

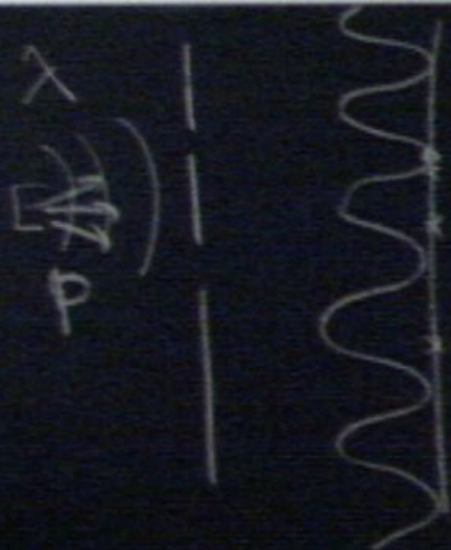
Title: Quantum 2

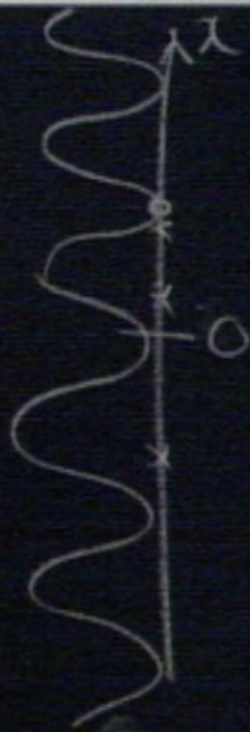
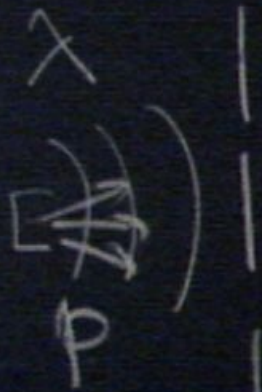
Date: Aug 12, 2009 09:00 AM

URL: <http://pirsa.org/09080052>

Abstract: Heisenberg Uncertainty Principle, Feynman sum over paths interpretation of quantum mechanics, and the harmonic oscillator: introduction to tunnelling, QFT (what is a photon?), and zero point energy.

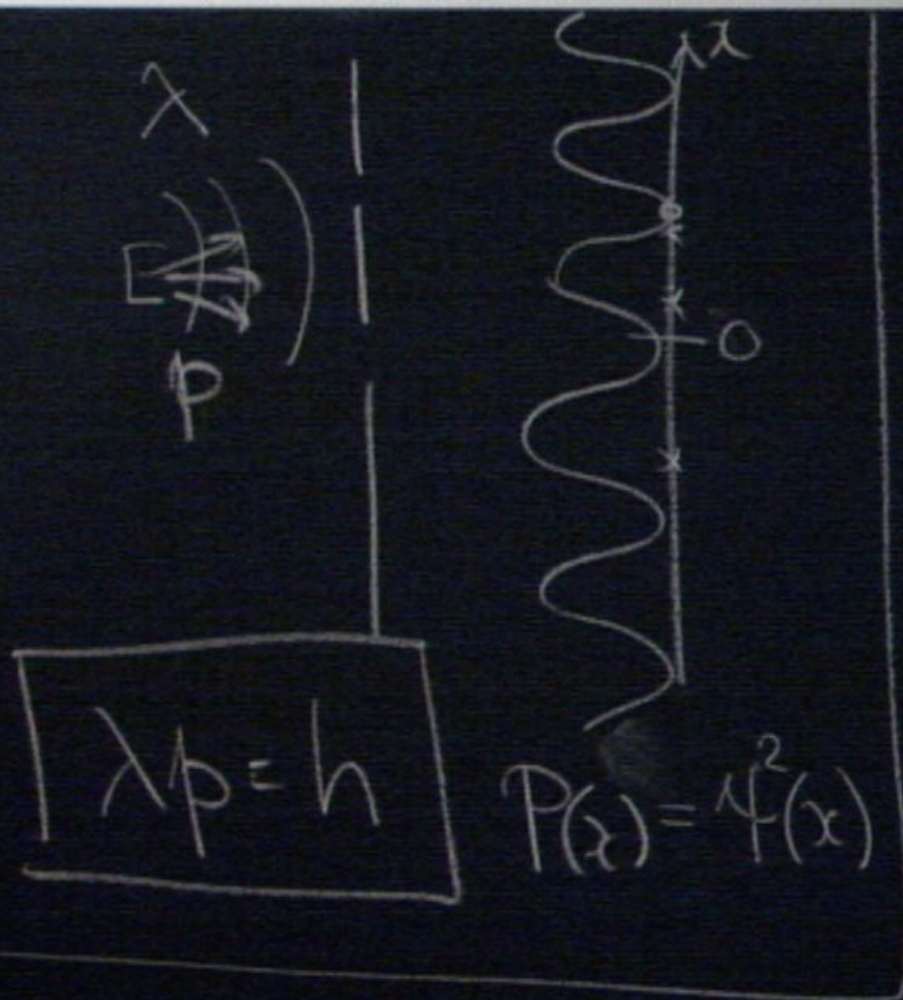




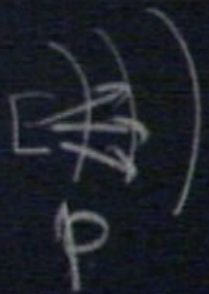


$$\lambda p = h$$

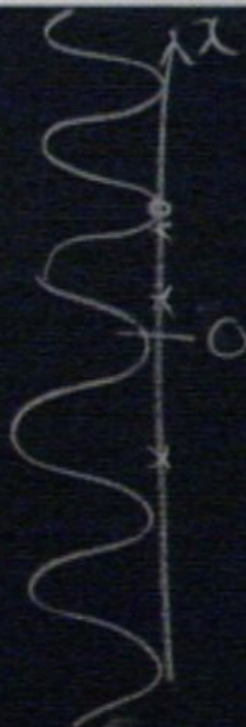
$$P(x) = \lambda^2(x)$$



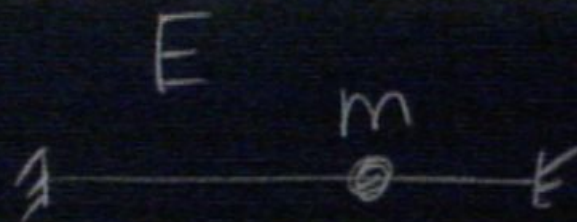
λ



$$\lambda p = h$$



$$P(x) = \psi^2(x)$$

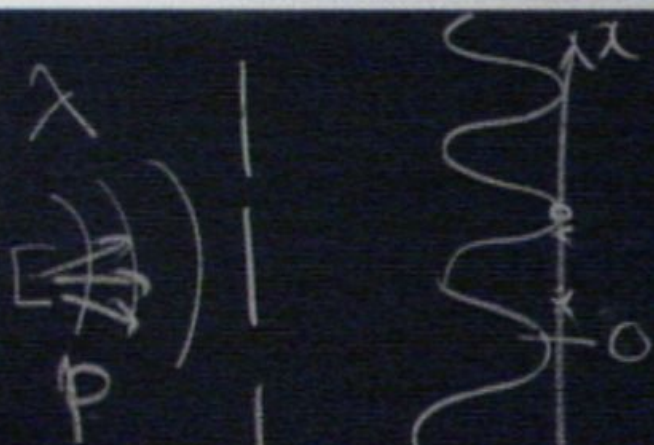




$$\lambda p = h$$

$$P(x) = \psi^2(x)$$

$$p = \pm \sqrt{2mE}$$



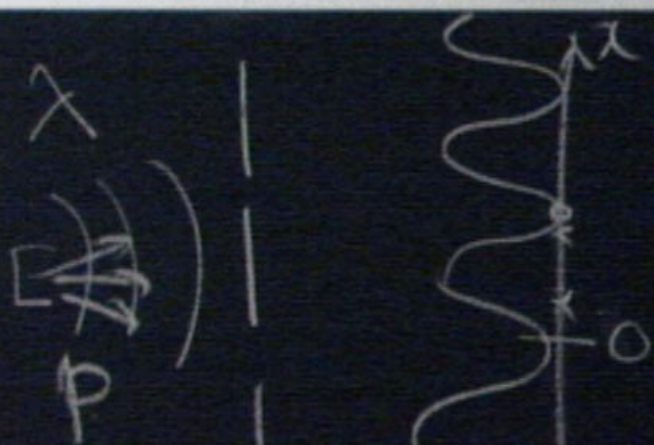
$$\lambda p = h$$

$$P(x) = \psi^2(x)$$

E

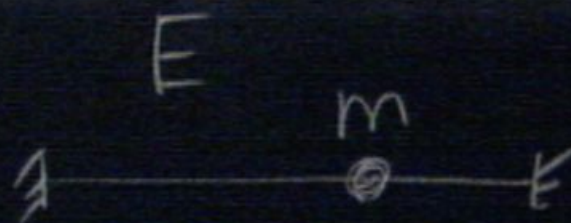
m

$$p = \pm \sqrt{2mE}$$



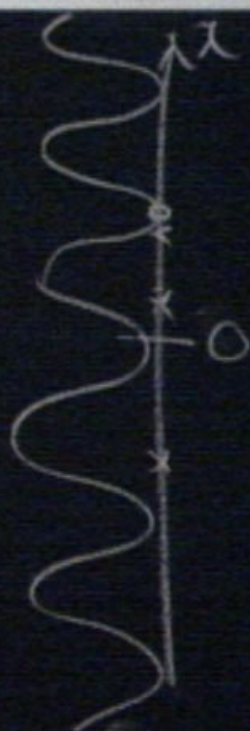
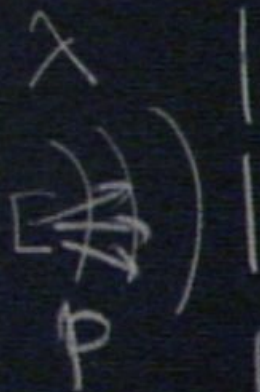
$$\lambda p = h$$

$$P(x) = \psi^2(x)$$



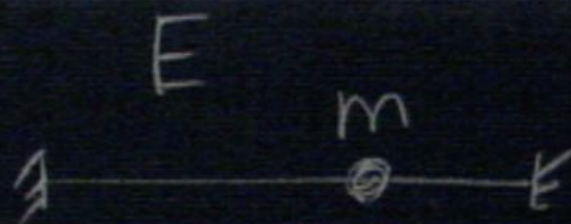
$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$



$$\lambda p = h$$

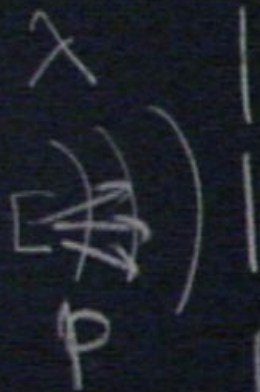
$$P(x) = \psi^2(x)$$



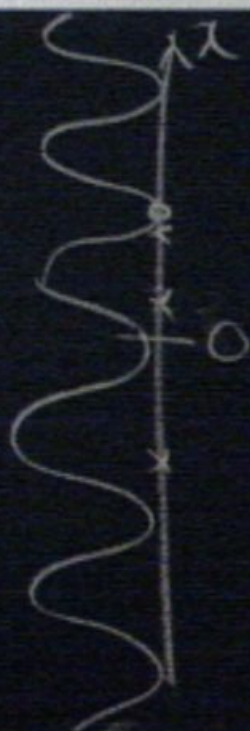
$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

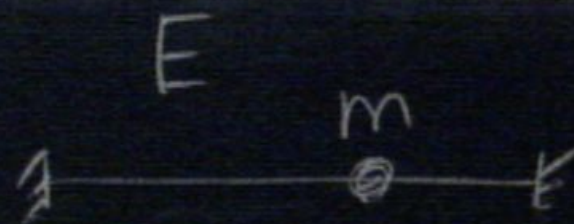




$$\lambda p = h$$



$$P(x) = \psi^2(x)$$

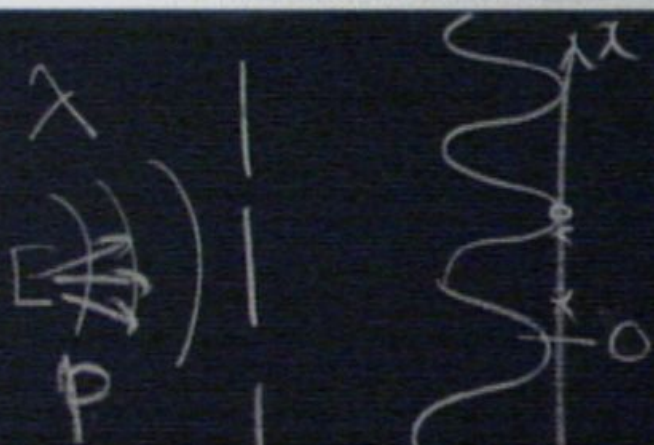


$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

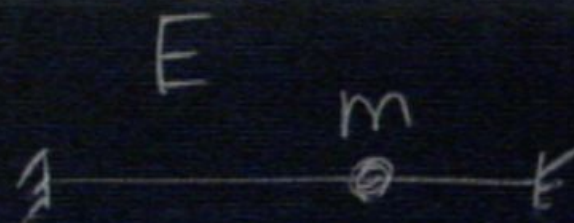


right and left



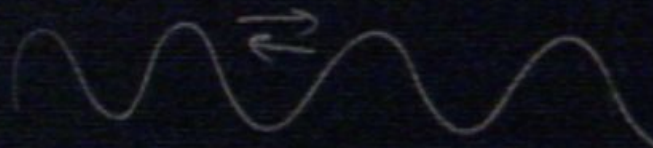
$$\lambda p = h$$

$$P(x) = \psi^2(x)$$

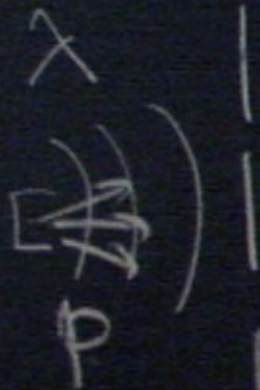


$$p = \pm \sqrt{2mE}$$

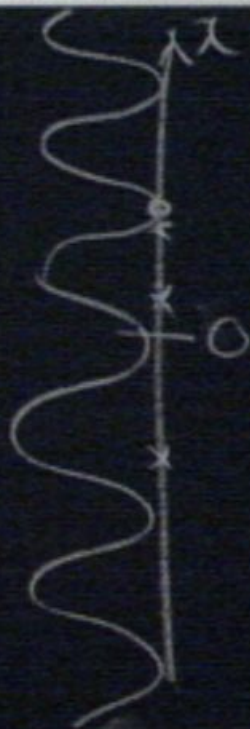
$$\lambda = \frac{h}{\sqrt{2mE}}$$



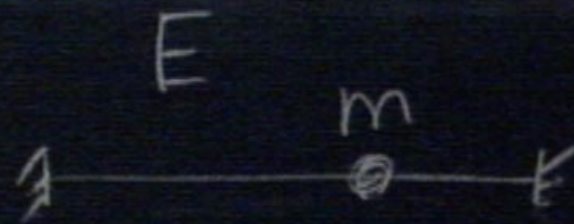
right and left



$$\lambda p = h$$



$$P(x) = \psi^2(x)$$

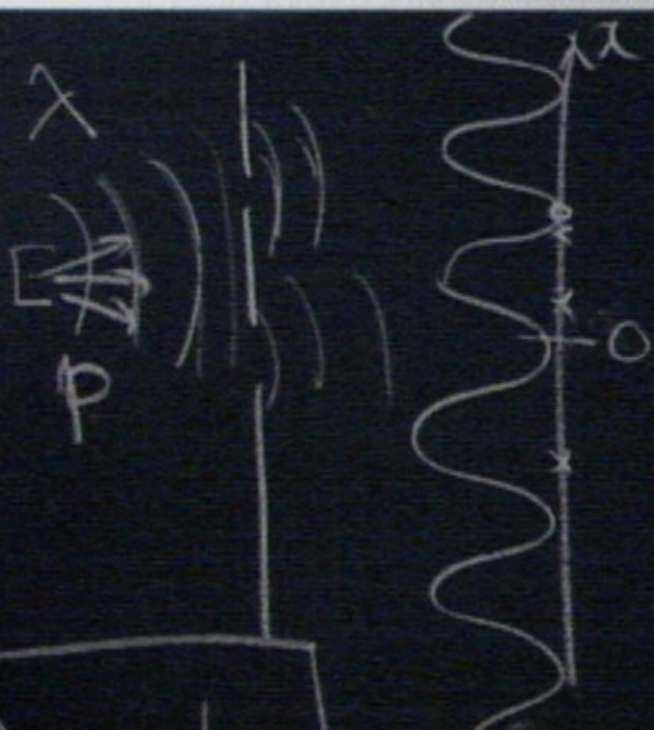


$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

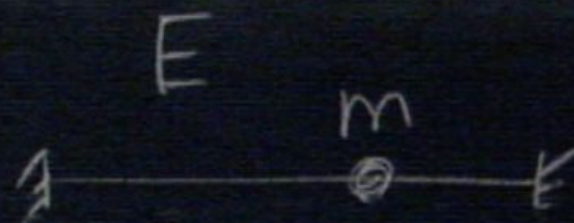


right and left



$$\lambda p = h$$

$$P(x) = \psi^2(x)$$



$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

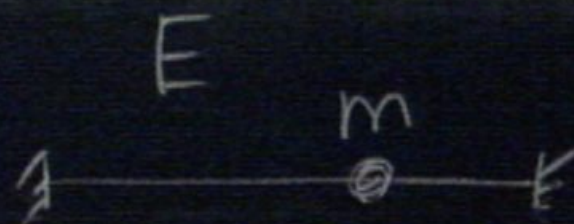


right and left



$$\lambda p = h$$

$$P(x) = \psi^2(x)$$

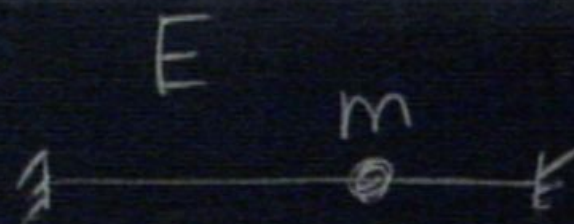
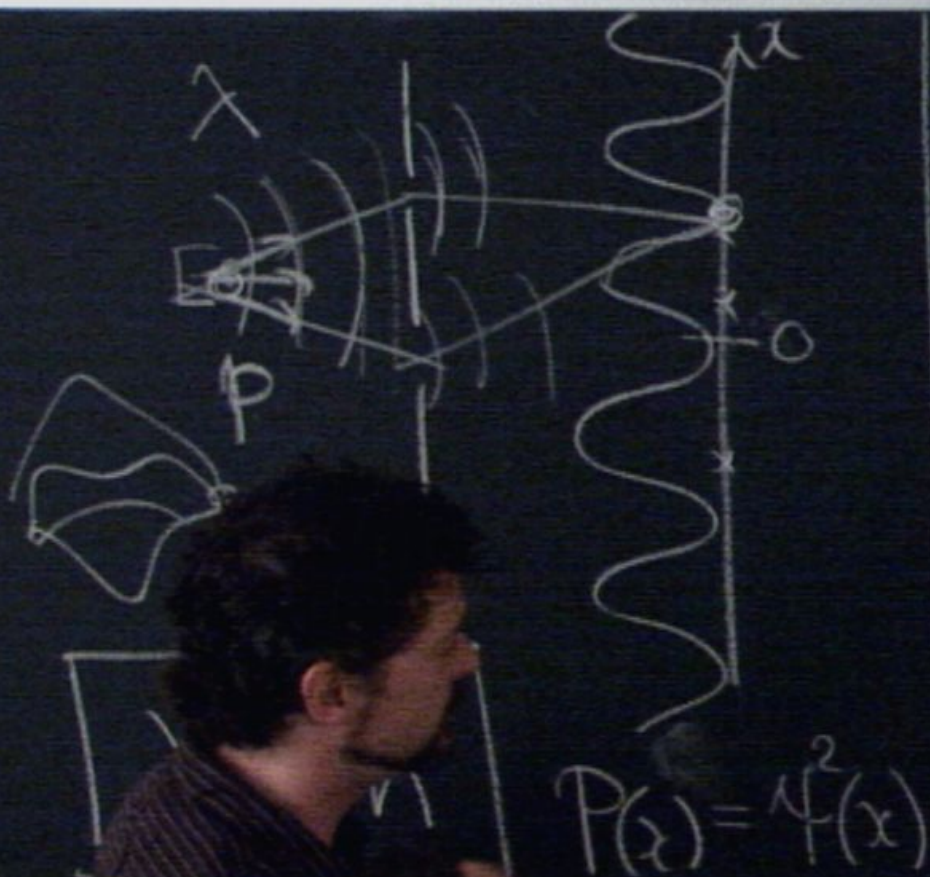


$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

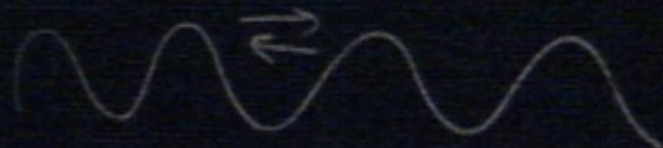


right and left



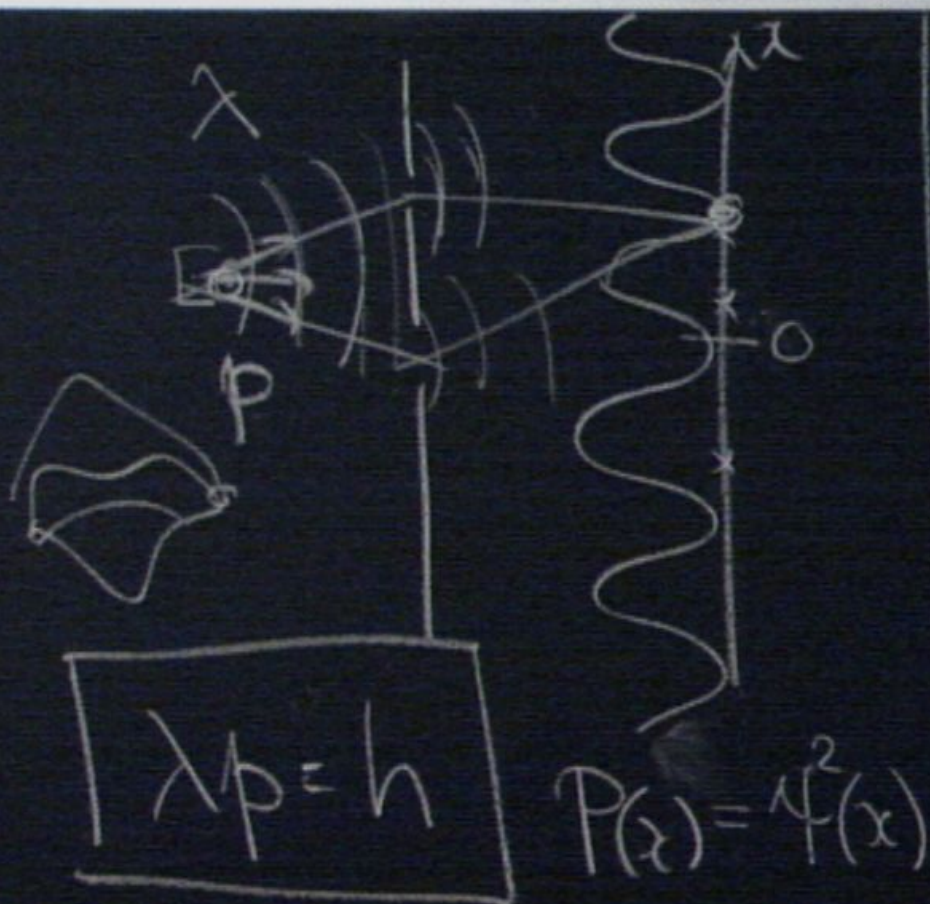
$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$



right and left





$$E$$

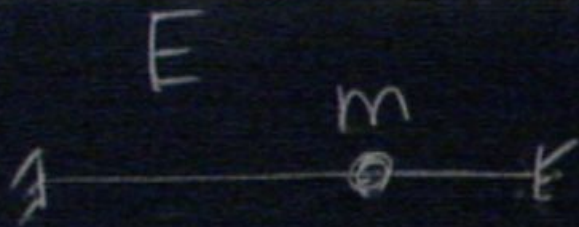
$$m$$

$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

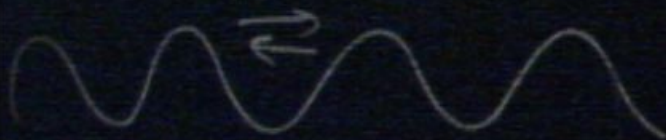
right and left





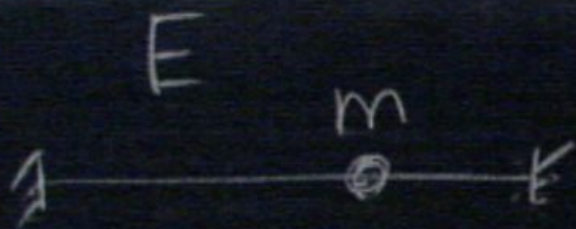
$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$



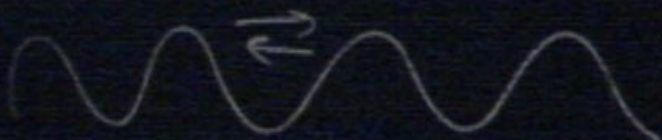
right and left



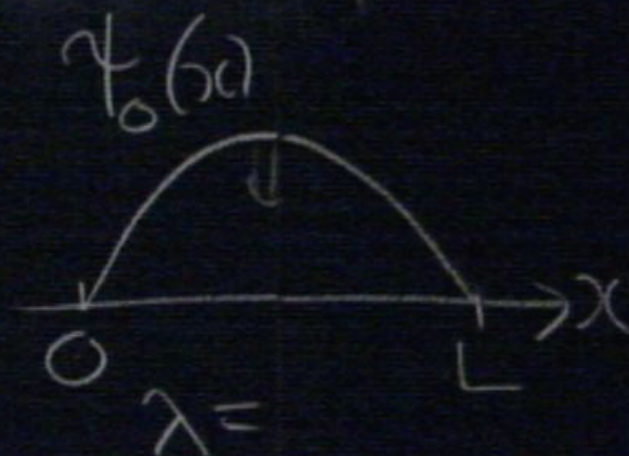


$$p = \pm \sqrt{2mE}$$

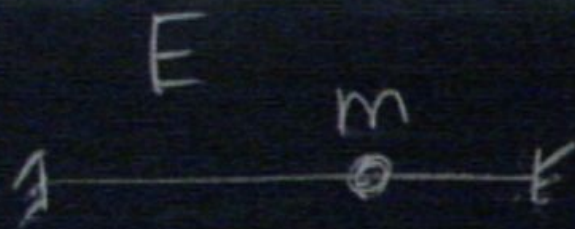
$$\lambda = \frac{h}{\sqrt{2mE}}$$



right and left



$\psi^2(x)$

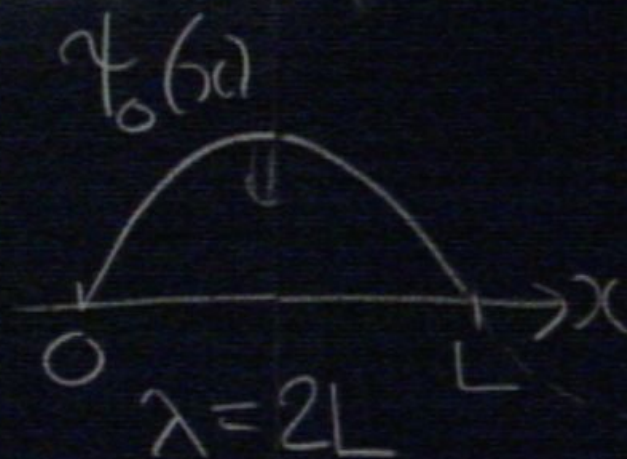


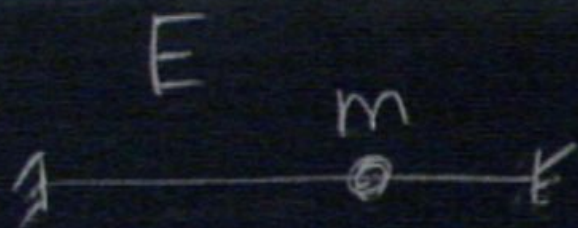
$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$



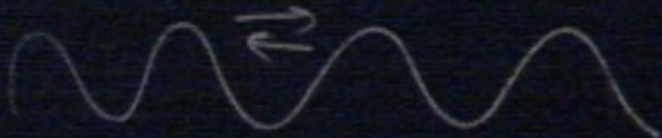
right and left



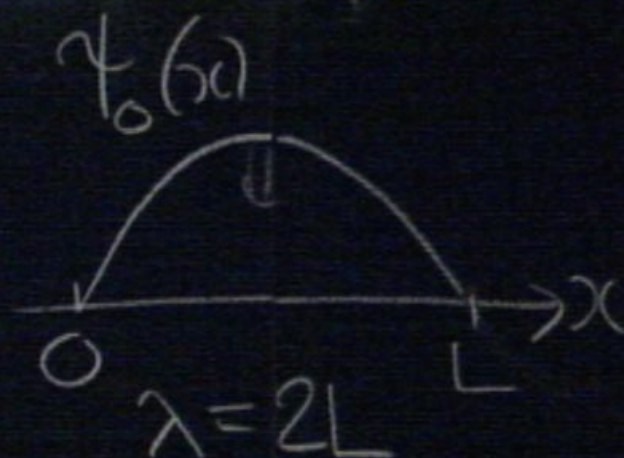


$$p = \pm \sqrt{2mE}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

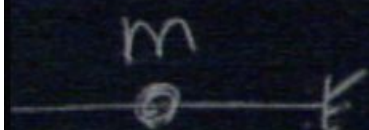


right and left



$\psi^2(x)$

m



$$\sqrt{2mE}$$

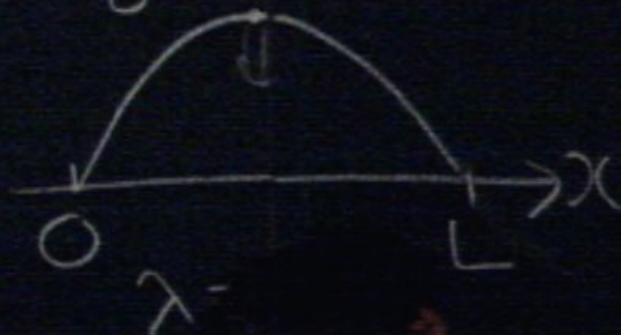
$$\frac{h}{\sqrt{2mE}}$$



and left



$$\psi_0(x)$$



$$\psi_0^2(x)$$



m

$$\sqrt{2mE}$$

$$\frac{h}{\sqrt{2mE}}$$



and left



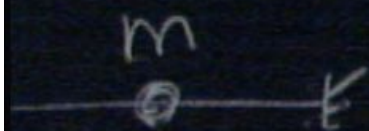
$$\psi_0(x)$$



$$\lambda = 2L$$

$$\psi_0^2(x)$$



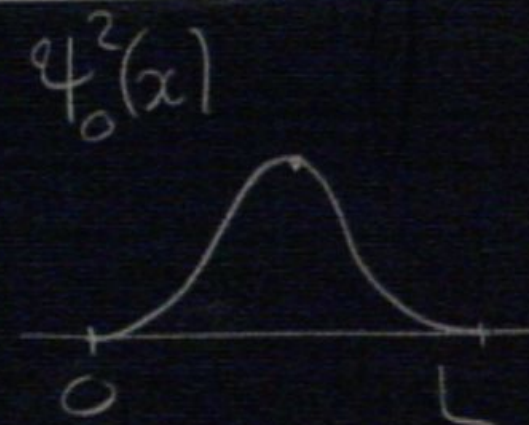
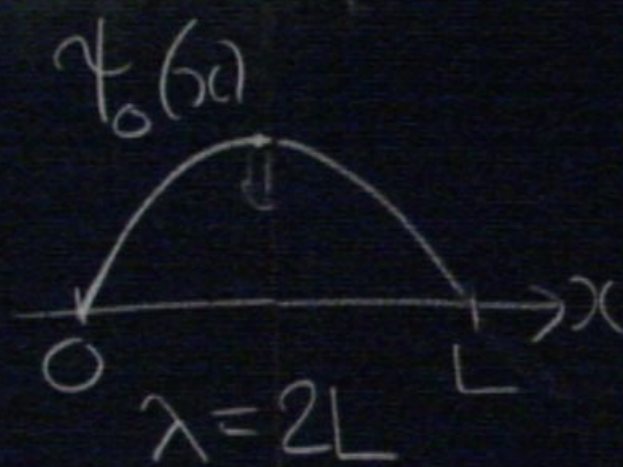


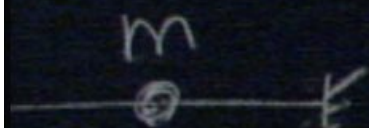
$$\sqrt{2mE}$$

$$\frac{h}{\sqrt{2mE}}$$



and left



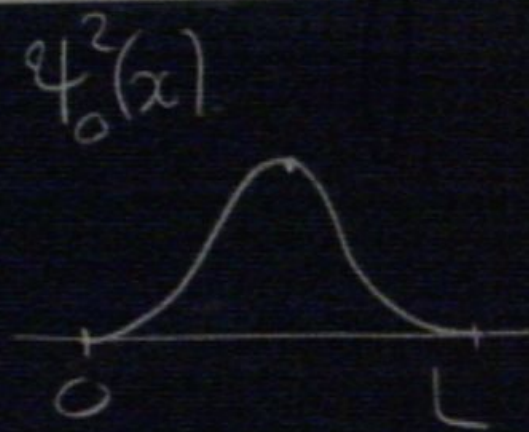
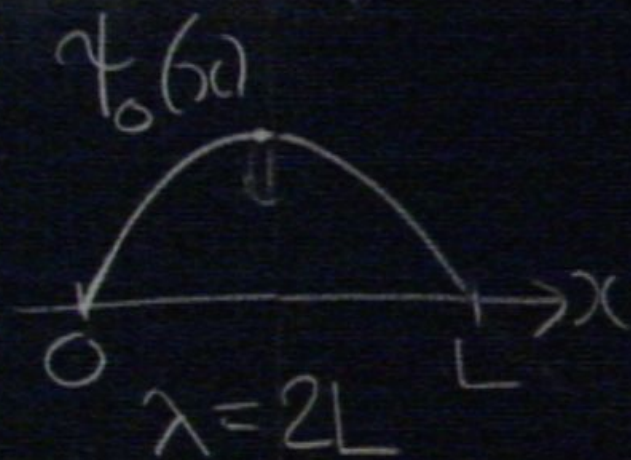


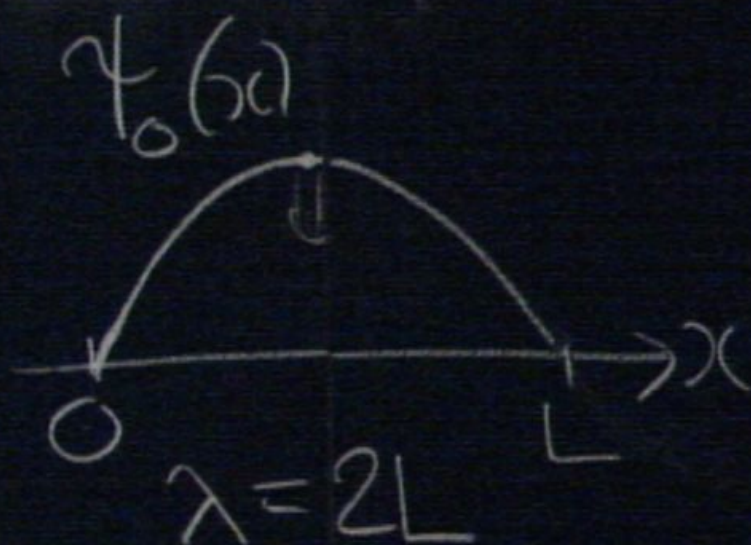
$$\sqrt{2mE}$$

$$\frac{h}{\sqrt{2mE}}$$



and left

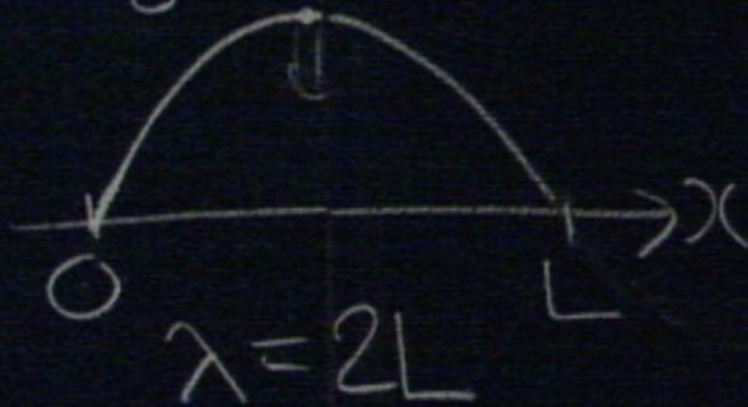




$$\psi_0^2(x) = P_0(x)$$



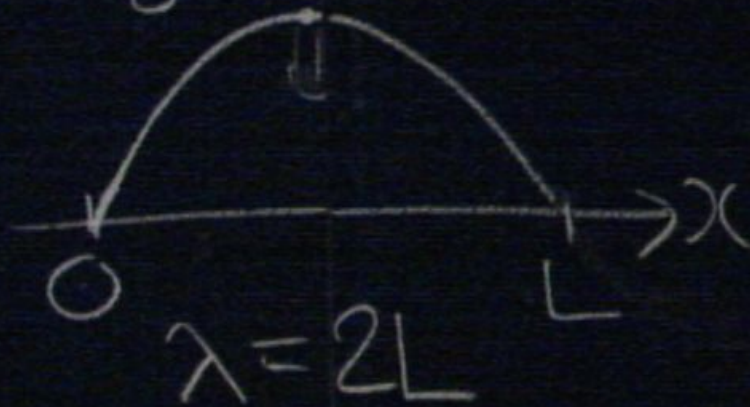
$$\psi_0(x)$$



$$\psi_0^2(x) = P(x)$$



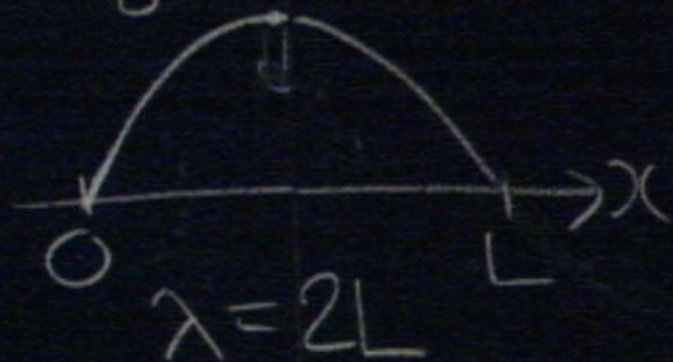
$$\psi_0(x)$$



$$\psi_0^2(x) = P(x)$$



$$\psi_0(x)$$

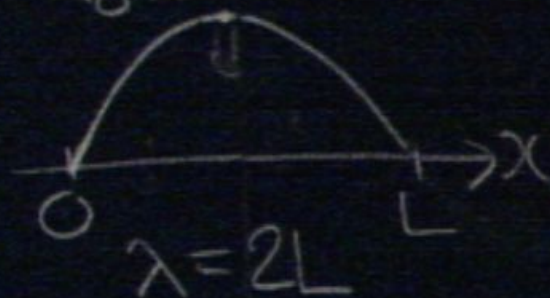


$$\psi_0^2(x) = P(x)$$



$$E_0 = \frac{p^2}{2m}$$

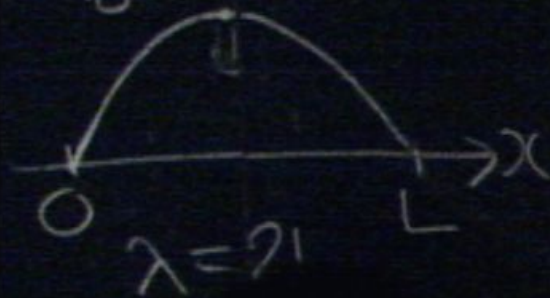
$\psi_0(x)$



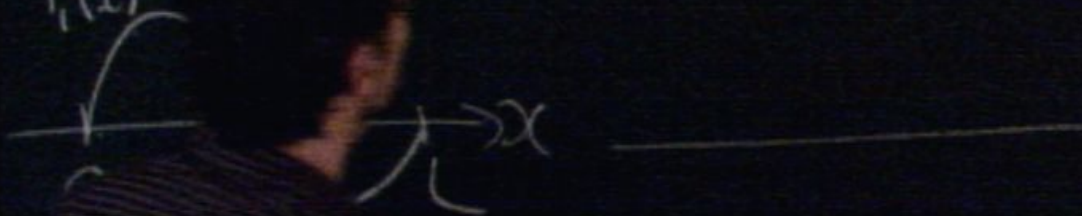
$\psi_0^2(x) = P(x)$



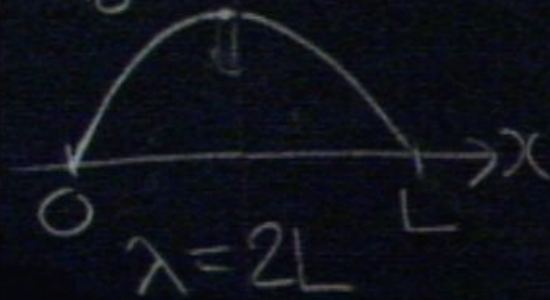
$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

$\psi_0(x)$  $\psi_0^2(x) = P(x)$ 

$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

 $\psi_1(x)$ 

$\psi_0(x)$

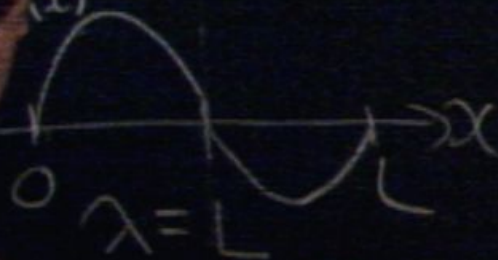


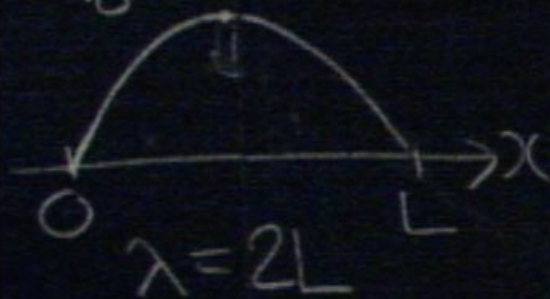
$$\psi_0^2(x) = P(x)$$



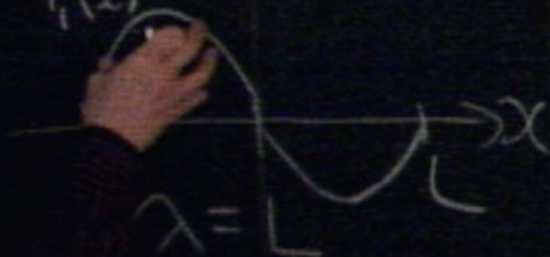
$$E_0 = \frac{\psi^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{h^2}{8mL^2}$$

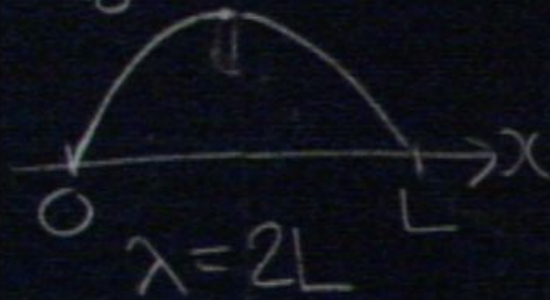
$\psi(x)$



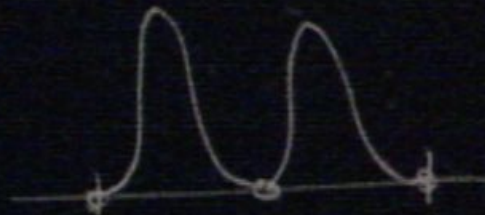
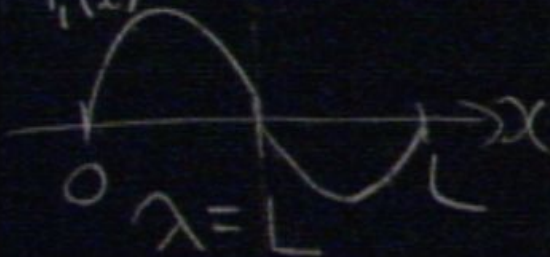
$\psi_0(x)$  $\psi_0^2(x) = P_0(x)$ 

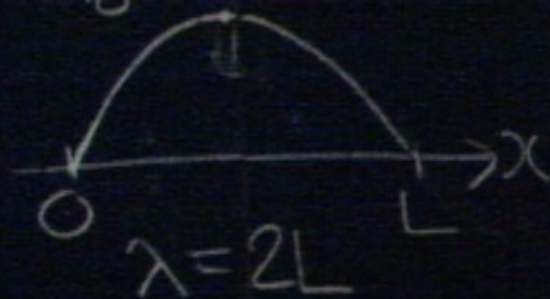
$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

 $\psi_1(x)$ 

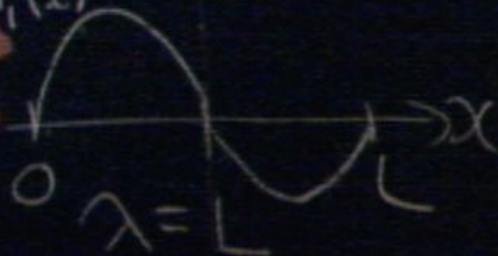
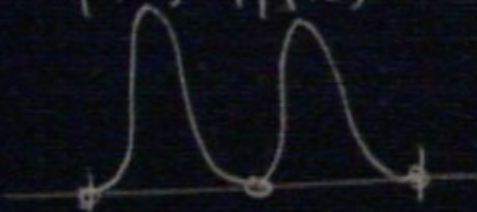
$\psi_0(x)$  $\psi_0^2(x) = P(x)$ 

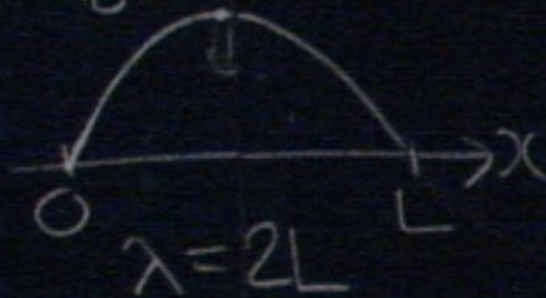
$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

 $\psi_1(x)$ 

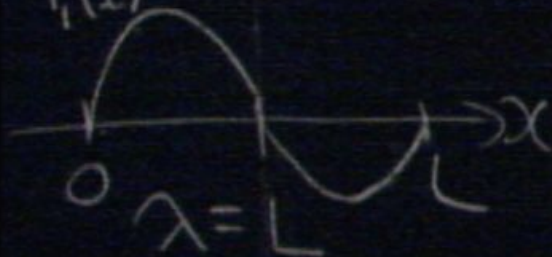
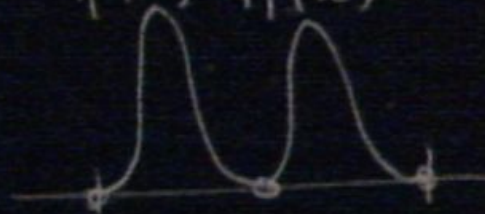
$\psi_0(x)$  $\psi_0^2(x) = P_0(x)$ 

$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

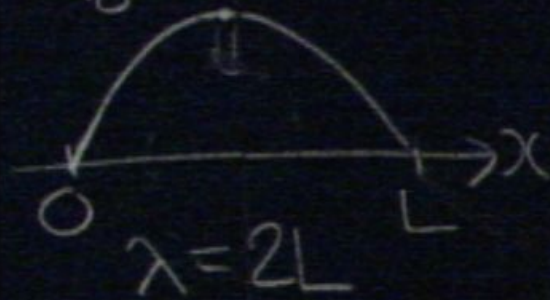
 $\psi_1(x)$  $\psi_1^2(x) = P_1(x)$ 

$\psi_0(x)$  $\psi_0^2(x) = P_0(x)$ 

$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

 $\psi_1(x)$  $\psi_1^2(x) = P_1(x)$ 

$\psi_0(x)$

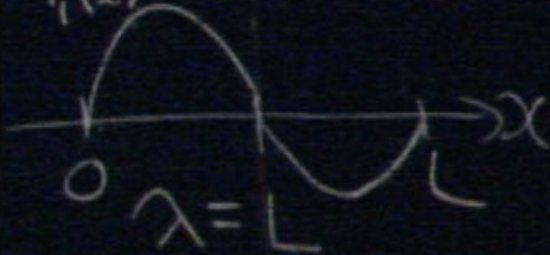


$\psi_0^2(x) = P_0(x)$

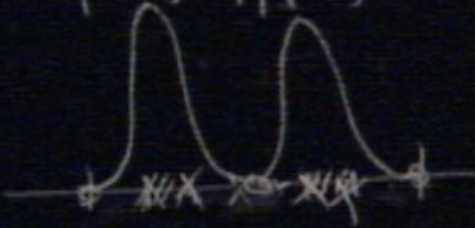


$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

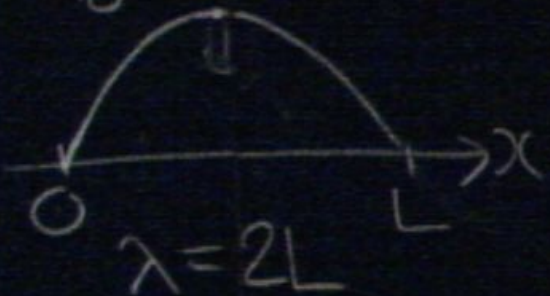
$\psi_1(x)$



$\psi_1^2(x) = P_1(x)$



$\psi_0(x)$

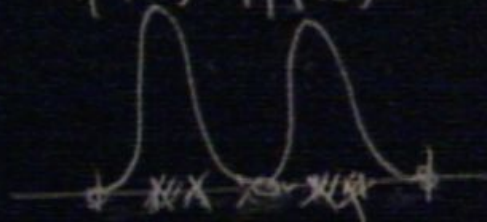


$\psi_0^2(x) = P_0(x)$

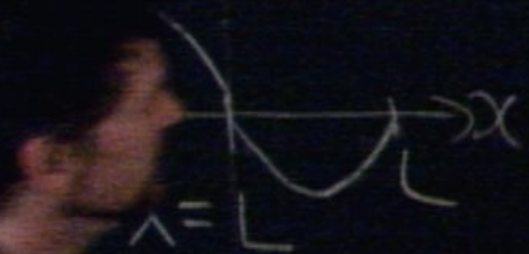


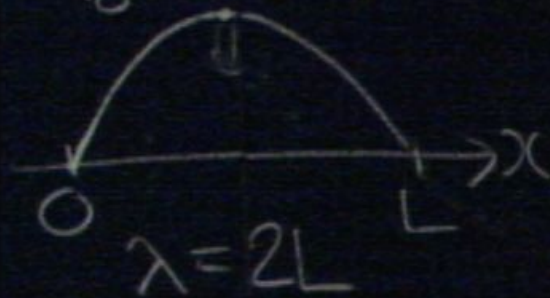
$$E_0 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{h^2}{8mL^2}$$

$\psi_1^2(x) = P_1(x)$

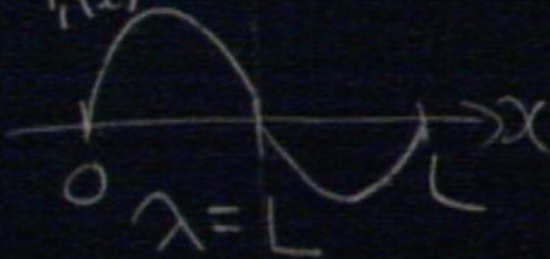


$$E_1 = \frac{h^2}{2mL^2}$$



$\psi_0(x)$  $\psi_0^2(x) = P_0(x)$ 

$$E_0 = \frac{\hbar^2}{2m} = \frac{\hbar^2}{2m\lambda^2} = \frac{\hbar^2}{8mL^2}$$

 $\psi_1(x)$  $\psi_1^2(x) = P_1(x)$ 

$$E_1 = \frac{\hbar^2}{2mL^2} = 4E_0$$

energy



ψ_0

0

$\psi_1(x)$

0

energy



E_0

ψ_0

0

$\psi_1(x)$

0

energy



E_0

ψ_0

0

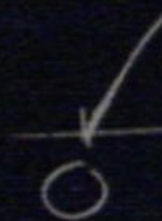
$\psi_1(x)$

0

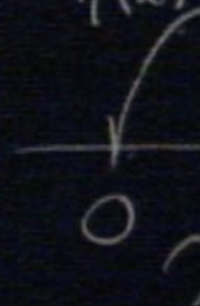
energy



ψ_0



$\psi_1(x)$



energy



energy



energy



energy

bound particle



energy

bound particle

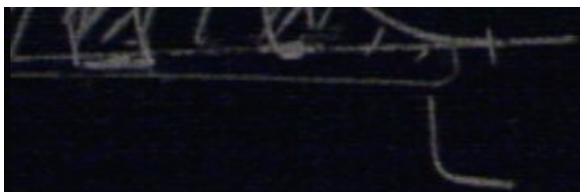


bound wave

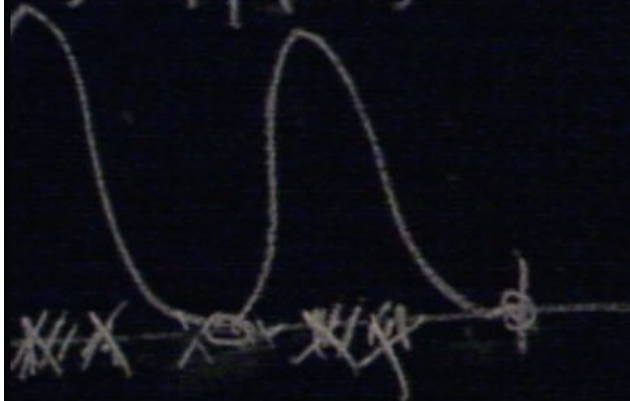
E_2

E_1

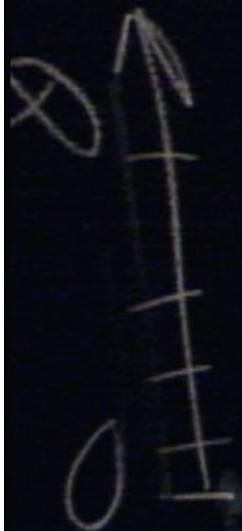
E_0

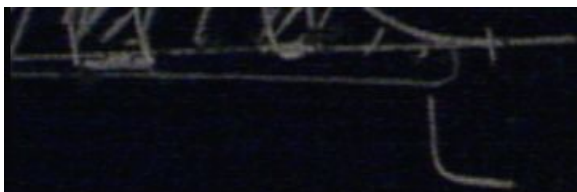


$$\psi(x) = P_1(x)$$

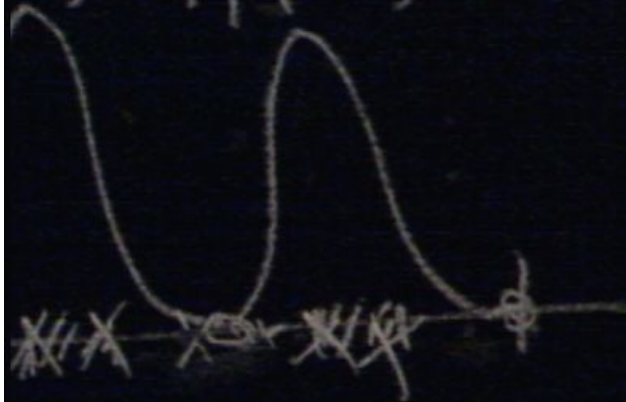


$$E_1 = \frac{h^2}{2ml^2} = 4E_0$$

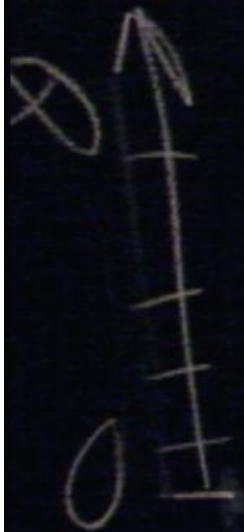




$$\psi(x) = P_1(x)$$



$$E_1 = \frac{h^2}{8ml^2} = 4E_0$$



energy



bound particle



bound wave



discrete harmonics

energy



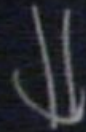
bound particle



bound wave



discrete harmonics (λ)



$$p = \frac{h}{\lambda}$$

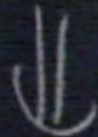
energy



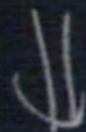
bound particle



bound wave



discrete harmonics (λ)



$$p = \frac{h}{\lambda}$$

$$\Downarrow$$

$$E = \frac{p^2}{2m}$$

energy



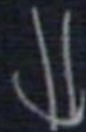
bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$\begin{aligned} p &= \frac{h}{\lambda} \\ E &= \frac{p^2}{2m} \end{aligned}$$

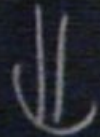
energy



bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$E = h\nu$$

$$\begin{aligned} p &= \frac{h}{\lambda} \\ E &= \frac{p^2}{2m} \end{aligned}$$

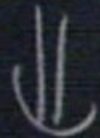
energy



bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$\begin{aligned} p &= \frac{h}{\lambda} \\ E &= \sum \frac{p^2}{2m} \end{aligned}$$

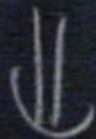
energy



bound particle



bound wave



discrete harmonics (λ)

total energy.

$$p = \frac{h}{\lambda}$$
$$E = \sum \frac{p^2}{2m}$$

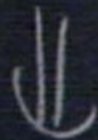
energy



bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$p = \frac{h}{\lambda}$$
$$\Downarrow$$
$$E = \sum m$$

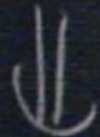
energy



* bound particle



bound wave



discrete harmonics (λ)



quantized energy.

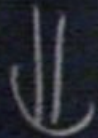
$$p = \frac{h}{\lambda}$$
$$\Downarrow$$
$$E = \sum \frac{p^2}{2m}$$

energy

* bound particle



bound wave



discrete harmonics (λ)



quantized energy

$$p = \frac{h}{\lambda}$$

$$E = \frac{p^2}{2m}$$

E_2

E_1

E_0



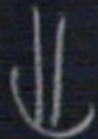
to point energy

energy

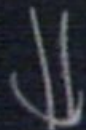
* bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$p = \frac{h}{\lambda}$$

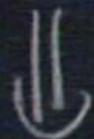
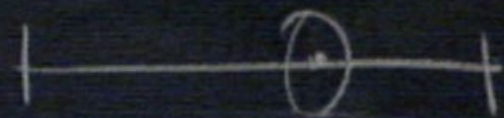
$$E = \frac{p^2}{2m}$$



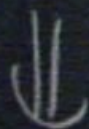
* zero point energy

energy

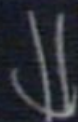
* bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$p = \frac{h}{\lambda}$$

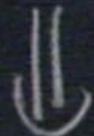
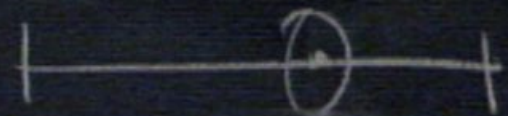
$$E = \frac{p^2}{2m}$$



* zero point energy

energy

* bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$p = \frac{h}{\lambda}$$

$$\Downarrow$$

$$E = \frac{p^2}{2m}$$

E_2

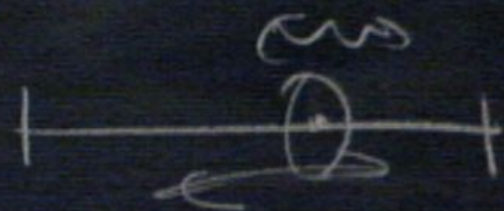
E_1

E_0

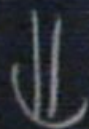
* zero point energy

energy

* bound particle



bound wave



discrete harmonics (λ)



quantized energy.

$$p = \frac{h}{\lambda}$$

$$E = \frac{p^2}{2m}$$

E_2

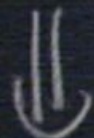
E_1

E_0

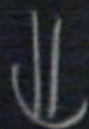
* zero point energy

energy

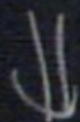
* bound particle



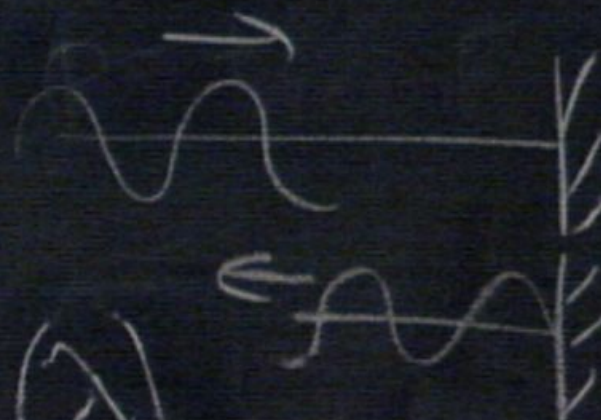
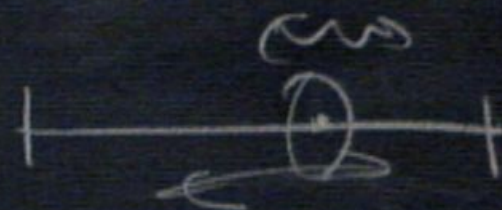
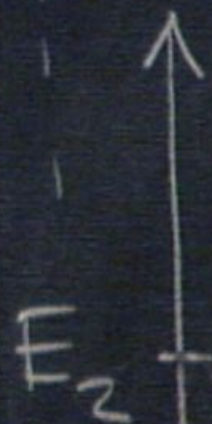
bound wave



discrete harmonics (λ)



quantized energy.



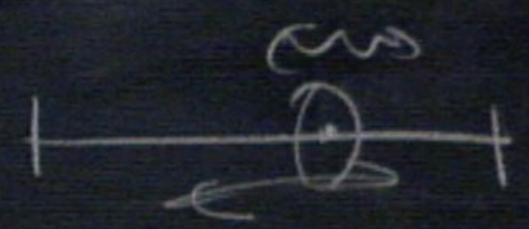
$$p = \frac{h}{\lambda}$$

$$E = \frac{p^2}{2m}$$

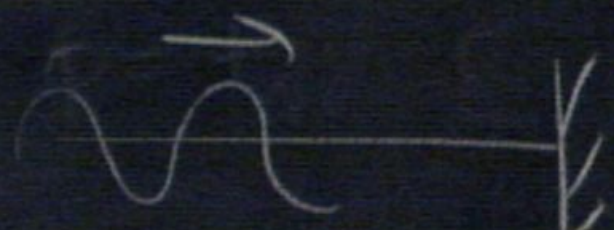
* zero point energy

energy

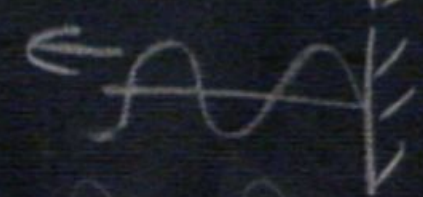
* bound particle



bound wave



discrete harmonics (λ)

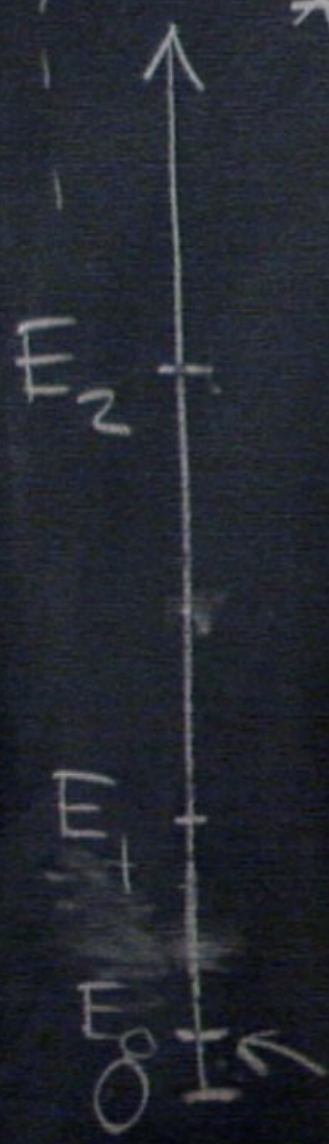
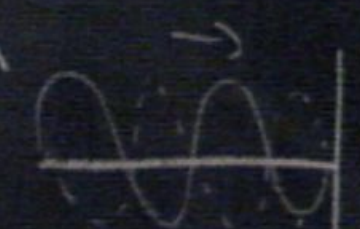


quantized energy.



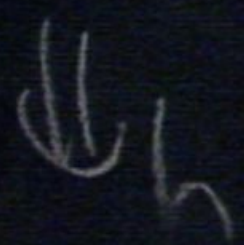
$$p = \frac{h}{\lambda}$$

$$E = \frac{p^2}{2m}$$

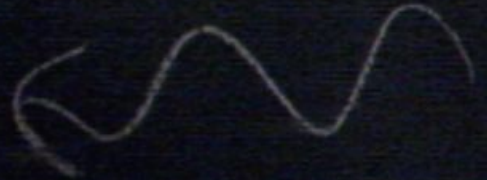


* zero point energy

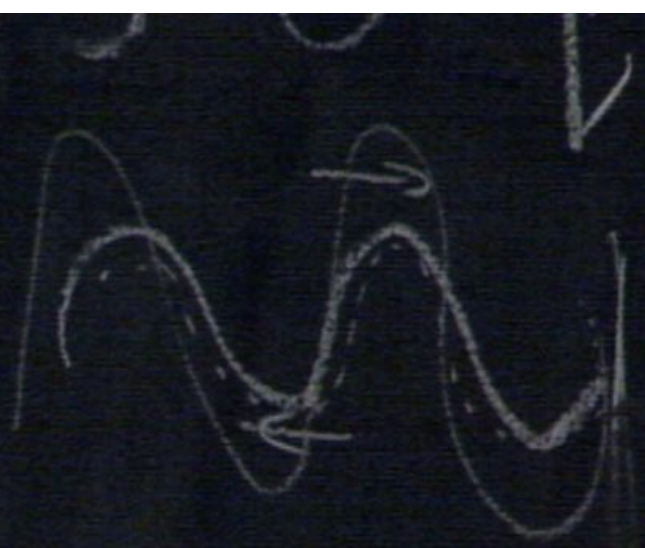
randomizes



ergy.



randomizes



ergy.



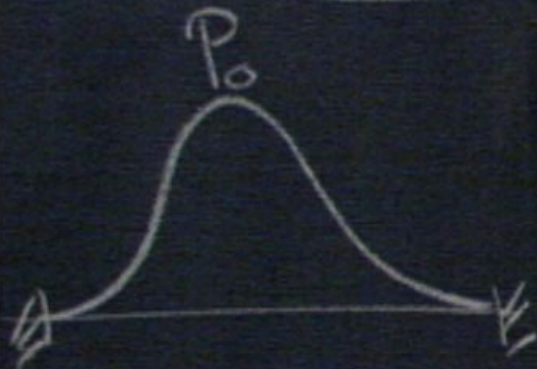
energy

Heisenberg Uncertainty Principle

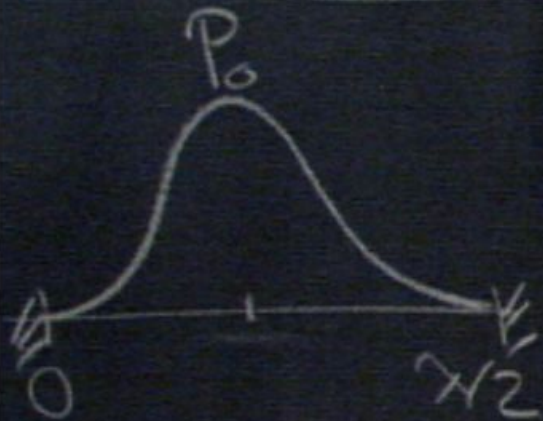
Heisenberg Uncertainty Principle



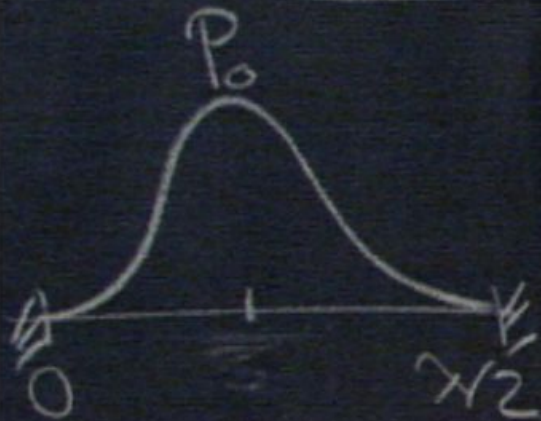
Heisenberg Uncertainty Principle



Heisenberg Uncertainty Principle

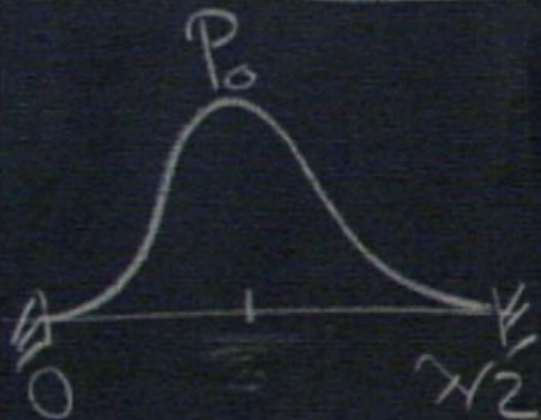


Heisenberg Uncertainty Principle



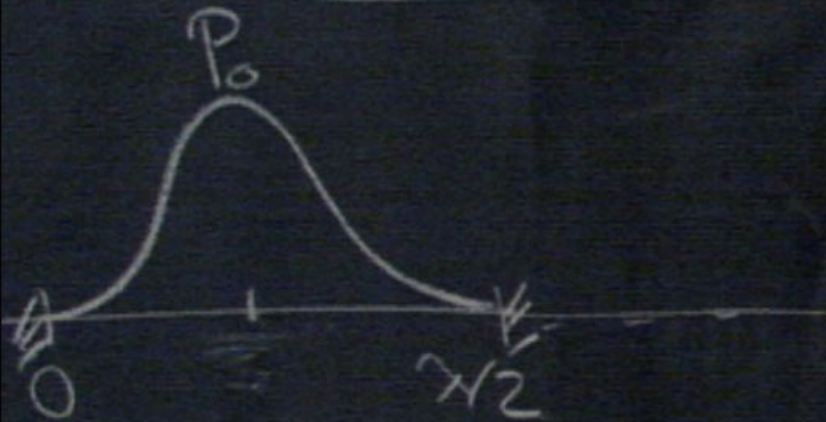
$$\Delta x =$$

Heisenberg Uncertainty Principle



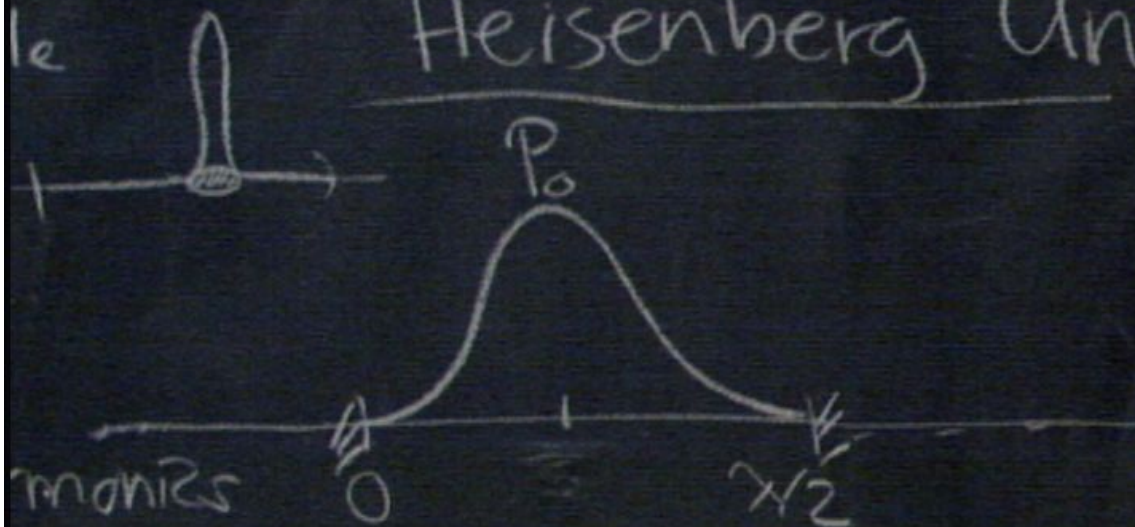
$$\Delta x =$$

Heisenberg Uncertainty Principle



$$\Delta x =$$

Heisenberg Uncertainty Principle

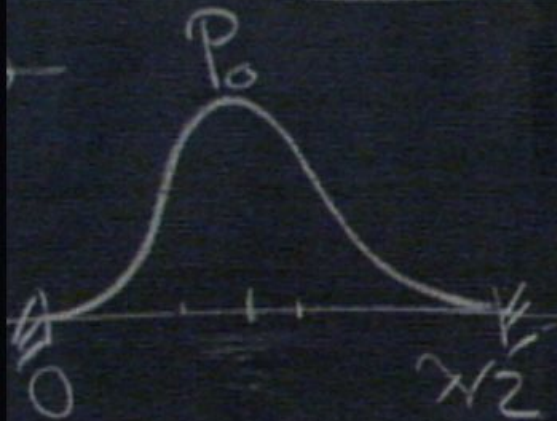


$$\Delta x =$$

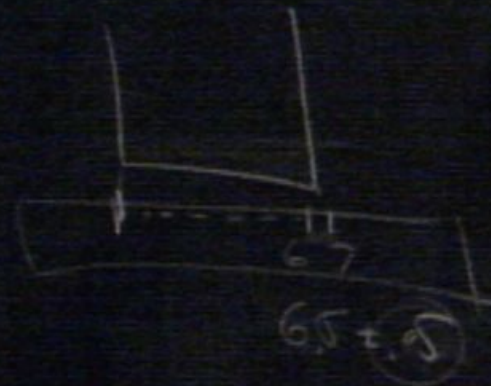
energy.

energy

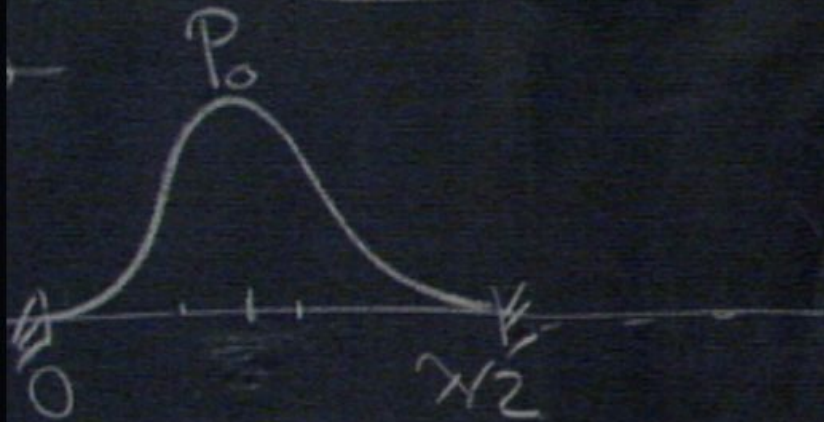
Heisenberg Uncertainty Principle



$$\Delta x =$$

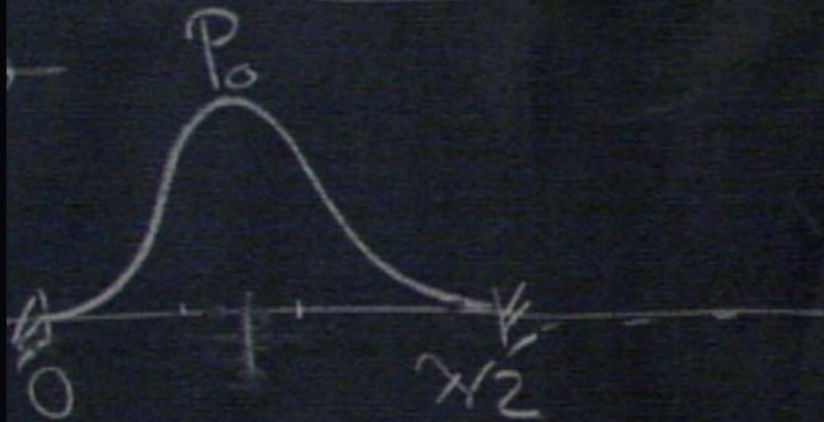


Heisenberg Uncertainty Principle



$$\Delta x =$$

Heisenberg Uncertainty Principle



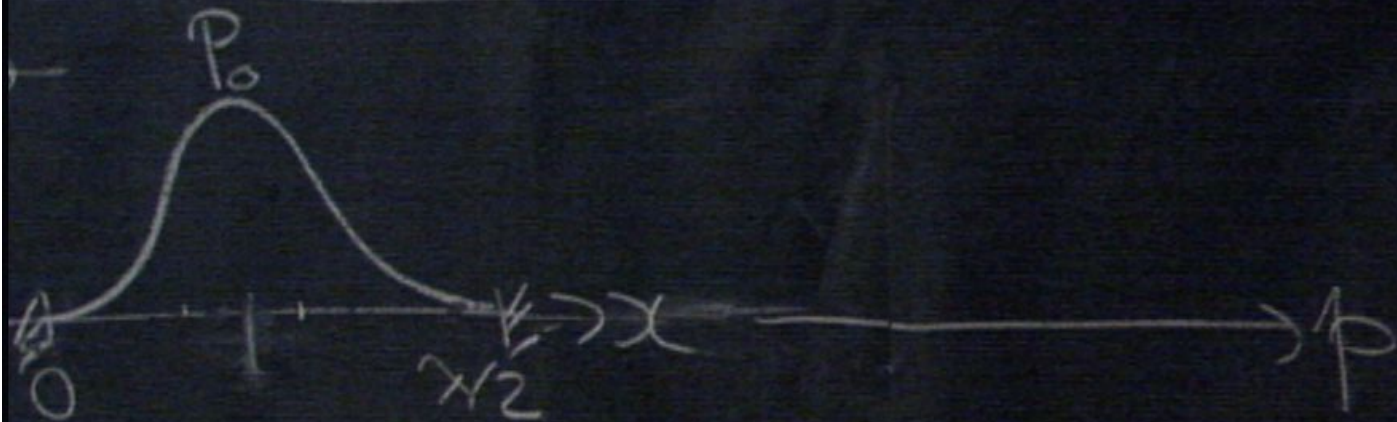
$$\Delta x = \frac{\lambda}{4}$$

Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{4}$$

Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{4}$$

Heisenberg Uncertainty Principle

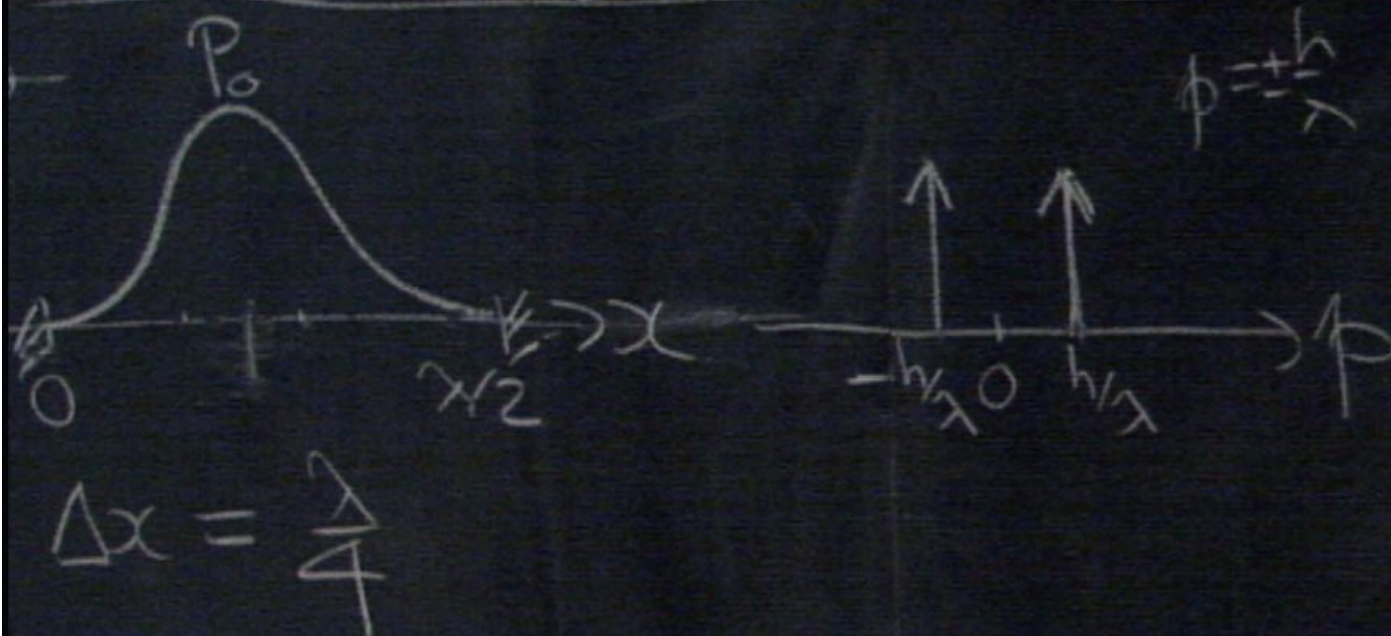


$$\Delta x = \frac{\lambda}{4}$$

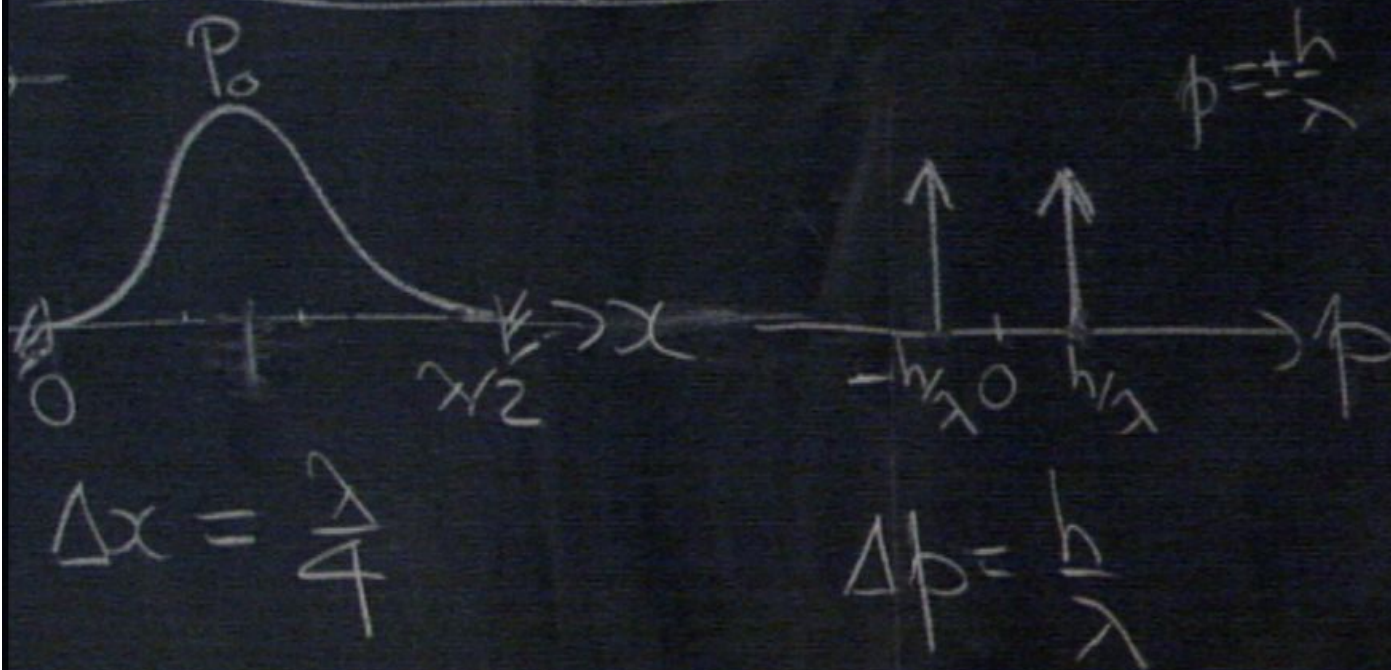
Heisenberg Uncertainty Principle

$$\Delta x = \frac{\lambda}{4}$$

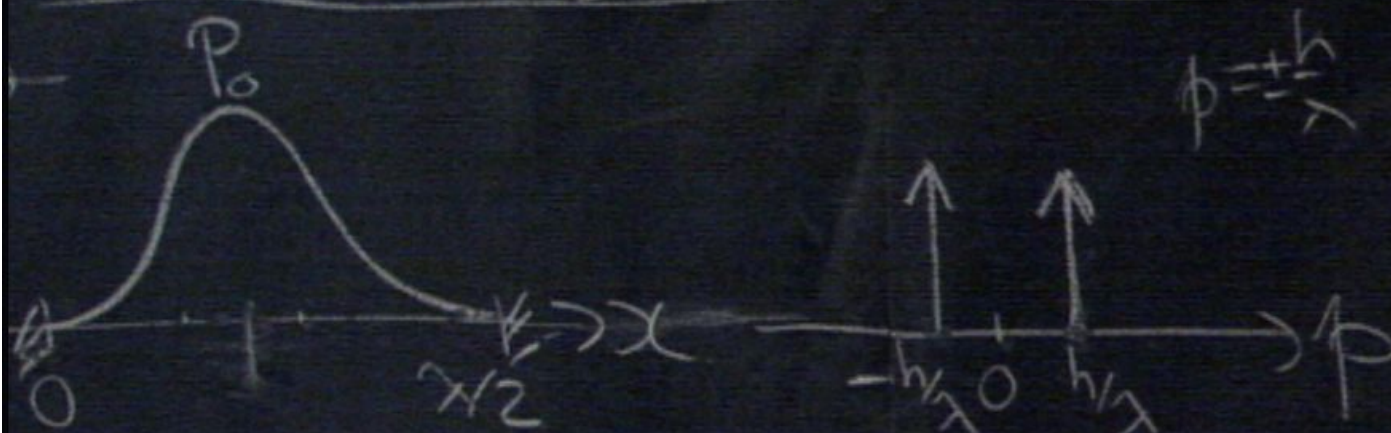
Heisenberg Uncertainty Principle



Heisenberg Uncertainty Principle



Heisenberg Uncertainty Principle

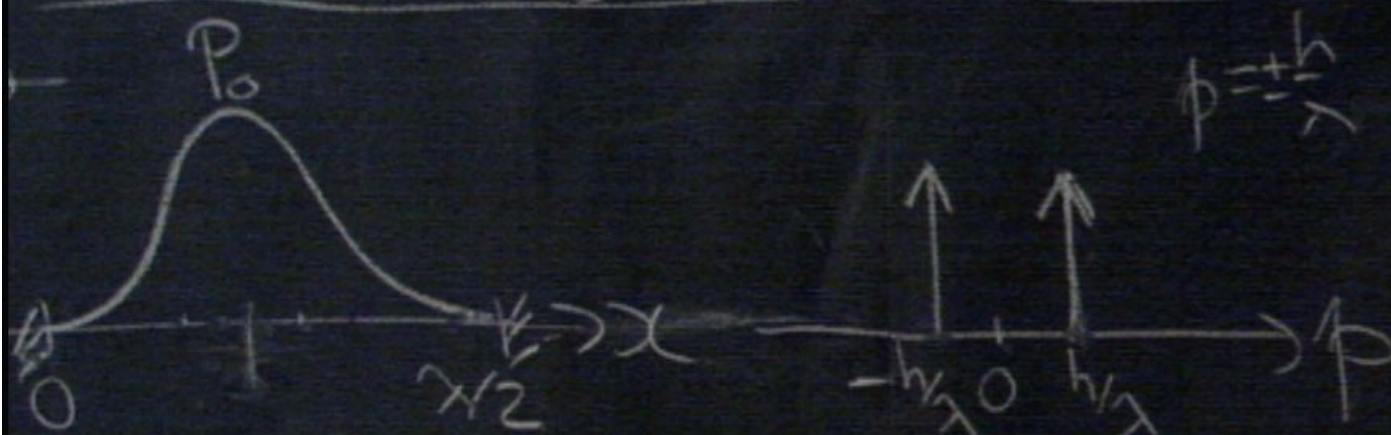


$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$

Heisenberg Uncertainty Principle

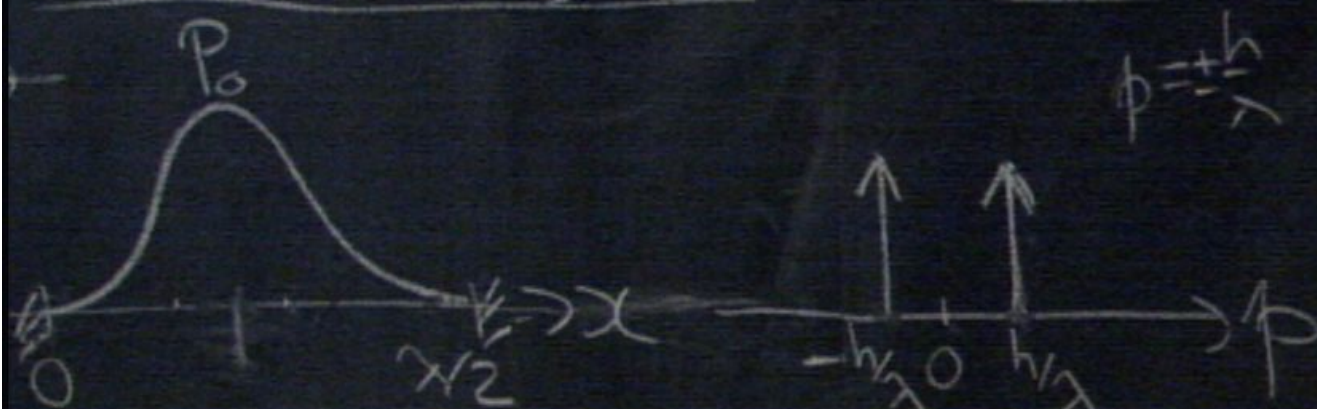


$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$

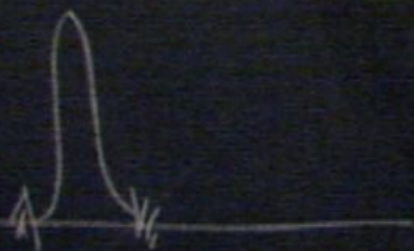
Heisenberg Uncertainty Principle



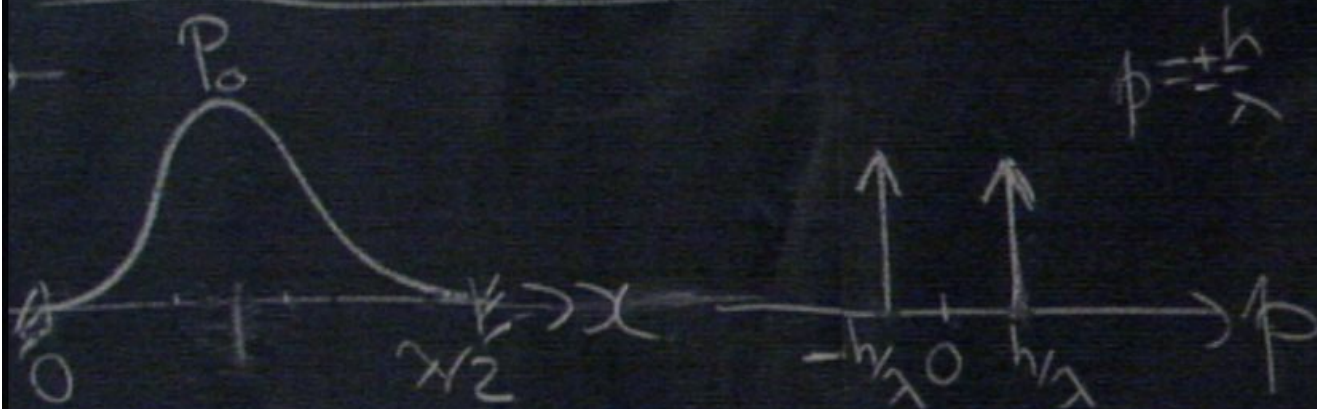
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



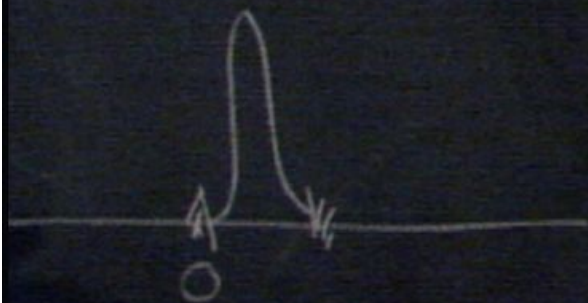
Heisenberg Uncertainty Principle



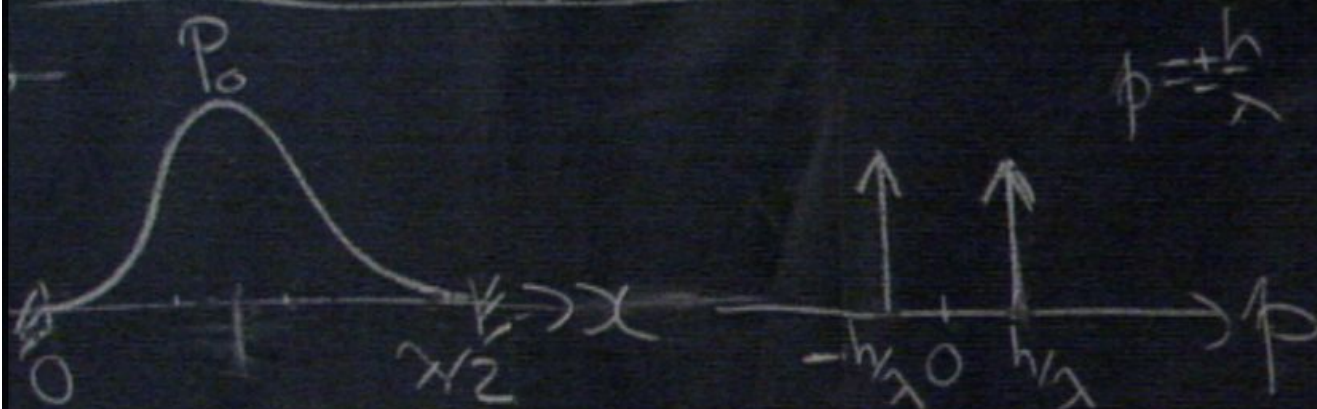
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



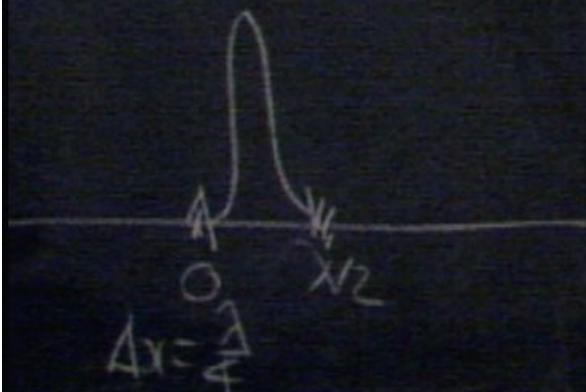
Heisenberg Uncertainty Principle



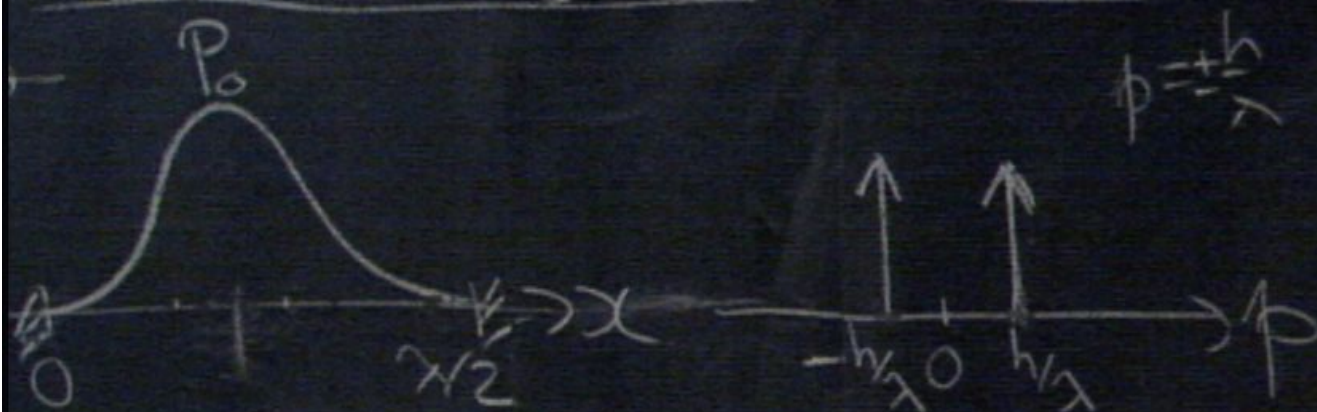
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



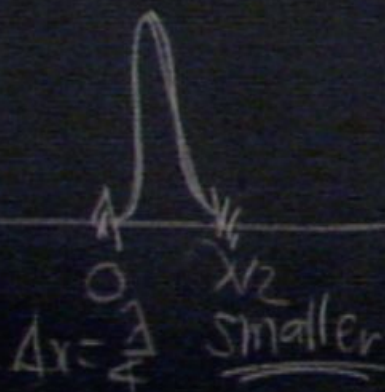
Heisenberg Uncertainty Principle



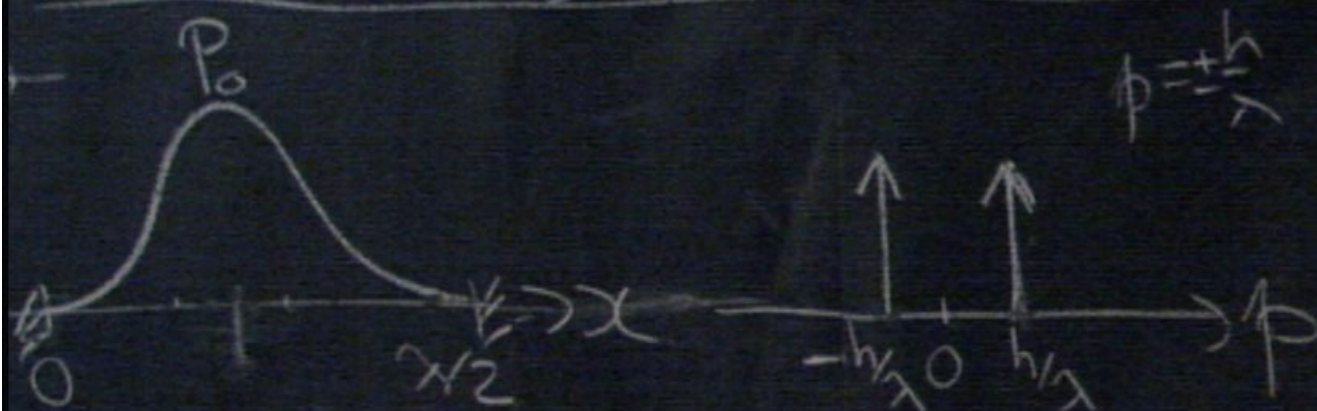
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



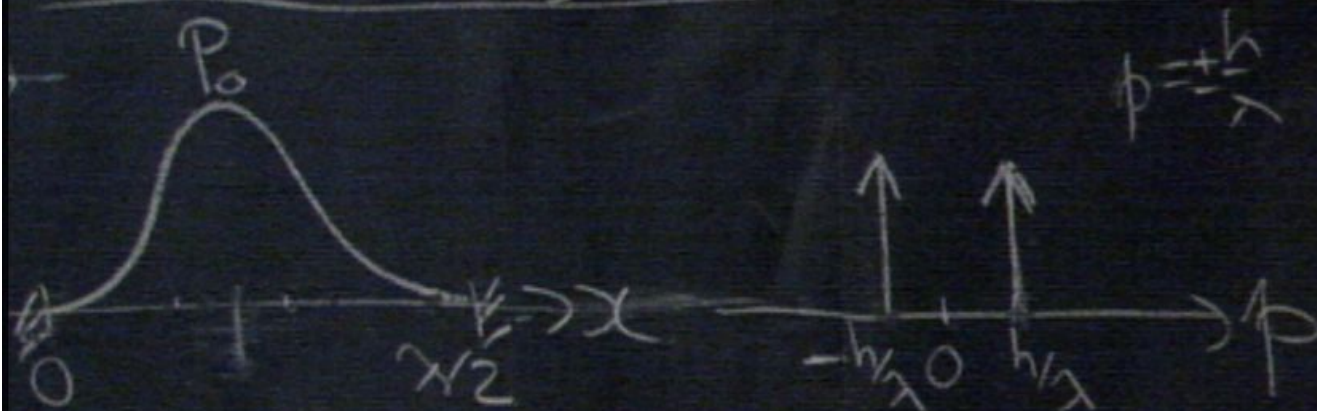
Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{4} \quad \Delta p = \frac{h}{\lambda} \quad \Delta x \Delta p = \frac{h}{4}$$



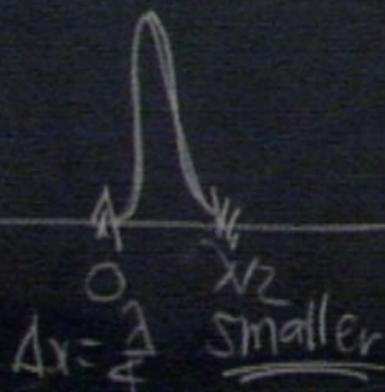
Heisenberg Uncertainty Principle



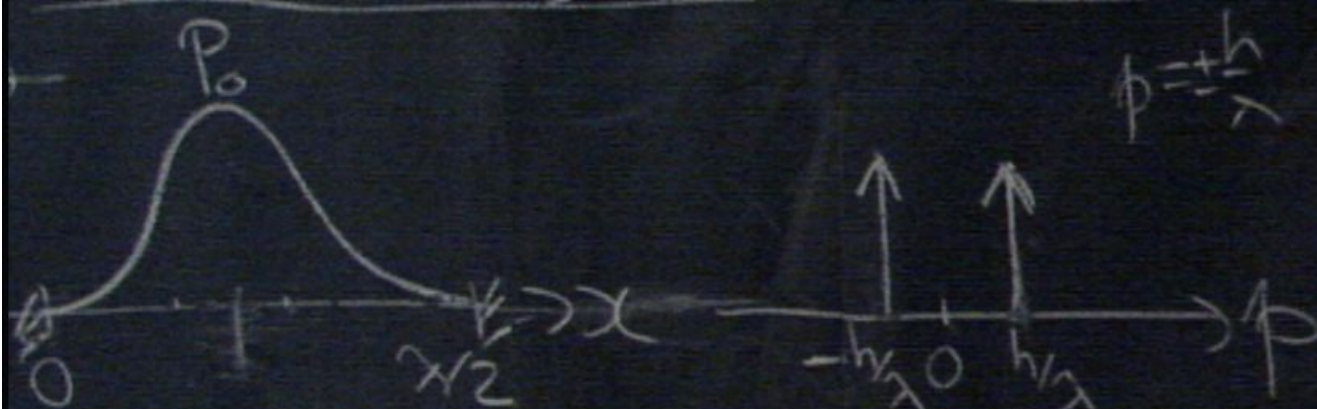
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



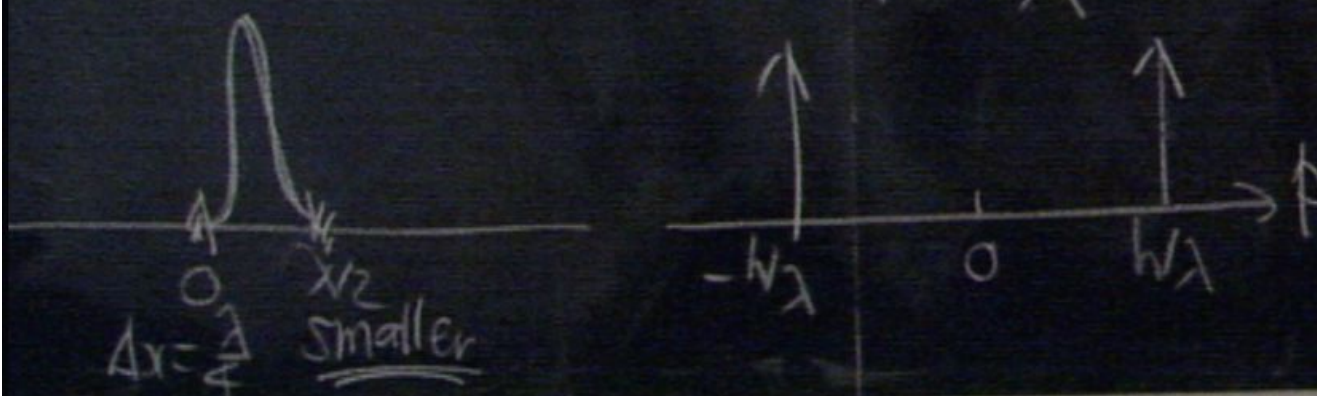
Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{4}$$

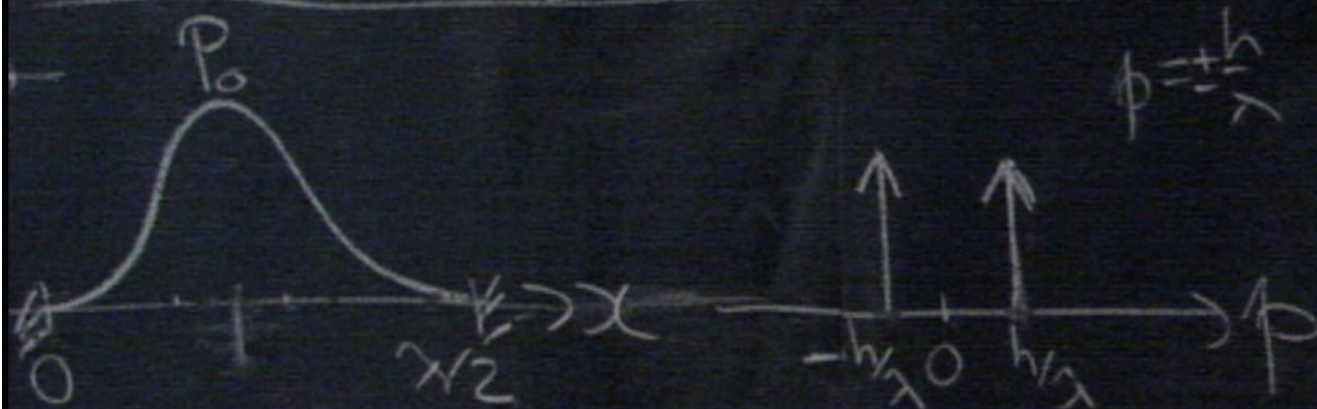
$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x = \frac{\lambda}{4} \text{ smaller}$$

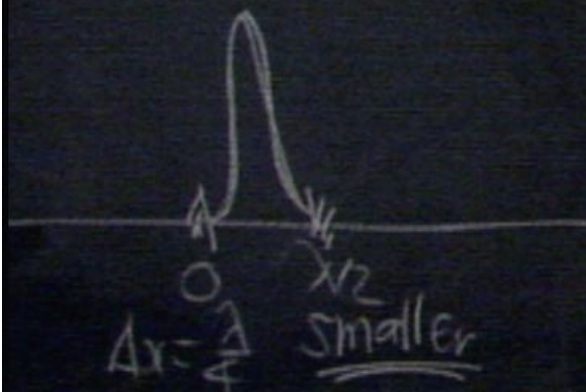
Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

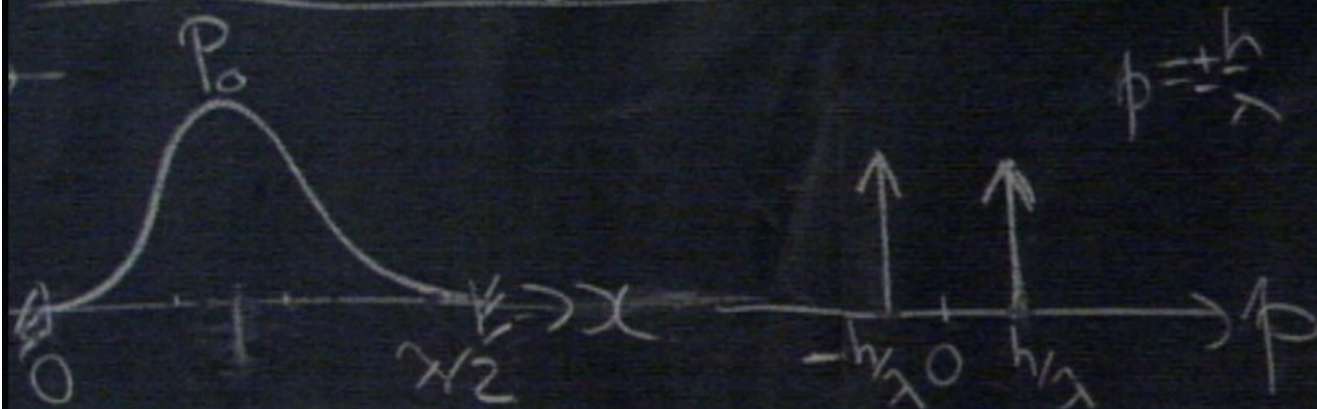
$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x = \frac{\lambda}{4} \text{ smaller}$$

$$\Delta p = \frac{h}{\lambda} \text{ larger}$$

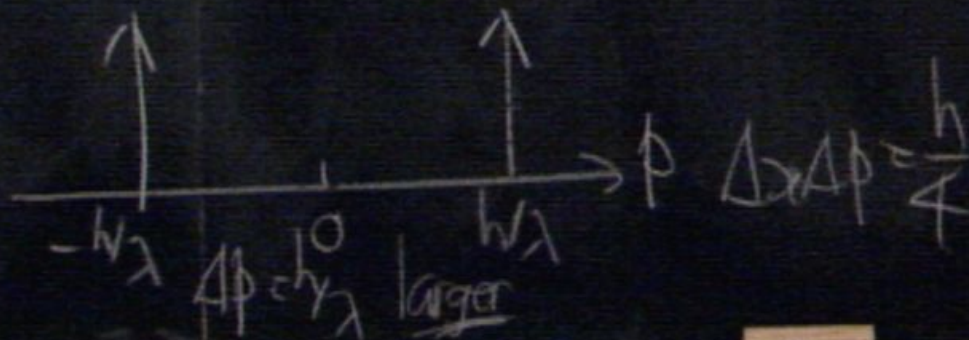
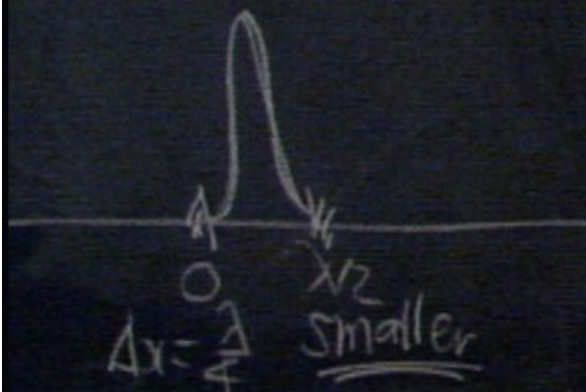
Heisenberg Uncertainty Principle



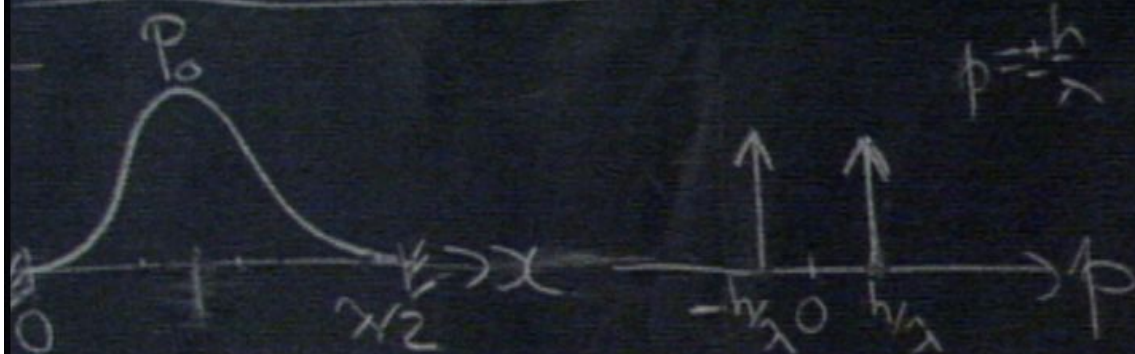
$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



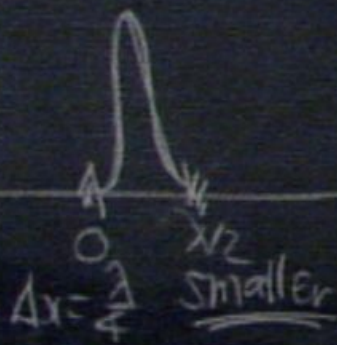
Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{2}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$

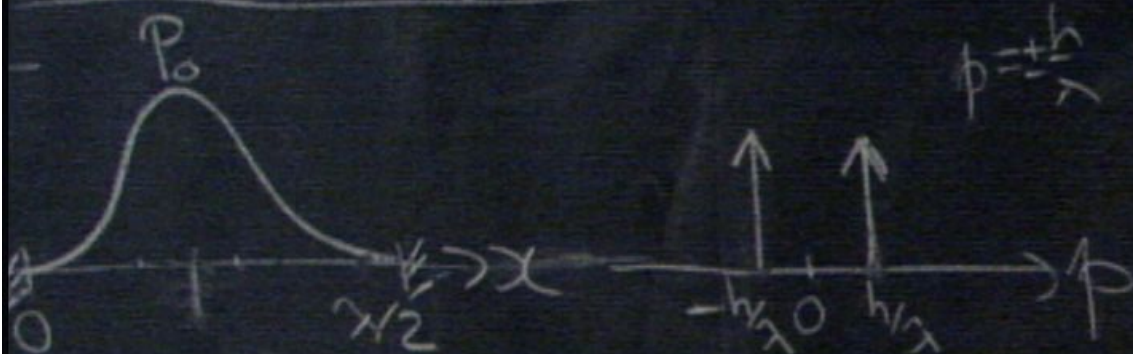


$$\Delta x = \frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$

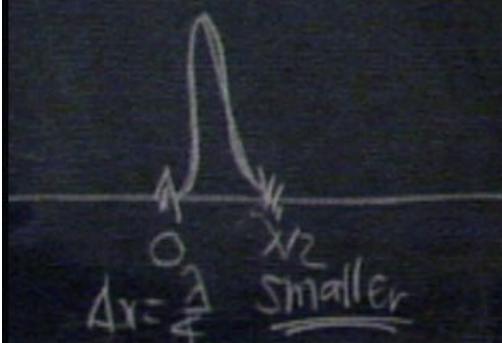
Heisenberg Uncertainty Principle



$$\Delta x = \frac{\lambda}{2}$$

$$\Delta p = \frac{h}{\lambda}$$

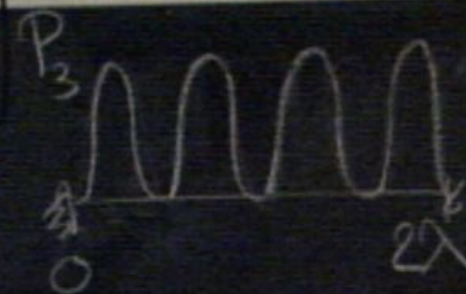
$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x = \frac{\lambda}{4} \text{ smaller}$$

$$\Delta p = \frac{h}{\lambda} \text{ larger}$$

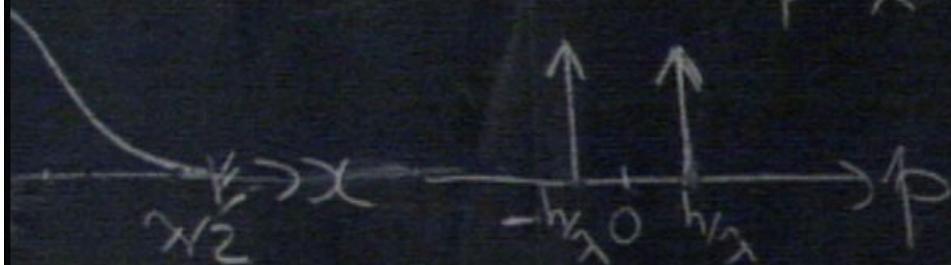
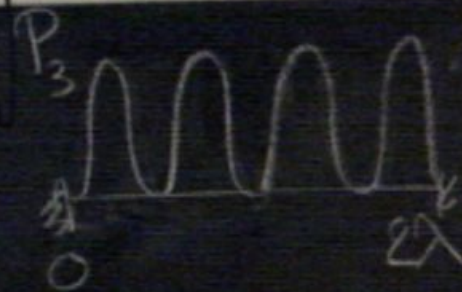
$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x =$$

Heisenberg Uncertainty Principle

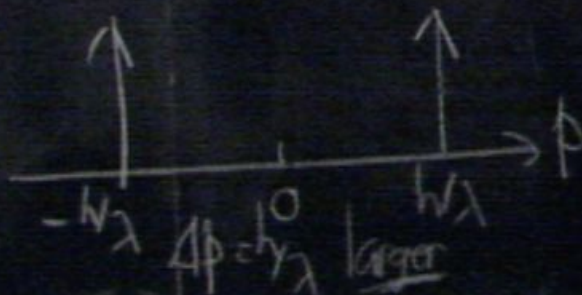
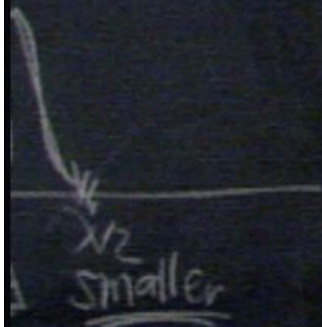
$$p = \pm \frac{h}{\lambda}$$



$$\frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$

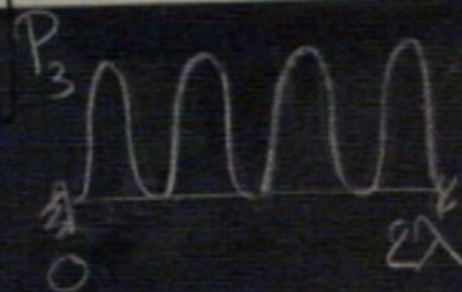


$$\Delta x \Delta p = \frac{h}{4}$$

$$\Delta x \Delta p = h$$

Heisenberg Uncertainty Principle

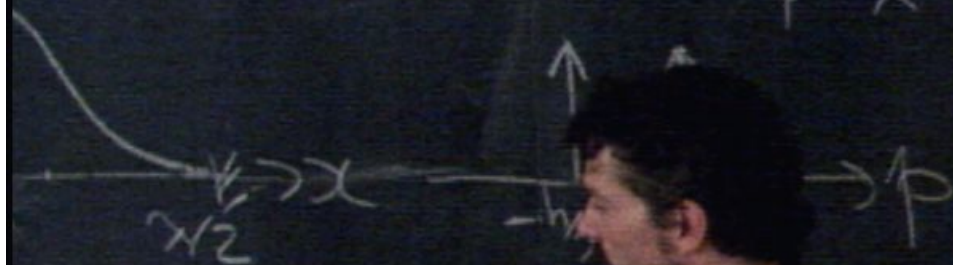
$$p = \pm \frac{h}{\lambda}$$



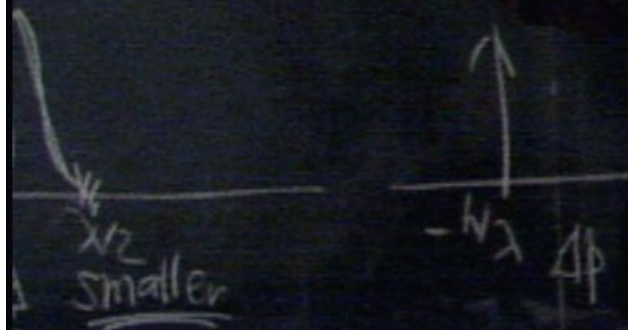
$$\left. \begin{array}{l} \Delta x = \lambda \\ \Delta p = \frac{h}{\lambda} \end{array} \right) \Delta x \Delta p = h$$

$$\Delta x \Delta p = \frac{h}{4}$$

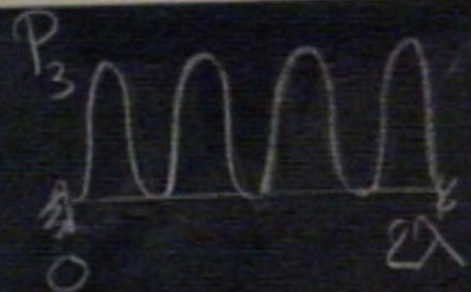
$$\Delta x \Delta p = \frac{h}{4}$$



$$\frac{\lambda}{4}$$



$$p = \pm \frac{h}{\lambda}$$

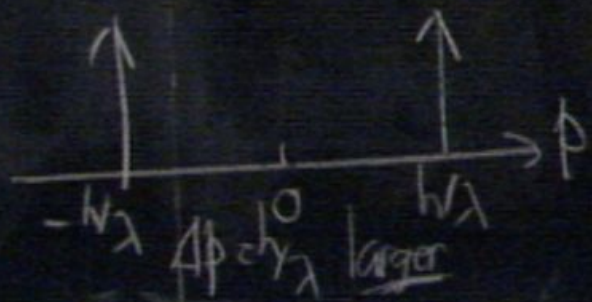
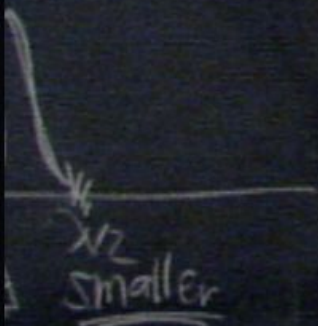


$$\left. \begin{array}{l} \Delta x = \lambda \\ \Delta p = \frac{h}{\lambda} \end{array} \right) \Delta x \Delta p = h$$

$$\frac{\lambda}{4}$$

$$\Delta p = \frac{h}{\lambda}$$

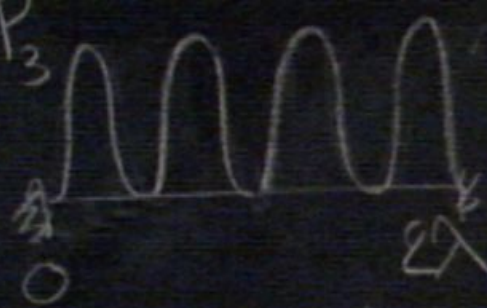
$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x \Delta p = \frac{h}{4}$$

Uncertainty Principle

$$p = \pm \frac{h}{\lambda}$$



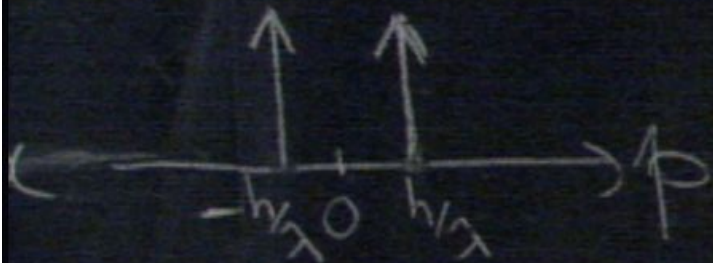
$$\left. \begin{array}{l} \Delta x = \lambda \\ \Delta p = \frac{h}{\lambda} \end{array} \right) \Delta x \Delta p = h > \frac{h}{4}$$

$$\Delta x \Delta p = \frac{h}{4}$$

$$\Delta x \Delta p = \frac{h}{4}$$

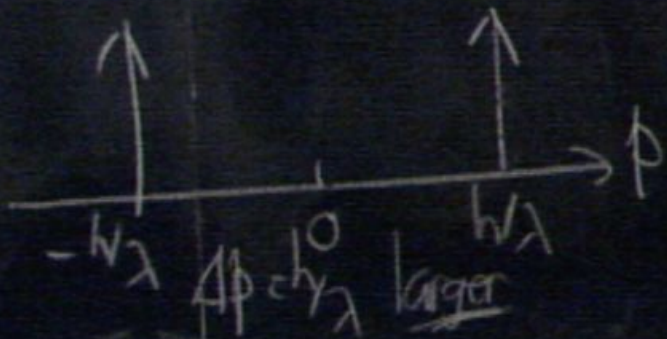
Uncertainty Principle

$$p = \pm \frac{h}{\lambda}$$

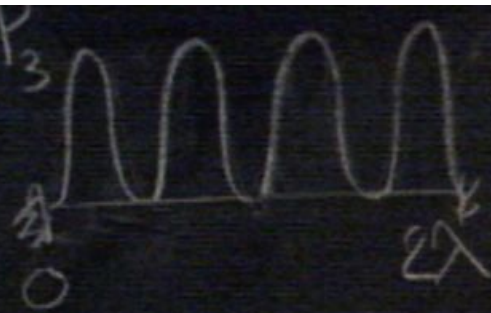


$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x \Delta p = \frac{h}{4}$$

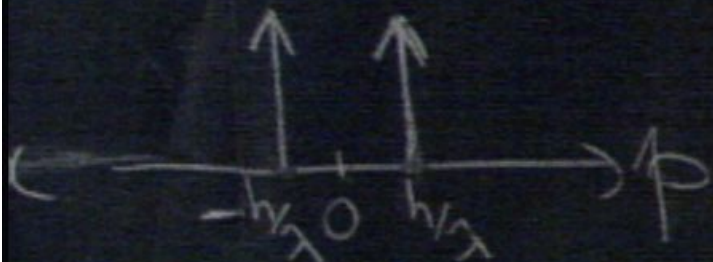


$$\left. \begin{array}{l} \Delta x = \lambda \\ \Delta p = \frac{h}{\lambda} \end{array} \right) \Delta x \Delta p = h > \frac{h}{4}$$

$$\Delta x \Delta p \geq$$

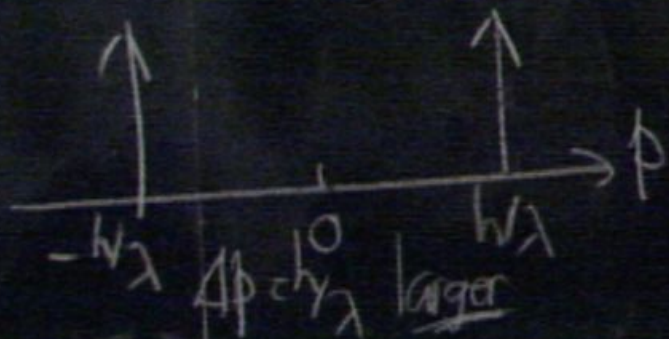
Uncertainty Principle

$$p = \pm \frac{h}{\lambda}$$

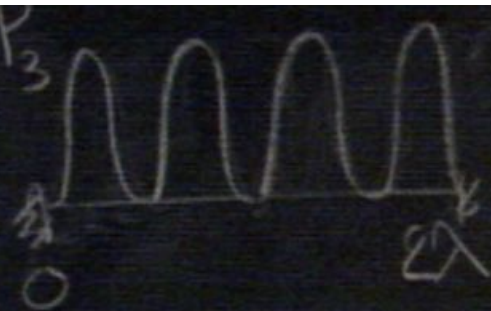


$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x \Delta p = \frac{h}{4}$$

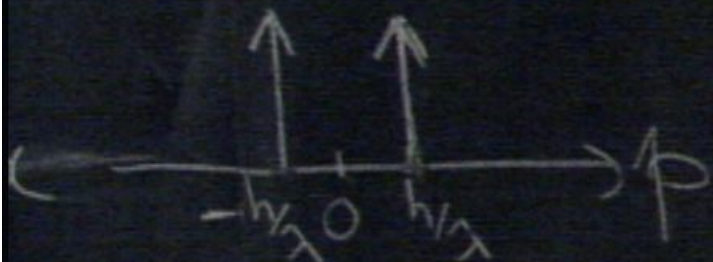


$$\left(\begin{array}{l} \Delta x = \lambda \\ \Delta p = \frac{h}{\lambda} \end{array} \right) \Delta x \Delta p = h > \frac{h}{4}$$

$$\boxed{\Delta x \Delta p \geq \frac{h}{4\pi}}$$

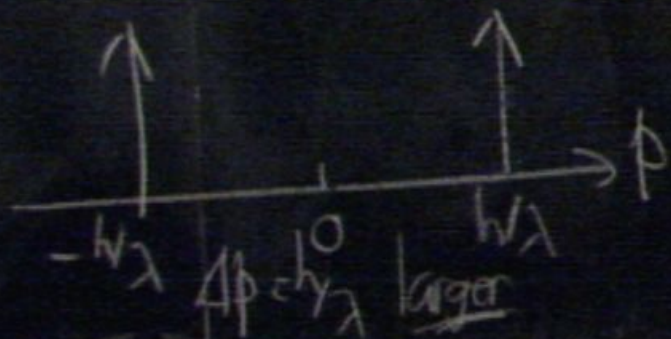
Uncertainty Principle

$$p = \pm \frac{h}{\lambda}$$

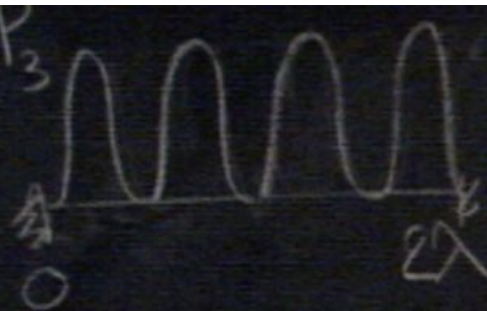


$$\Delta p = \frac{h}{\lambda}$$

$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x \Delta p = \frac{h}{4}$$



$$\Delta x = \lambda$$

$$\Delta p = \frac{h}{\lambda}$$

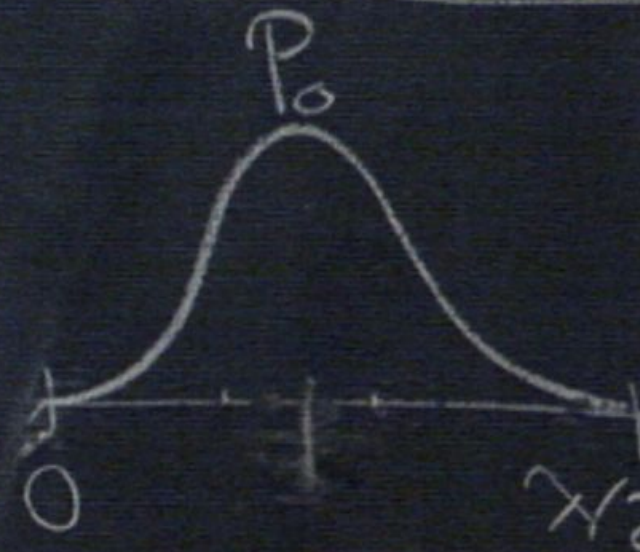
$$\Delta x \Delta p = h > \frac{h}{4}$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

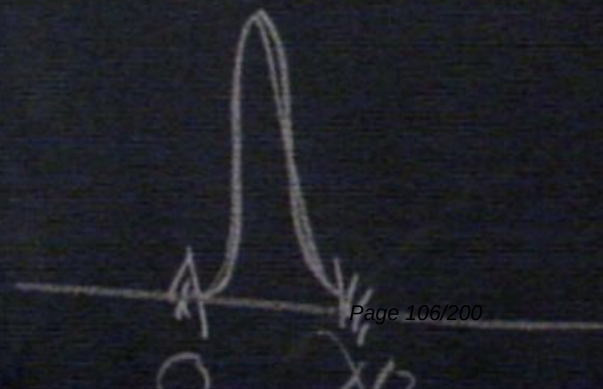
Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

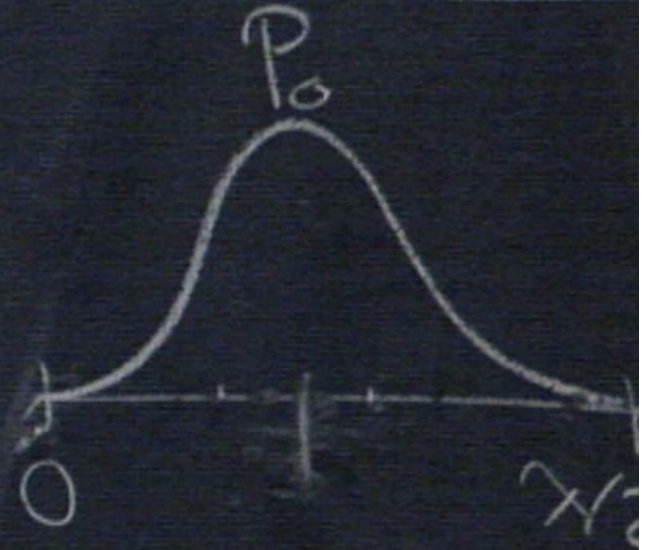


Strong Interpretation HUP

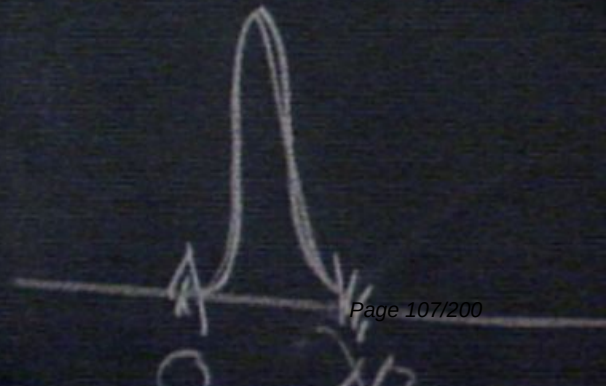
particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

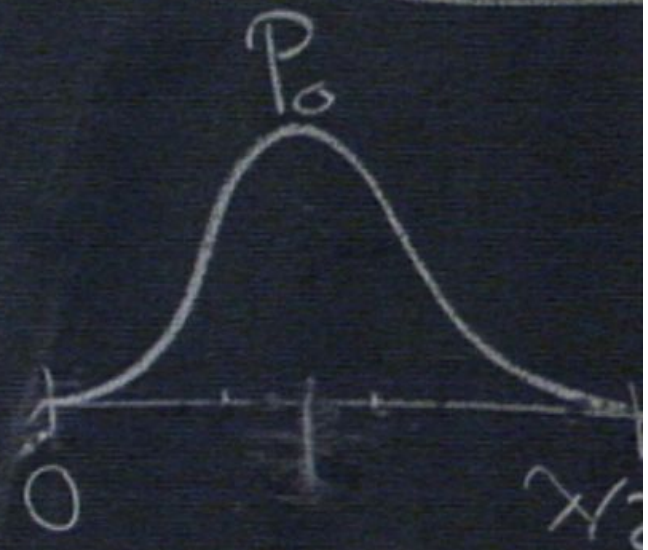


Strong Interpretation HUP

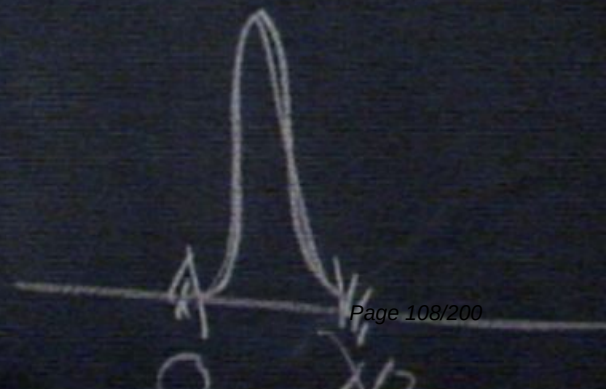
particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$



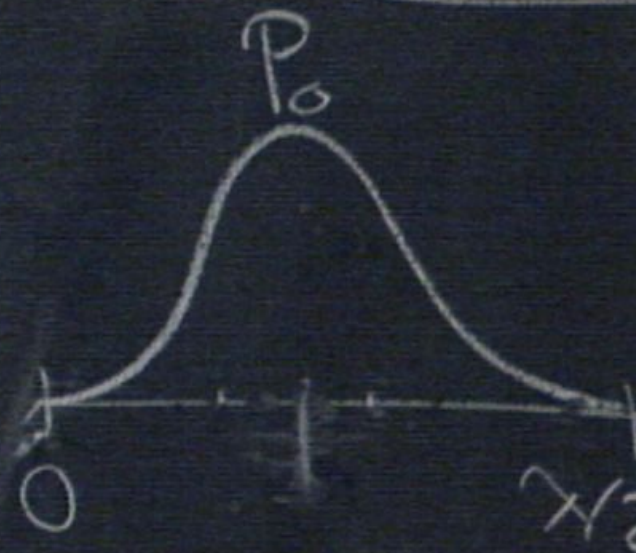
Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

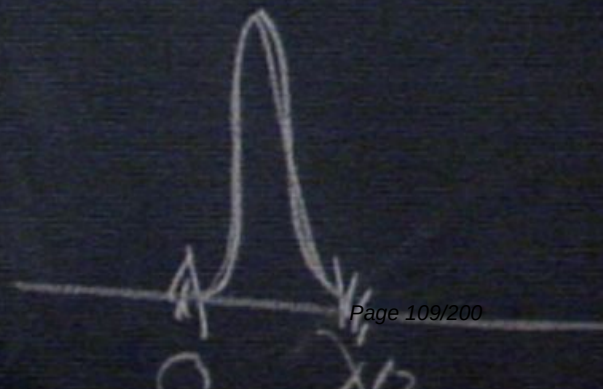
$$\Delta x = 0 \quad \Delta p = 0$$

classical

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$



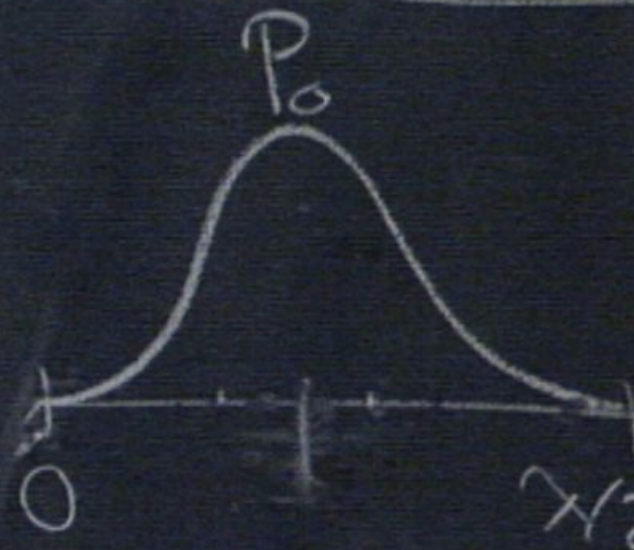
Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

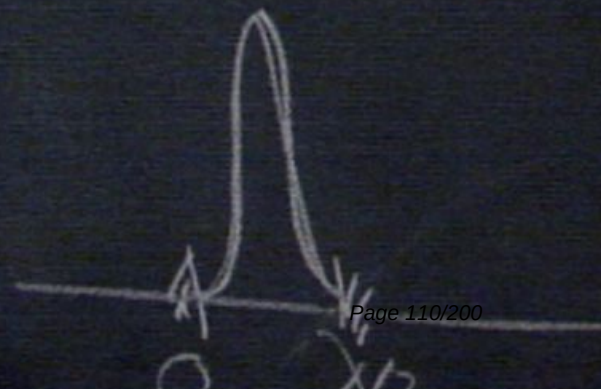
$$\Delta x = 0 \quad \Delta p = 0$$

classical

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

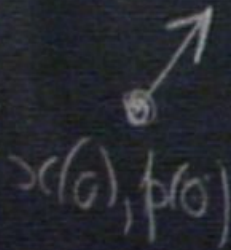


Strong Interpretation HUP

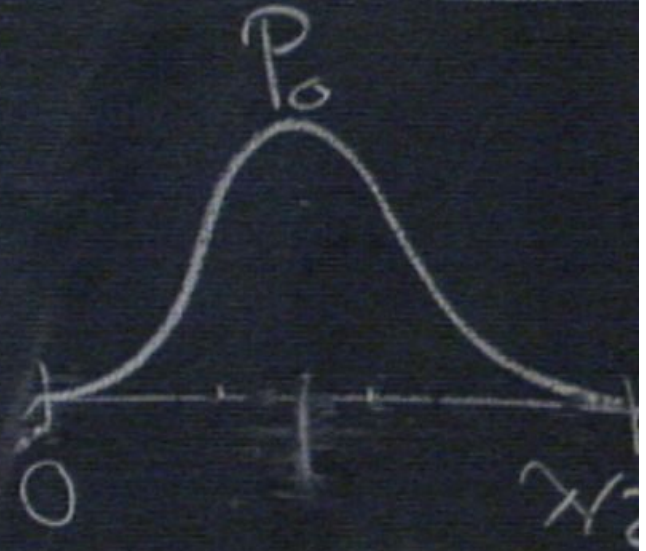
particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

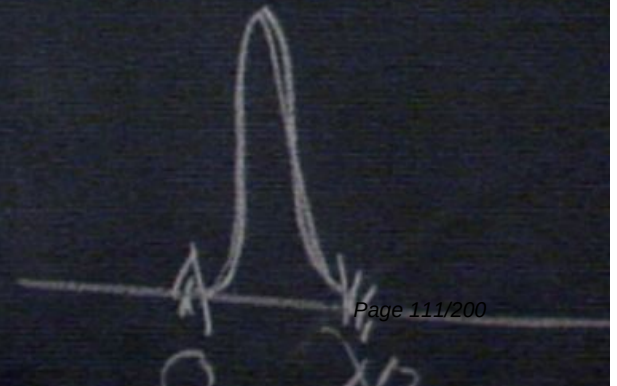
classical



Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

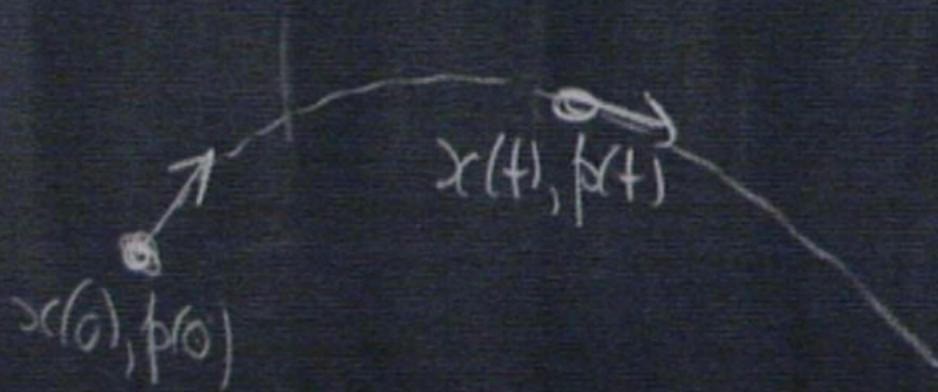


Strong Interpretation HUP

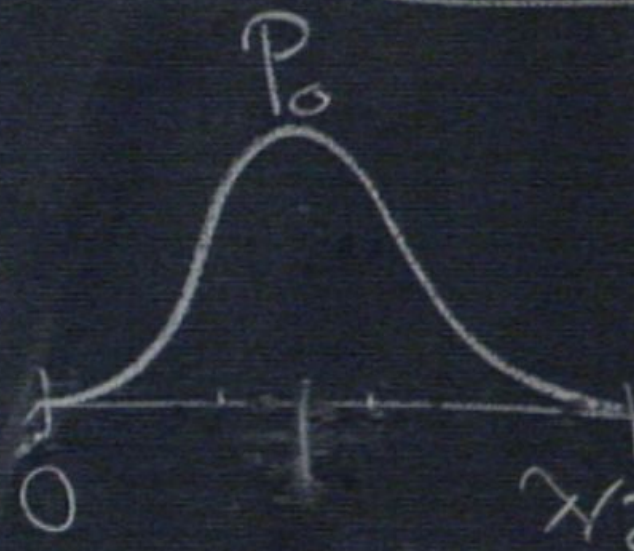
particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

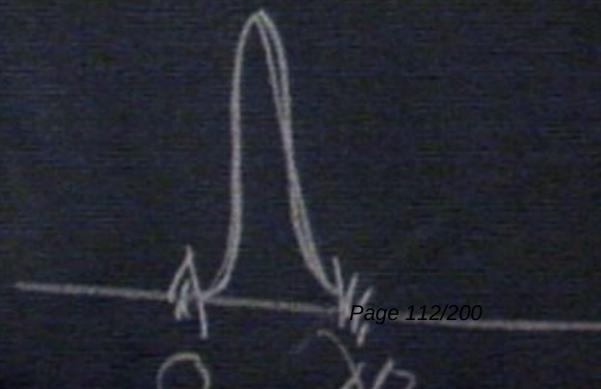
classical



Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

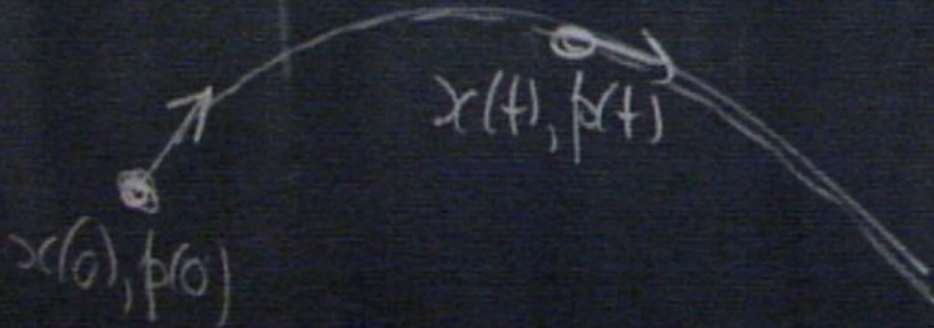


Strong Interpretation HUP

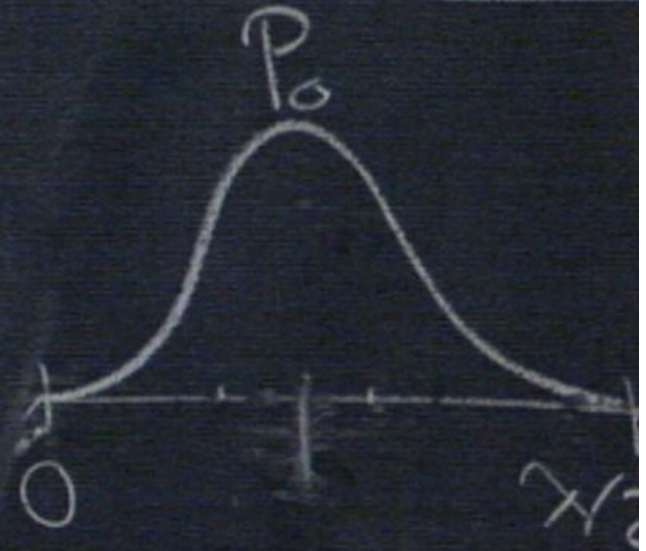
particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

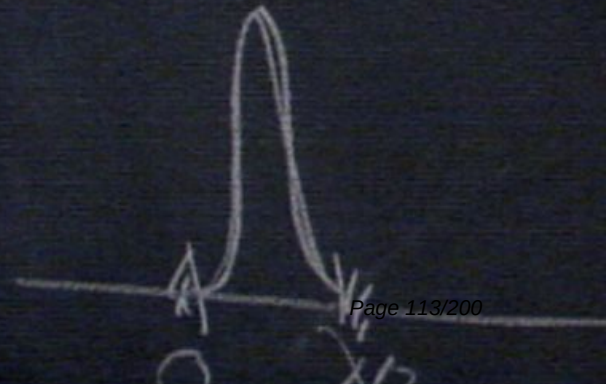
classical



Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

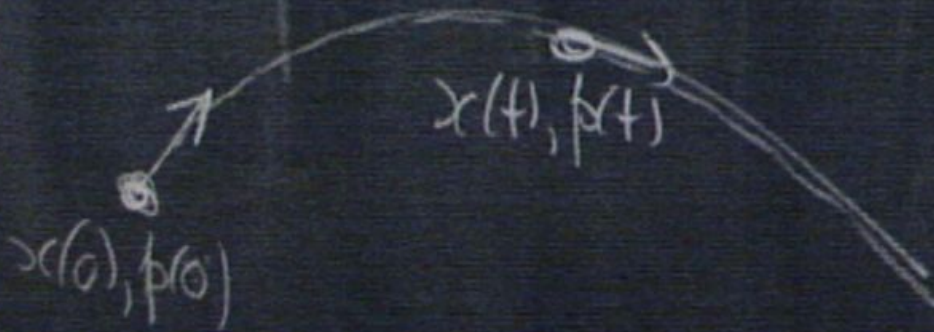


Strong Interpretation HUP

particle cannot simultaneously
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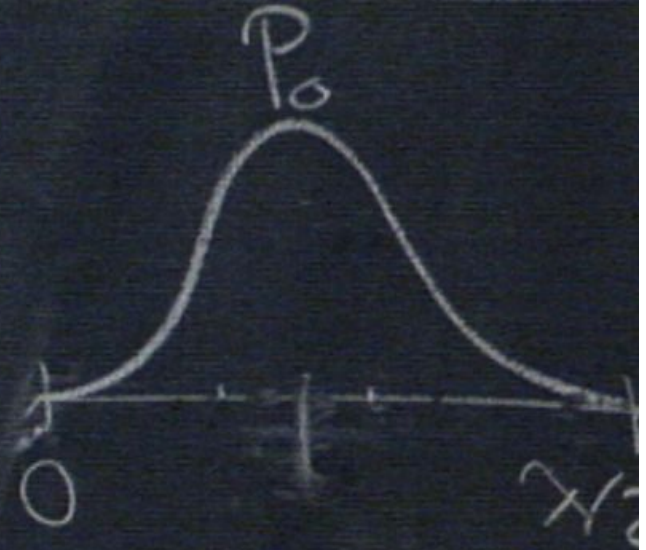
$$\Delta x = 0 \quad \Delta p = 0$$

classical

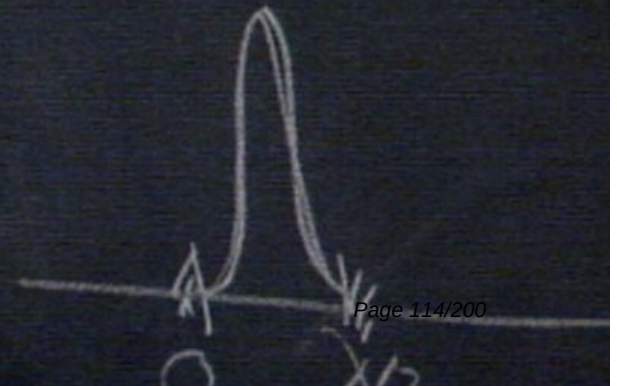


quantum

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

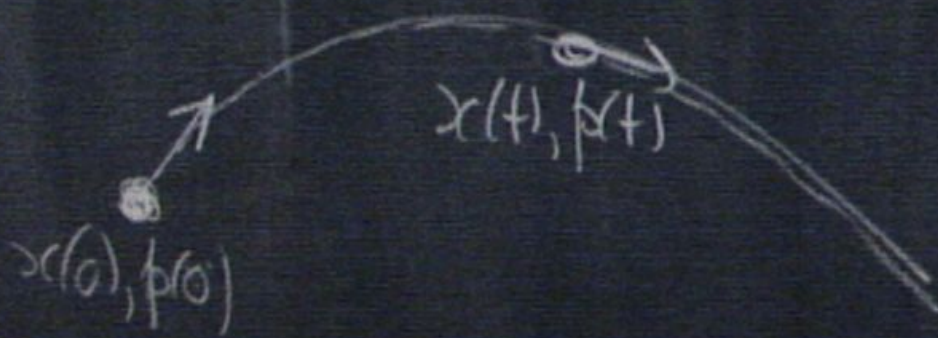


Strong Interpretation HUP

particle cannot simultaneously
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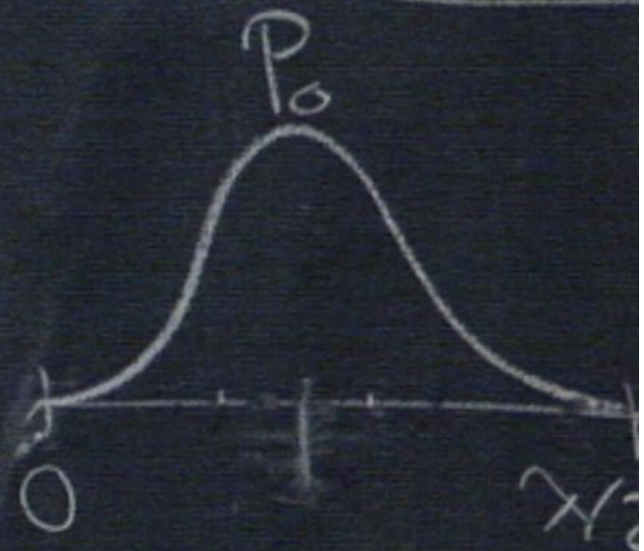
$$\Delta x = 0 \quad \Delta p = 0$$

classical

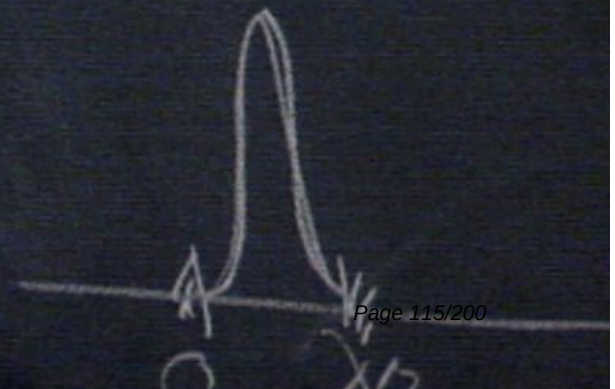


quantum

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

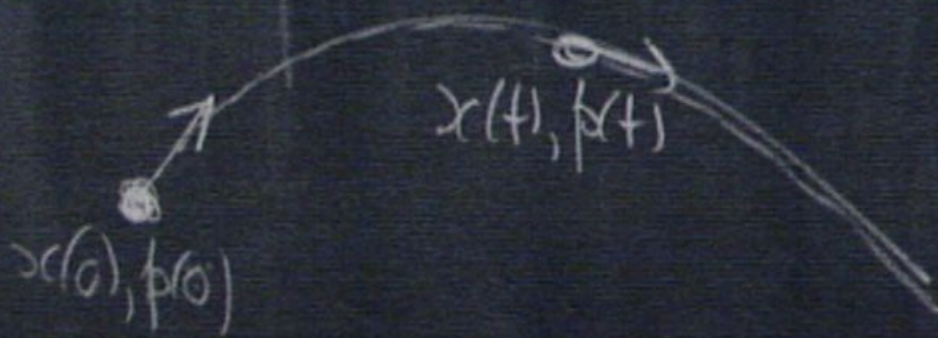


Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

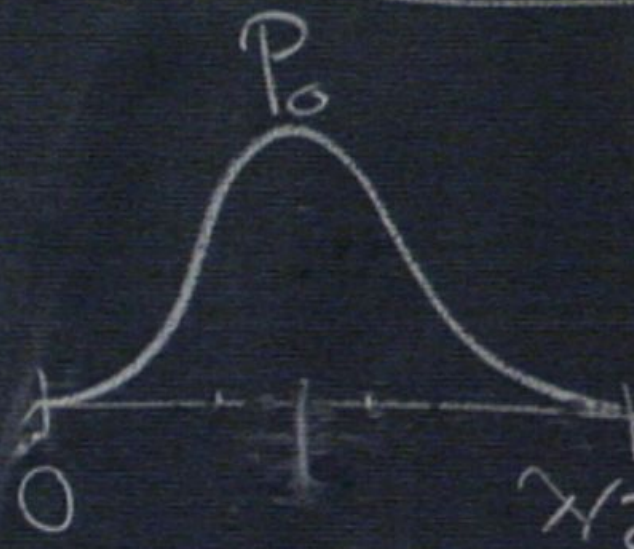
$$\Delta x = 0 \quad \Delta p = 0$$

classical

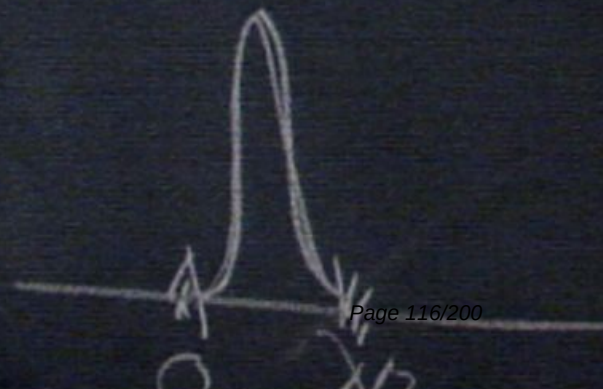


quantum

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

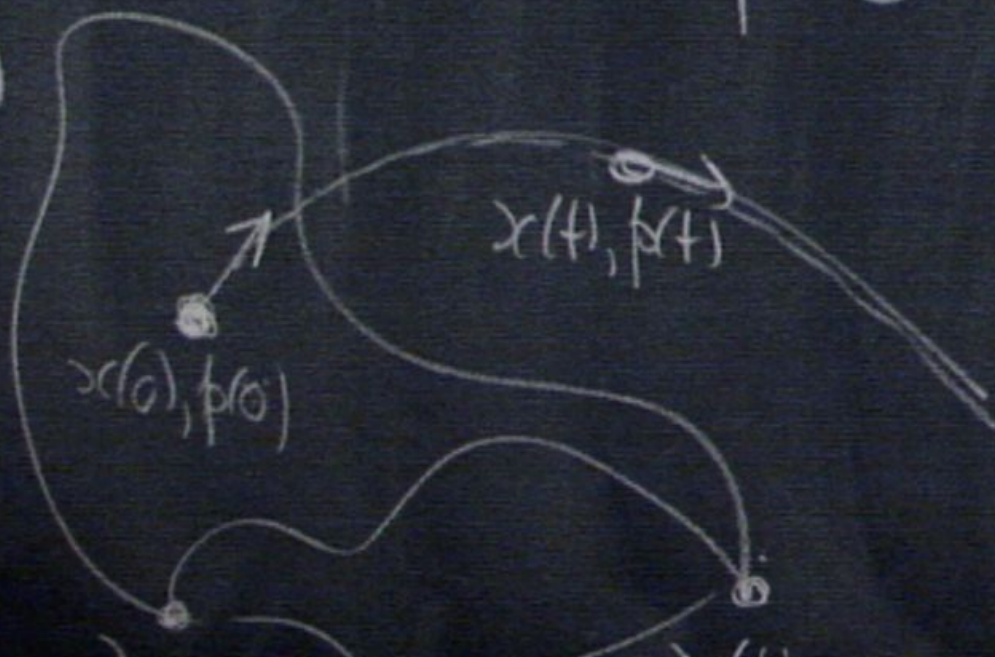


Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

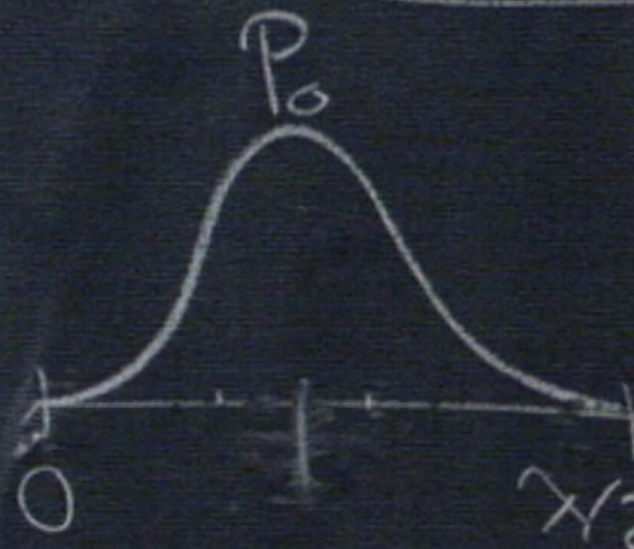
$$\Delta x = 0 \quad \Delta p = 0$$

classical



quantum

Heisenberg



$$\Delta x = \frac{\lambda}{4}$$

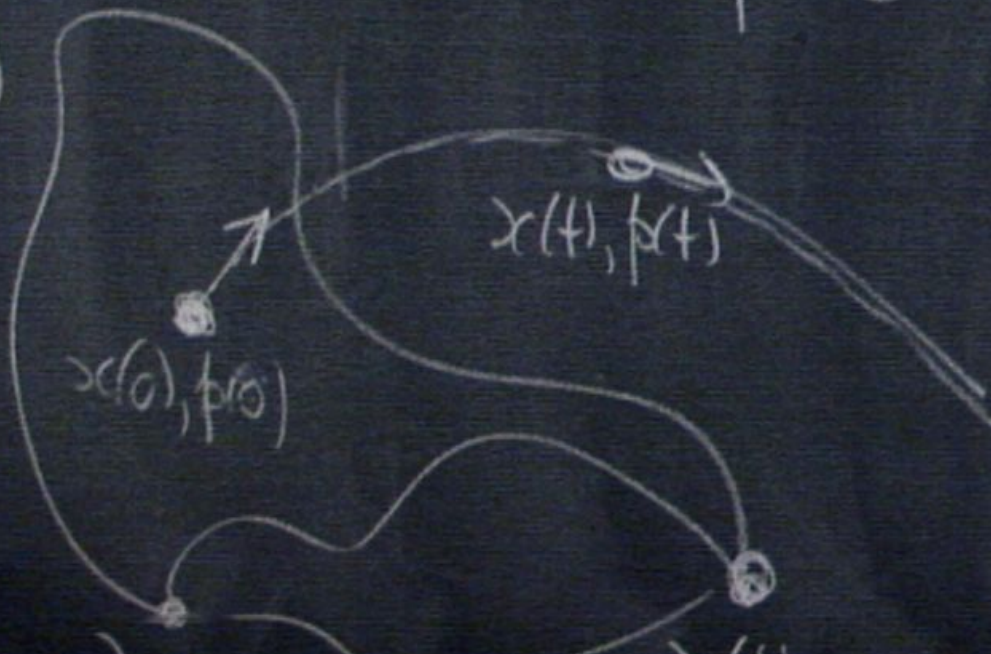


Strong Interpretation HUP

particle cannot simultaneously
possess definite pos. & mom.

$$\Delta x = 0 \quad \Delta p = 0$$

classical

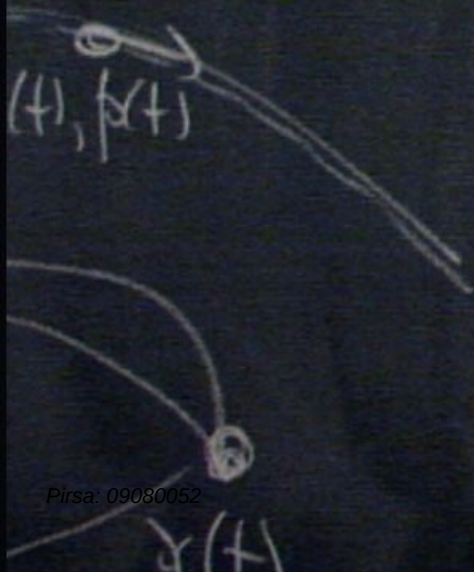


quantum

HUP

Instantaneously
& mom.

$$\Delta p = 0$$



HUP

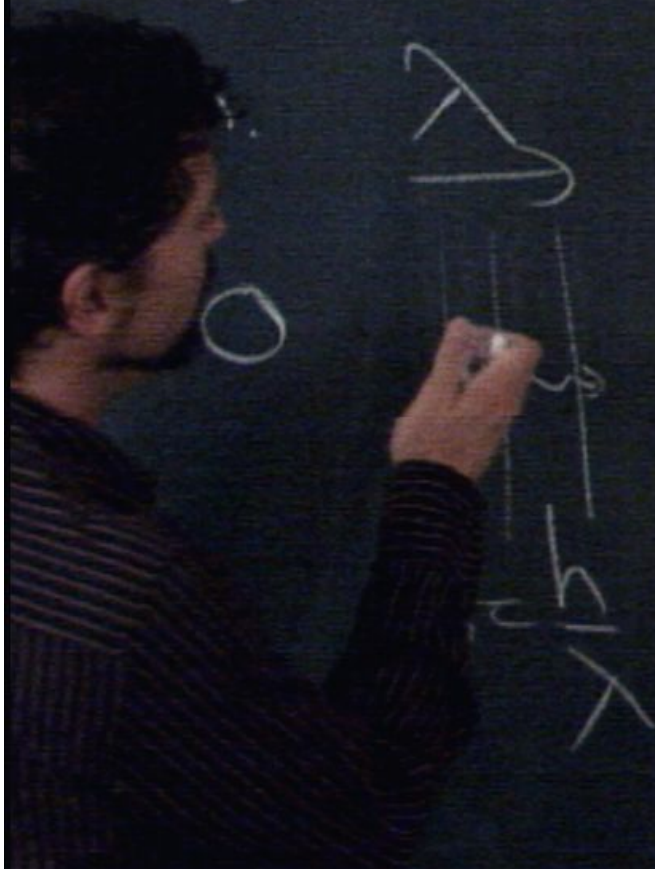
Instantaneously

2



HUP

neously



HP

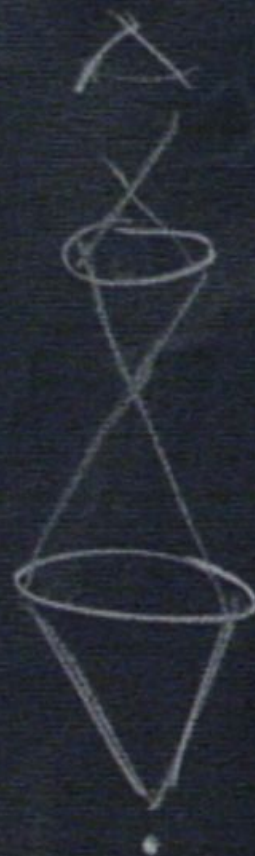
nearly

mon.

$$\Delta p = 0$$



A diagram showing a particle with vertical lines and a wavy line. The equation $p = \frac{h}{\lambda}$ is written below it.
$$p = \frac{h}{\lambda}$$



HP

nearly

mon.

$$\Delta p = 0$$



HUP

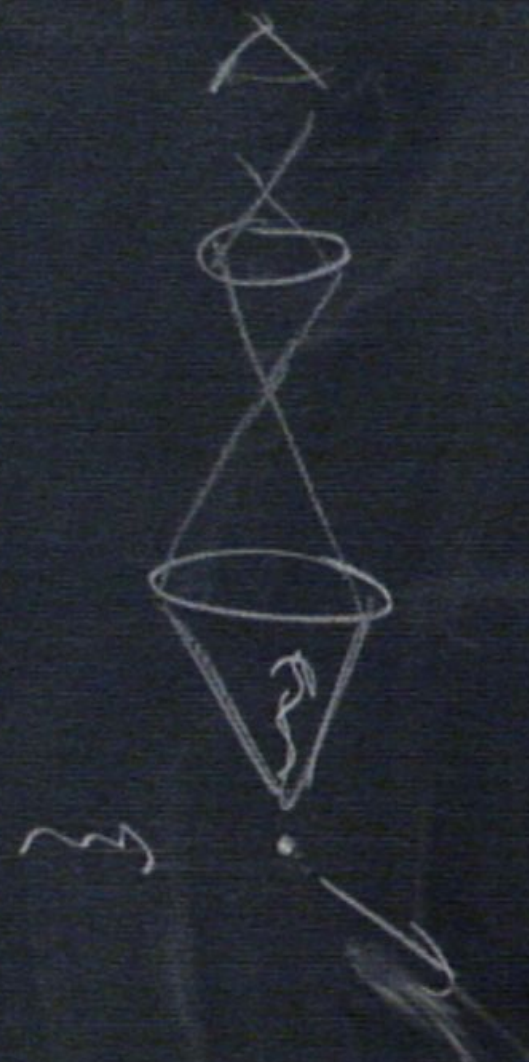
neously

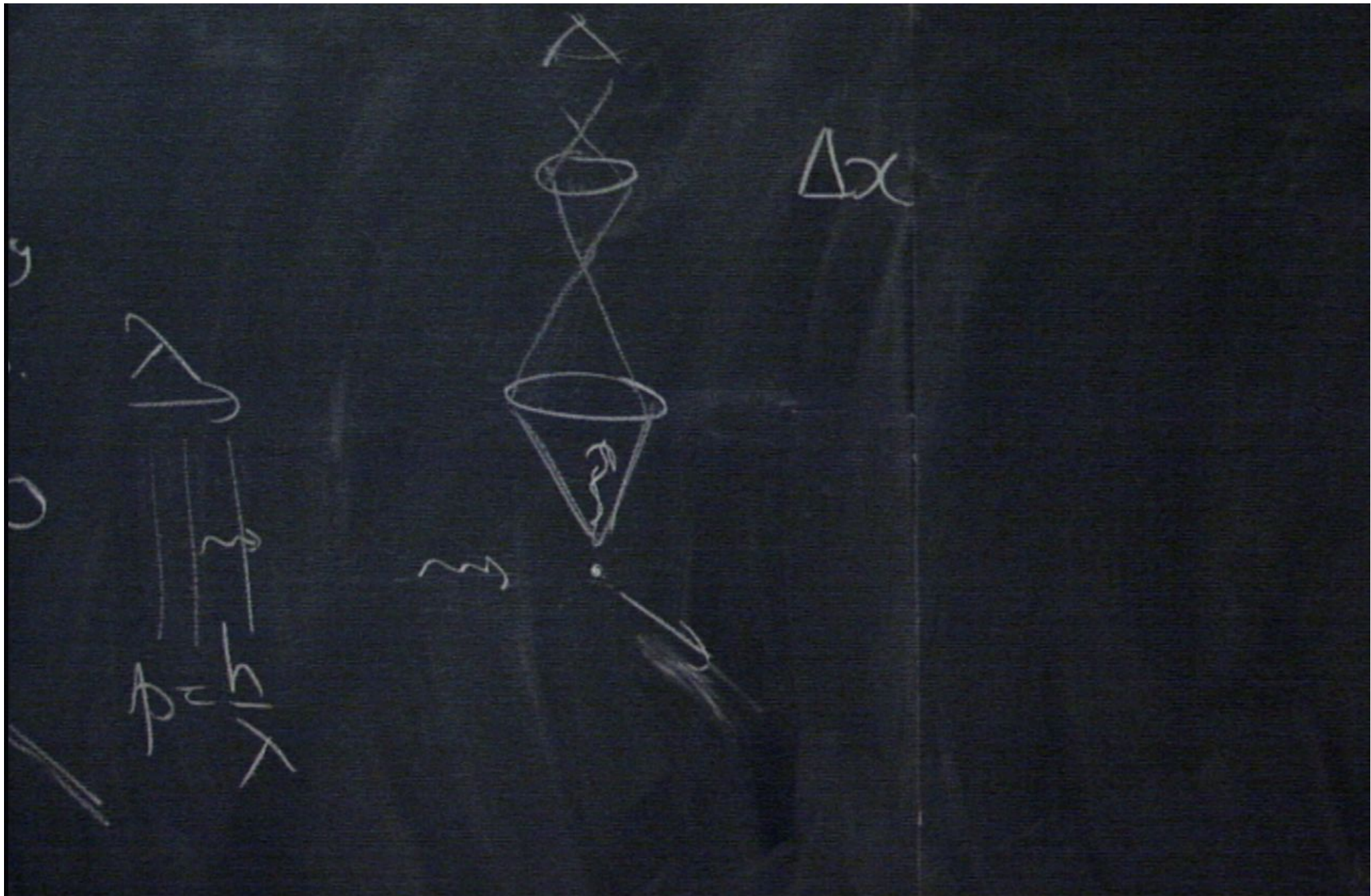
mom.

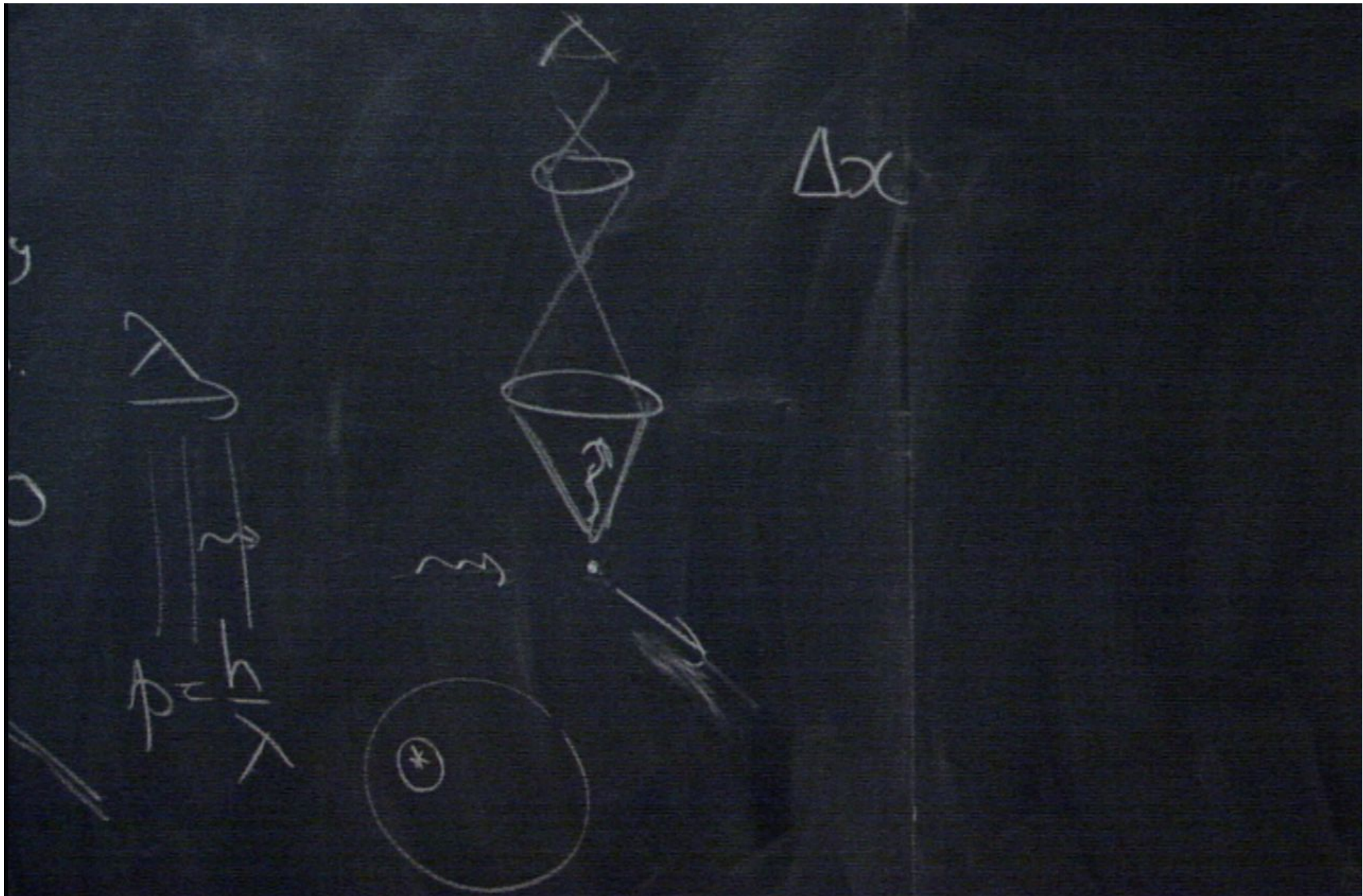
$$\Delta p = 0$$

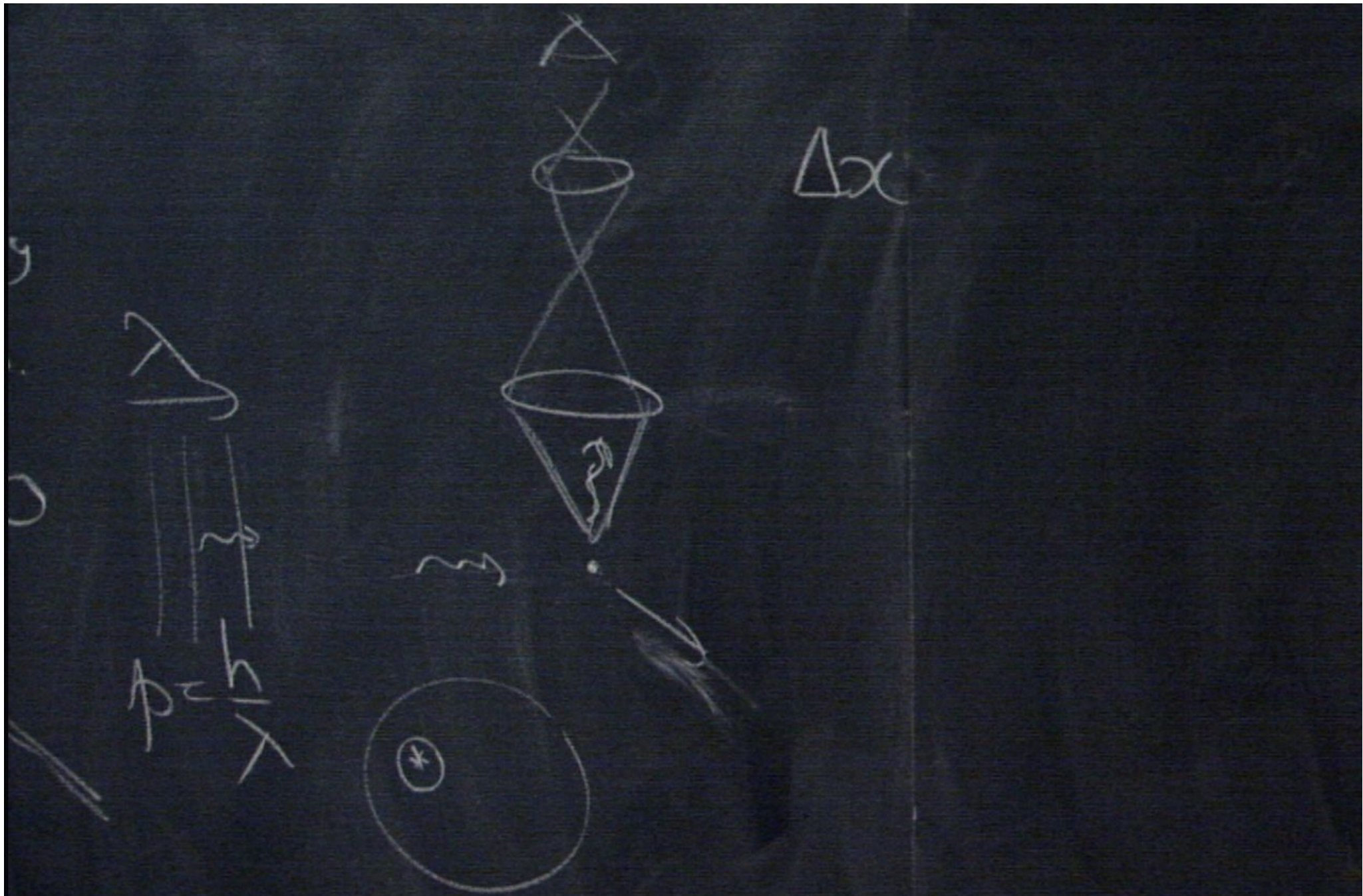


A hand-drawn diagram showing a particle beam. A curved line represents the beam's path, with an arrow pointing to the right. A label "p = h/lambda" is written near the start of the beam.



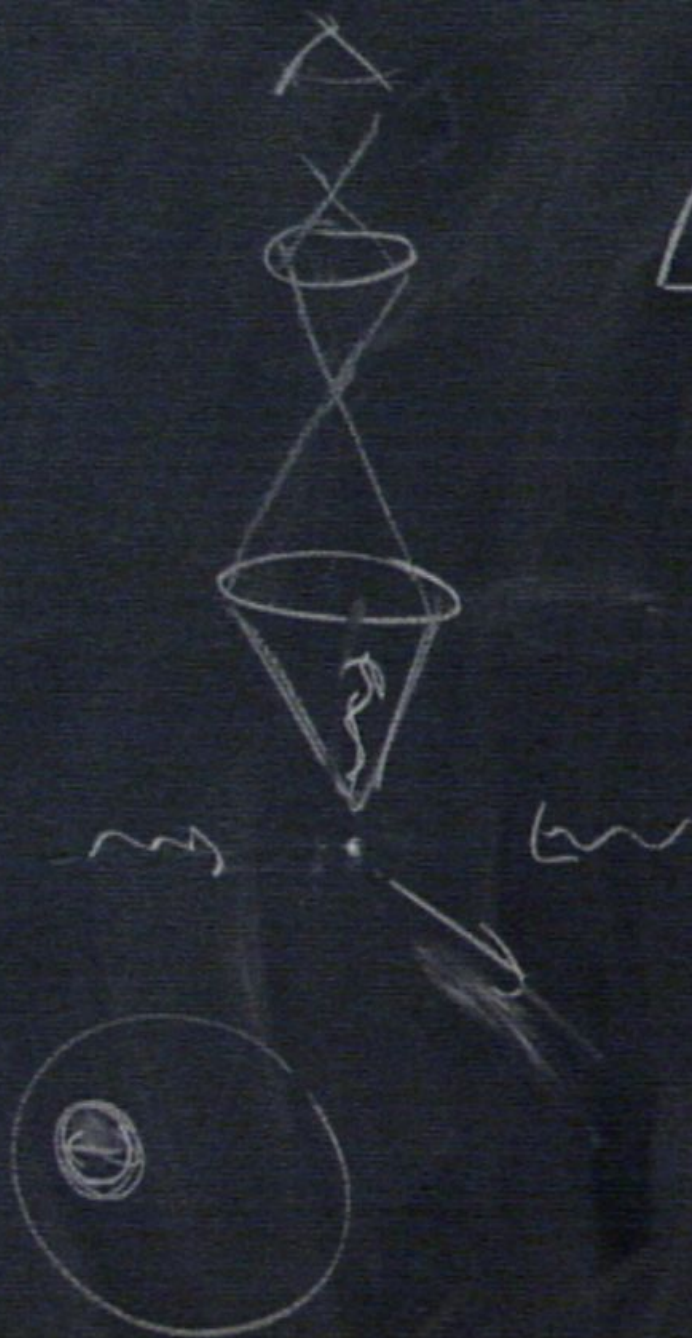






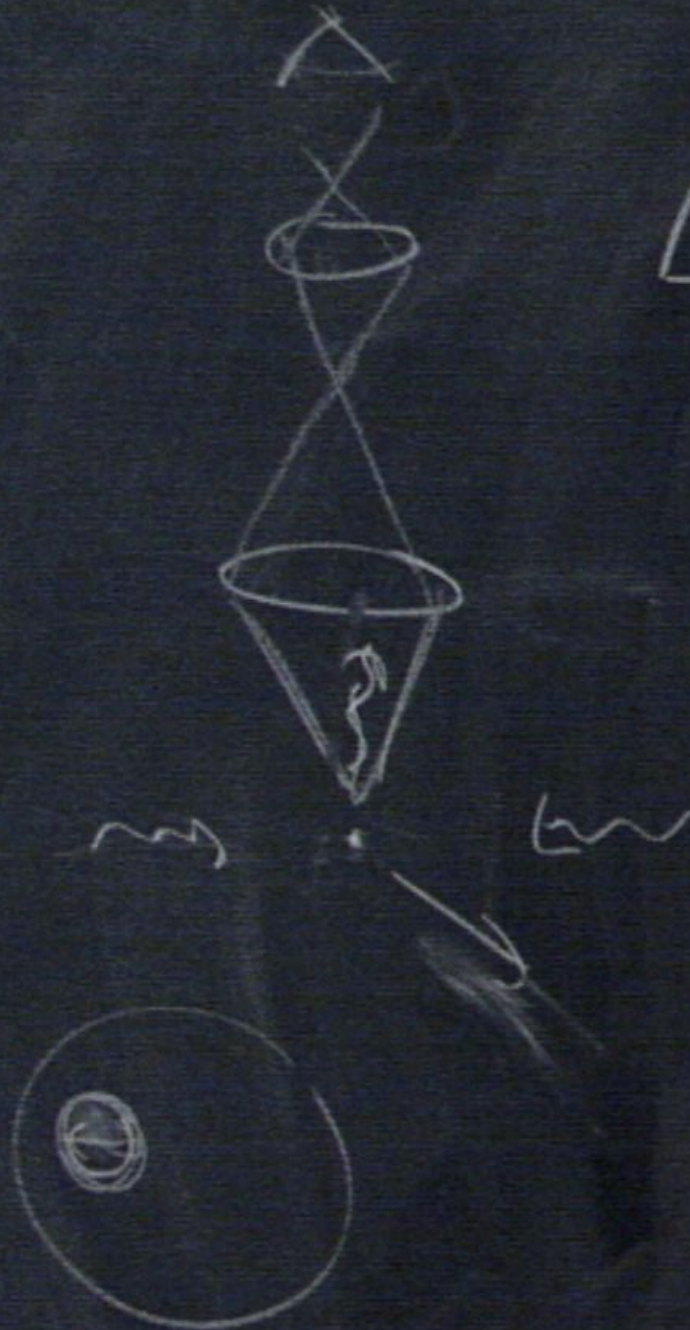
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$p = \frac{h}{\lambda}$$



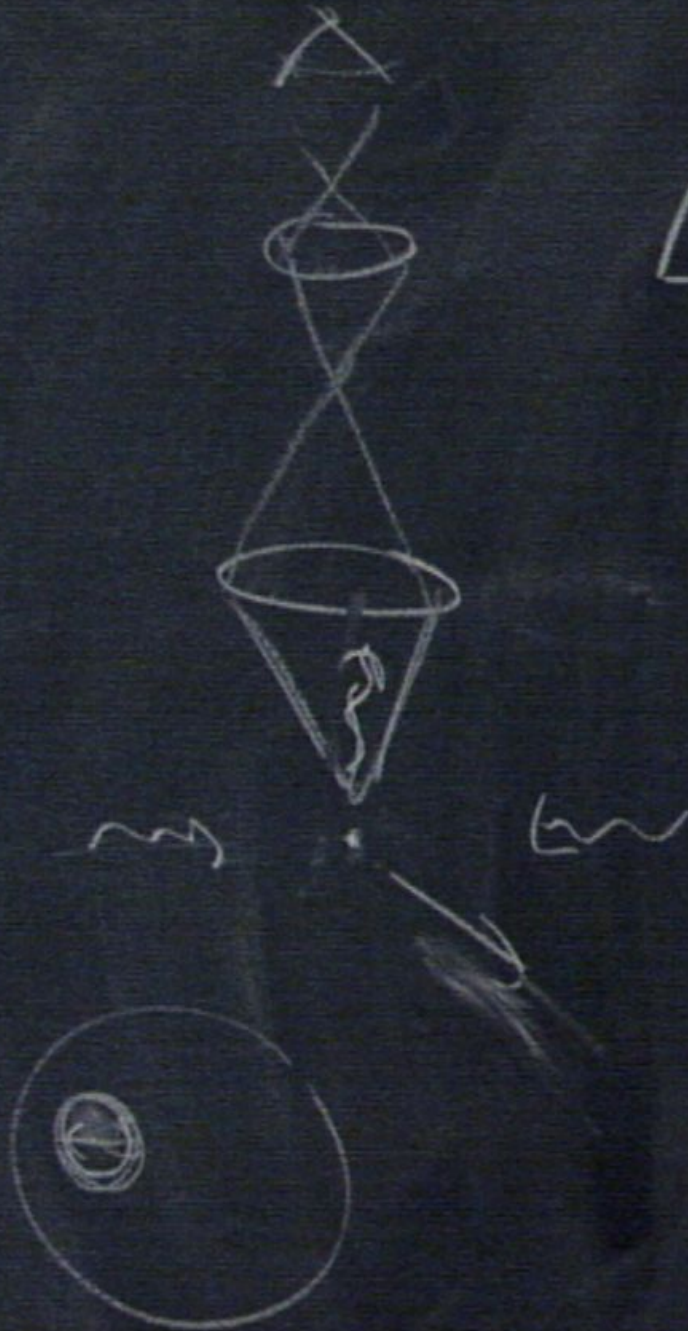
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

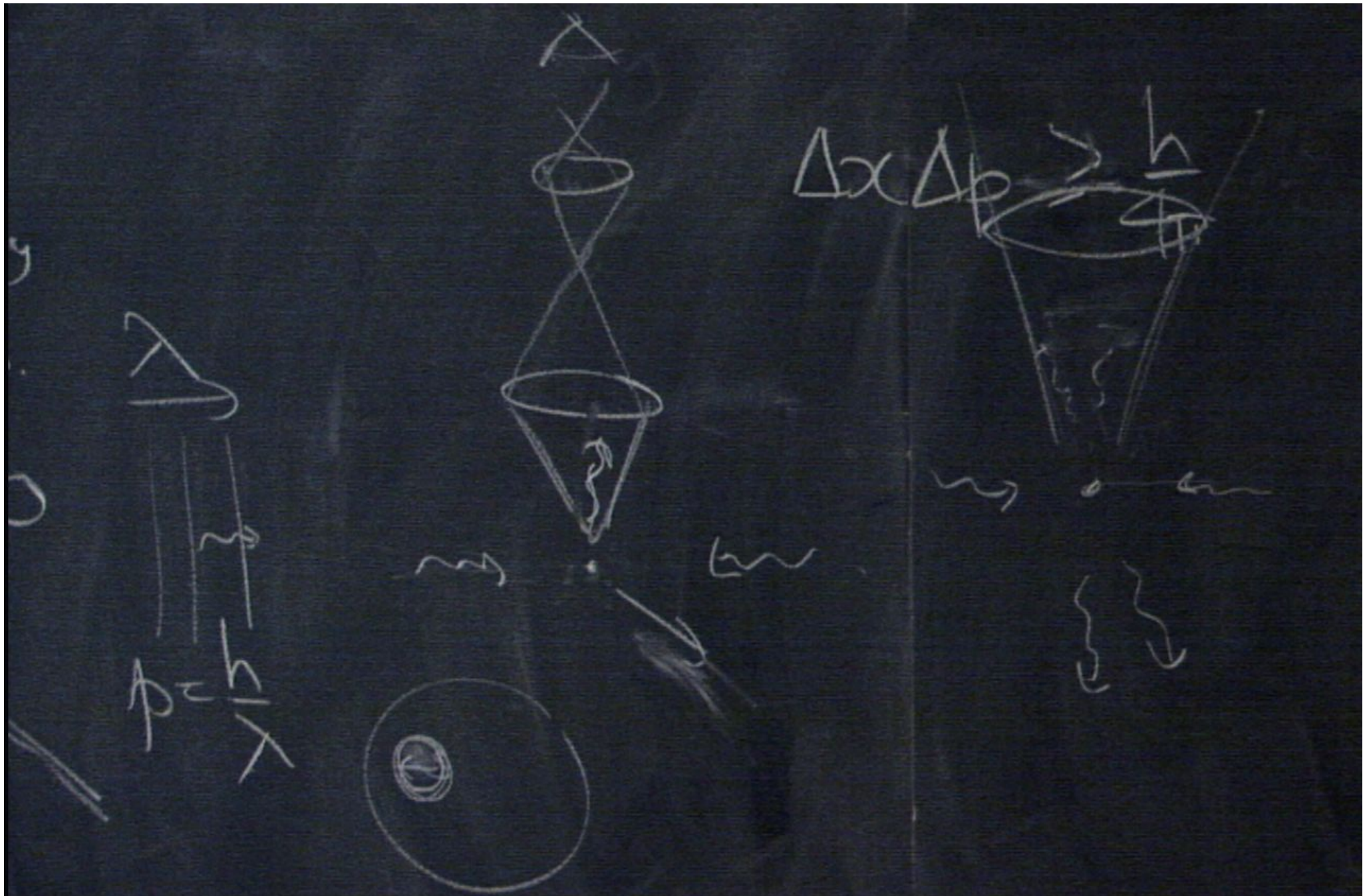
$$p = \frac{h}{\lambda}$$

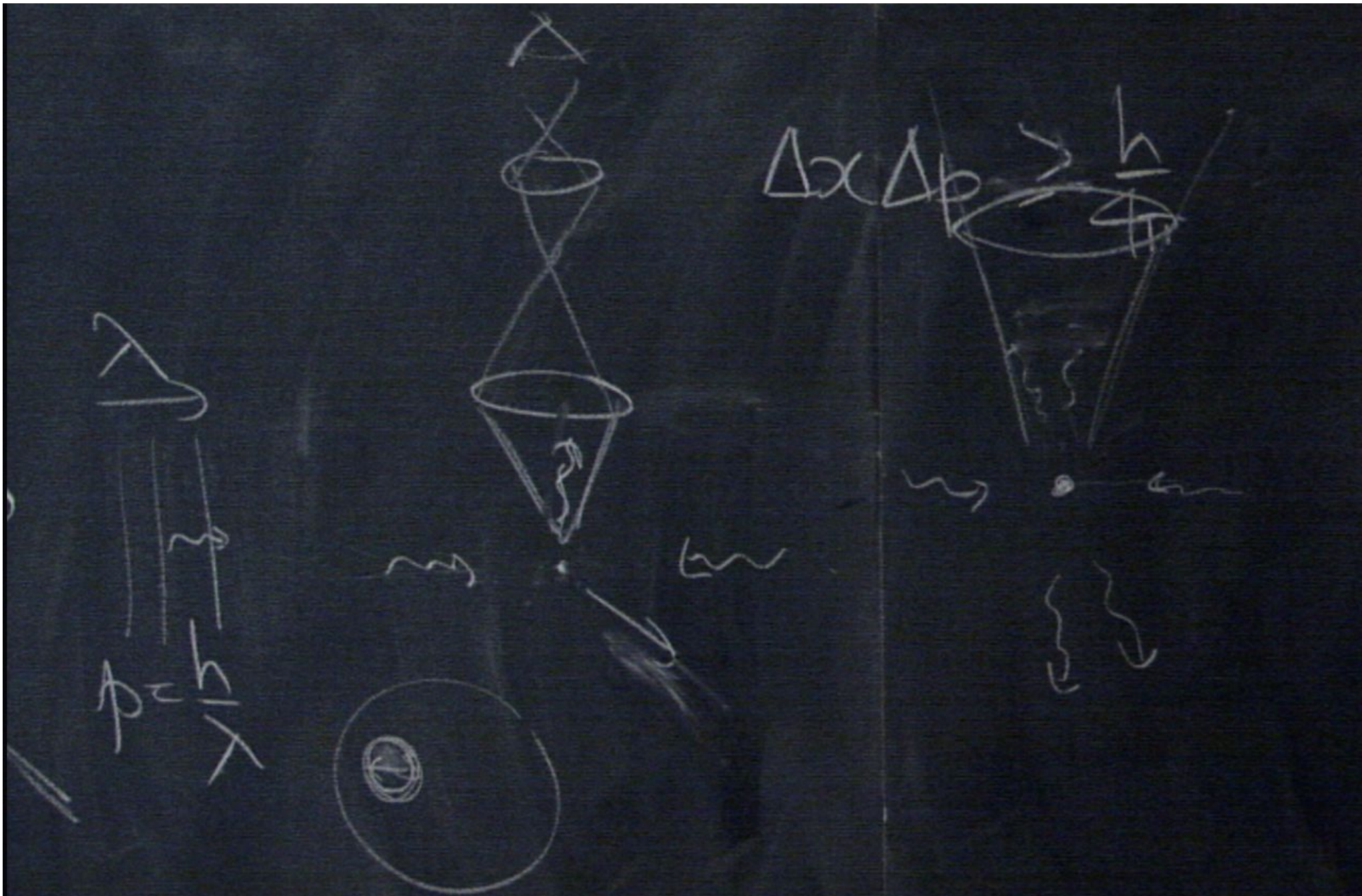


$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$p = \frac{h}{\lambda}$$



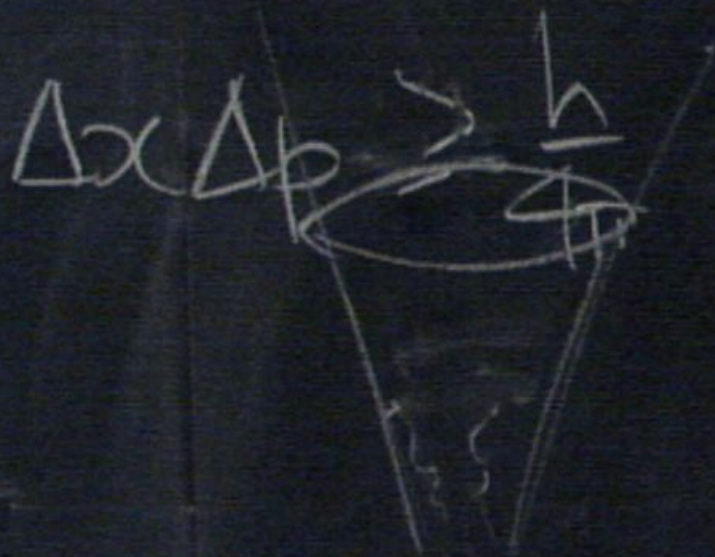


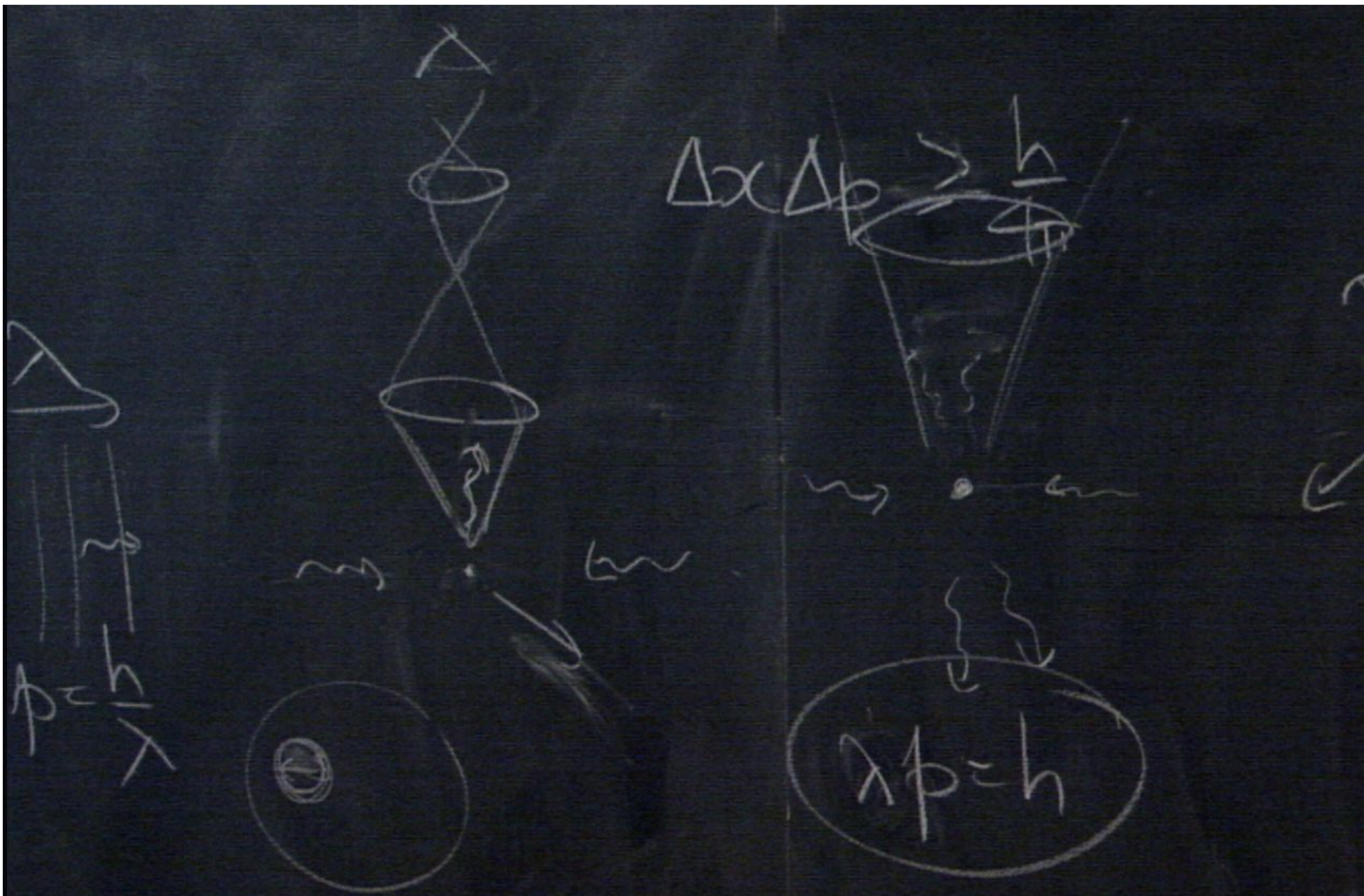


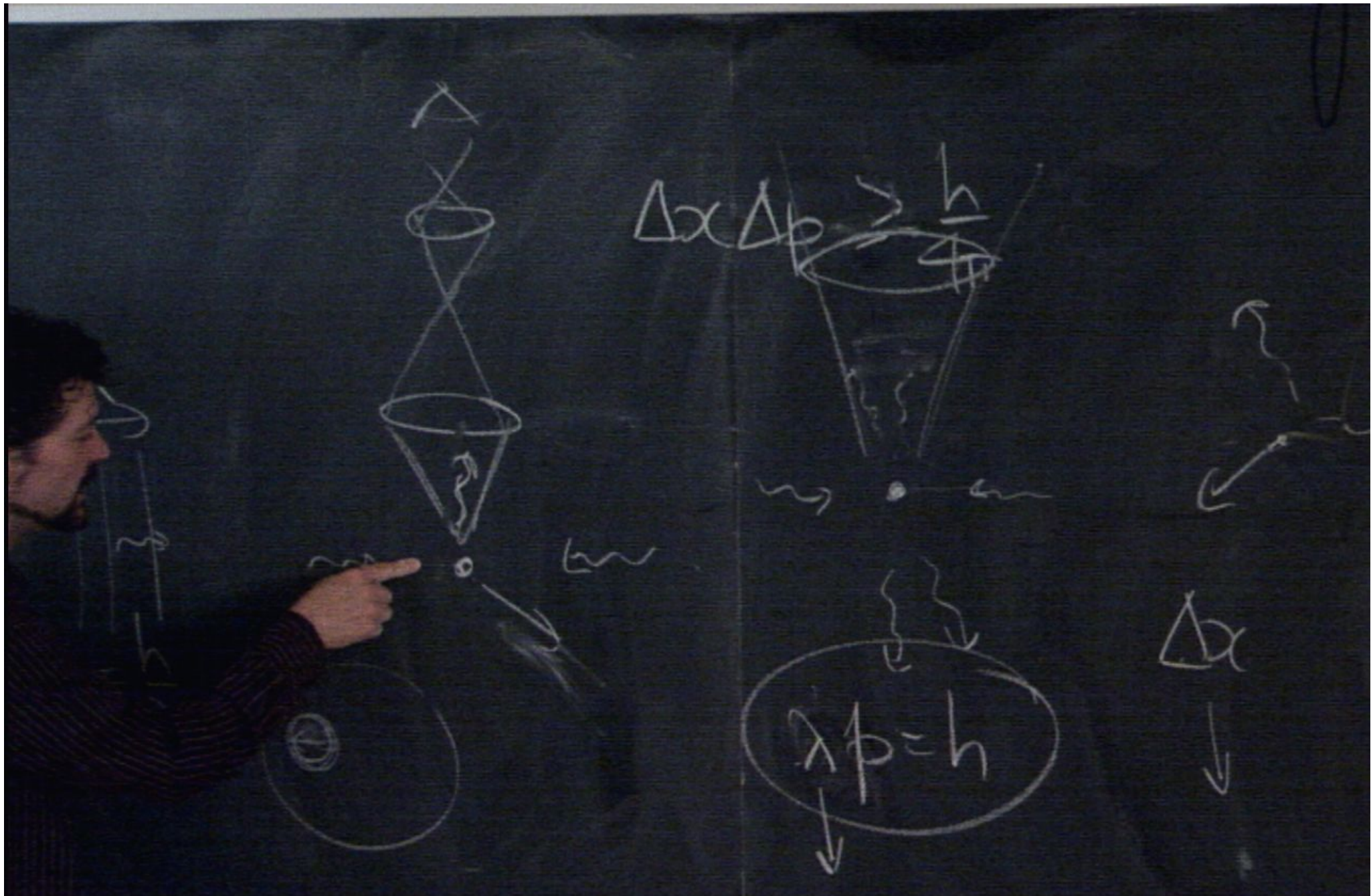
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$


A diagram illustrating the Heisenberg uncertainty principle. It shows a cone-like shape with its vertex at a point, representing the spread of possible values for position and momentum. The cone is drawn with two lines diverging from a central point, and a horizontal line across its top. The text $\Delta x \Delta p \geq \frac{h}{4\pi}$ is written above the cone.

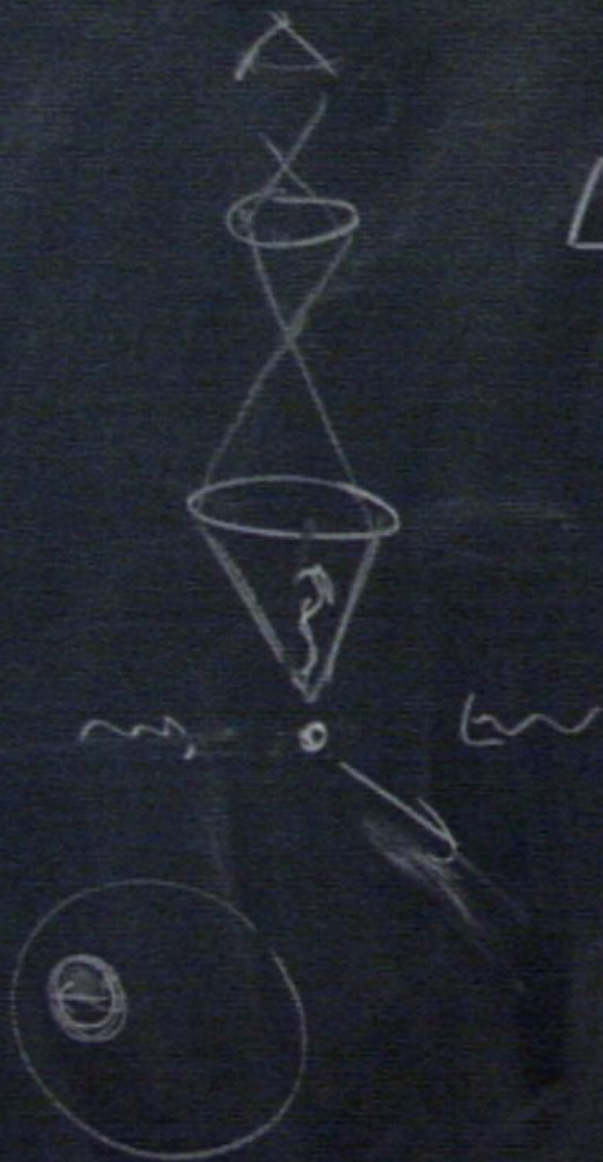








$$p = \frac{h}{\lambda}$$

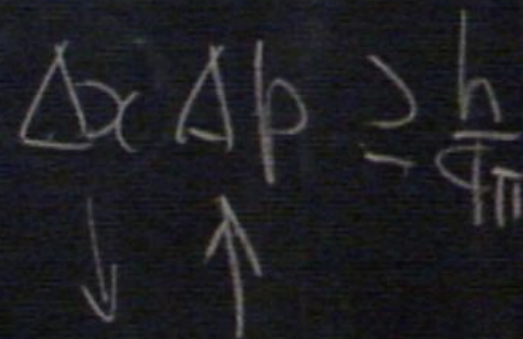
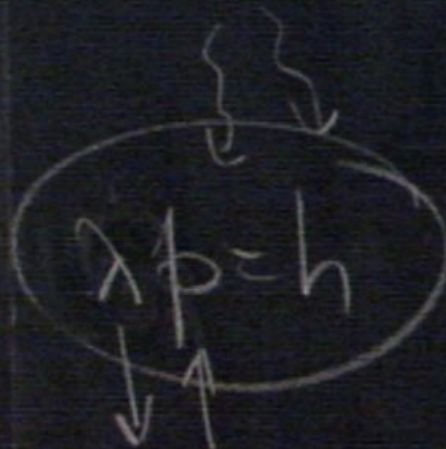
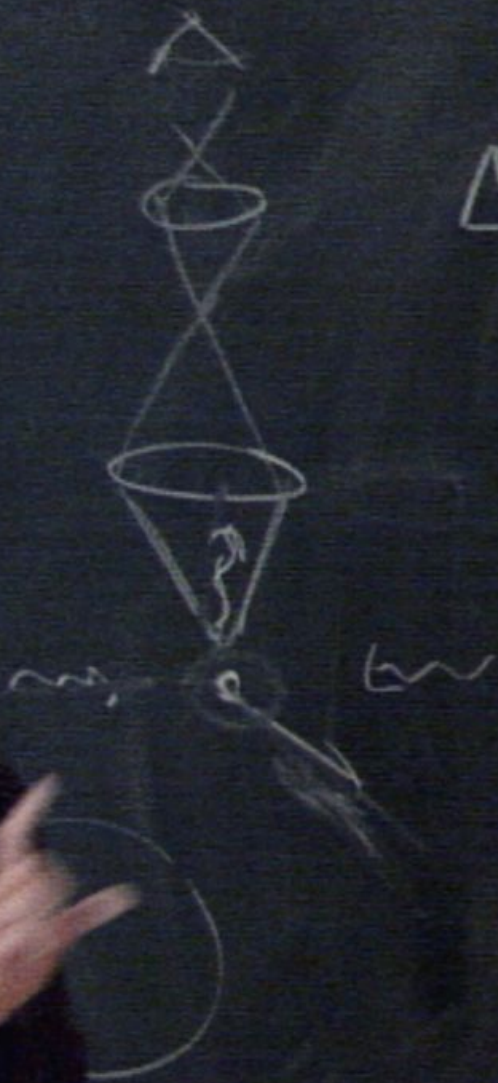


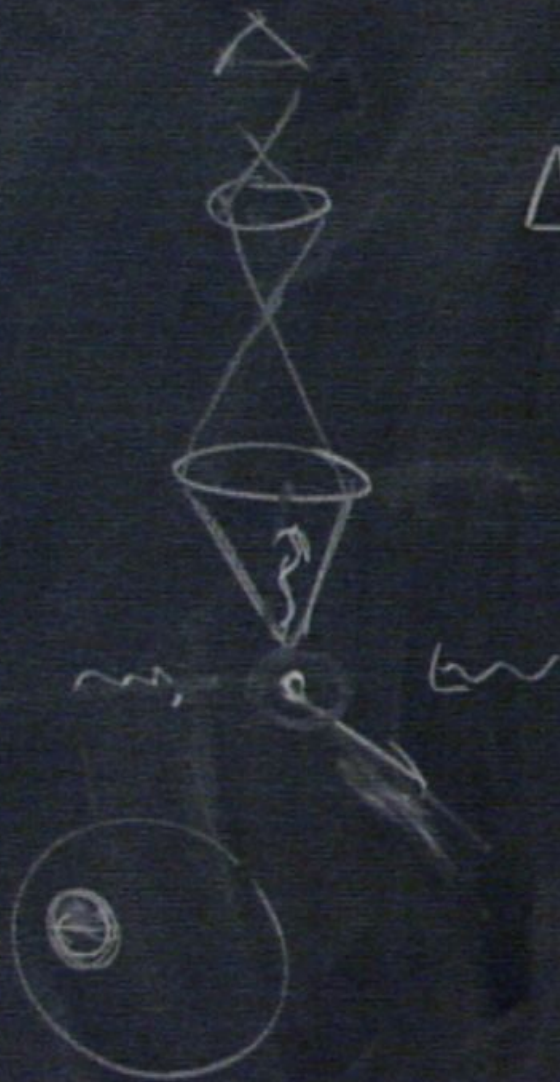
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\lambda p = h$$

$$\Delta x$$

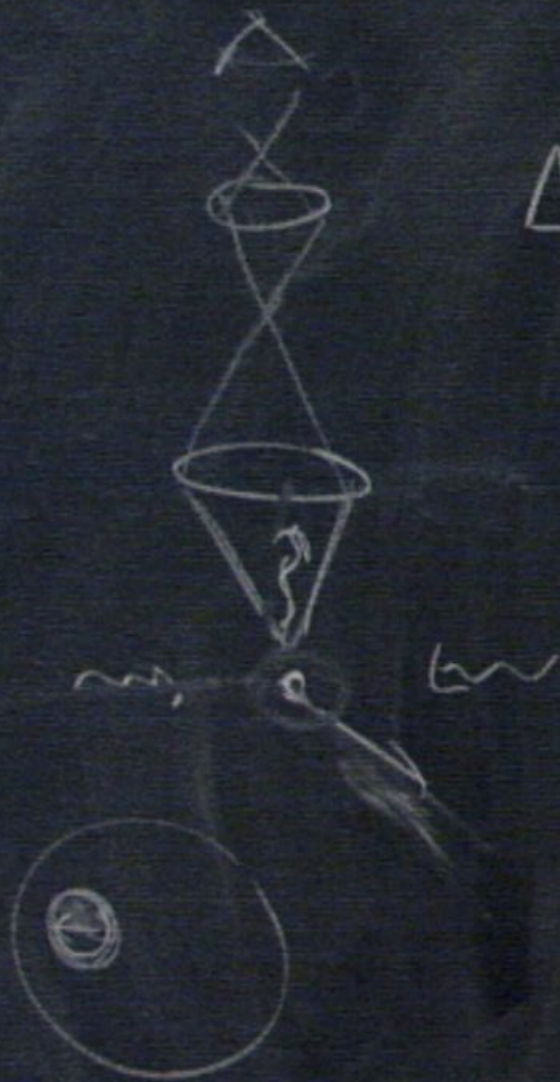






$$\lambda p = h$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$



$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

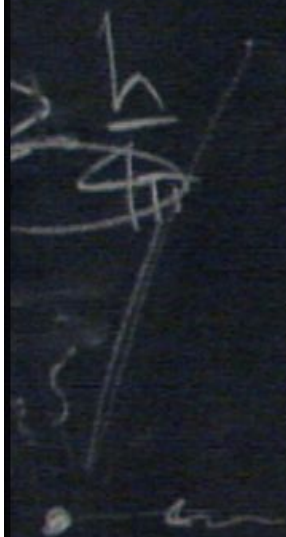
A diagram showing a light source emitting a beam of light that is focused onto a small object. The light is then collected by a lens and passes through a series of lenses to an observer's eye. The diagram illustrates the trade-off between the precision of position measurement (Δx) and the precision of momentum measurement (Δp).

$$\lambda p = h$$

A diagram showing a light source emitting a beam of light that is focused onto a small object. The light is then collected by a lens and passes through a series of lenses to an observer's eye. The diagram illustrates the trade-off between the precision of position measurement (Δx) and the precision of momentum measurement (Δp).

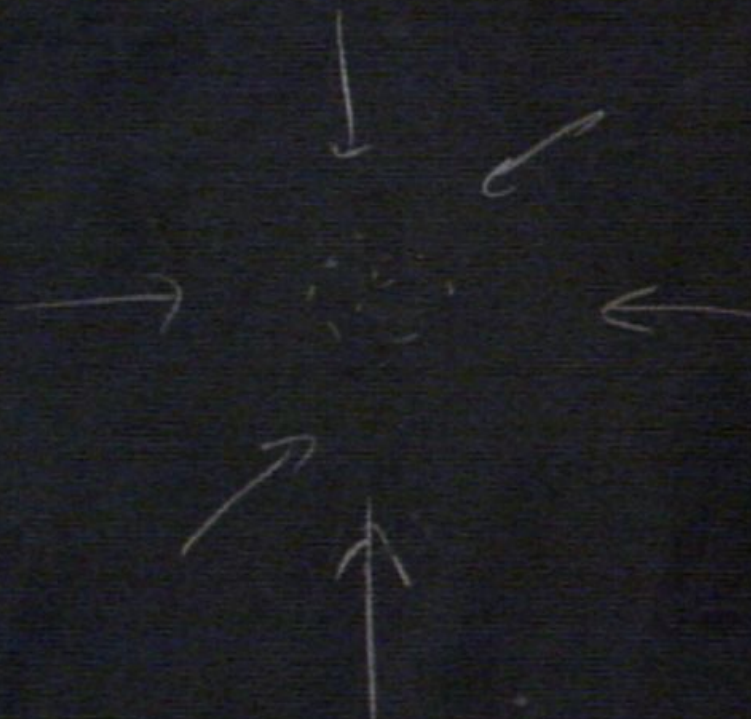
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

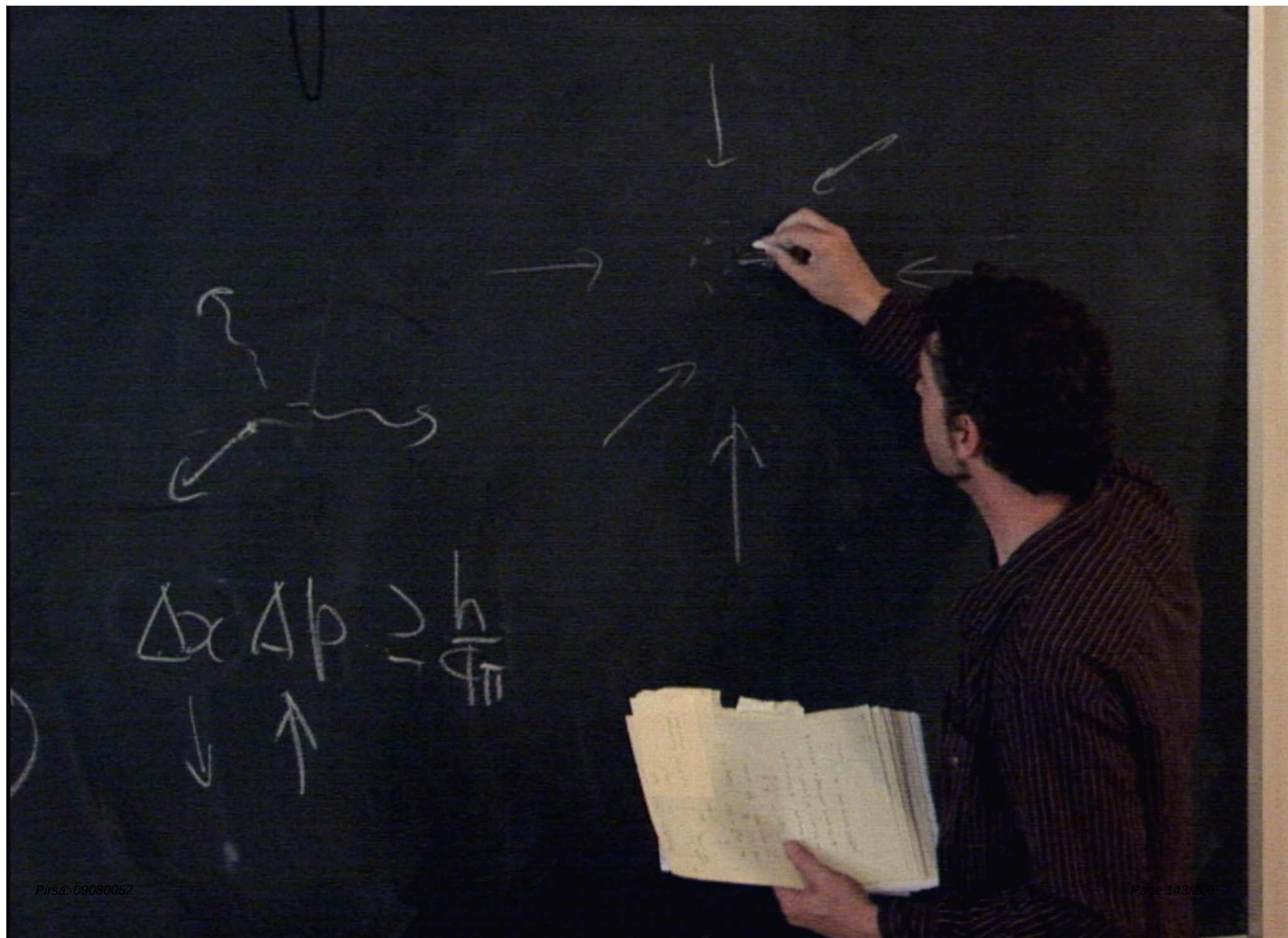
A diagram showing a light source emitting a beam of light that is focused onto a small object. The light is then collected by a lens and passes through a series of lenses to an observer's eye. The diagram illustrates the trade-off between the precision of position measurement (Δx) and the precision of momentum measurement (Δp).

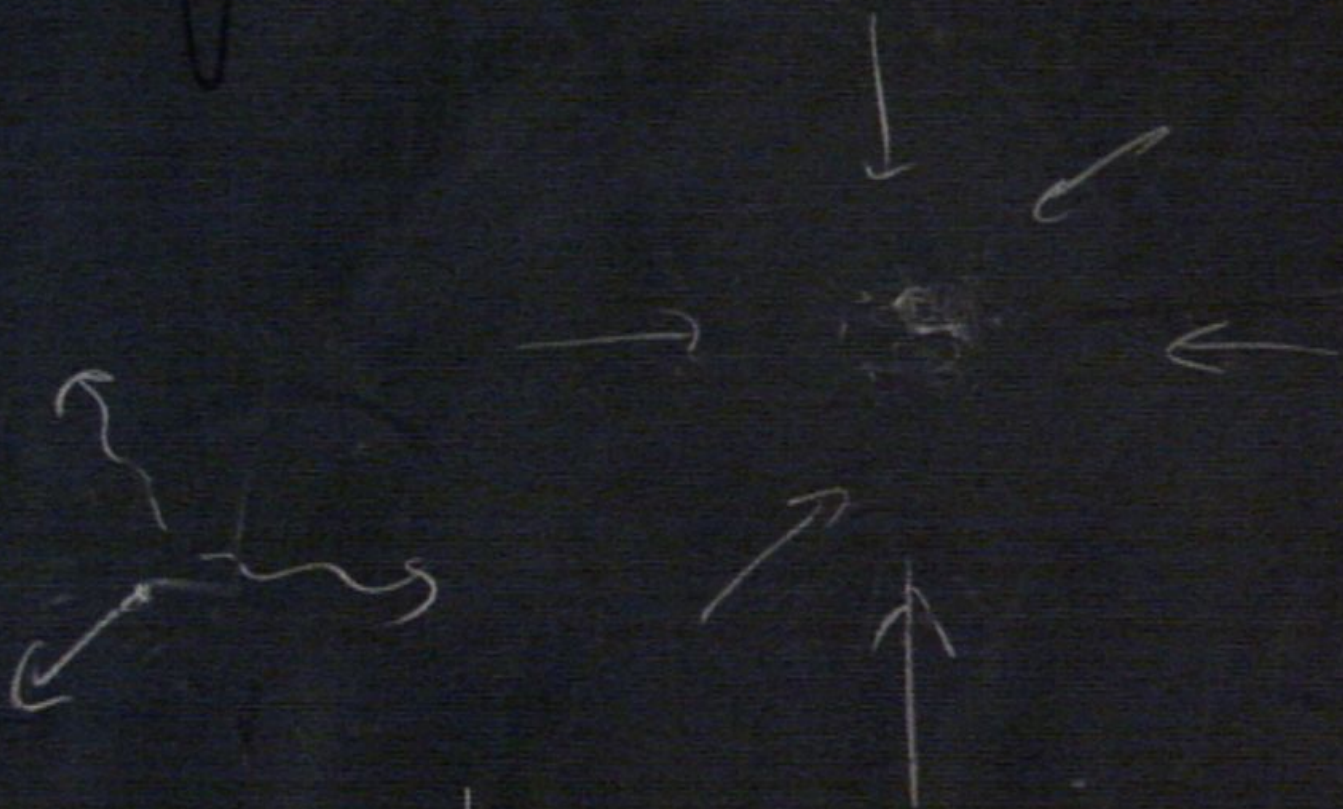


$$p = h$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

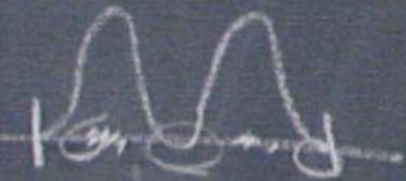




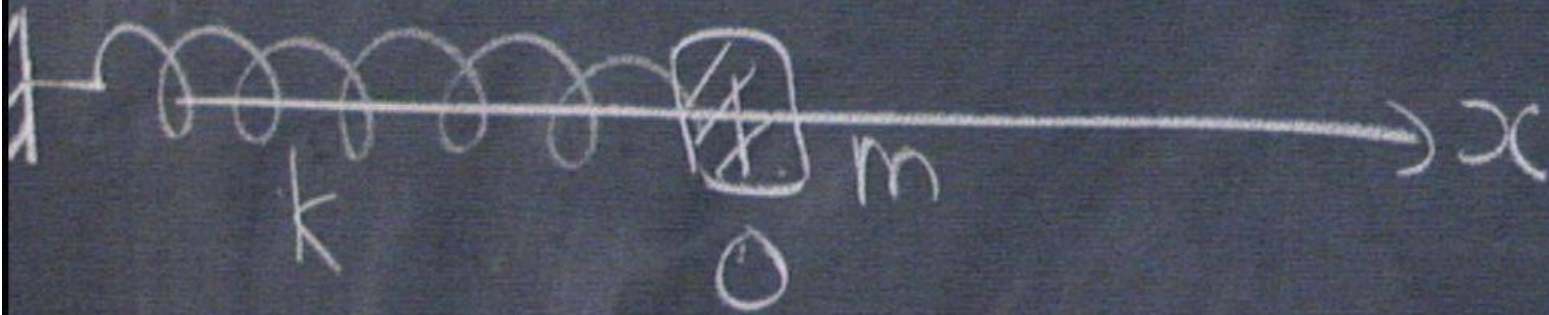


$$\Delta \alpha \Delta p \geq \frac{h}{4\pi}$$

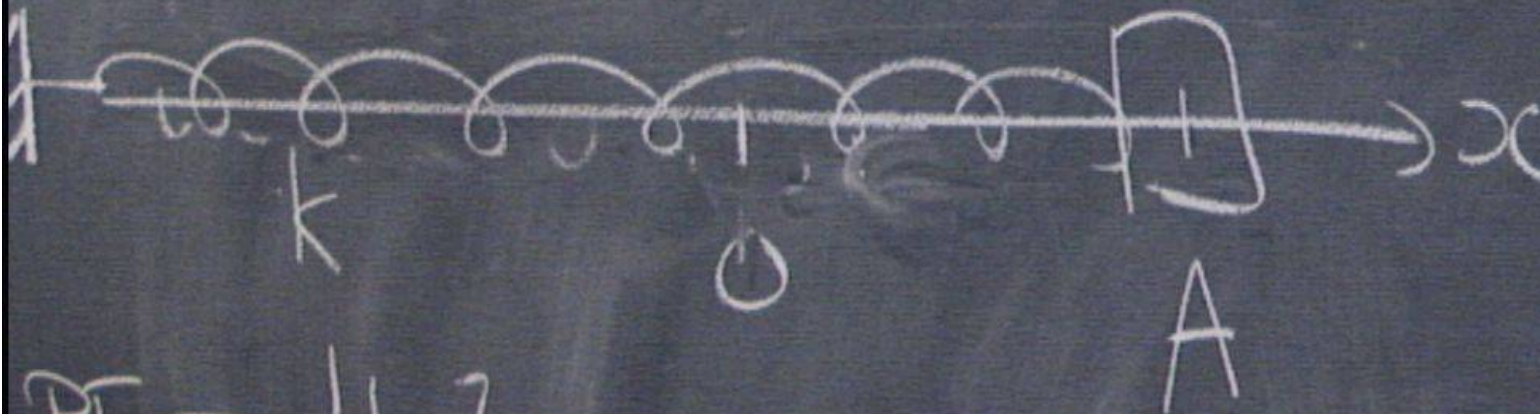
$$\lambda = \frac{h}{p}$$



Harmonic Oscillator

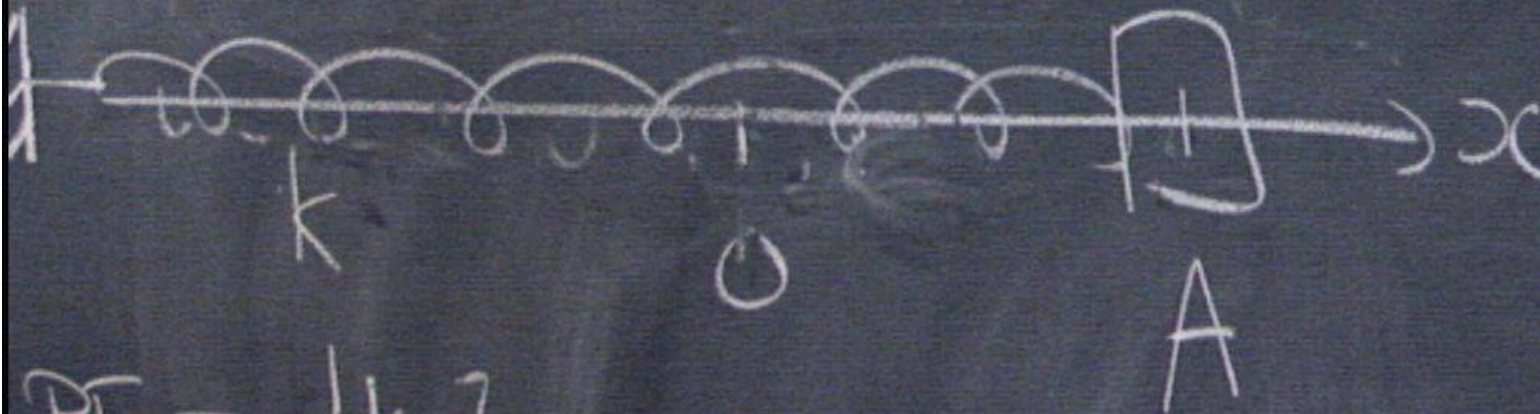


Harmonic Oscillator



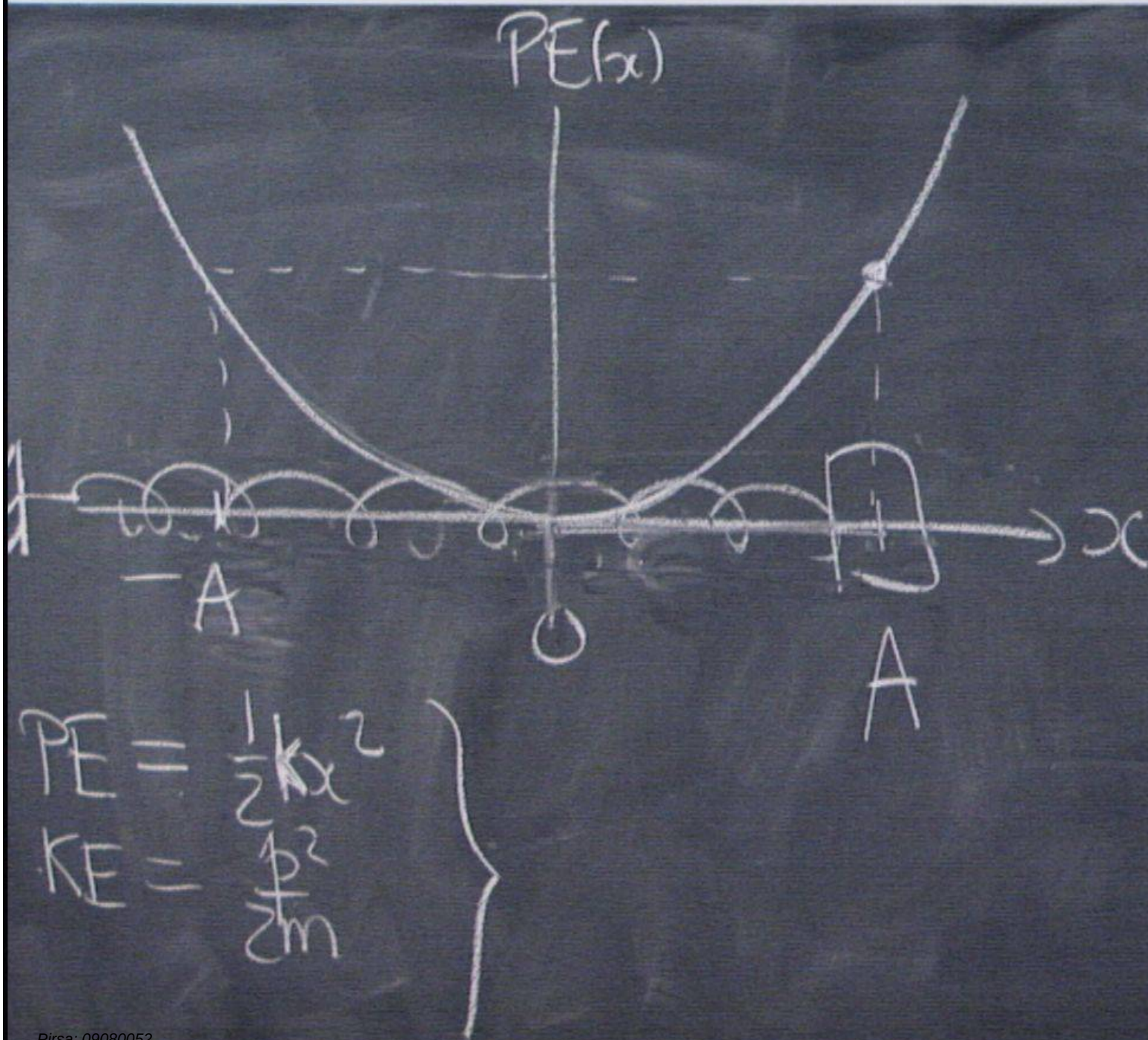
$$PE = \frac{1}{2}kx^2$$

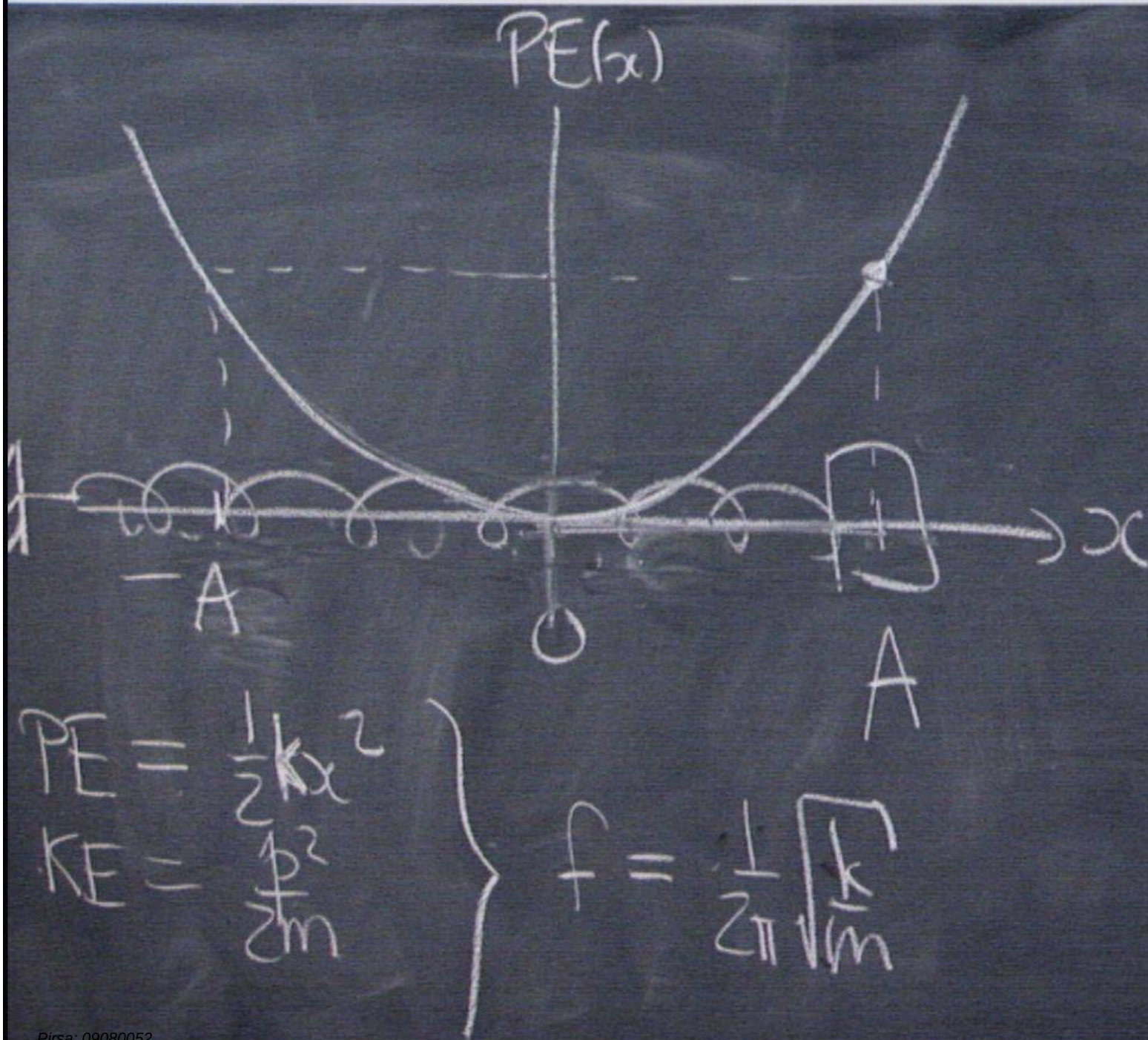
Harmonic Oscillator

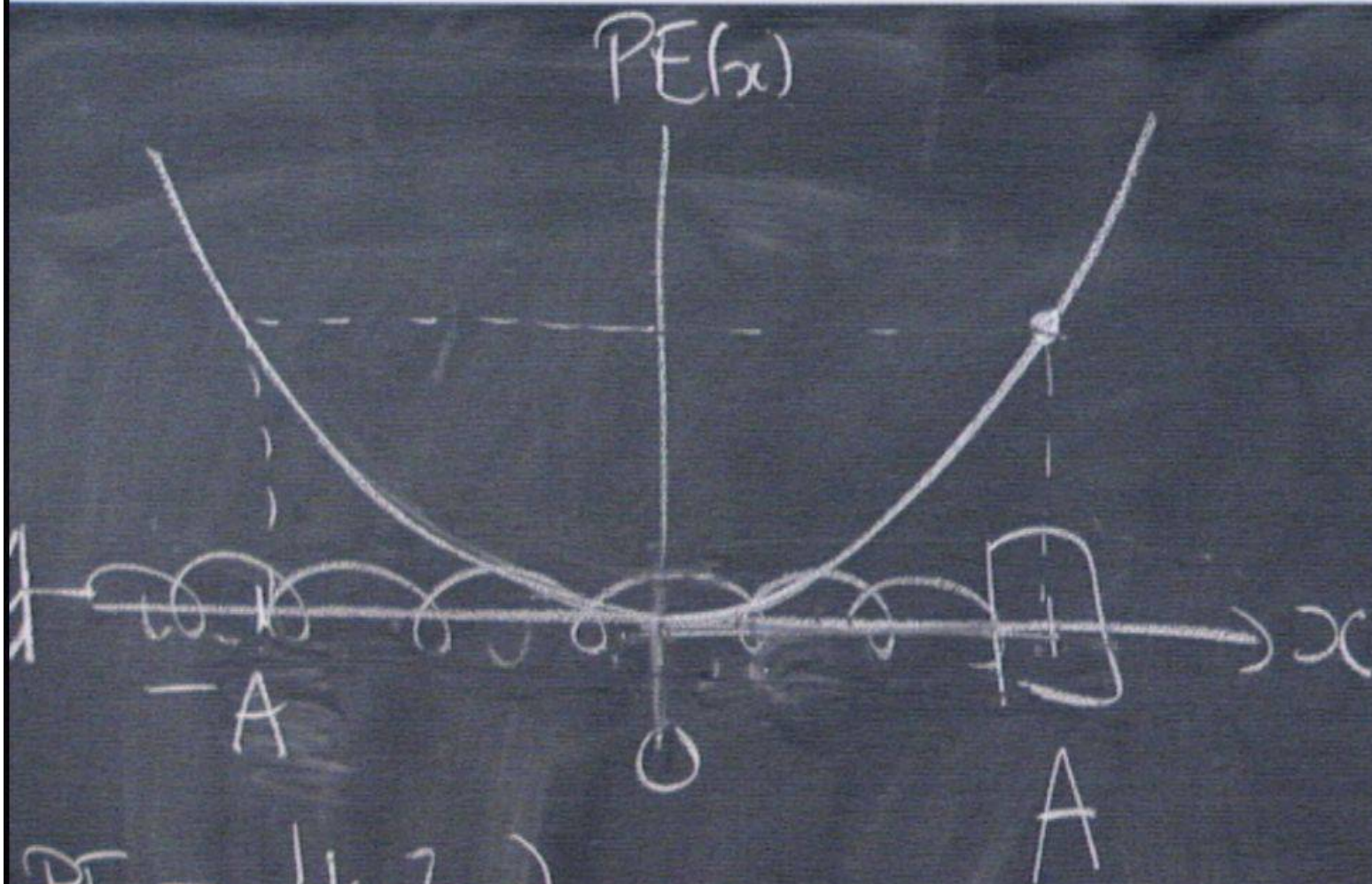


$$PE = \frac{1}{2} k x^2$$

$$KE = \frac{p^2}{2m}$$



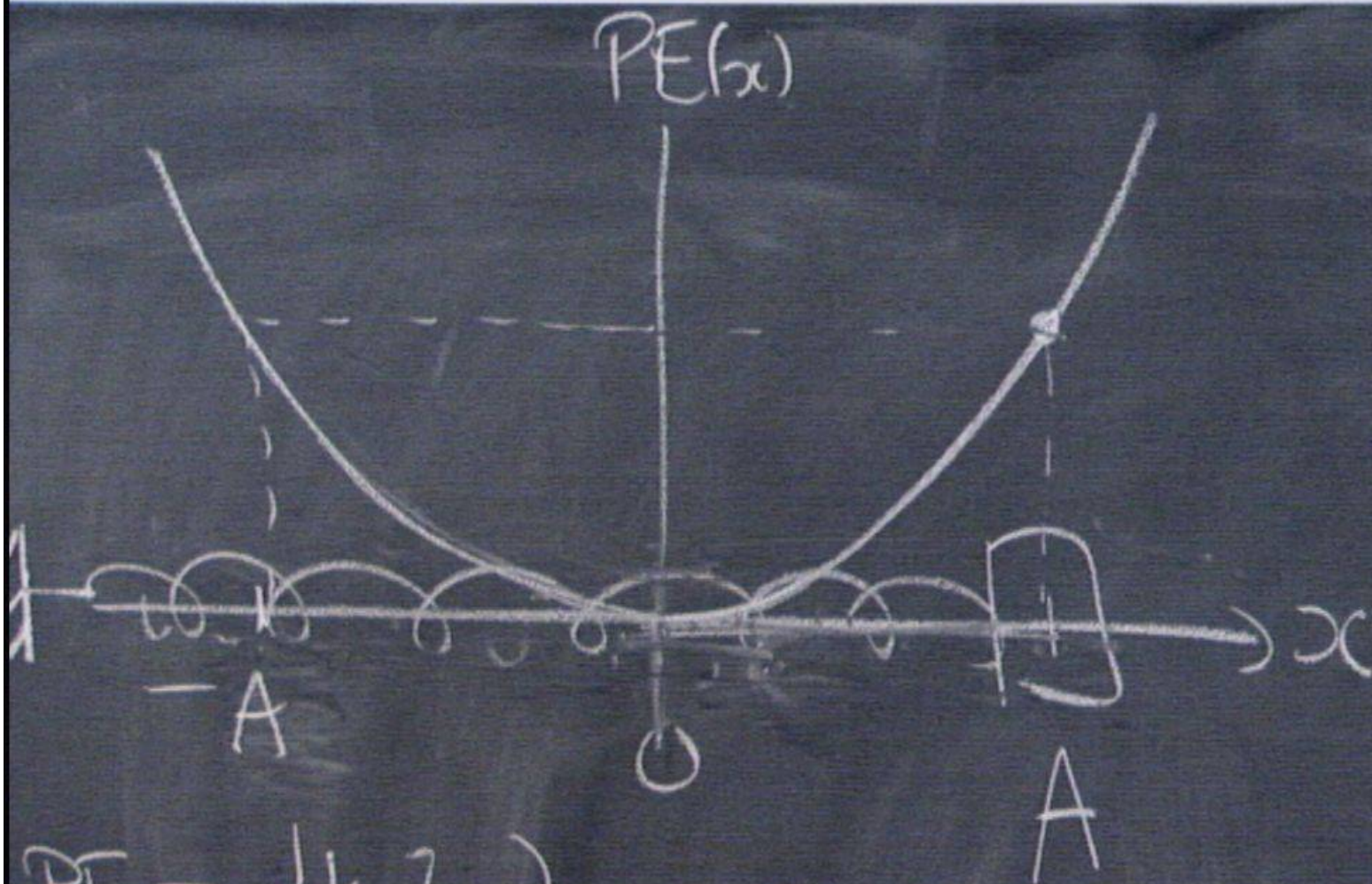




$$PE = \frac{1}{2} k x^2$$

$$KE = \frac{p^2}{2m}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

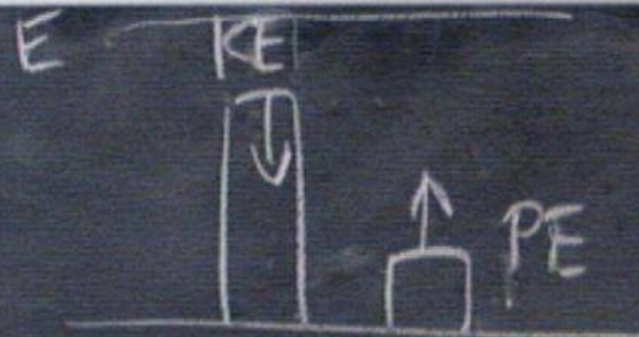
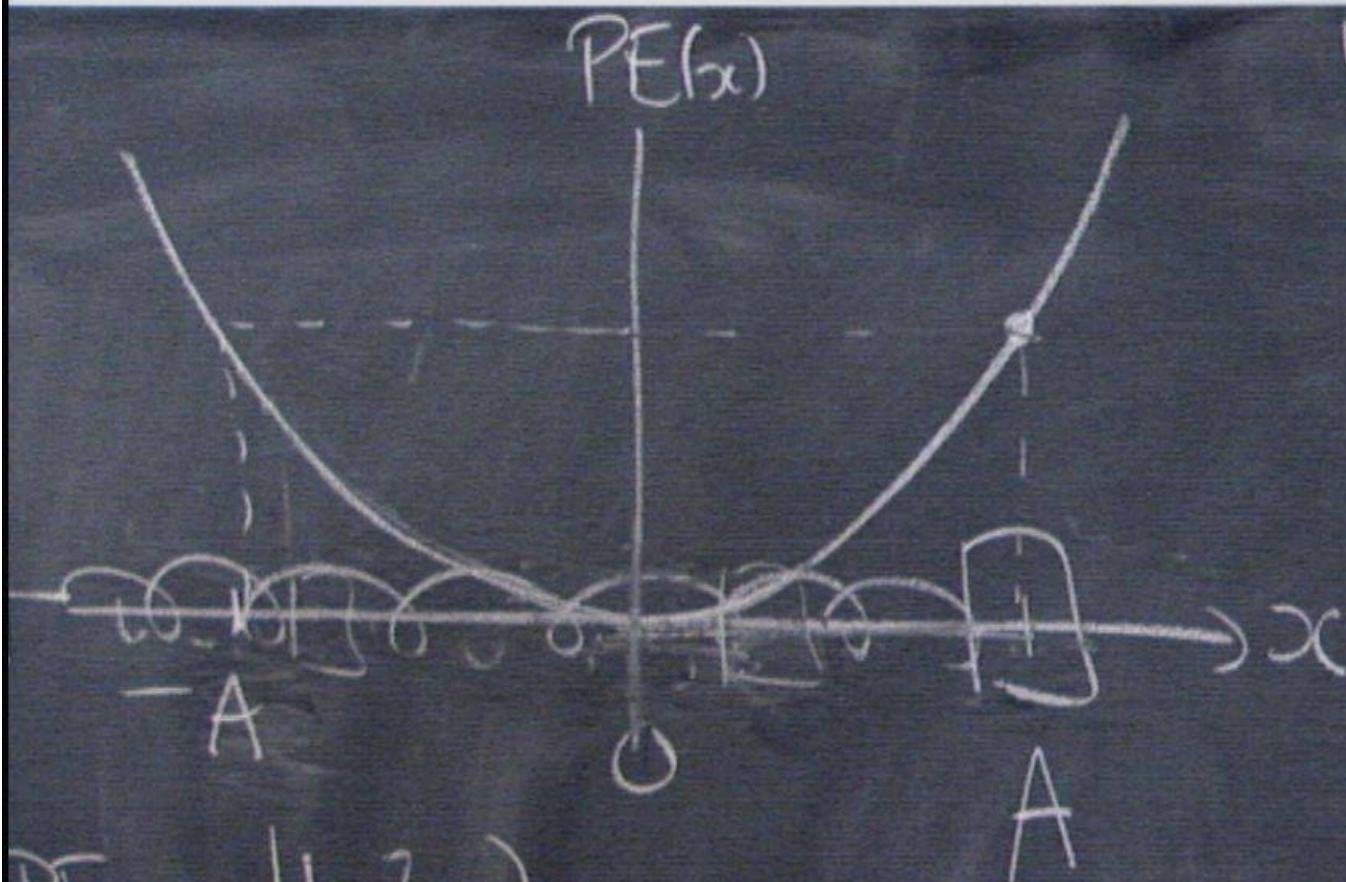


$$PE = \frac{1}{2} k x^2$$

$$KE = \frac{p^2}{2m}$$

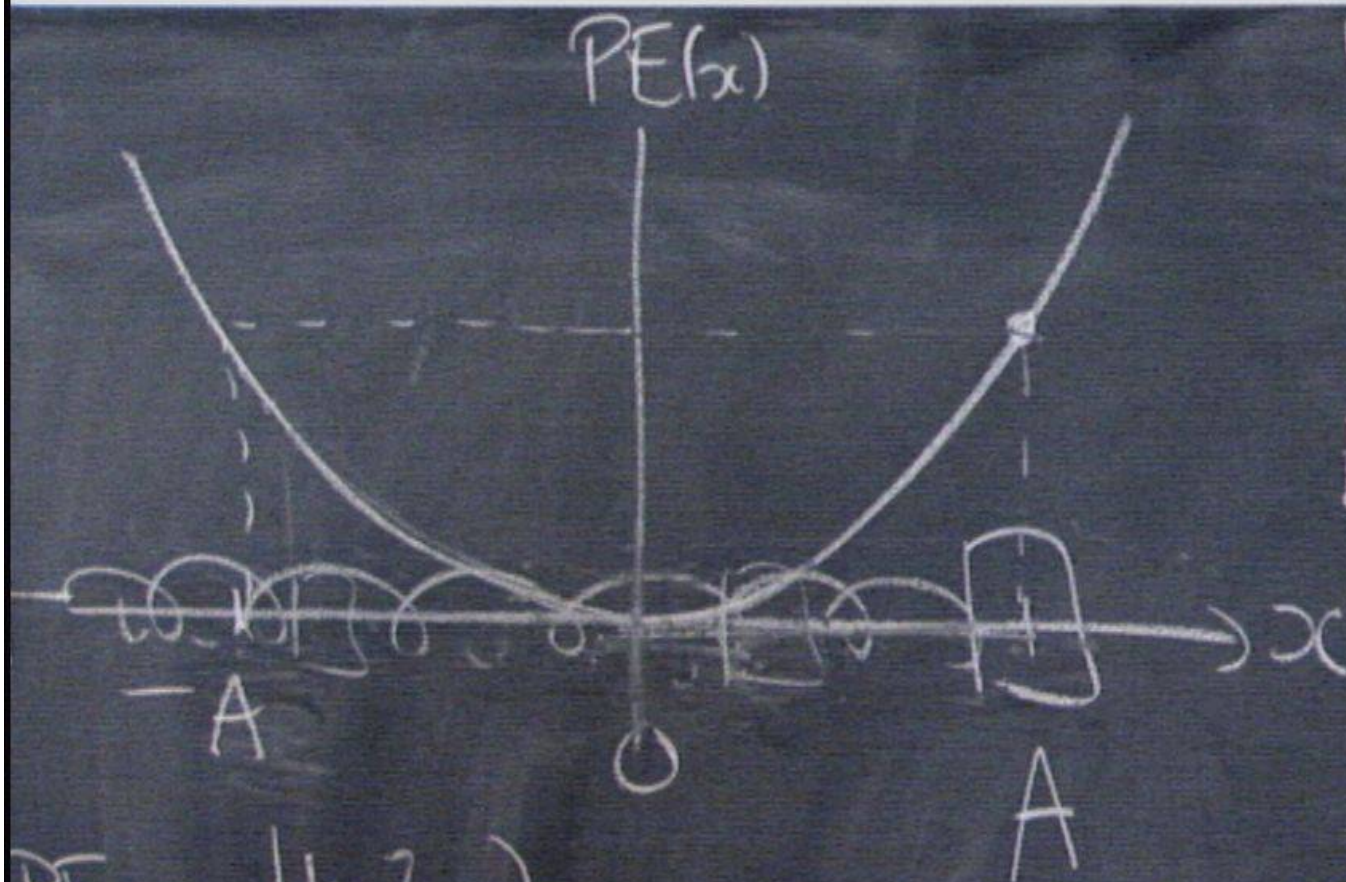
$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

$$F = KE(t) + PE(t) = \frac{p^2(t)}{2m} + \frac{1}{2} k x^2(t)$$



$$\left. \begin{aligned} PE &= \frac{1}{2} k x^2 \\ KE &= \frac{p^2}{2m} \end{aligned} \right\} f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

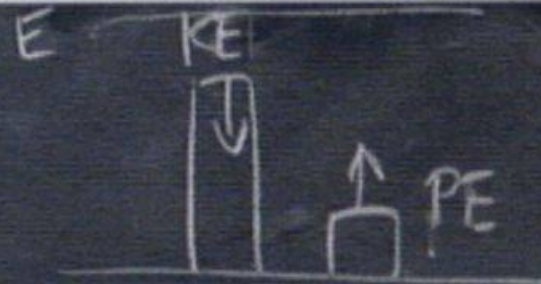
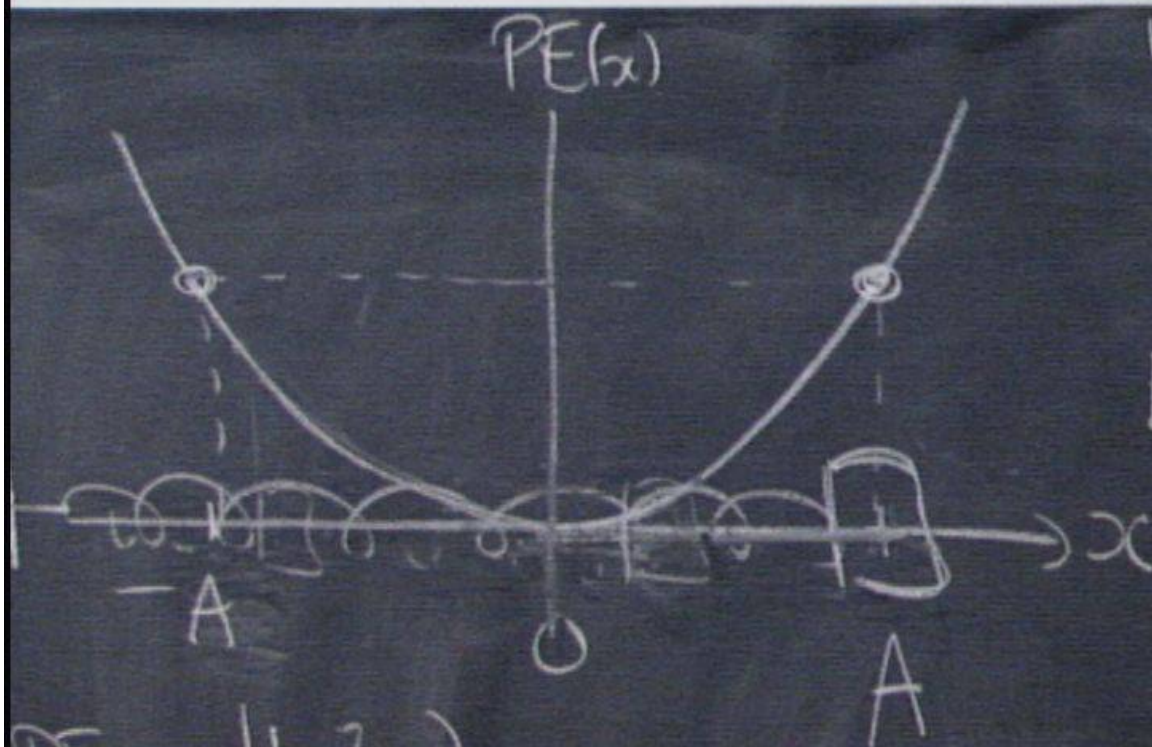
$$E = KE(t) + PE(t) = \frac{p^2(t)}{2m} + \frac{1}{2} k x^2(t)$$



$$E = \frac{p^2}{2m} + \frac{1}{2}kx^2$$

$$\left. \begin{aligned} PE &= \frac{1}{2}kx^2 \\ KE &= \frac{p^2}{2m} \end{aligned} \right\} f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

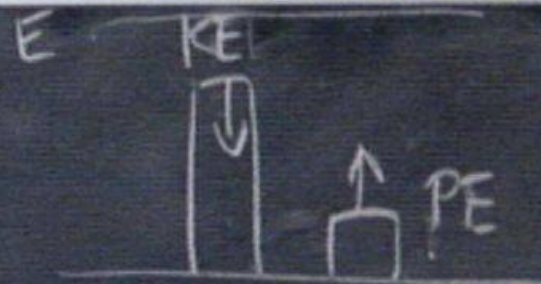
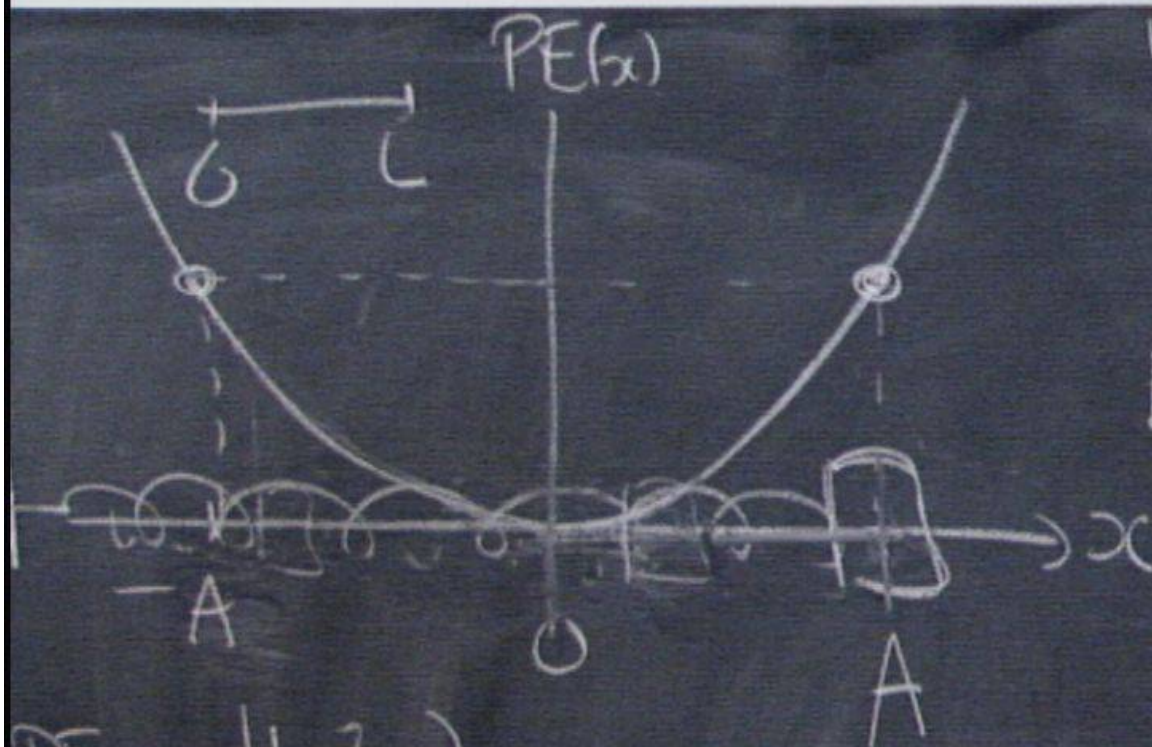
$$E = KE(t) + PE(t) = \frac{p^2(t)}{2m} + \frac{1}{2}kx^2(t)$$



$$E = \cancel{\frac{1}{2}mv^2} + \frac{1}{2}kx^2 = \frac{1}{2}kA^2$$

$$\left. \begin{aligned} PE &= \frac{1}{2}kx^2 \\ KE &= \frac{p^2}{2m} \end{aligned} \right\} f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

$$E = KE(t) + PE(t) = \frac{p^2(t)}{2m} + \frac{1}{2}kx^2(t)$$

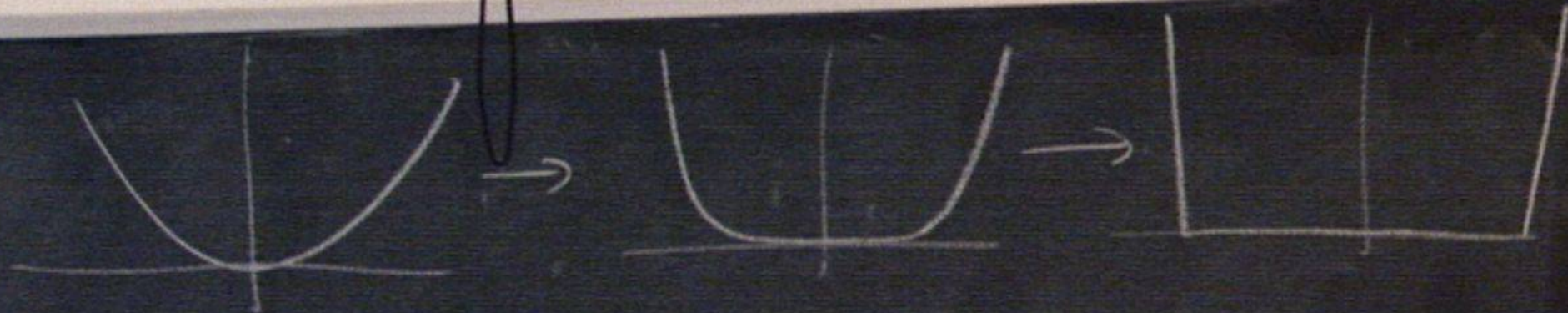


$$E = \cancel{\frac{p^2}{2m}} + \frac{1}{2}kx^2 = \frac{1}{2}kA^2$$

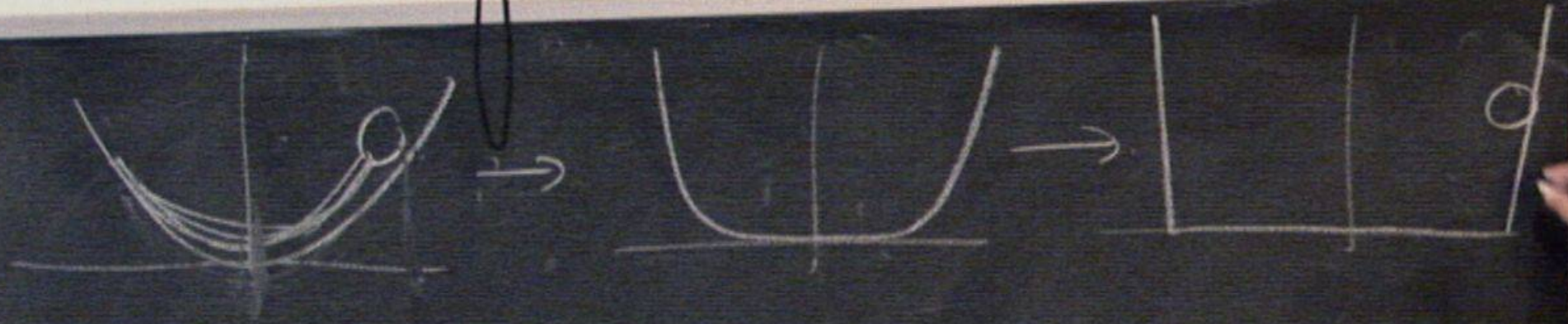
for given E , particle bounded
 $-A \leq x \leq A$

$$\left. \begin{aligned} PE &= \frac{1}{2}kx^2 \\ KE &= \frac{p^2}{2m} \end{aligned} \right\} f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

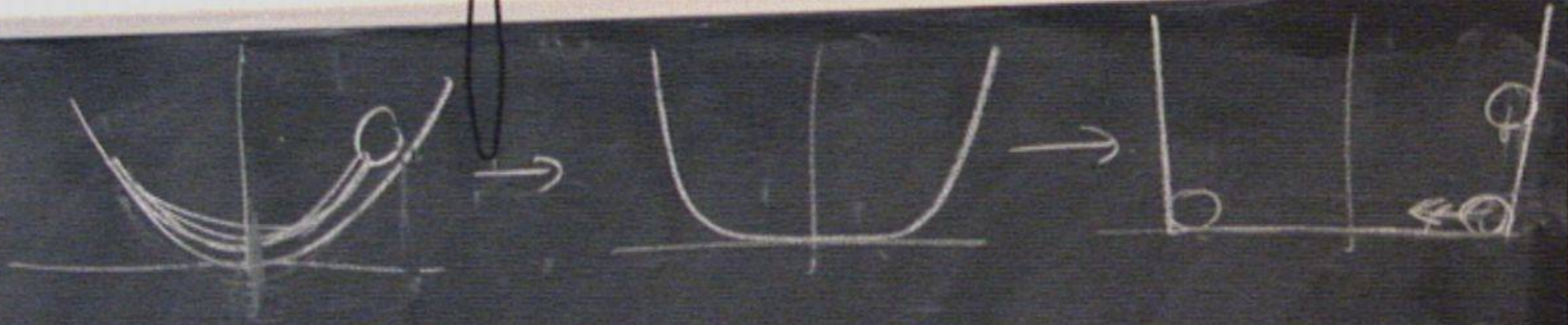
$$E = KE(t) + PE(t) = \frac{p^2(t)}{2m} + \frac{1}{2}kx^2(t)$$



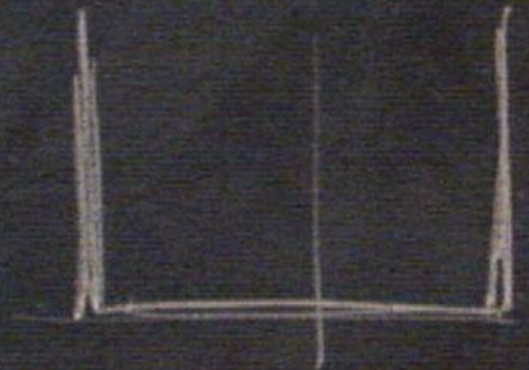
YOUNG



you



Younis



||



Y-axis

E



O

E



E_0



O



E



E_0



$\frac{1}{2}hf$

0

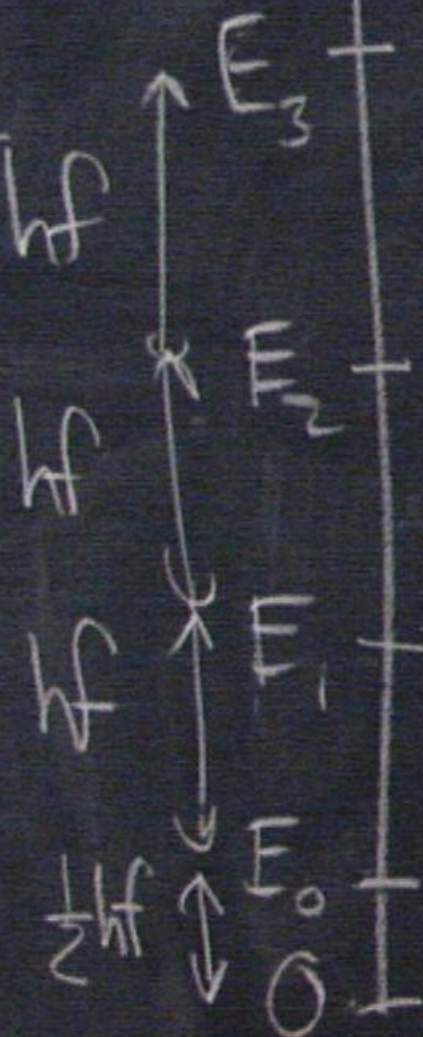
quantum

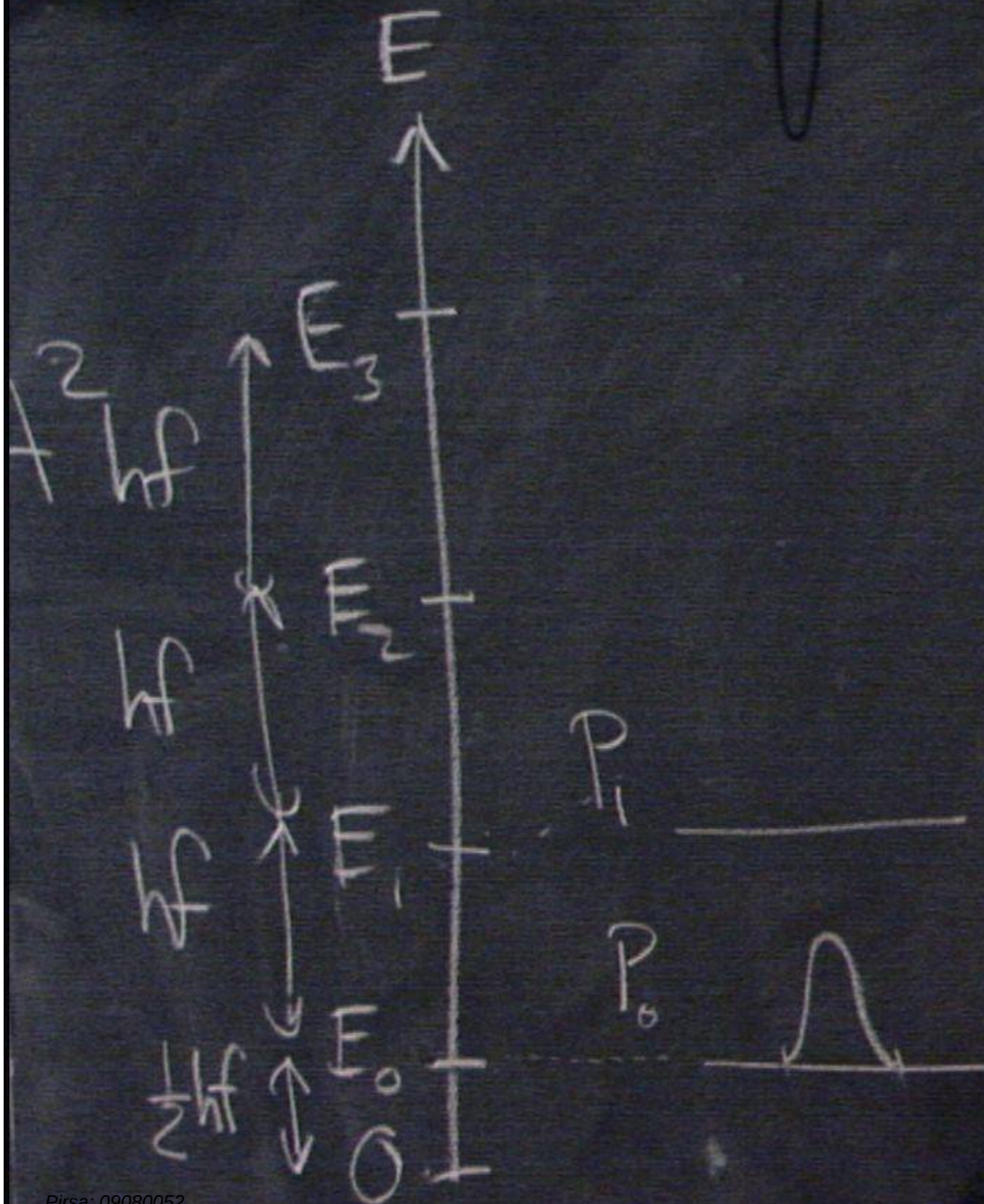
PE

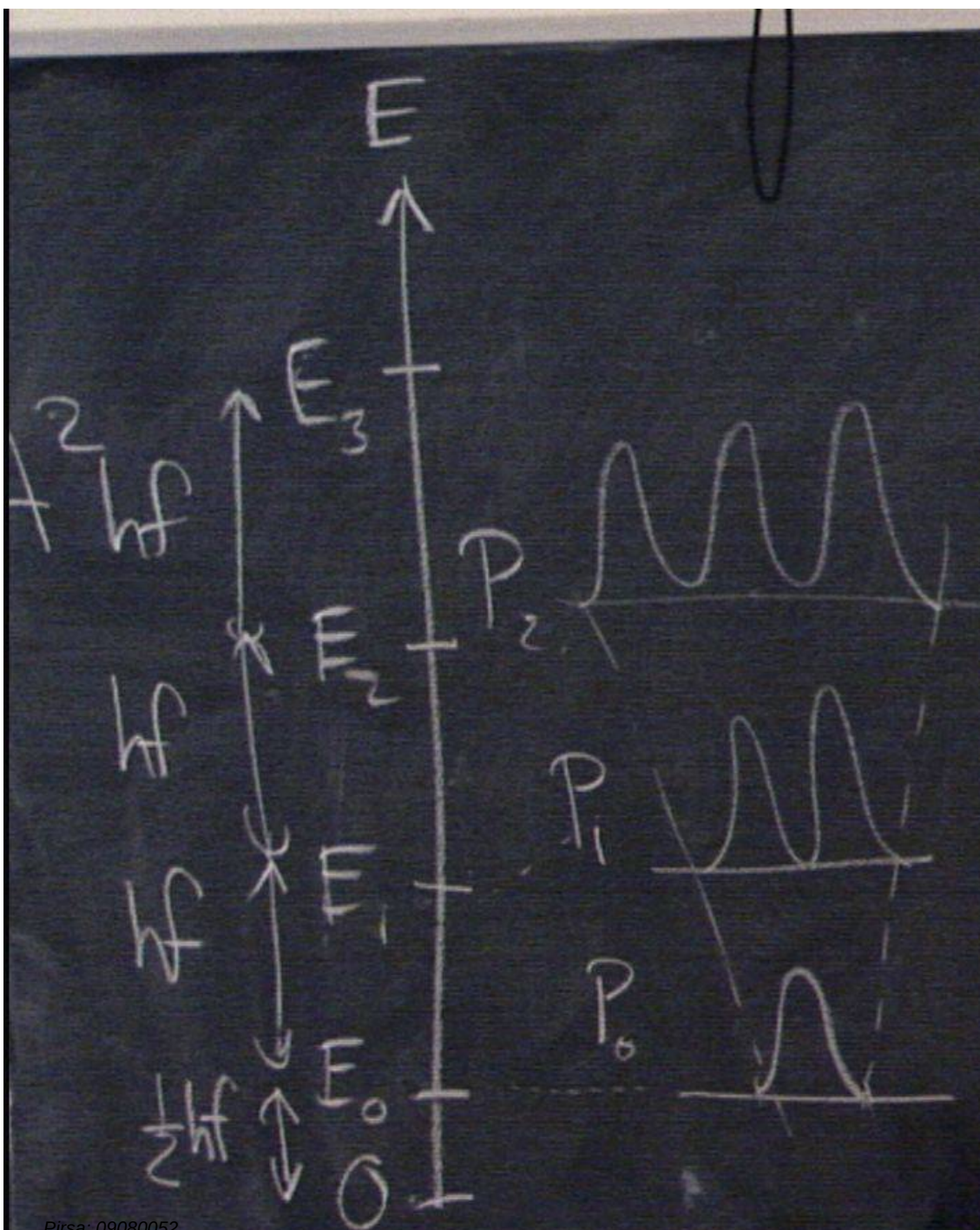
$$kx^2 = \frac{1}{2}kA^2 \quad hf$$

↑
A

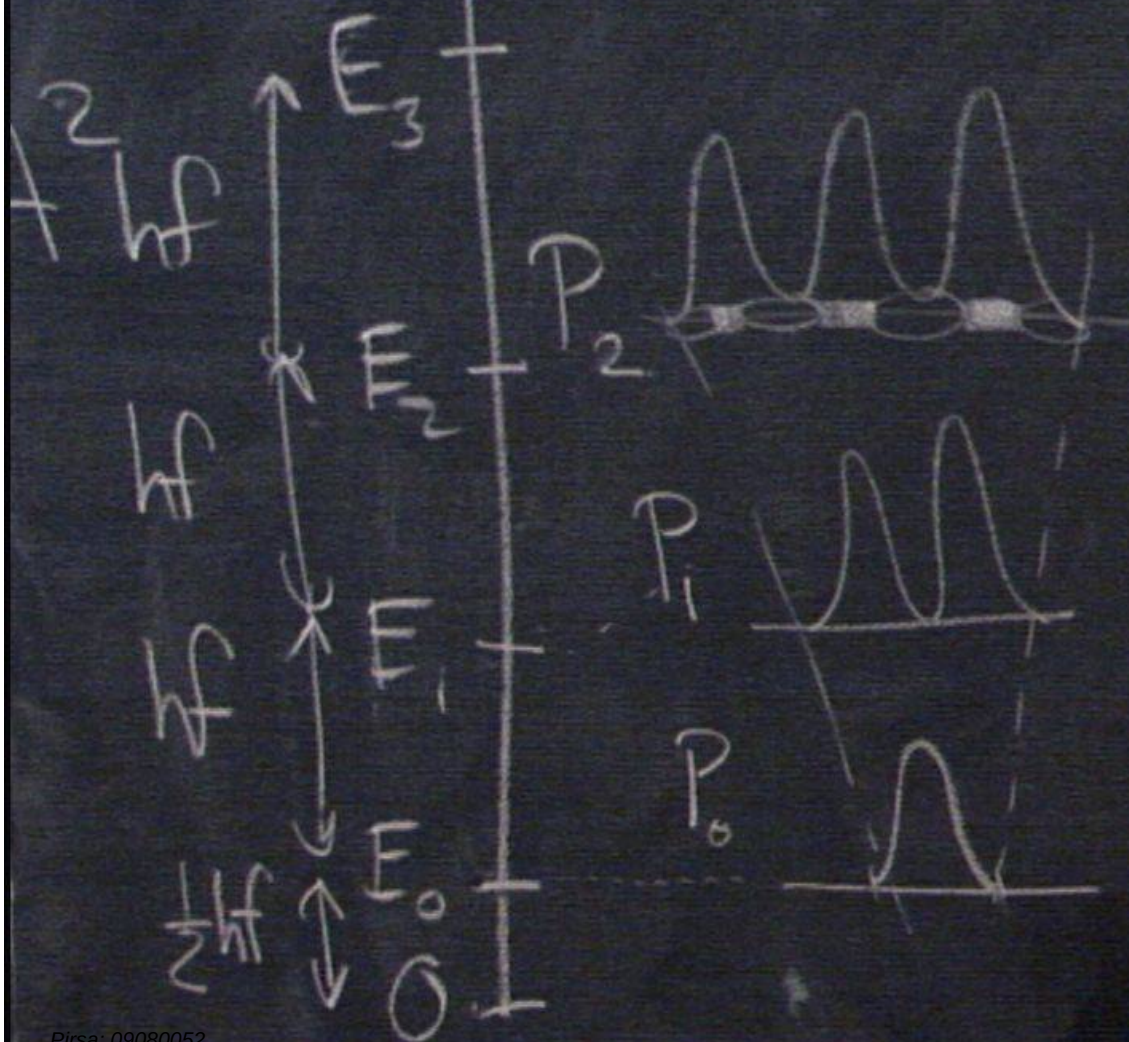
, particle



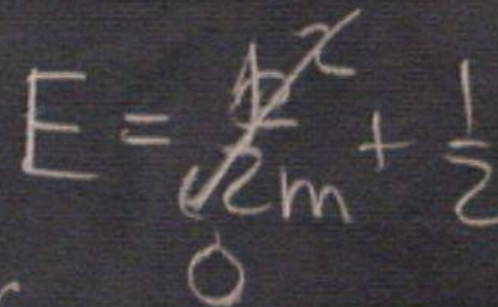




$$E_n = (n + \frac{1}{2})hf, n = 0, 1, 2, \dots$$

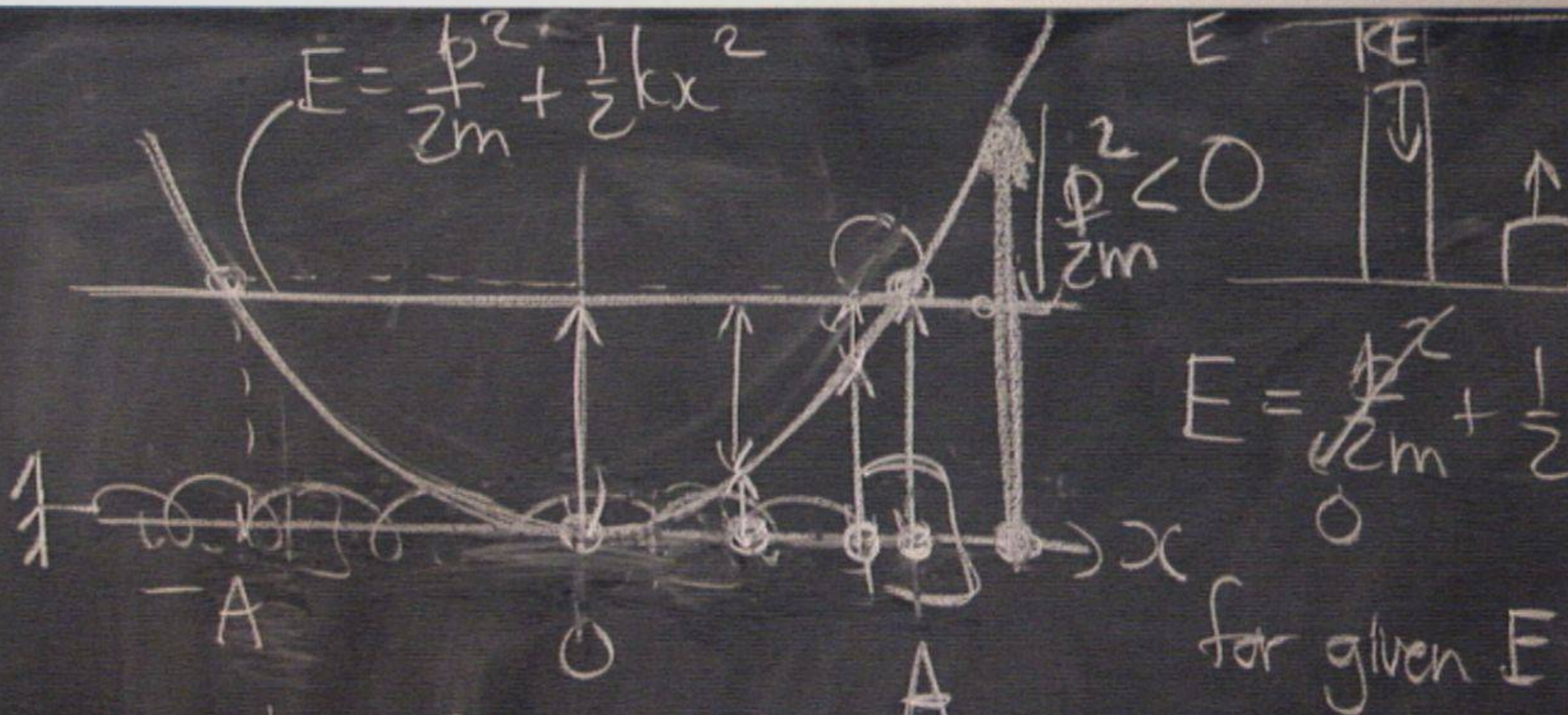


A diagram showing two blocks on a horizontal surface. The left block is labeled 'KE' and has a downward arrow pointing from its center. The right block is smaller and has an upward arrow pointing from its center.


$$-A \subseteq \mathcal{X} \subseteq A$$

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Pirsa: 09080052

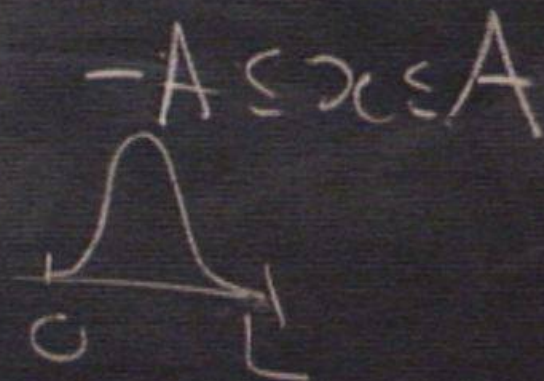


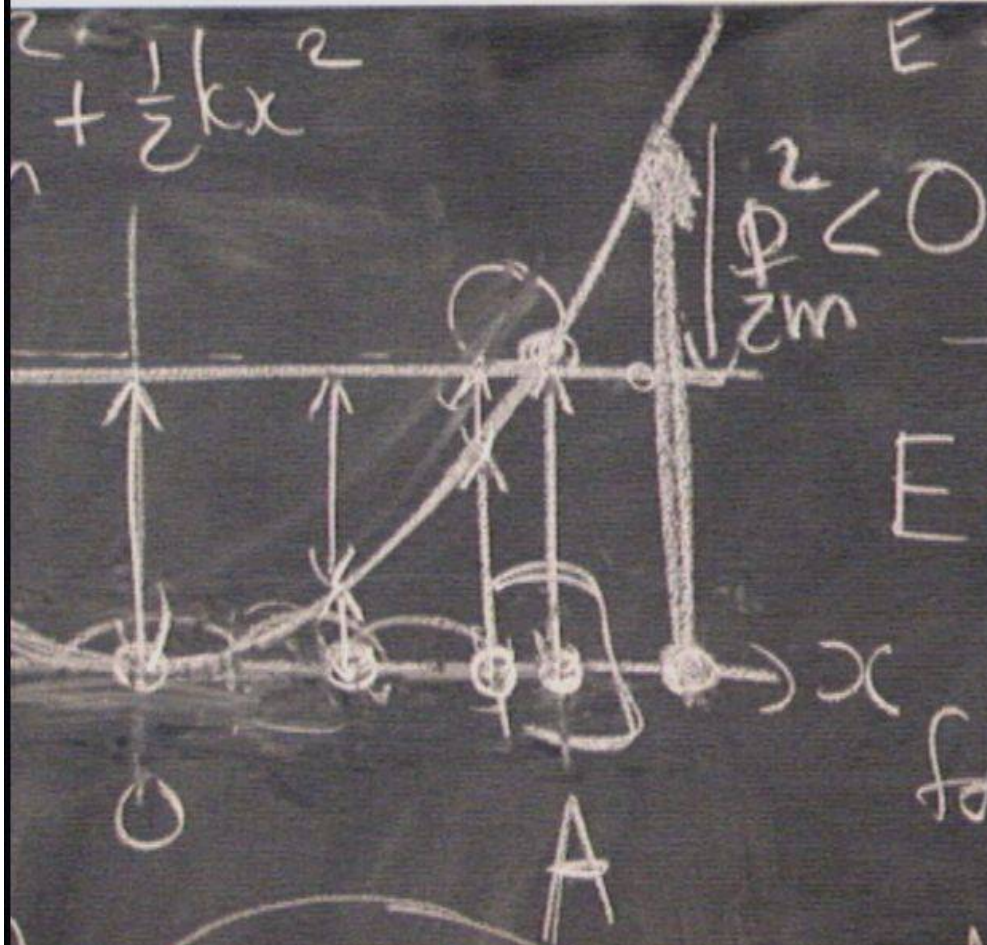
$$PE = \frac{1}{2}kx^2$$

$$KE = \frac{p^2}{2m}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

$$E = KE(t) + PE(t) = \frac{p(t)^2}{2m} + \frac{1}{2}kx(t)^2$$



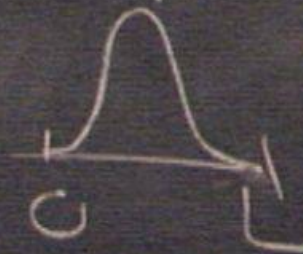


$E = KE + PE$
 $E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$
 $E = \frac{1}{2}kA^2$

$E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = \frac{1}{2}kA^2$
 A

for given E , particle hf

$-A \leq x \leq A$



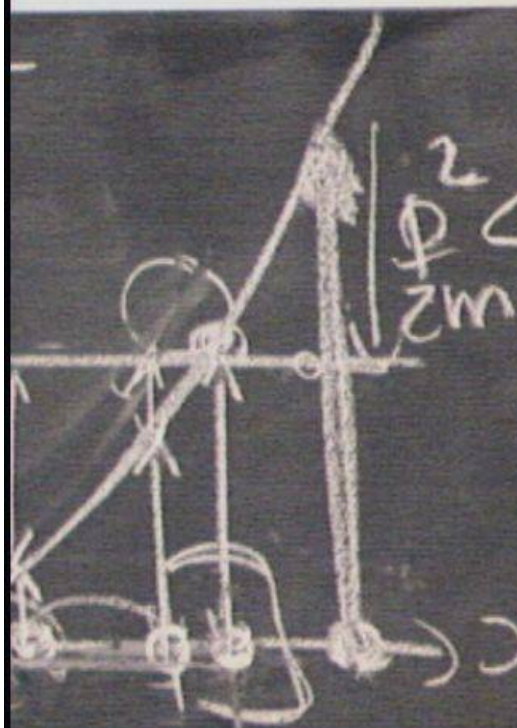
$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$

$$e^{\frac{1}{\hbar} p x} = \cos \frac{p x}{\hbar} + i \sin \frac{p x}{\hbar}$$

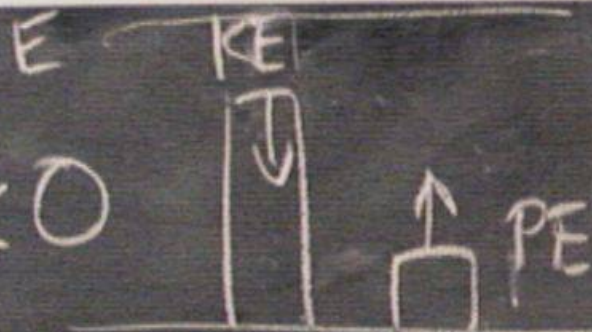
↑ PE

$$\frac{1}{2} k x^2 = \frac{1}{2} k A^2 \cos^2 \omega t$$

↑ E₃



$$\Phi < 0$$



$$e^{i\frac{1}{\hbar} p x} = \cos \frac{p x}{\hbar} + i \sin \frac{p x}{\hbar}$$

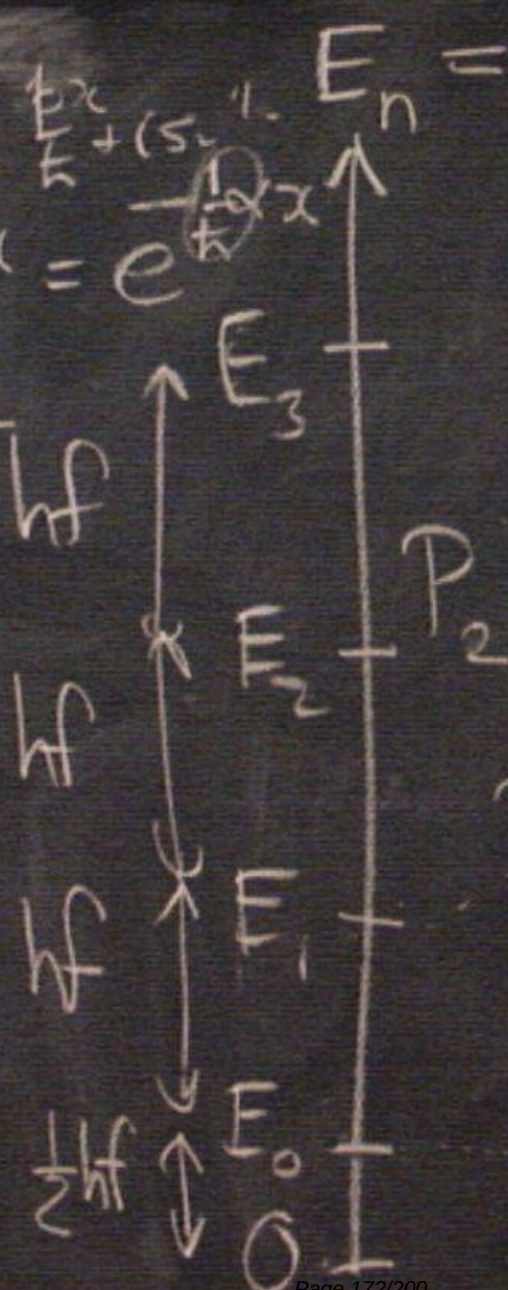
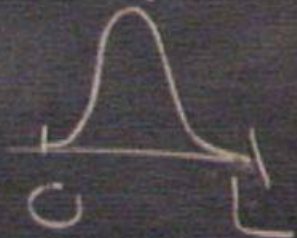
$$e^{i\frac{1}{\hbar} (i \alpha) x} = e^{-\frac{\alpha x}{\hbar}}$$

$$E_n =$$

$$E = \frac{1}{2} m \dot{x}^2 + \frac{1}{2} k x^2 = \frac{1}{2} k A^2$$

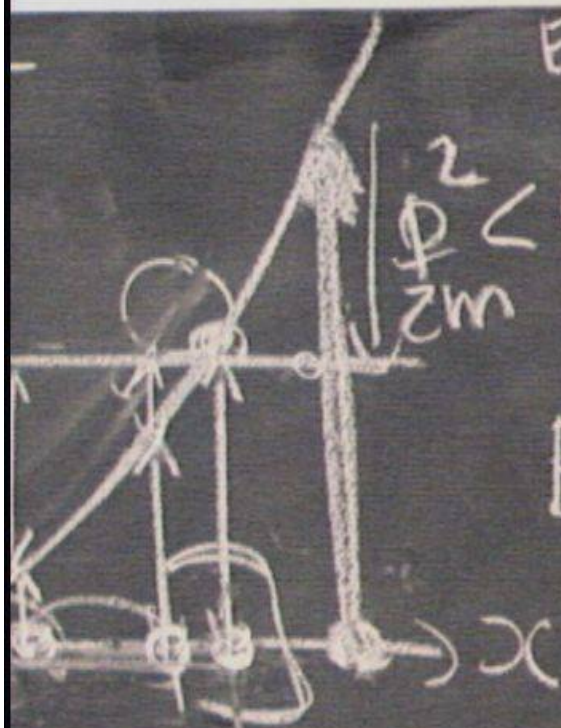
for given E, particle

$$-A \leq x \leq A$$

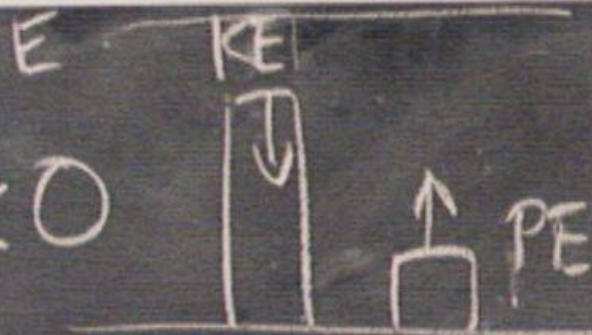


$$\frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

$$+ \frac{1}{2} k x(t)^2$$



$$\Phi < 0$$



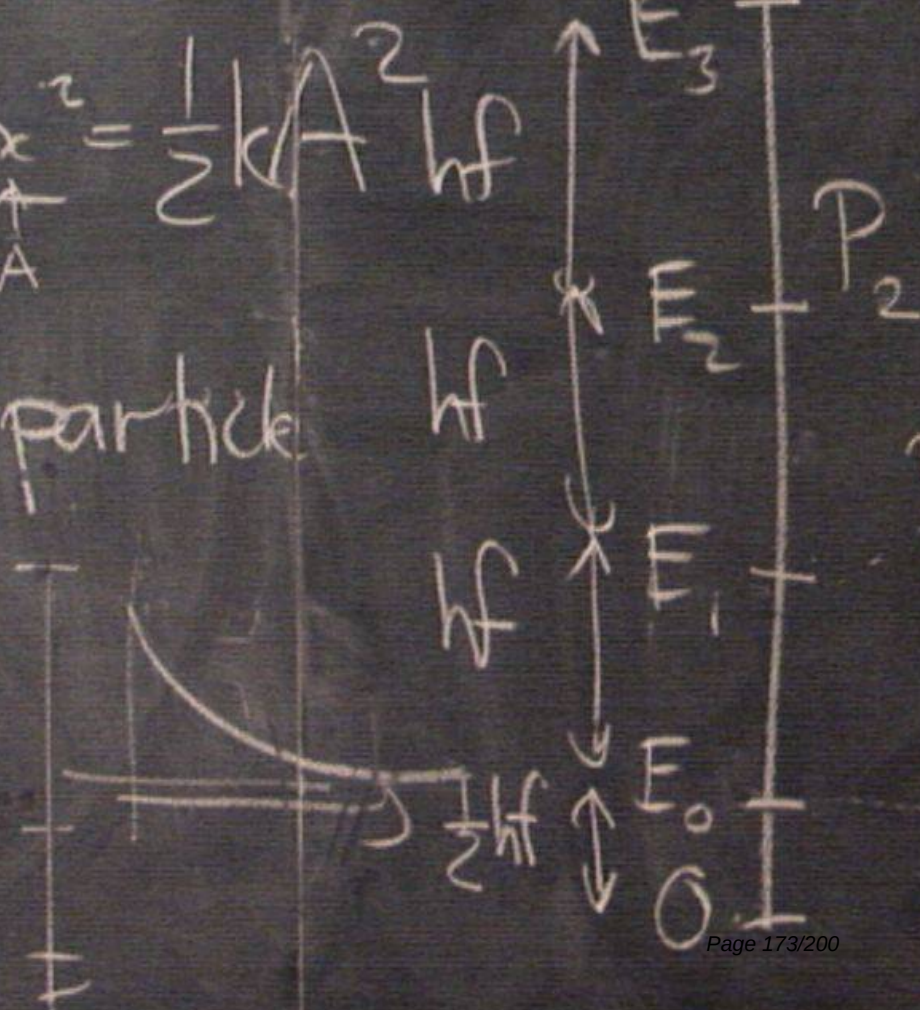
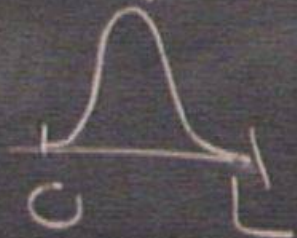
$$e^{i\frac{1}{\hbar} p x} = \cos \frac{p x}{\hbar} + i \sin \frac{p x}{\hbar}$$

$$e^{i\frac{1}{\hbar} (i \alpha) x} = e^{-\frac{\alpha x}{\hbar}}$$

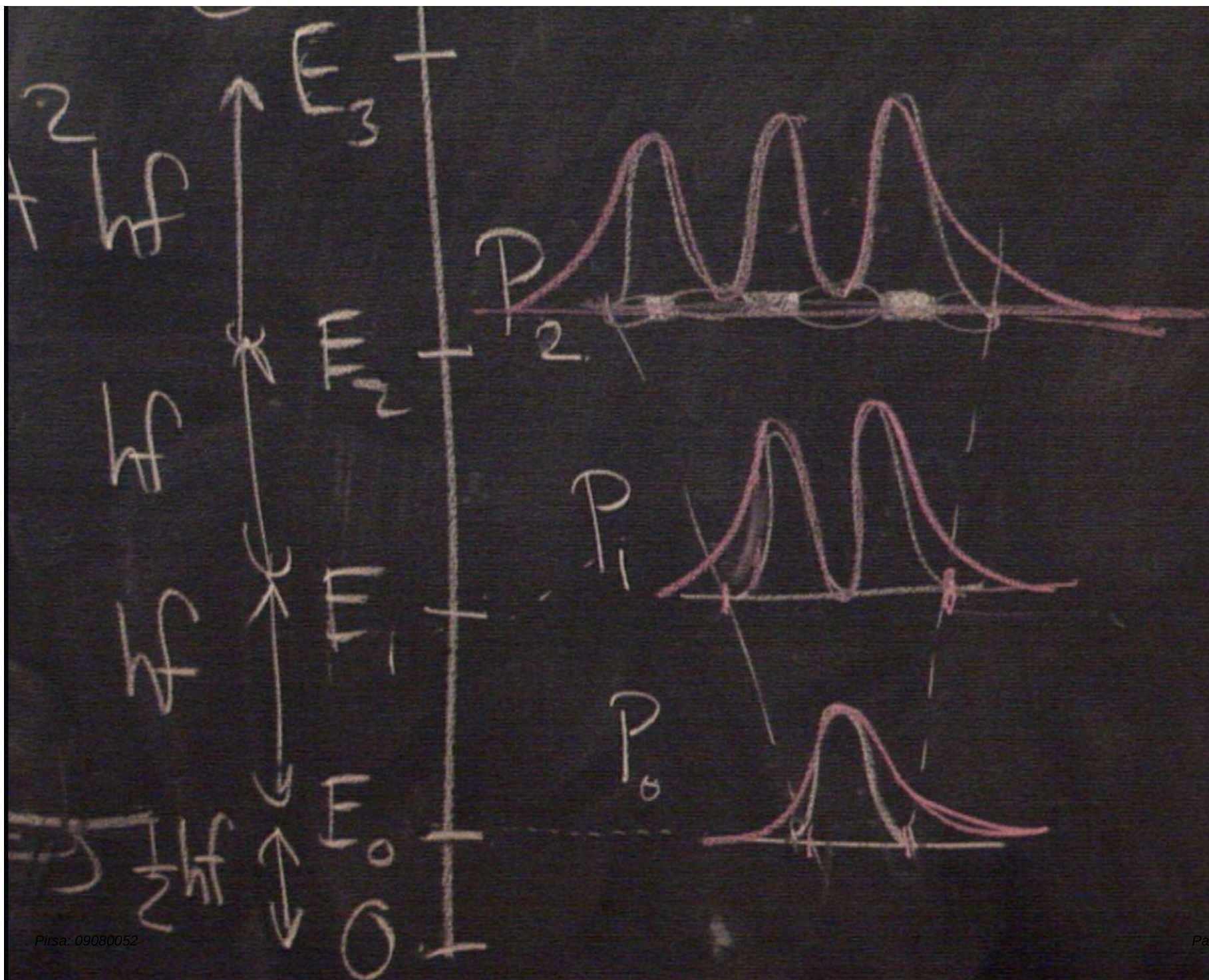
$$E = \frac{1}{2} m \dot{x}^2 + \frac{1}{2} k x^2 = \frac{1}{2} k A^2$$

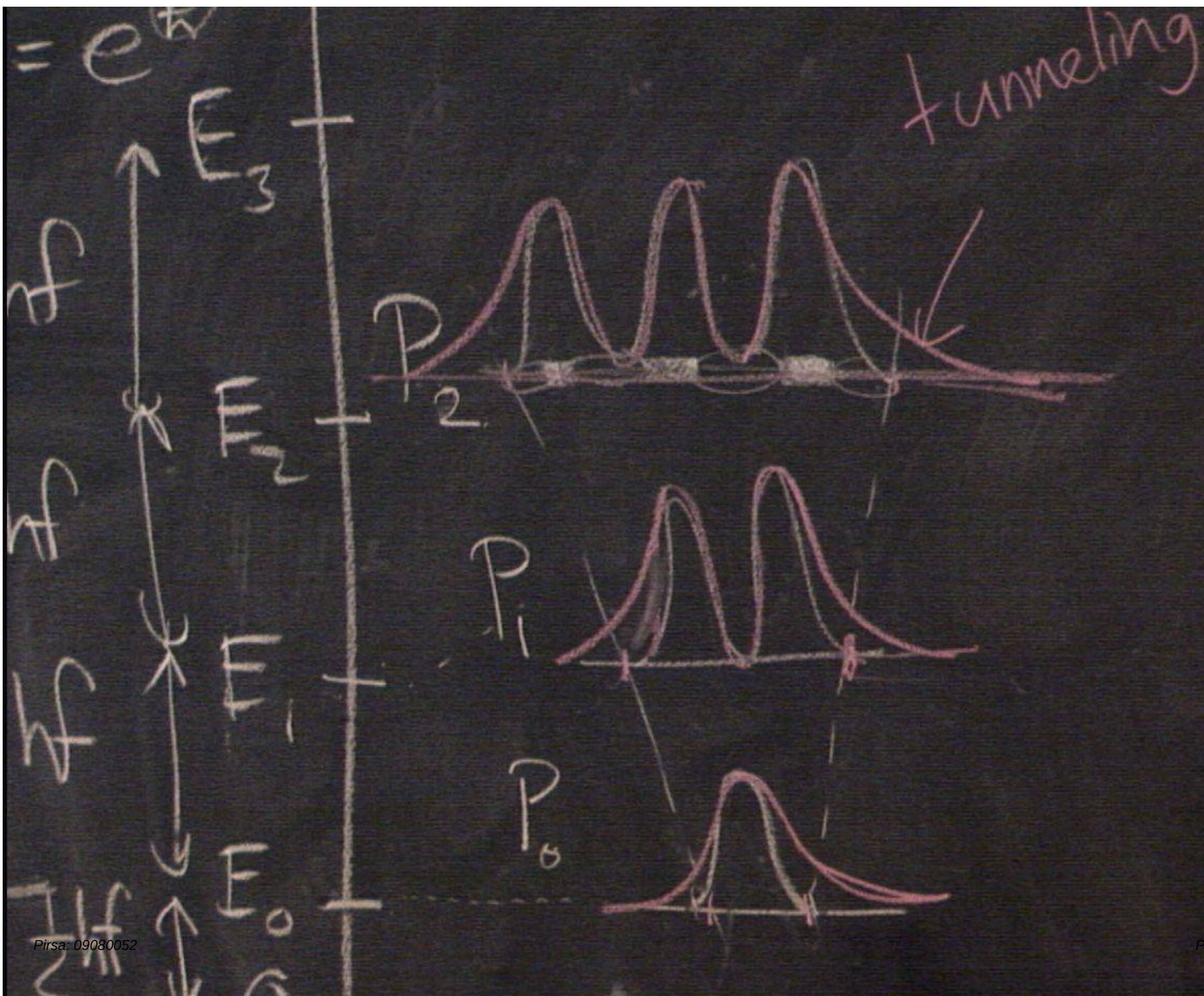
for given E, particle

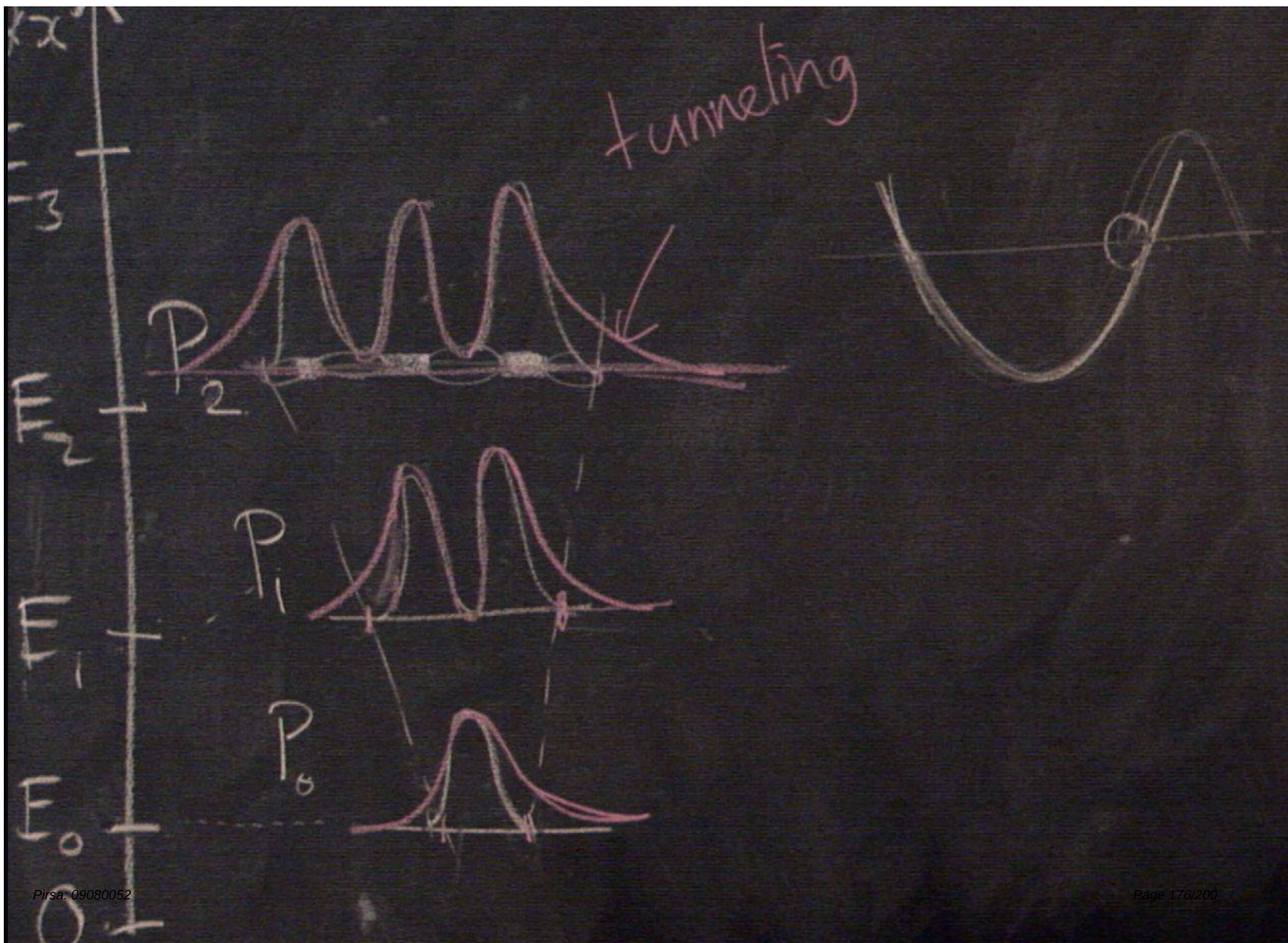
$$-A \leq x \leq A$$

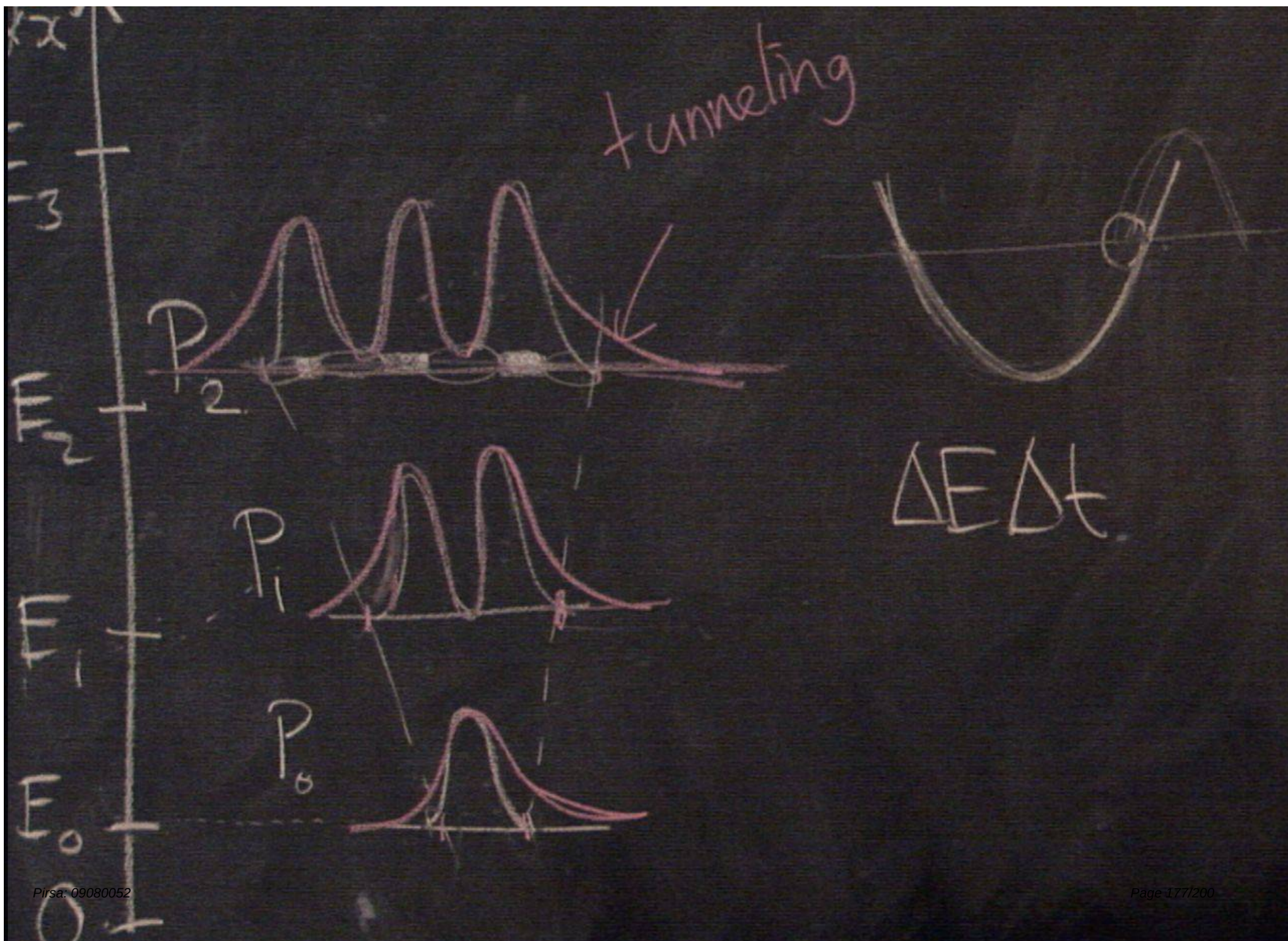


$$\frac{1}{2} \sqrt{\frac{k}{m}}$$

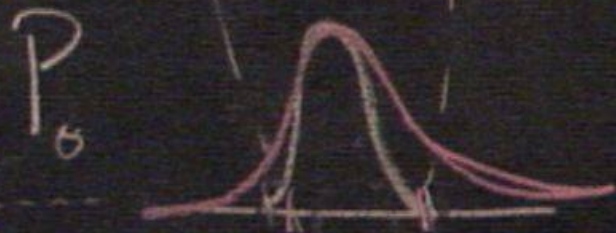
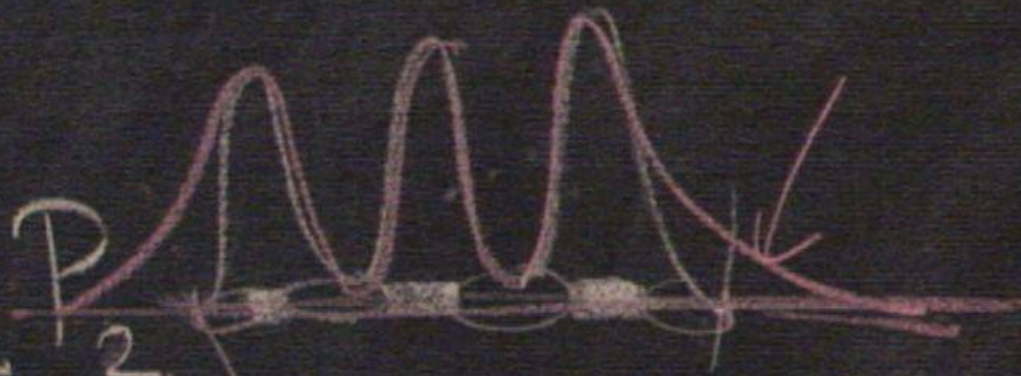






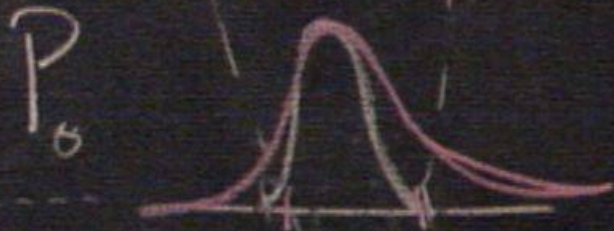
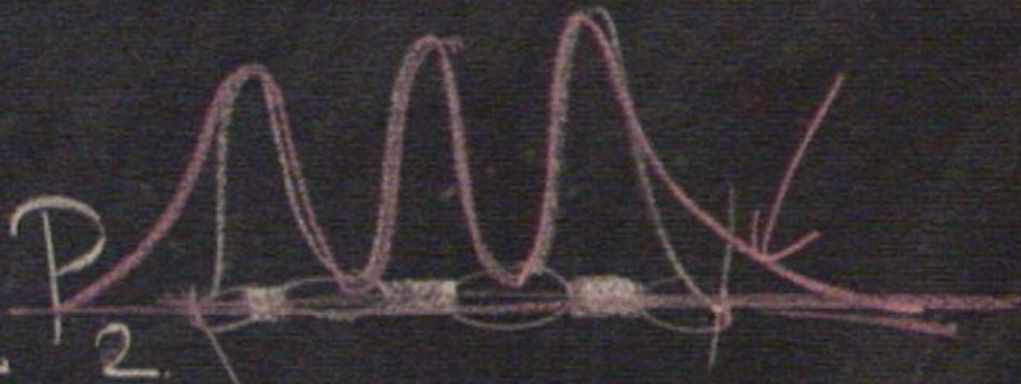


tunneling



$$\Delta E \Delta t \geq \frac{\hbar}{4\pi}$$

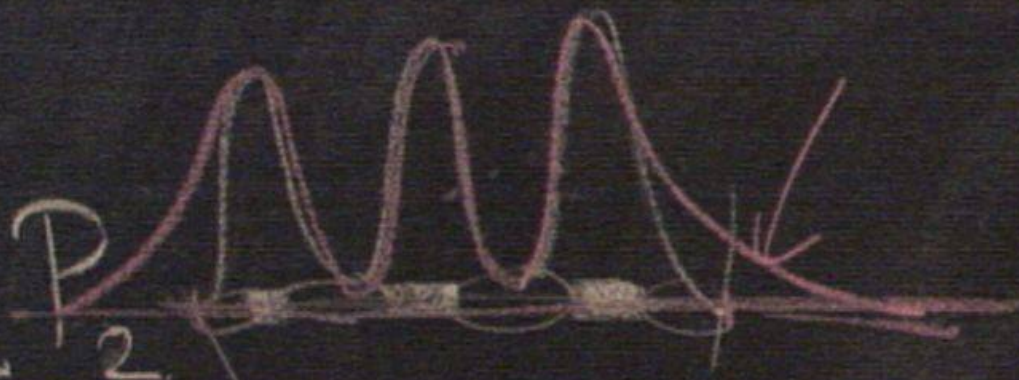
tunneling



$$\Delta E \Delta t \geq \frac{\hbar}{4\pi}$$



tunneling

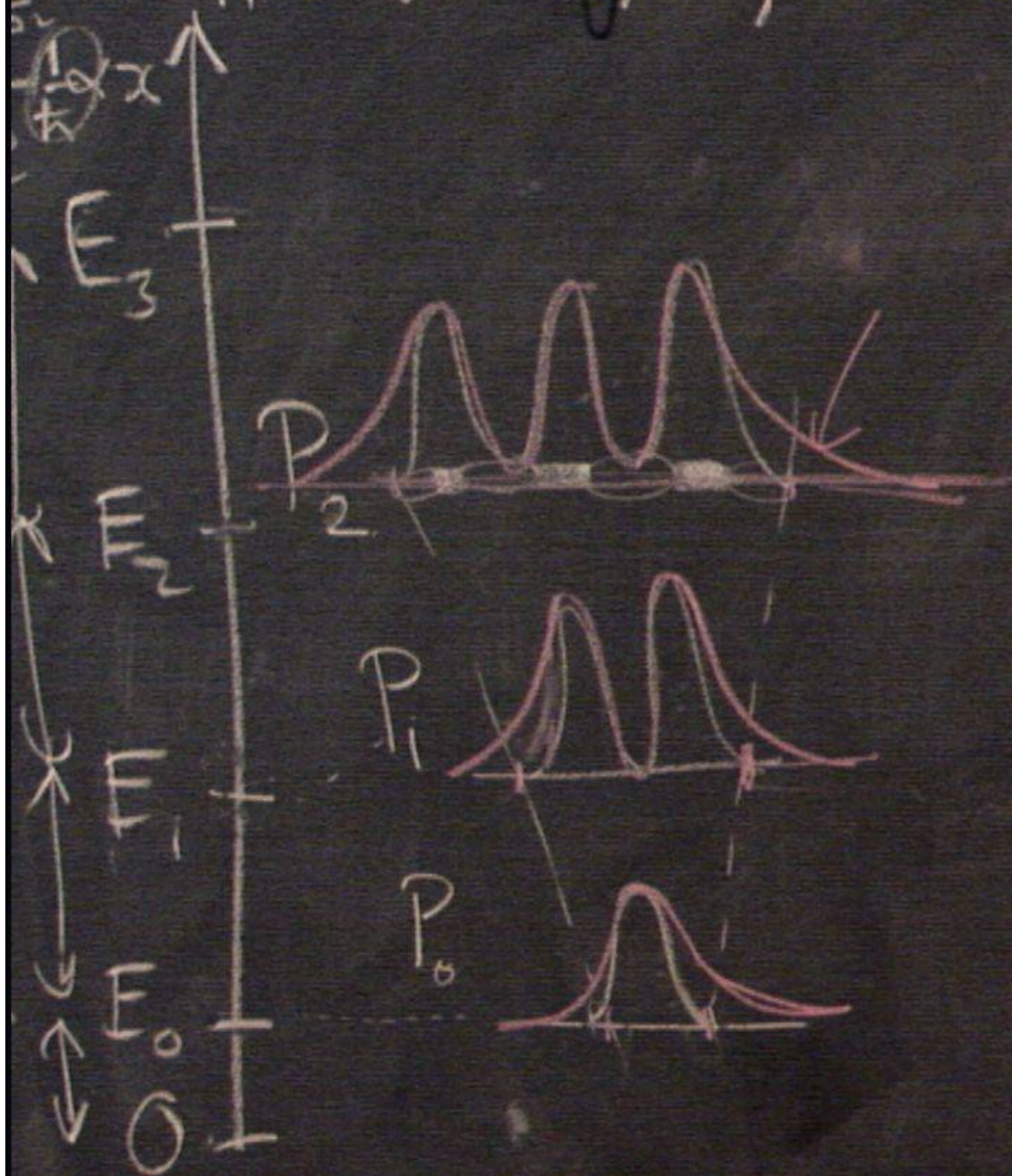


$$\Delta E \Delta t \geq \frac{\hbar}{4\pi}$$

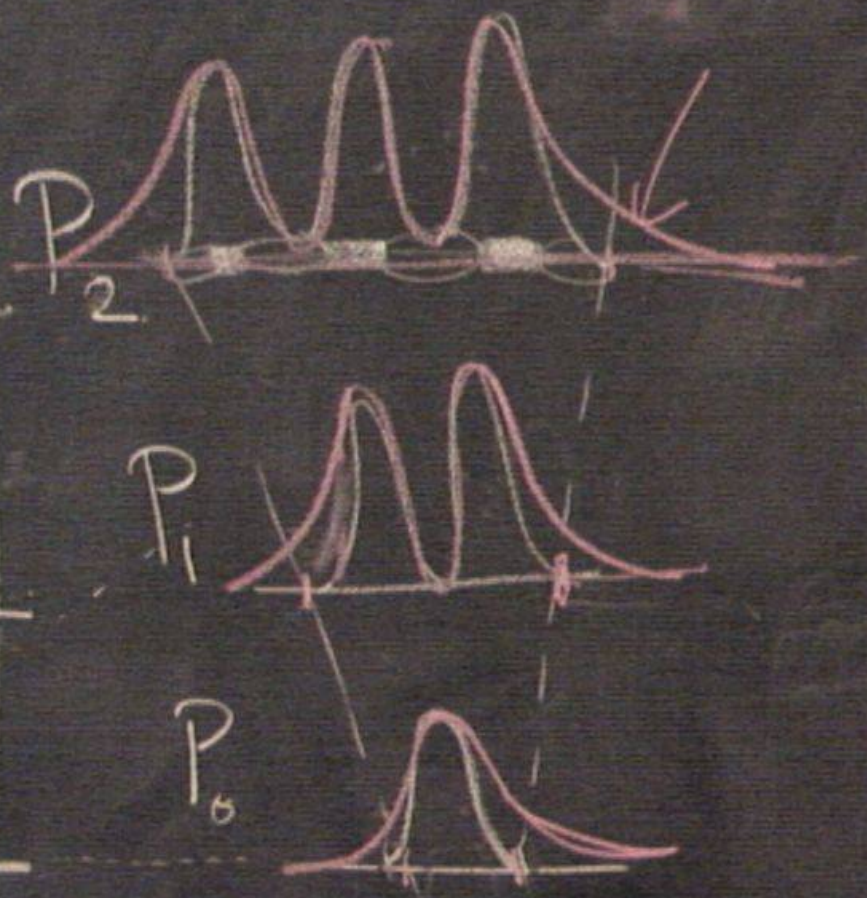
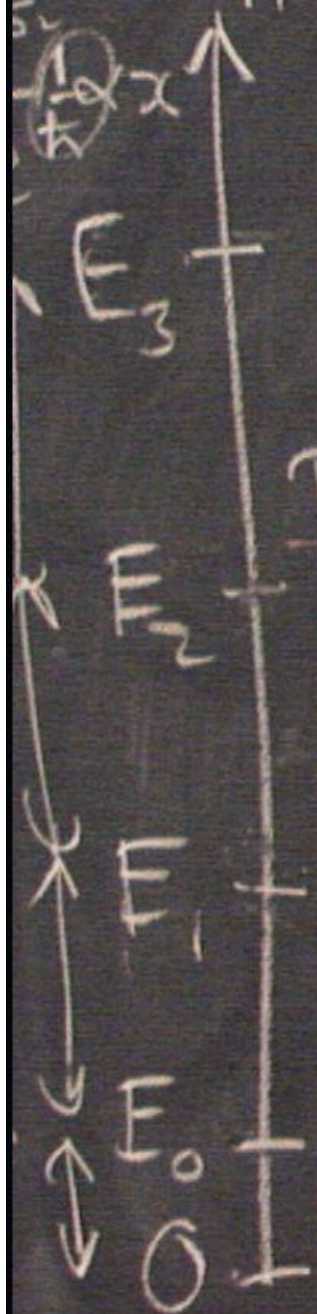


$$E_n = (n + \frac{1}{2})hf, n = 0, 1, 2, \dots$$

$$\Delta E = hf$$



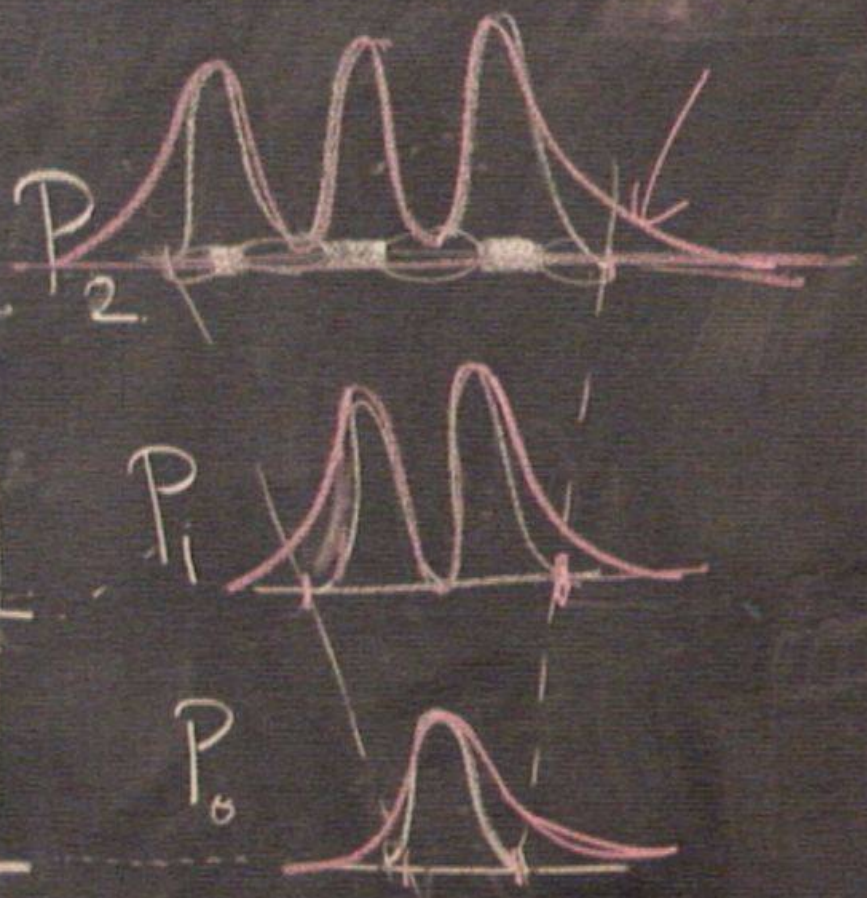
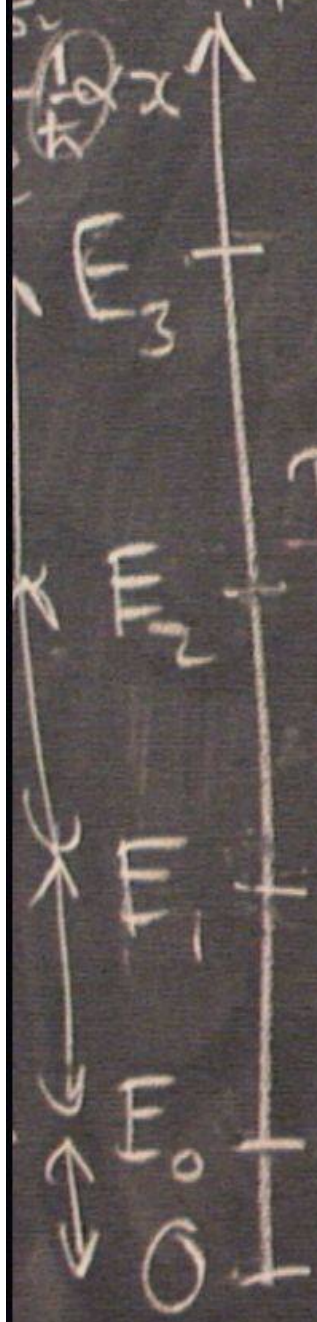
$$E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$$



$$\Delta E = hf$$

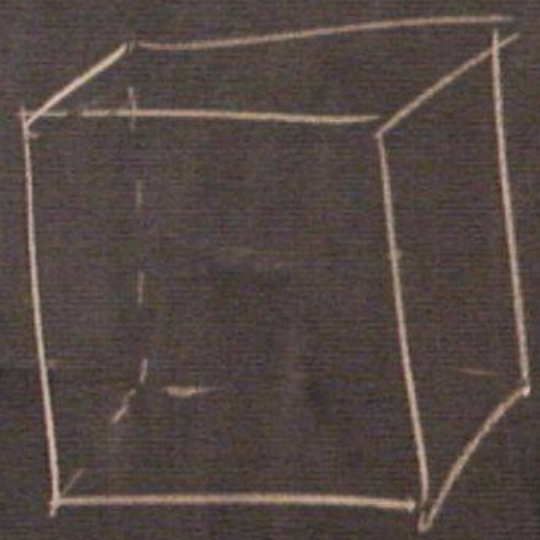
$$E_{\text{photon}} = hf$$

$$E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$$

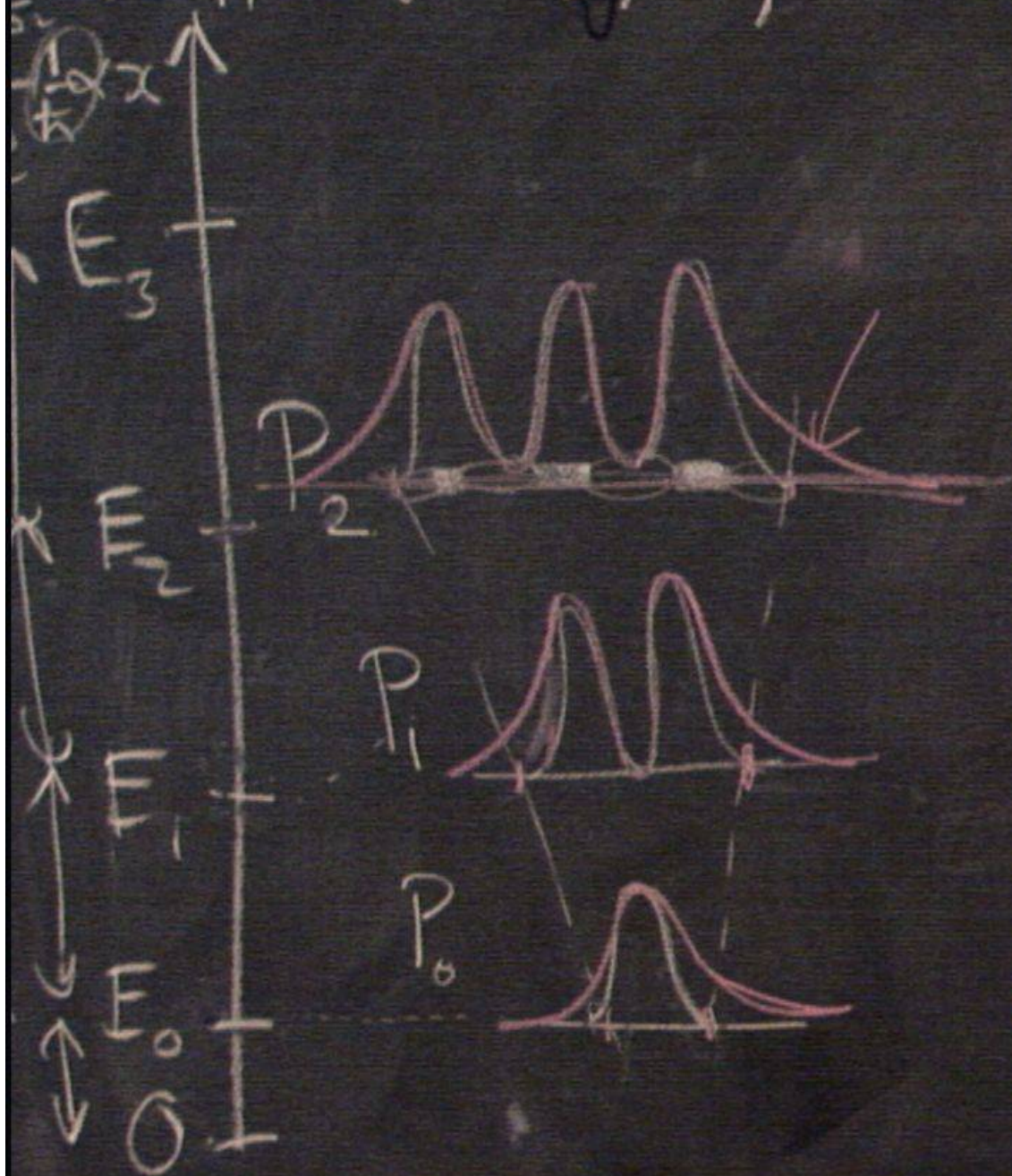


$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

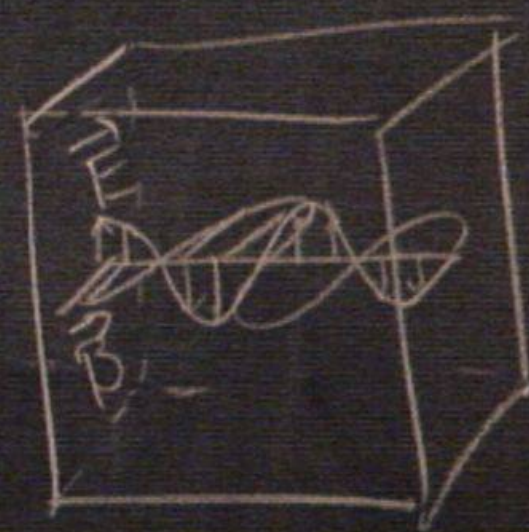


$$E_n = (n + \frac{1}{2})hf, n = 0, 1, 2, \dots$$

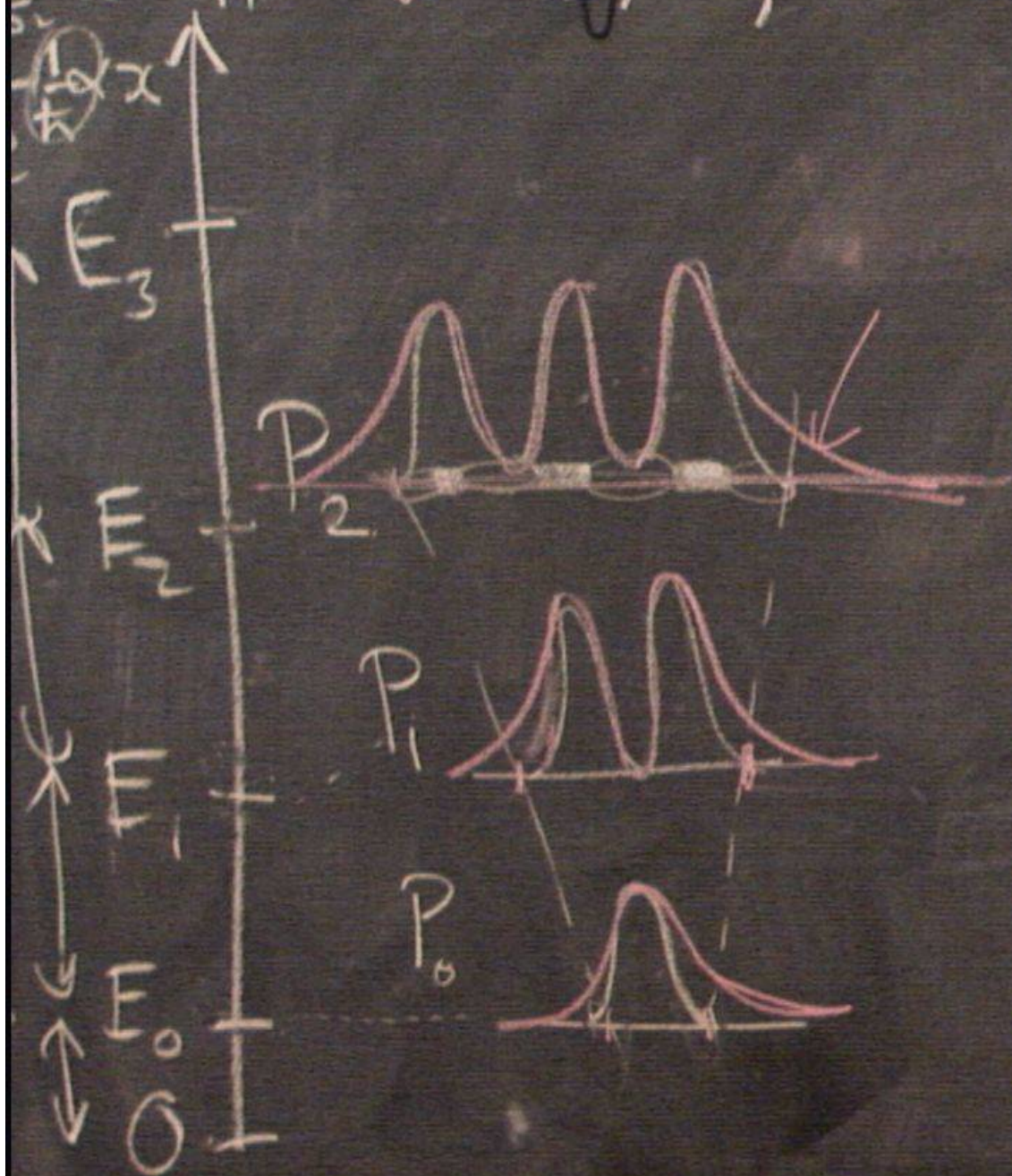


$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

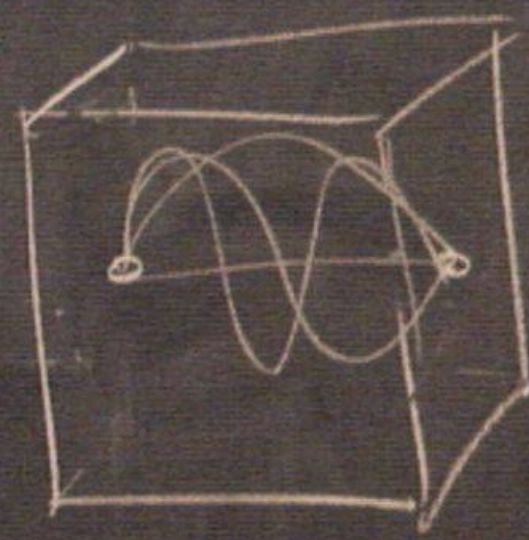


$$E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$$

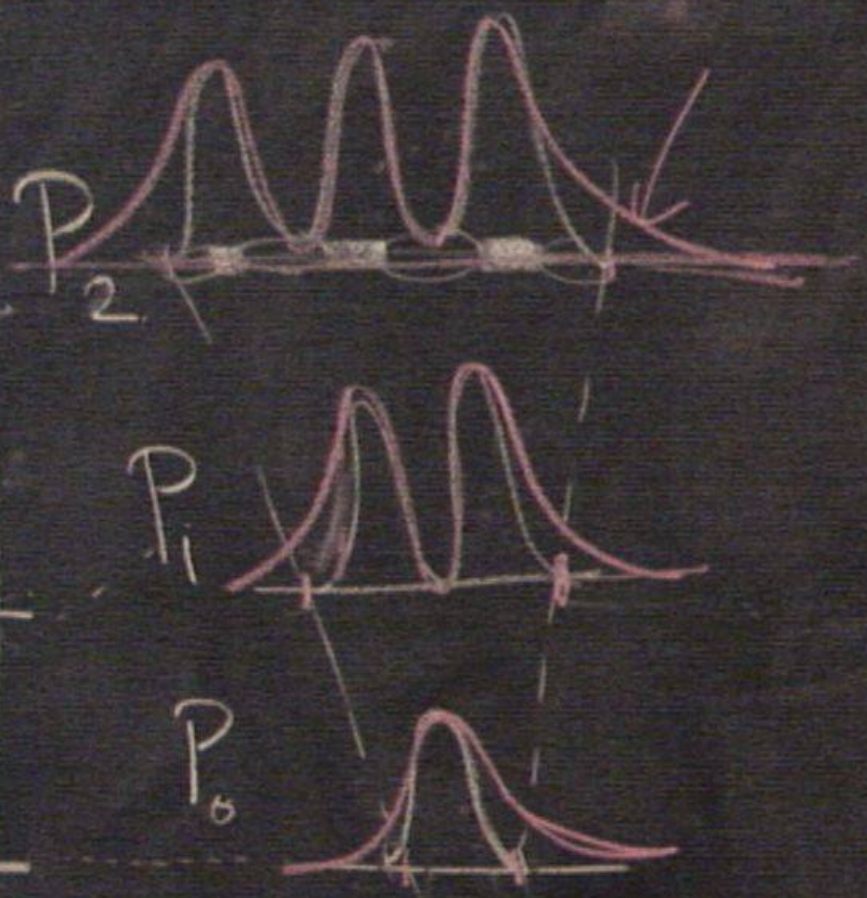


$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

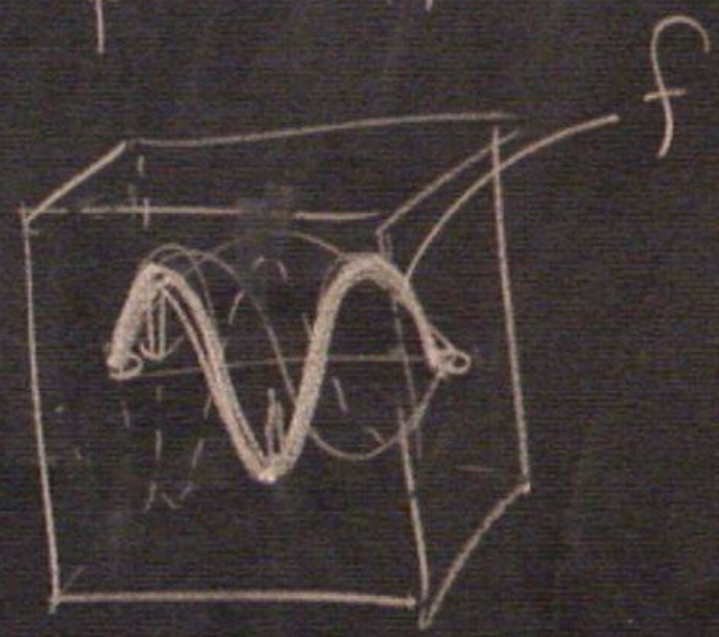


5.1. $E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$

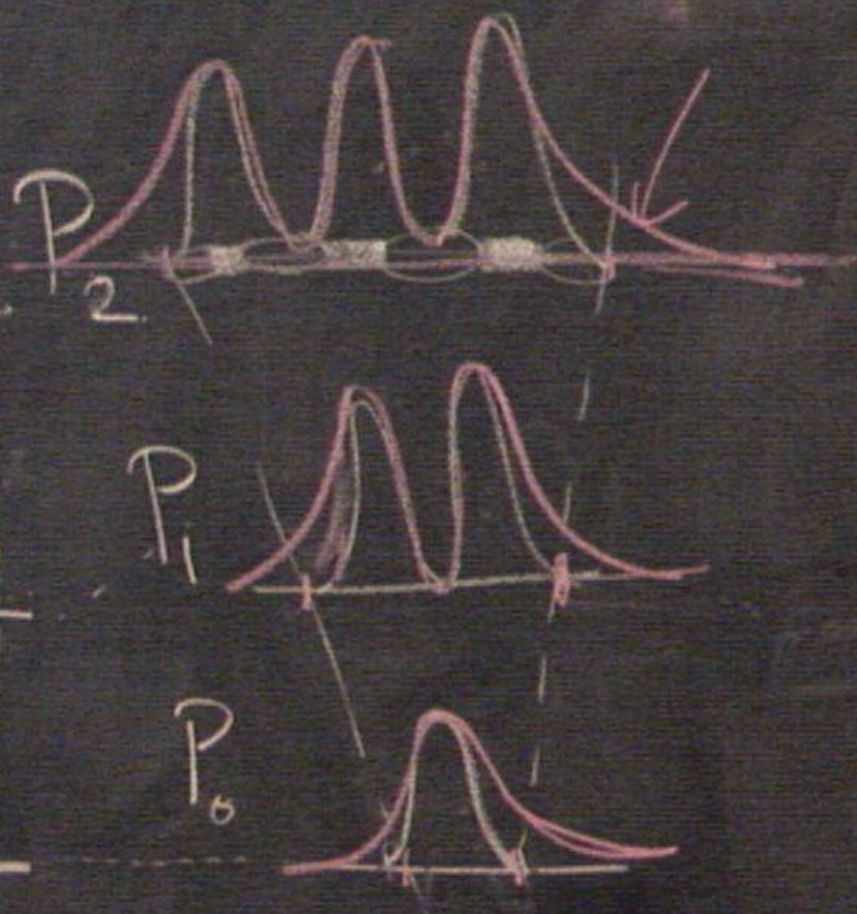
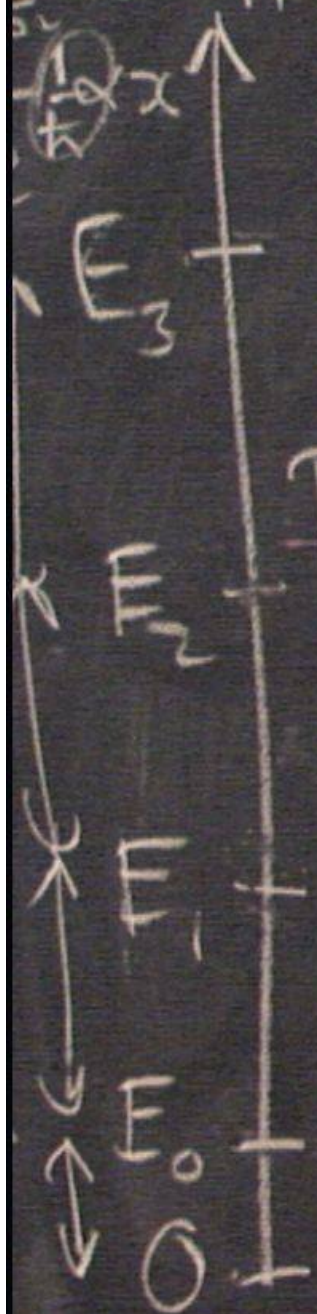


$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

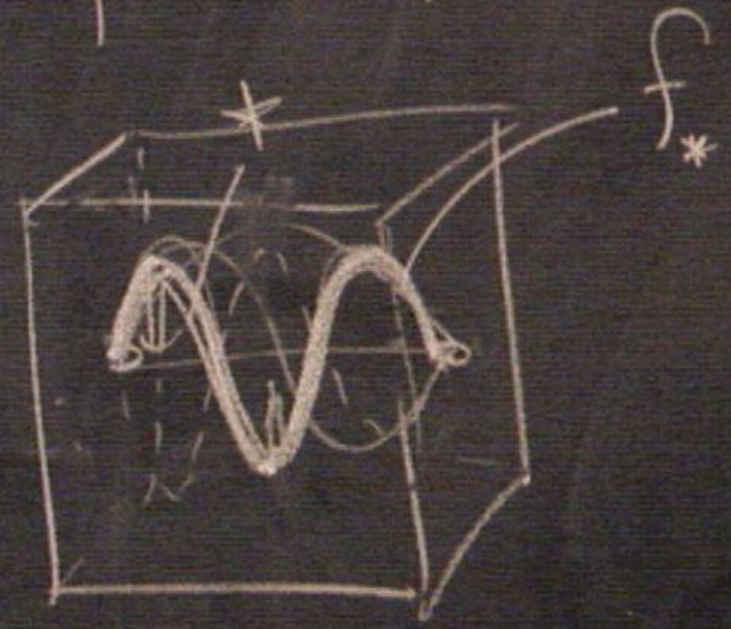


$$E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$$

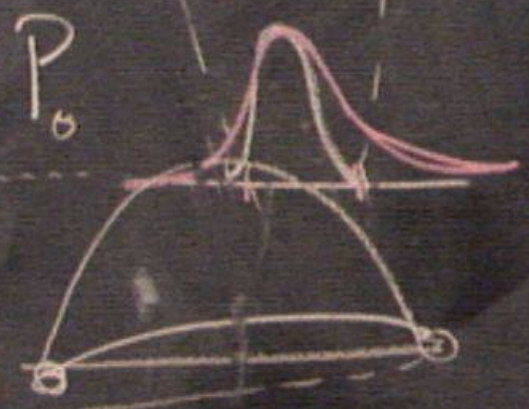
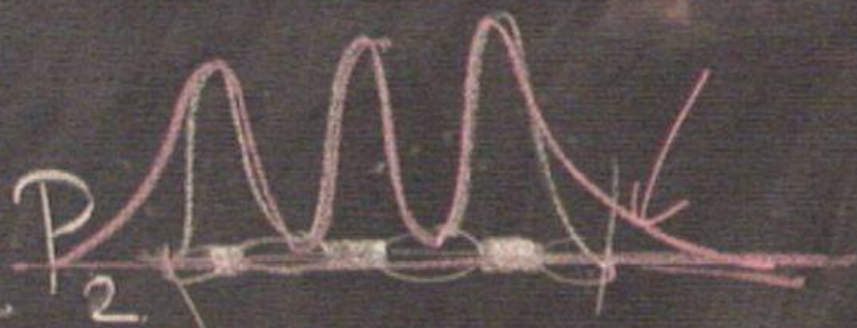
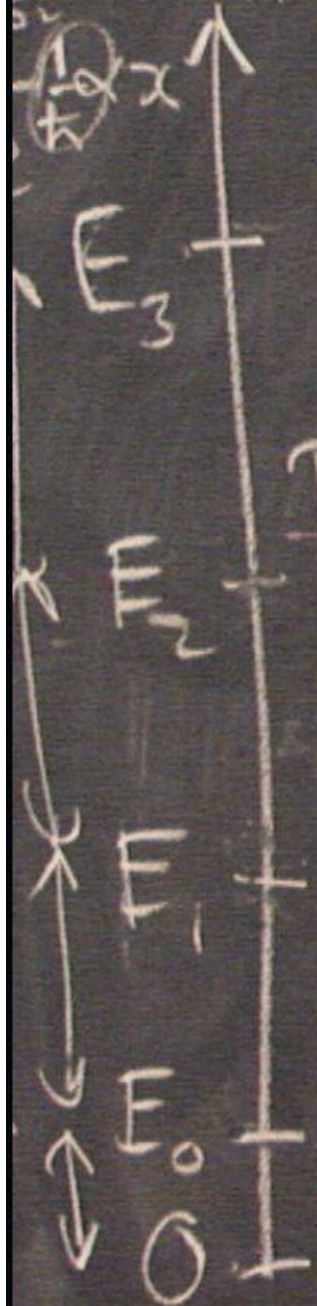


$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

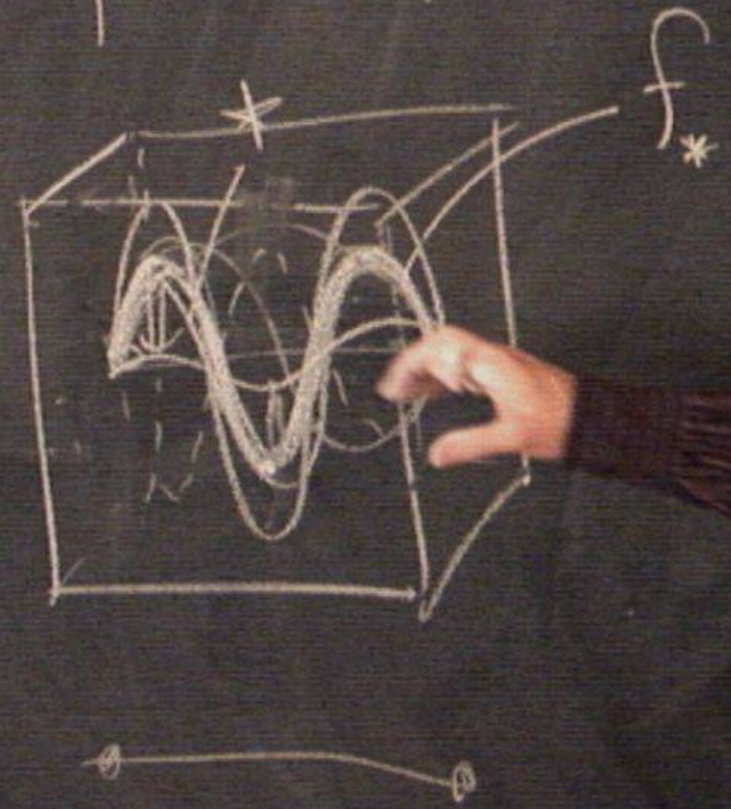


$$E_n = (n + \frac{1}{2})hf, n=0,1,2,\dots$$



$$\Delta E = hf$$

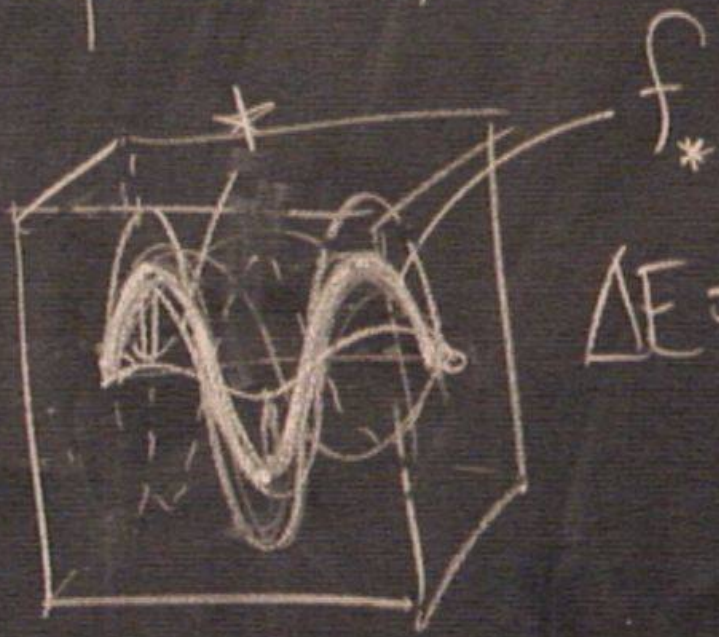
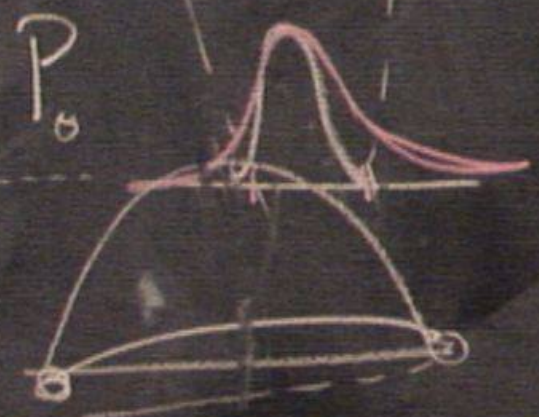
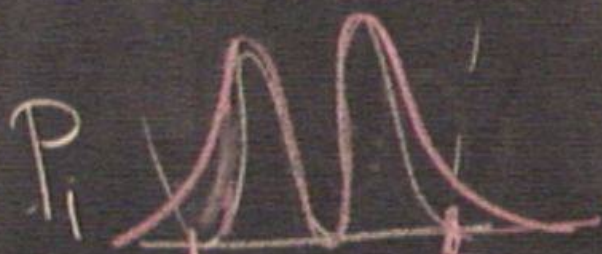
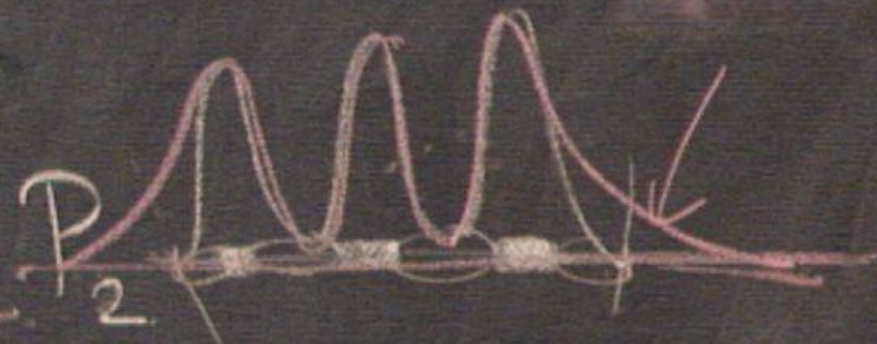
$$E_{\text{photon}} = hf$$



$n = (n_1 + 2/n_2), n_1 = 0, 1, 2, \dots$

$$\Delta E = hf$$

$$E_{\text{photon}} = hf$$

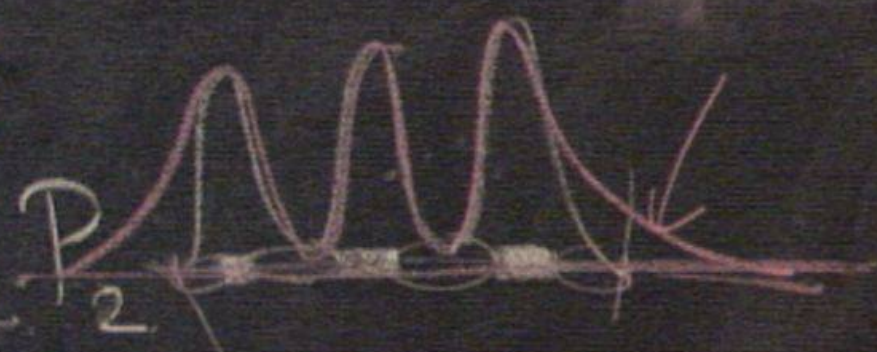


$$\Delta E = hf_*$$

$n = (n + \frac{1}{2})\pi, n = 0, 1, 2, \dots$

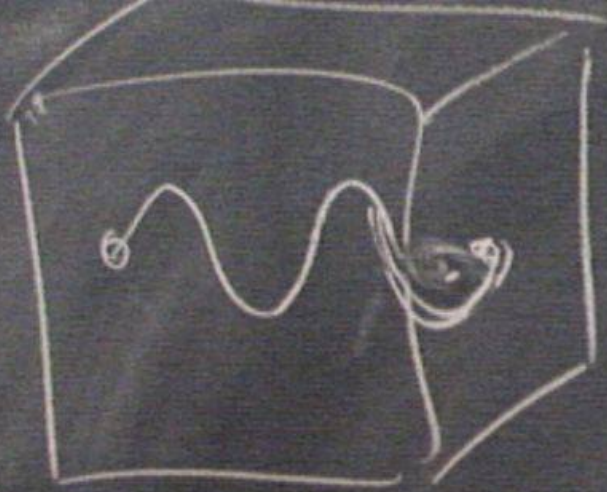
$$\Delta E = hf$$

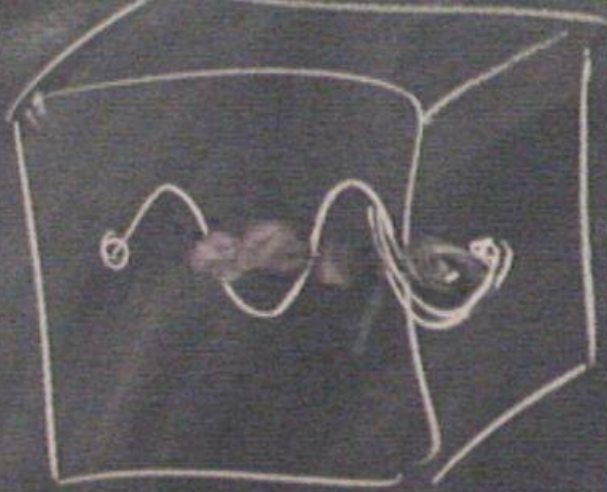
$$E_{\text{photon}} = hf$$



$$\Delta E = hf^*$$

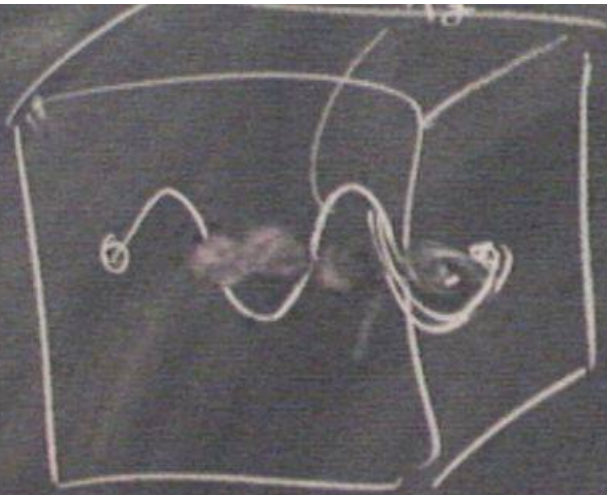
QFT





$$E_n = \left(n + \frac{1}{2}\right) h f$$

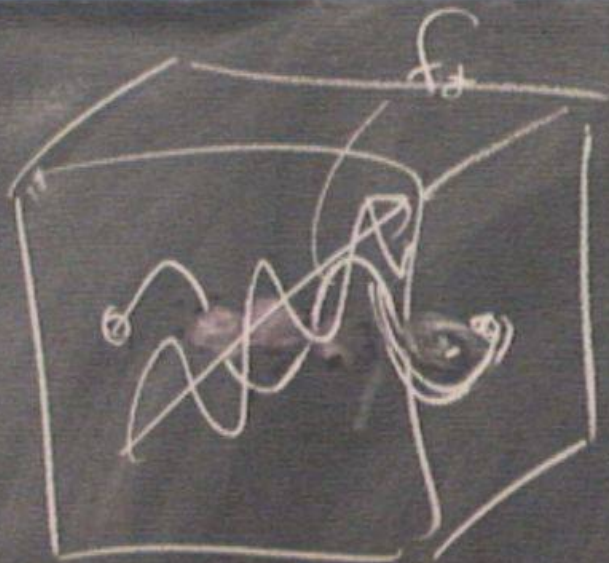
$$E =$$



$$E_n = \left(n + \frac{1}{2}\right) h f$$

$$E_0 = \frac{1}{2} h f$$

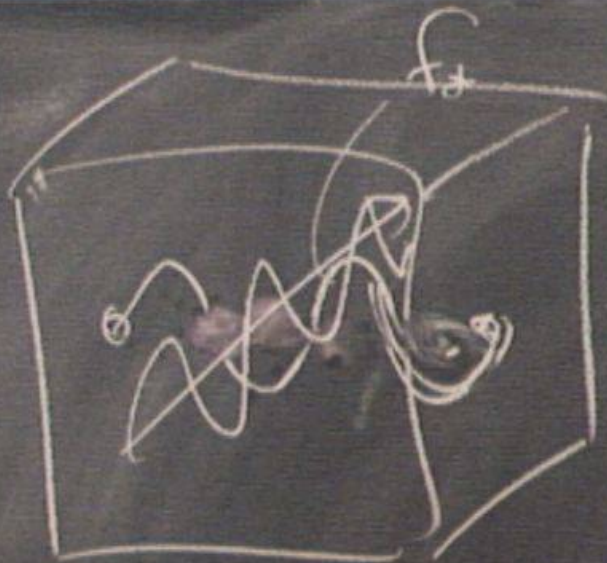
$$E =$$



$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

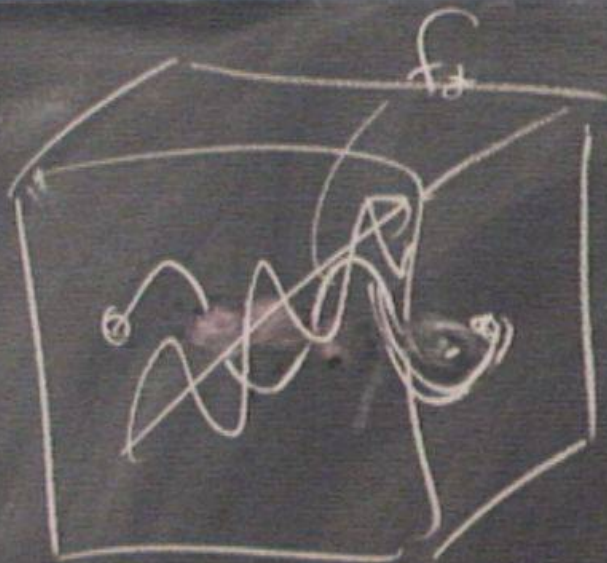
$$E = \frac{1}{2} hf_*$$



$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

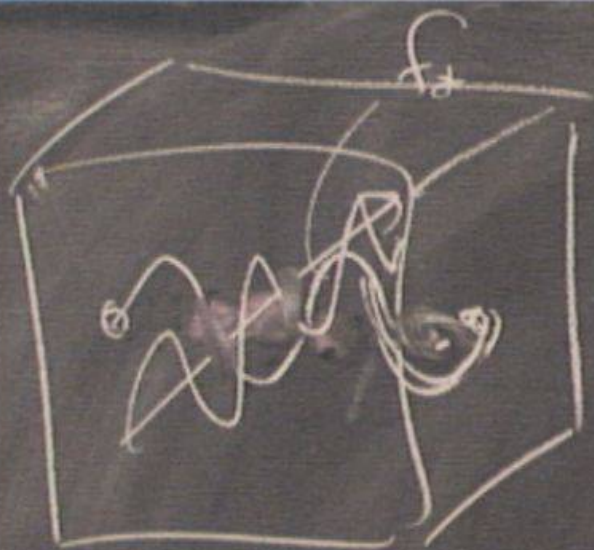
$$E = \frac{1}{2} hf_* + \frac{1}{2} hf_{**}$$



$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

$$E = \frac{1}{2} hf_* + \frac{1}{2} hf_{**} + \frac{1}{2} hf_{***}$$



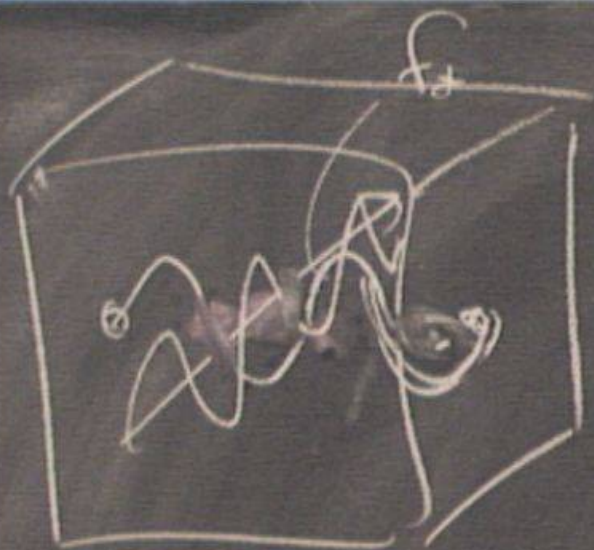
$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta B$$

$$E = \frac{1}{2} hf_* + \frac{1}{2} hf_*$$



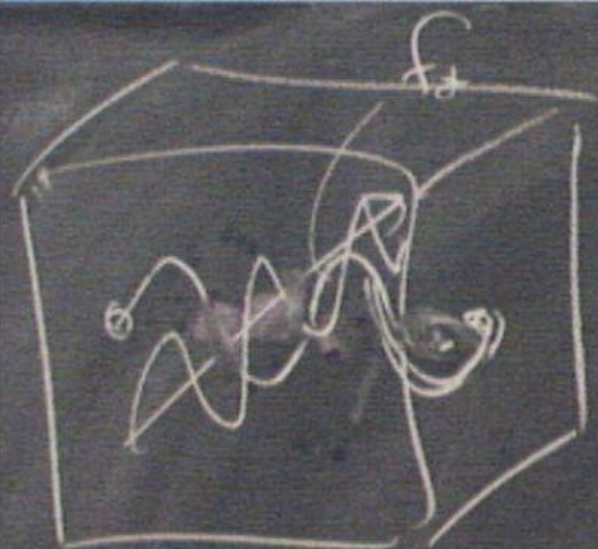
$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta B \geq \frac{h}{4\pi}$$

$$E = \frac{1}{2} hf_* + \frac{1}{2} hf_{**} + \frac{1}{2} hf_{***}$$



$$E_n = \left(n + \frac{1}{2}\right) h f$$

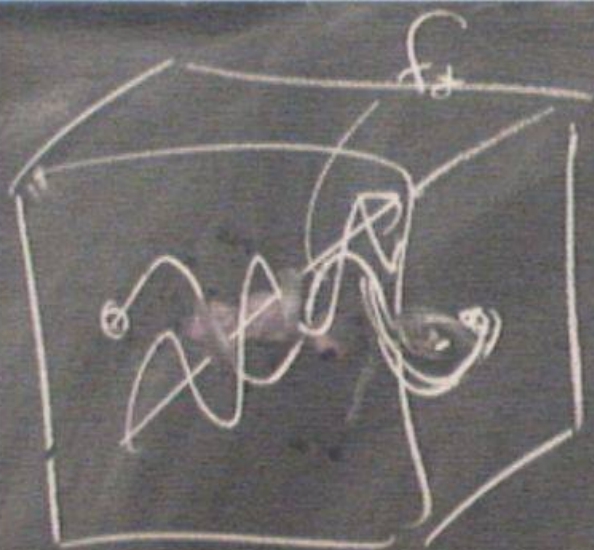
$$E_0 = \frac{1}{2} h f_*$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta B \geq \frac{h}{4\pi}$$

$$E = \frac{1}{2} h f_* + \frac{1}{2} h f_{**} + \frac{1}{2} h f_{***}$$

Casimir effect



$$E_n = \left(n + \frac{1}{2}\right) hf$$

$$E_0 = \frac{1}{2} hf_*$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta B \geq \frac{h}{4\pi}$$

$$E = \frac{1}{2} hf_* + \frac{1}{2} hf_{**} + \frac{1}{2} hf_{***}$$



Casimir effect