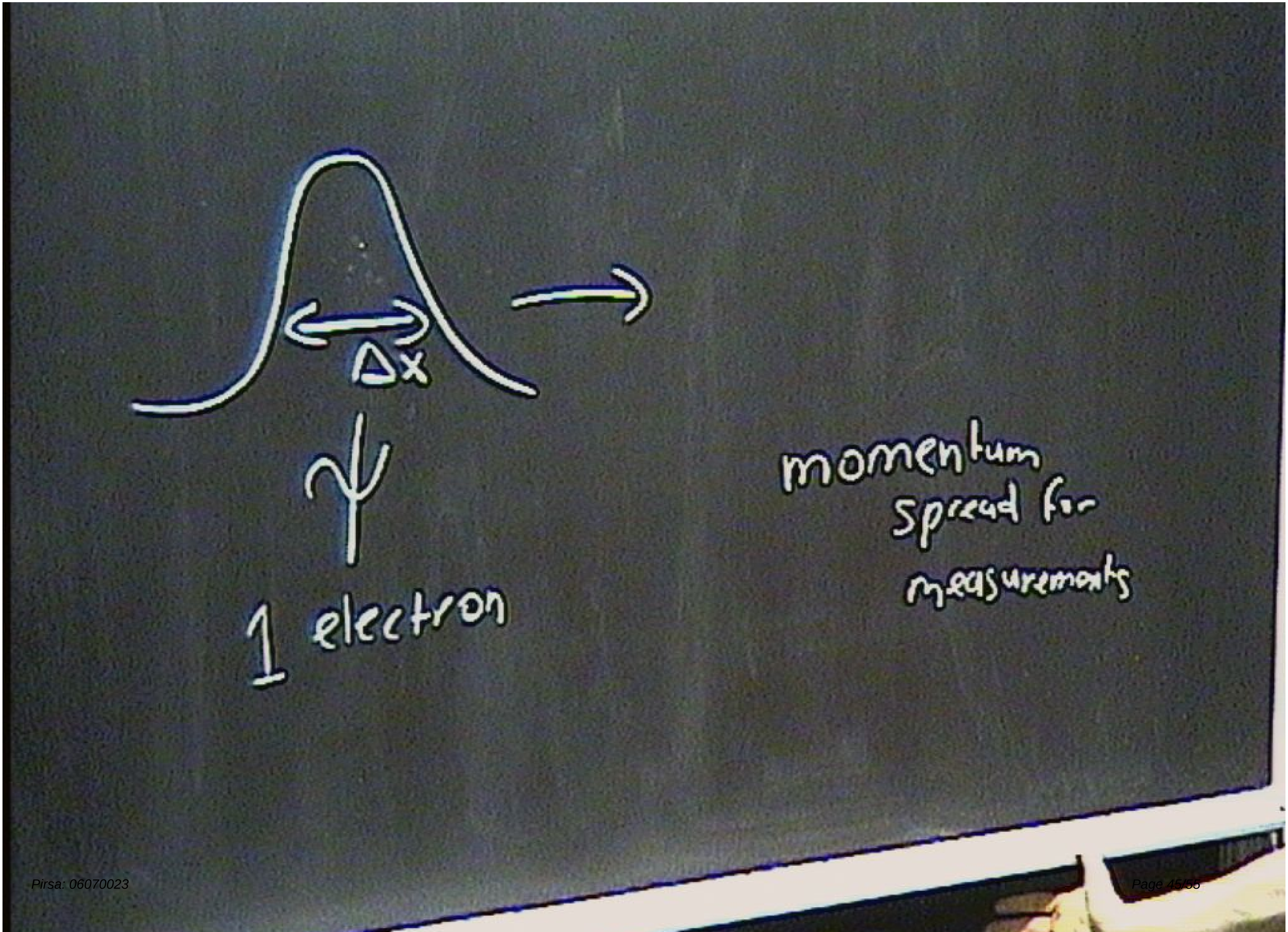
Heisenberg's uncertainty principle

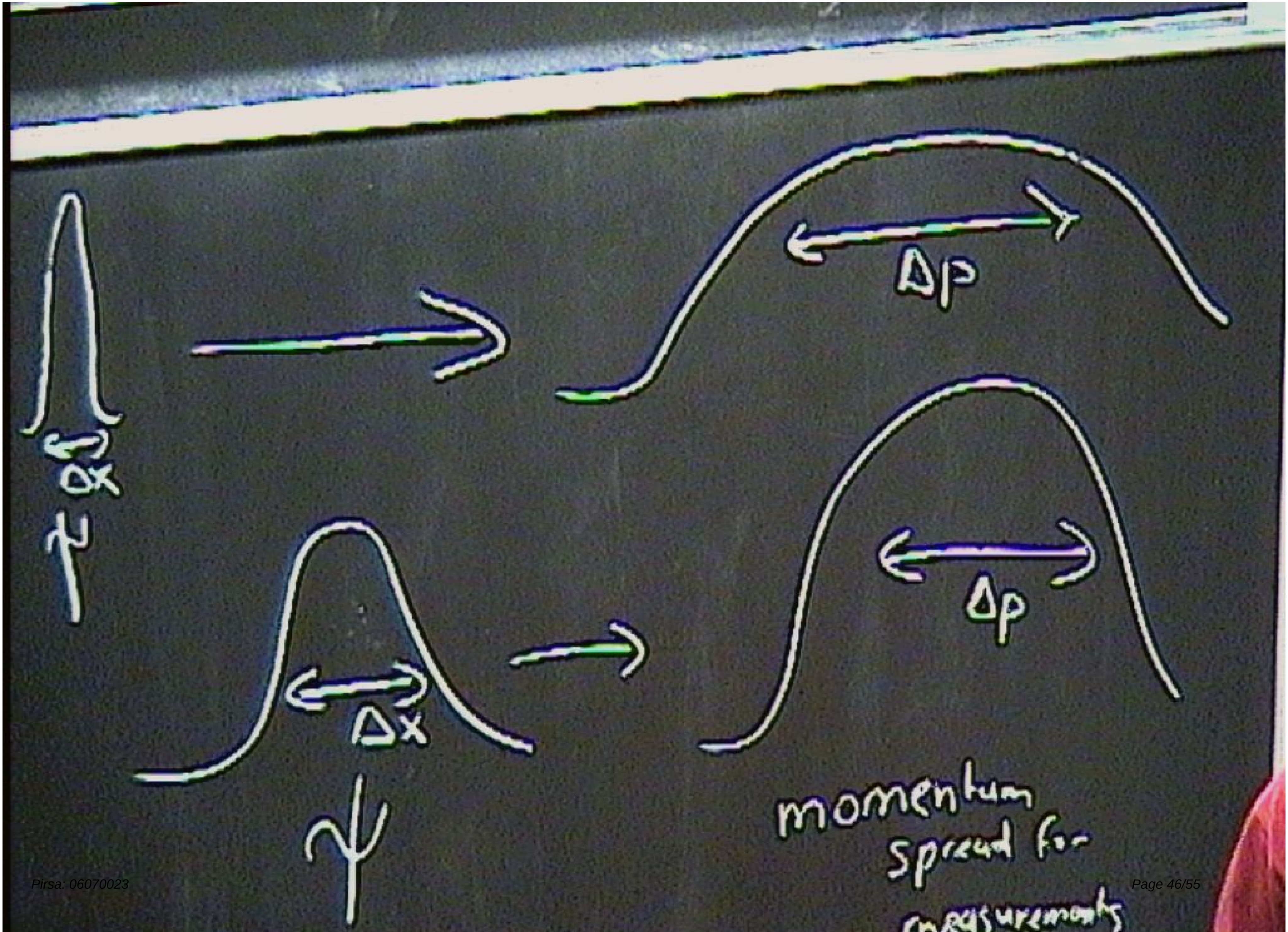
is somewhat different.)

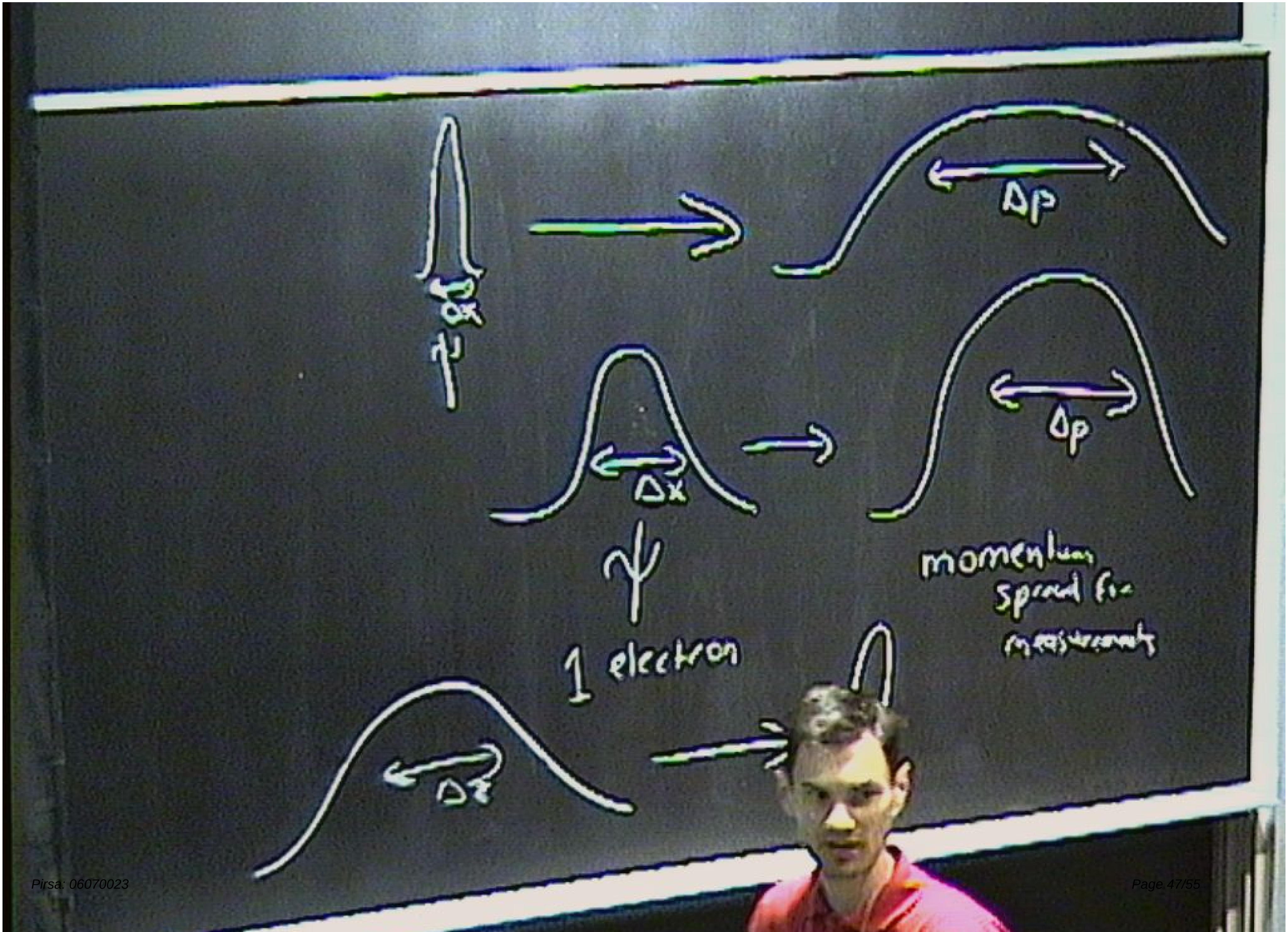
- nothing to do with imperfect equipment or unskilled physicists.
- Defining trait of quantum theory
- x and p do not simultaneously exist?
- N.B. As it is an inequality $\Delta x \, \Delta p$ can be as large as we like
- Only certain states have $\Delta x \, \Delta p = h$ (minimum uncertainty states)
- Eg. Gaussian states. $\psi(x) = A \exp(-x^2)$, where A is a constant

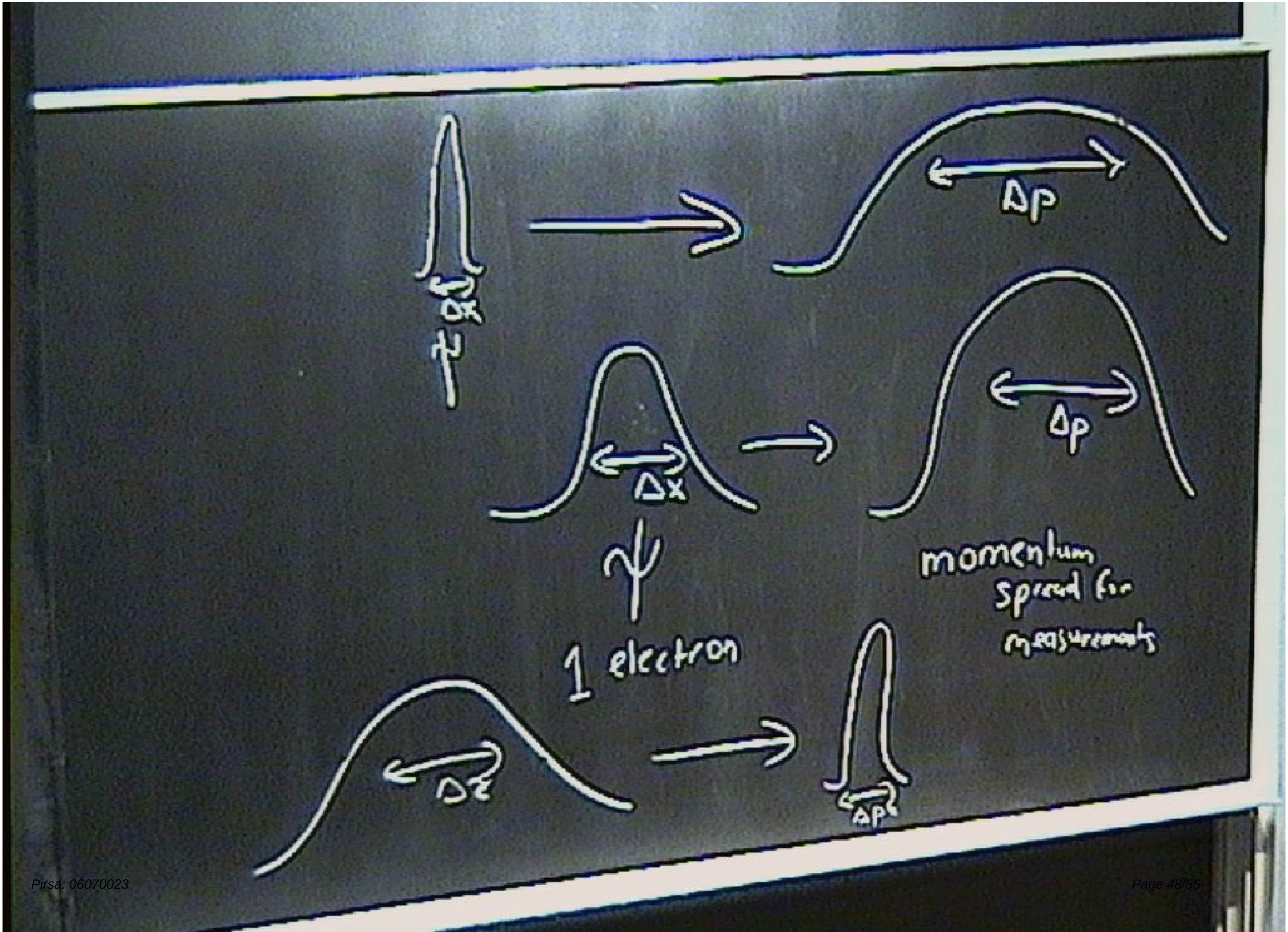


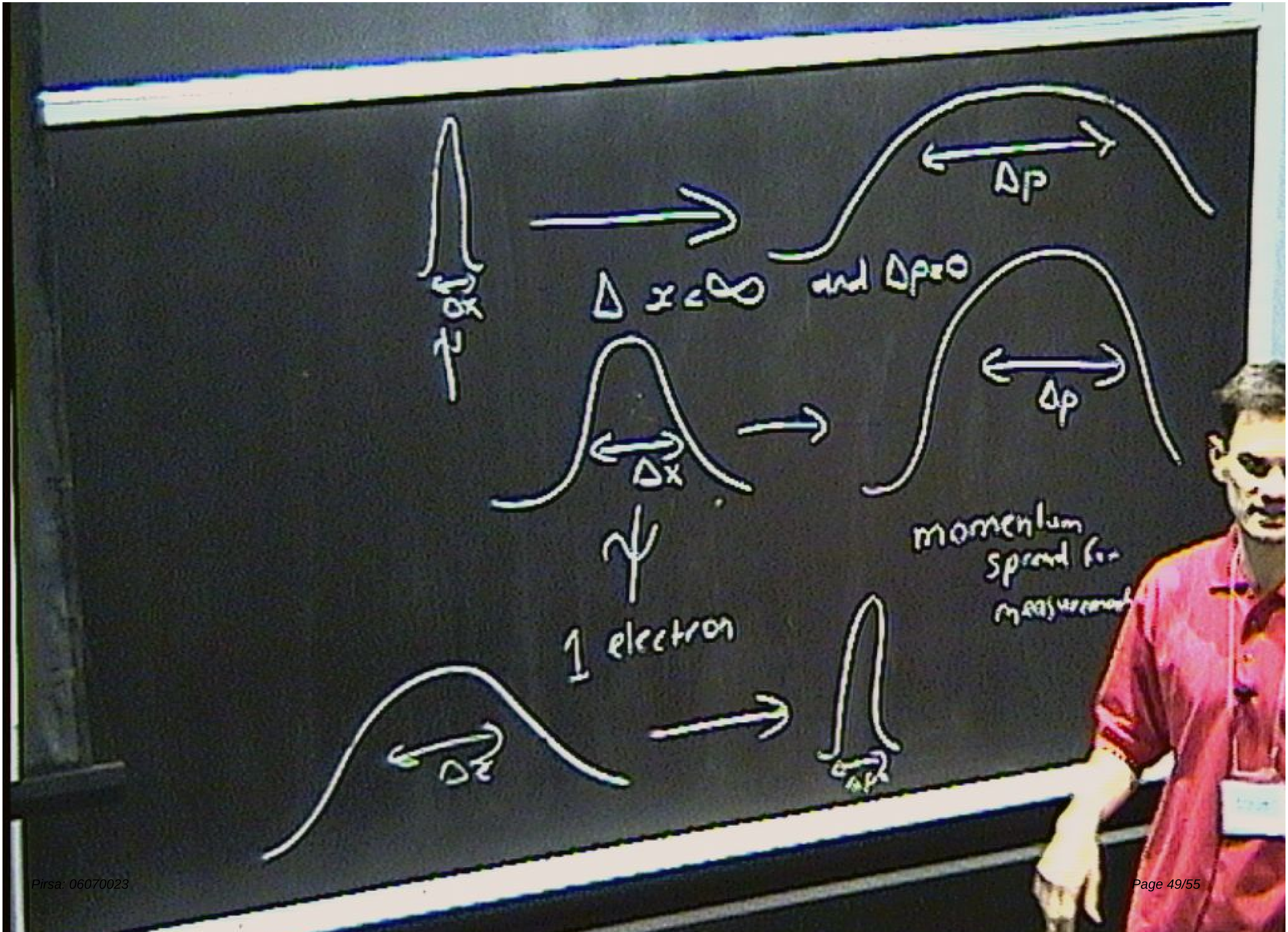
Δx
ψ
1 electron


Δx
ψ
1 electron
momentum
spread for
measurements


Δx
ψ
Δp
Δx
ψ
Δp
momentum
spread for
measurements

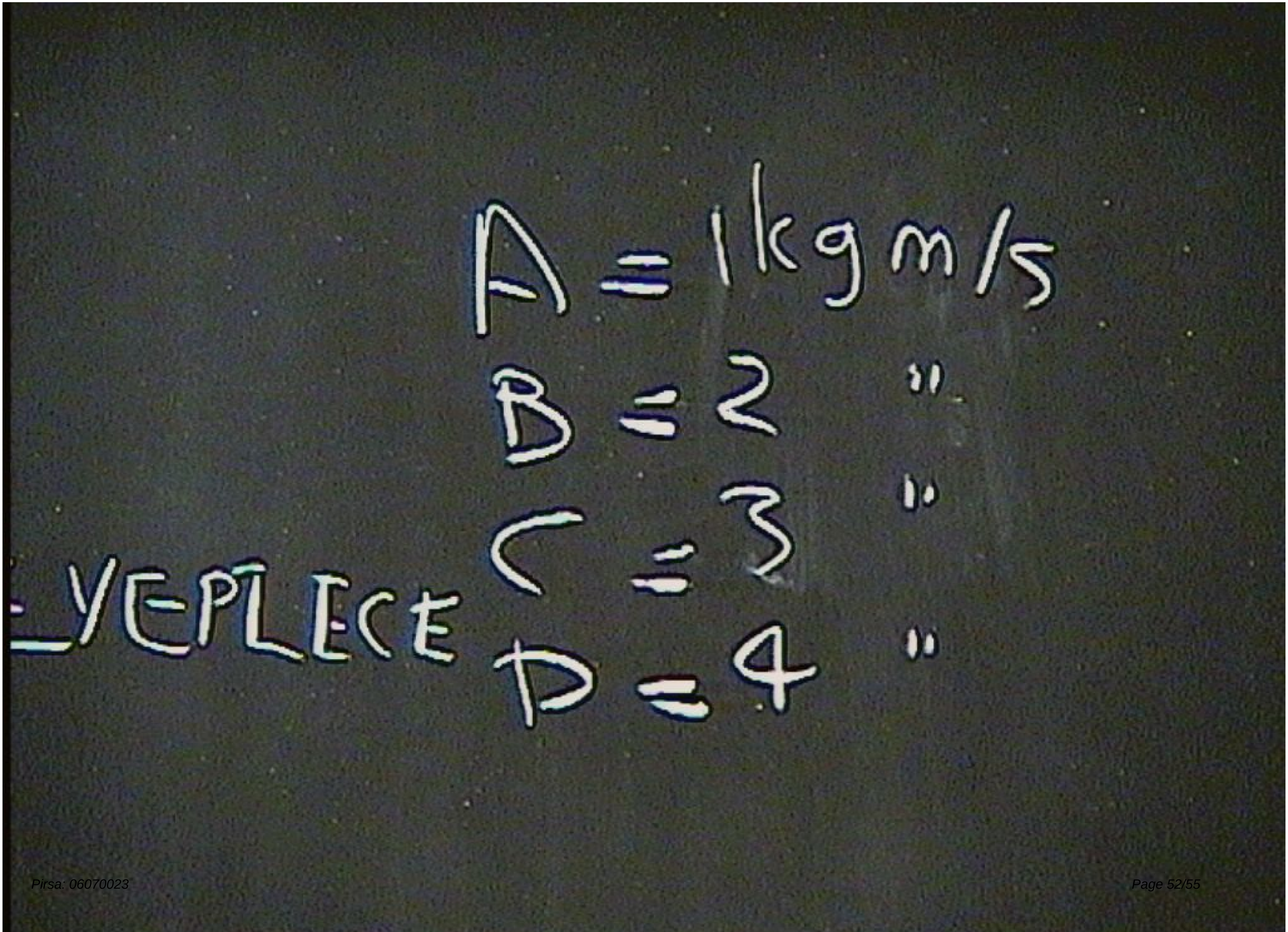

Δp
Δx
Δx
Δp
1 electron

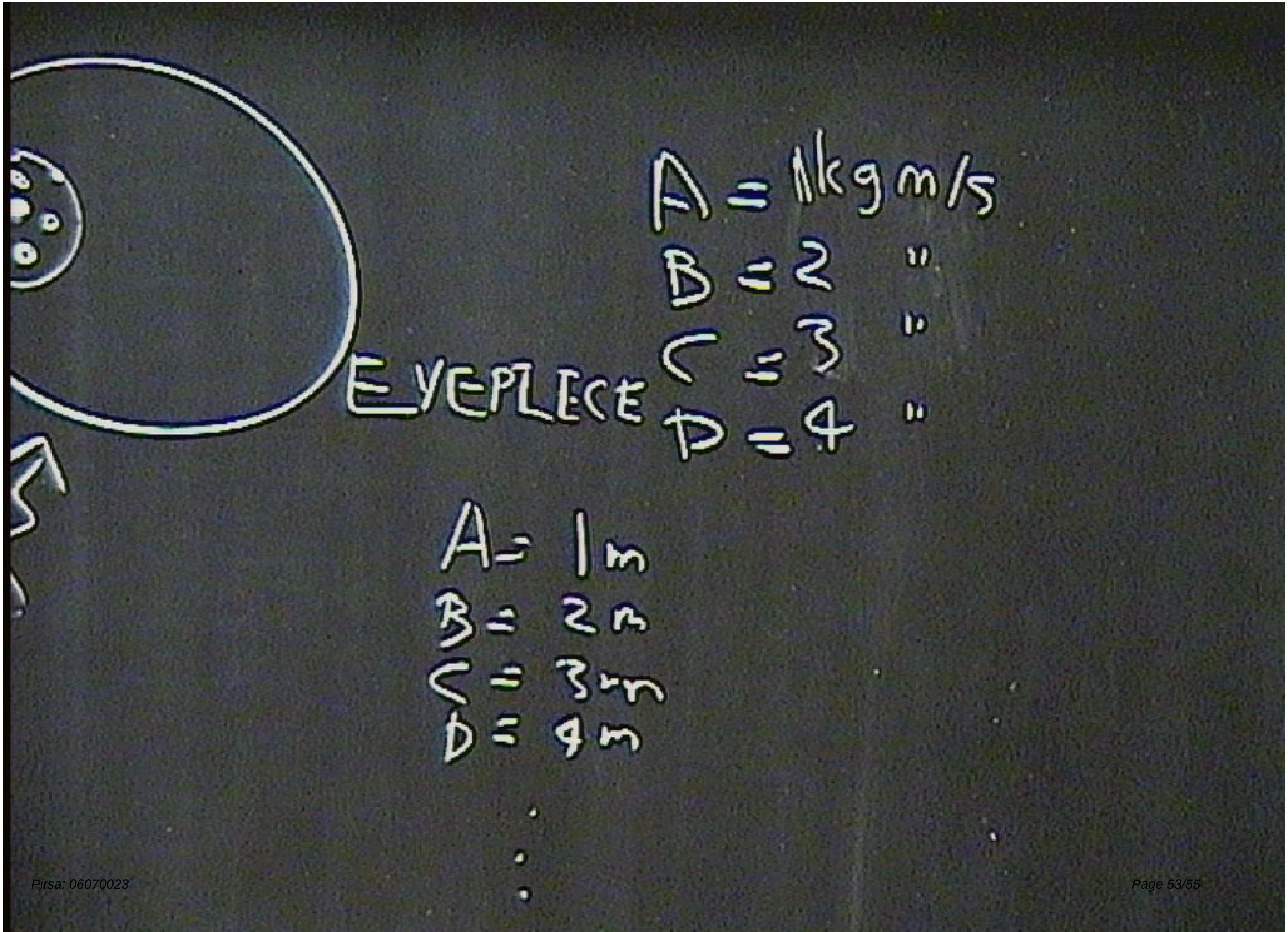

Δp
Δx
ψ
Δp
Δx
ψ
1 electron
momentum spread for measurements
Δx
Δp


Δp
Δx
ψ
and Δp≈0
Δx
ψ
Δp
momentum
spread for
measurement
1 electron
Δx
Δp

- nothing to do with imperfect equipment or unskilled physicists.
- Defining trait of quantum theory
- x and p do not simultaneously exist?
- N.B. As it is an inequality $\Delta x \, \Delta p$ can be as large as we like
- Only certain states have $\Delta x \, \Delta p = h$ (minimum uncertainty states)
- Eg. Gaussian states. $\psi(x) = A \exp(-x^2)$, where A is a constant

- application: quantum cryptography.
- Want to set up a secret string of numbers
- Called a *cryptographic key*
- Hide information in, say, the position and momentum of an electron.
- Any attempt to snoop or eavesdrop on the electron by way of measuring it, will necessarily disturb in a noticeable way.
- Can always tell if someone is eavesdropping
- Commercial reality. Quantum internet currently running in Boston.
- http://www.magiqtech.com
- $US 50,000


A = 1 kg m/s
B = 2 "
C = 3 "
D = 4 "
YEPIECE


A = 1kg m/s
B = 2 "
C = 3 "
D = 4 "
EYEPIECE
A = 1m
B = 2m
C = 3m
D = 4m

- application: quantum cryptography.
- Want to set up a secret string of numbers
- Called a *cryptographic key*
- Hide information in, say, the position and momentum of an electron.
- Any attempt to snoop or eavesdrop on the electron by way of measuring it, will necessarily disturb in a noticeable way.
- Can always tell if someone is eavesdropping
- Commercial reality. Quantum internet currently running in Boston.
- http://www.magiqtech.com
- $US 50,000

- quantum theory is hard because it's difficult to get a picture of what's going on.
- abstract rules for 'turning the handle'
- A number of pictures have been proposed.
- More on this in Dr Hans Westman's keynote presentation *Cats, collapses and the nature of reality in quantum theory …*