Title: The Emergence of Gravity

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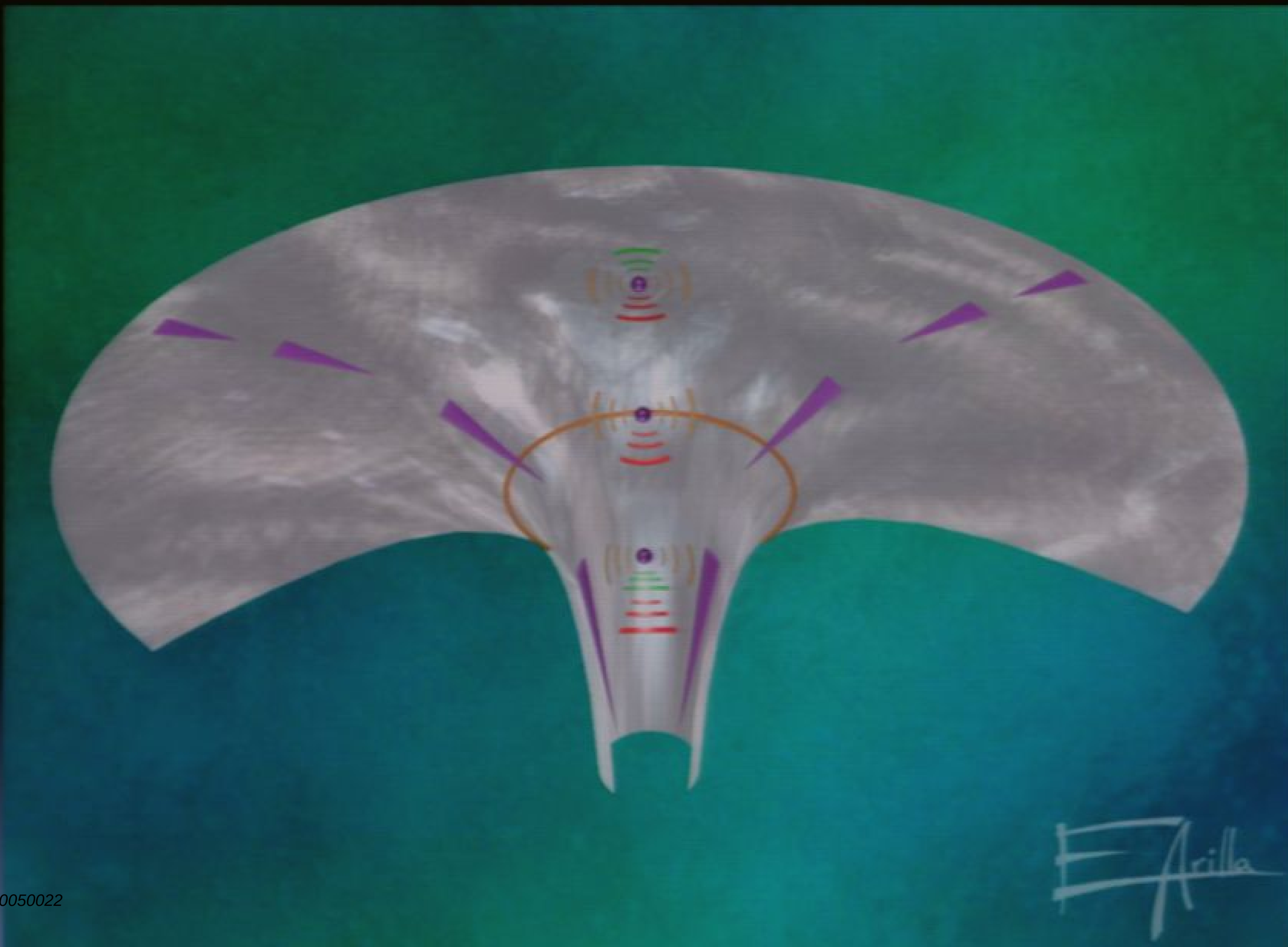
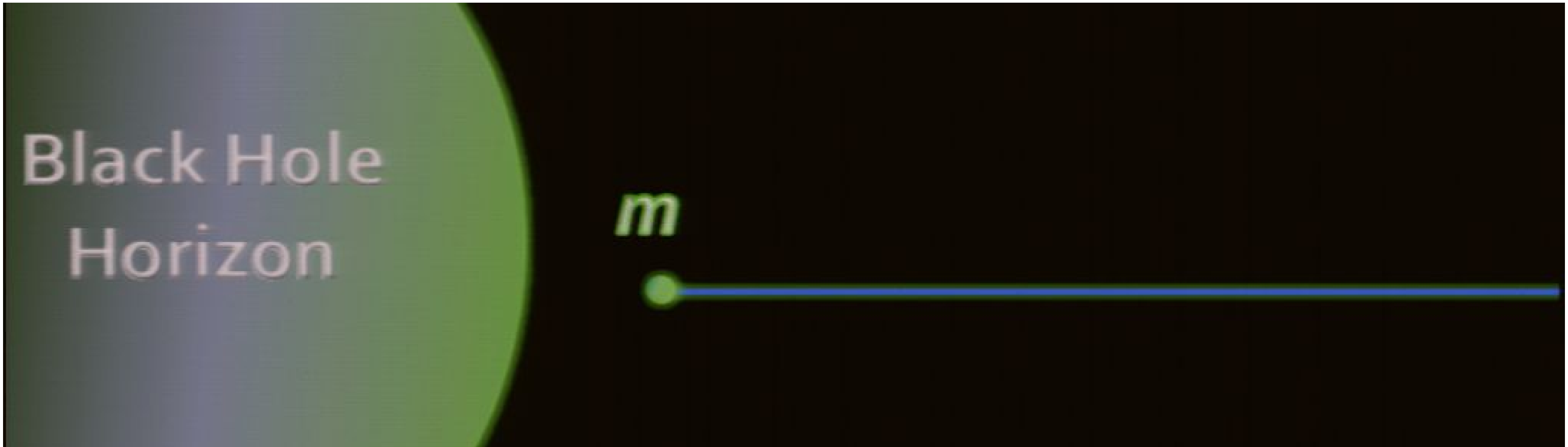
URL: http://pirsa.org/10050022

Abstract: Theoretical insights originated from the study of black holes combined with developments in string theory indicate that space time and gravity are emergent. A central role in these developments is played by the holographic principle. I will present a heuristic argument that indicates that at a microscopic level gravity is an entropic force caused by changes in the available phase space due to the displacement of material bodies. Refinement of the argument makes clear that this entropic view on gravity is consistent with quantum mechanics and supported by various results in string theory. I end with some thoughts on the possible emergence of the other forces of Nature.

Black Holes

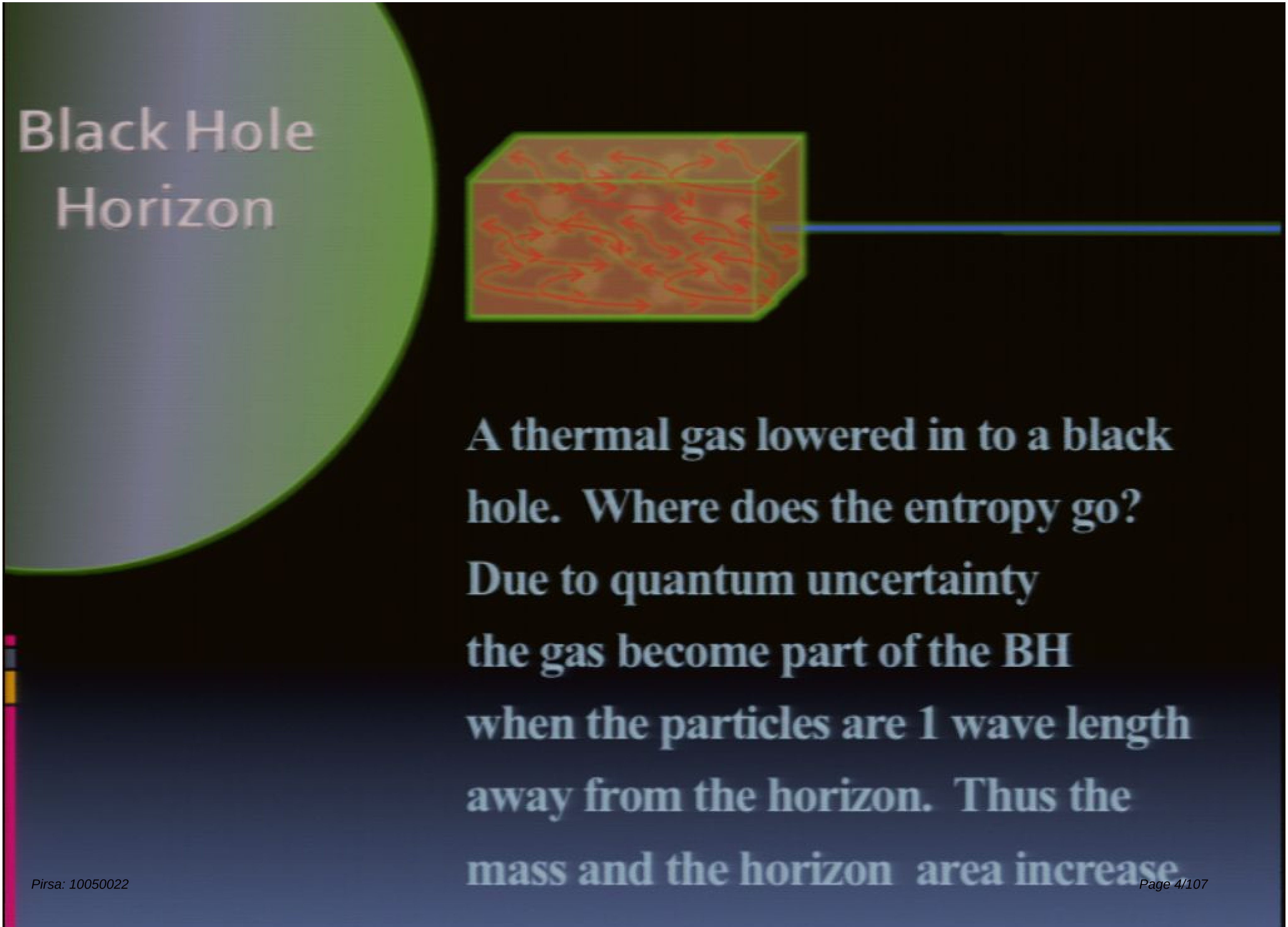




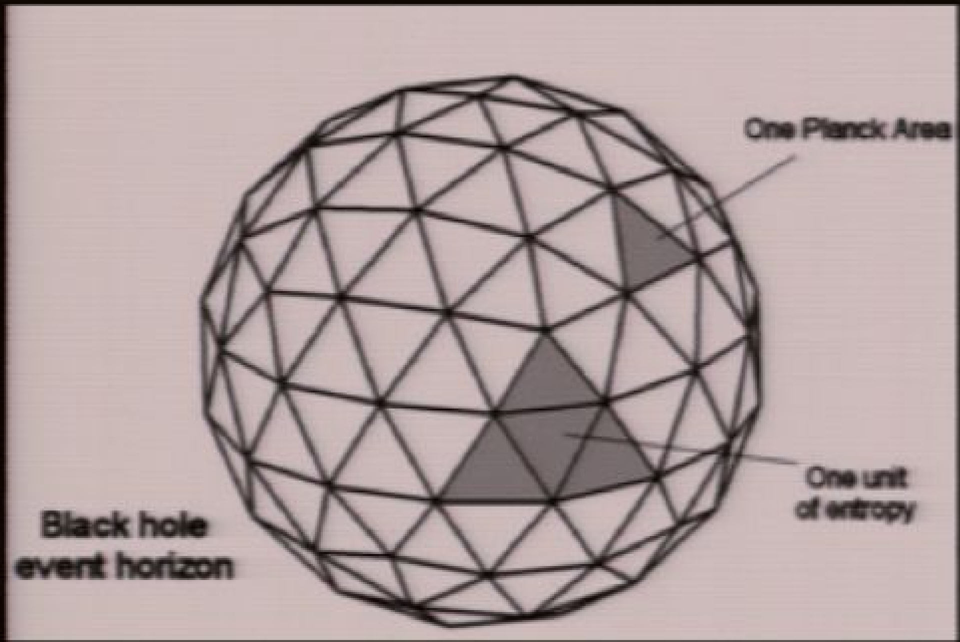
- **Black hole thought experiments.**

Consider a particle gradually lowered in to a black hole. Classically, the energy associated with the particle gets redshifted, and vanishes when the particle is at the horizon.

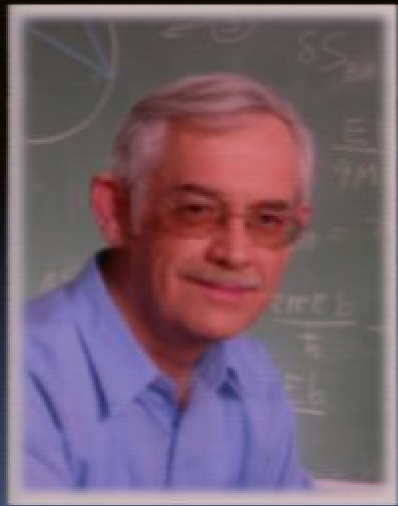
Penrose
Christodoulou
Bekenstein
Hawking


Black Hole
Horizon
A thermal gas lowered in to a black
hole. Where does the entropy go?
Due to quantum uncertainty
the gas become part of the BH
when the particles are 1 wave length
away from the horizon. Thus the
mass and the horizon area increase.

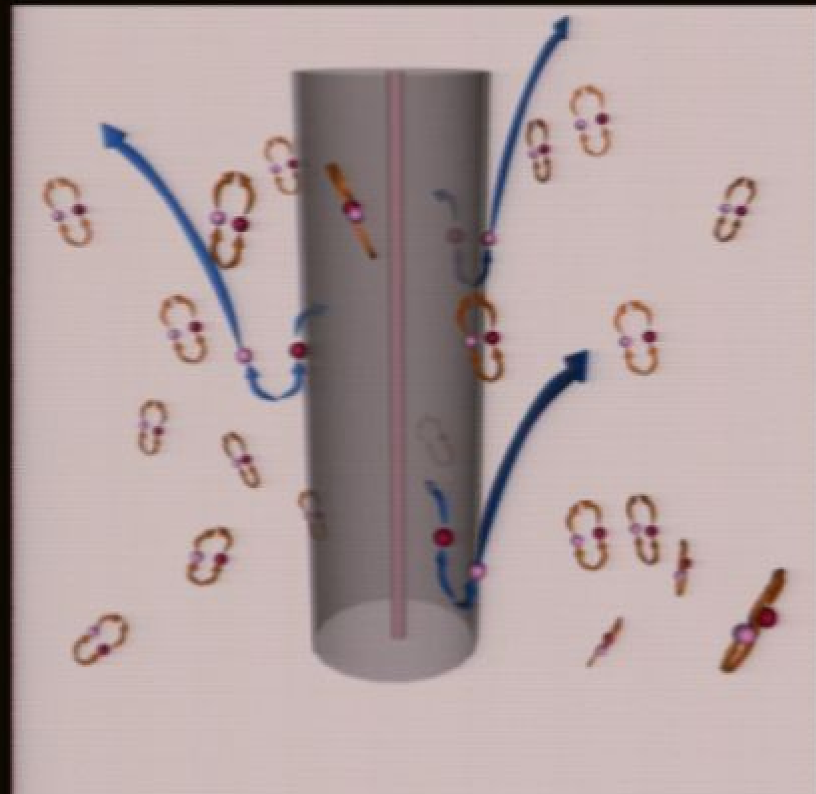
Black Hole Entropy



$$S_{BH} = k_B \frac{Ac^3}{4G\hbar}$$



HAWKING

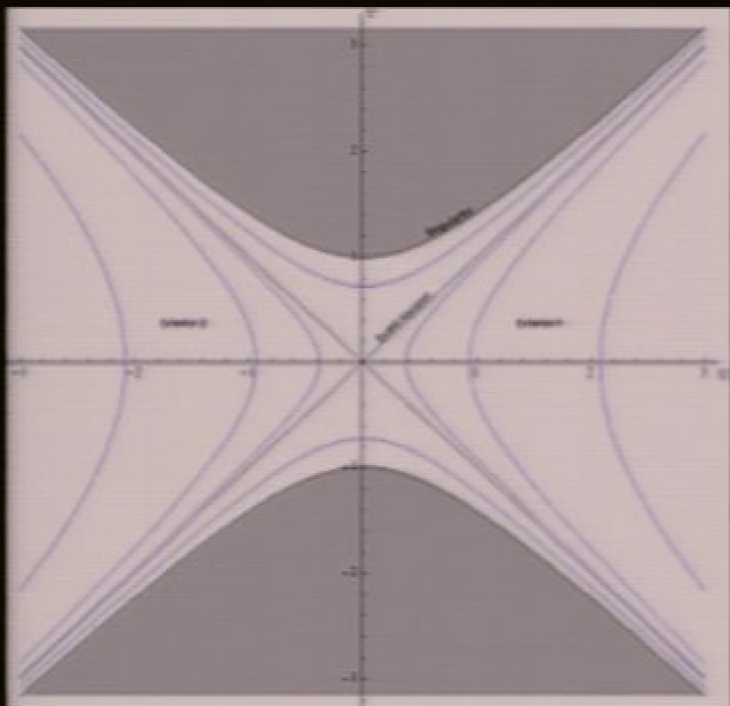


$$k_B T = \frac{1}{2\pi}\frac{\hbar g}{c}$$

- Hawking temperature
  is expressed in surface acceleration

$$g = \frac{GM}{R^2}$$

RINDLER HORIZONS + UNRUH EFFECT



- Hawking effect = Unruh effect
- Temperature expressed in terms of acceleration

$$k_B T = \frac{1}{2\pi}\frac{\hbar a}{c}$$

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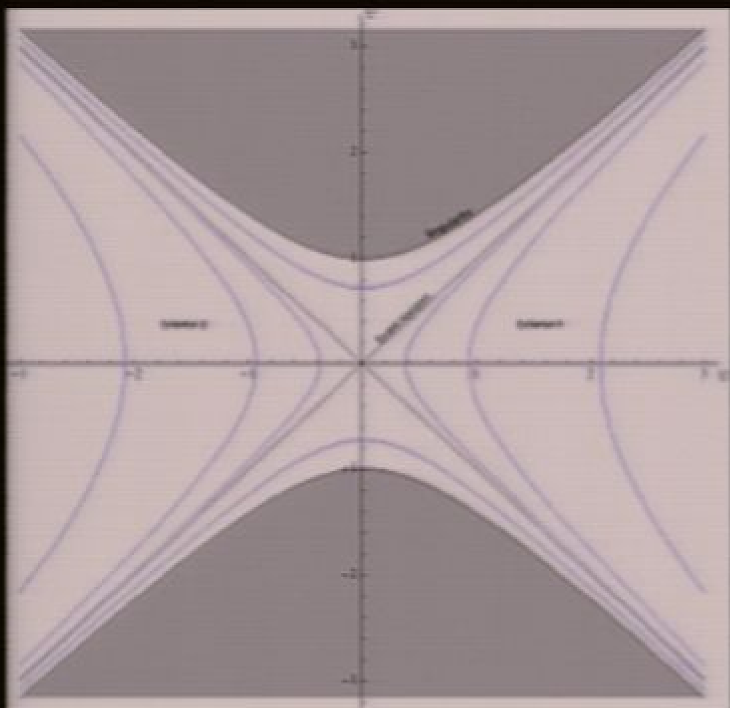

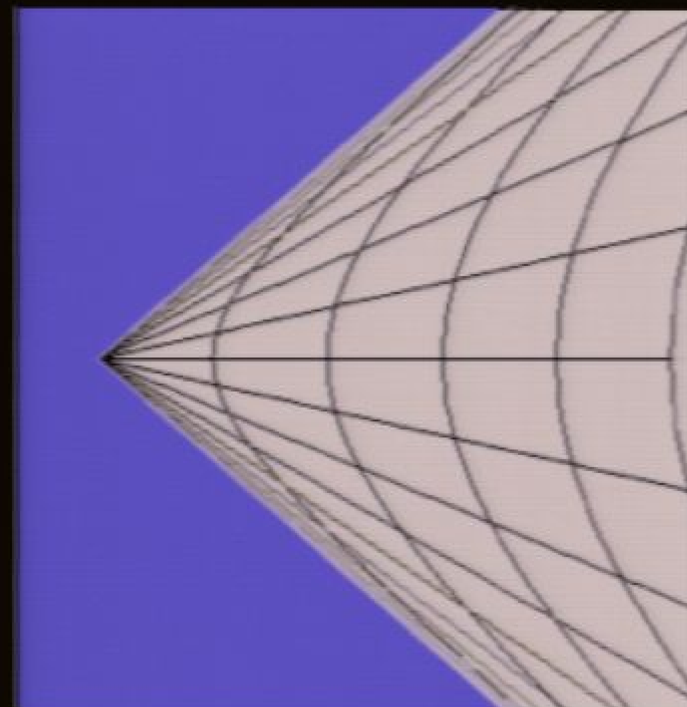

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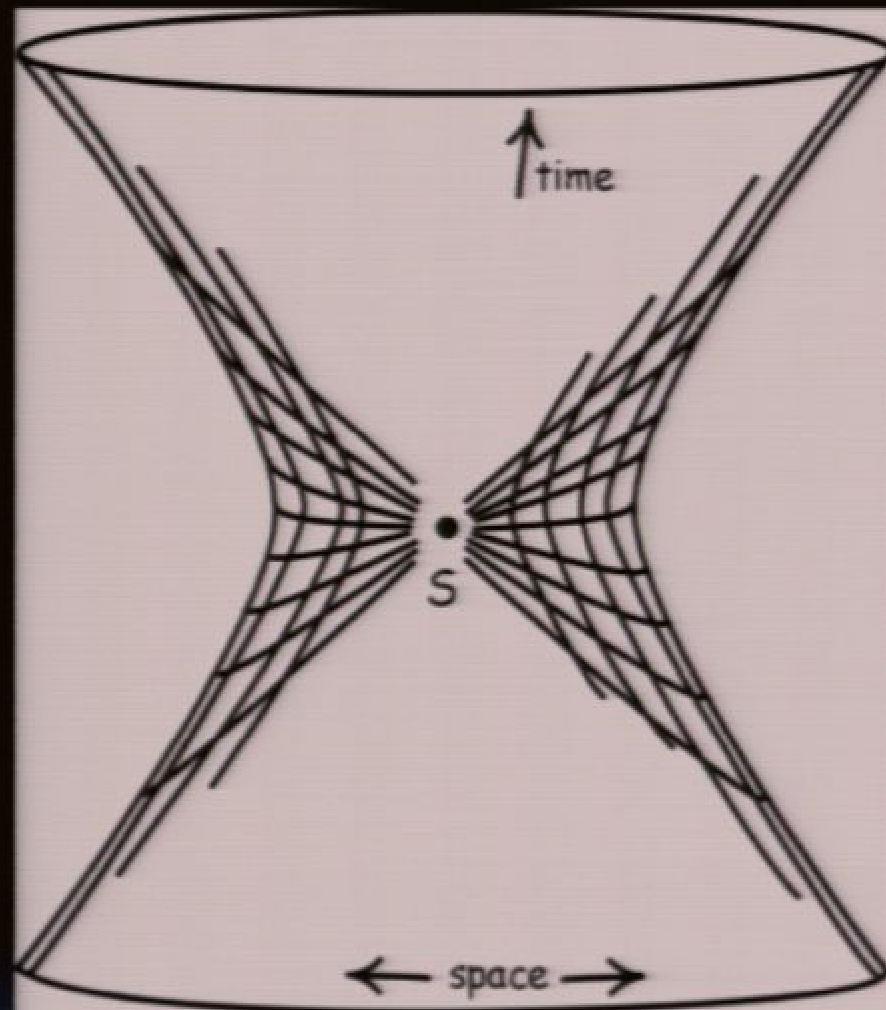
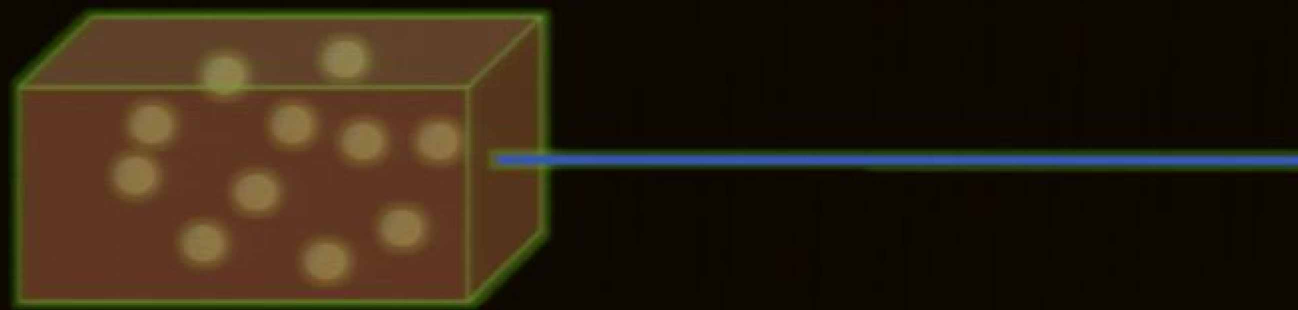
De Sitter Space



Cosmological Horizons
with temperature

$$k_B T = \frac{1}{2\pi}\frac{\hbar}{c}a_0$$

$$a_0 = c^2\sqrt{\Lambda}$$



What happens to collection of particles?

Particles never really cross the horizon, but become part of the degrees of freedom associated with the horizon.

De Sitter Space

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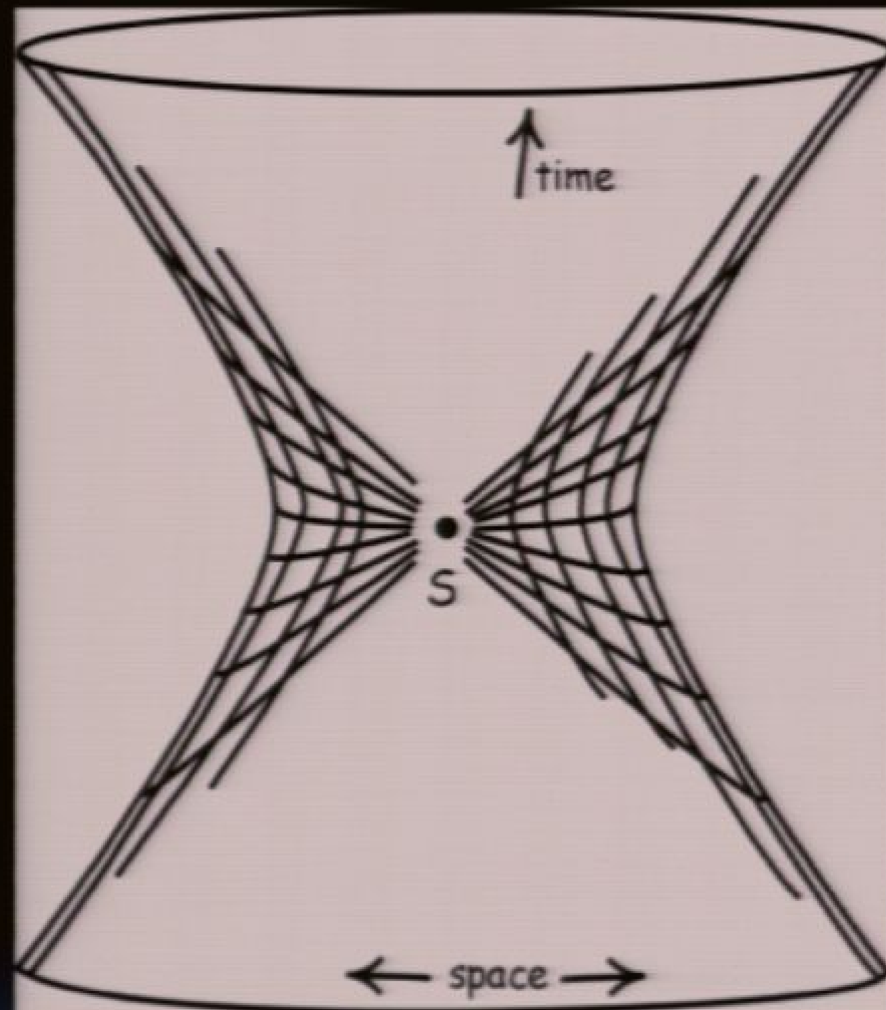

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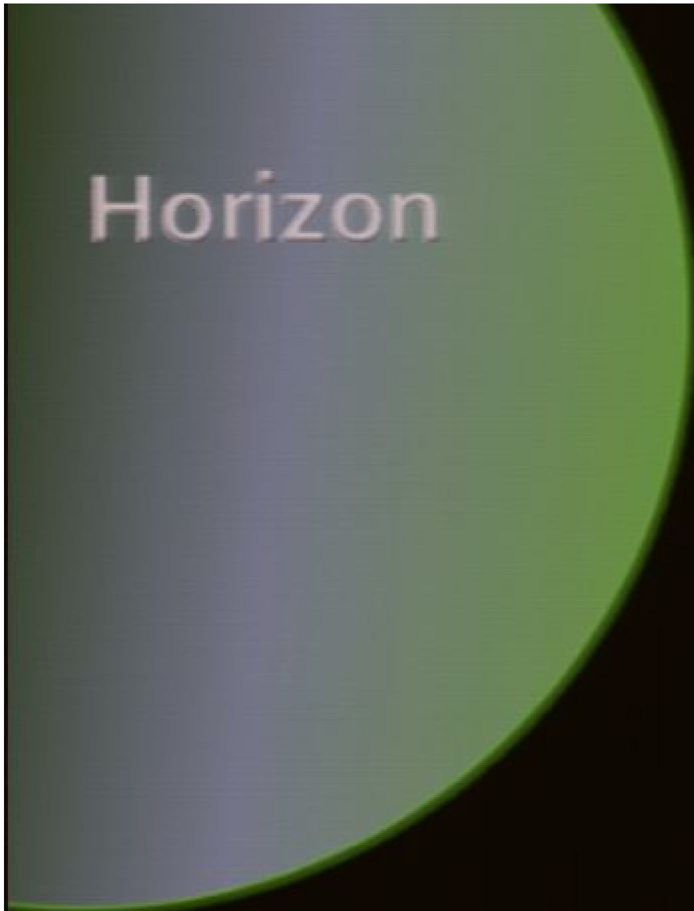

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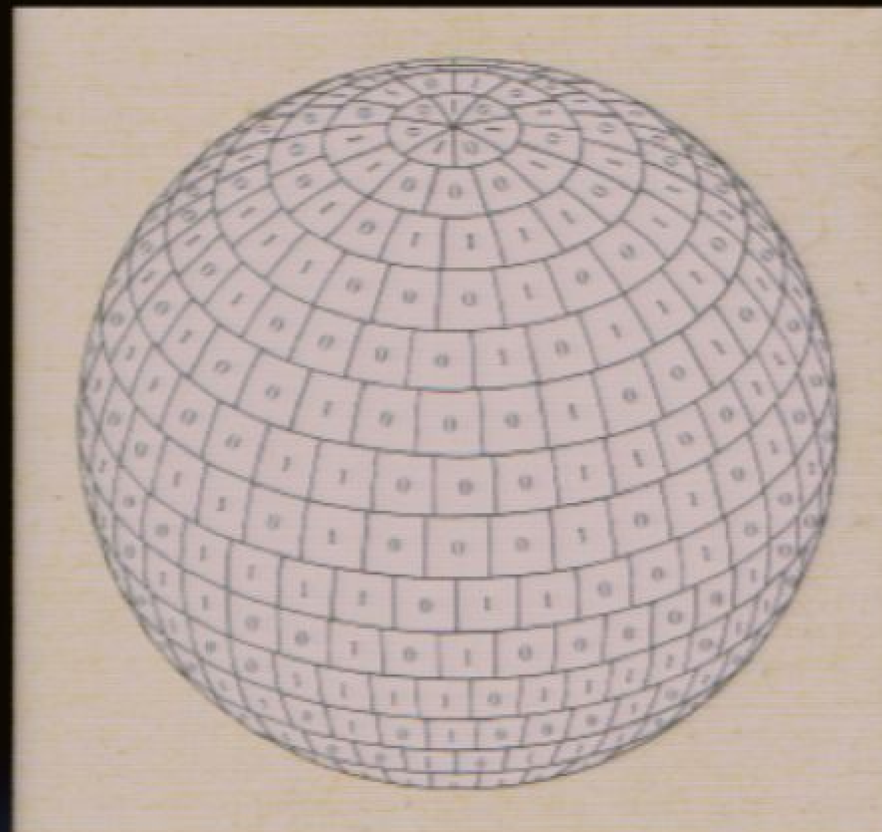
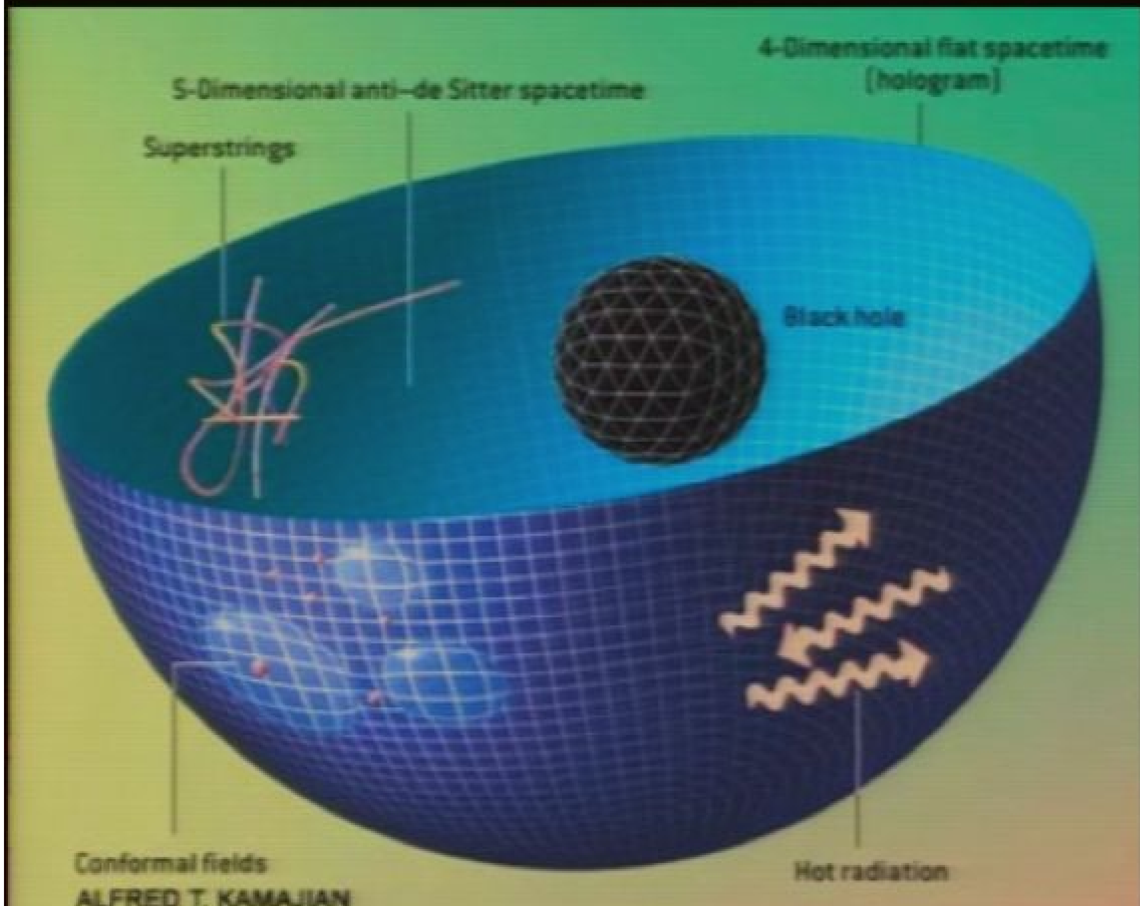
Holographic principle



# of bits (degrees of freedom)
= Area in Planck units

ADS/CFT CORRESPONDENCE



EQUIVALENCE BETWEEN FIELD THEORY ON THE "BOUNDARY" AND GRAVITY IN THE "BULK"

ONE SPACE DIMENSION EMERGES CORRESPONDING TO THE "SCALE" OF THE BOUNDARY THEORY. RADIAL EVOLUTION IS LIKE RENORMALIZATION GROUP FLOW.

Bulk description

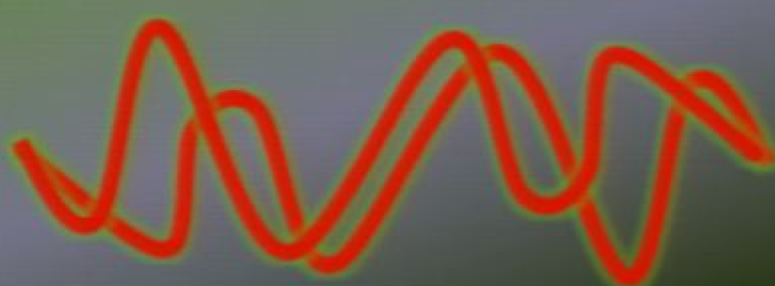
Black Hole In AdS space

Particle gets lowered in to black hole

Boundary description:

Delocalized state gets thermalized by heath bath

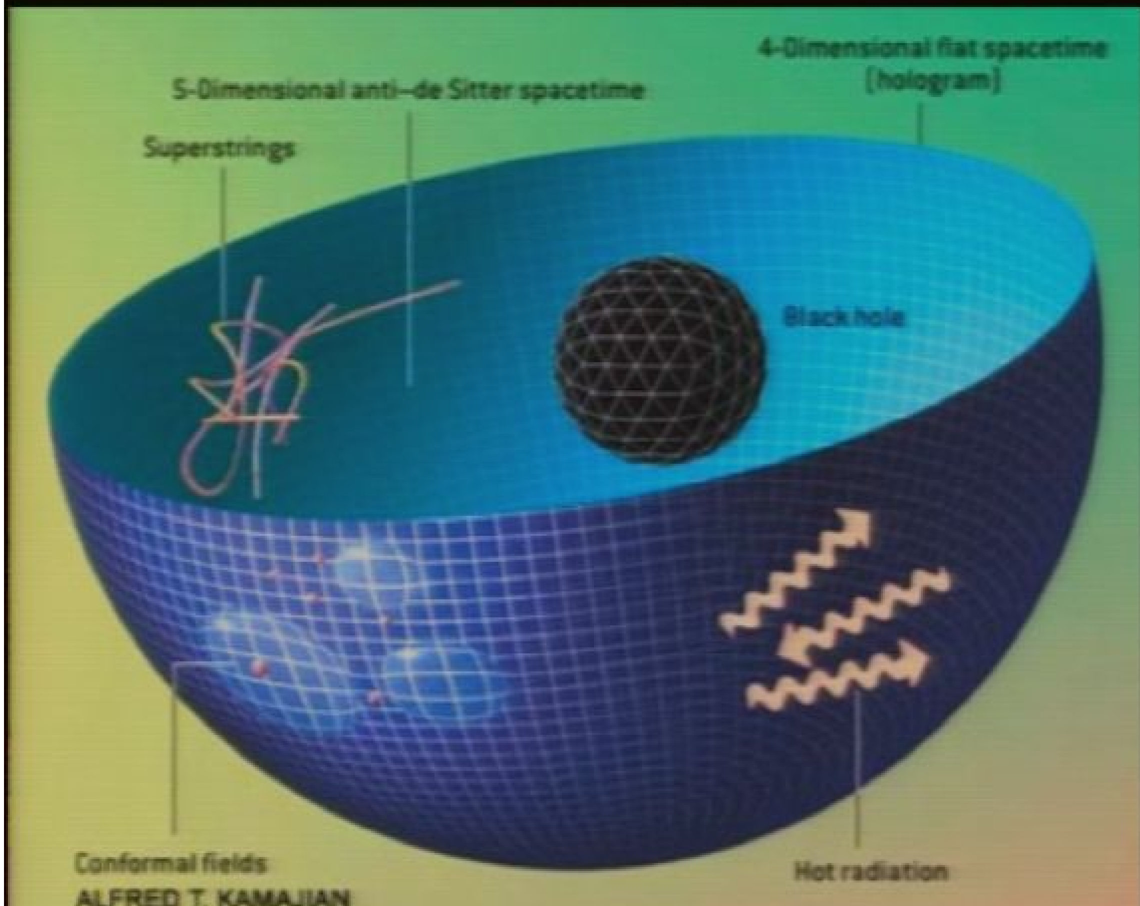
Hot CFT



Thermal Heat Bath

T

ADS/CFT CORRESPONDENCE



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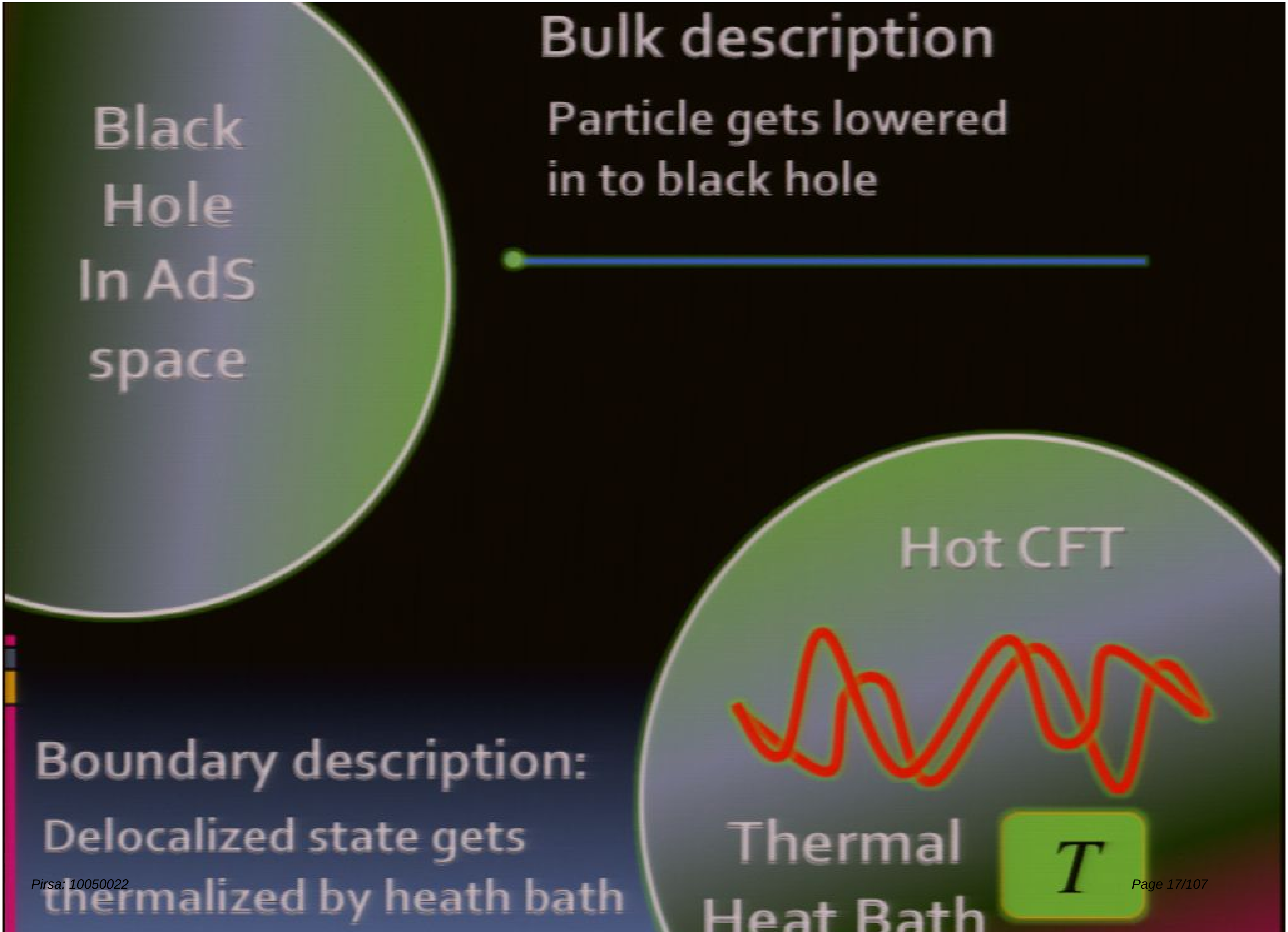
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SUPPOSE: SPACE IS EMERGENT

- How does gravity emerge?
- And what about inertia in the emergent directions?

- Assumptions:

  - Holographic principle is true.

  - Information stored on “screens”

  - Time is defined microscopically.

Main Idea

The number of true microscopic degrees of freedom is very large, and the microscopic dynamics is very fast. The associated information is invisible to us, and the dynamics appears random to us. Usual concepts like particles, mass, positions are macroscopic and emergent, and are associated with a finite entropy = measure of the amount of information.

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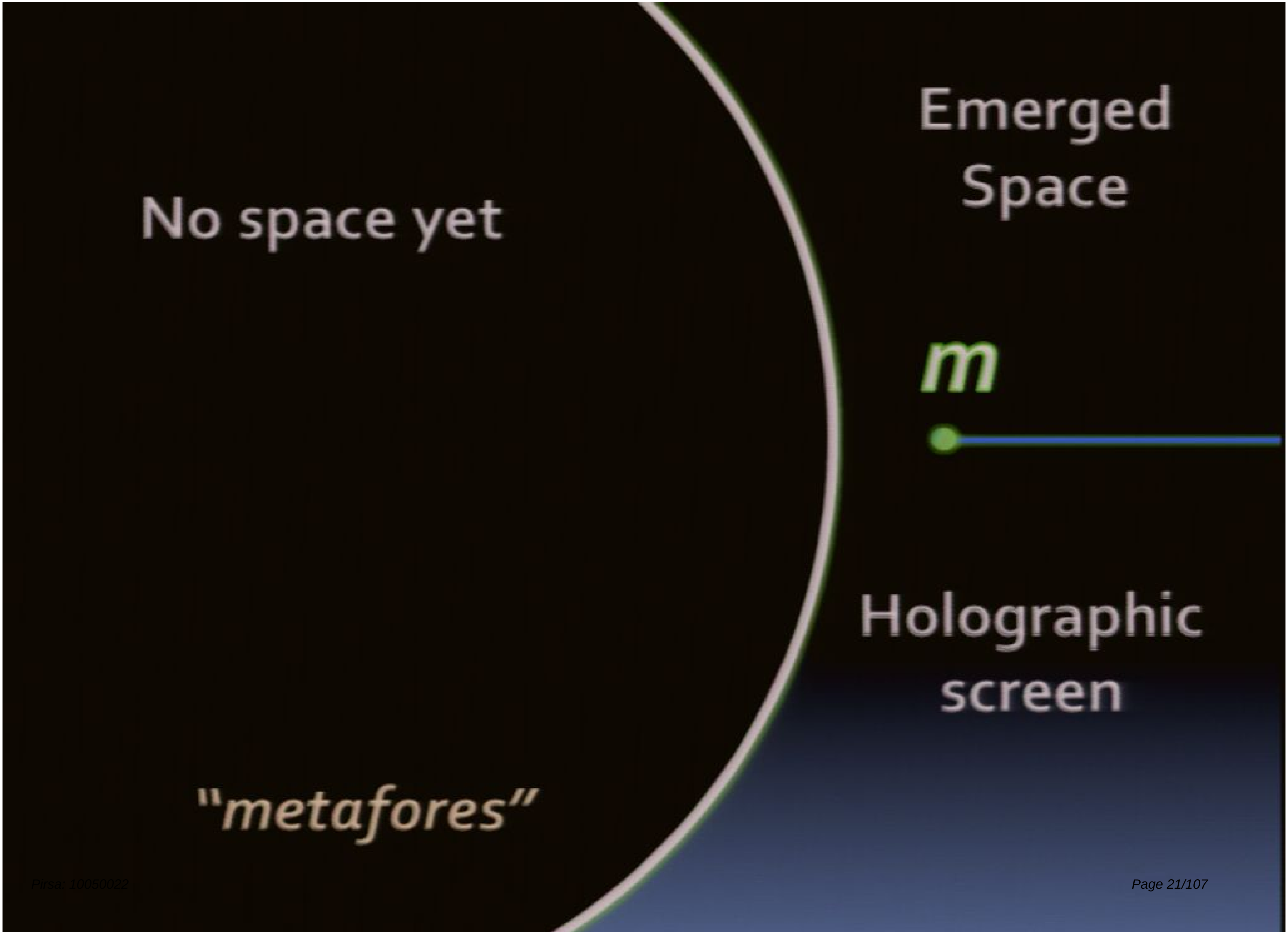
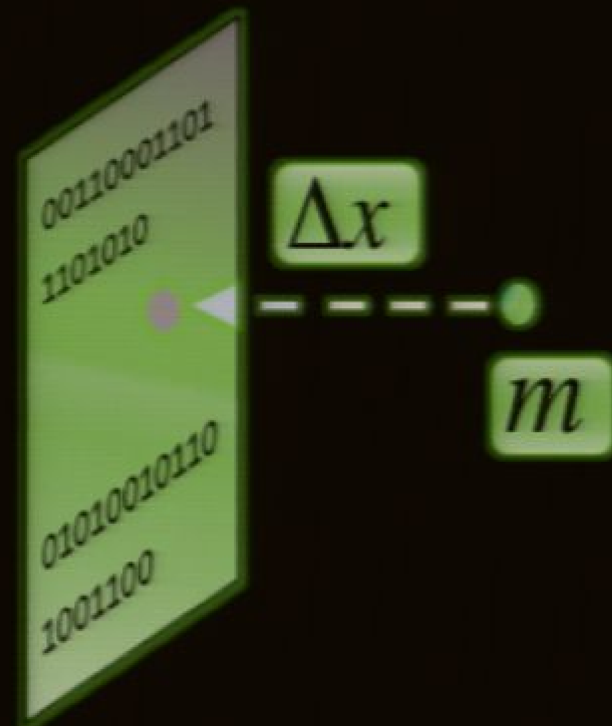

No space yet
Emerged
Space
m
Holographic
screen
"metafores"

A HEURISTIC DERIVATION OF NEWTON'S LAW OFGRAVITY



information is stored on holographic screens
moving a particle over one Compton wavelength
leads to one more bit of information

$$\Delta S = 2\pi\, k_B$$

$$\Delta x = \frac{\hbar}{mc}$$

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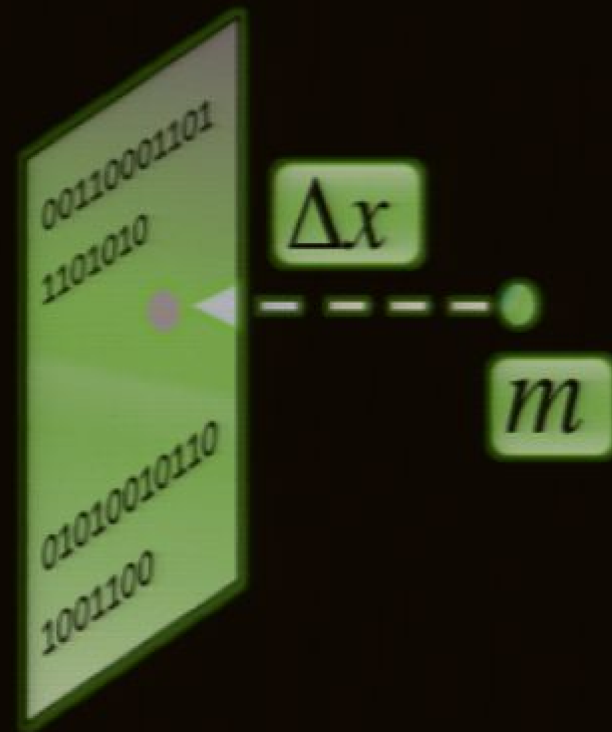

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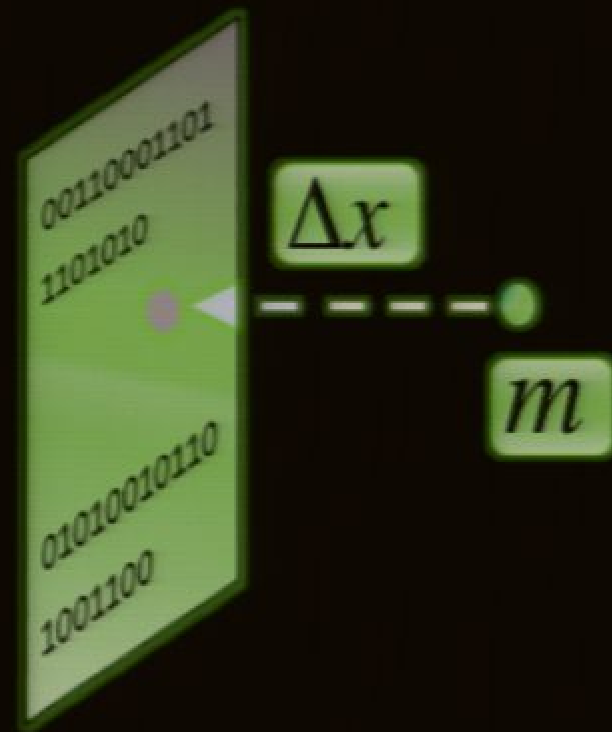

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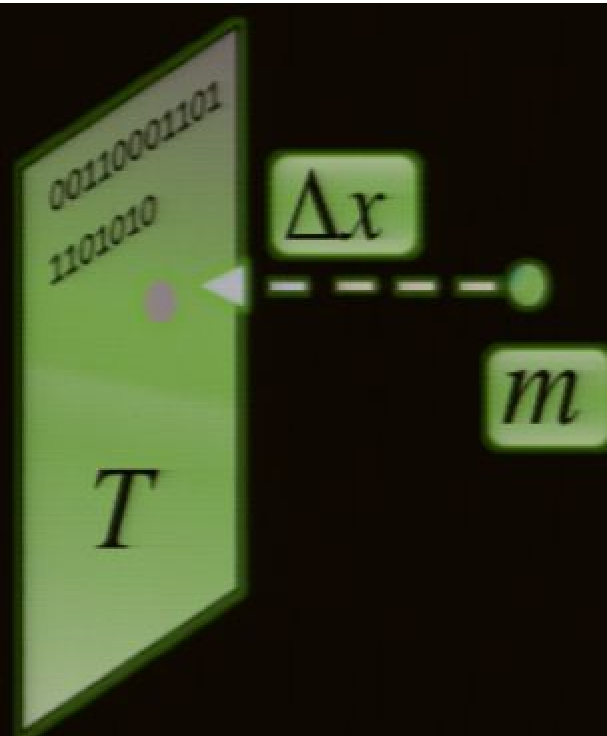
$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar} \Delta x$$

$$k_B T = \frac{1}{2\pi}\frac{\hbar a}{c}$$

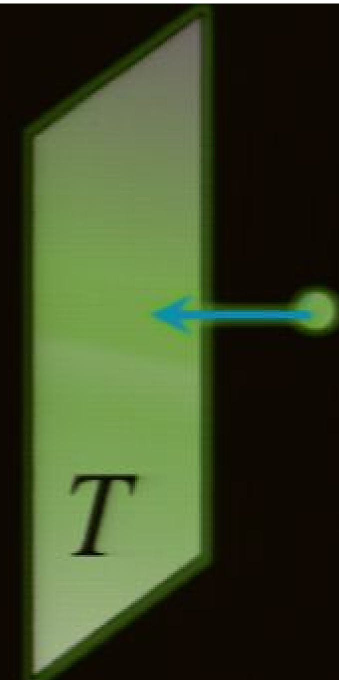


To get a force one needs a temperature.
By taking that temperature to be the Unruh temperature one finds Newton's law of inertia

$$F\Delta x = T\Delta S$$

$$F = ma$$

$$F = \frac{GMm}{R^2}$$



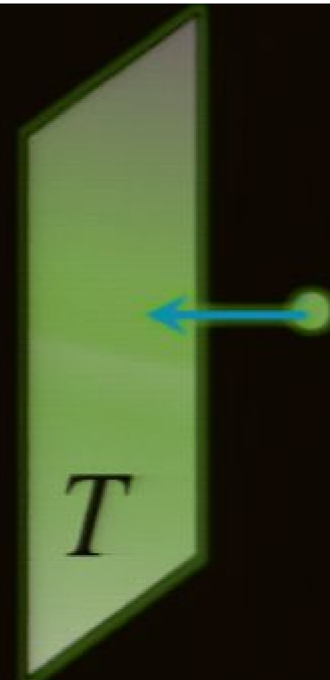
In order to get an entropic force I need a temperature

$$\tfrac{1}{2} k_B T = Mc^2 / \ \# bits$$

$$E = Mc^2$$

$$\# \ bits = \frac{Ac^3}{G\hbar}$$

$$F\Delta x = T\Delta S$$



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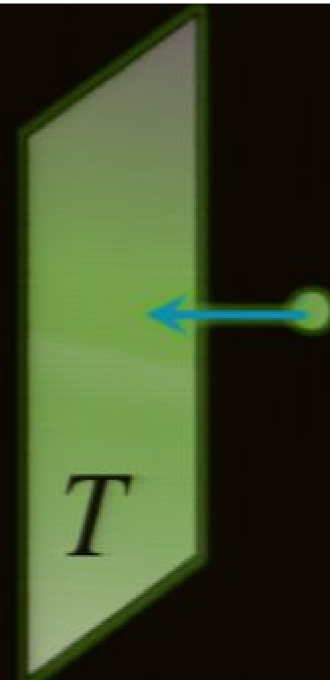

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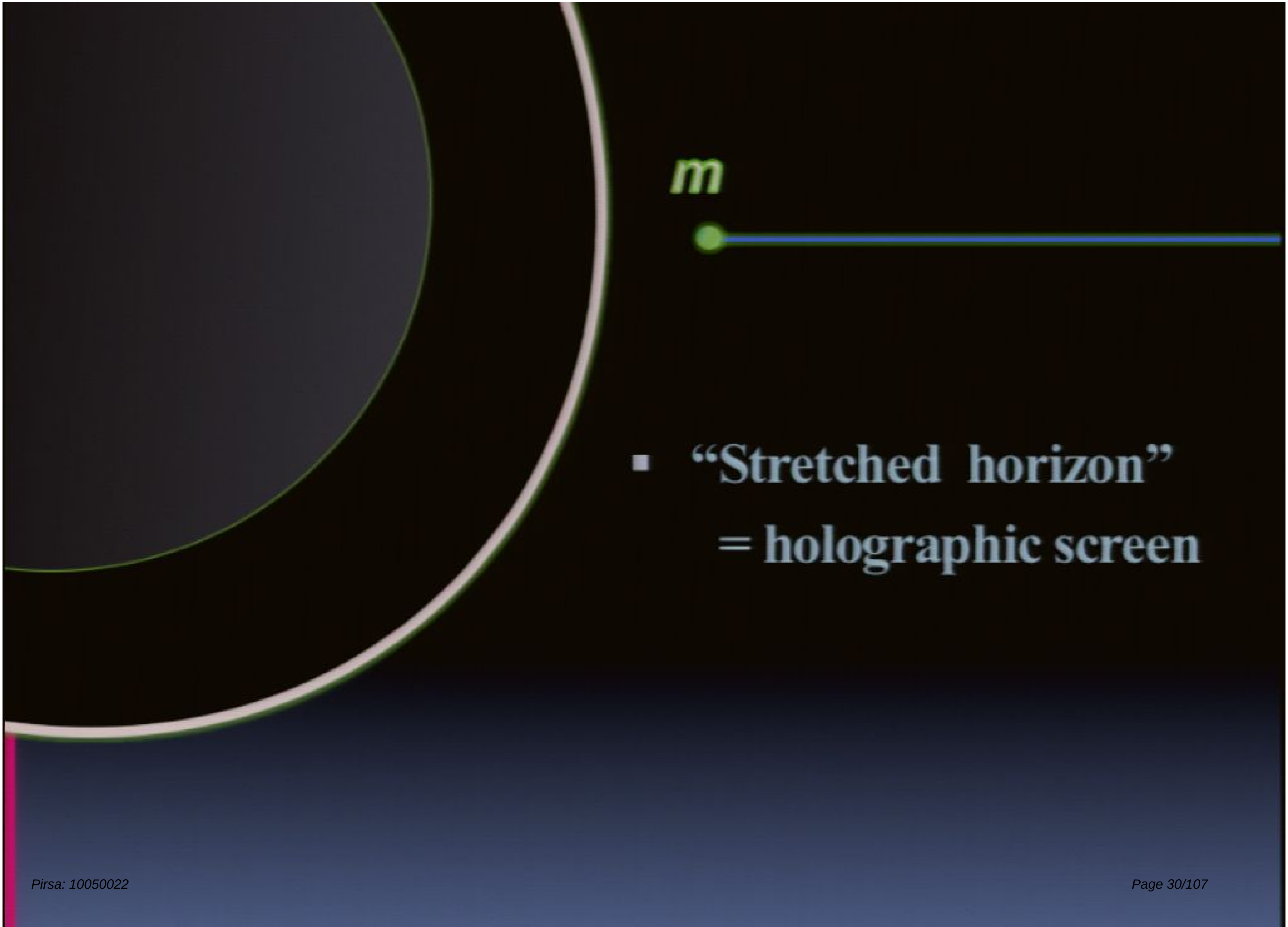
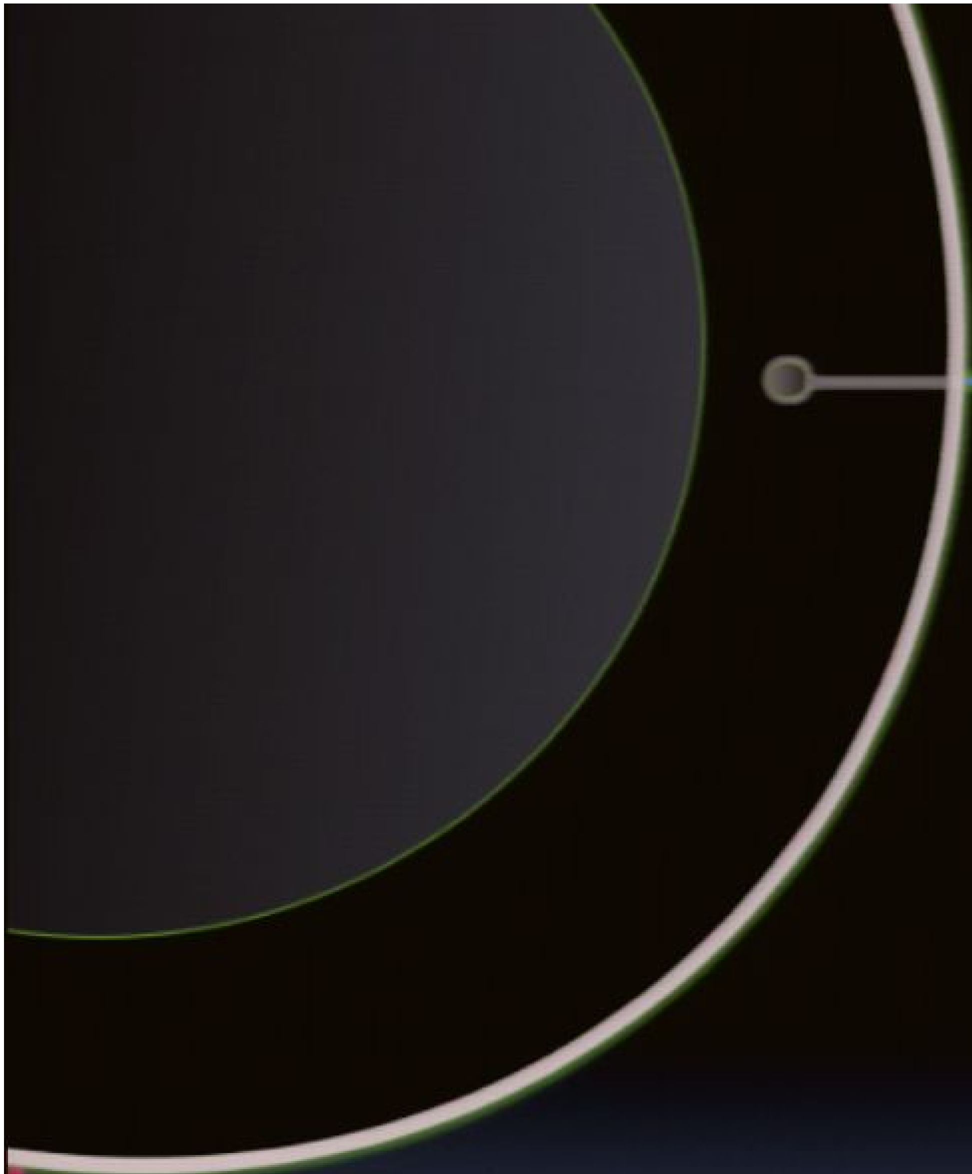
This was just heuristic

- The presented argument is based on dimensional analysis.
- I reversed the logic that led to the holographic principle.
- The main statement is new and essential:

GRAVITY IS AN ENTROPIC FORCE.

- Does it hold for arbitrary location of the screen?
- Or is it valid only near black hole horizons?

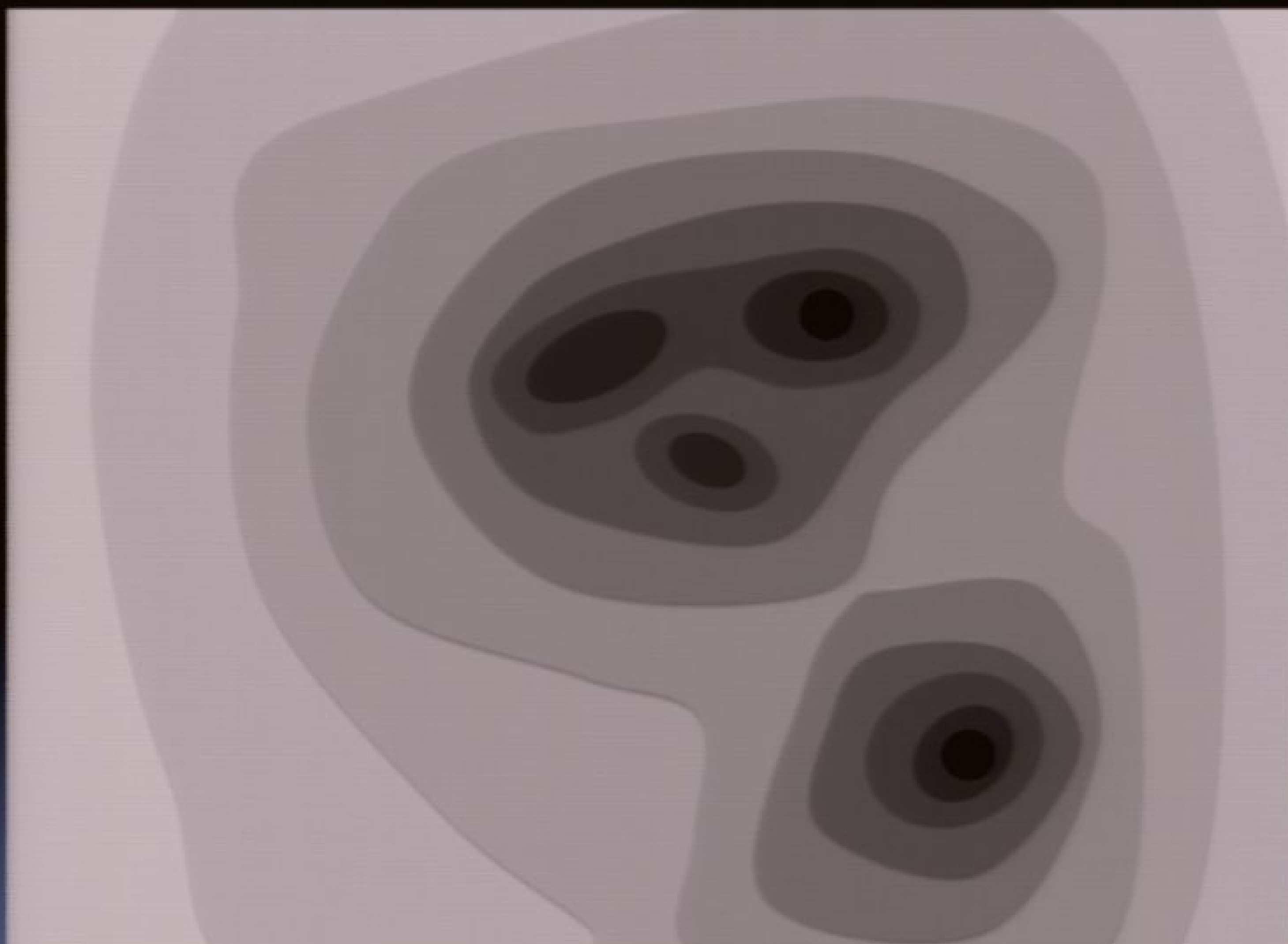

m
▪ "Stretched horizon"
= holographic screen



- What is the holographic description of lowering the particle beyond the screen?

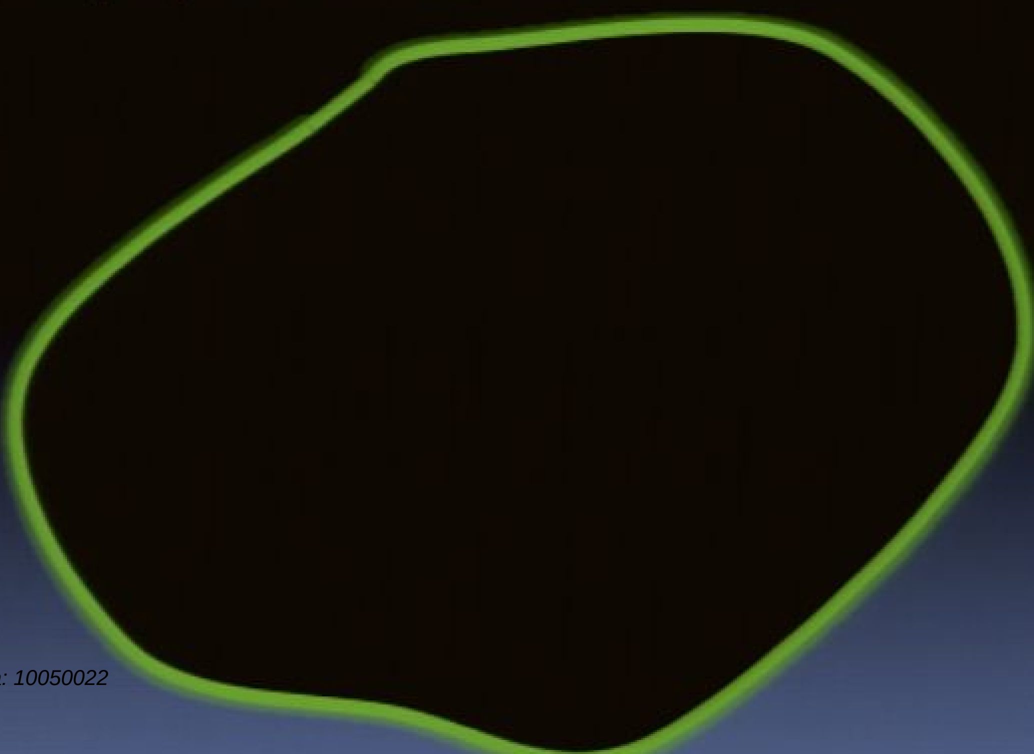
$$F\Delta x = T_H \Delta S_{BH}$$

Holographic screens at equipotential (= equal redshift) surfaces



General mass distribution

Equipotential surface



Gauss 's Law

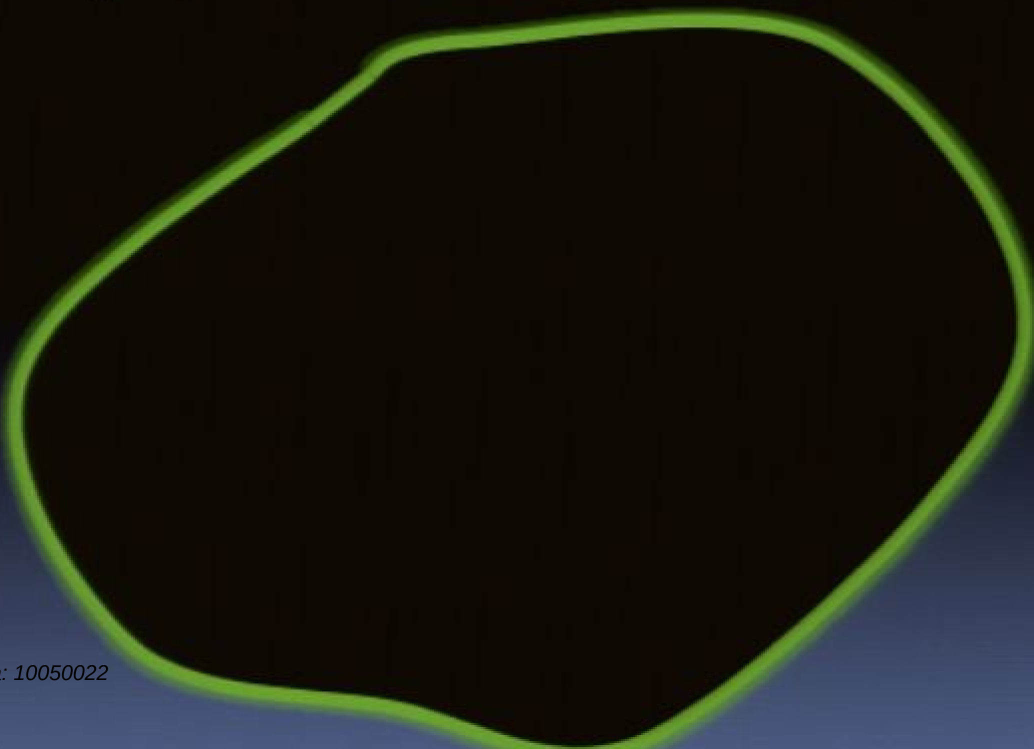
=> Poisson equation

General mass distribution

$$Mc^2 = \int k_B T \, dn$$

$$k_B T = \frac{1}{2\pi} \frac{\hbar}{c} \nabla \Phi$$

Equipotential surface



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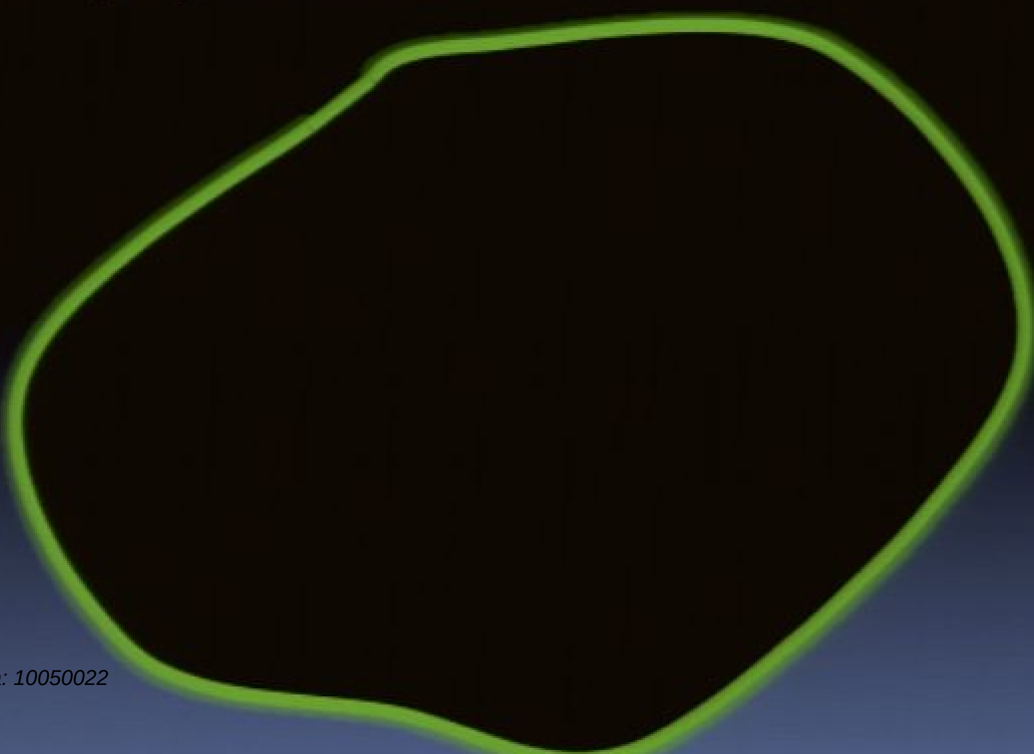
$$dn = \frac{c^3}{G\hbar} dA$$



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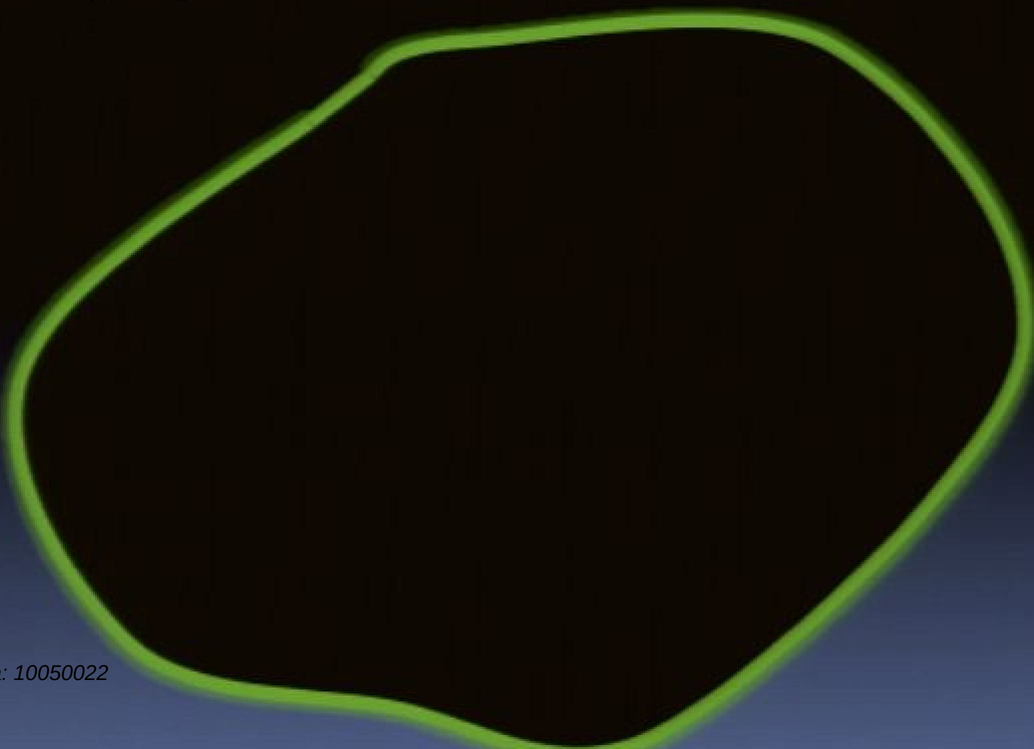


$$\int \nabla\Phi dA = 8\pi G M$$

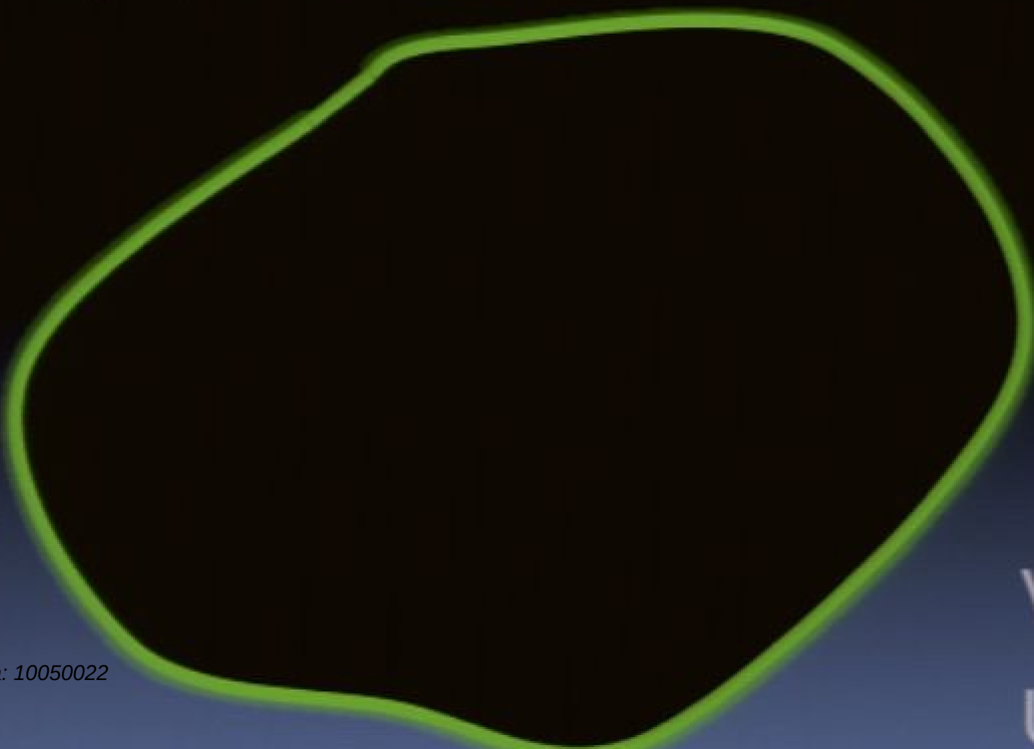
Gauss 's Law

=> Poisson equation

General mass distribution

$$ {}_i\partial r_i = J $$

Equipotential surface



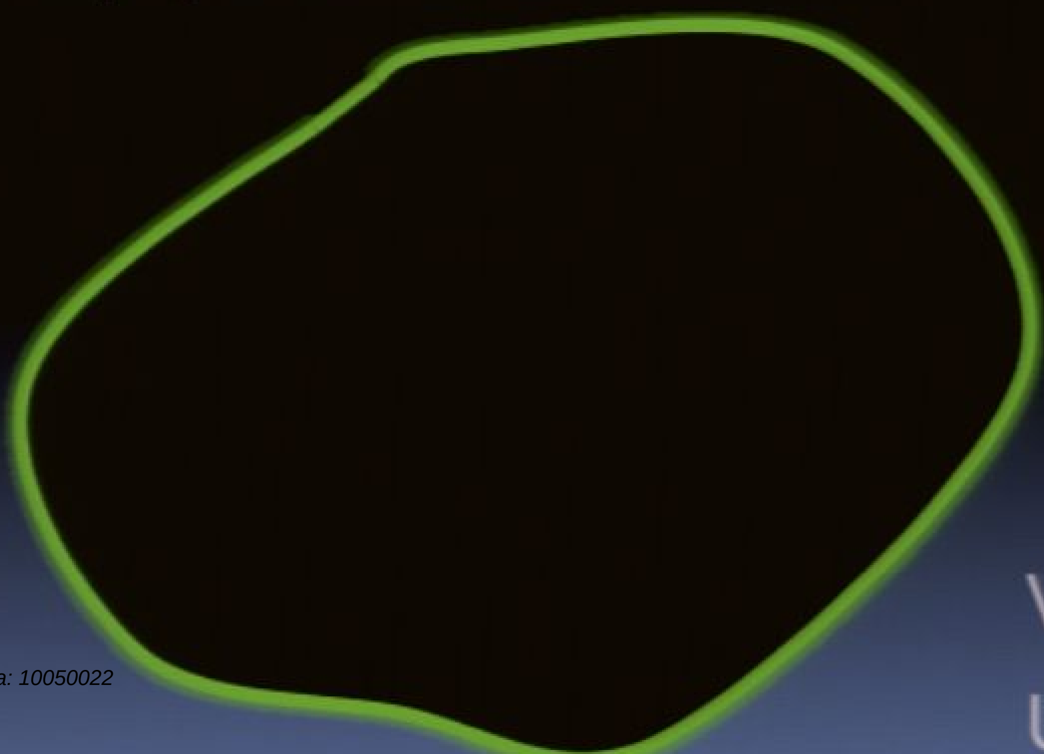
Virtual displacement

Use electrostatic analogy

General mass distribution

$$\sum_i F_i \delta r_i = \int T \delta s$$

Equipotential surface



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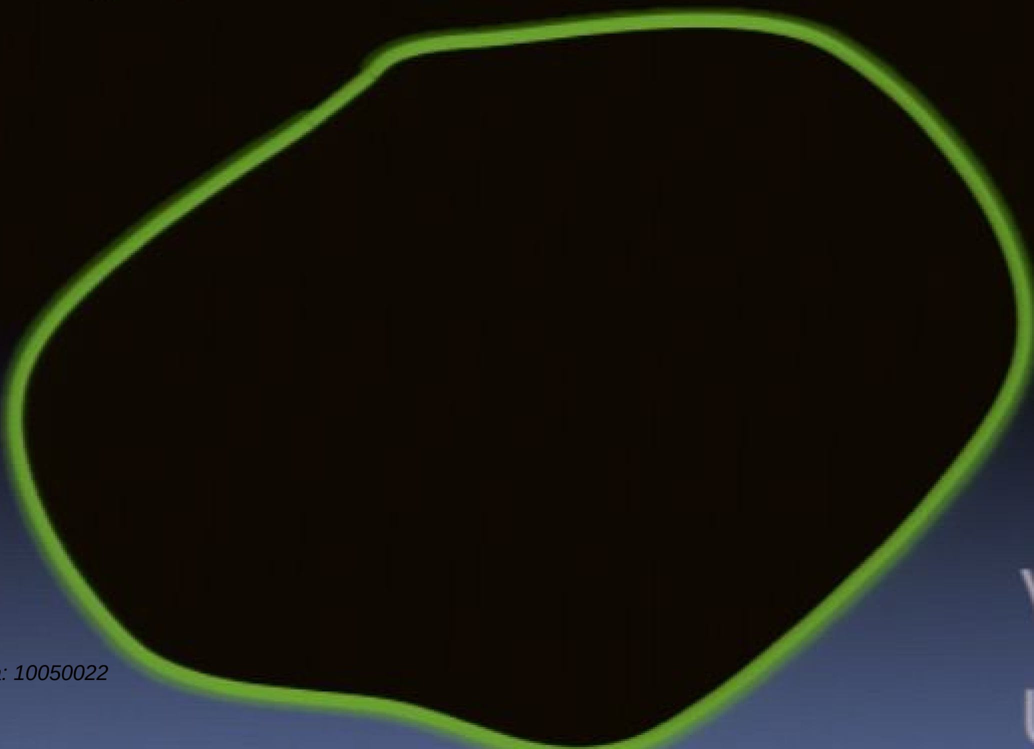
$$= \frac{k_B c}{\ldots}$$

Equipotential surface



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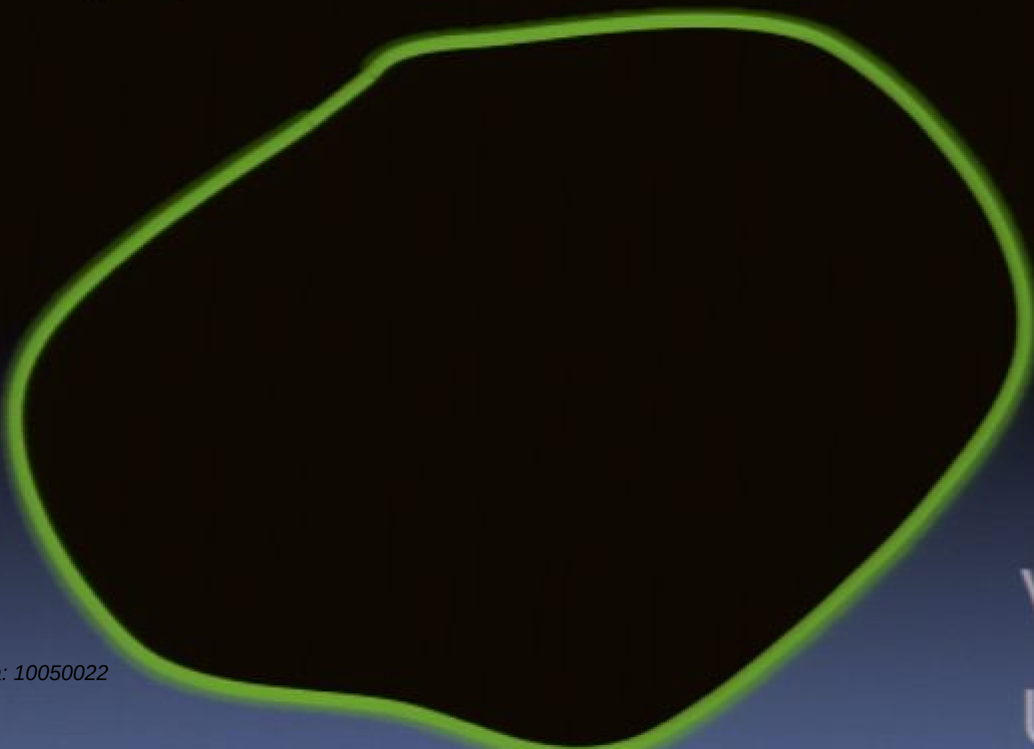
$$\delta s = \frac{k_B c}{2G\hbar} \delta \Phi$$

Equipotential surface



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What about General Relativity?

Surface of constant redshift

Komar mass

=> Einstein equation

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Surface of constant redshift

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What about General Relativity?

- Choose approximate local timelike Killing vector

$$\int \nabla \Phi \, dA = 8\pi G M$$

Komar mass

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What about General Relativity?

$$\int R_{ab}\xi^a n^b = 8\pi G\int\left(T_{ab} - \tfrac{1}{2}g_{ab}T\right)\xi^a n^b$$

- Choose approximate local timelike Killing vector

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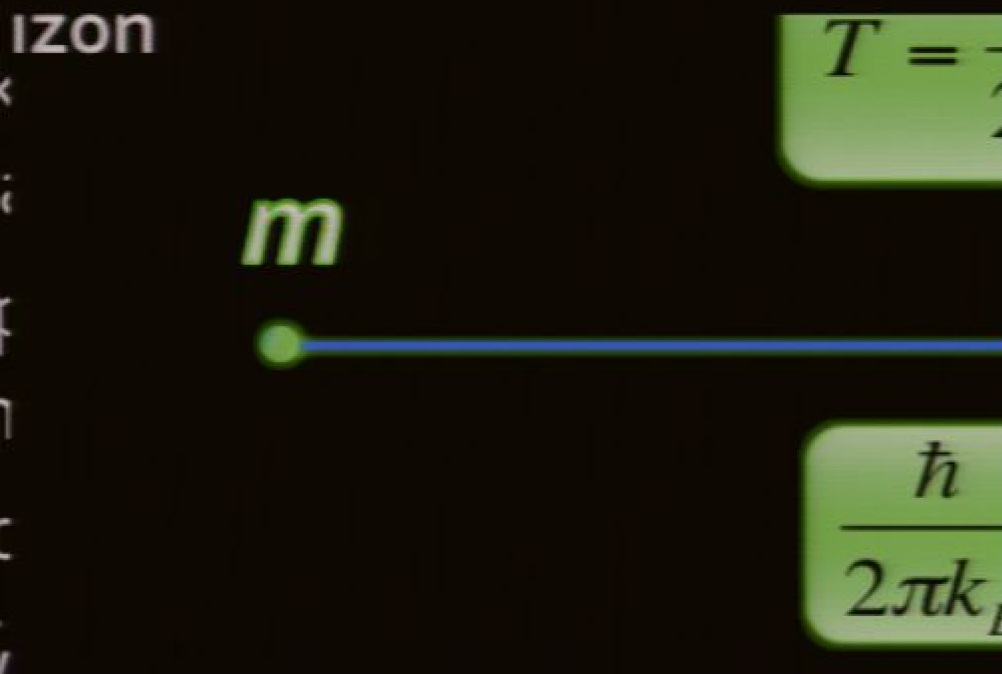
An invariance (or ambiguity).

- Planck 

drop out of the gr…
- Their p… nt to the argum…
- They c… ensionless factor, … actor (normalized Newton potential).
- This makes the argment robust. But can one fix this freedom?

An invariance (or ambiguity).

- Planck constant and c eventually drop out of the graviational force.
- Their precise values seem irrelevant to the argument.
- They can be multiplied by any dimensionless factor, or function of the redshift factor (normalized Newton potential).
- This makes the argment robust. But can one fix this freedom?

$$T \nabla_x S = ma$$

Rindler Horizon

$$T = \frac{\hbar}{2\pi k_B} \frac{a}{c}$$

m

$$\frac{\hbar}{2\pi k_B} \frac{dS}{dx} = mc$$

Suggestive link with QM:

$$c \longrightarrow v$$

What is this velocity v?

Equipotential surface

$$\Phi = \frac{v^2}{2}$$

$$T = \frac{\hbar}{2\pi k_B}\frac{dv}{dx}$$

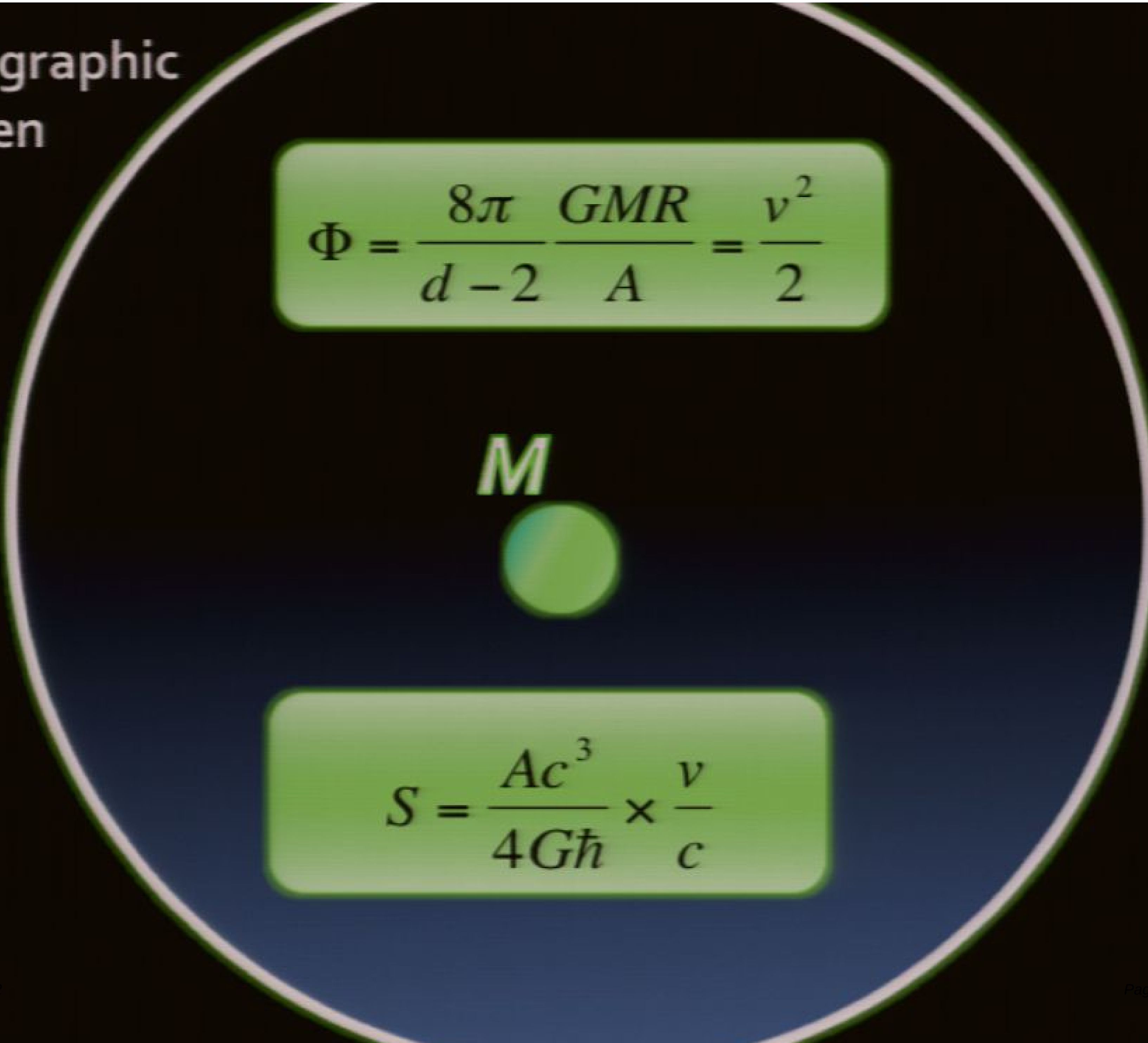
m

$$\frac{\hbar}{2\pi k_B}\nabla_x S = mv$$

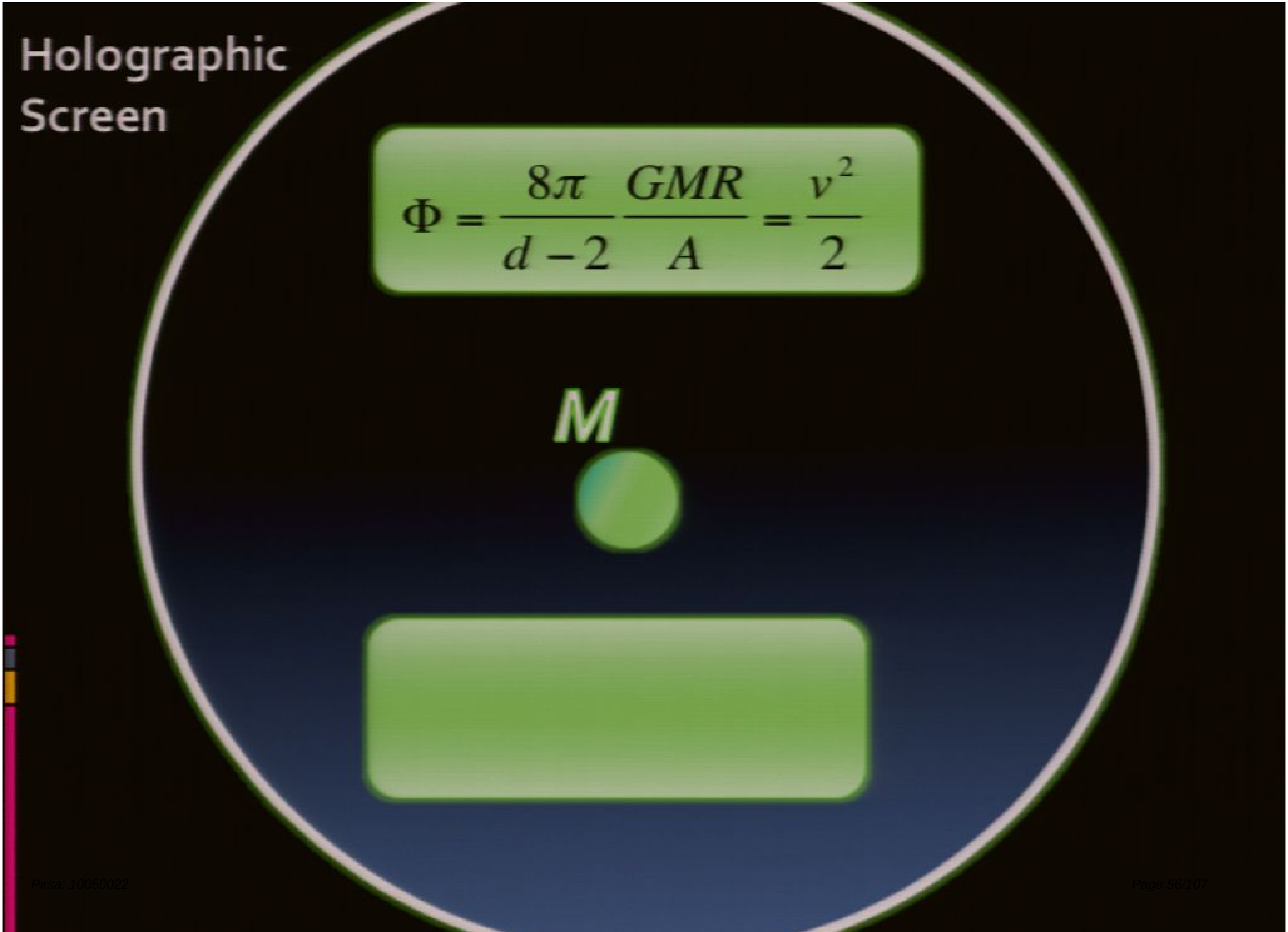
v = escape velocity

Holographic Screen

$$\Phi = \frac{8\pi}{d-2}\frac{GMR}{A} = \frac{v^2}{2}$$



$$S = \frac{Ac^3}{4G\hbar} \times \frac{v}{c}$$


Holographic
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Gravity as an Emergent Force

- At a microscopic scale Nature is described by many degrees of freedom. The precise nature of these and their dynamics are not important for the macroscopic physics.
- Gravity arises due to the fact that the amount of "information" (e.g. phase space volume) of the microscopic degrees of freedom is influenced by the macroscopic observable positions of material objects.
- "Gravity is the cost of moving information around"

Holographic Screen

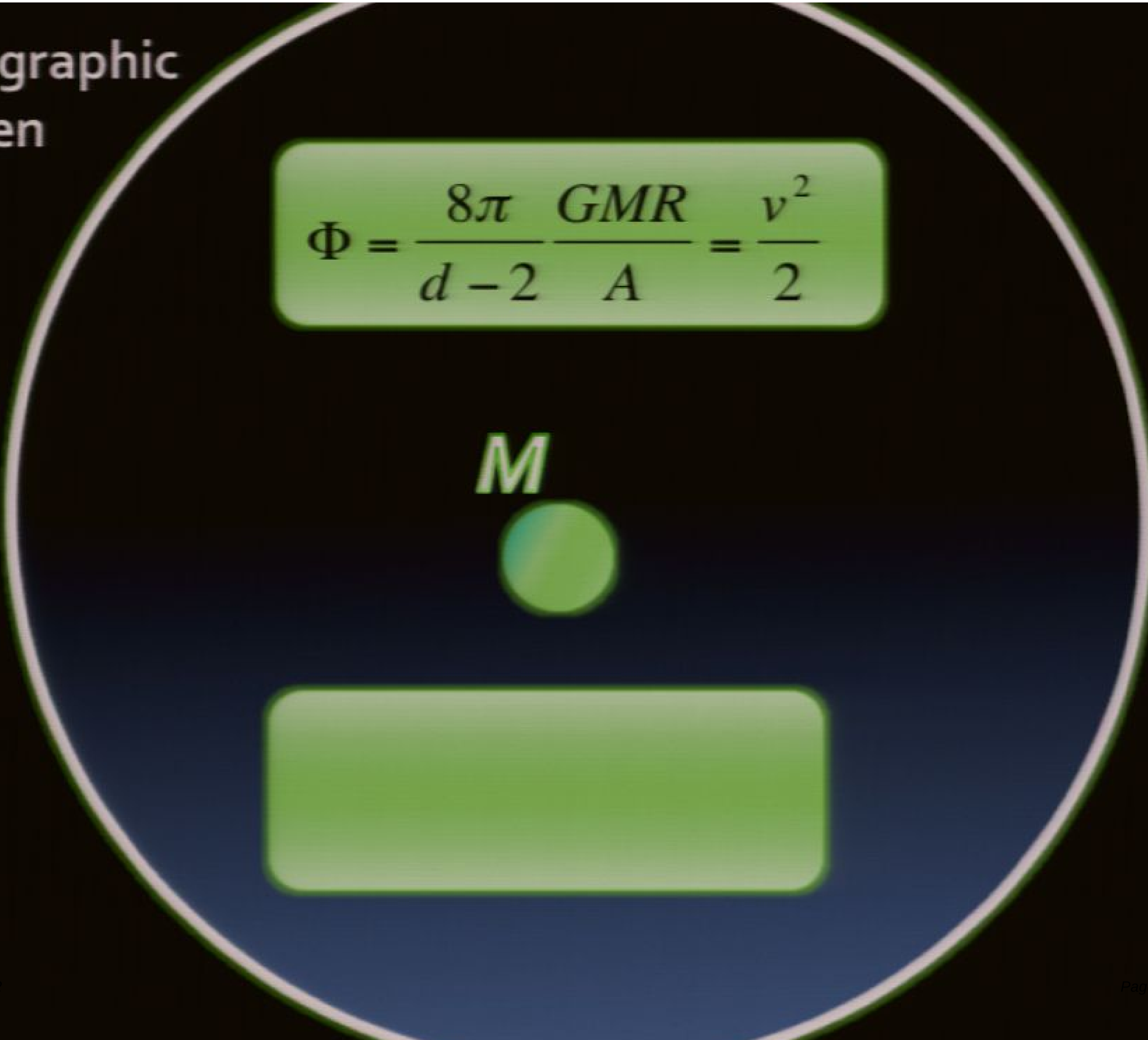
$$\Phi = \frac{8\pi}{d-2}\frac{GMR}{A} = \frac{v^2}{2}$$

M

$$S = \sqrt{2\pi \frac{Ac^3}{4G\hbar} \times \frac{ER}{\hbar c}}$$

Holographic Screen

$$\Phi = \frac{8\pi}{d-2}\frac{GMR}{A} = \frac{v^2}{2}$$



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$$S = \sqrt{2\pi \frac{Ac^3}{4G\hbar} \times \frac{ER}{\hbar c}}$$

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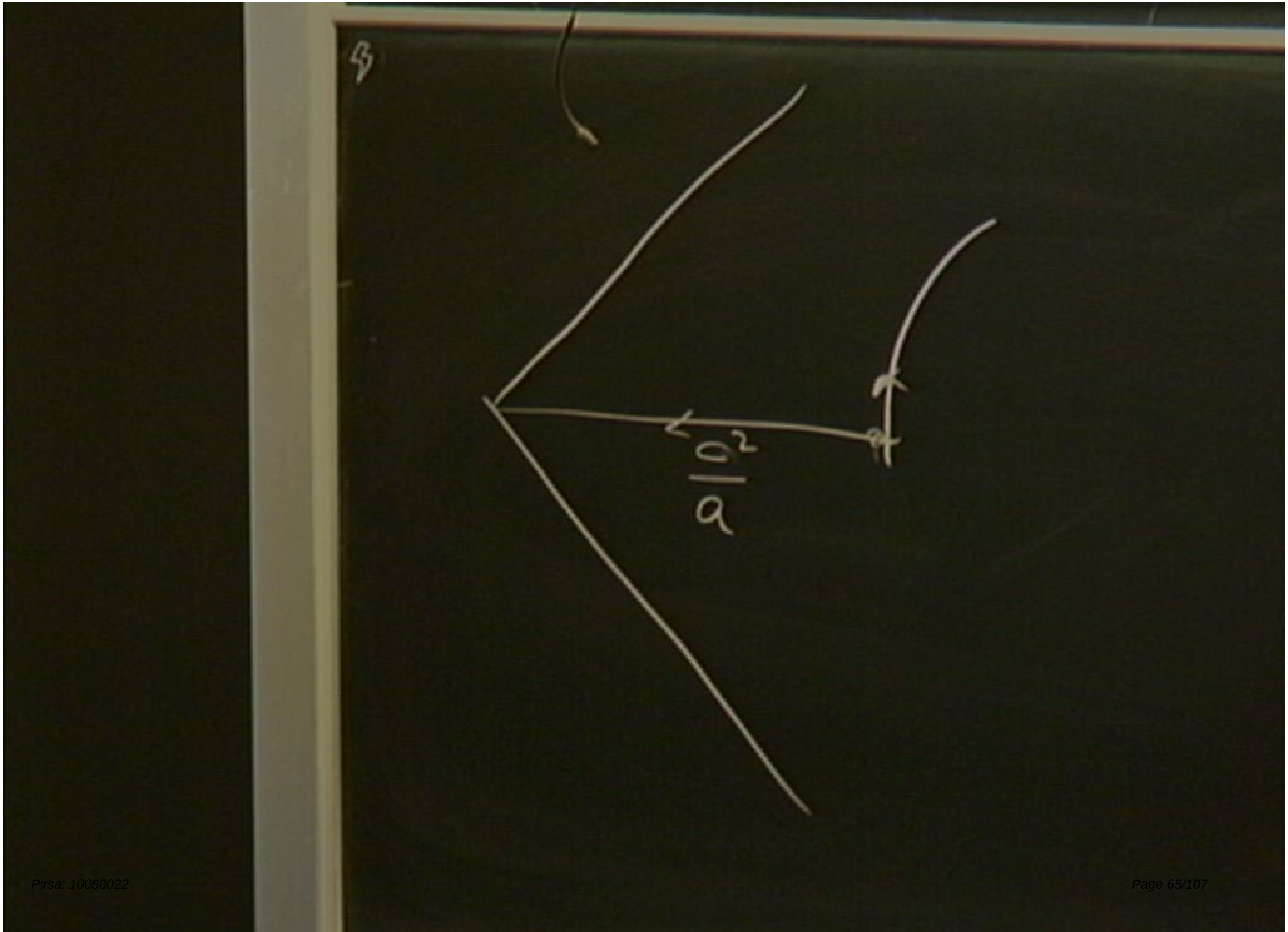
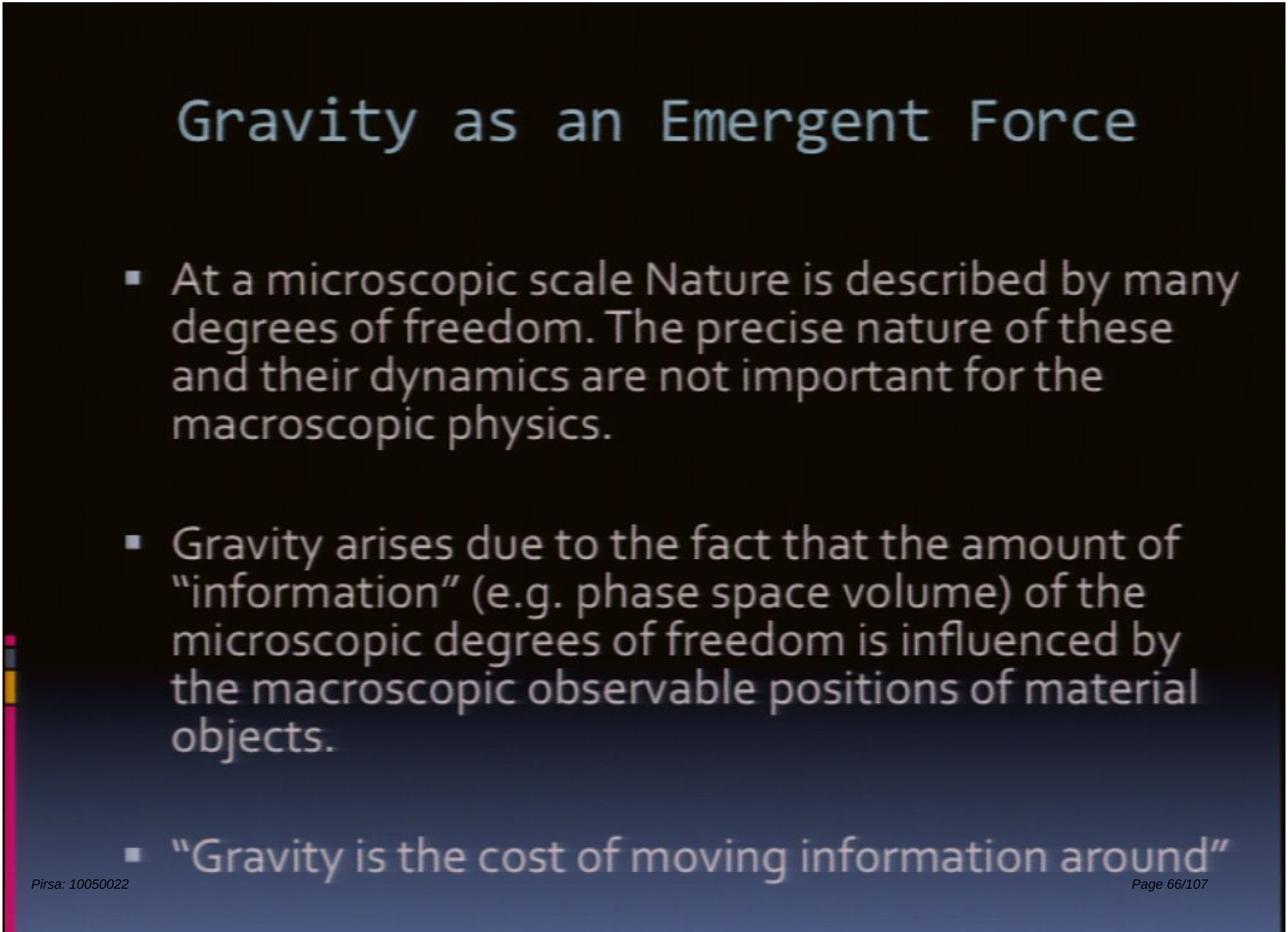
$$2\pi \frac{Ac}{}$$

Gravity as an Emergent Force

- At a microscopic scale Nature is described by many degrees of freedom. The precise nature of these and their dynamics are not important for the macroscopic physics.
- Gravity arises due to the fact that the amount of "information" (e.g. phase space volume) of the microscopic degrees of freedom is influenced by the macroscopic observable positions of material objects.
- "Gravity is the cost of moving information around"


$\frac{c^2}{a}$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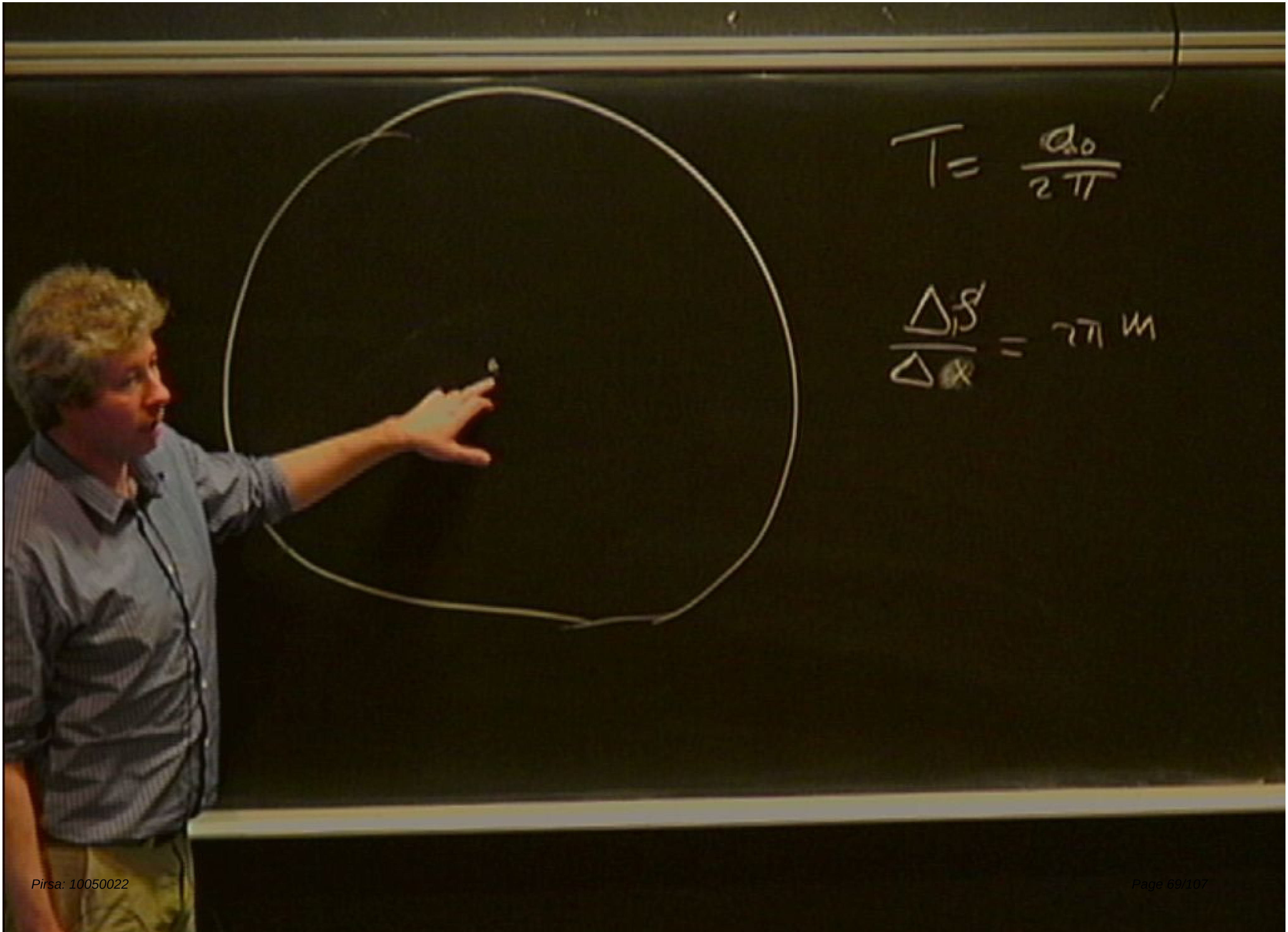
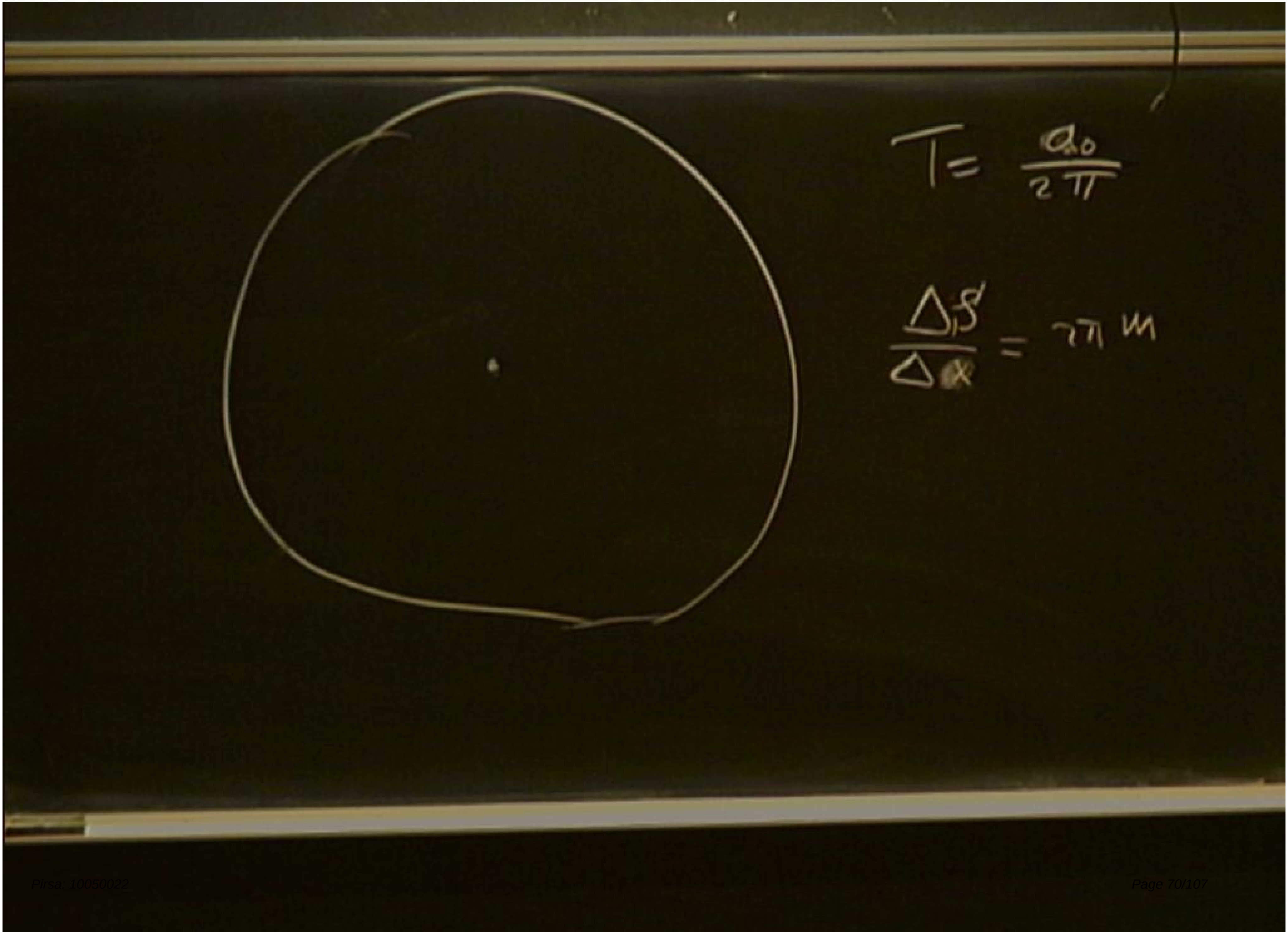

T = a0/2π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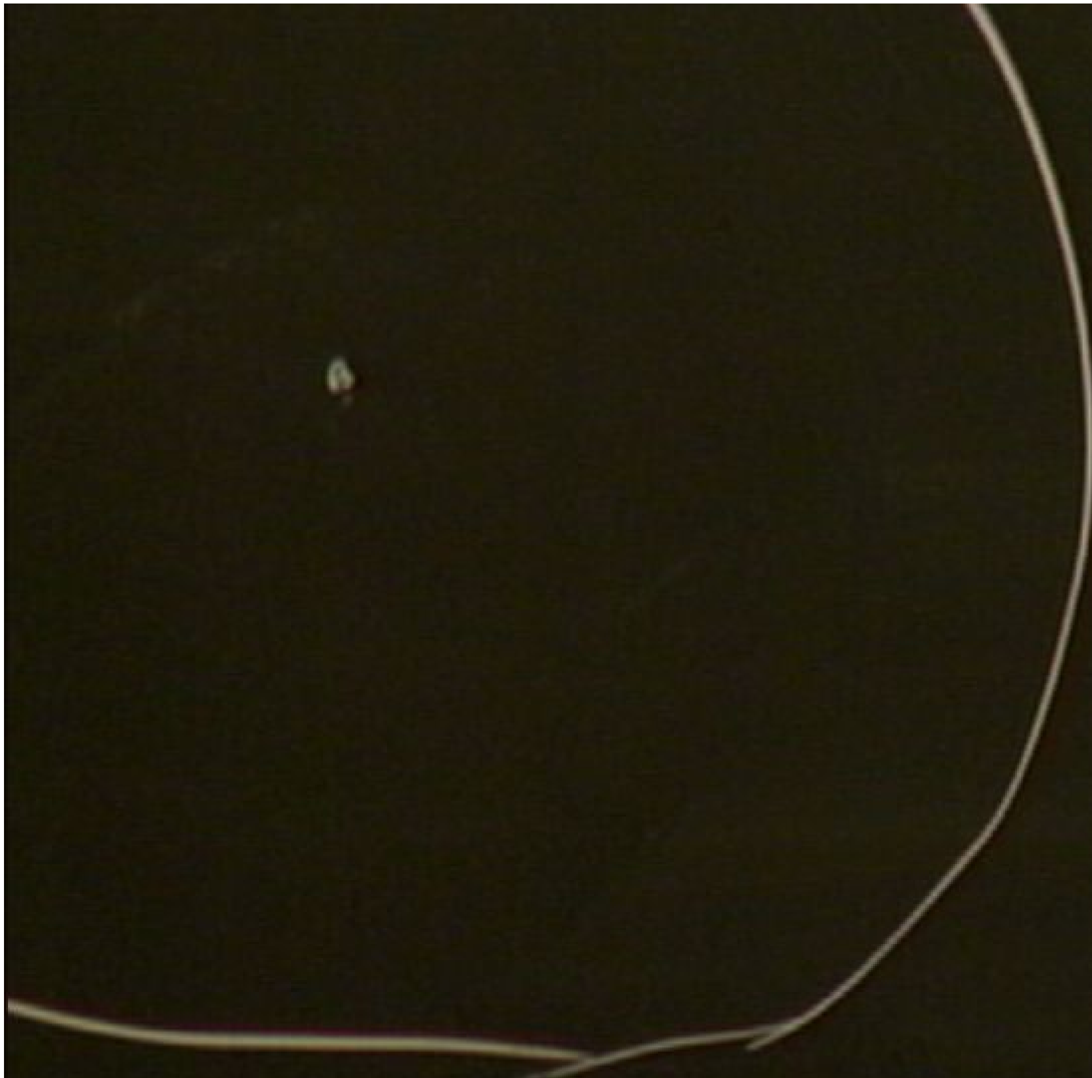

$$\frac{\Delta_i \delta}{\Delta x} = 2\pi m$$

$$T = \frac{\sqrt{a^2 + a_0^2}}{2\pi}$$

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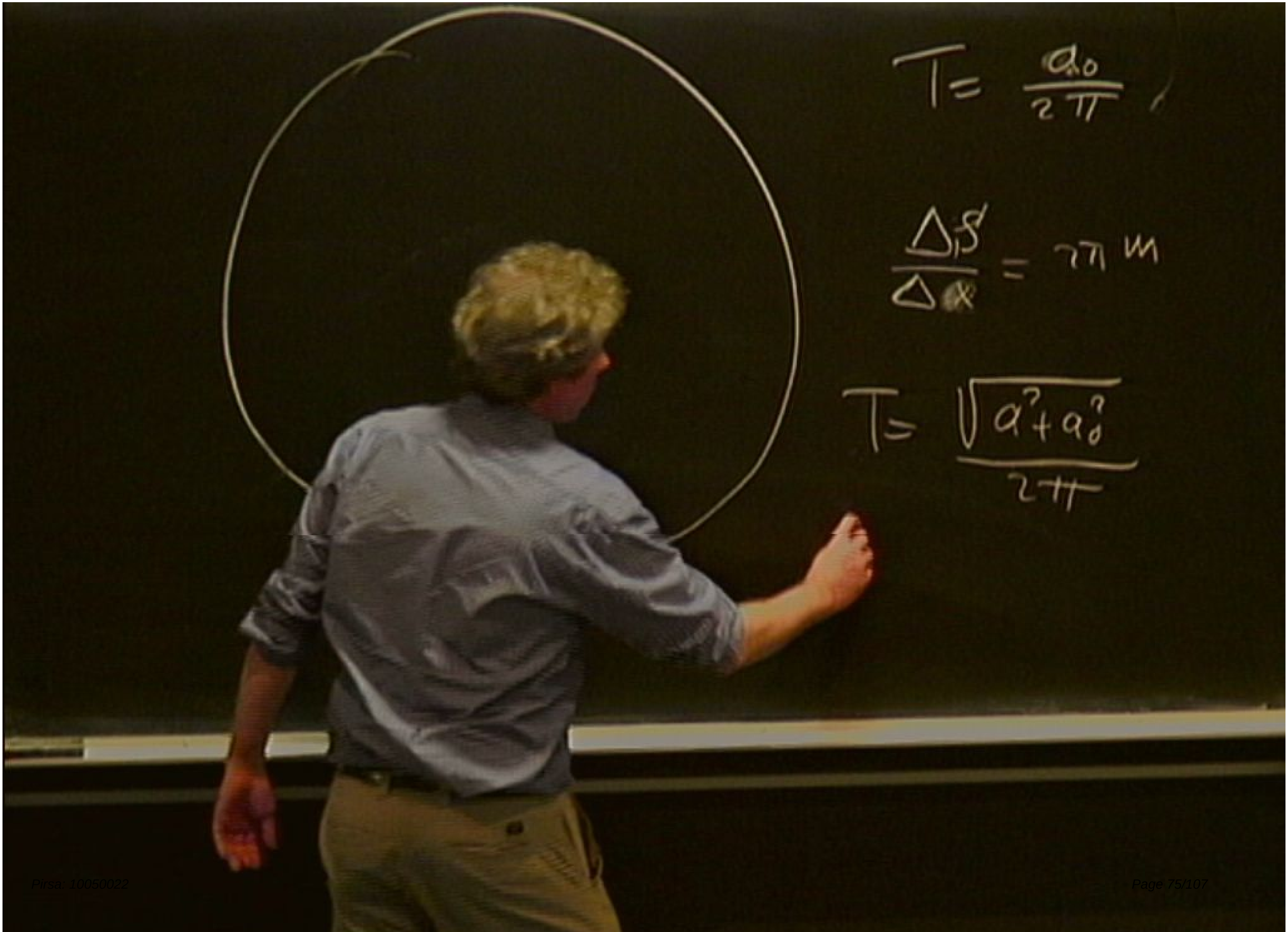

$T = \frac{a_0}{2\pi}$
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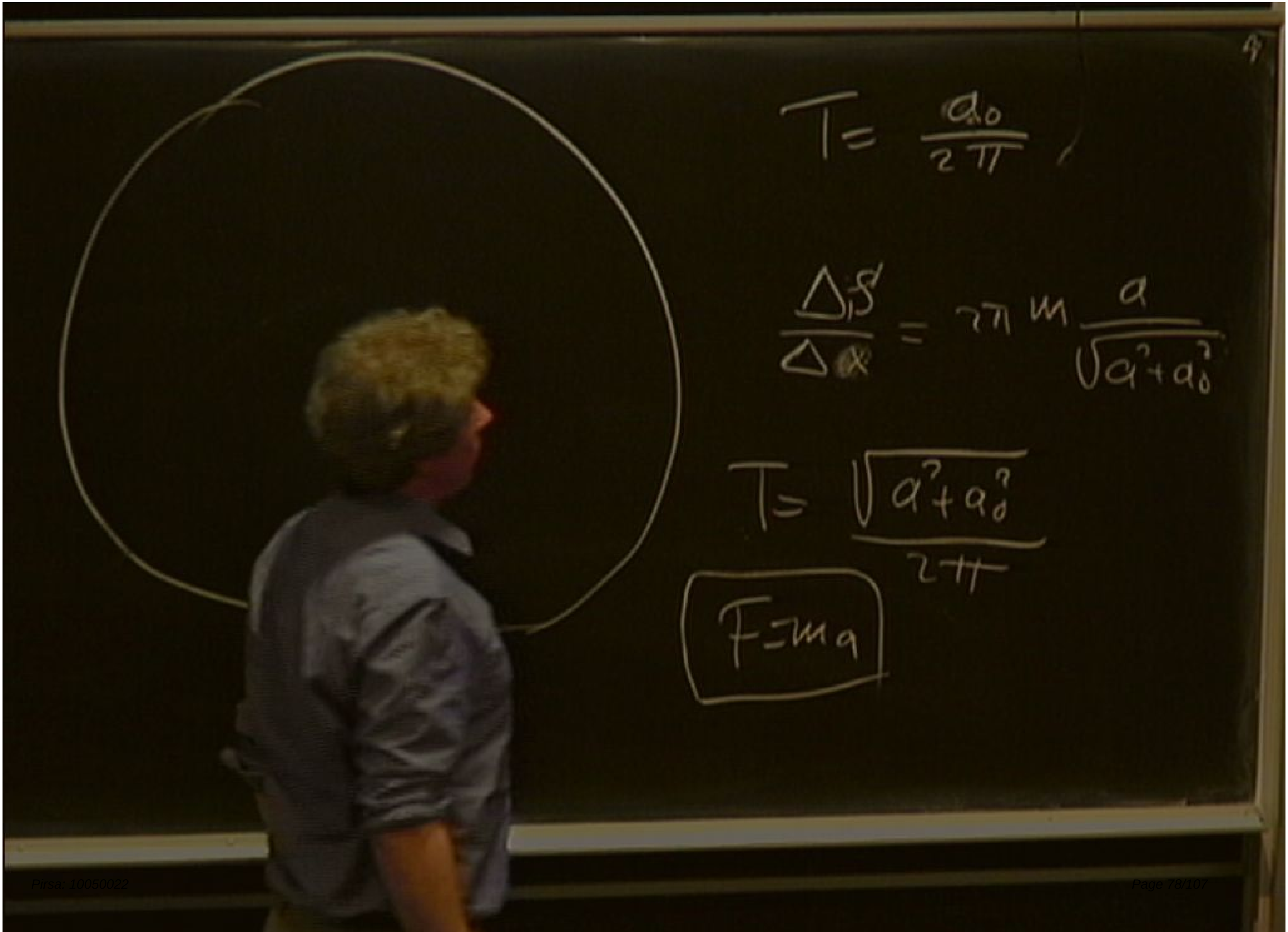
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Δs / Δx = 2π m a / √(a² + a0²)
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F = ma

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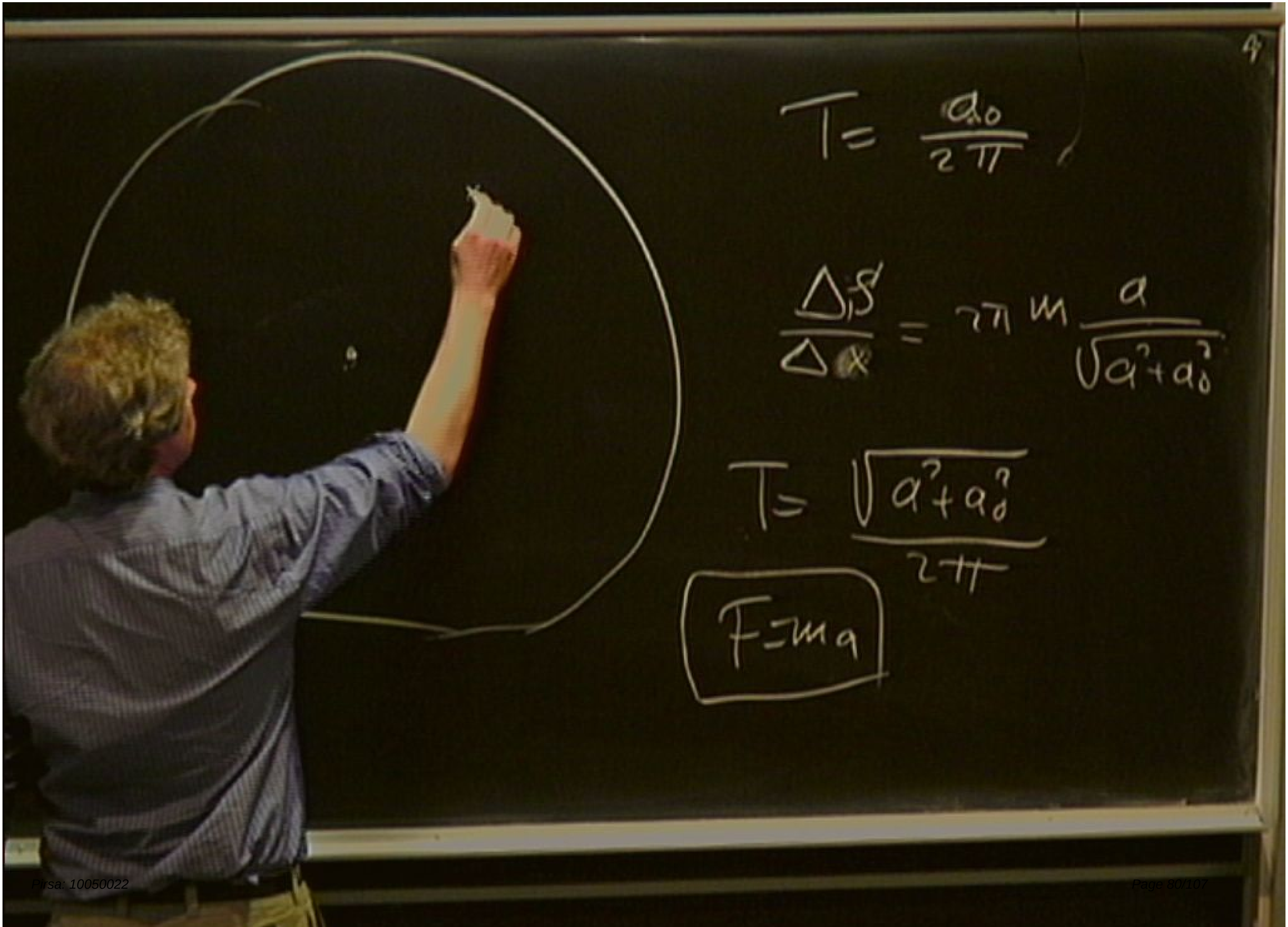
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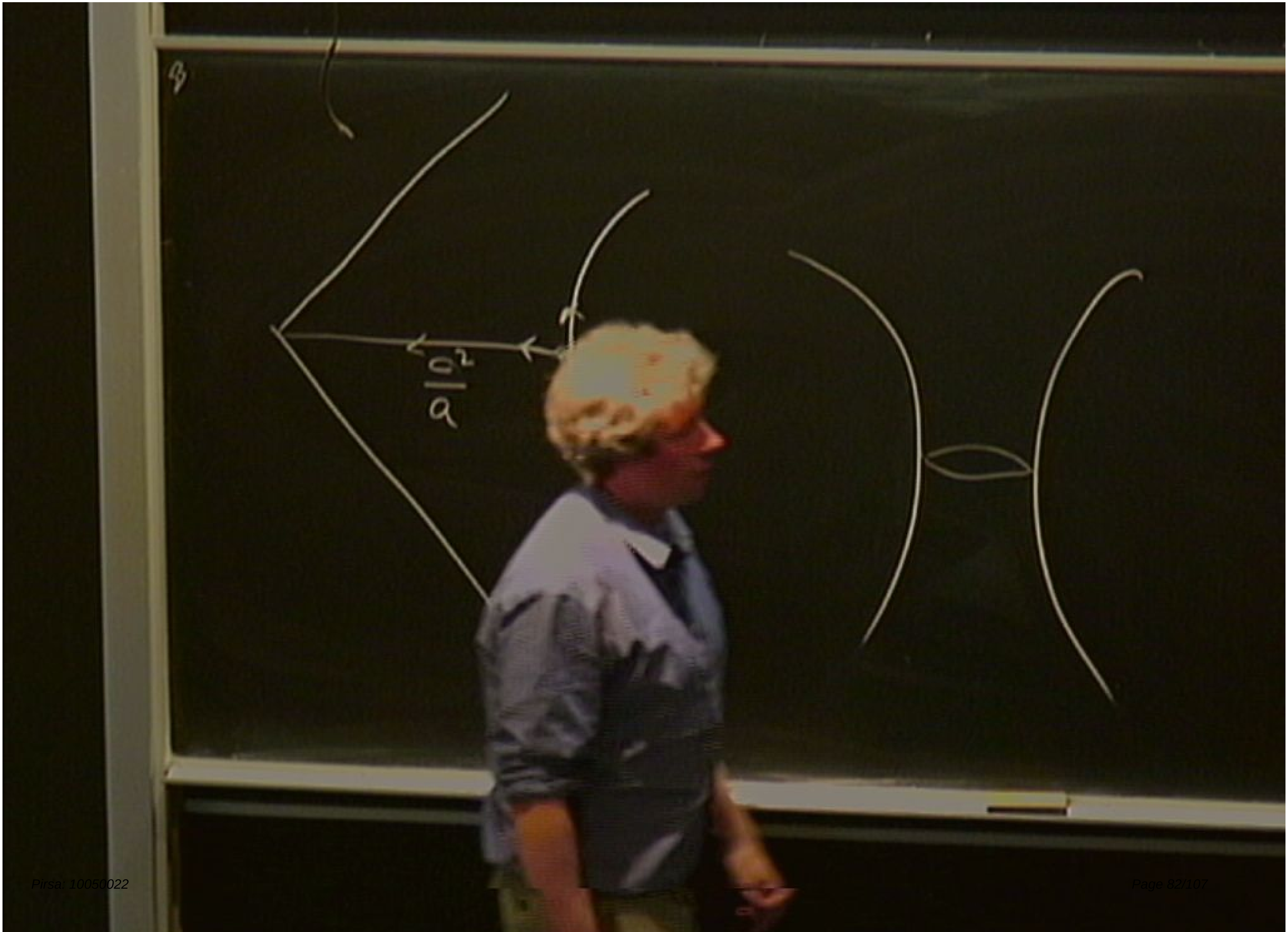
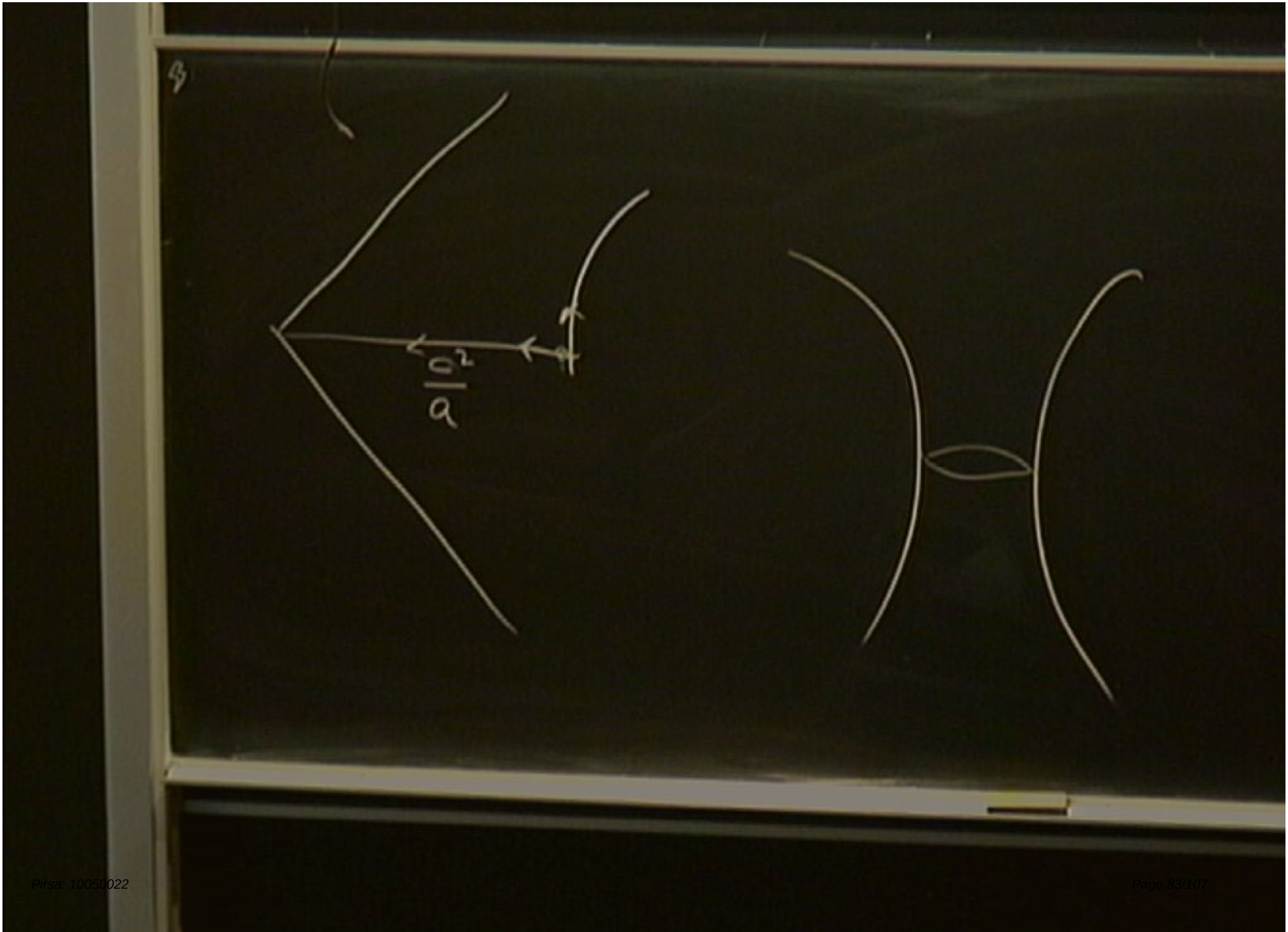

$\frac{a^2}{a}$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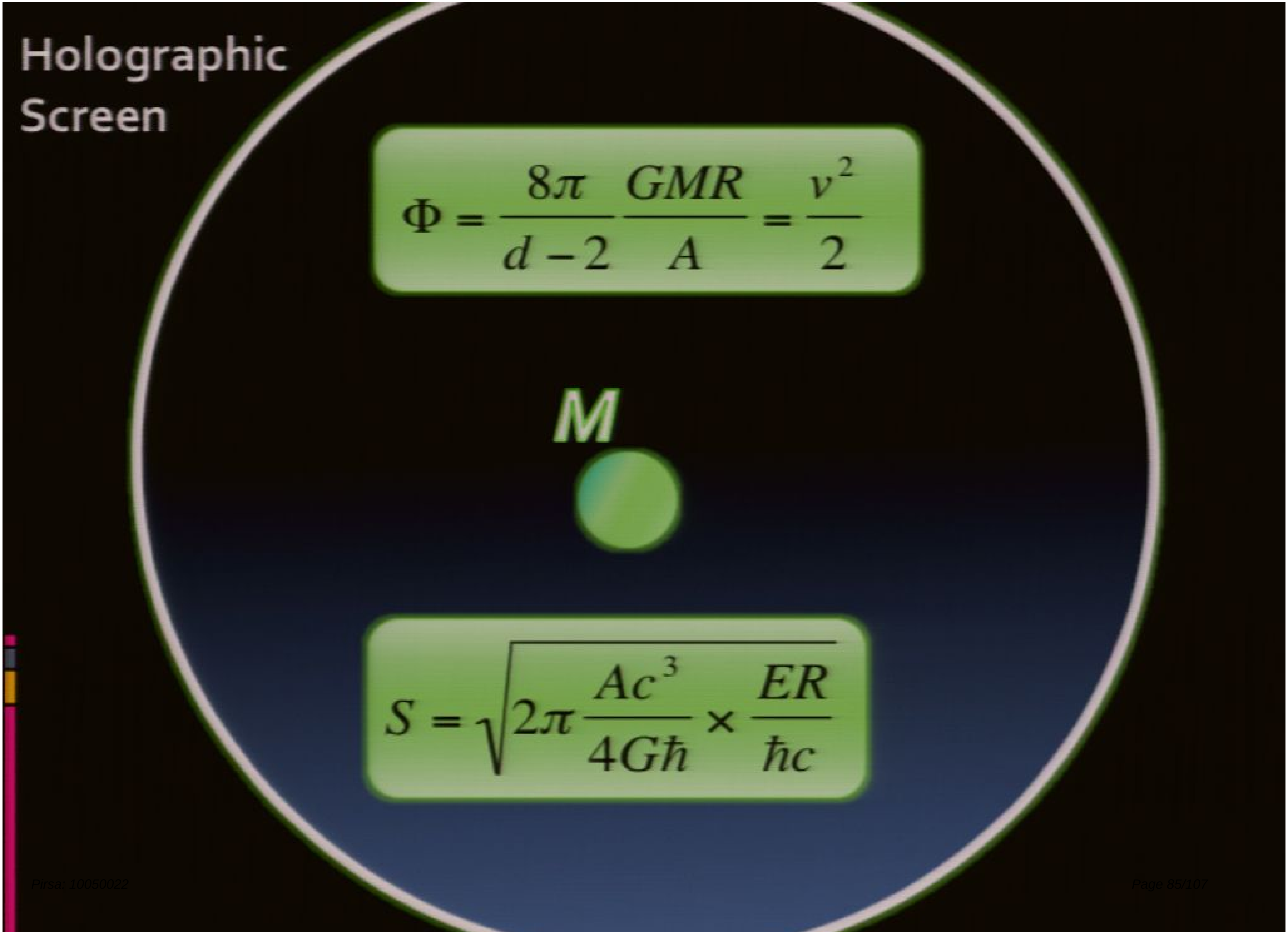
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Equipotential surface

$$\Phi = \frac{v^2}{2}$$

$$T = \frac{\hbar}{2\pi k_B} \frac{dv}{dx}$$

m

$$\frac{\hbar}{2\pi k_B} \nabla_x S = mv$$

v = escape velocity

$$T\nabla_x S = ma$$

Rindler Horizon

$$T = \frac{\hbar}{2\pi k_B}\frac{a}{c}$$

m

$$\frac{\hbar}{2\pi k_B}\frac{dS}{dx} = mc$$

Suggestive link with QM:

$$c \longrightarrow v$$

What is this velocity v?

Equipotential surface

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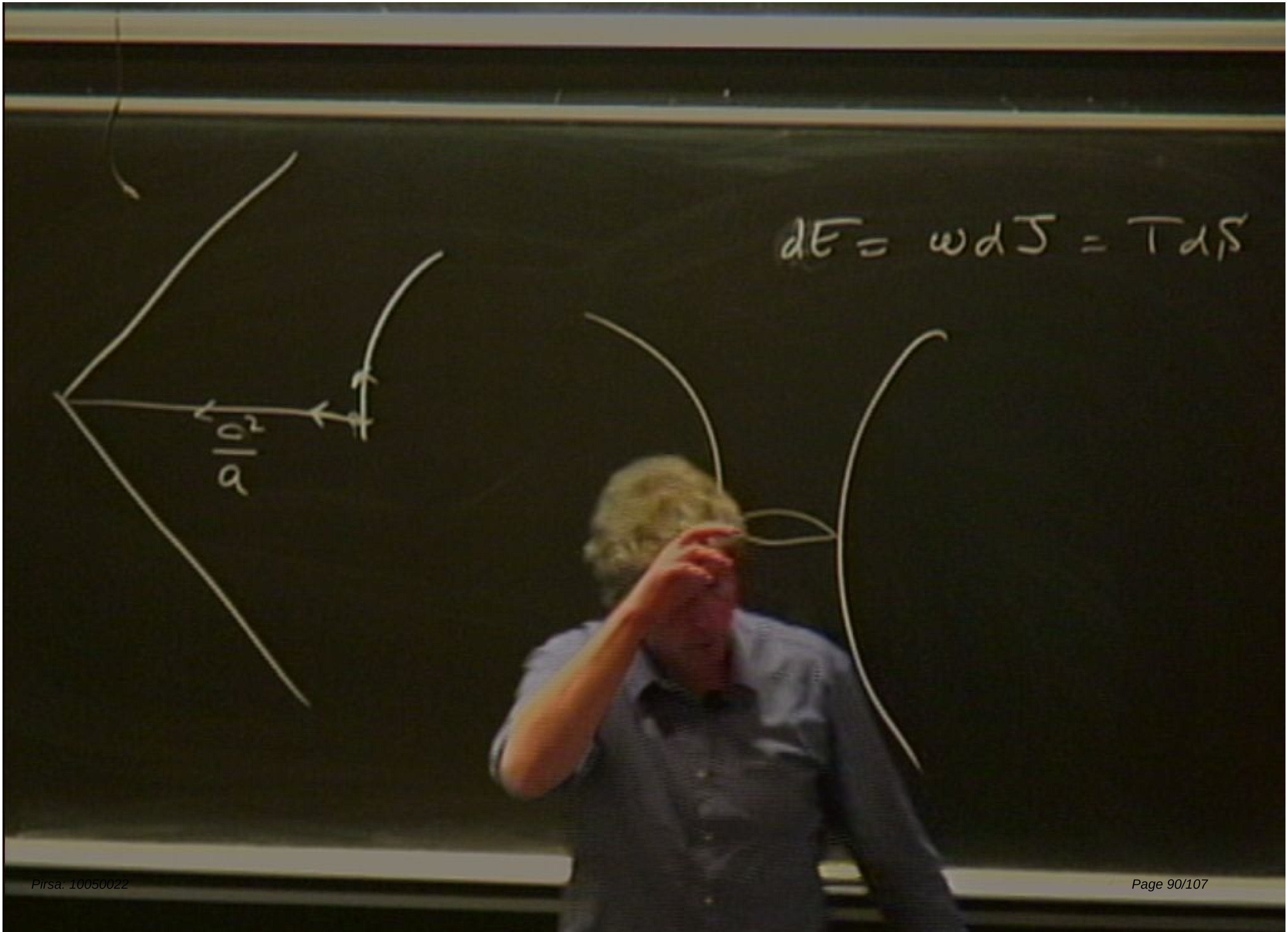
dE = ω dJ = T dS
c²/a

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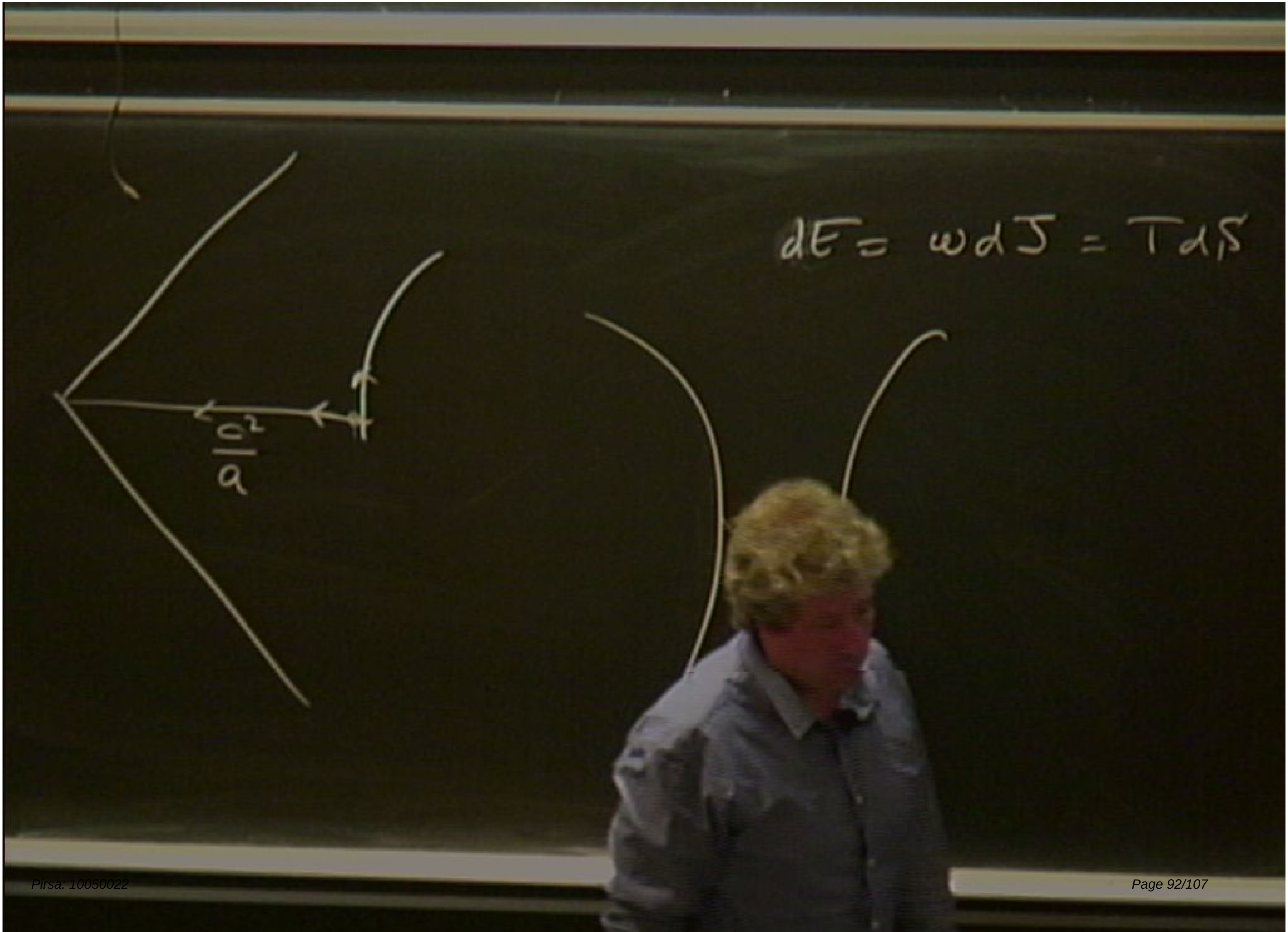
dE = ωdJ = TdS
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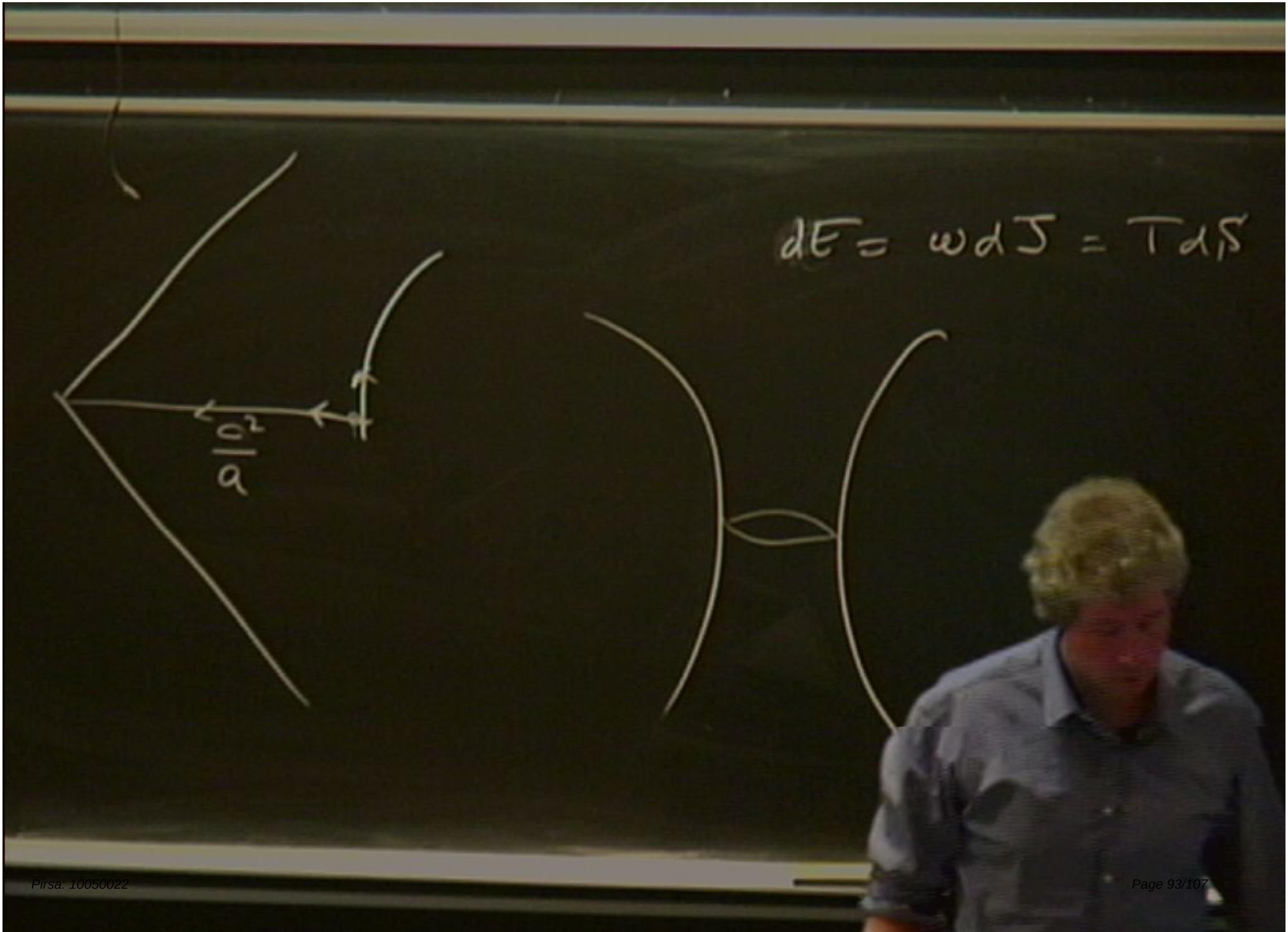
dE = ωdJ = TdS
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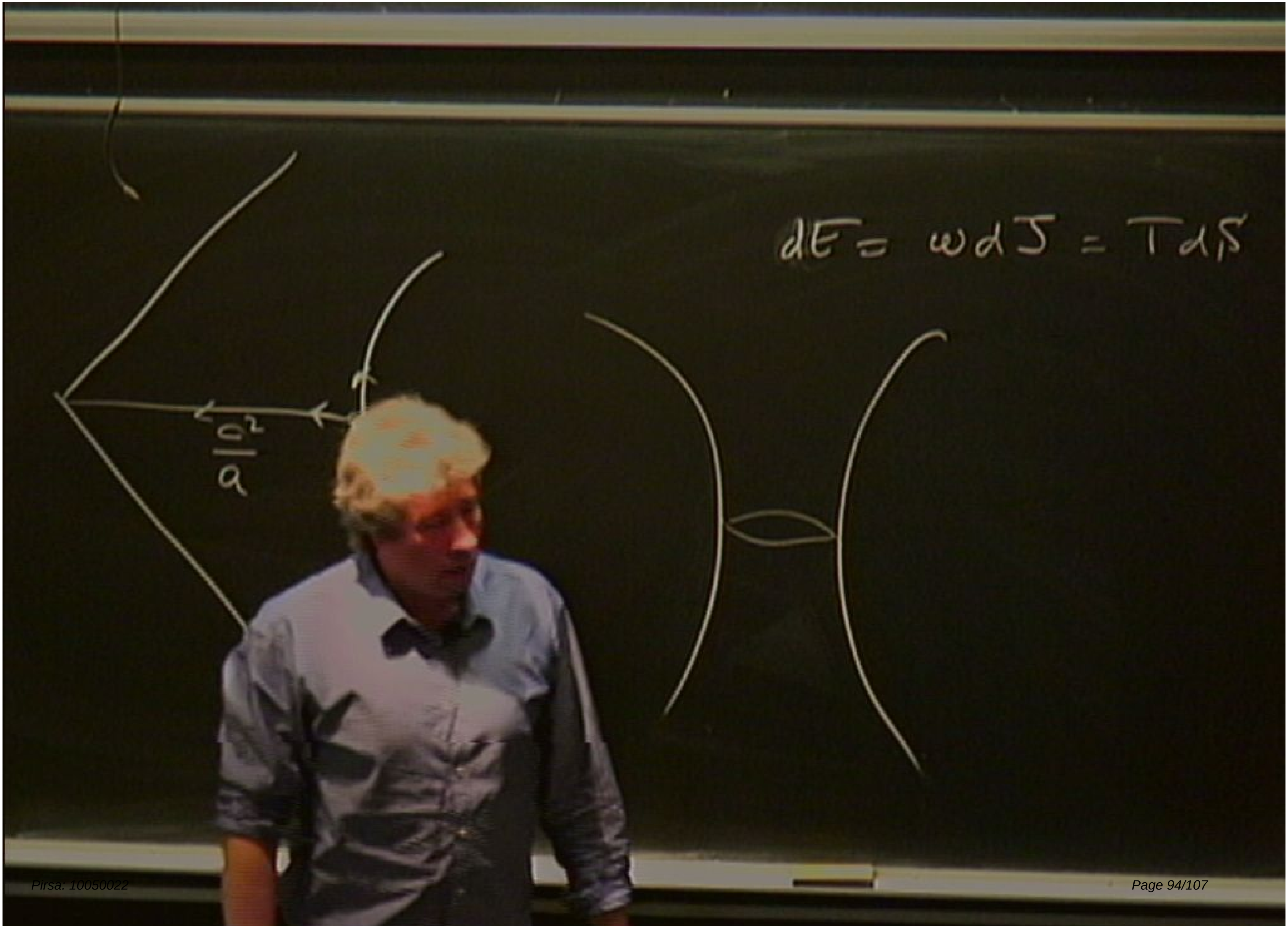
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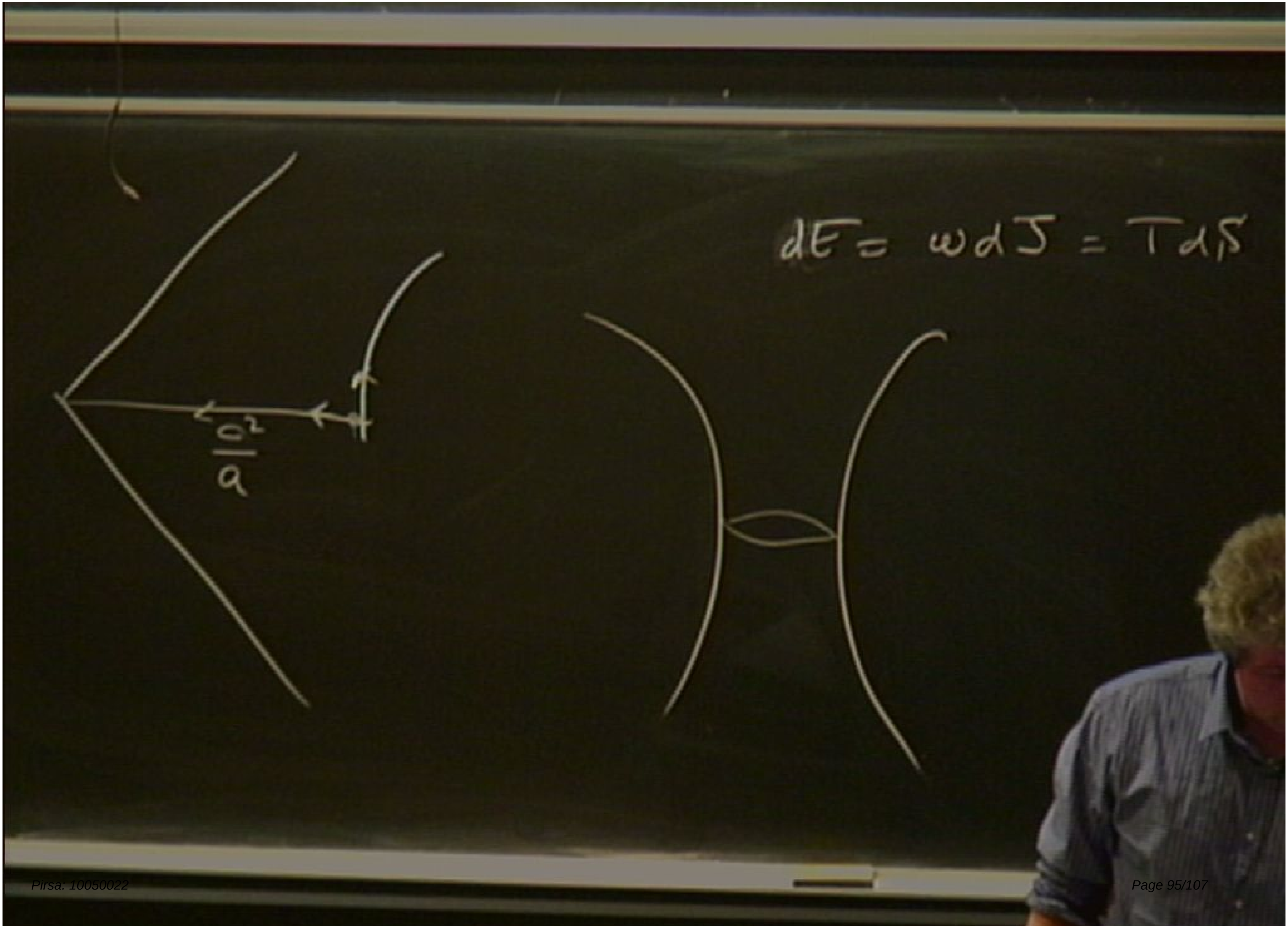
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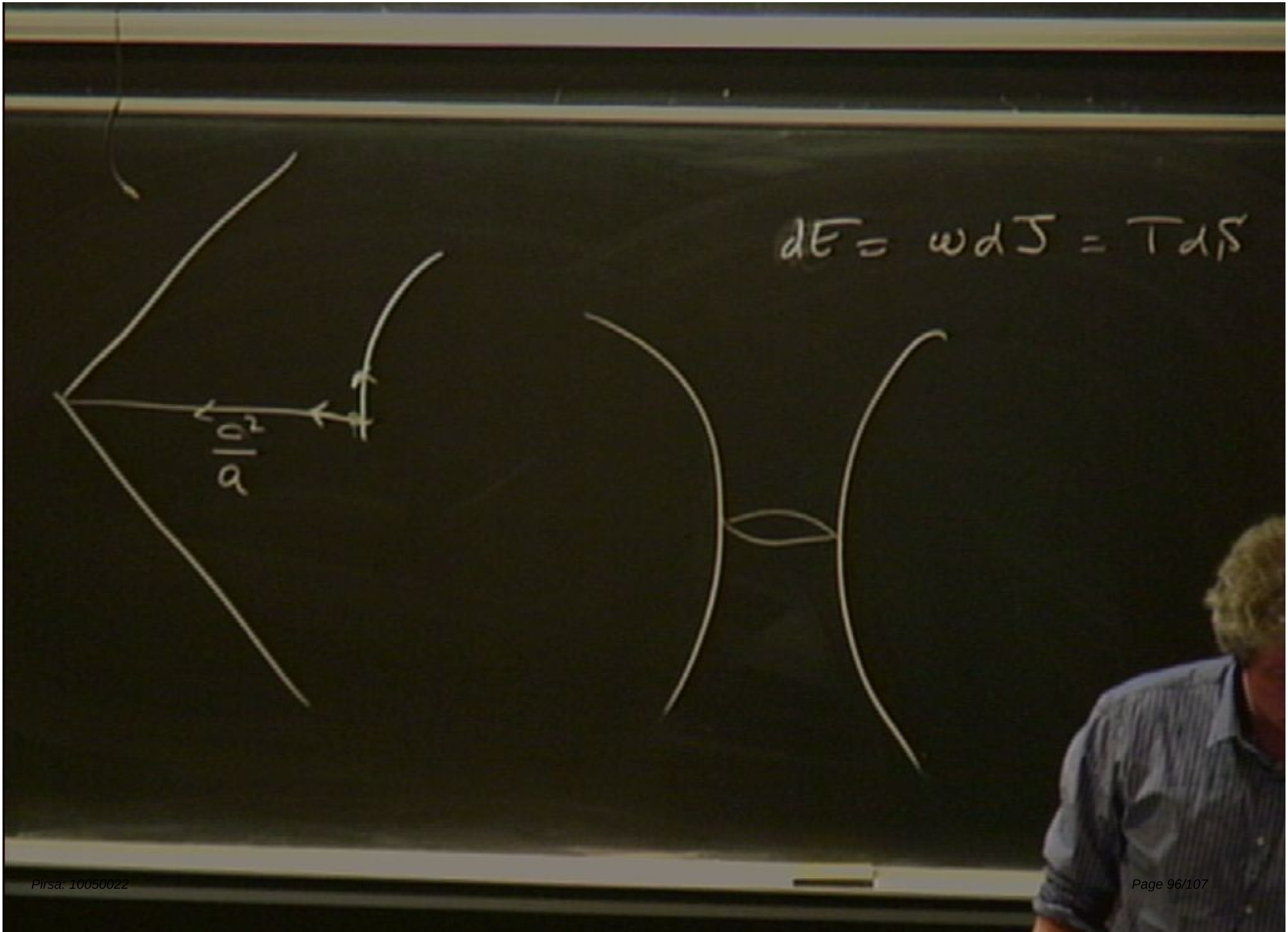
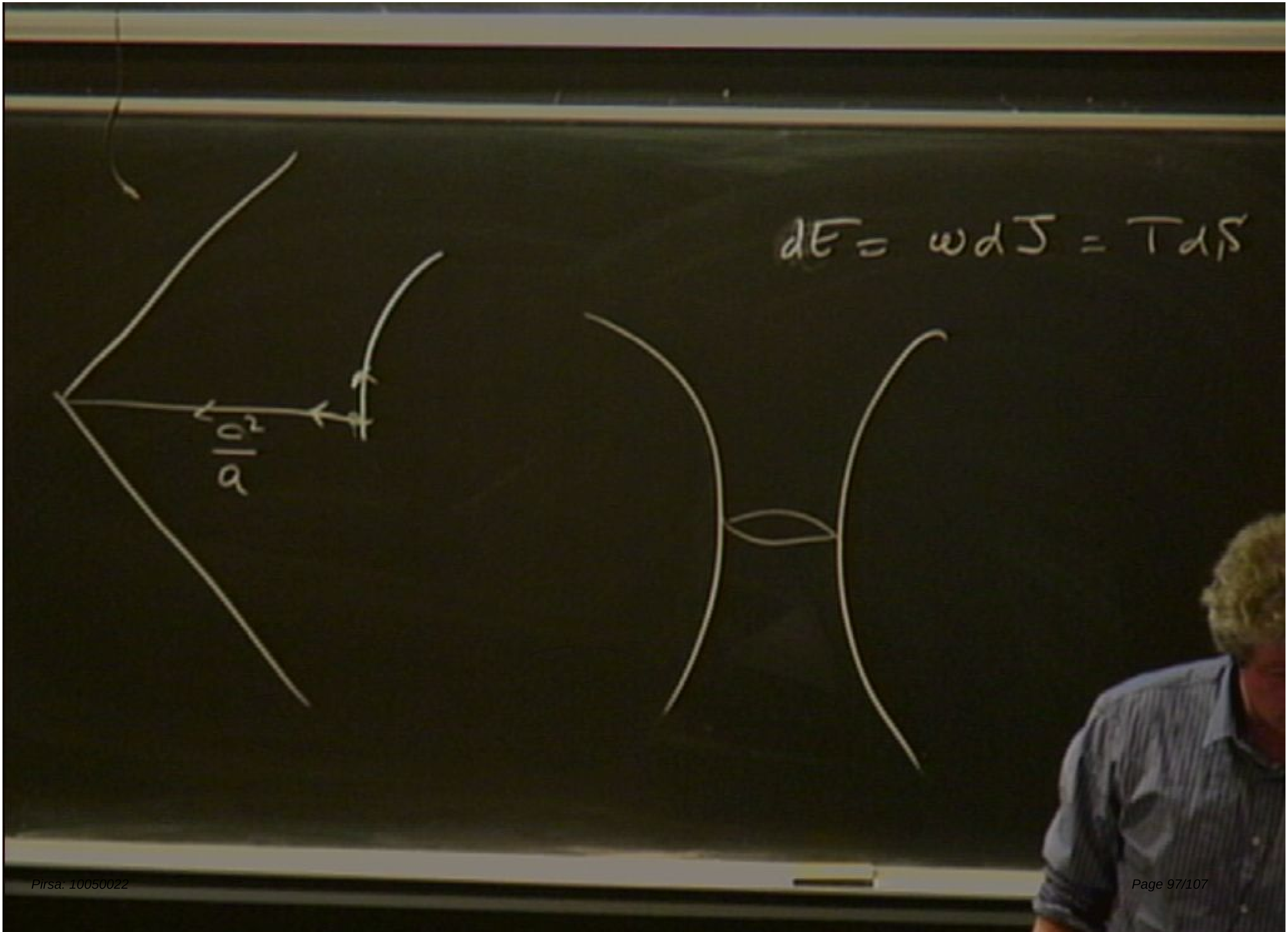
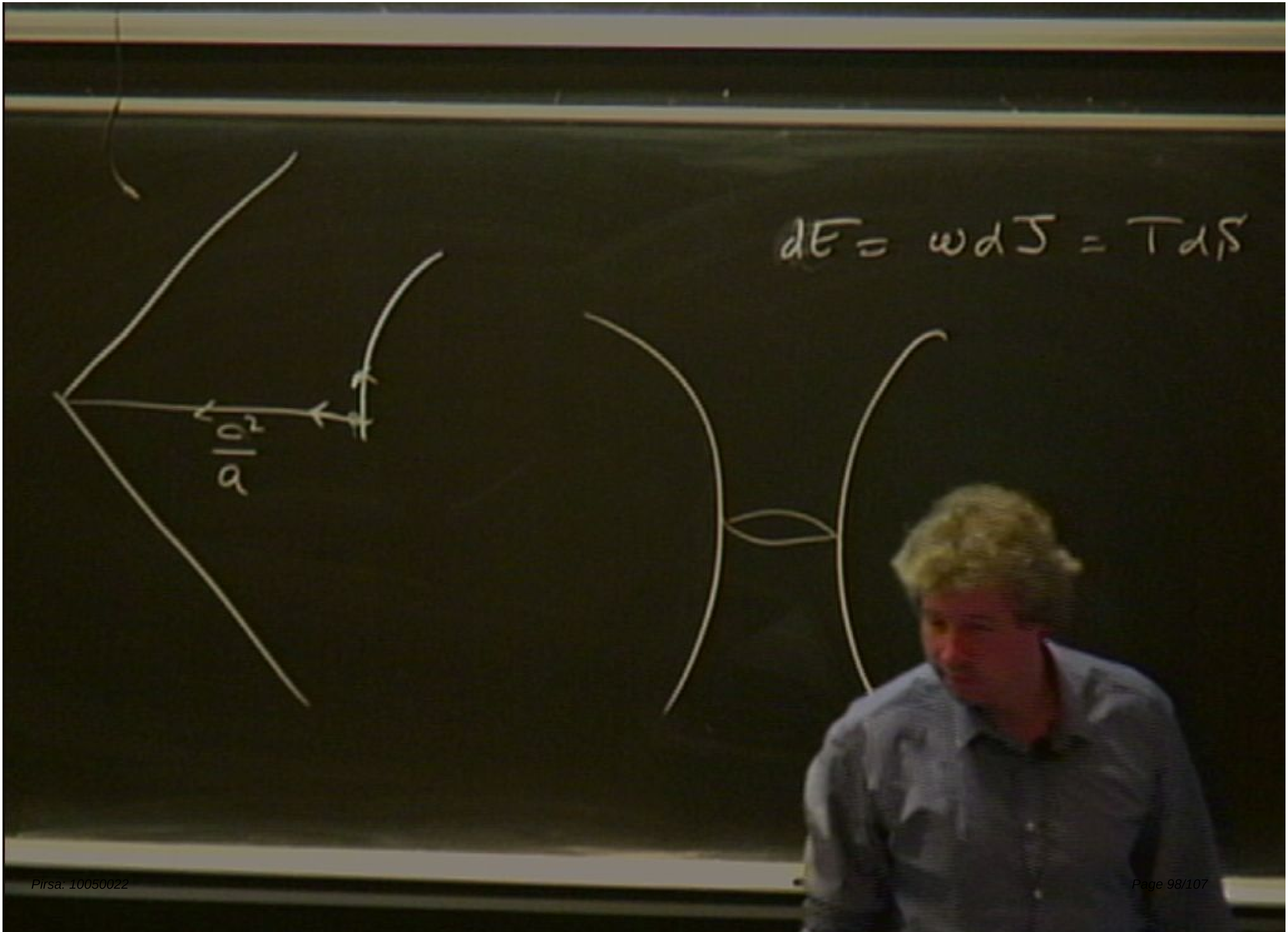

$dE = \omega\, dJ = T\, dS$
$\frac{c^2}{a}$


dE = ω dJ = T dS
c²/a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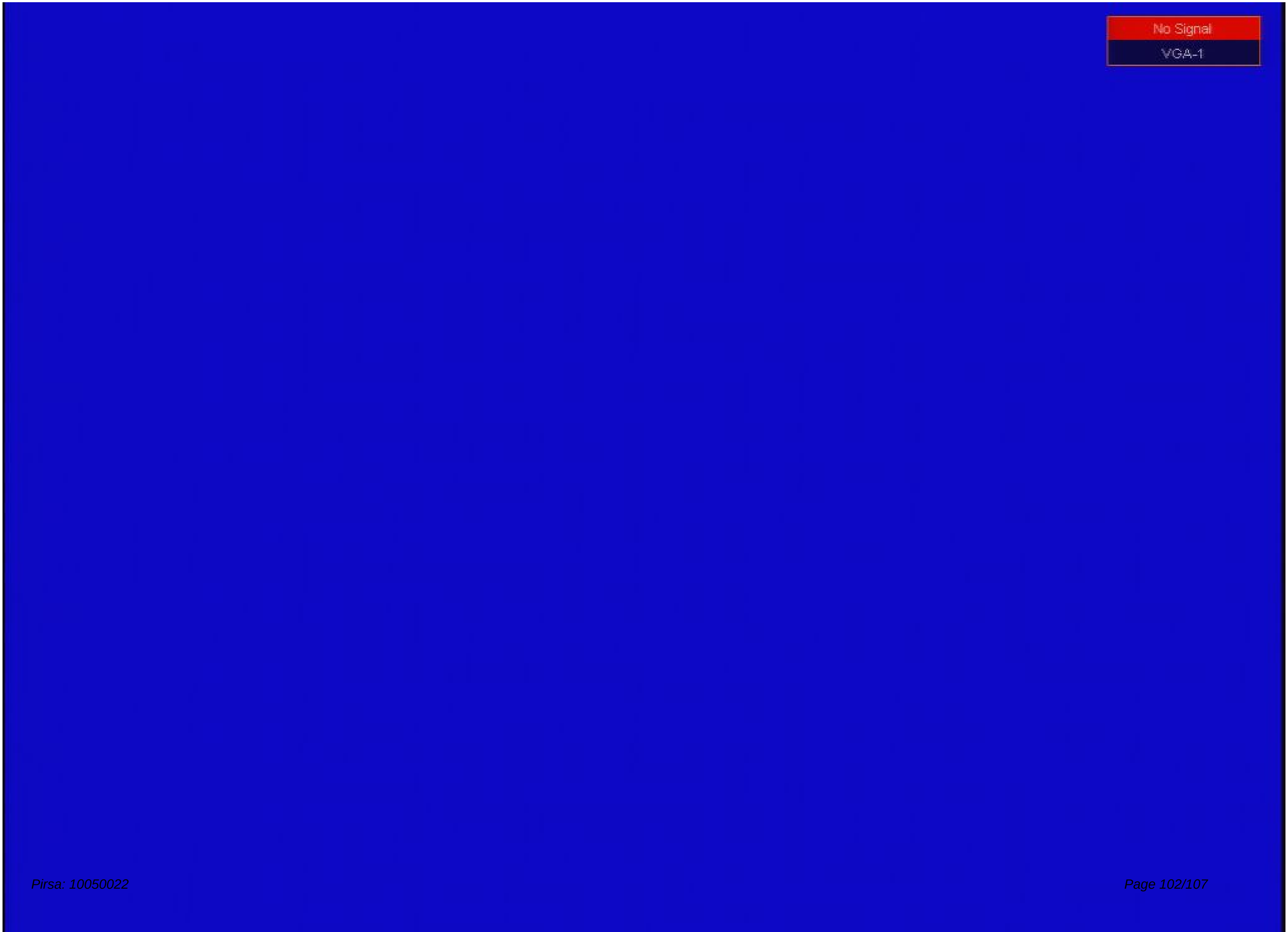
No Signal
VGA-1

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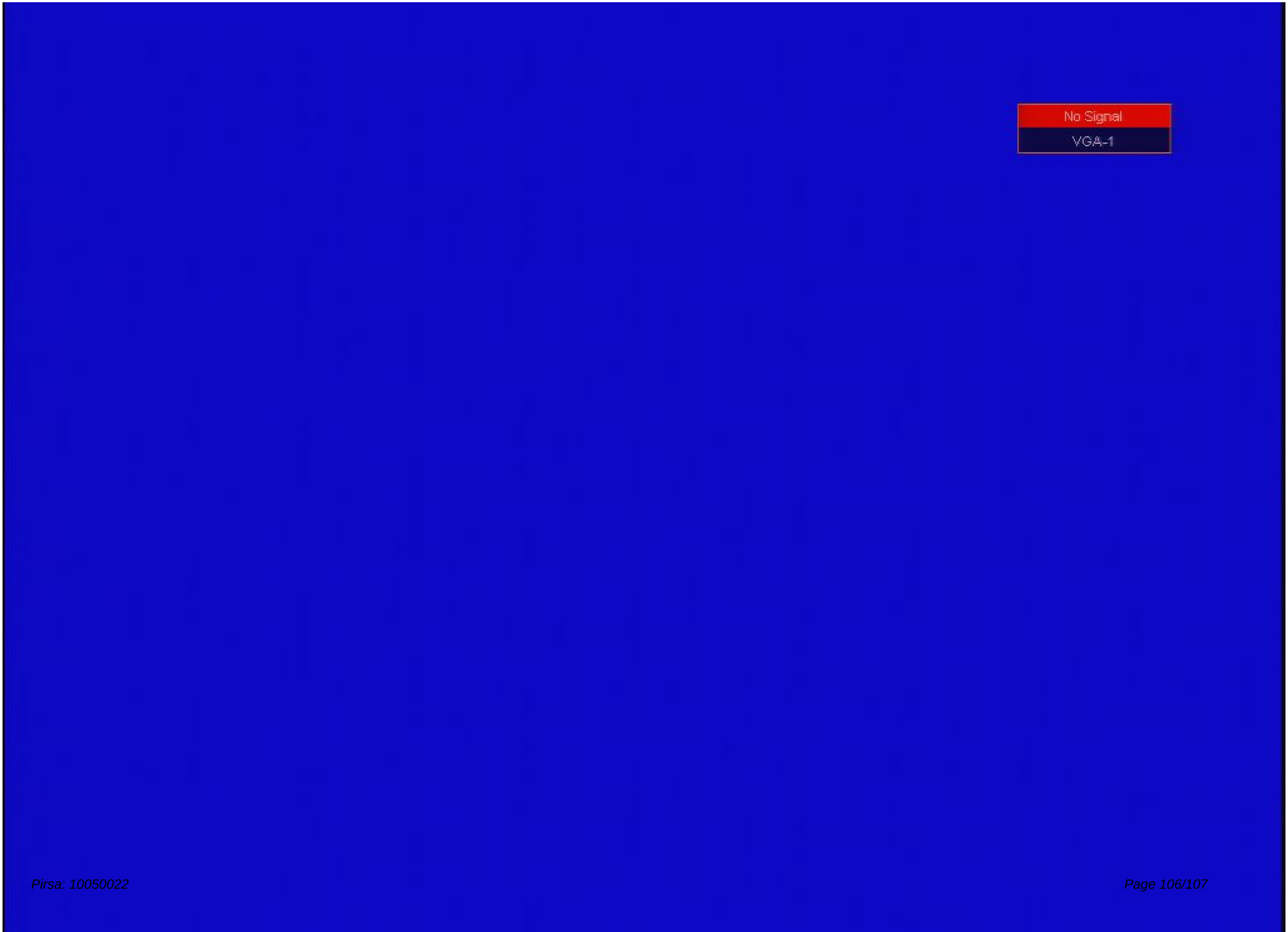
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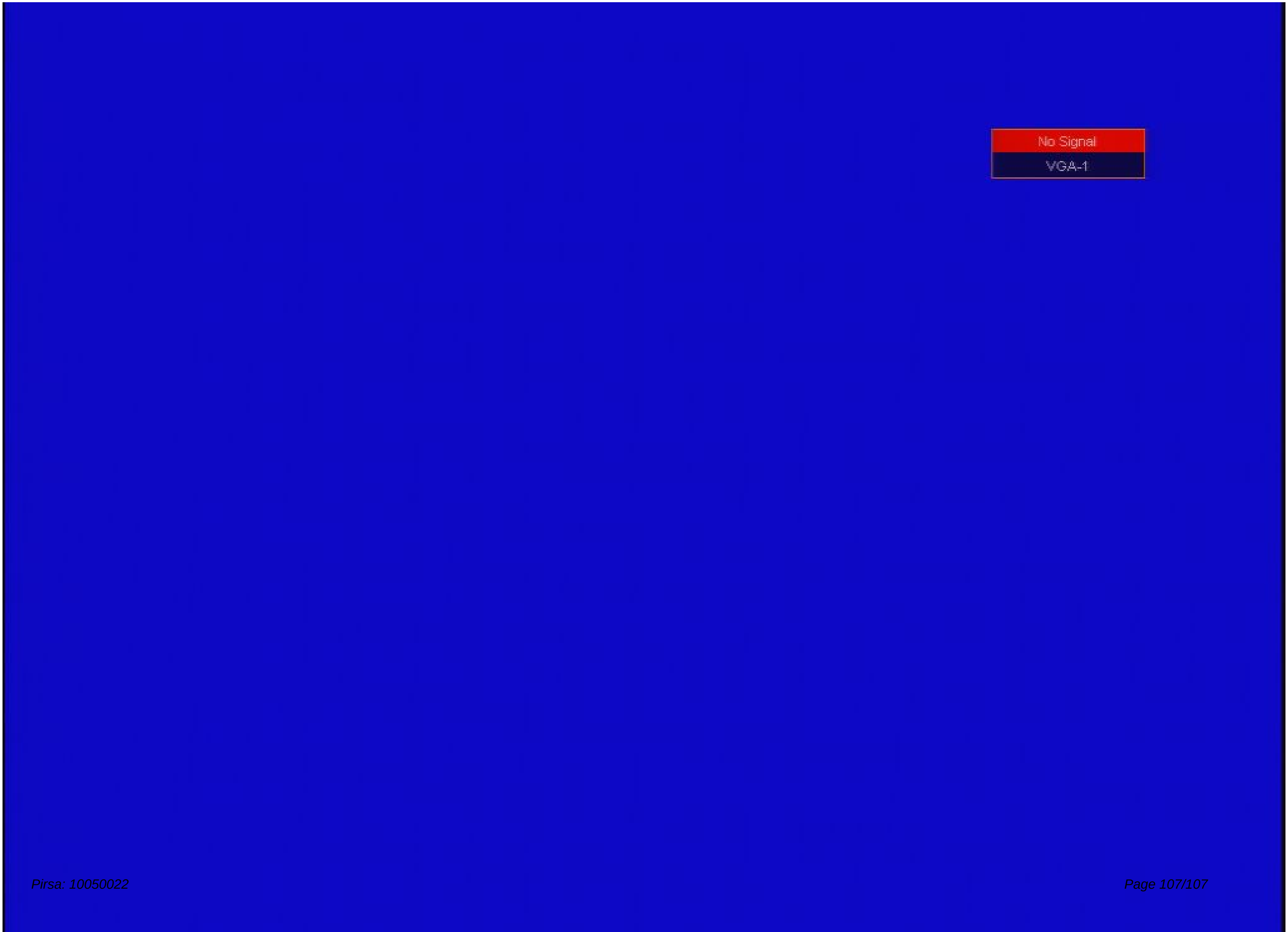
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