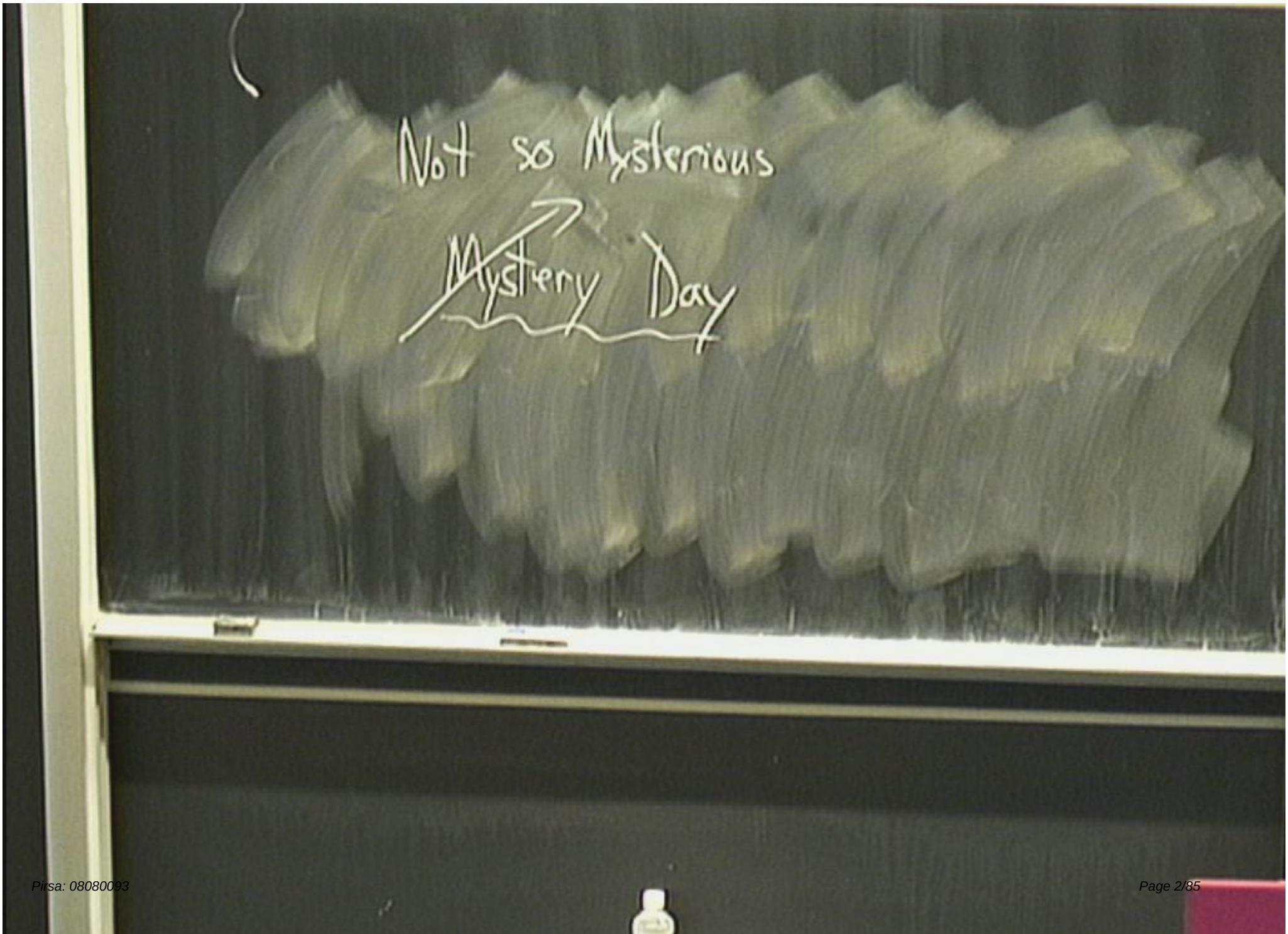
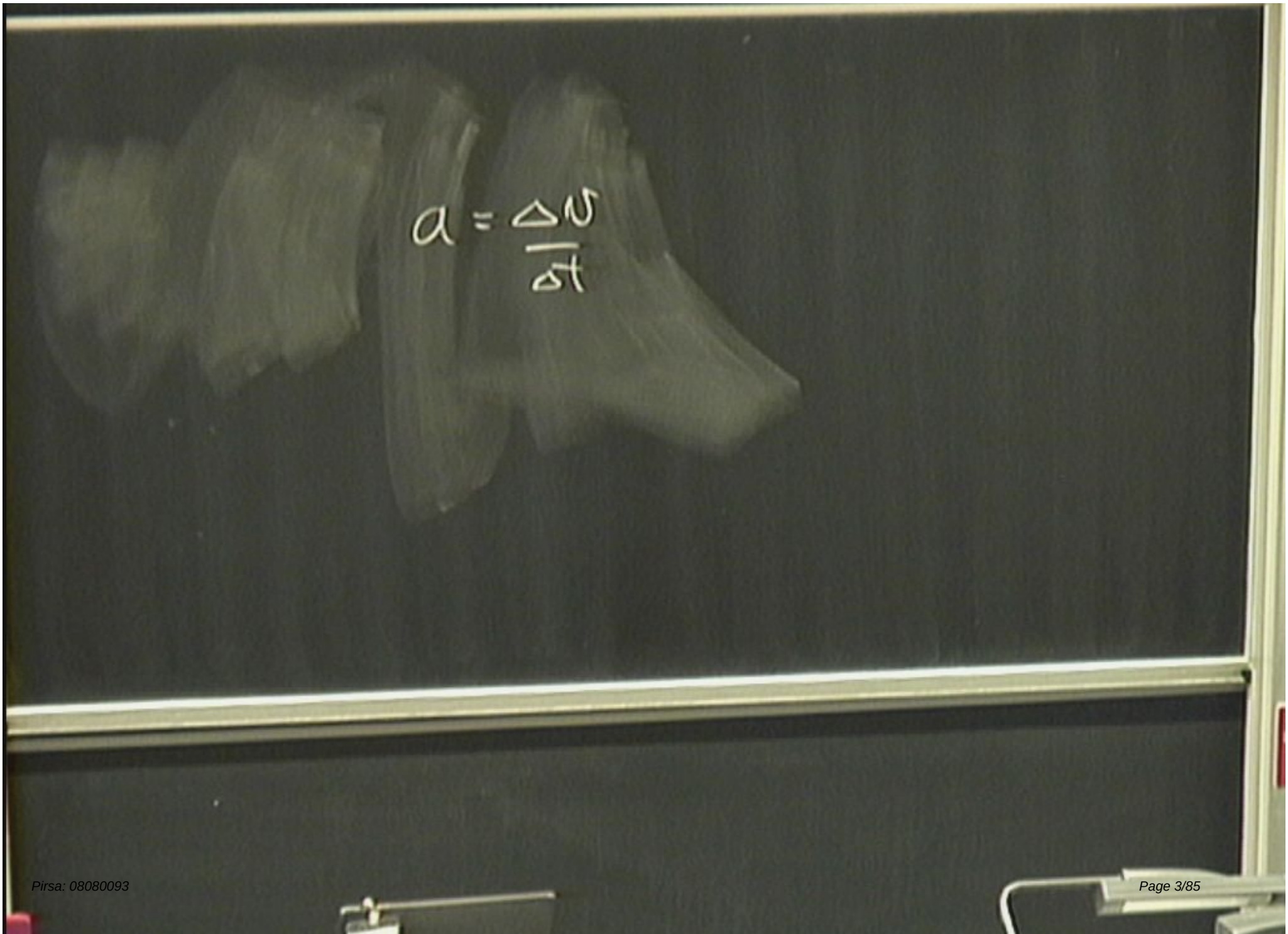
Title: The Mystery of Dark Matter

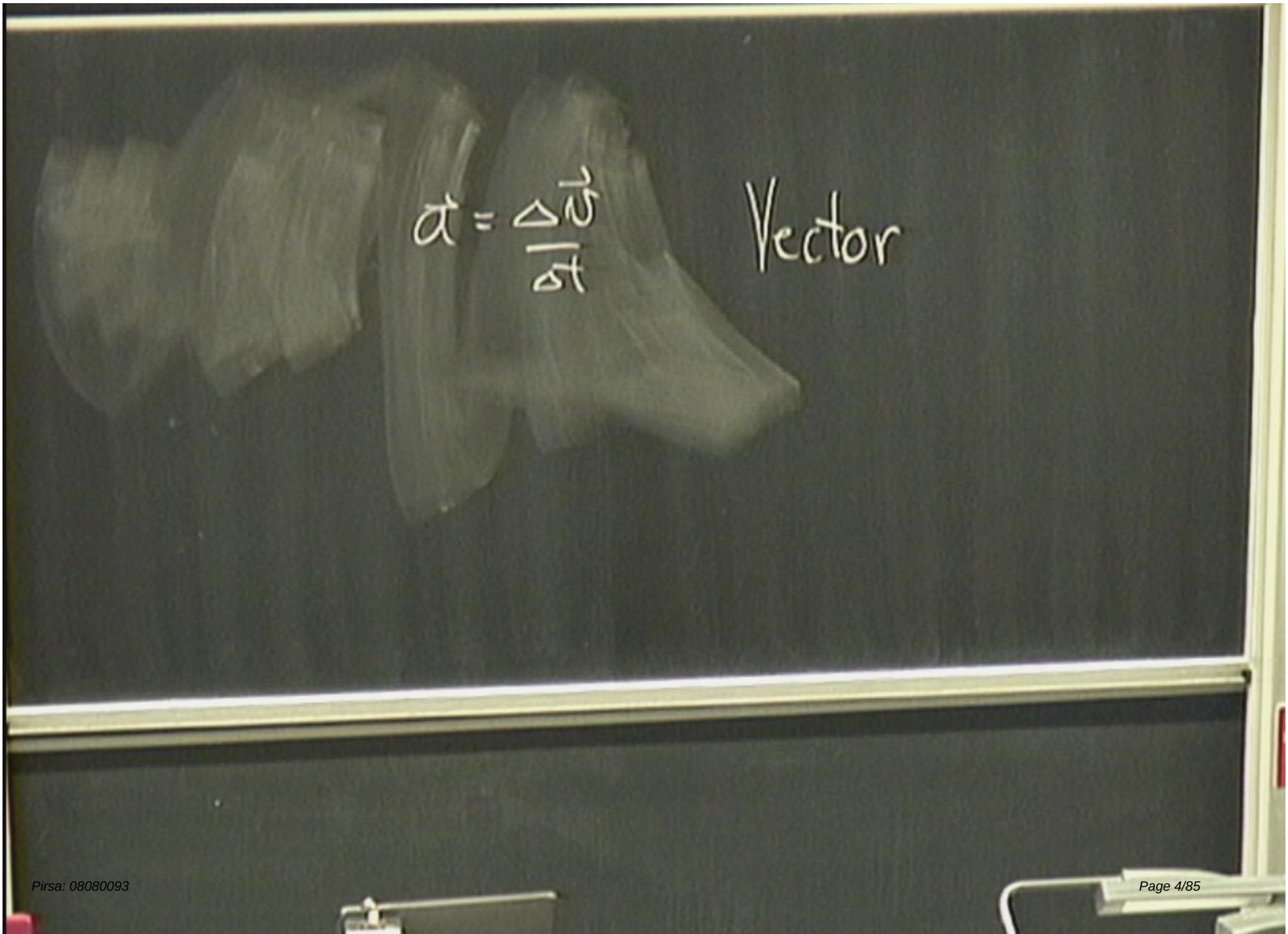
Date: Aug 19, 2008 10:30 AM

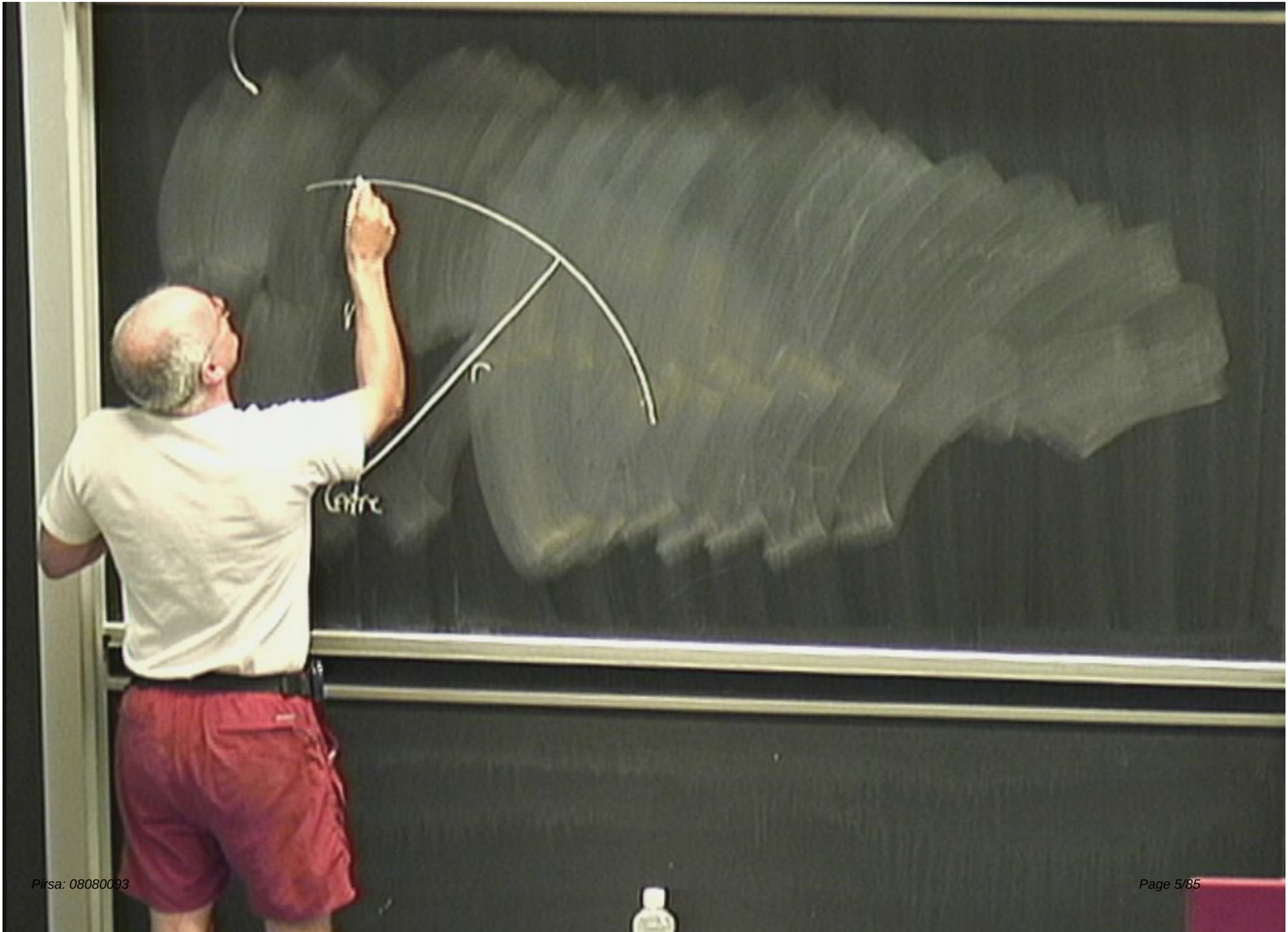
URL: http://pirsa.org/08080093

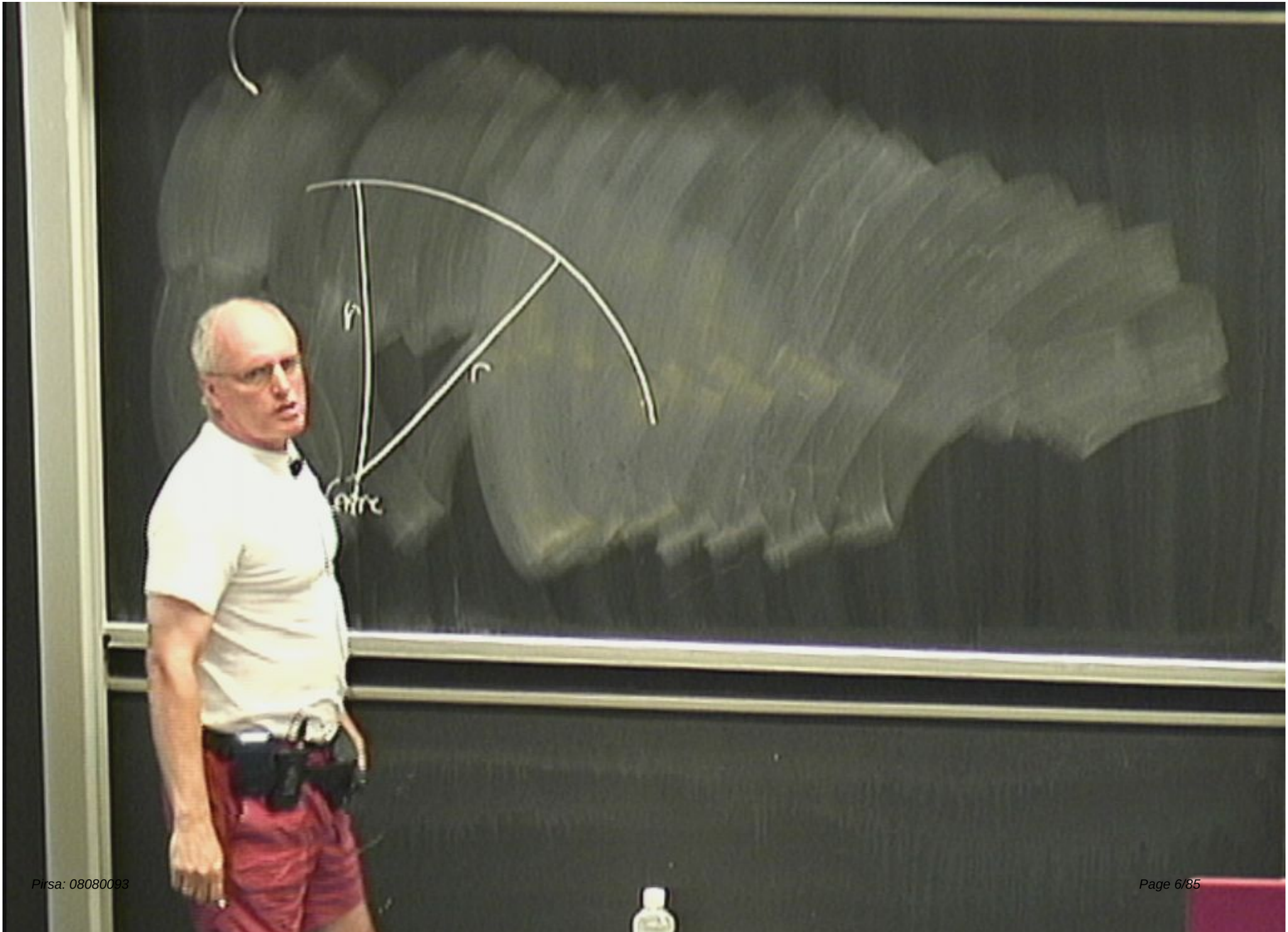
Abstract: In the 1980â€™s when Vera Rubin was analyzing how stars in galaxies revolve around the galactic core, she made an incredible discovery. The stars where moving much faster than anyone expected. This discovery helped open up a door in physics whose implications are far stranger than the best plot in any science fiction movie. Join us as we explore the mystery of dark matter.

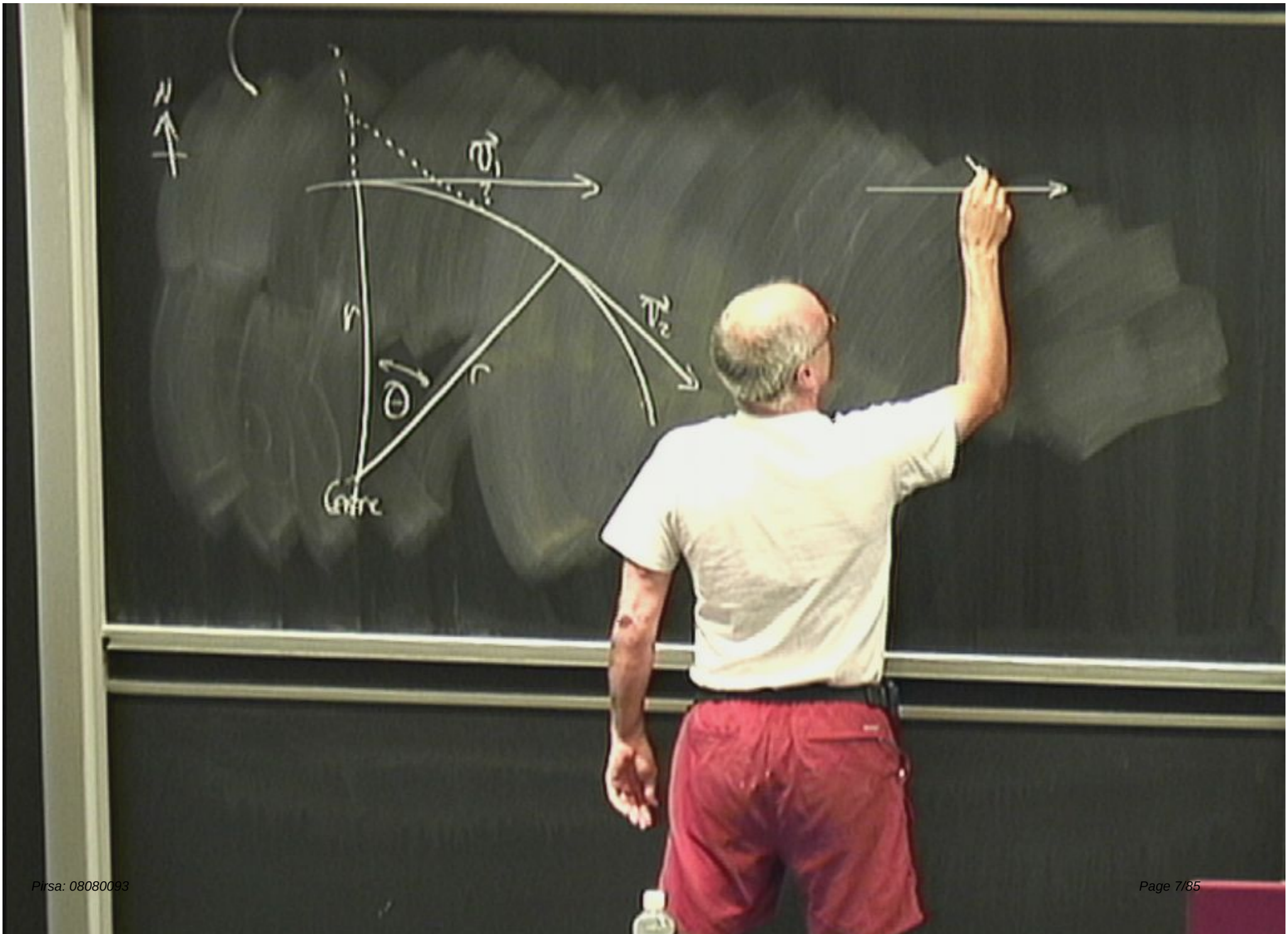

Not so Mysterious
Mystery Day


$a = \frac{\Delta v}{\Delta t}$


$a = \frac{\Delta \vec{v}}{\Delta t}$
Vector




r
r
Centre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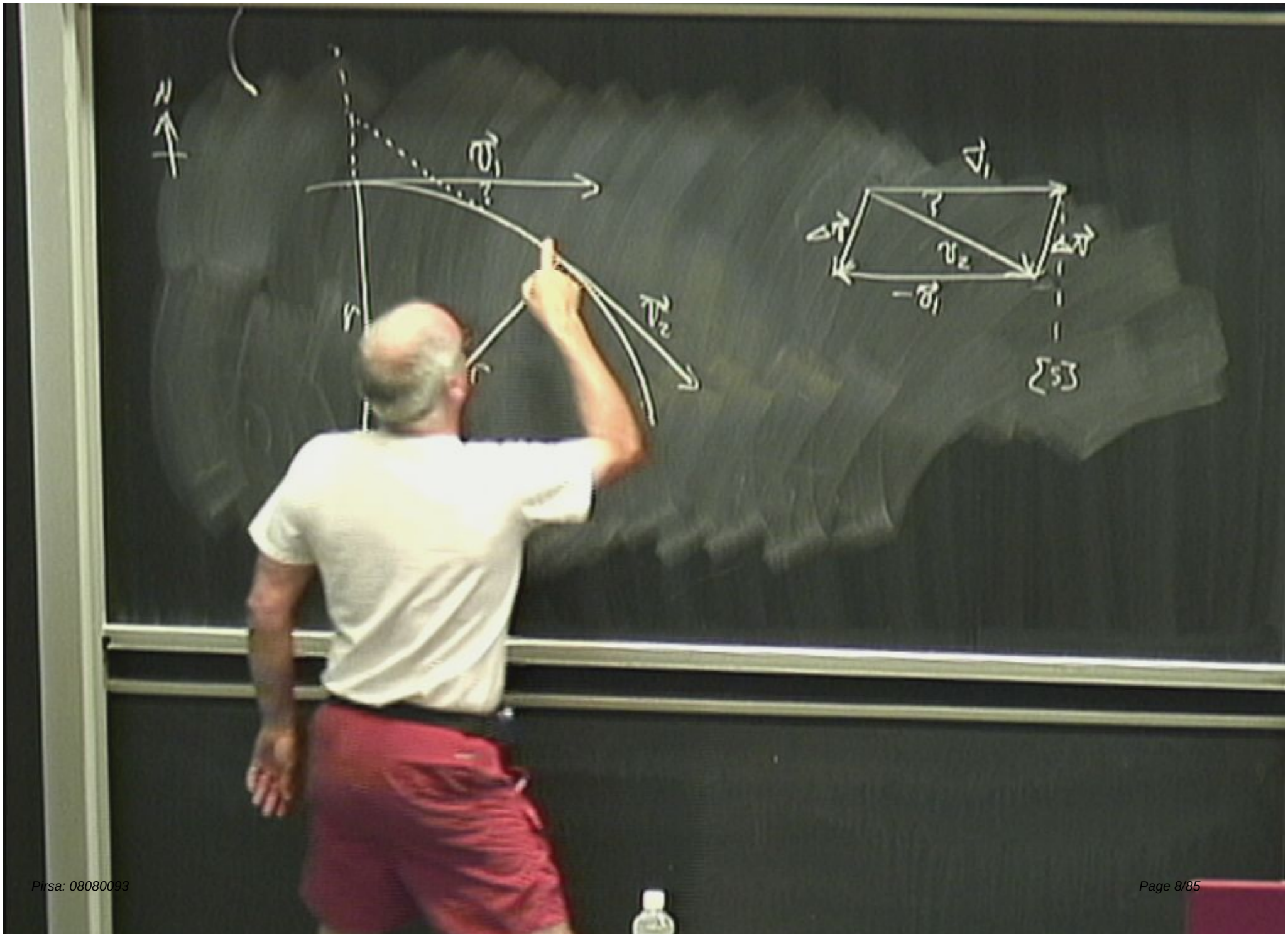
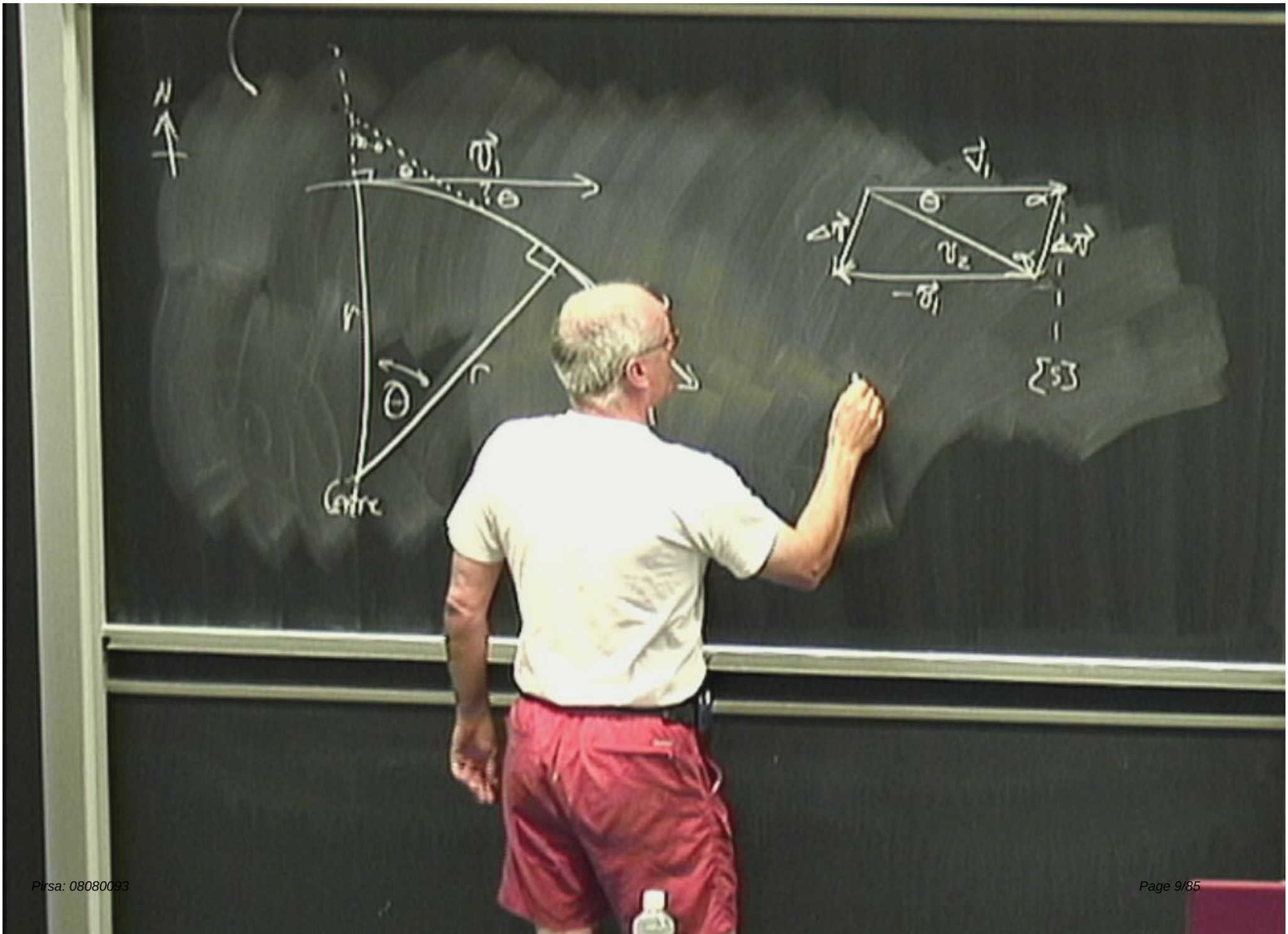
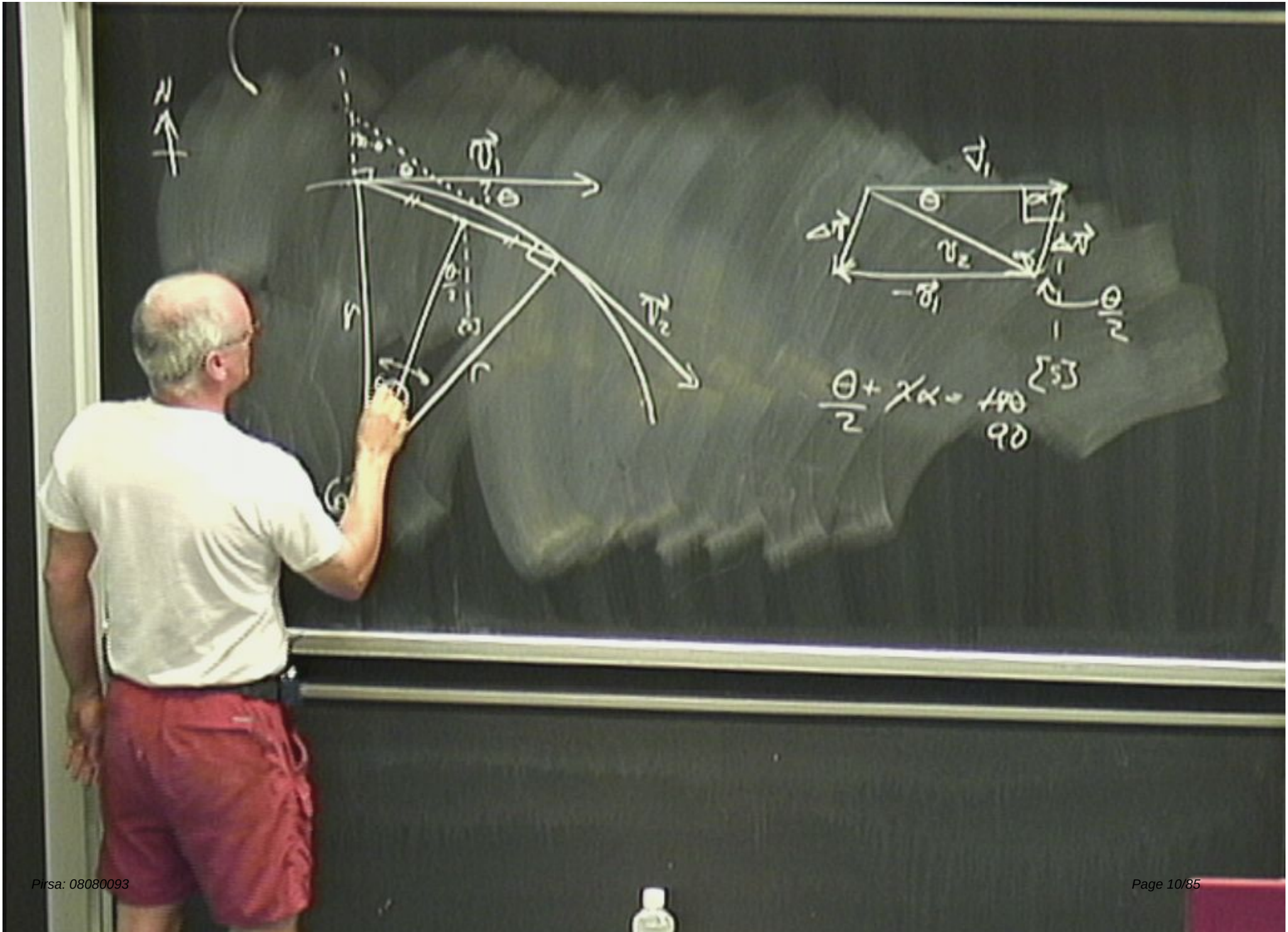
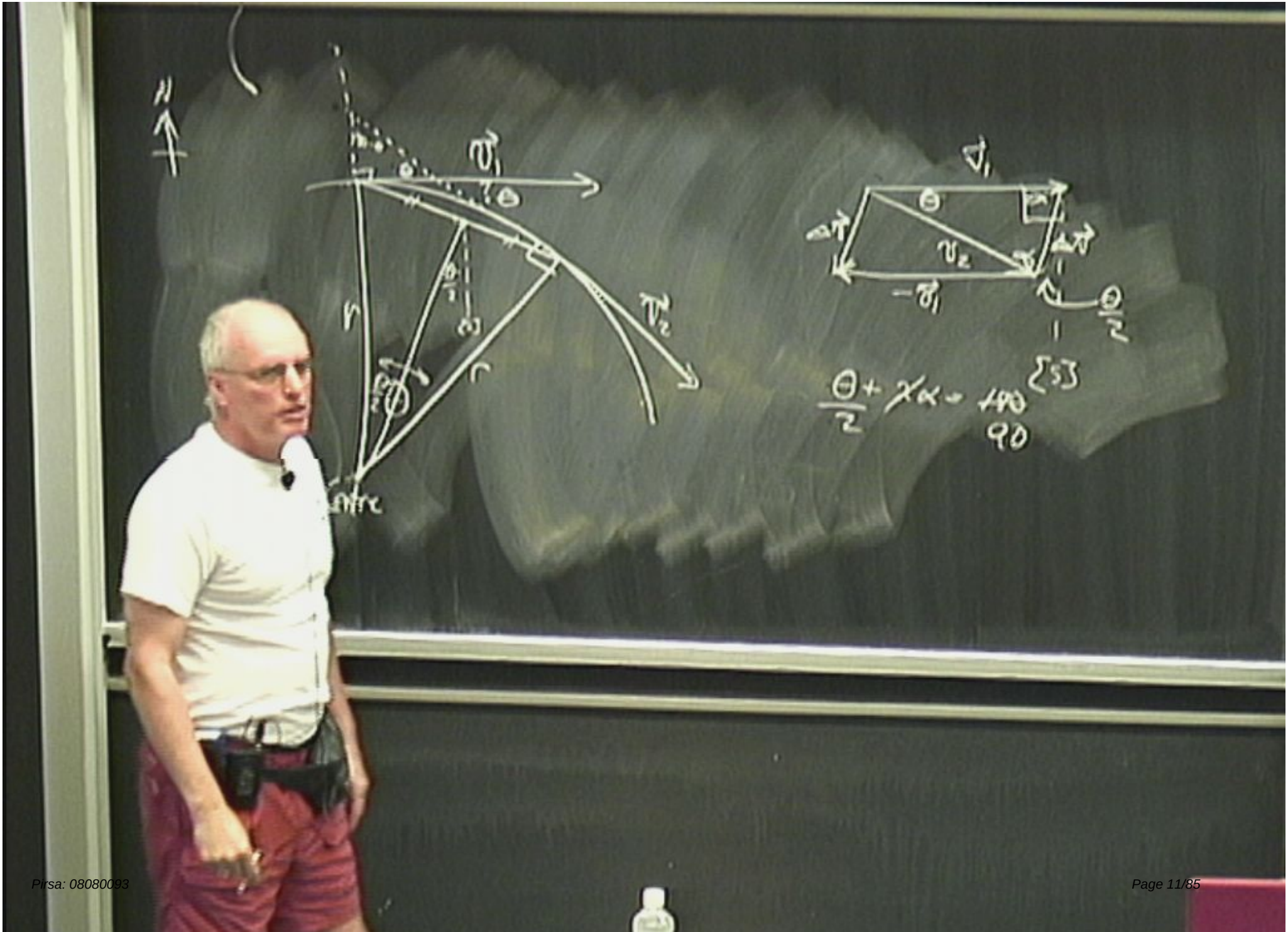
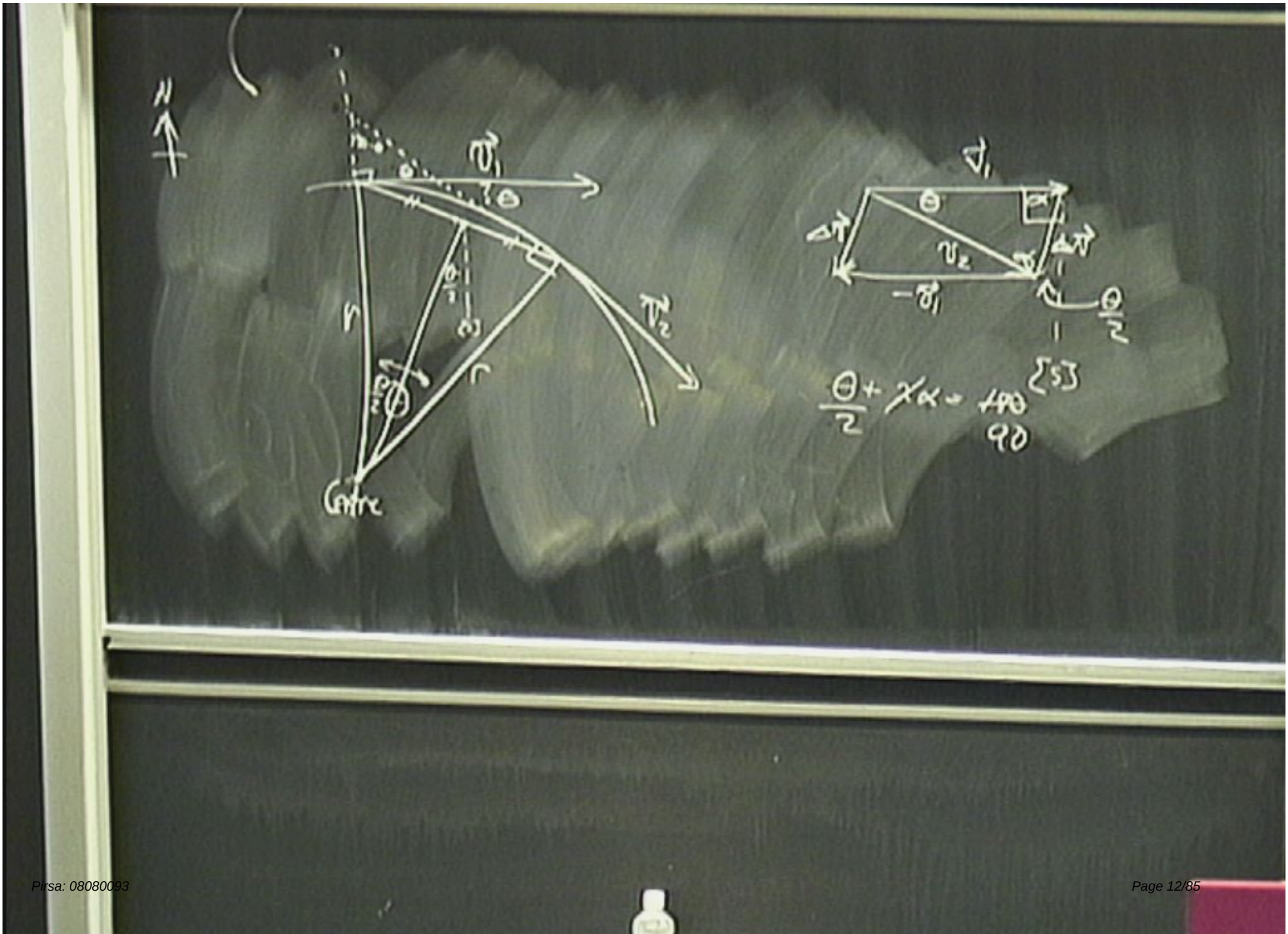
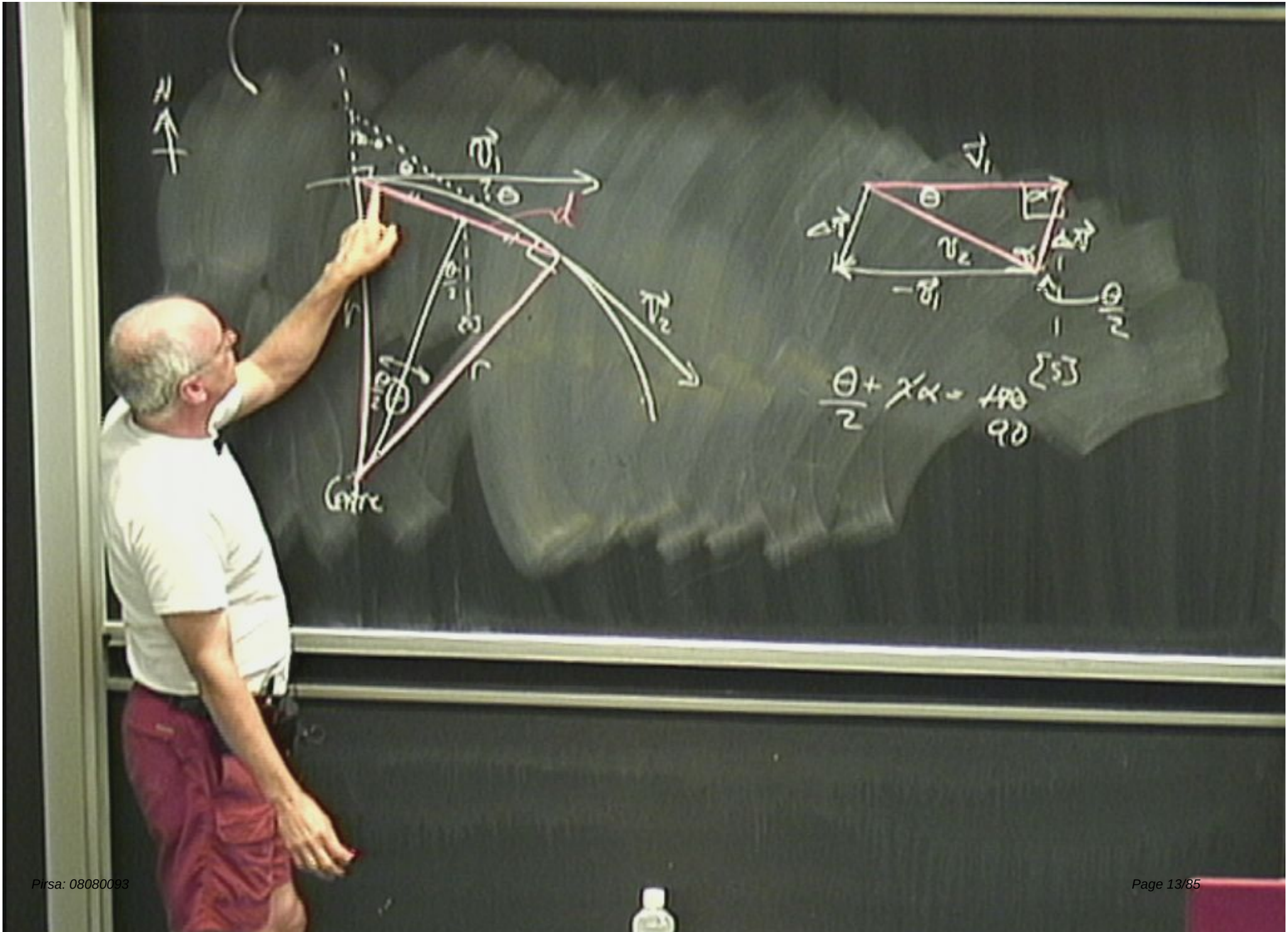


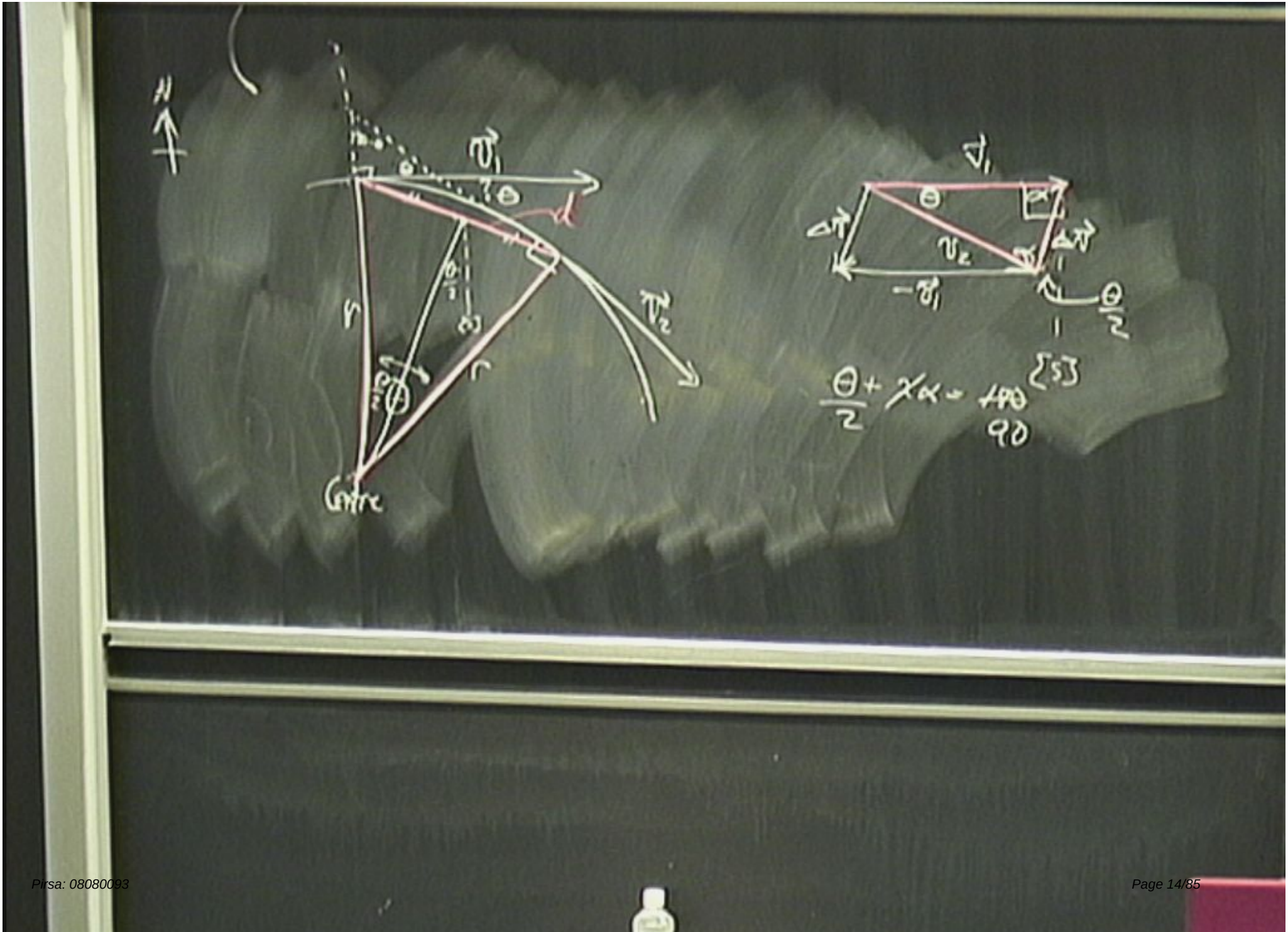

N
θ
r
θ
Centre
θ
[S]

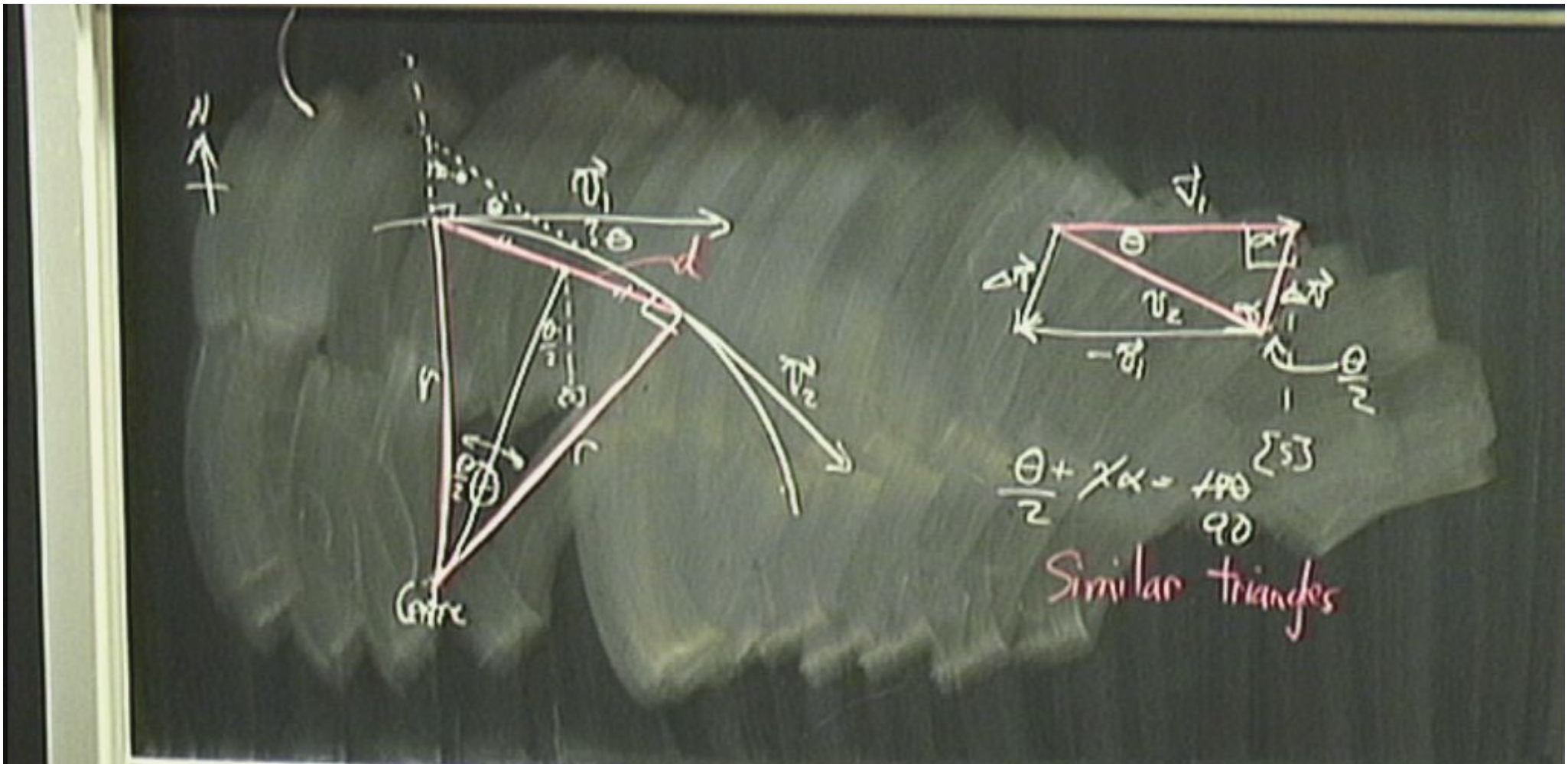

$\vec{v}_1$
θ
$\vec{v}_2$
$-\vec{v}_1$
$\theta/2$
$\frac{\theta}{2} + \chi\alpha = 180$
90

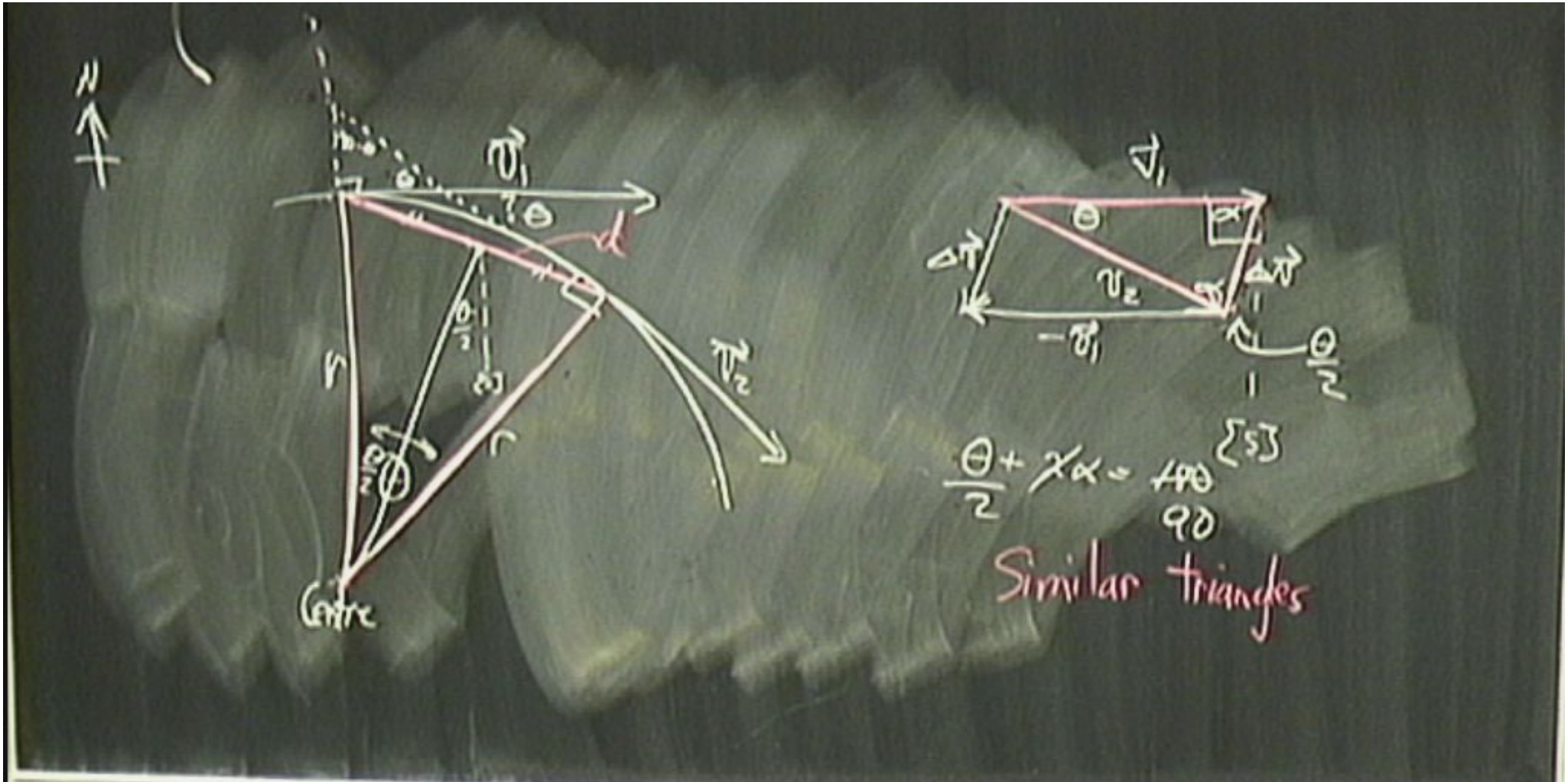

Entre
[5]
90

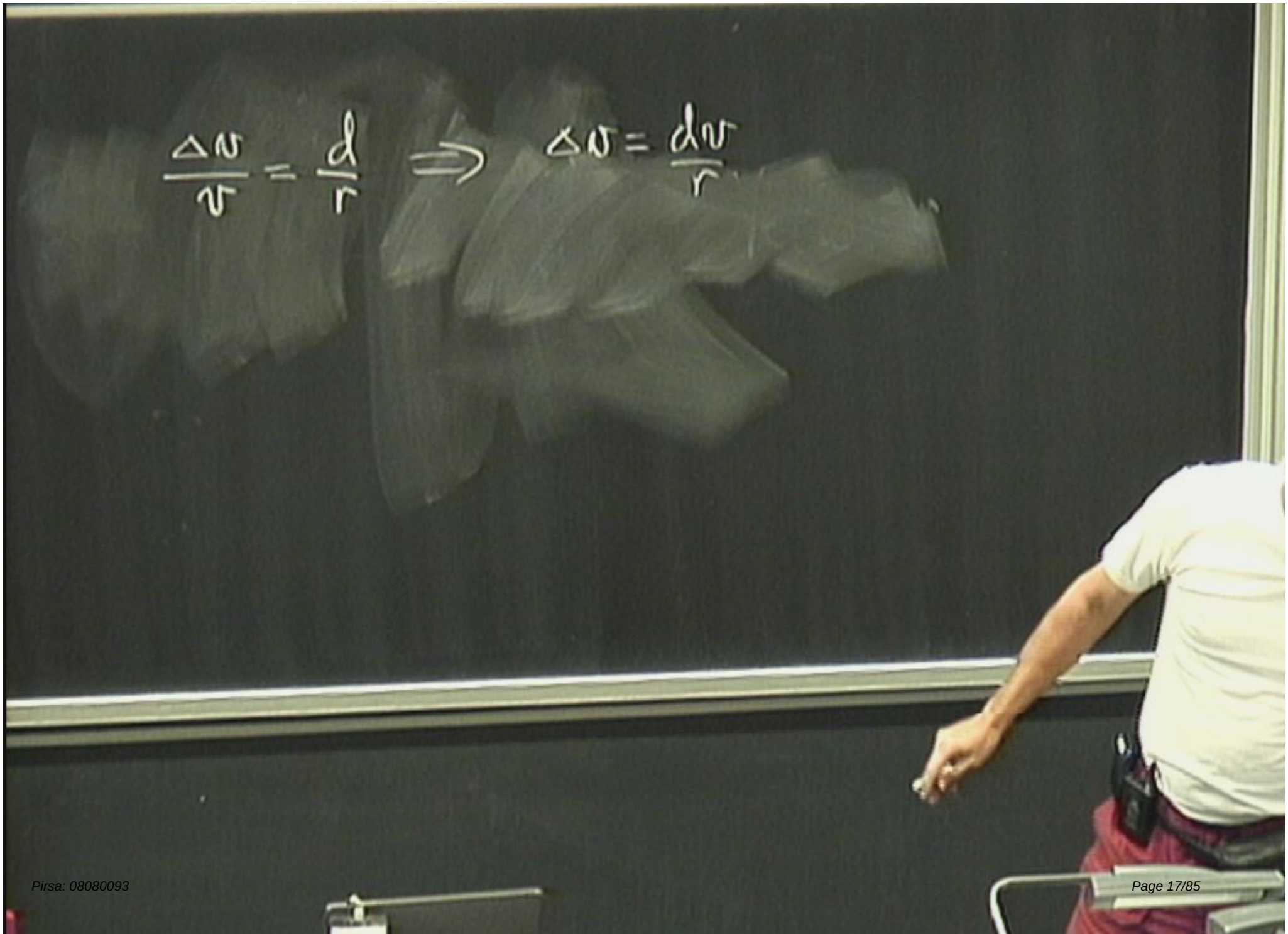

N
$\vec{v}_1$
θ
$\vec{v}_2$
r
Centre
$\vec{v}_1$
θ
$\vec{v}_2$
$-\vec{v}_1$
$\Delta\vec{v}$
$\theta/2$
[s]
$\frac{\theta}{2} + \chi\alpha = 180$
90

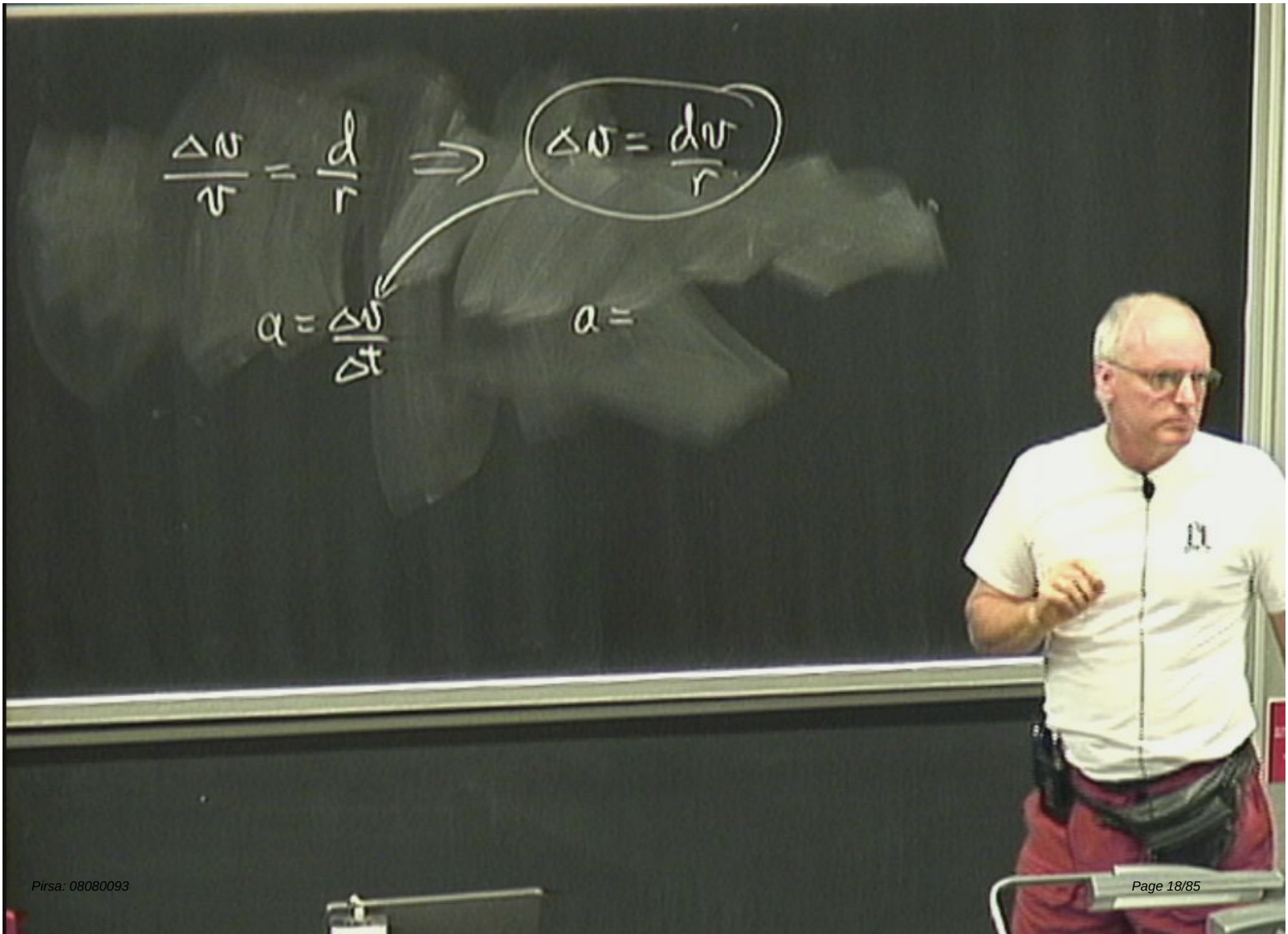

Centre
$\frac{\theta}{2} + \alpha = 90$

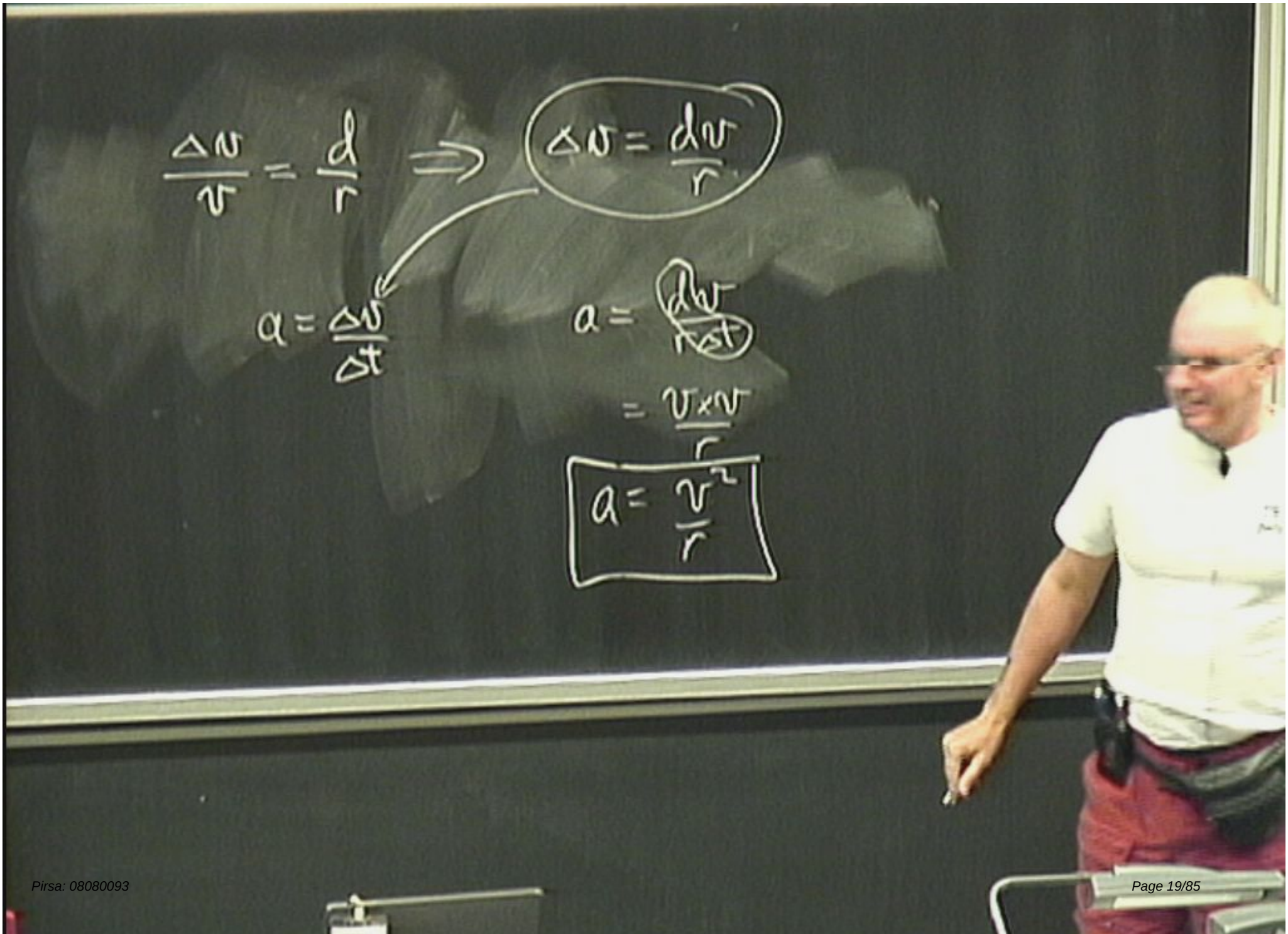

Centre
$\frac{\theta}{2} + \alpha = 90$

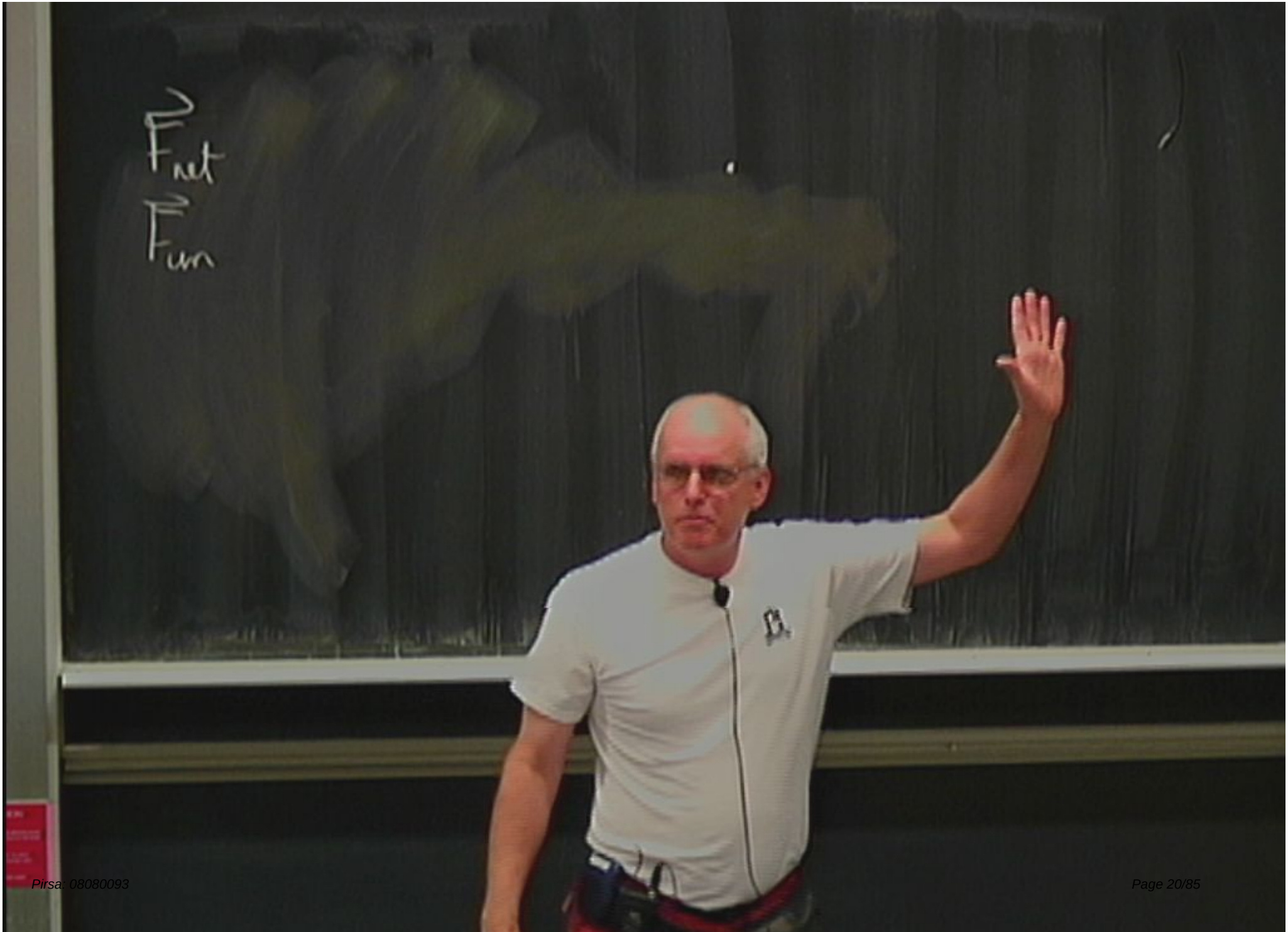

Centre
Similar triangles

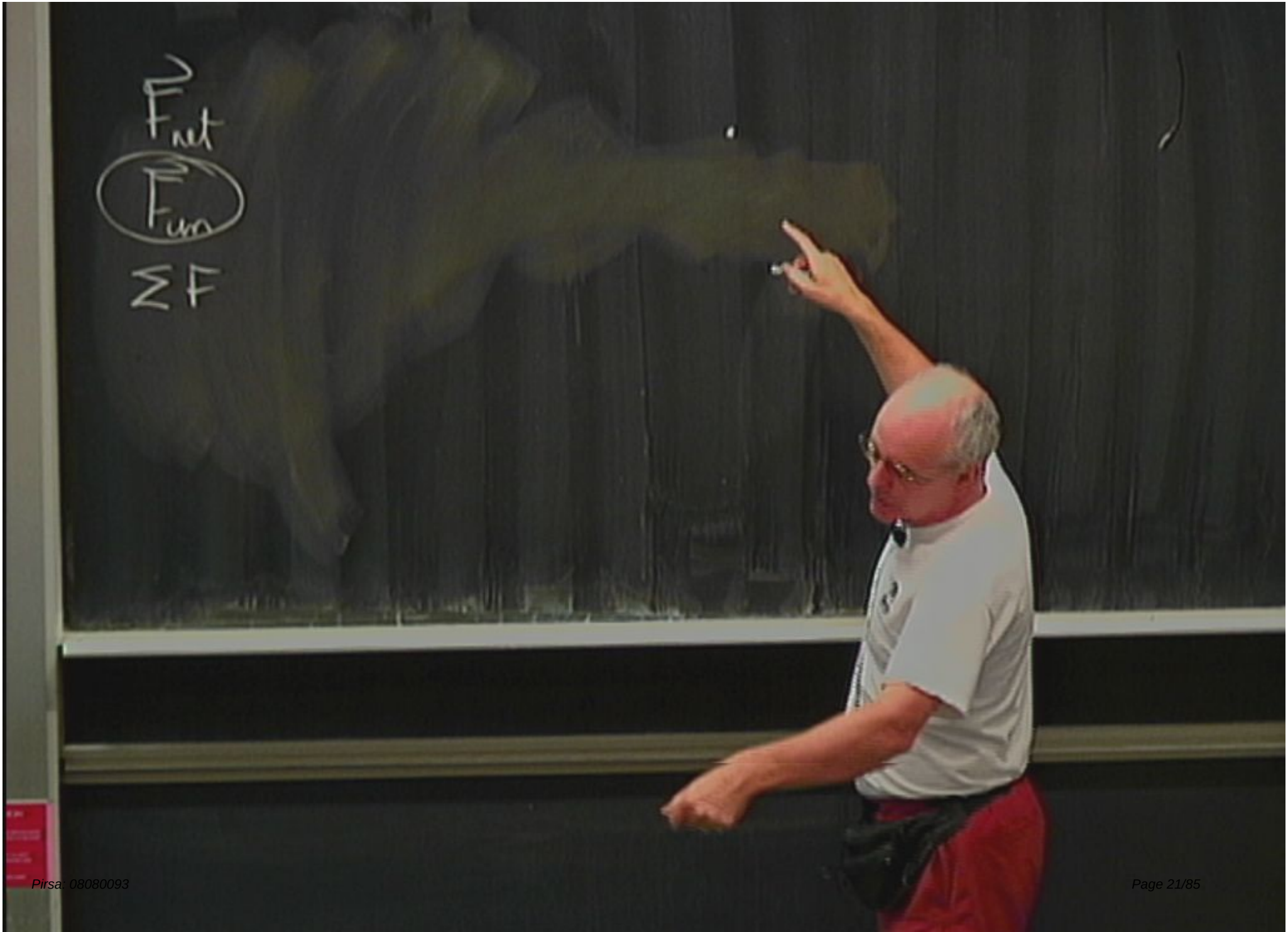

N
$\vec{v}_1$
θ
$\theta/2$
r
$\vec{v}_2$
Centre
$\vec{v}_1$
θ
α
$\vec{v}_2$
$-\vec{v}_1$
$\theta/2$
[5]
$\frac{\theta}{2} + \alpha = 90$
Similar triangles

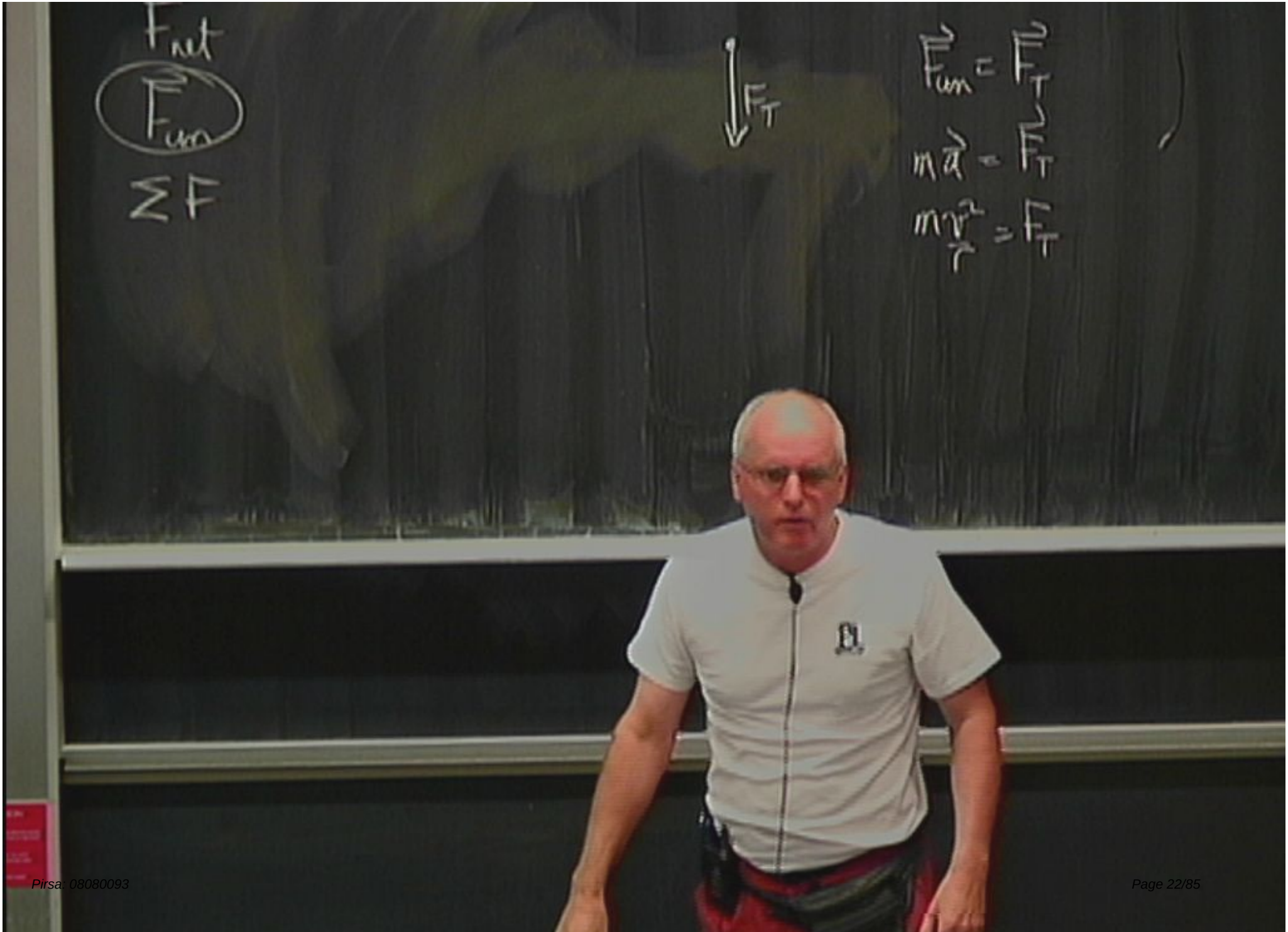

$\frac{\Delta v}{v} = \frac{d}{r} \Rightarrow \Delta v = \frac{dv}{r}$

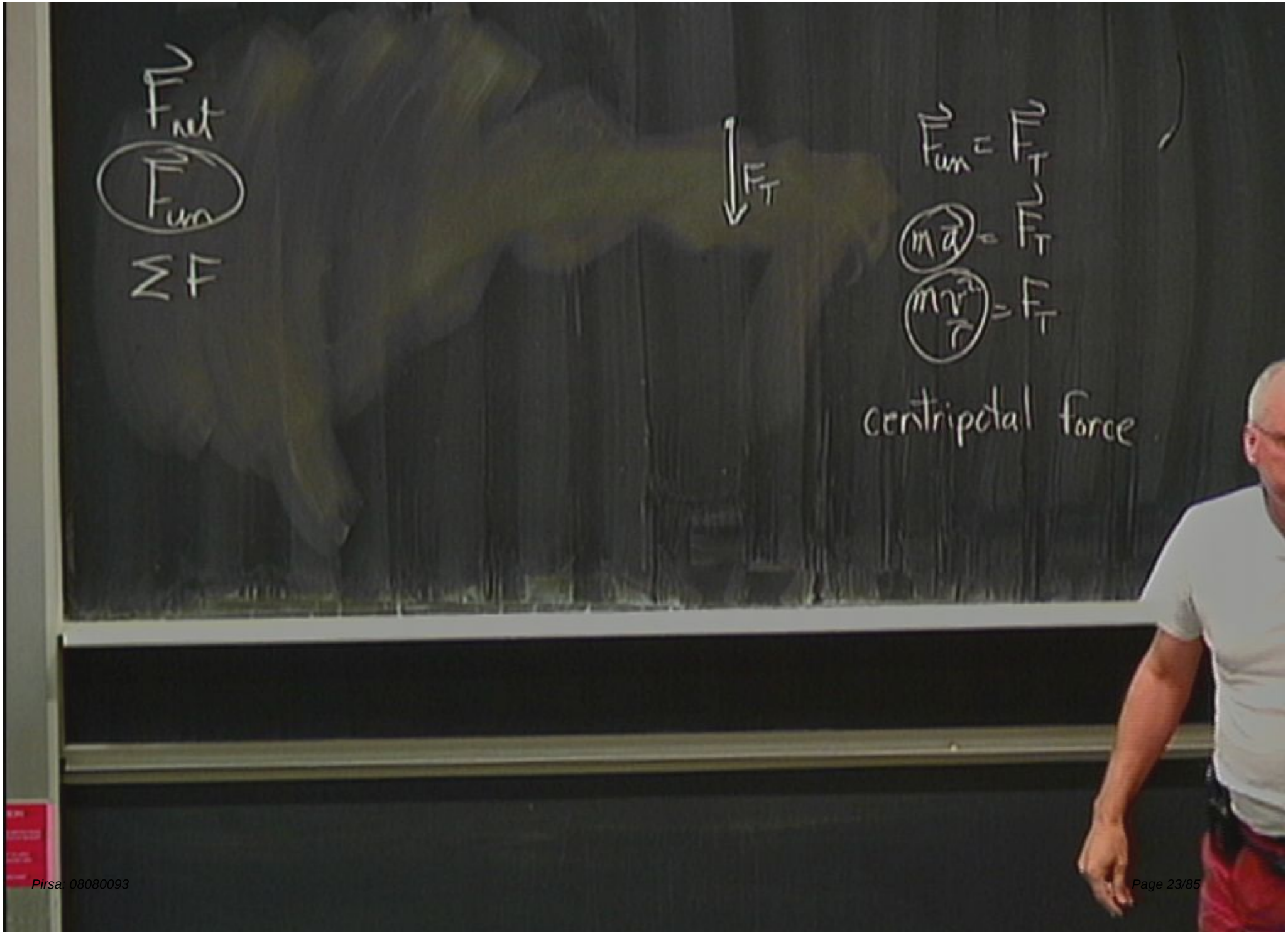

$\frac{\Delta v}{v} = \frac{d}{r} \Rightarrow \Delta v = \frac{dv}{r}$
$a = \frac{\Delta v}{\Delta t}$
$a =$


$\frac{\Delta v}{v} = \frac{d}{r} \Rightarrow \Delta v = \frac{dv}{r}$
$a = \frac{\Delta v}{\Delta t}$
$a = \frac{dv}{r\,dt}$
$= \frac{v \times v}{r}$
$a = \frac{v^2}{r}$


$\vec{F}_{net}$
$\vec{F}_{un}$


F net
F un
ΣF


F_{net}
F_{um}
ΣF
F_T
$\vec{F}_{um} = \vec{F}_T$
$m\vec{a} = \vec{F}_T$
$m\frac{v^2}{r} = F_T$


$\vec{F}_{net}$
$\vec{F}_{net}$
ΣF
$\vec{F}_T$
$\vec{F}_{net} = \vec{F}_T$
$ma = F_T$
$\frac{mv^2}{r} = F_T$
centripetal force

$$\frac{\Delta v}{v} = \frac{d}{r} \Rightarrow \Delta v = \frac{dv}{r}$$

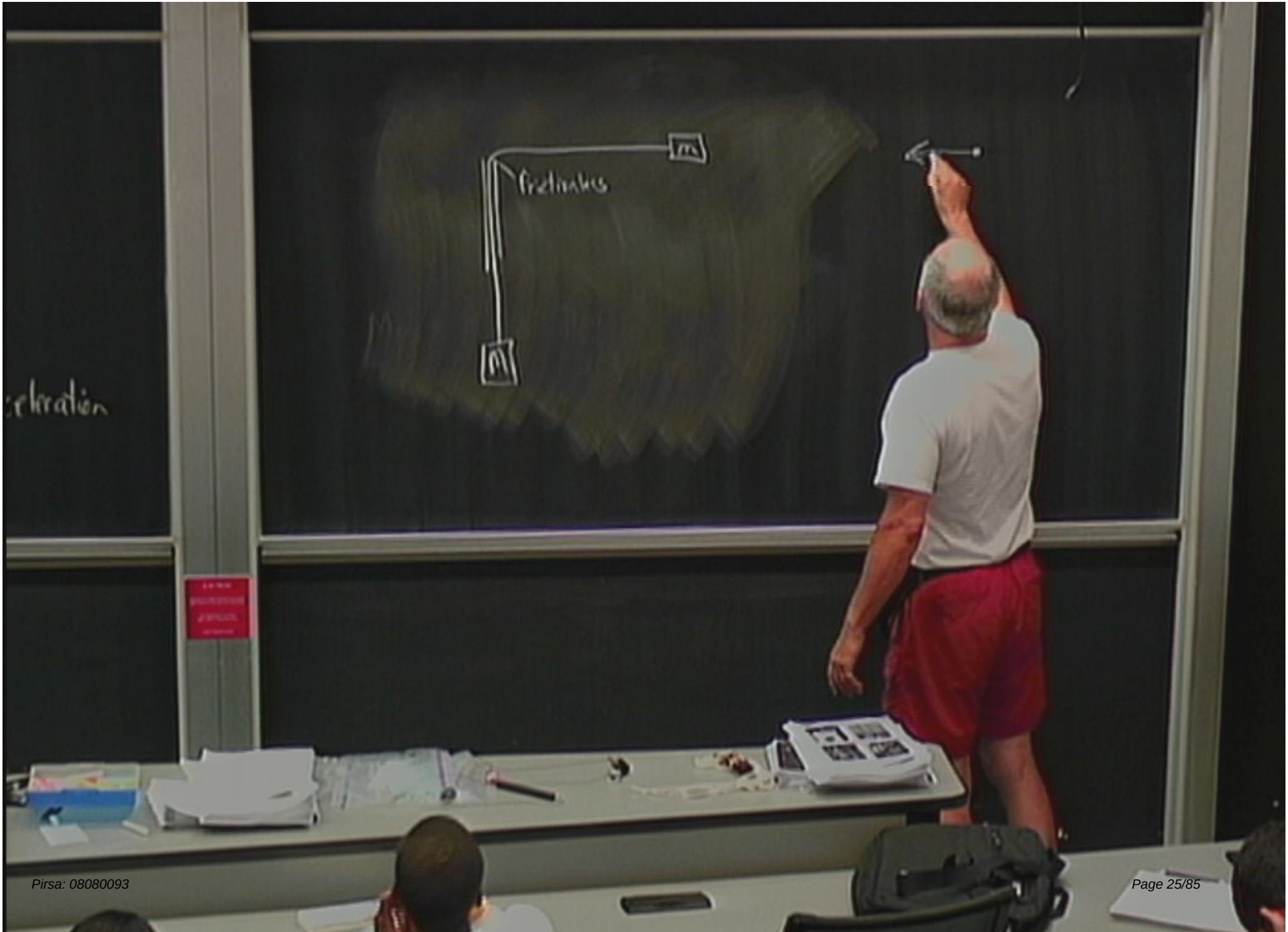
$$a = \frac{\Delta v}{\Delta t}$$

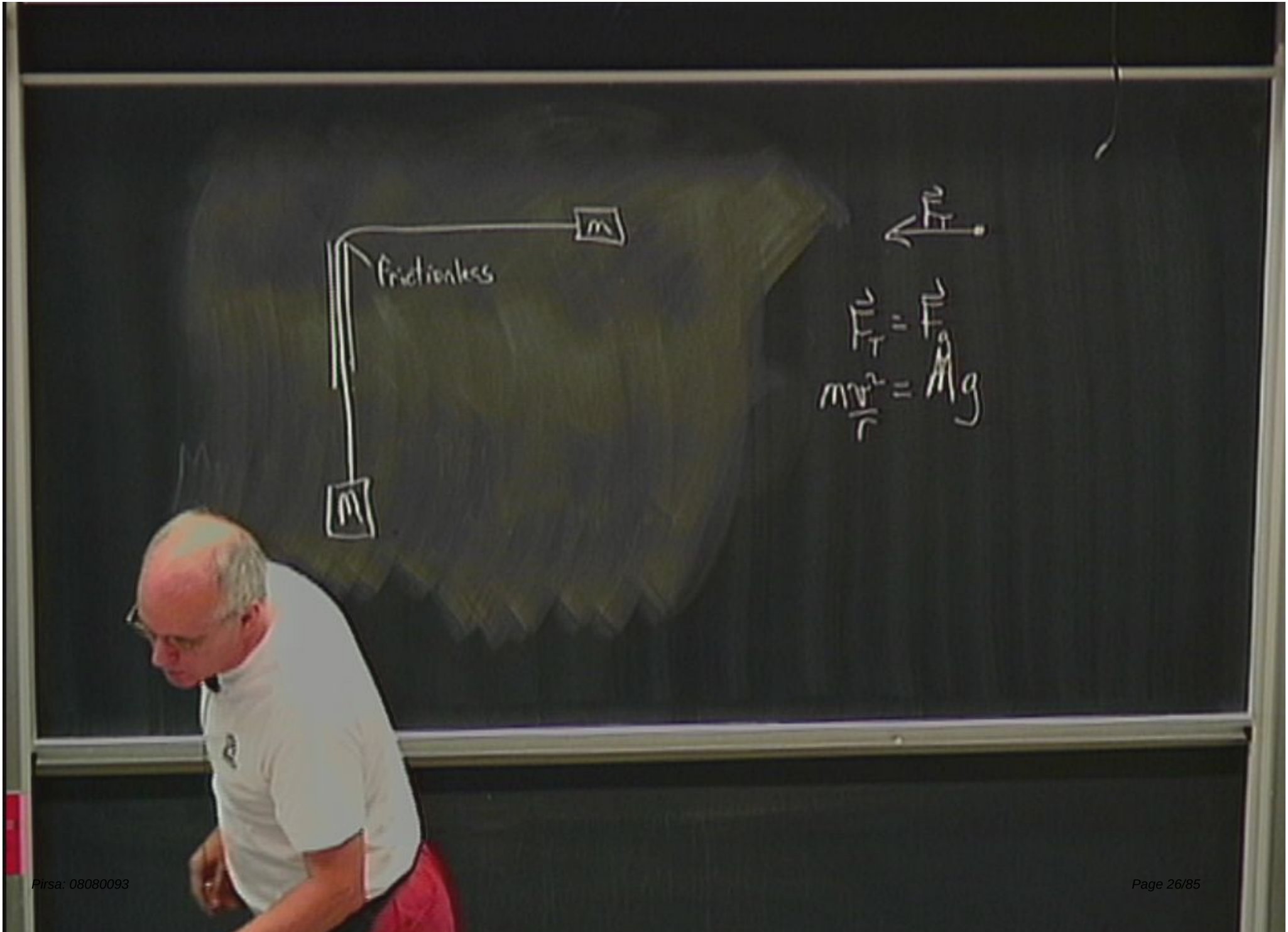
$$a = \frac{dv}{r\,dt}$$

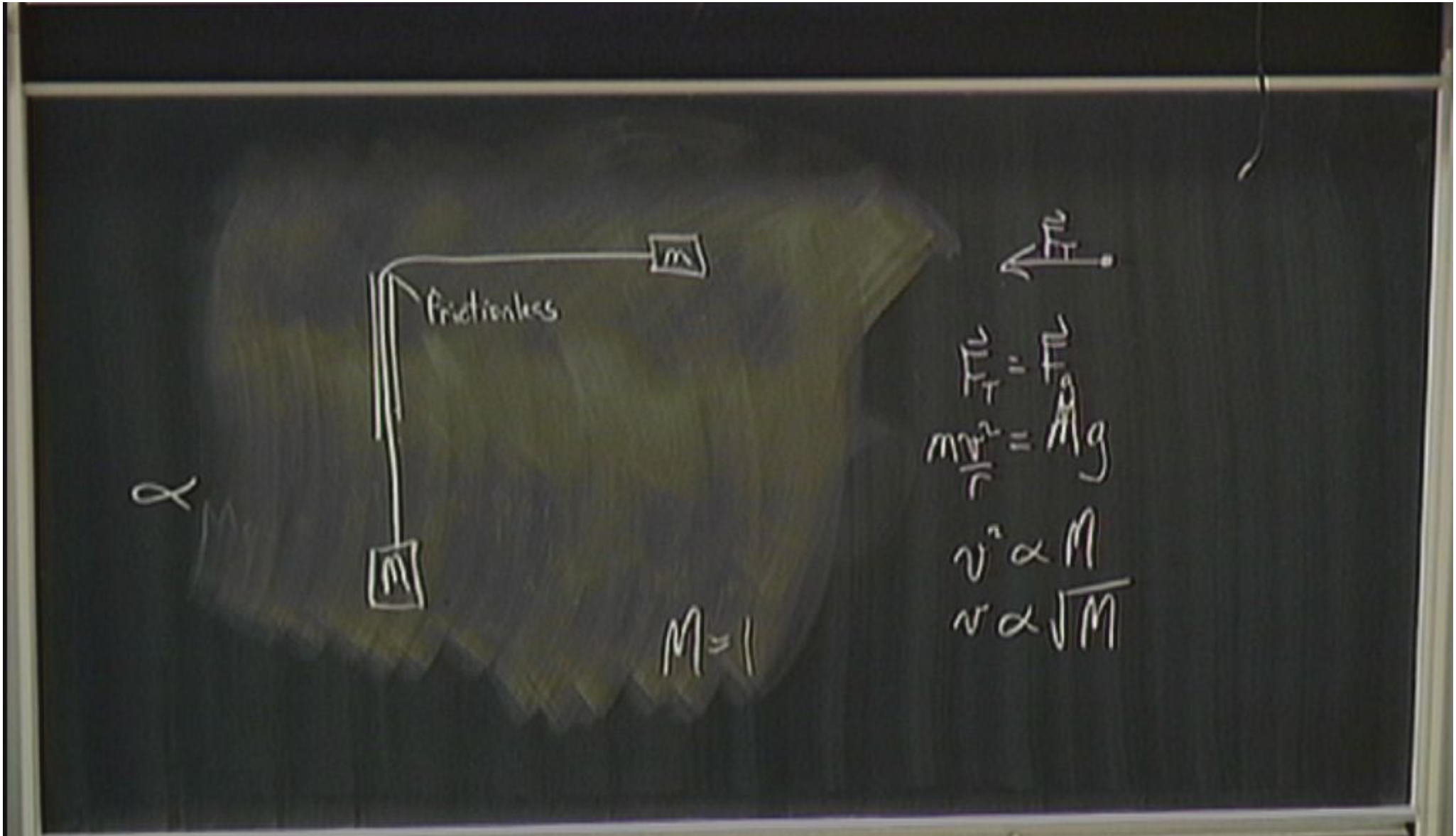
$$= \frac{v \times v}{r}$$

$$\boxed{a = \frac{v^2}{r}}$$

centripetal acceleration


m
m


M
Frictionless
M
T
T
$\frac{mv^2}{r} = Mg$


M
Frictionless
M
α M
M = 1
F_T
$F_T = F_G$
$\frac{mv^2}{r} = Mg$
$v^2 \alpha M$
$v \alpha \sqrt{M}$

$$\frac{\Delta v}{v} = \frac{d}{r} \Rightarrow \Delta v = \frac{dv}{r}$$

$$a = \frac{\Delta v}{\Delta t}$$

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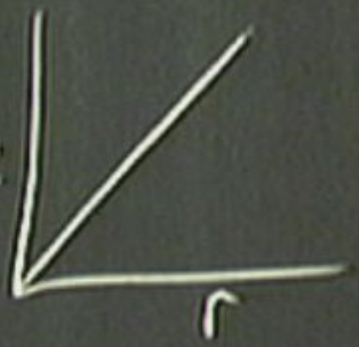
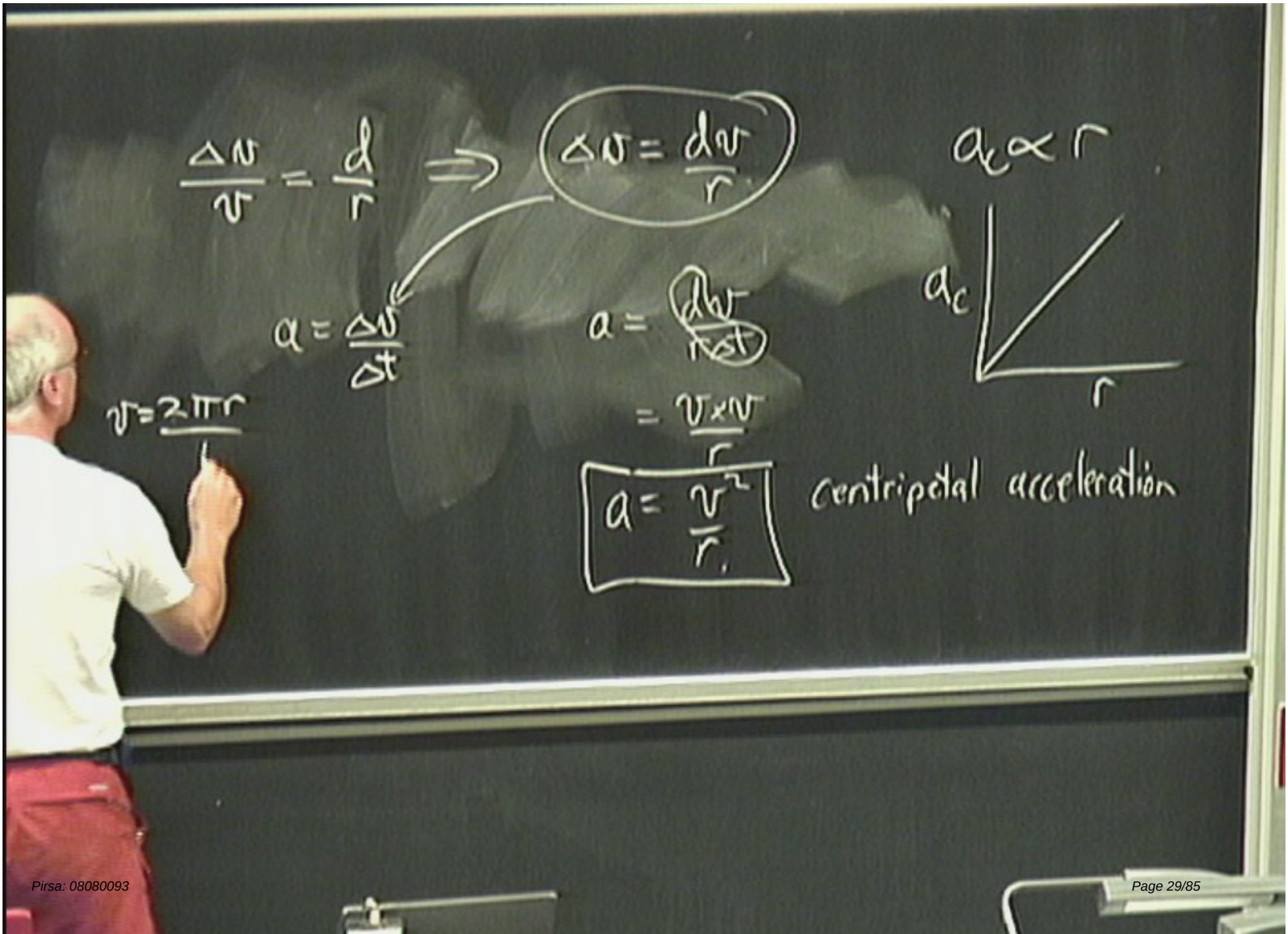
$$= \frac{v \times v}{r}$$

$$\boxed{a = \frac{v^2}{r}}$$

centripetal acceleration

$a_c \propto r$

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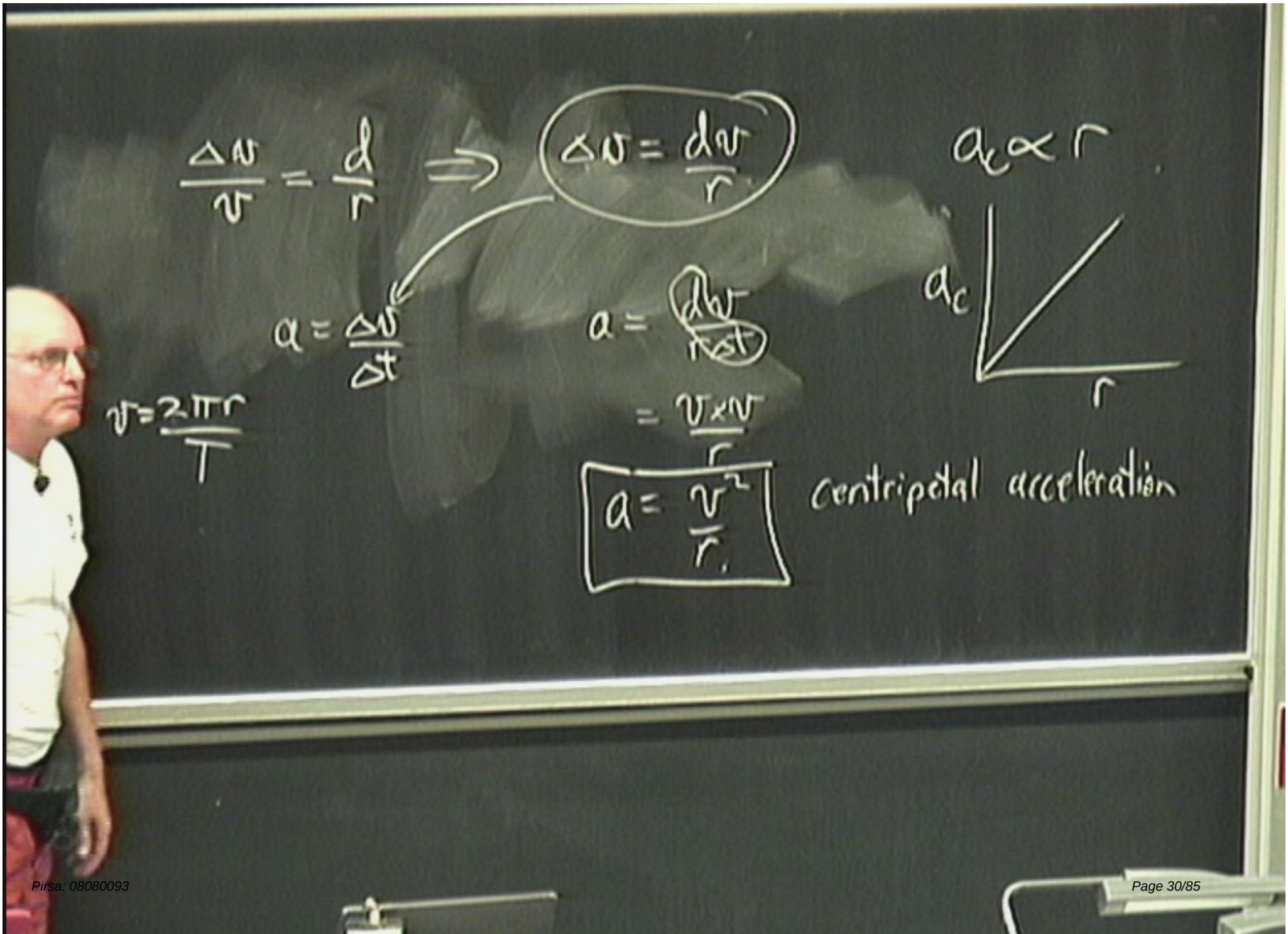
$a_c \propto r$
$a = \frac{\Delta v}{\Delta t}$
$a = \frac{dv}{r\,dt}$
a_c
r
$v = \frac{2\pi r}{T}$
$= \frac{v \times v}{r}$
$a = \frac{v^2}{r}$
centripetal acceleration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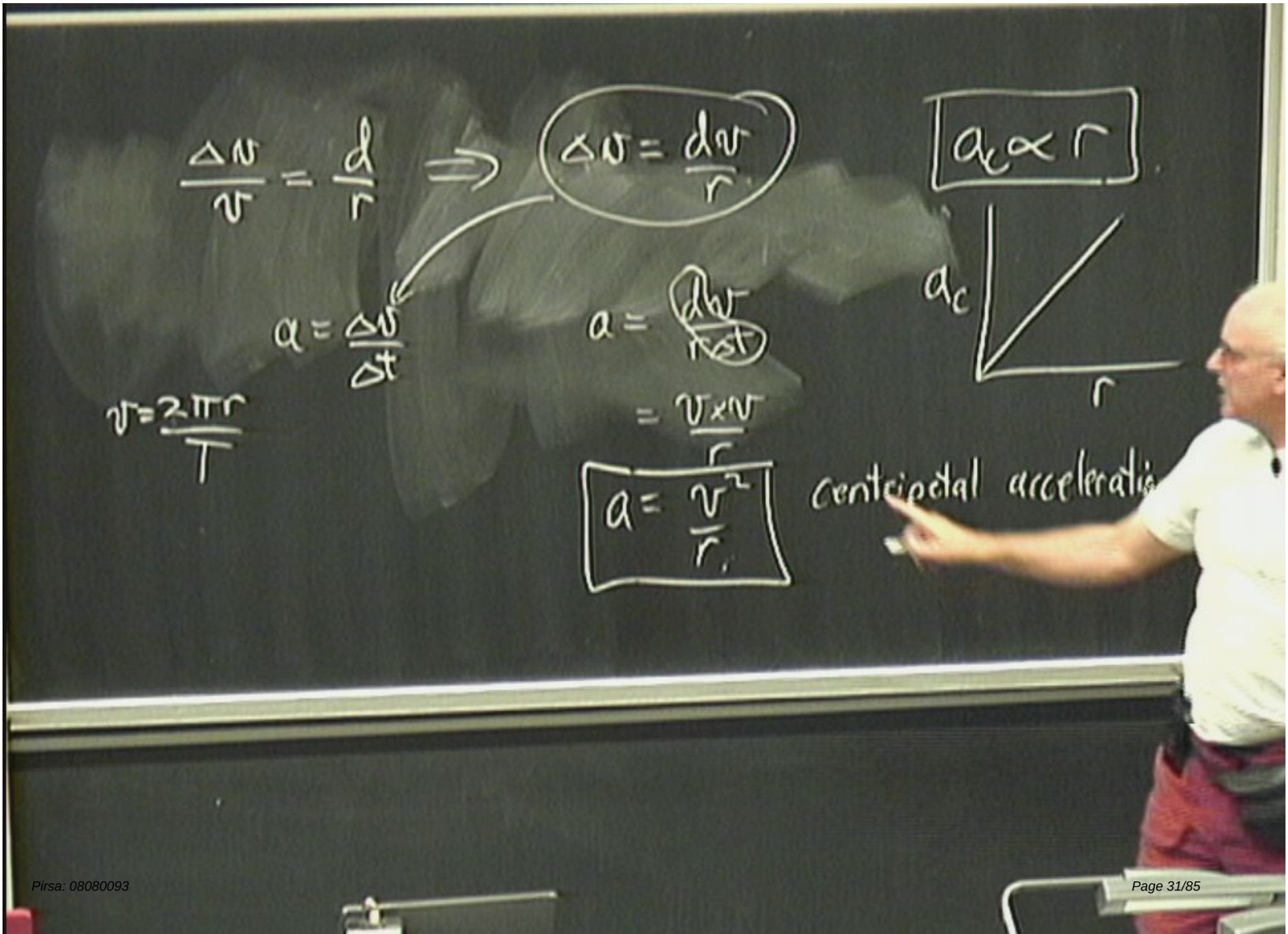
$a = \frac{dv}{r\,dt}$
a_c
r
$v = \frac{2\pi r}{T}$
$= \frac{v \times v}{r}$
$a = \frac{v^2}{r}$
centripetal acceleration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$a = \frac{\Delta v}{\Delta t}$
$a = \frac{dv}{dt}$
a_c
r
$v = \frac{2\pi r}{T}$
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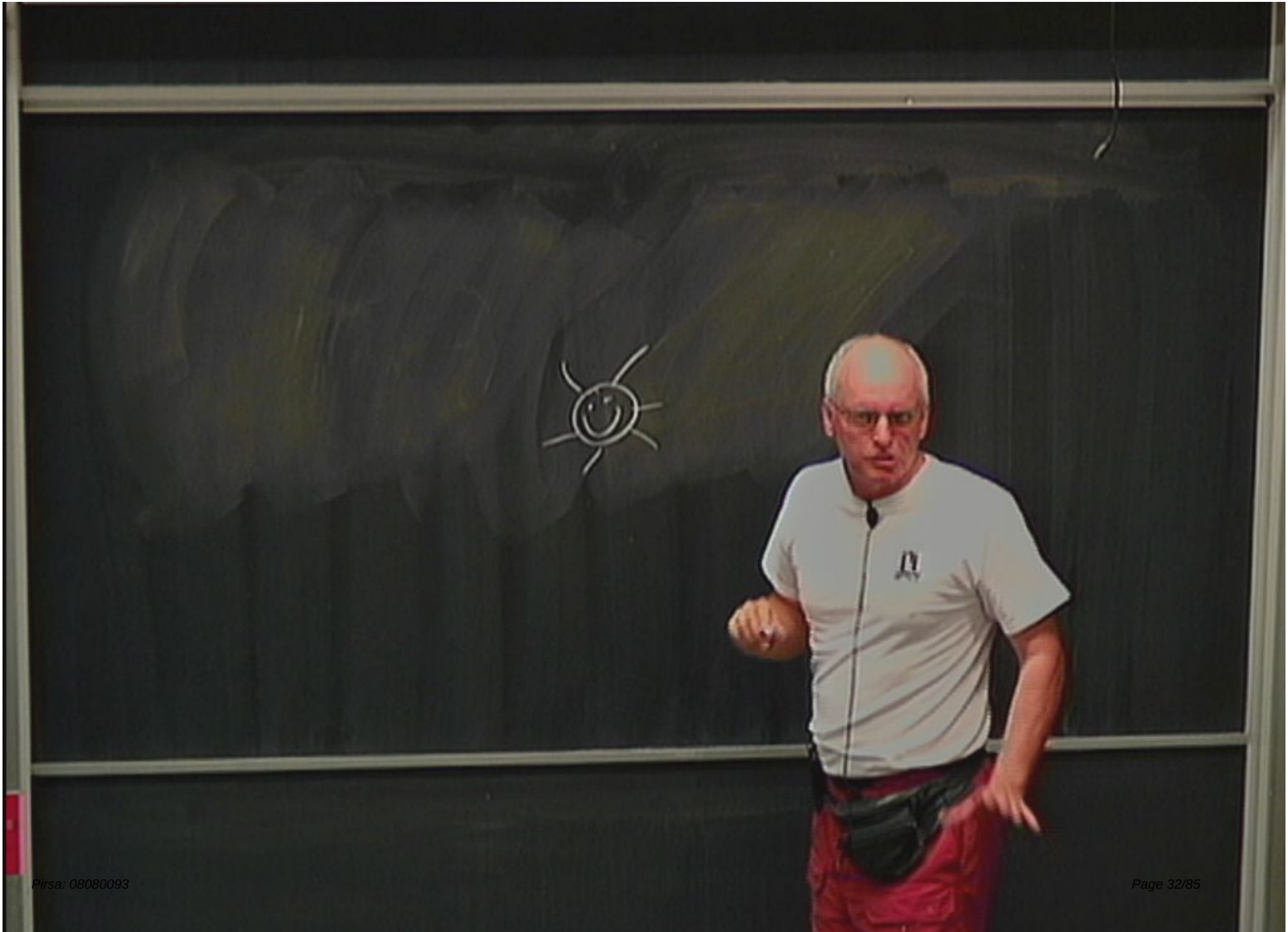
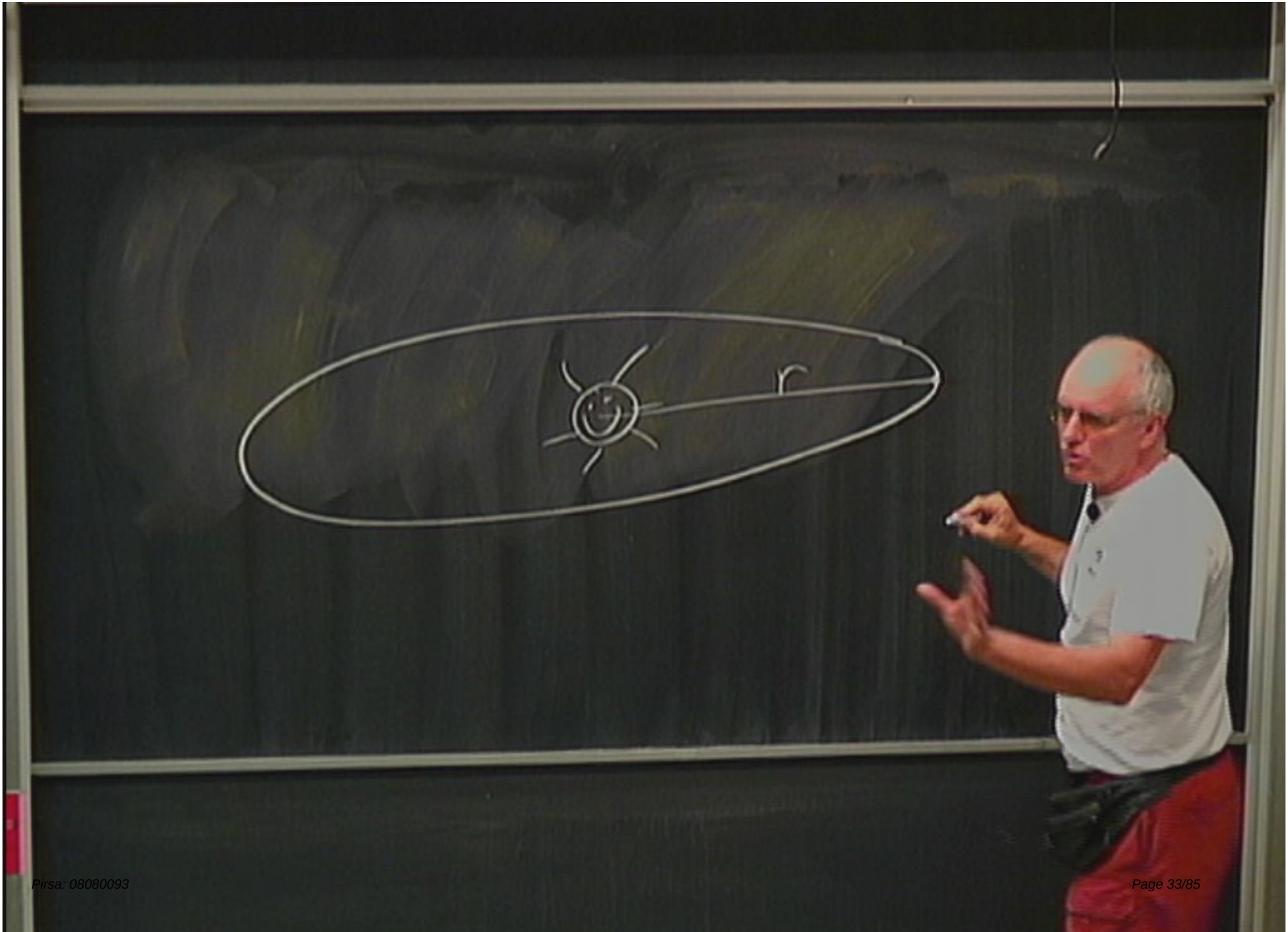
$a = \frac{v^2}{r}$
centripetal acceleratio

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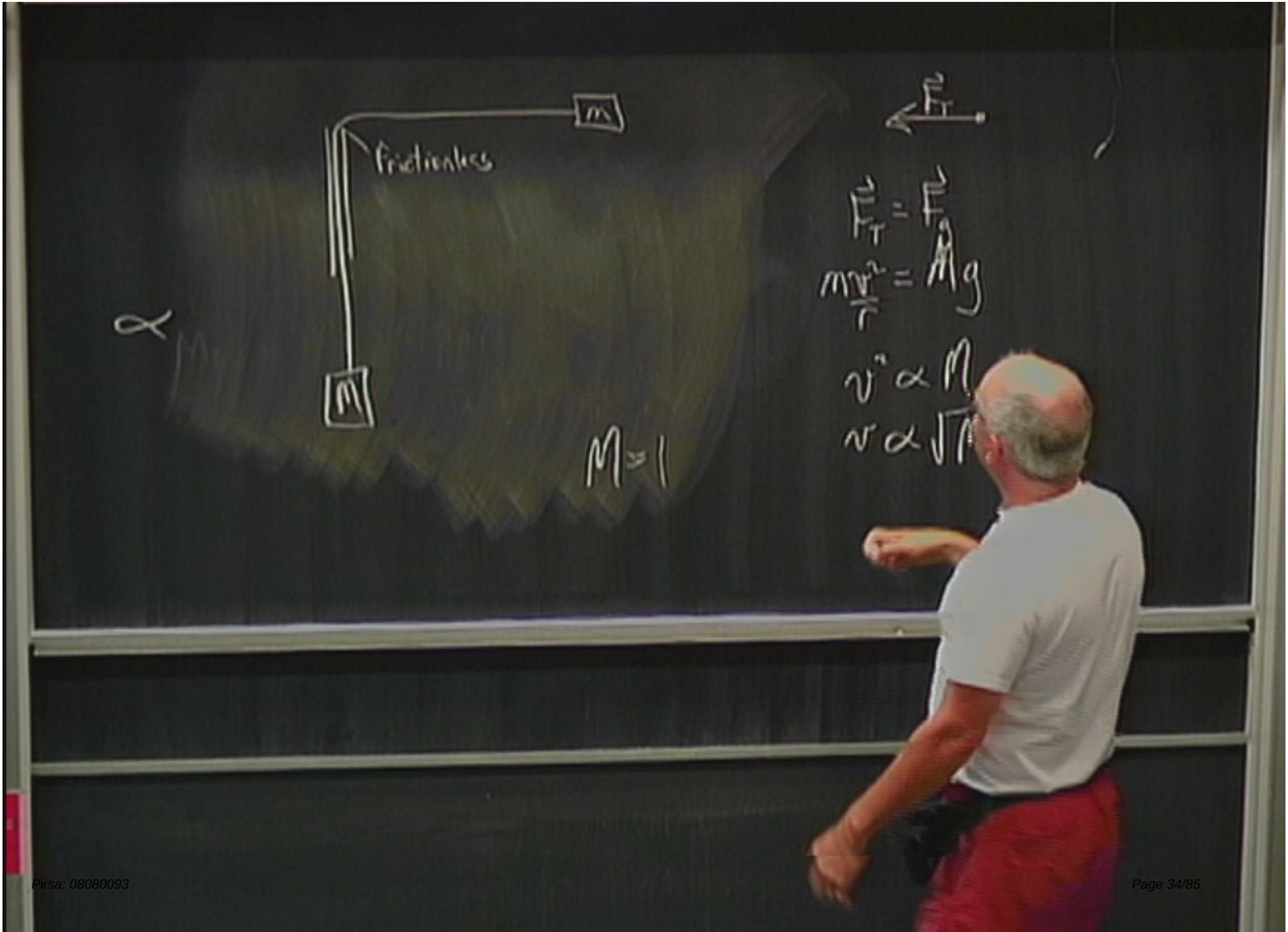
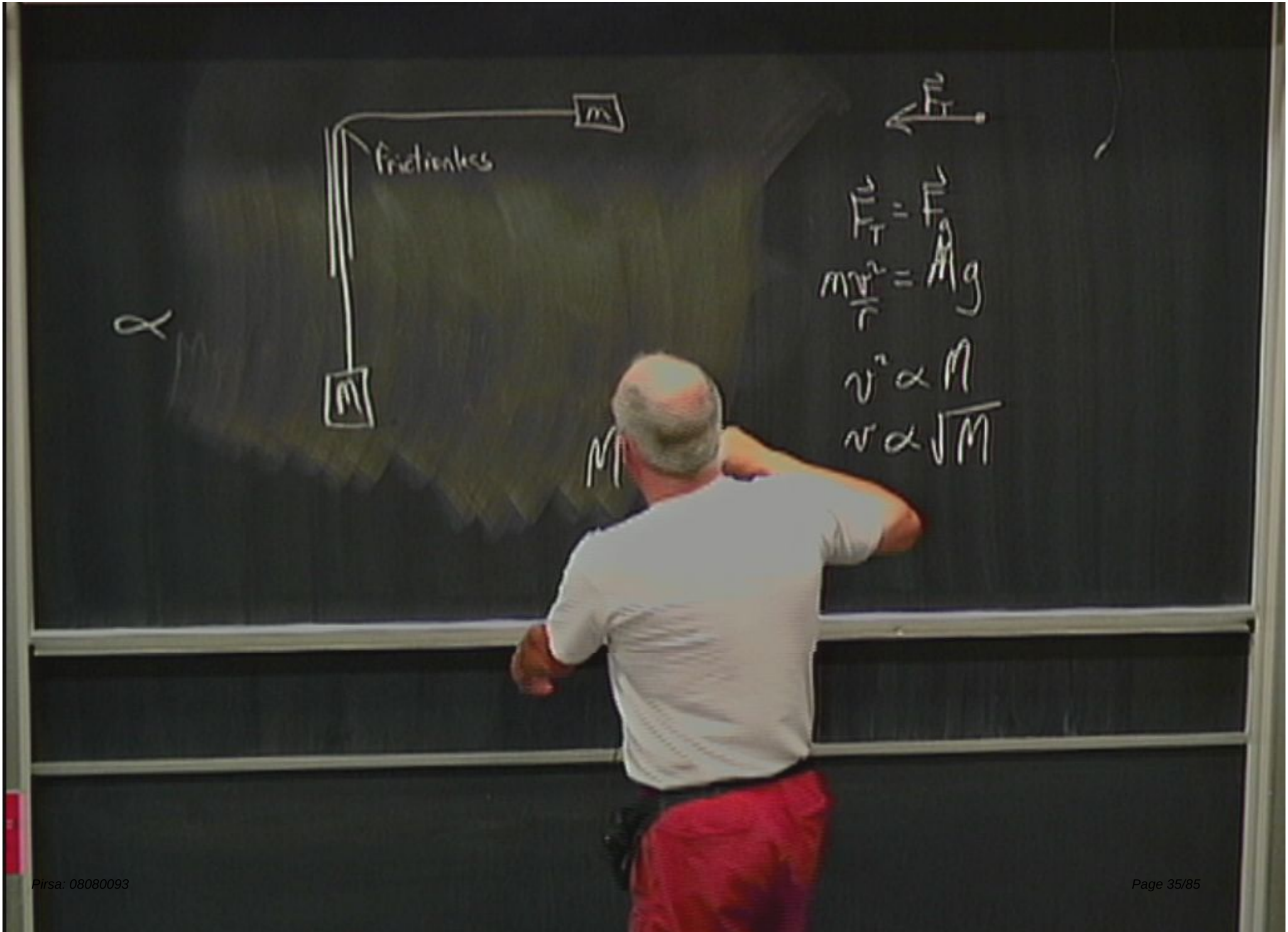
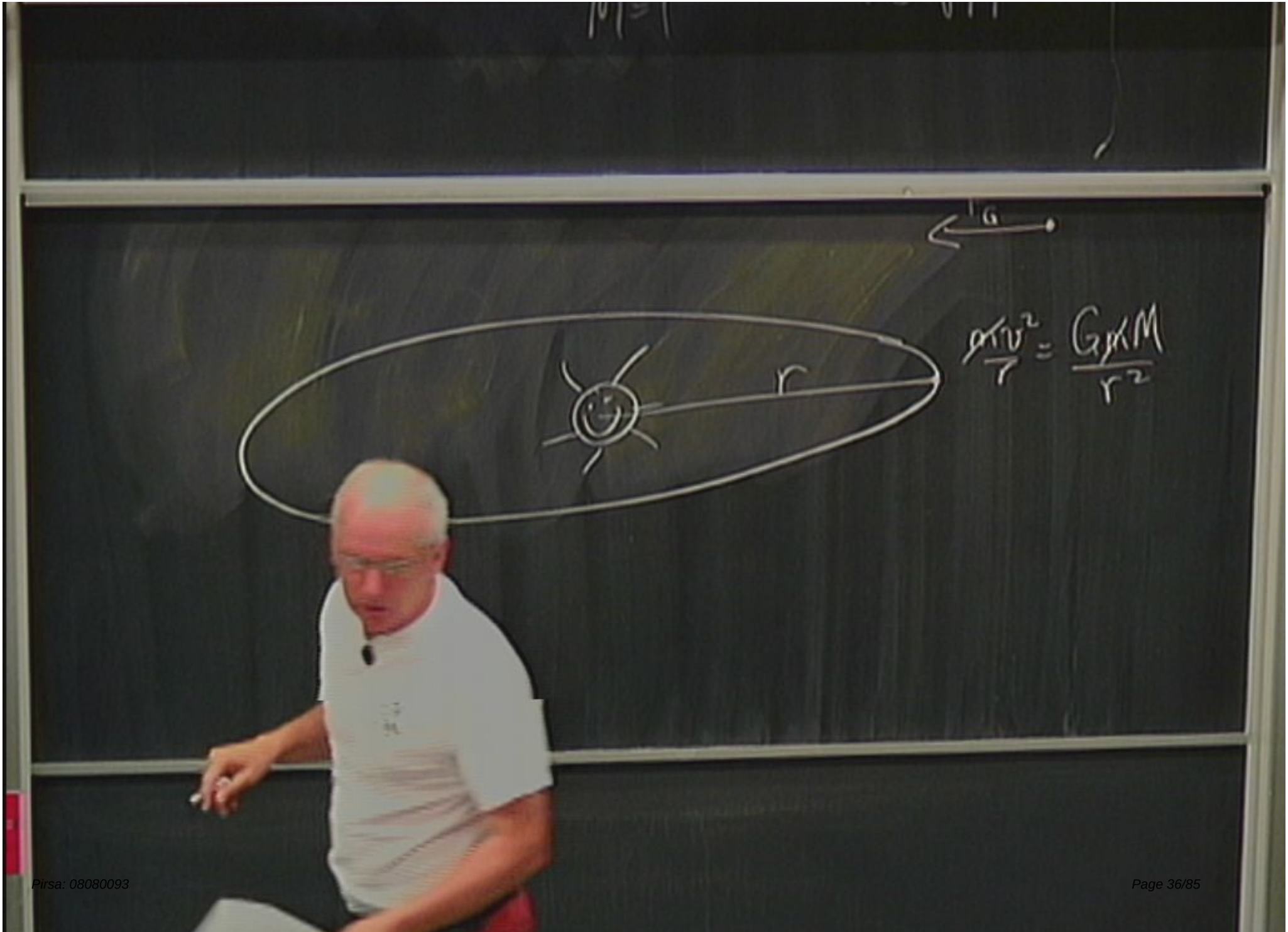
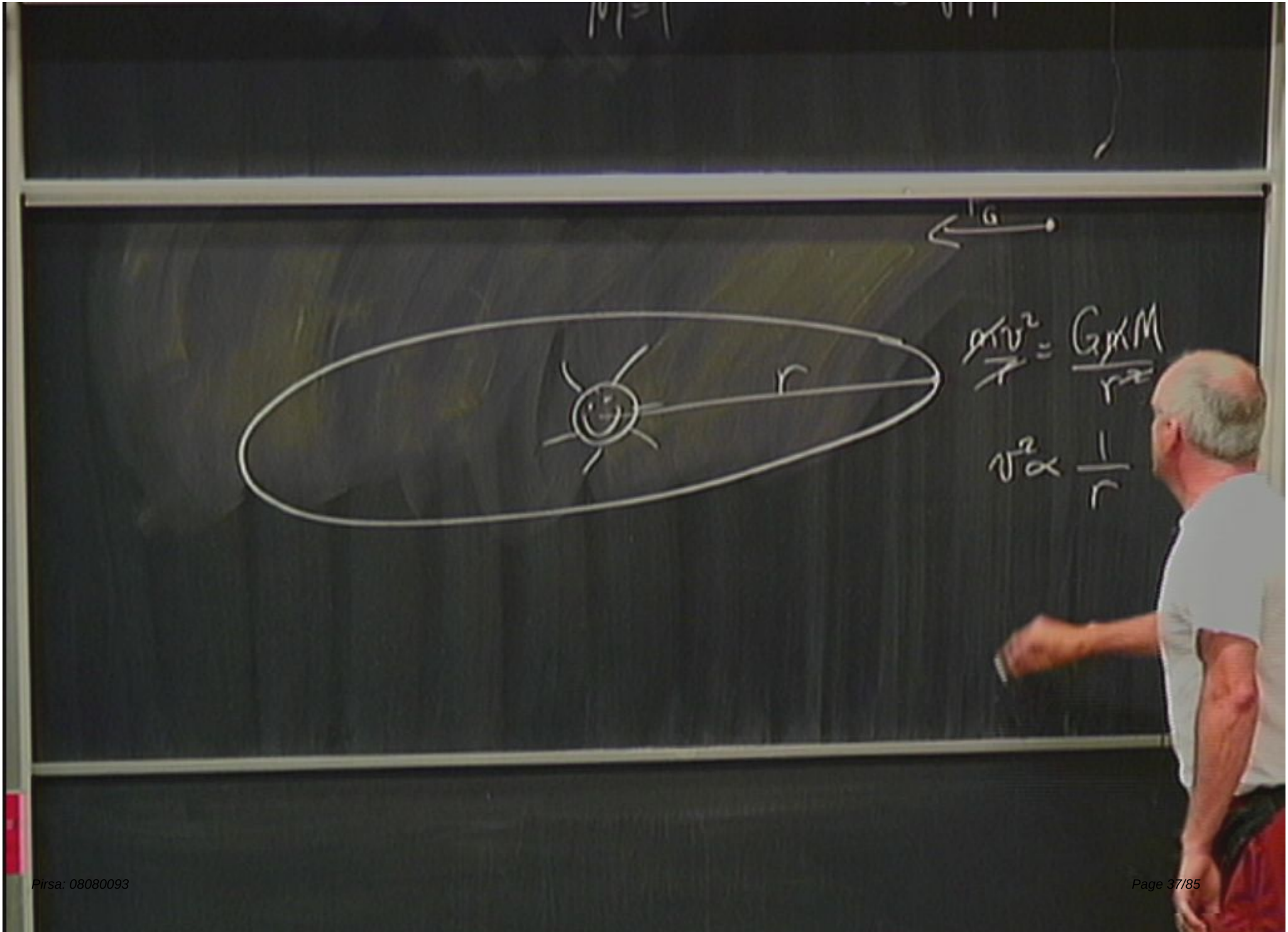
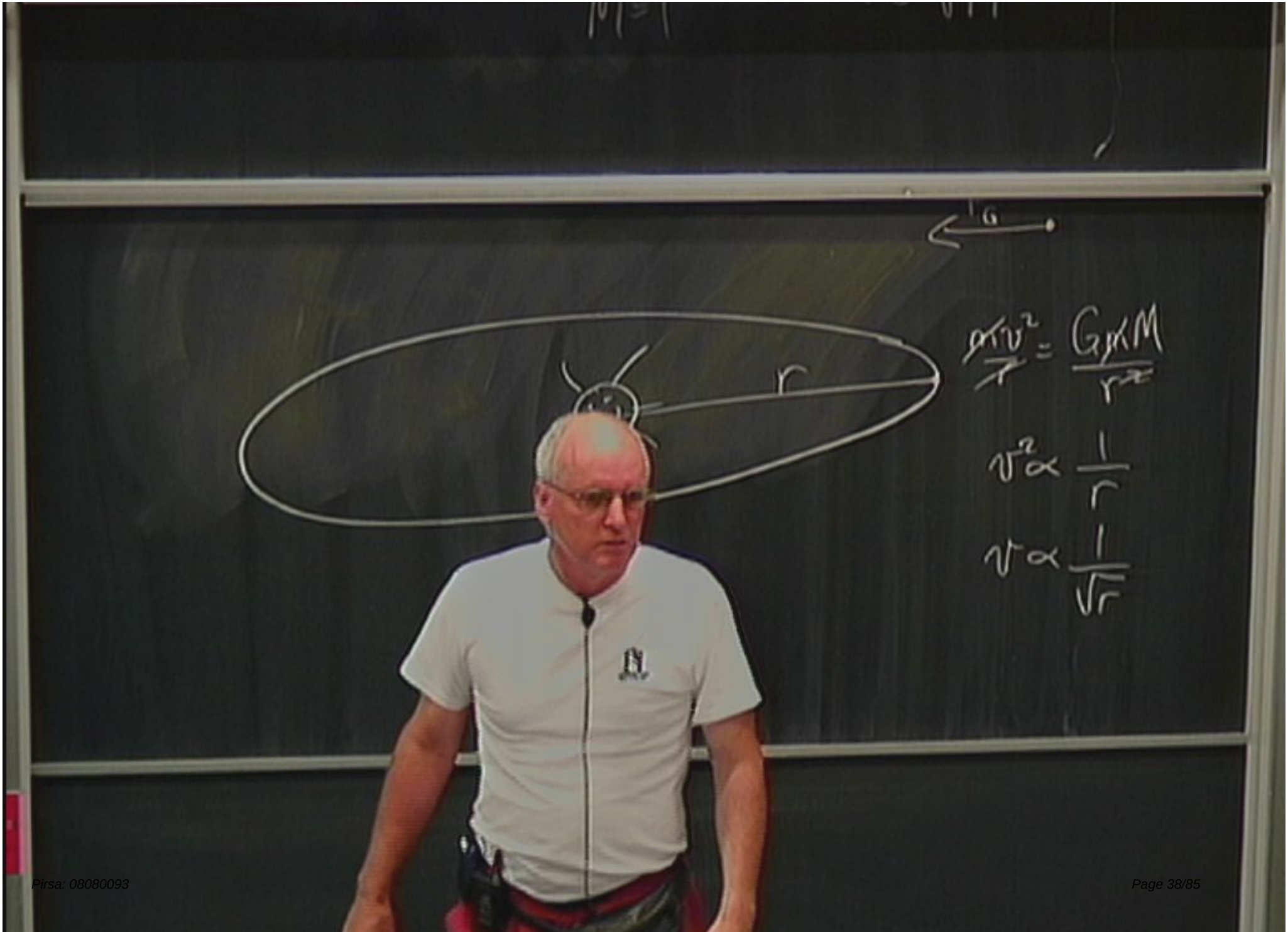
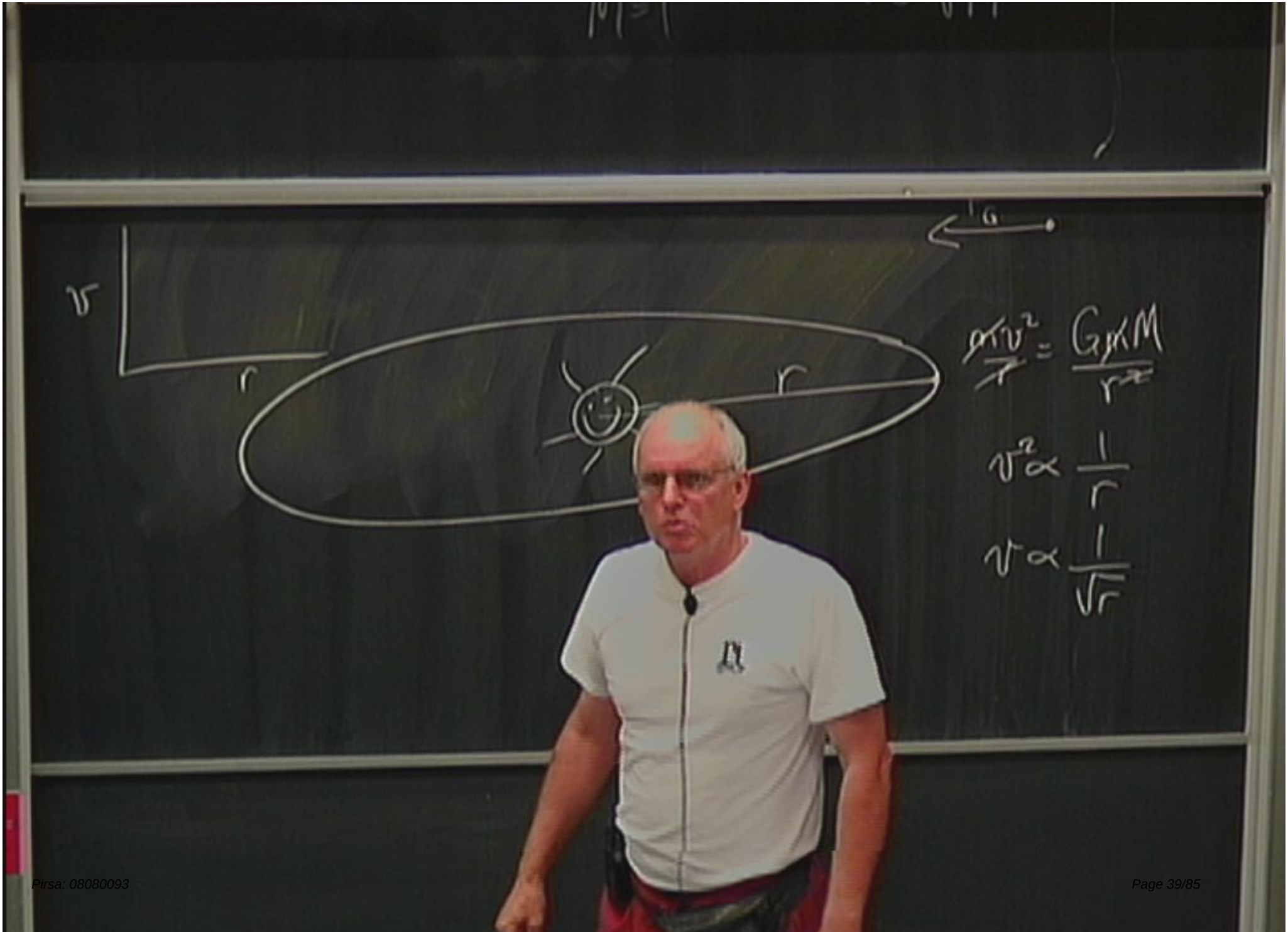

m
Frictionless
m
F_T
$F_T = F_g$
$\frac{mv^2}{r} = Mg$
$v^2 \propto M$
$v \propto \sqrt{M}$
$\propto$
M = 1

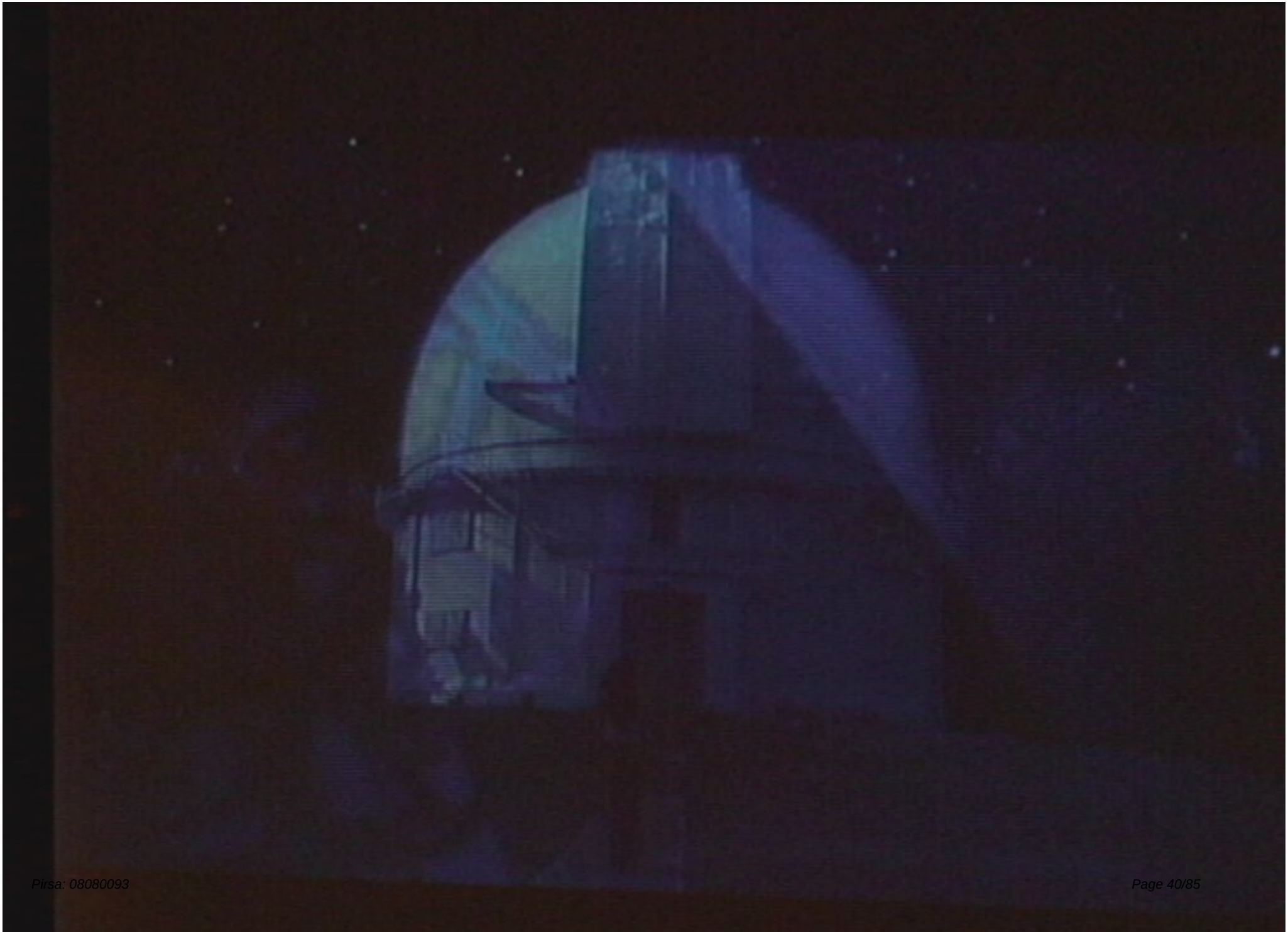

m
Frictionless
M
F_T
$F_T = F_G$
$\frac{mv^2}{r} = Mg$
$v^2 \propto M$
$v \propto \sqrt{M}$
$\propto$

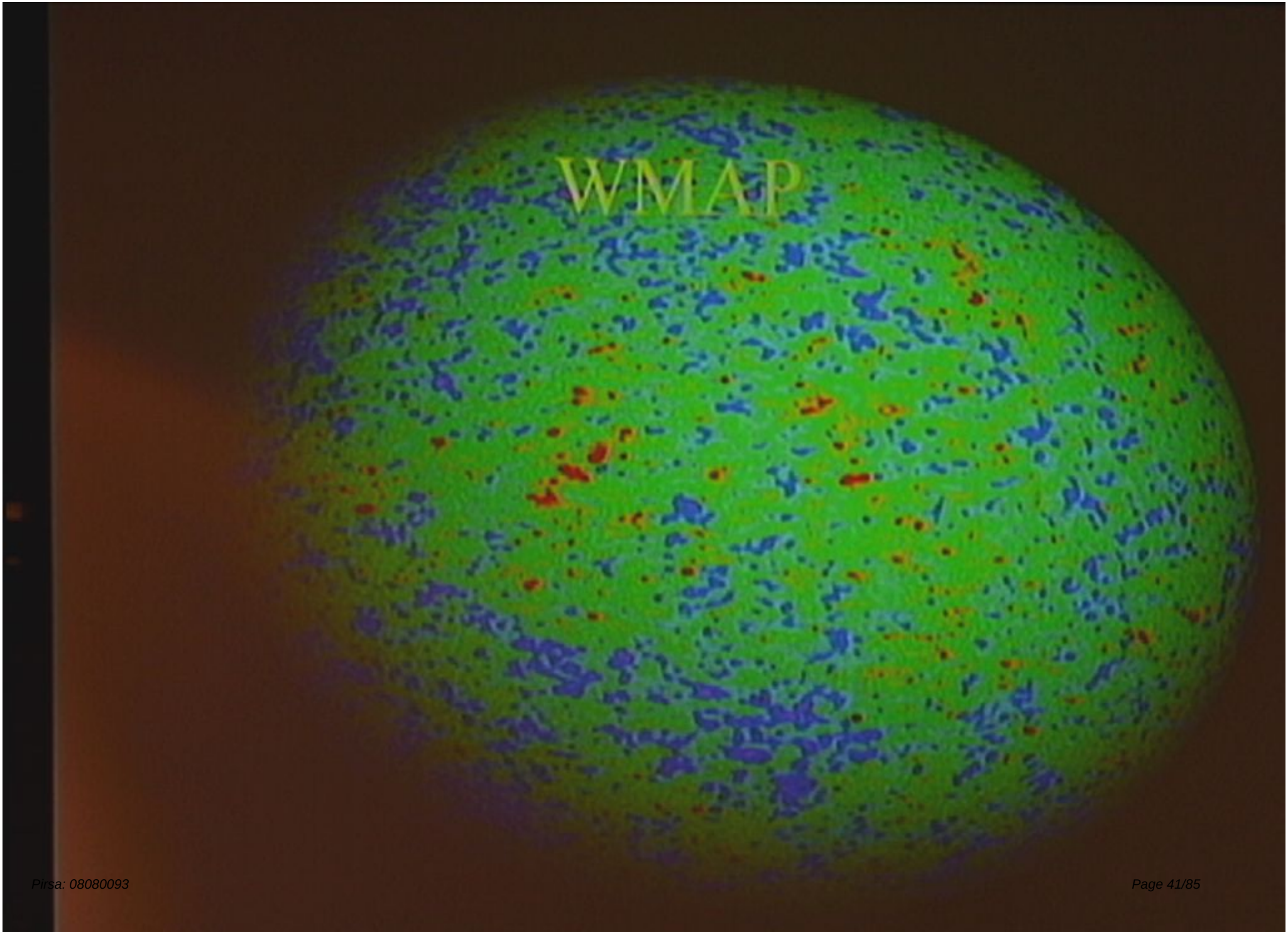

r
$\frac{\mu m v^2}{r} = \frac{G\mu m M}{r^2}$


G
r
$\frac{\alpha m v^2}{r} = \frac{G \alpha M}{r^2}$
$v^2 \propto \frac{1}{r}$


G
r
$\frac{mv^2}{r} = \frac{GmM}{r^2}$
$v^2 \propto \frac{1}{r}$
$v \propto \frac{1}{\sqrt{r}}$

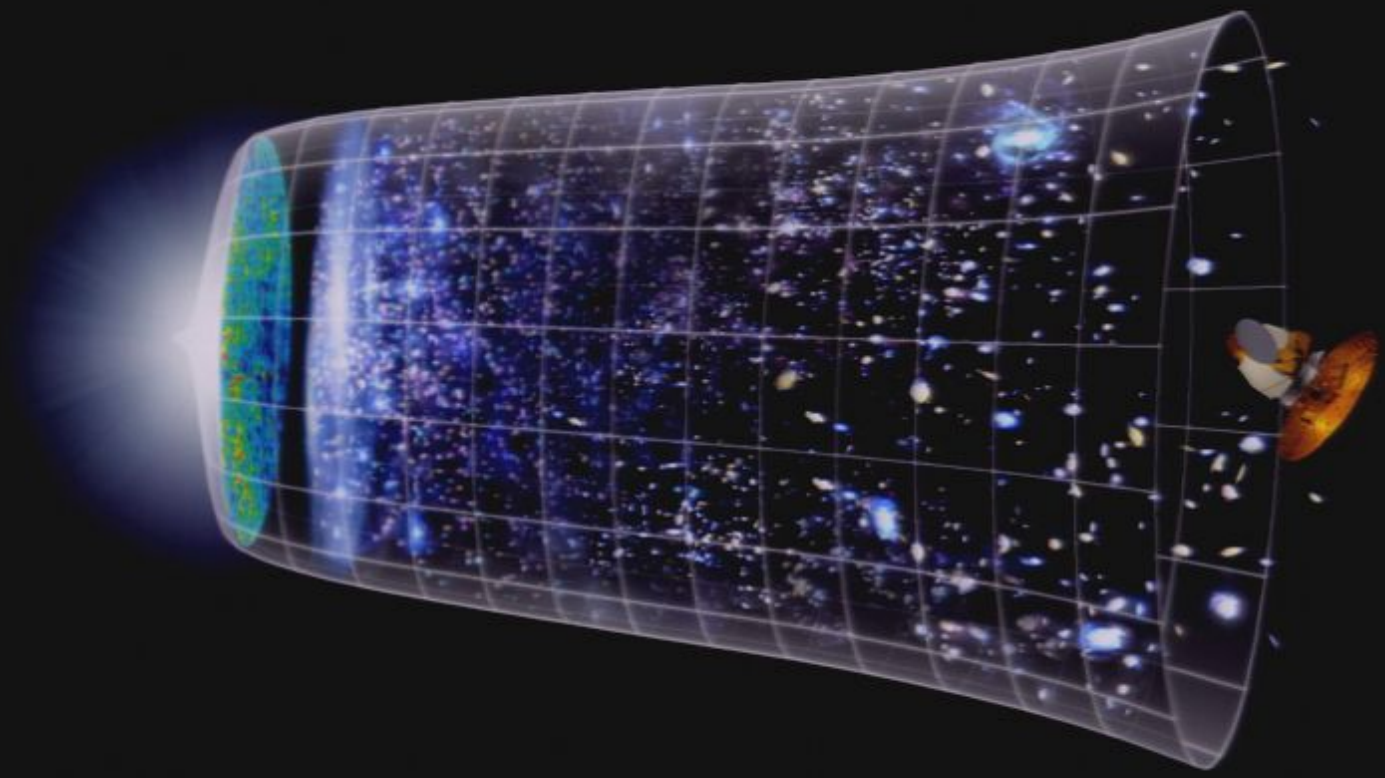

v
r
r
G
$\frac{mv^2}{r} = \frac{GmM}{r^2}$
$v^2 \propto \frac{1}{r}$
$v \propto \frac{1}{\sqrt{r}}$




WMAP


Baryons = you, me, cows, planets, stuff…

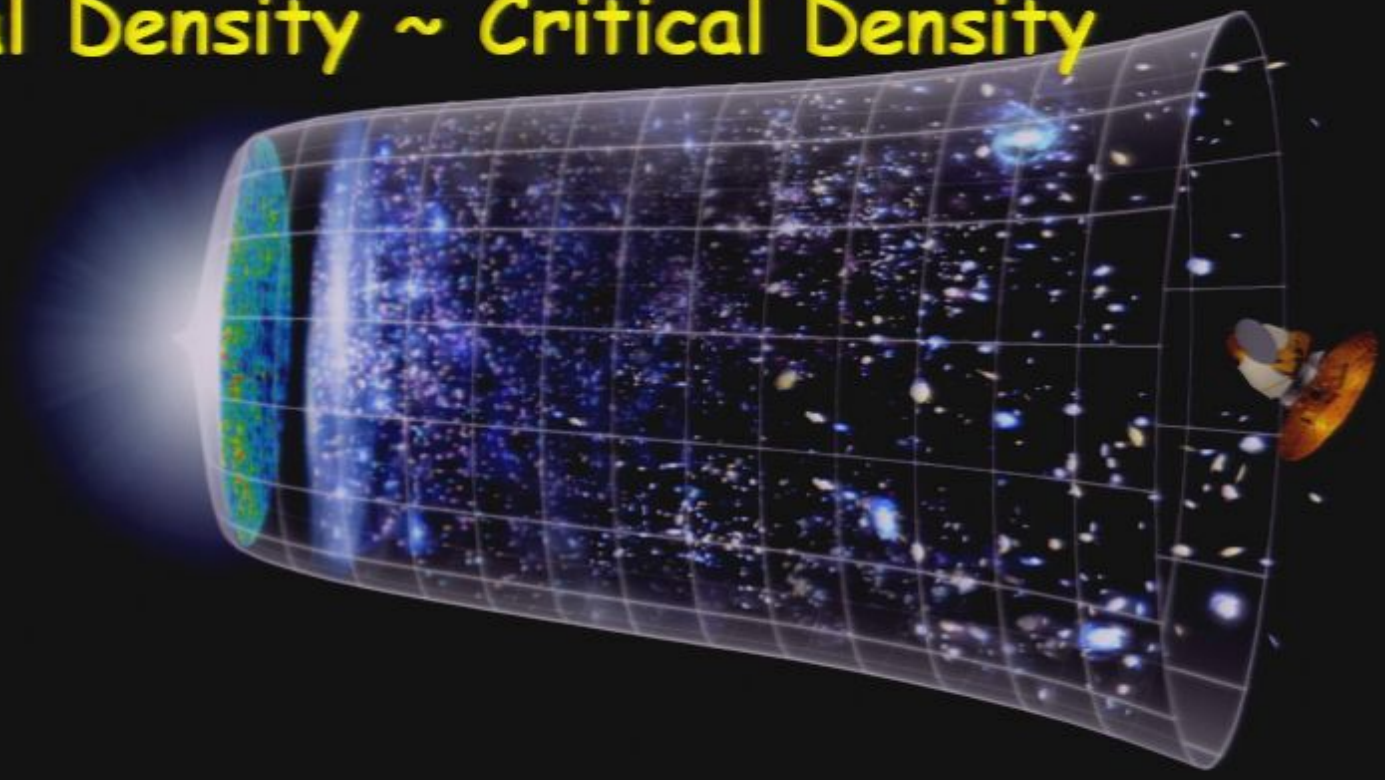
Density Budget of the Early Universe



Baryons = you, me, cows, planets, stuff…

Density Budget of the Early Universe

- Total Density ~ Critical Density

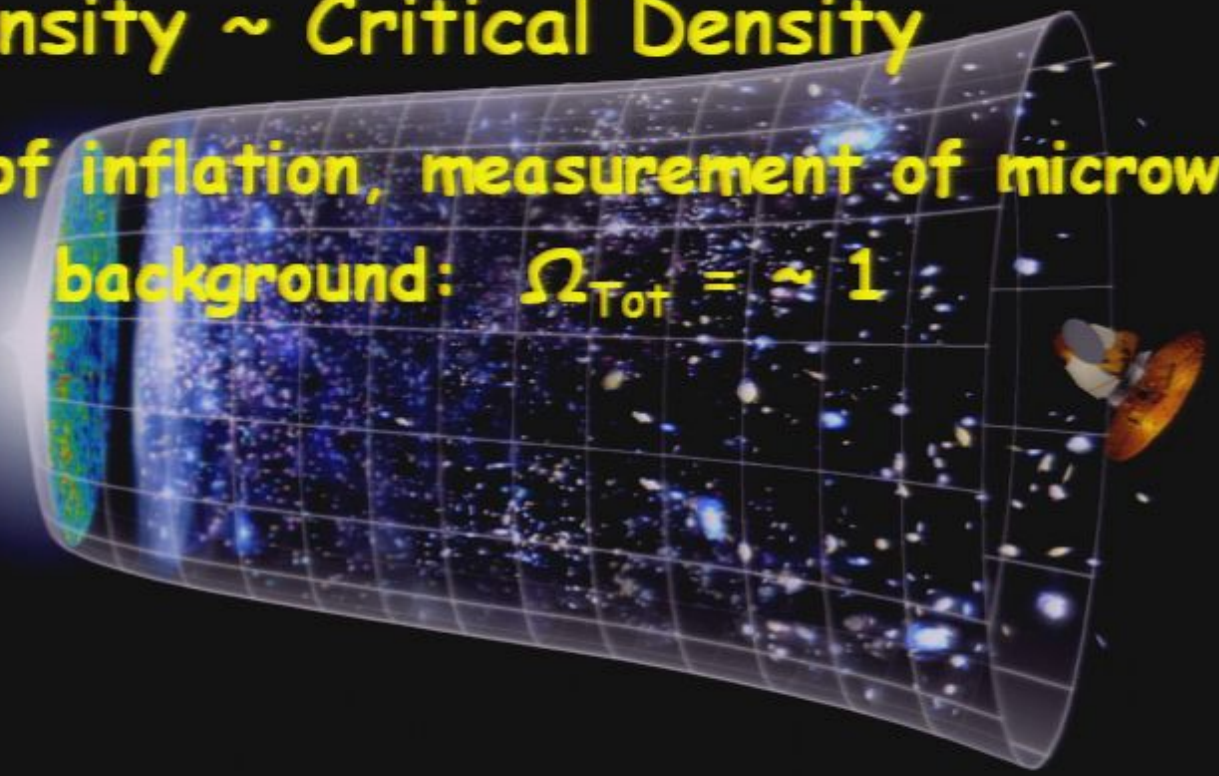


Baryons = you, me, cows, planets, stuff…

Density Budget of the Early Universe

- Total Density ~ Critical Density

Theory of inflation, measurement of microwave background: $\Omega_{Tot} = \sim 1$

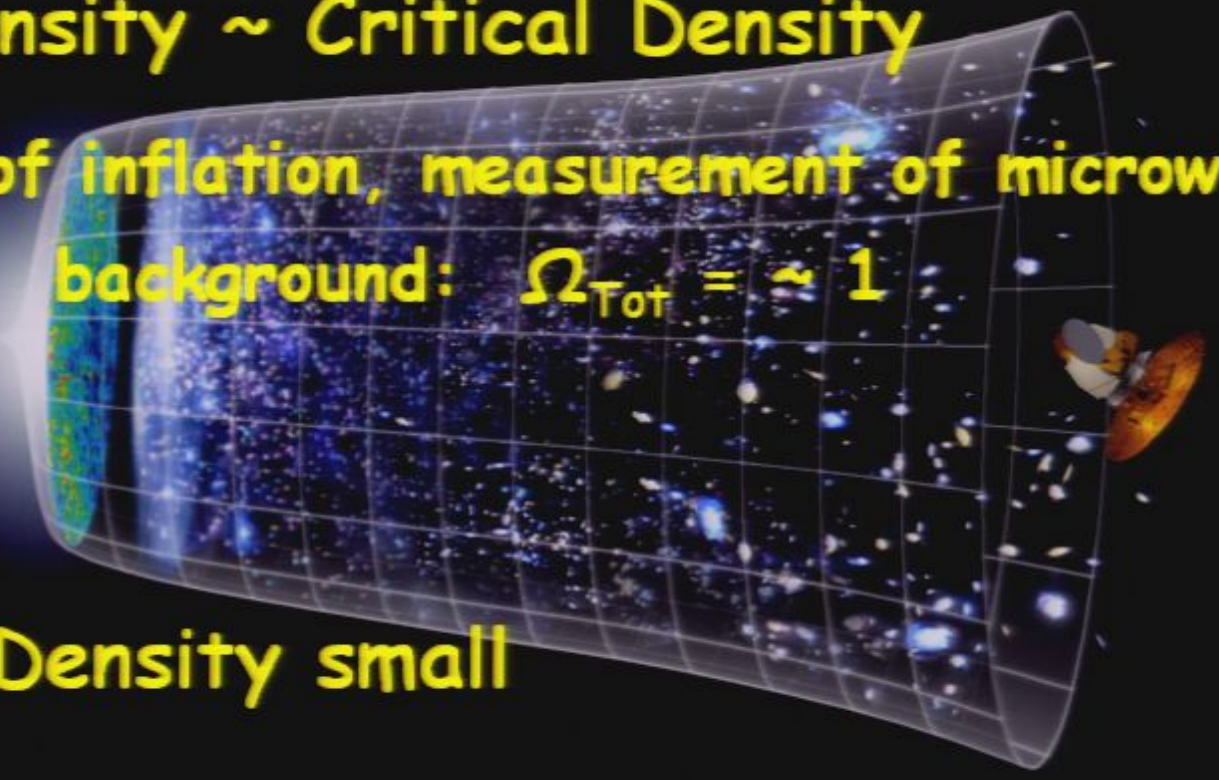


Baryons = you, me, cows, planets, stuff…

Density Budget of the Early Universe

- Total Density ~ Critical Density

  Theory of inflation, measurement of microwave background: $\Omega_{Tot} = \sim 1$

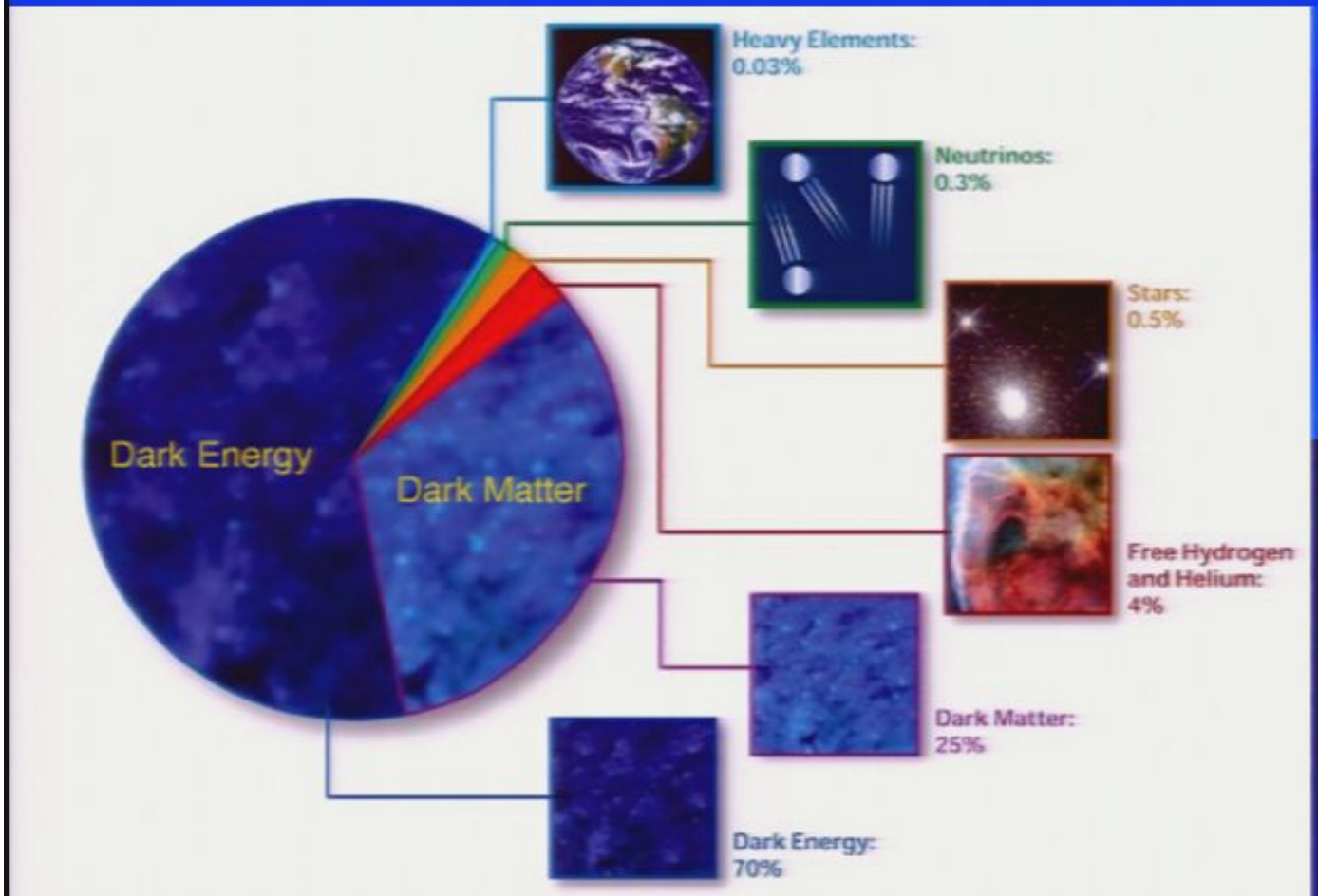


- Baryon Density small

$\Omega_{Baryons} \sim 5\ \%$

Baryons = you, me, cows, planets, stuff…

The Density Budget of the Universe




The Dark Side of the Universe
Darth Matter

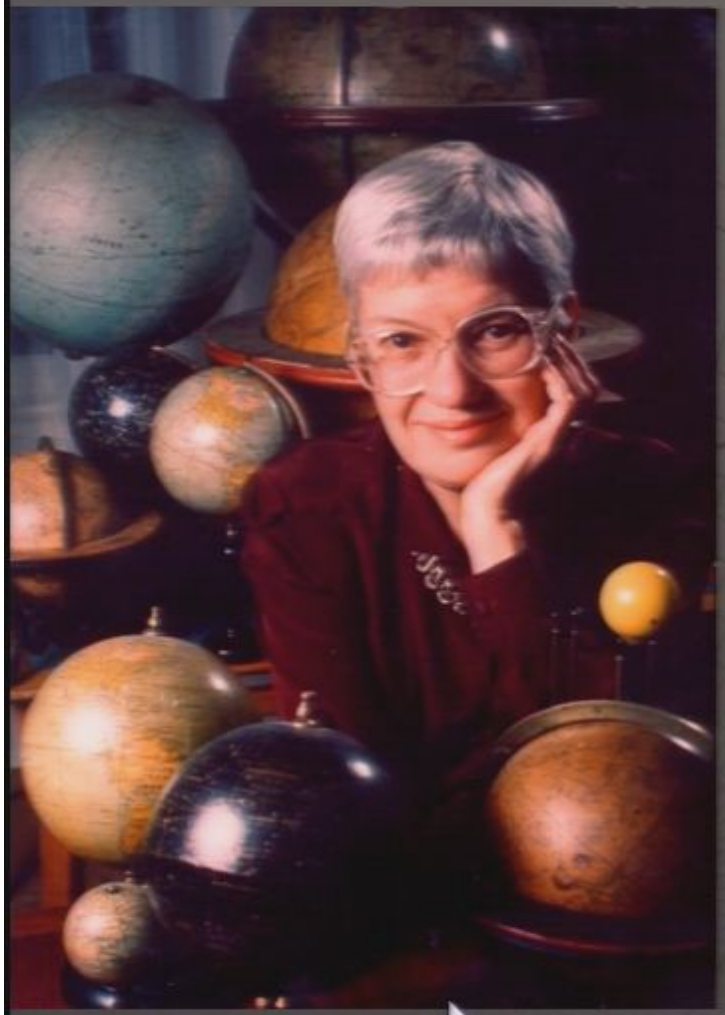


Photo credit: Mark Godfrey

Vera Rubin determined the velocities as a function of distance from the galactic center of clouds of ionized hydrogen (in astrophysical terminology, HII regions). This was done by measurement of the Doppler shift of their H-alpha emission lines. The hydrogen clouds move with the stars and other visible matter in the galaxies. Their velocities are more easily and directly measured than other visible matter.

Rubin found that the velocities of the clouds did not decrease with increasing distance from the galactic center, and in some cases even increased a little. This is in striking contrast to the decrease in velocity with radius predicted by Keplerian motion, which would occur if all the mass of the galaxy were concentrated in the center of the galaxy.

Detailed observations were first made by Rubin and W.K. Ford of the Andromeda galaxy and published in "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions," Astrophysical Journal 159, 379 (1970). They then made observations of over 60 other spiral galaxies which apparently confirmed that the presence of dark matter was a general phenomenon ["Rotation Velocities of 16 Sa Galaxies and a Comparison of Sa, Sb, and Sc Rotation Properties," Astrophys. J. 289, 81 (1985), with D. Burstein, W. K. Ford, Jr., and N. Thonnard].

An external galaxy; a spiral like our own.

An external galaxy; a spiral like our own.

Which way does it rotate?

An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?

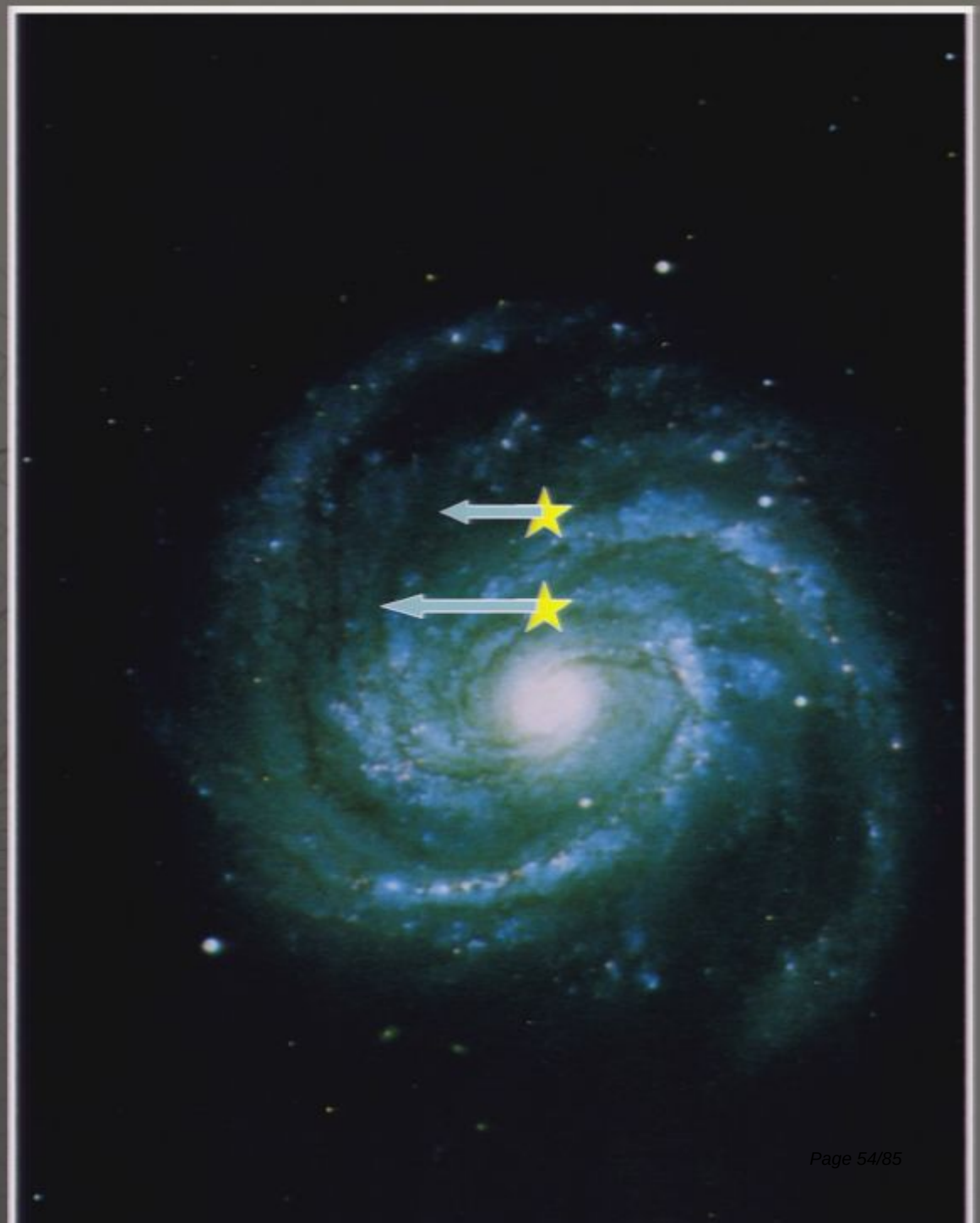
An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?

An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?

WRONG!

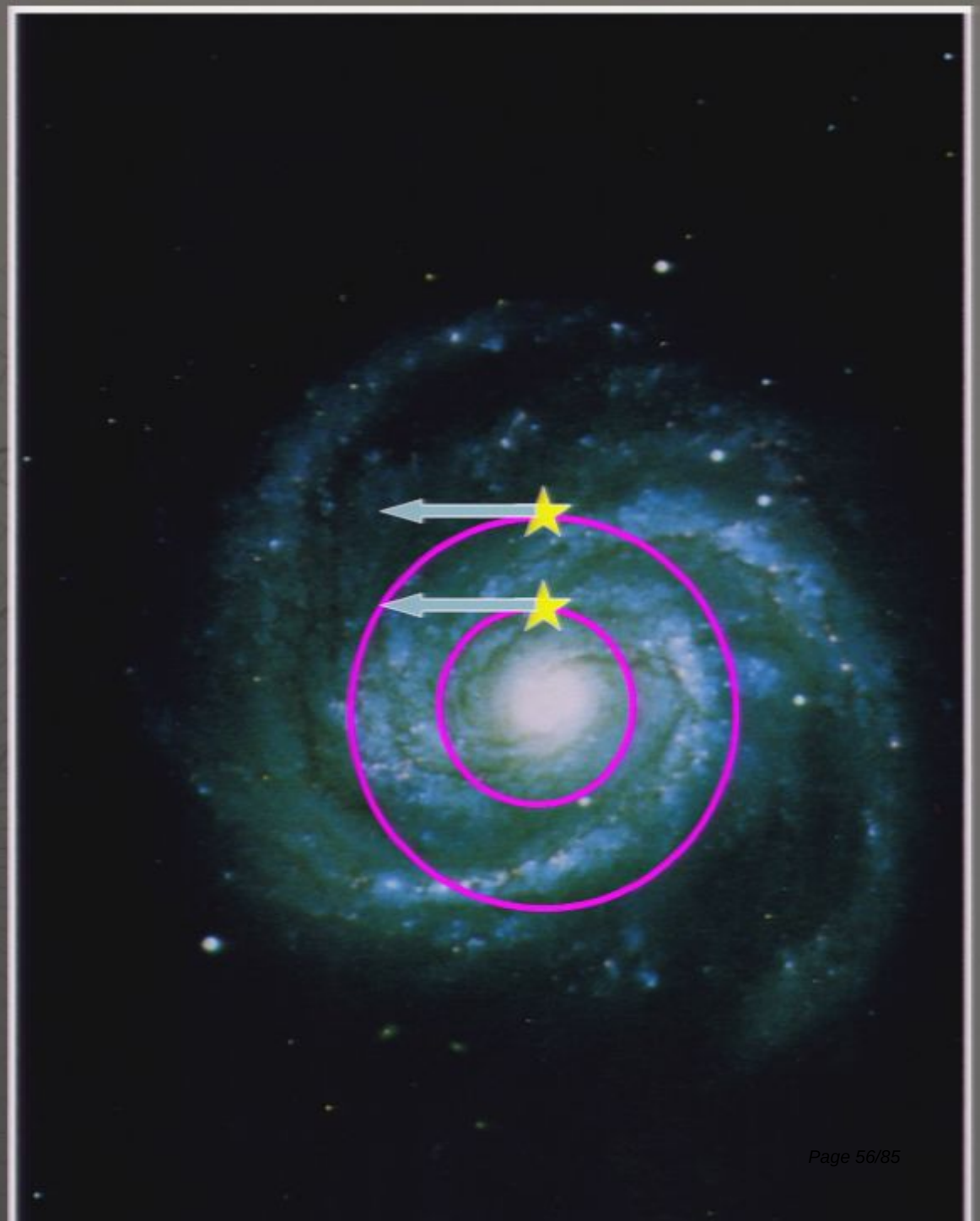


An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?

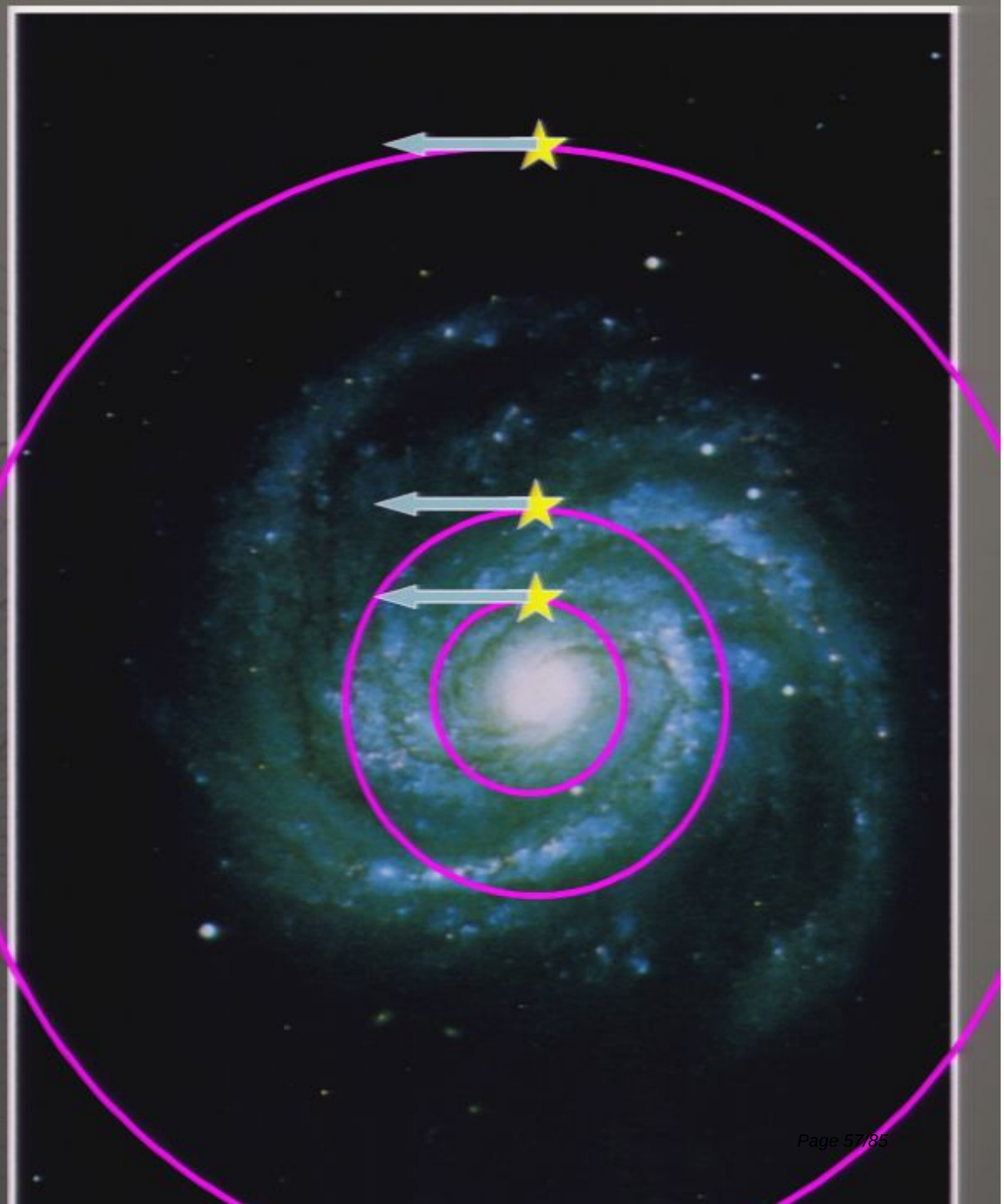
An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?



An external galaxy; a spiral like our own.

How does it rotate? i.e. what is rotation curve?



We believe that only 10% of the mass of this object is baryonic matter (in the form of stars, stellar remnants, interstellar gas, interstellar dust) and the other 90% is "dark matter"

Vera Rubin

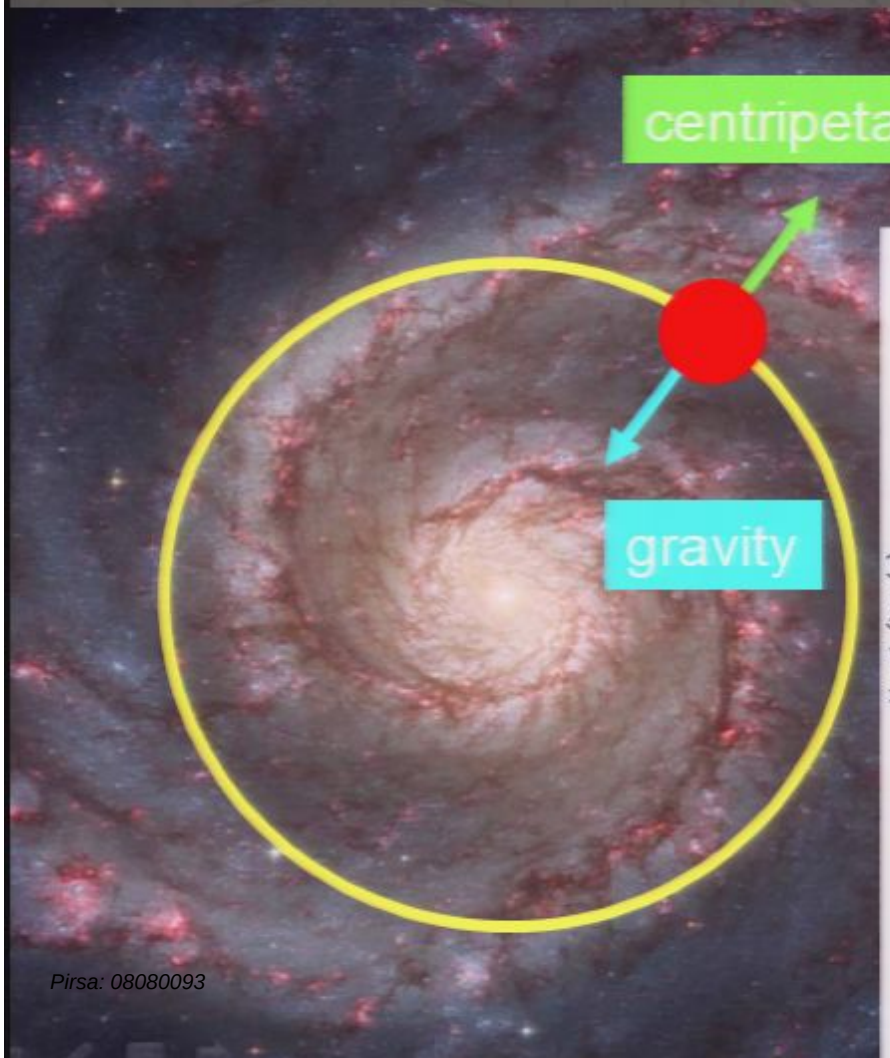
showed that 90% of a typical galaxy's mass is "dark matter"

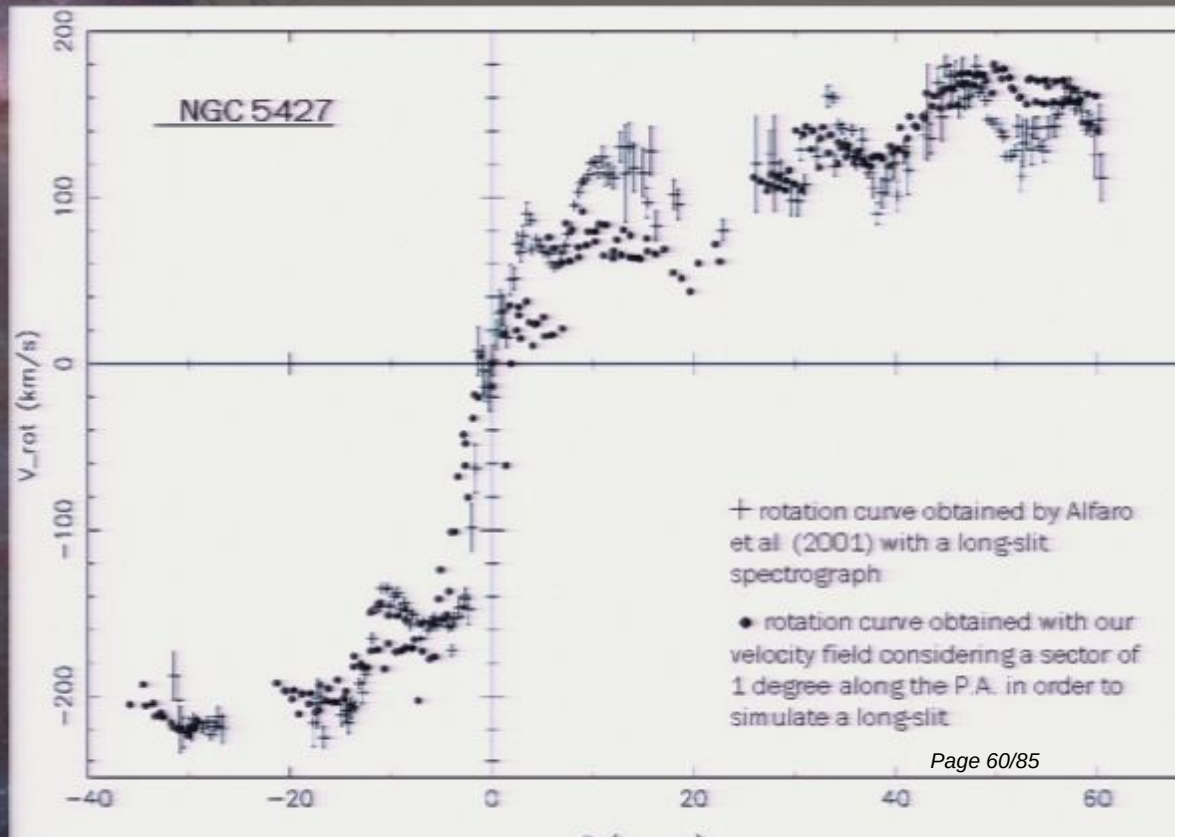
Basic Idea

centripetal = gravity

From this, you can calculate the orbital speed, if you know the mass of the galaxy

(Specifically the mass inside the orbit)





Keeping the Math Weenies Happy

Newton's Law of Gravity

$$F_G = G\frac{Mm_{\text{star}}}{r_{\text{orbit}}^2}$$

Orbital Force

$$F_{\text{orbital}} = \frac{m_{\text{star}}v^2}{r_{\text{orbit}}}$$

"Relevant" Mass

$$M = M_{\text{galaxy}}\frac{r_{\text{orbit}}^3}{r_{\text{sphere}}^3}$$

inside

M_{galaxy}

outside

Approach

$$F_G = F_{\text{orbital}}$$

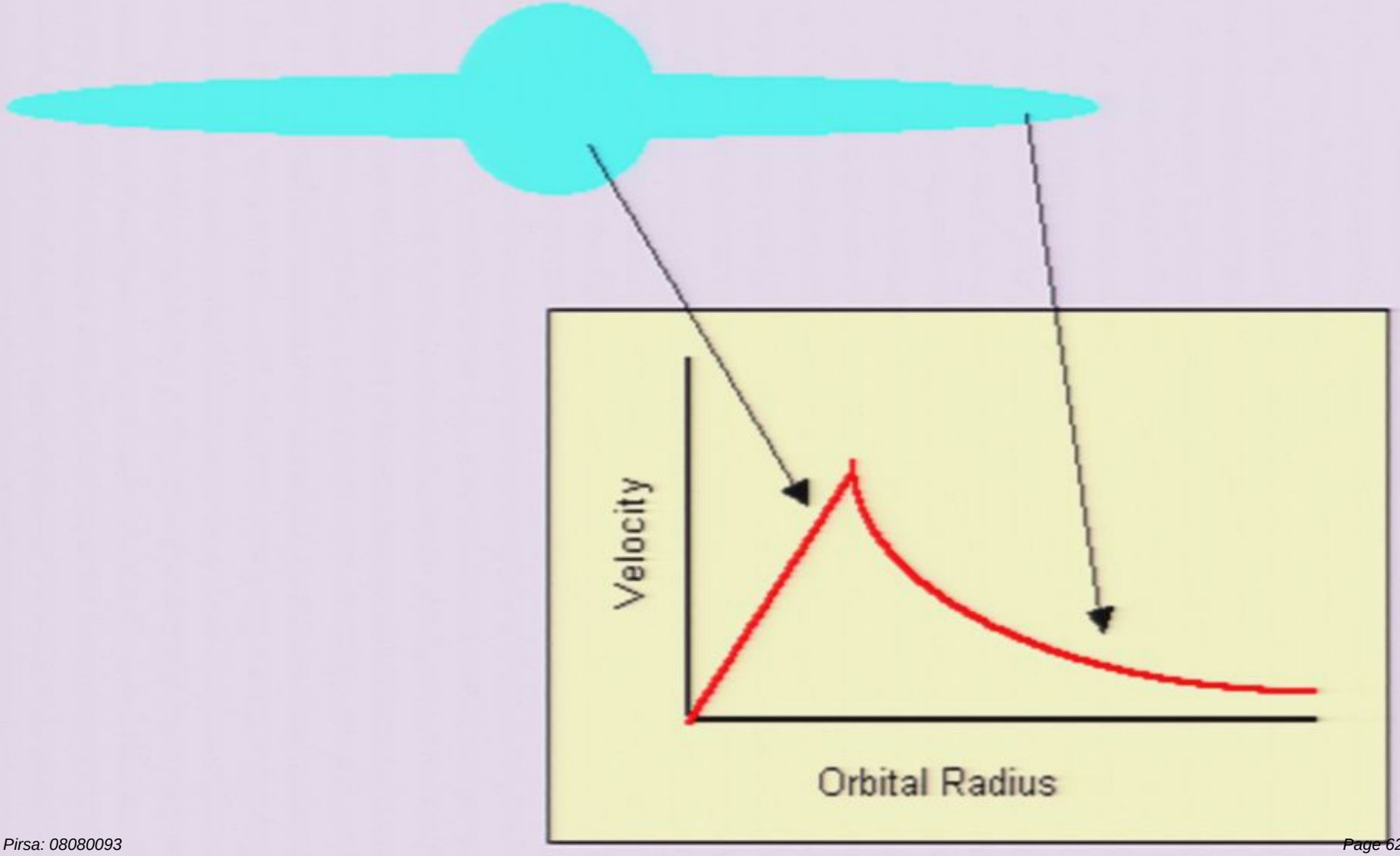
Answer (**inside**)

$$v = \frac{\sqrt{GM_{\text{galaxy}}}}{r_{\text{sphere}}^3}r_{orbit} \propto r_{orbit}$$

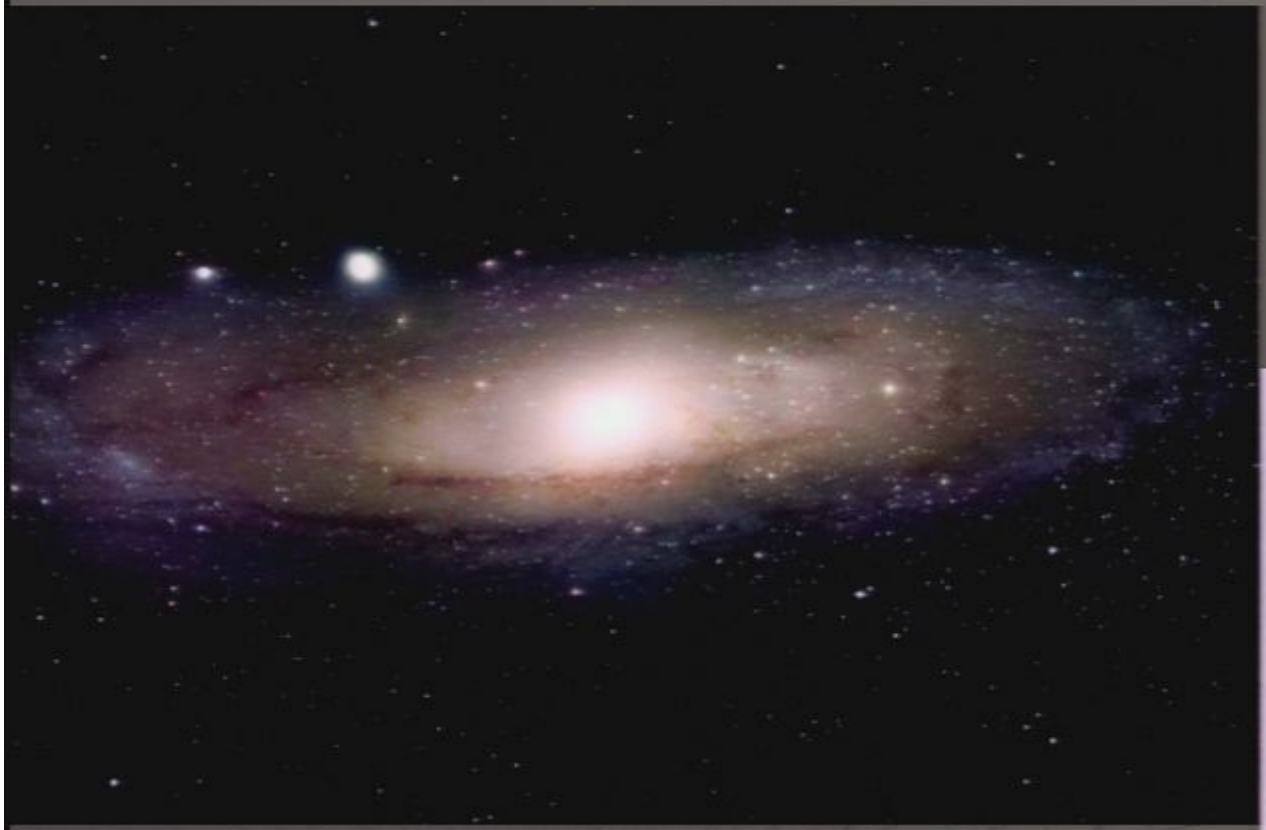
Answer (**outside**)

$$v = \frac{\sqrt{GM_{\text{galaxy}}}}{\sqrt{r_{\text{orbit}}}} \propto \frac{1}{\sqrt{r_{\text{orbit}}}}$$

"Expected" Galactic Rotation Speeds

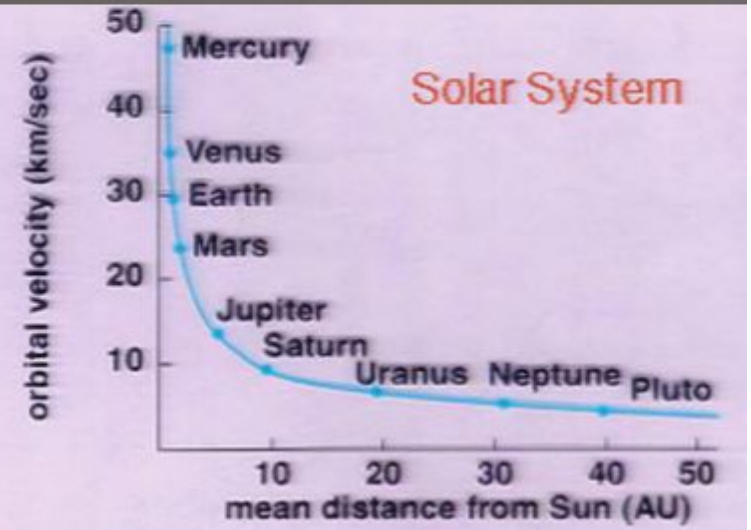


Evidence for "dark matter"

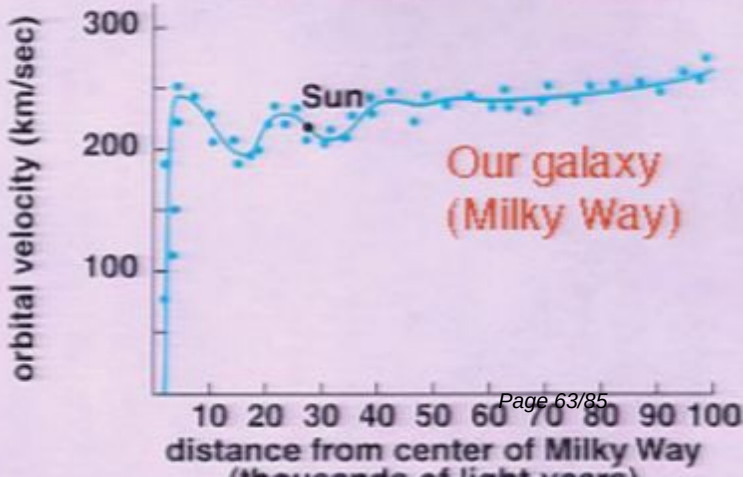


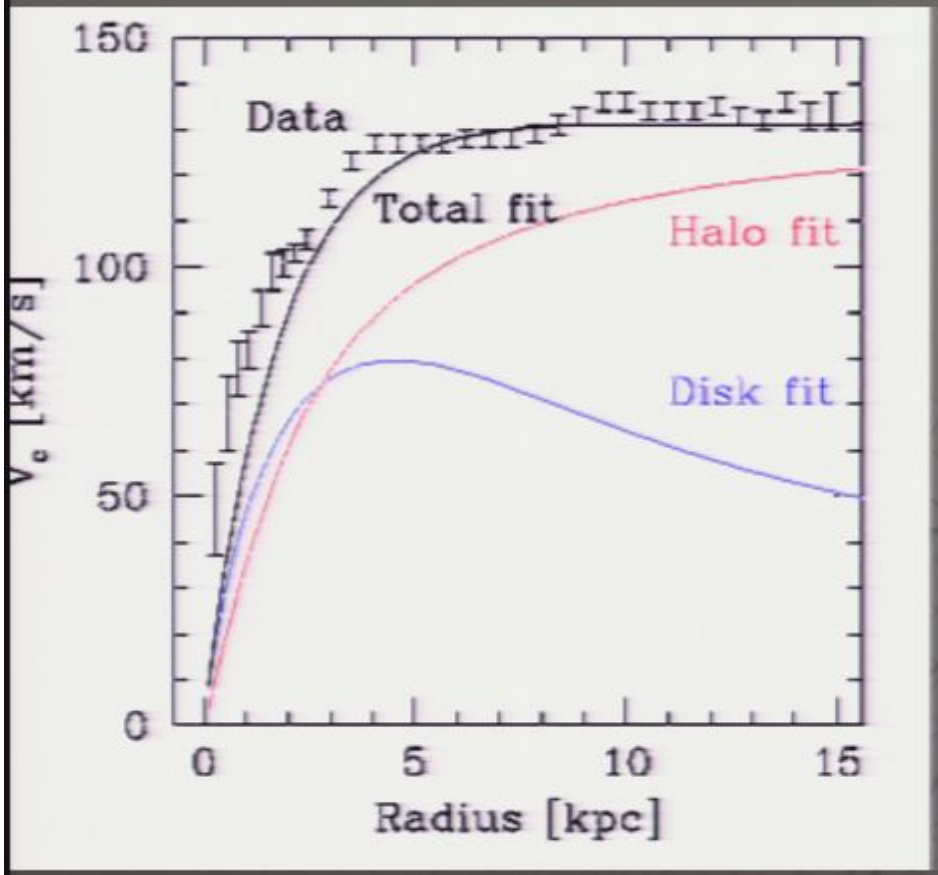
Galactic rotation curves

(velocity of stars in periphery far is too high)

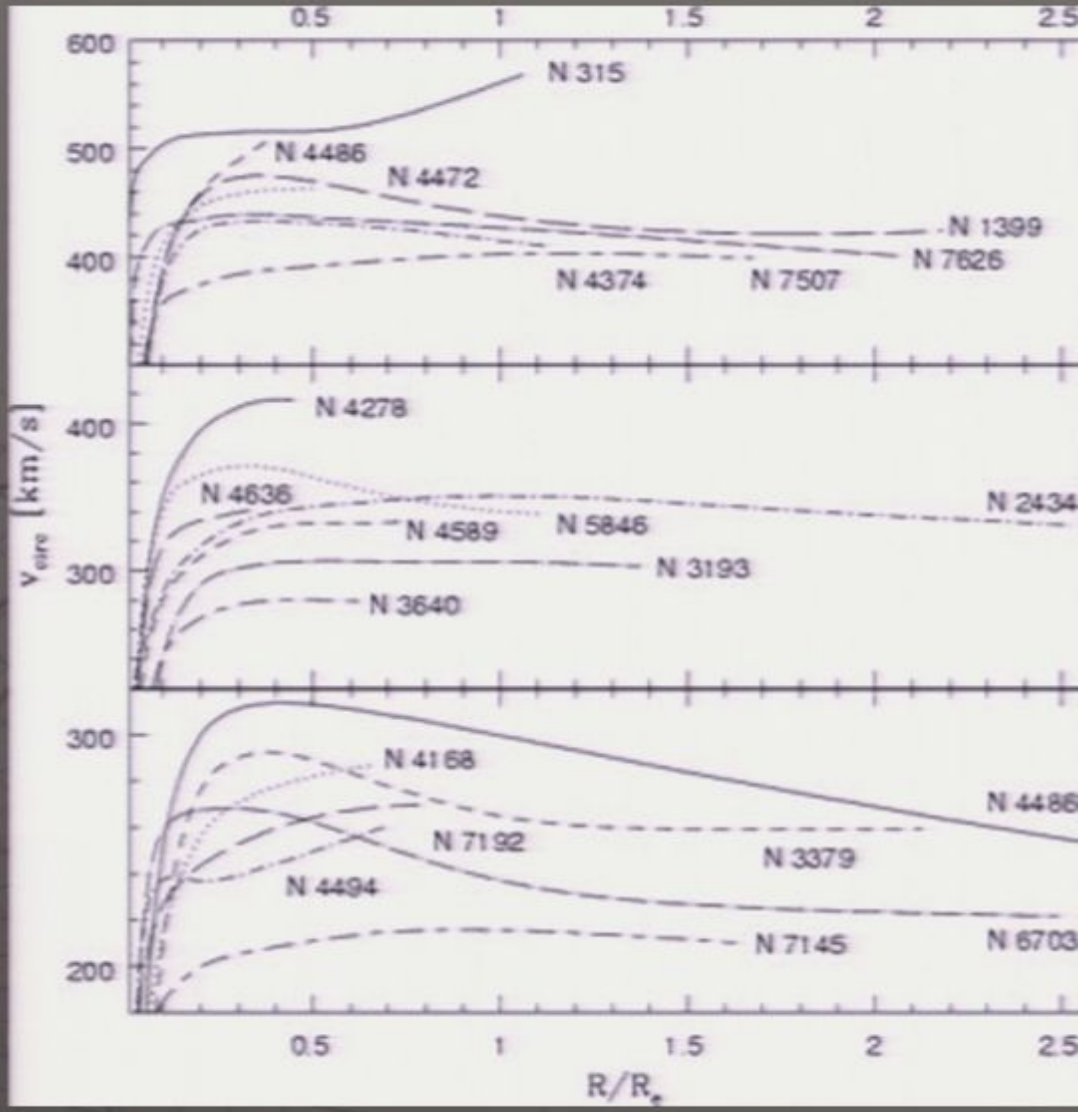


By Newton's law: density drops like r^{-2} at large radii and mass interior M(r) is proportional to r at large radii. When r becomes greater then the extent of mass the velocities should drop like $r^{-1/2}$ (as in solar System Graph) . The problem what we observe is in the graph below..

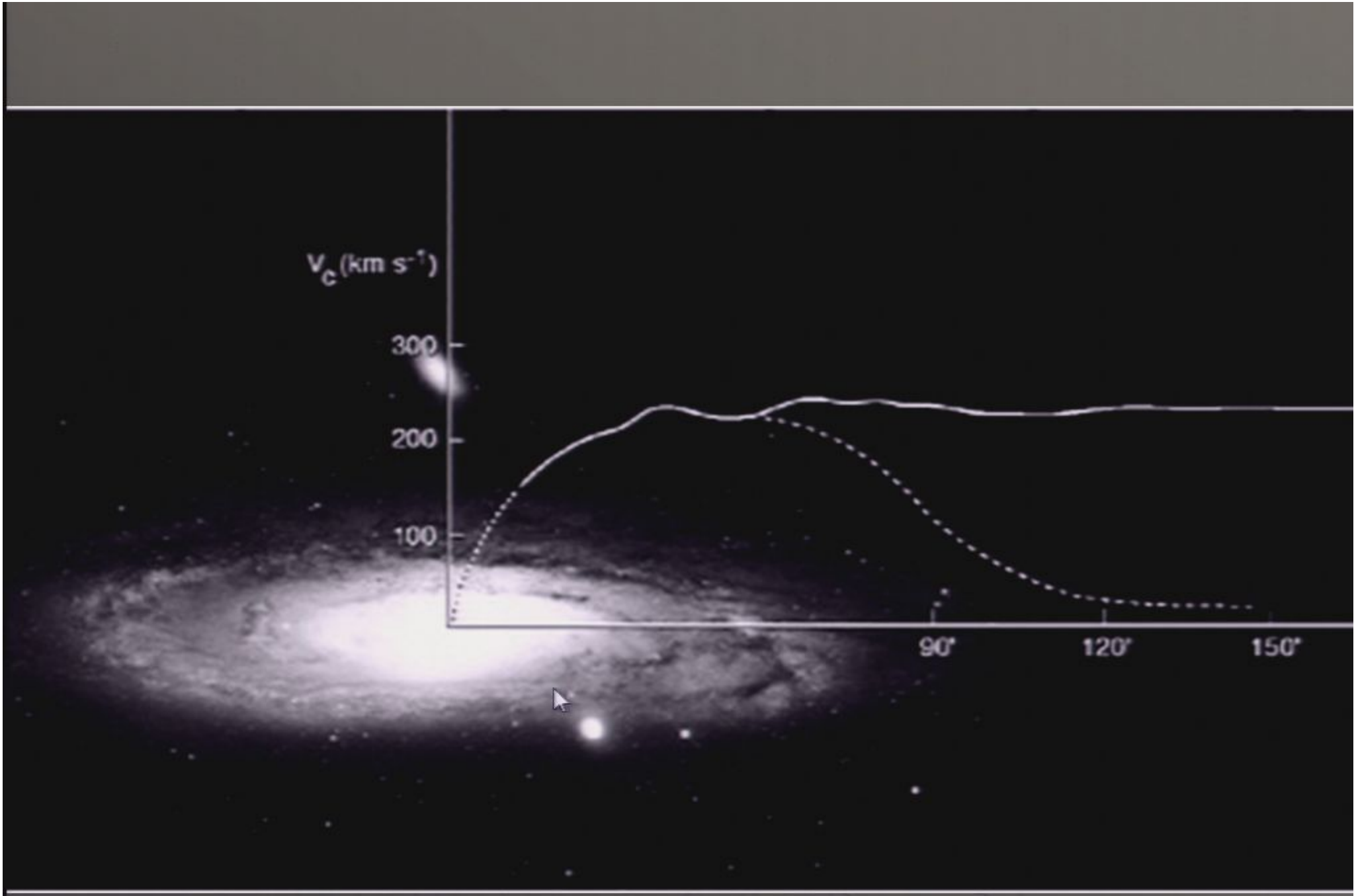




NGC 2403: rotation velocity as a function of distance from center. The rotation curve is fitted well by a disk of luminous matter and a halo of dark matter.



Rotation curves for 21 elliptical galaxies.


V_c (km s^{-1})
300
200
100
90°
120°
150°

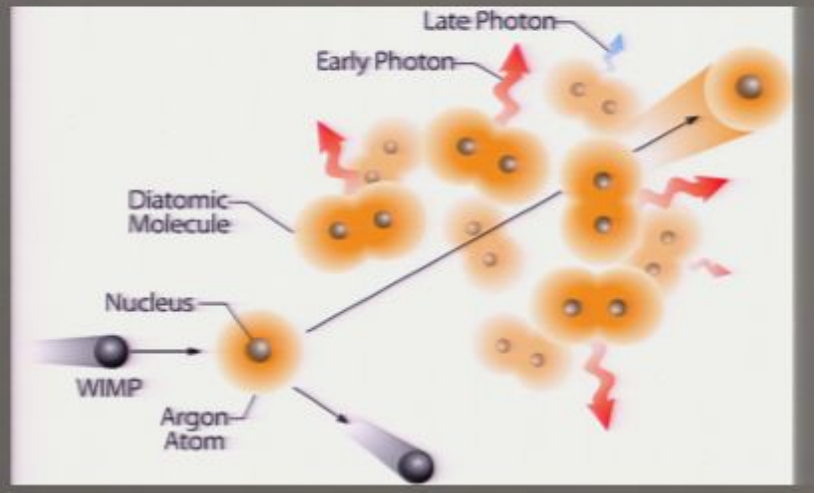
What are the Candidates

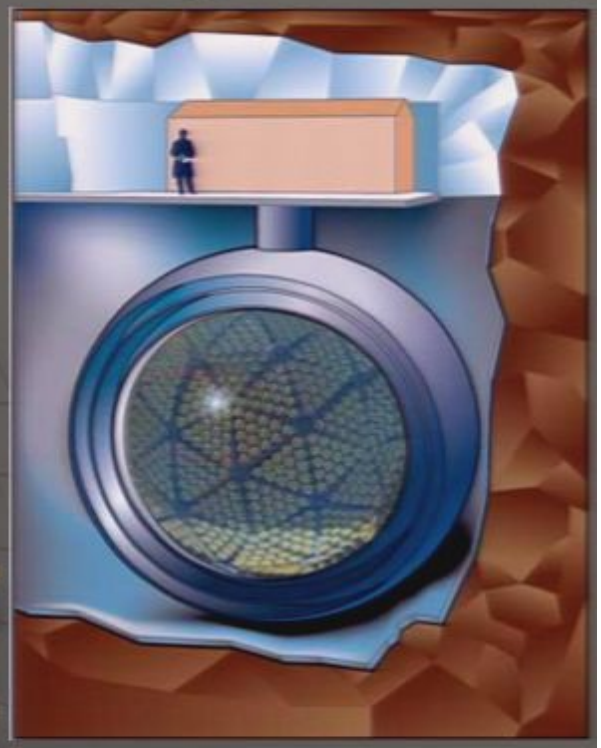
W.I.M.P: Weakly interacting massive particle, Specifically the neutralino.

Neutralino from standard model it is the lightest of the hypothesized WIMPs, yet still it is up to 100 times more massive than a proton.

Its interactions are not electromagnetic, so we cannot see them at any wavelength.

They also don't feel the strong nuclear force, meaning that they rarely interact with atomic nuclei (rarely indicates that they sometimes do, and that is what WIMP observatories are looking for.



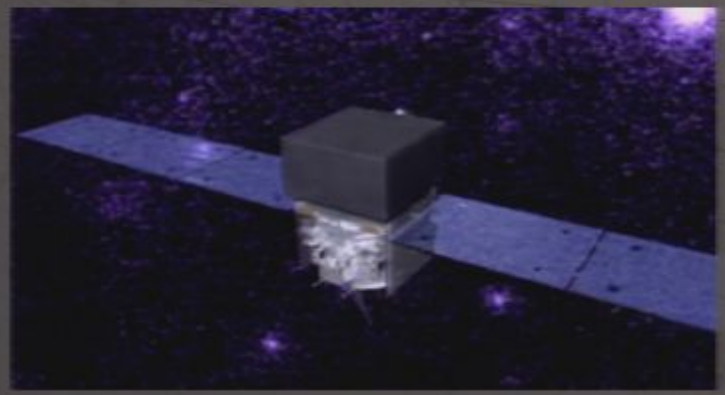


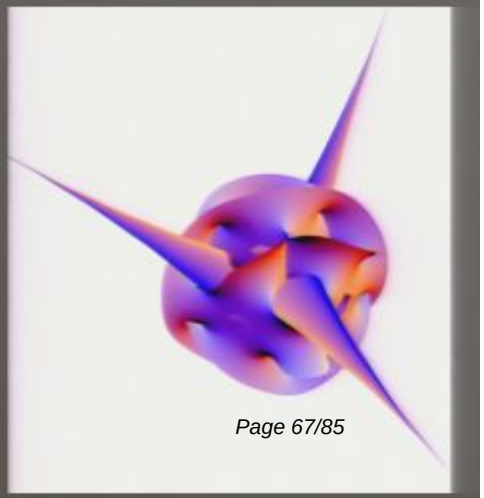
What are the Candidates

Axion

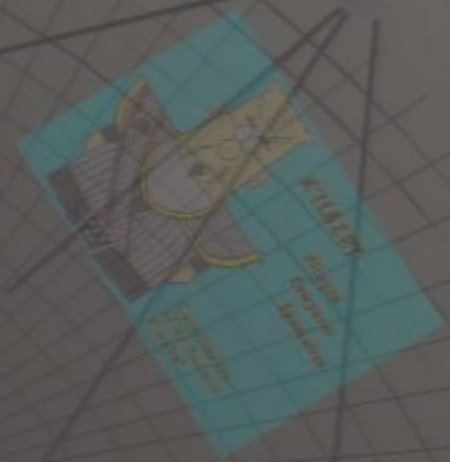
- This is a hypothetical particle that would solve an inconsistency within the Standard Model.
- It has barely a trillionth the mass of the electron.
- This particle would interact with a magnetic field, producing a signal strength of at most 10^{-23} watt (the frequency is uncertain).

GLAST
(Gamma-ray Large
Area Space Telescope)

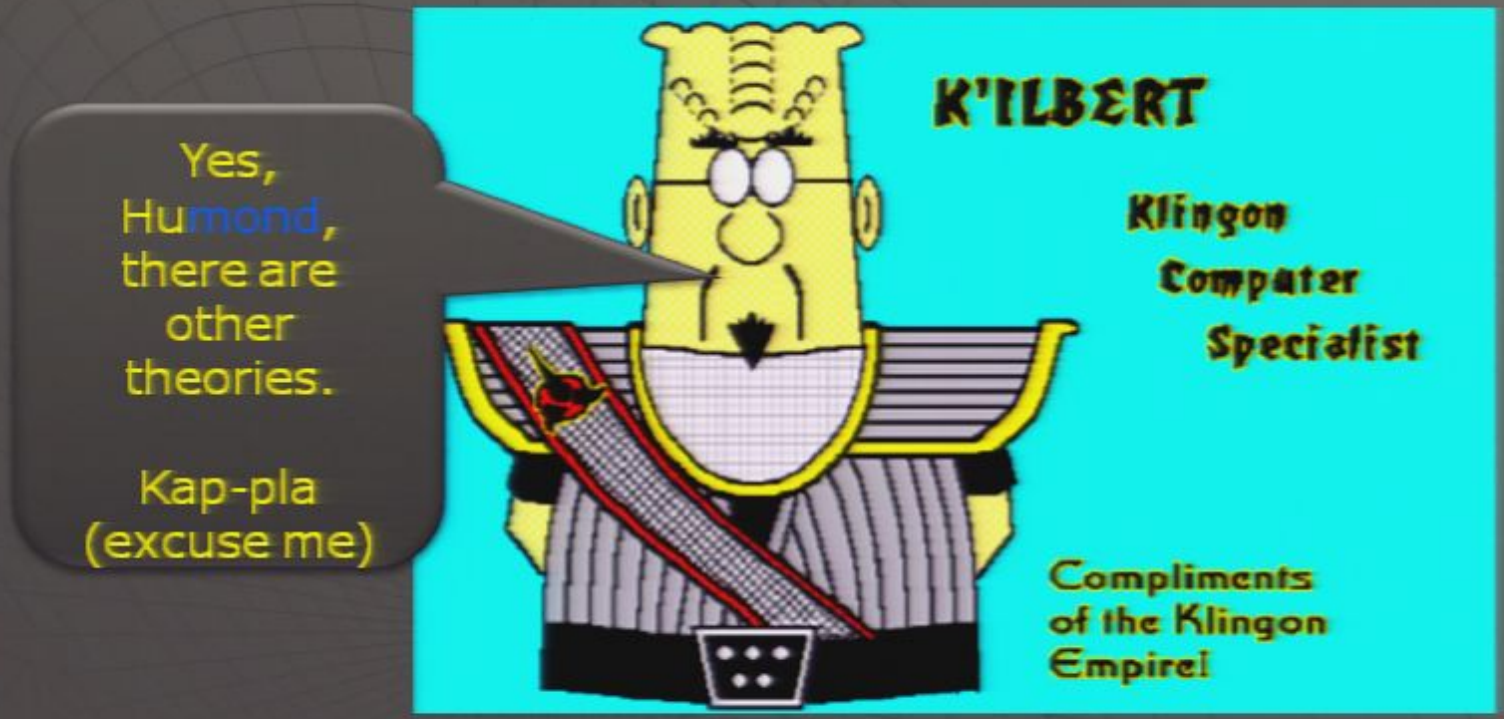




Dark Matter not only Solution



Dark Matter not only Solution



Mordehai Milgrom
1983

MOND: Modified Newtonian Dynamics

MOND: Modified Newtonian Dynamics

What if Newton was wrong?

Newton said that Force was proportional to Acceleration

MOND: Modified Newtonian Dynamics

What if Newton was wrong?

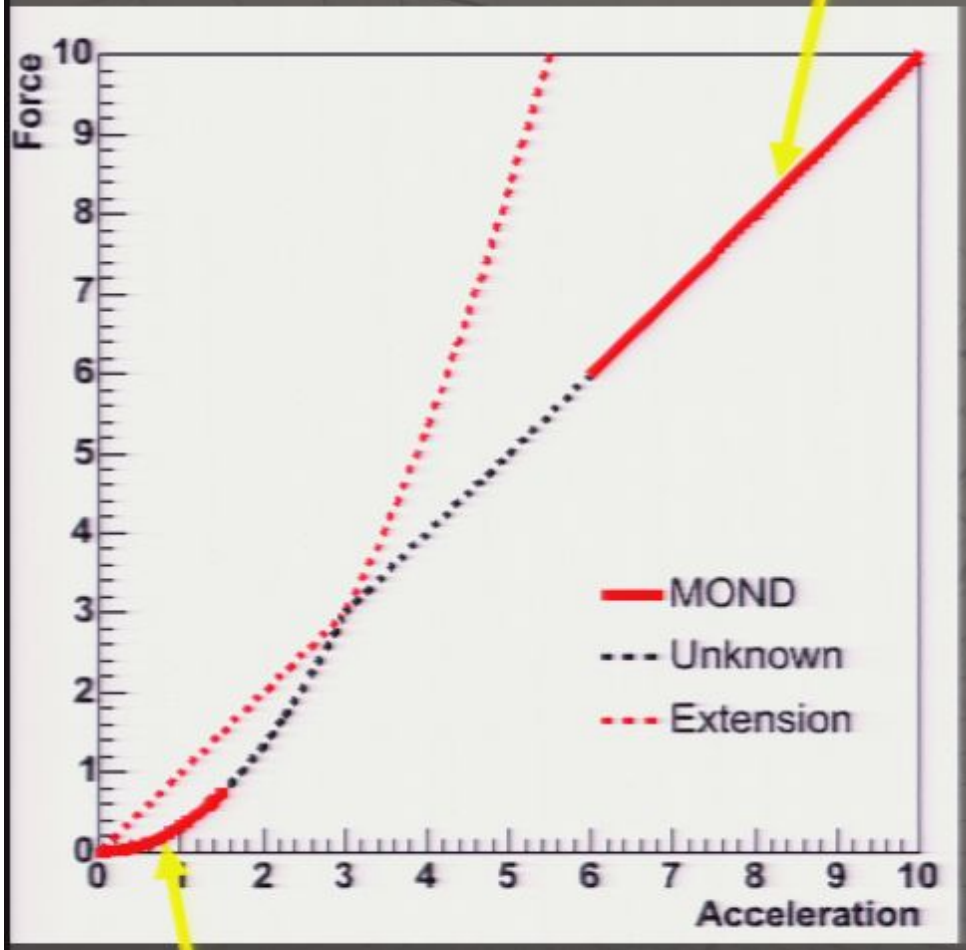
Newton said that Force was proportional to Acceleration

MOND

Newton was right for large accelerations, but for small accelerations, his formula breaks down?

MOND

Newton's Law



MOND Modification

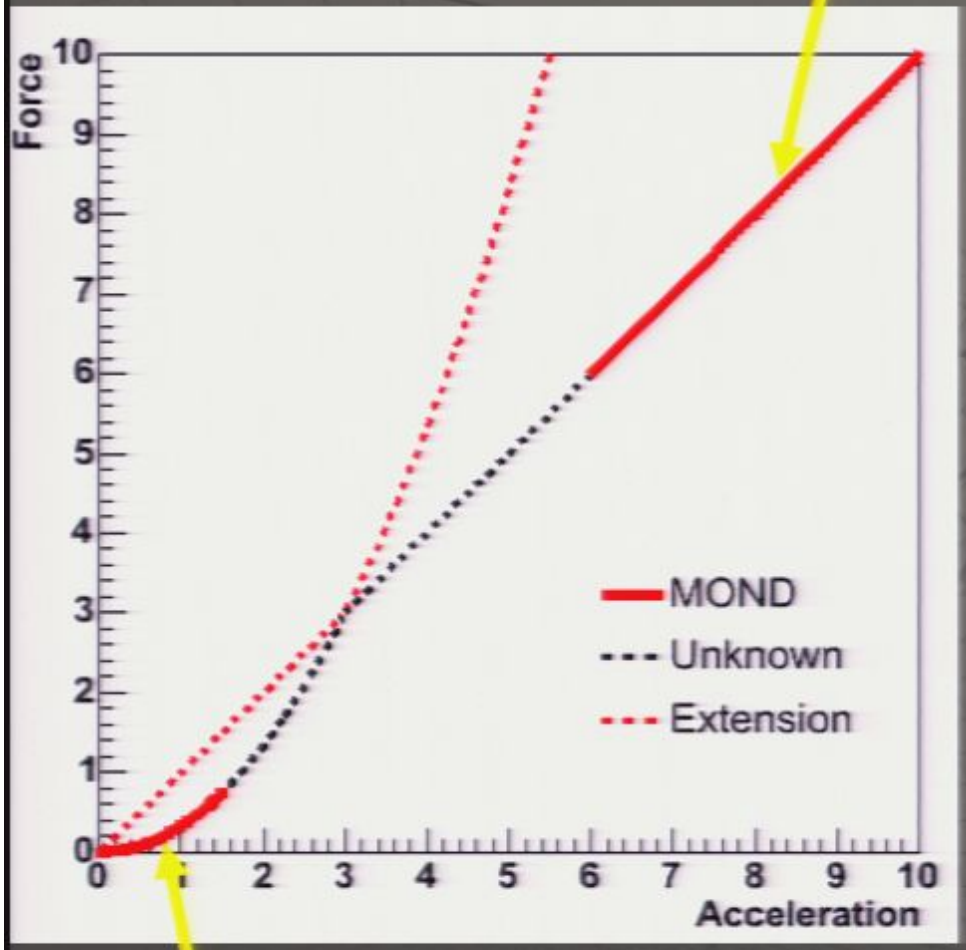
Comments and Thoughts:

How does MOND go from one behavior to the other?

Why hasn't anyone else seen this modification of Newton's laws?

MOND

Newton's Law



MOND Modification

Comments and Thoughts:

How does MOND go from one behavior to the other?

No Idea….

Why hasn't anyone else seen this modification of Newton's laws?

We're talking very small accelerations here… 1/10,000,000,000 × Earth's gravity….. (10^{-9} m/s^2)

MOND: Modification of Newtonian Dynamics

What if Newton was wrong?

$$F = ma$$

MOND

$$F = \begin{cases} ma & a >> a_o \\ \frac{m}{a_o} a^2 & a << a_o \end{cases}$$

MOND: Modification of Newtonian Dynamics

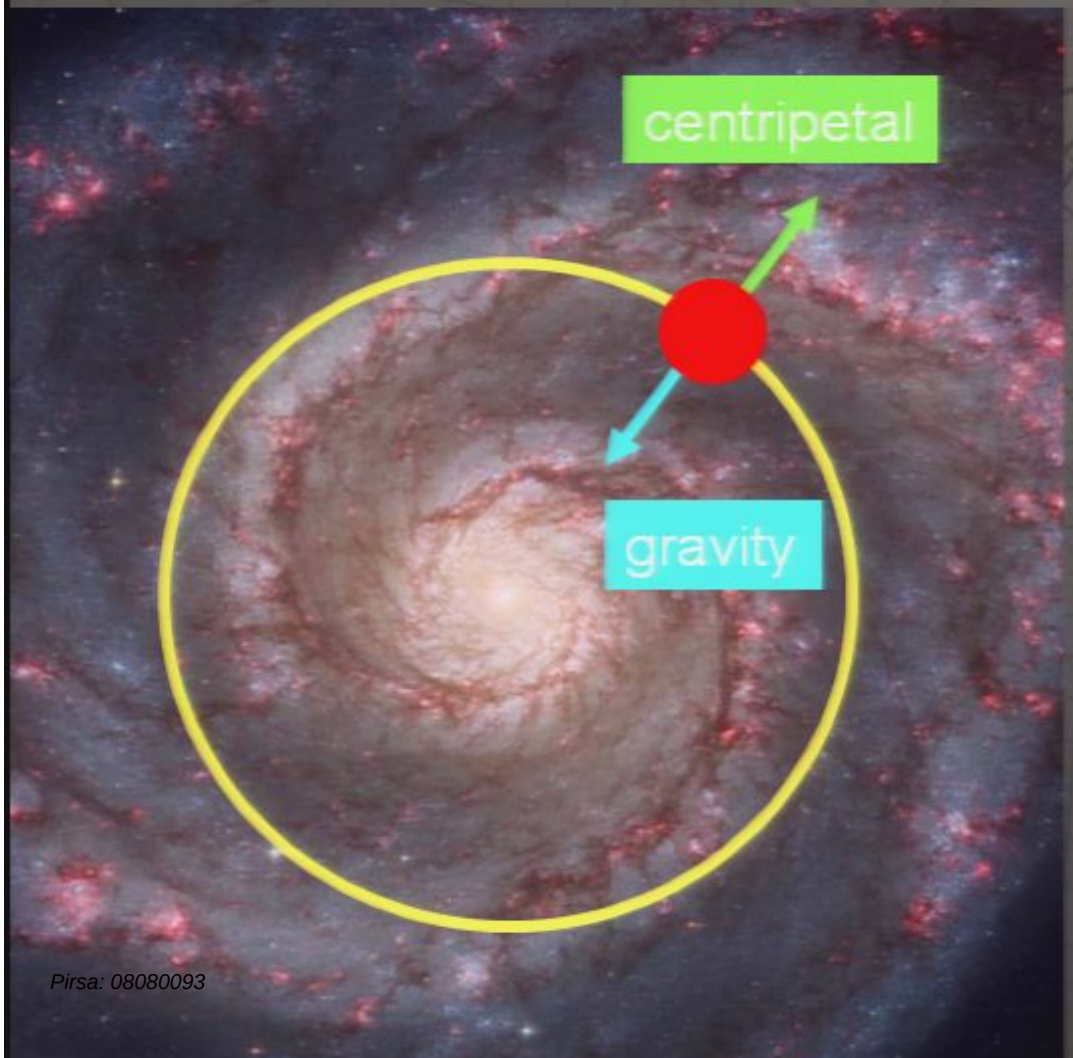
What is the characteristic scale of a_o?

MOND

10^{-9} m/s^2

$$F = \begin{cases} ma & a >> a_o \\ \frac{m}{a_o} a^2 & a << a_o \end{cases}$$

MOND:Basic Idea

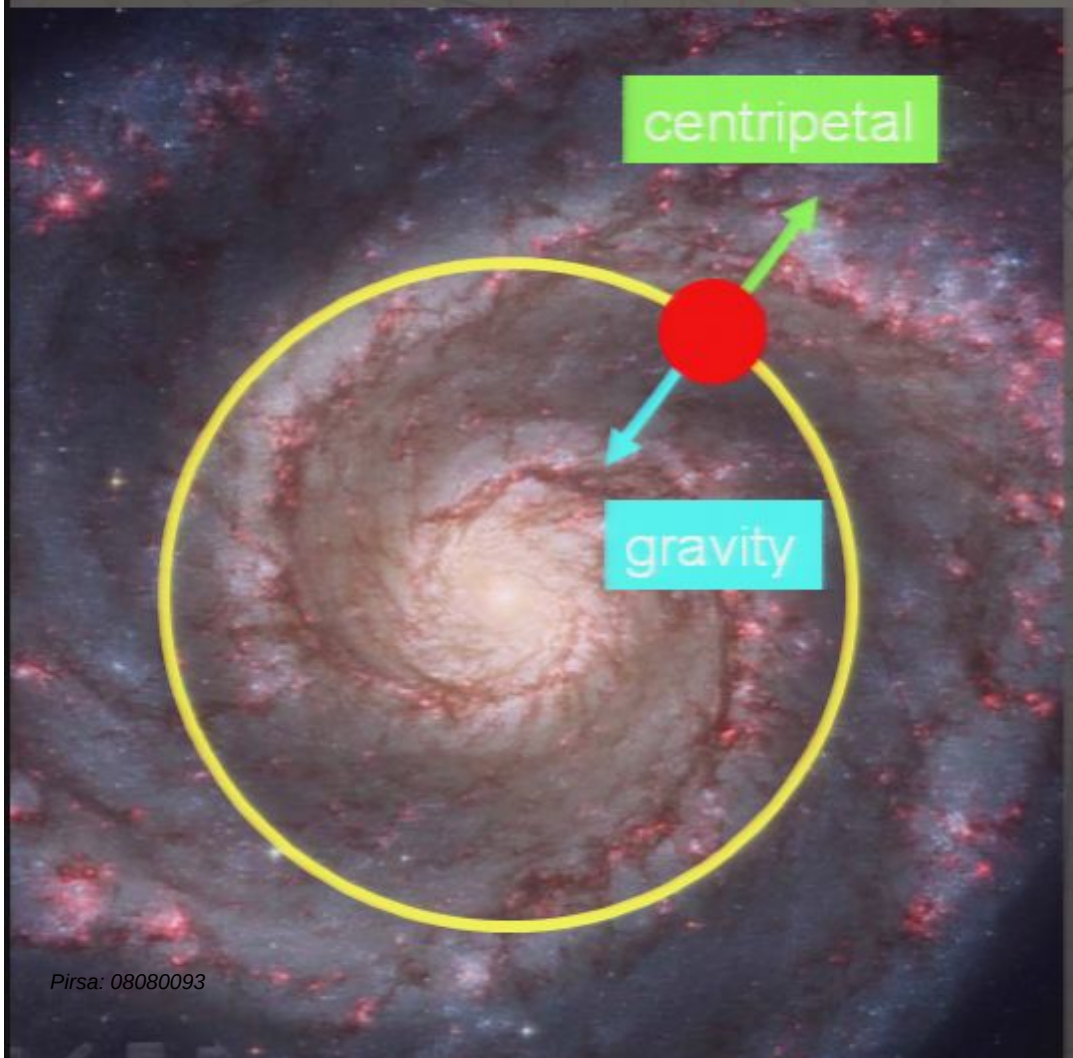


centripetal = gravity

$$m_{star}\frac{v^2}{r_{orbit}}$$

$$G\frac{Mm_{star}}{r_{orbit}^2}$$

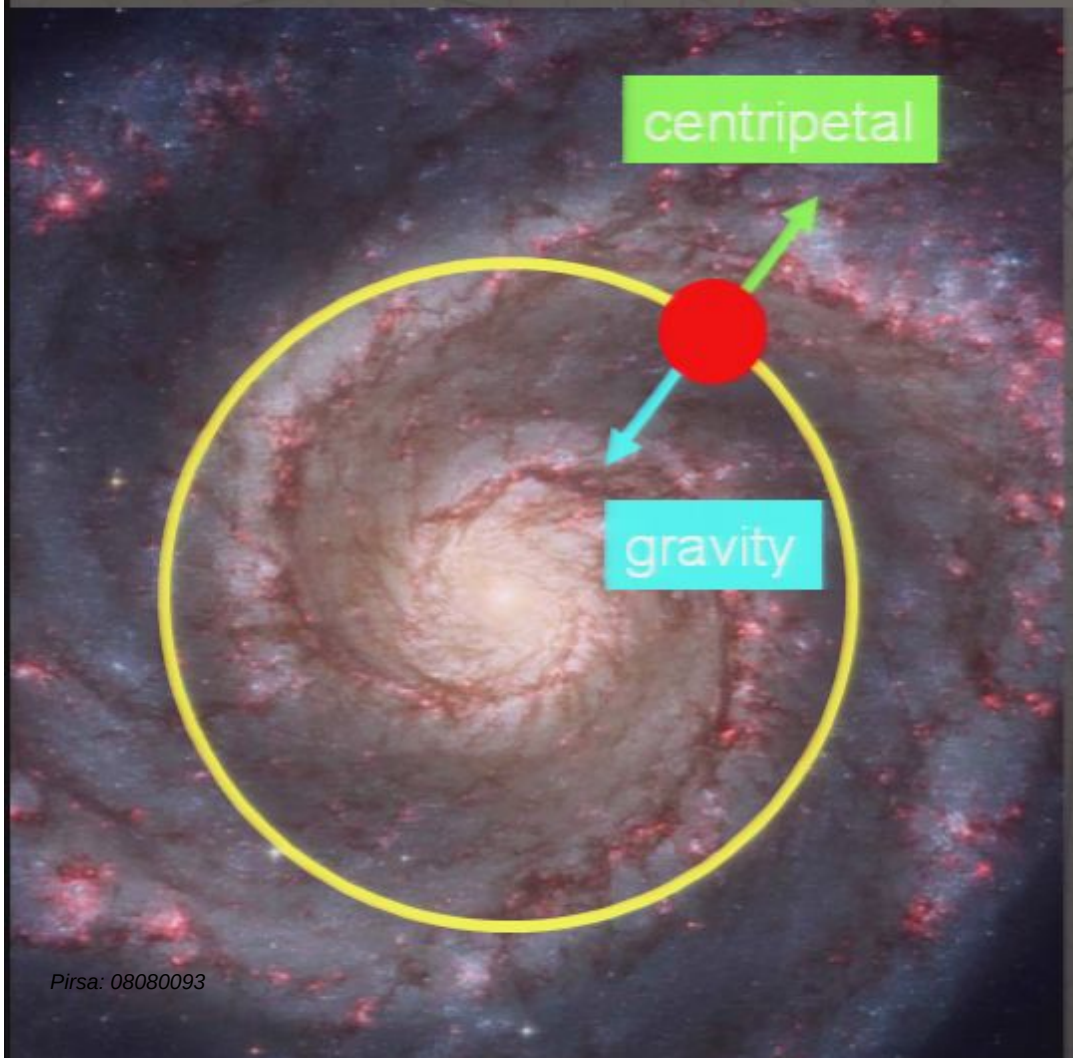
MOND:Basic Idea



centripetal = gravity

$$\frac{m_{star}}{a_o}\left[\frac{v^2}{r_{orbit}}\right]^2 = G\frac{Mm_{star}}{r_{orbit}^2}$$

MOND:Basic Idea

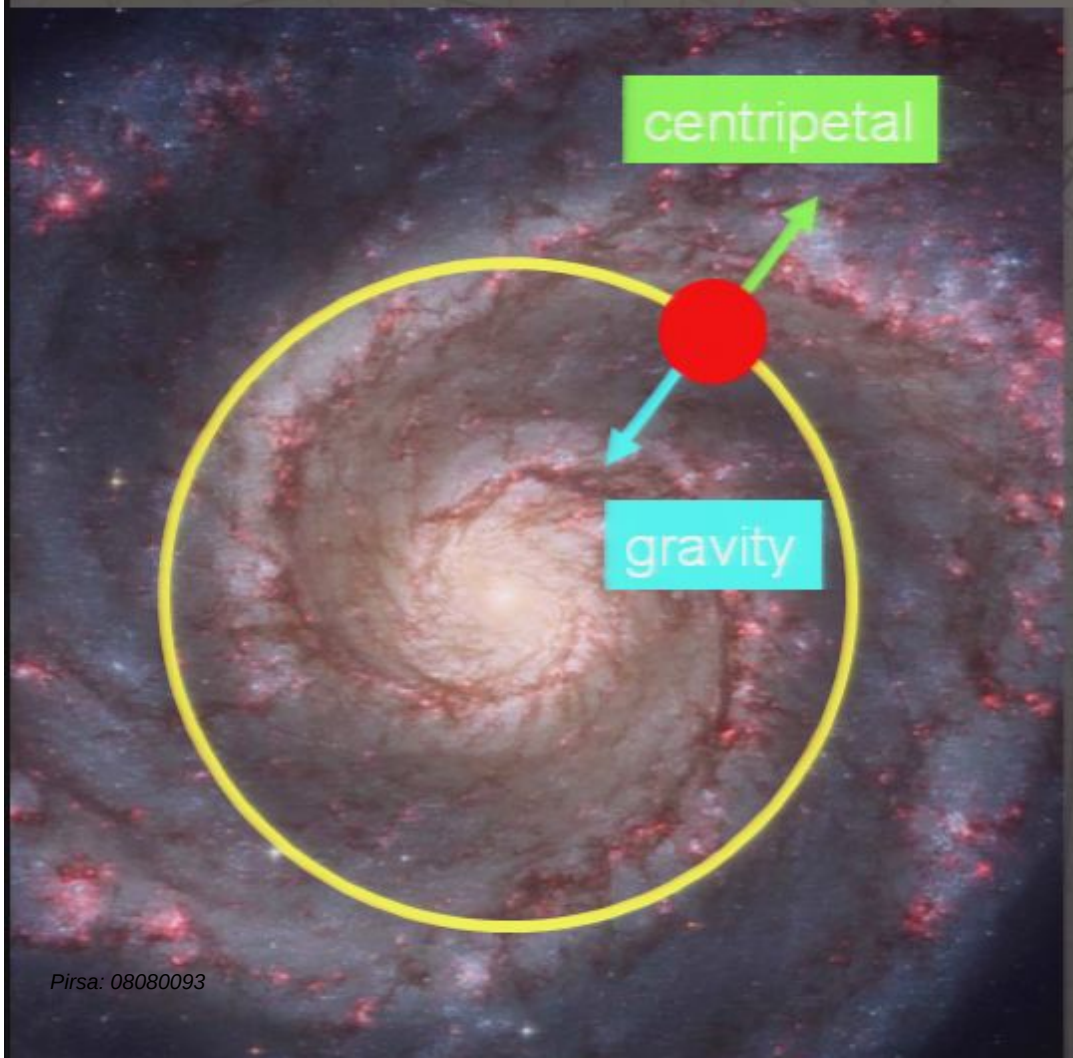


centripetal = gravity

$$\frac{m_{star}}{a_o}\left[\frac{v^2}{r_{orbit}}\right]^2 = G\frac{Mm_{star}}{r_{orbit}^2}$$

$$v^4 = GMa_o$$

MOND:Basic Idea

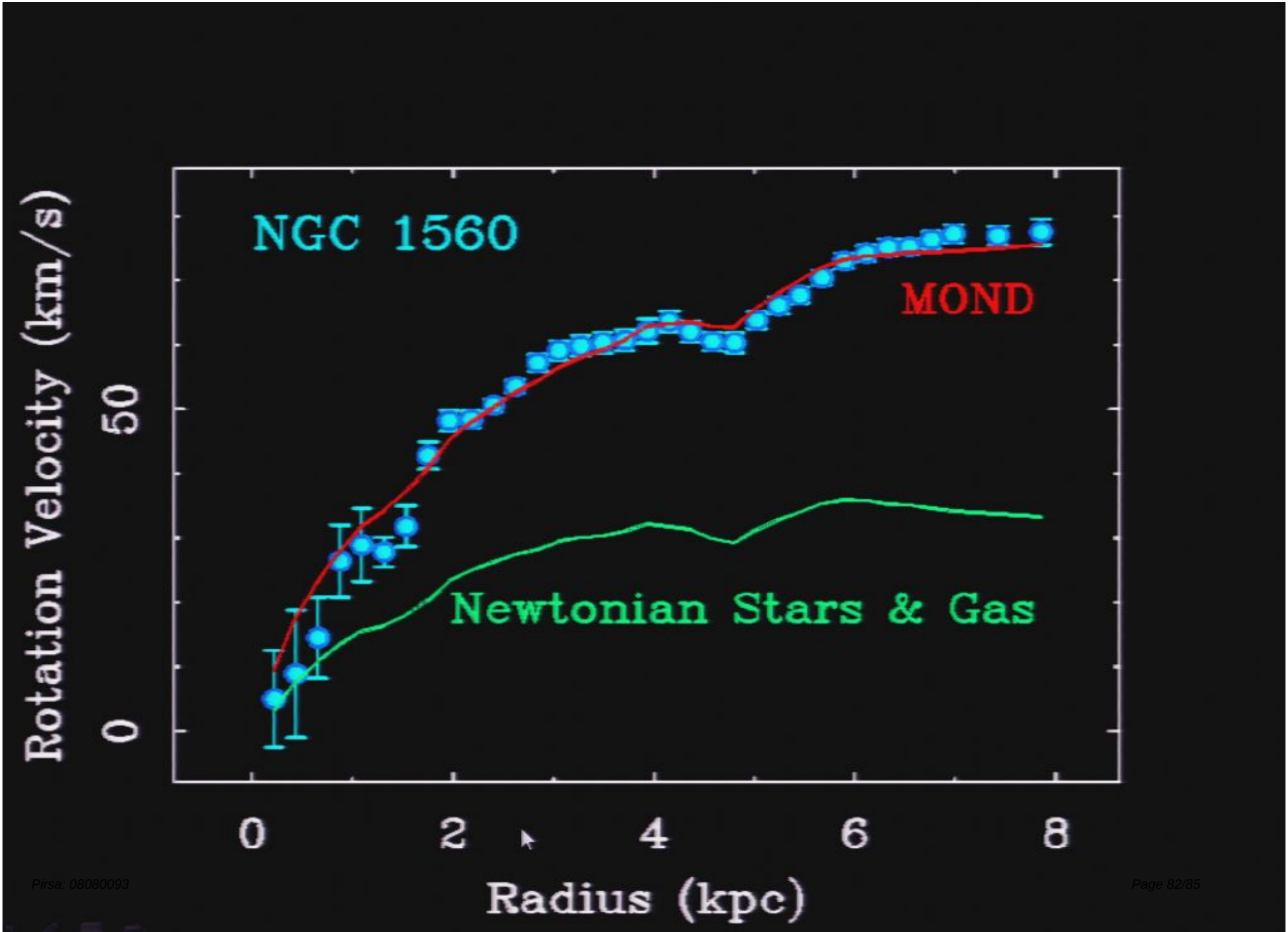


centripetal = gravity

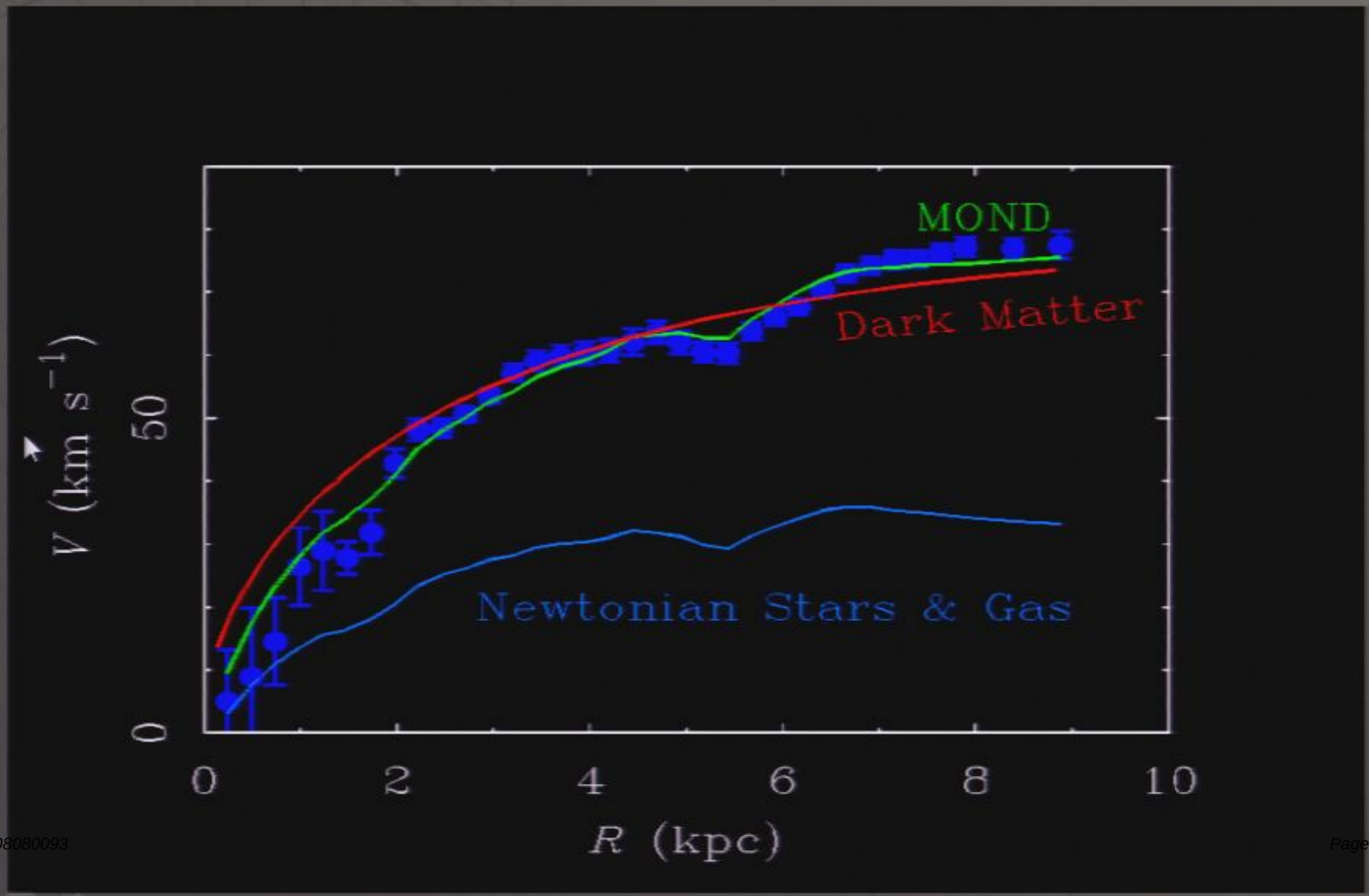
$$\frac{m_{star}}{a_o}\left[\frac{v^2}{r_{orbit}}\right]^2 = G\frac{Mm_{star}}{r_{orbit}^2}$$

$$v^4 = GMa_o$$

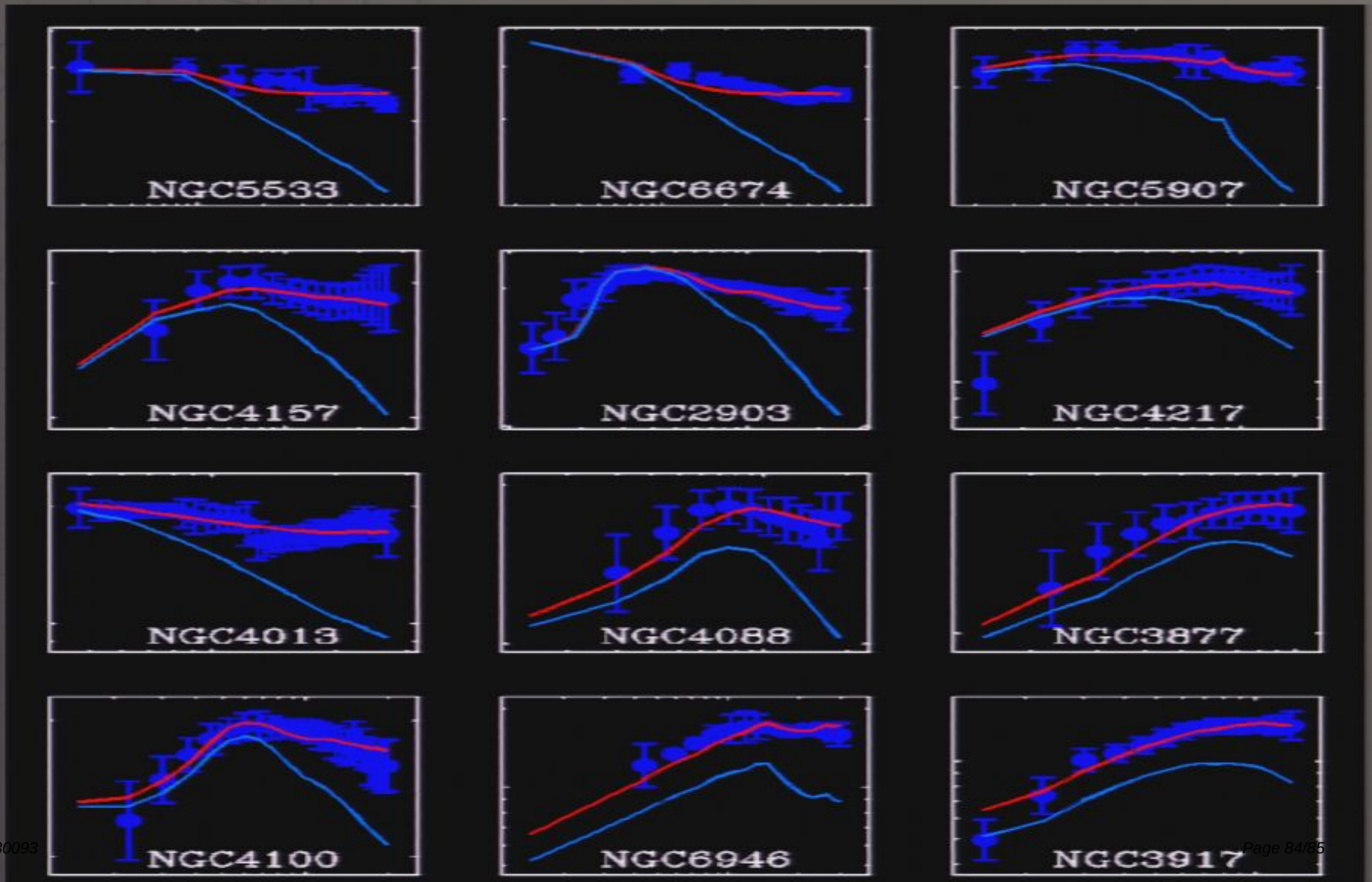
But does it work?


NGC 1560
MOND
Newtonian Stars & Gas
Rotation Velocity (km/s)
0
50
0
2
4
6
8
Radius (kpc)

How about MOND vs DM



Lots of Data Fits



Blue is DM detected only by its Gravity (The one picture that changed it all)