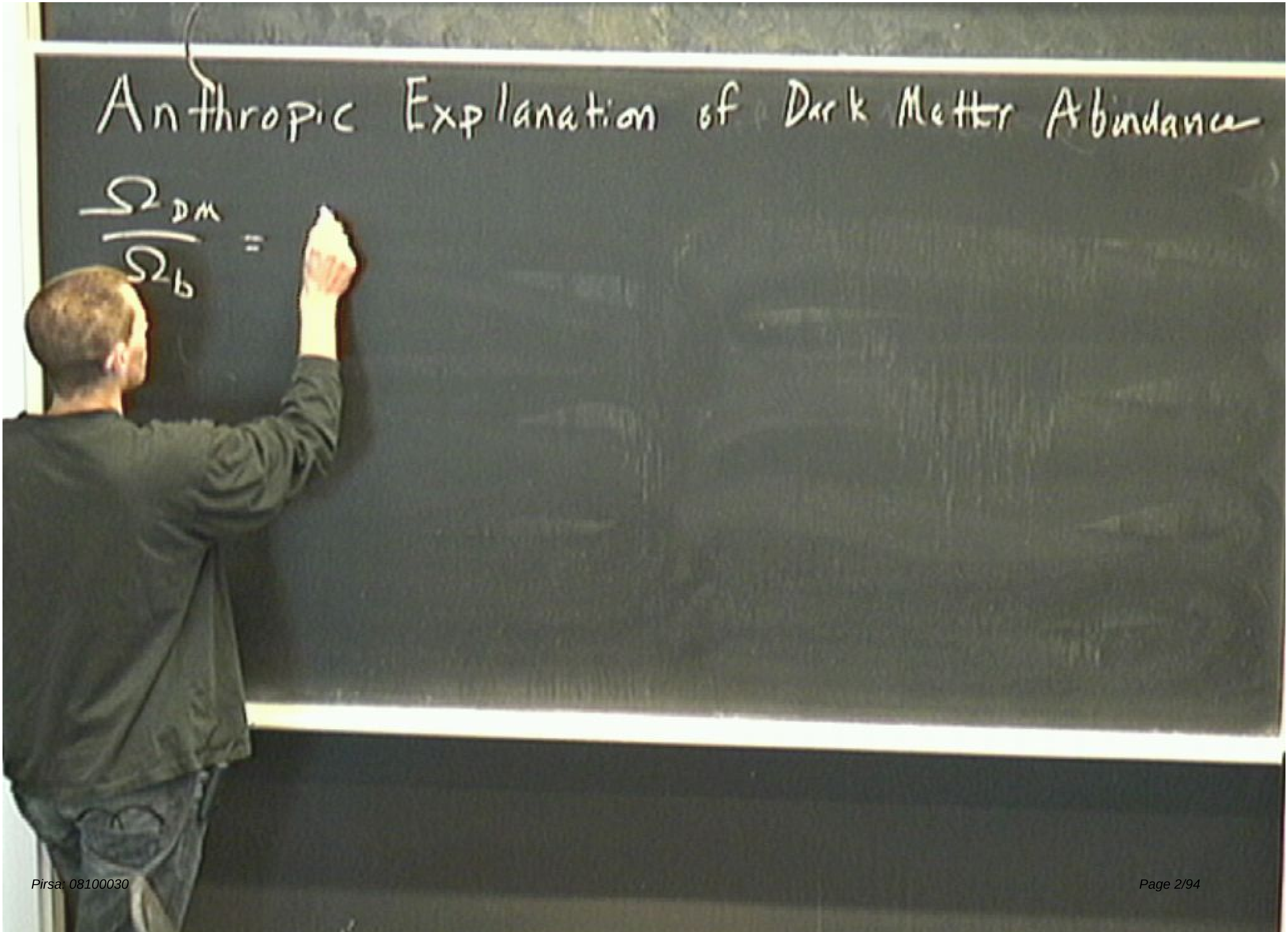
Title: Anthropic explanation of the dark matter abundance in models with high-scale axions

Date: Oct 07, 2008 11:00 AM

URL: http://pirsa.org/08100030

Abstract: TBA


Anthropic Explanation of Dark Matter Abundance
$\frac{\Omega_{DM}}{\Omega_b} =$

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$$\frac{\Omega_{DM}}{\Omega_b} = \zeta \approx 5$$

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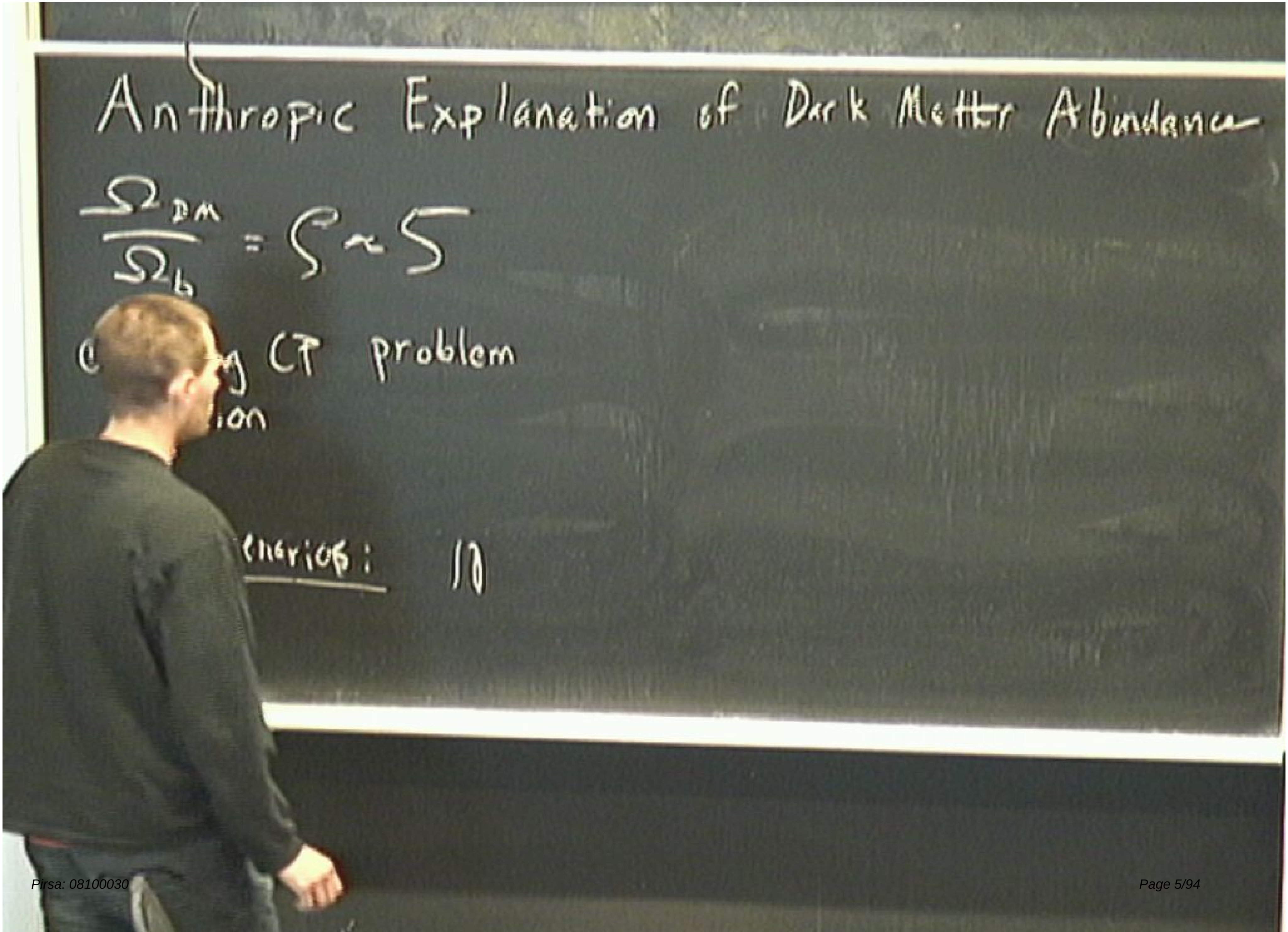
① Strong CP problem

→ axion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CP problem
ion
enarios:
1)

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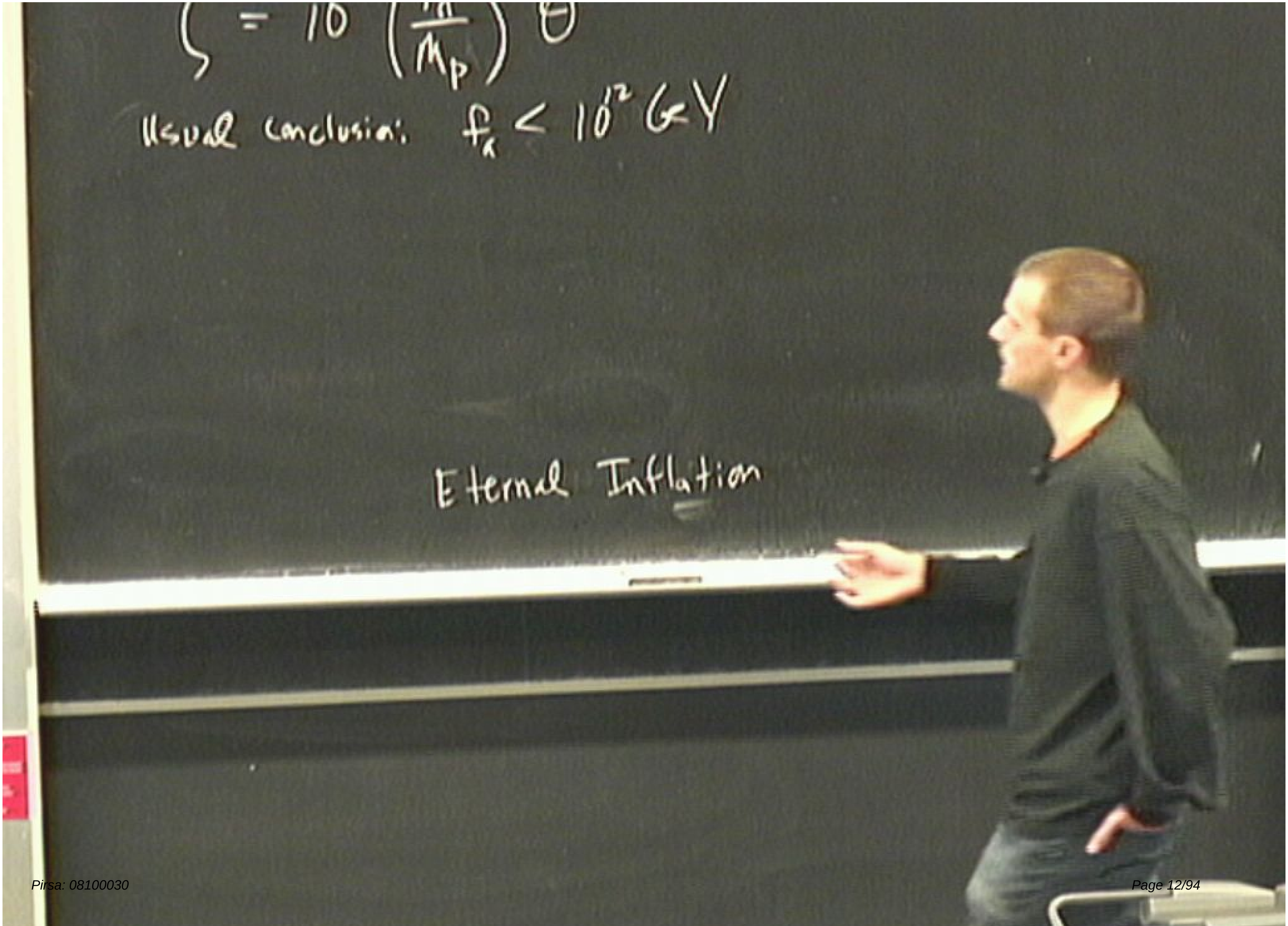
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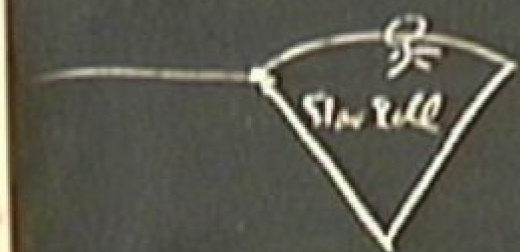
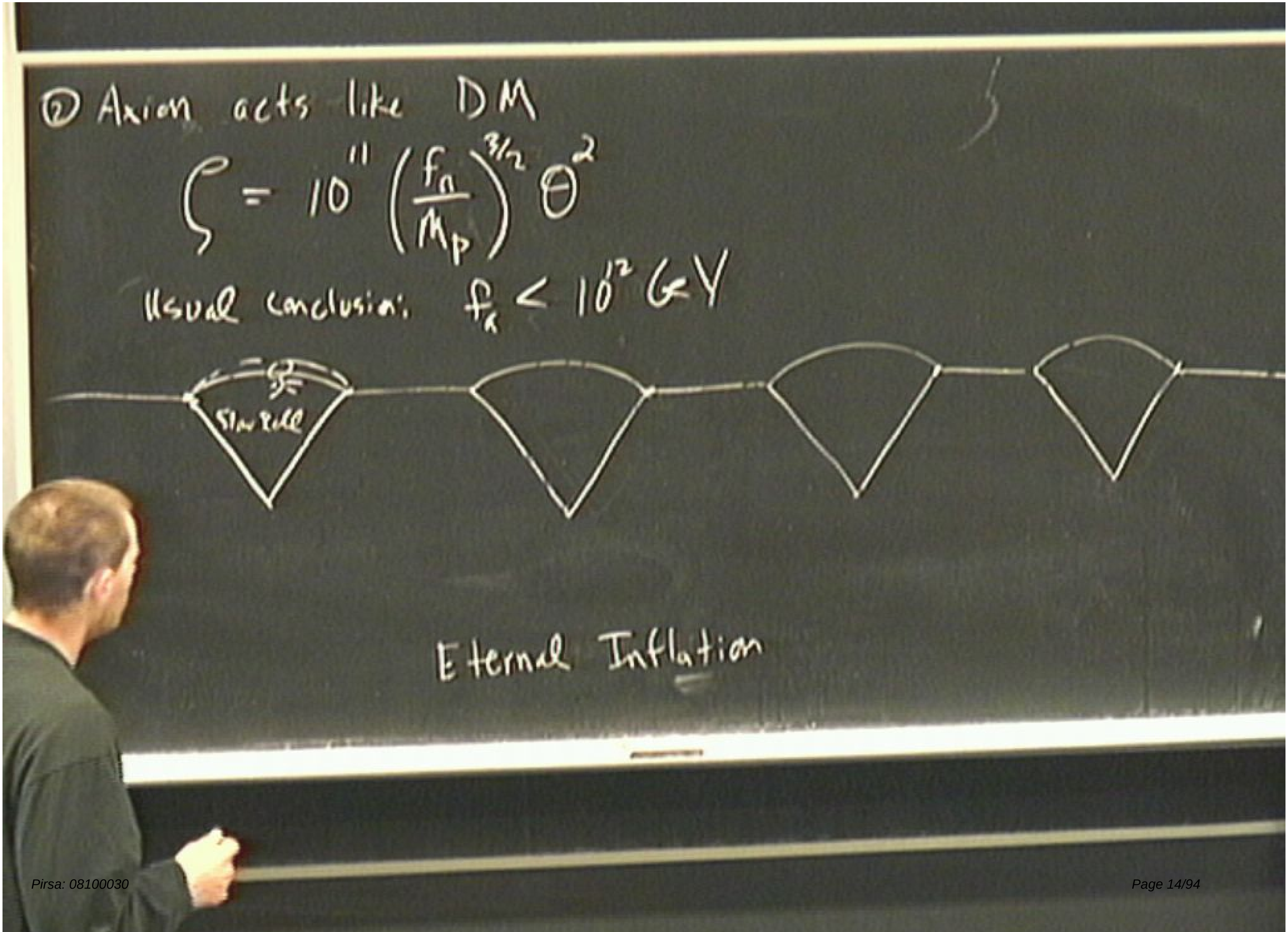


Eternal Inflation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slow roll
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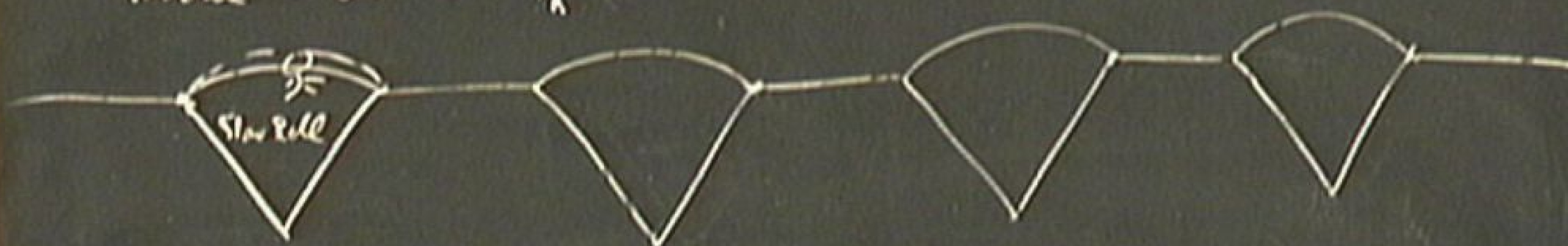

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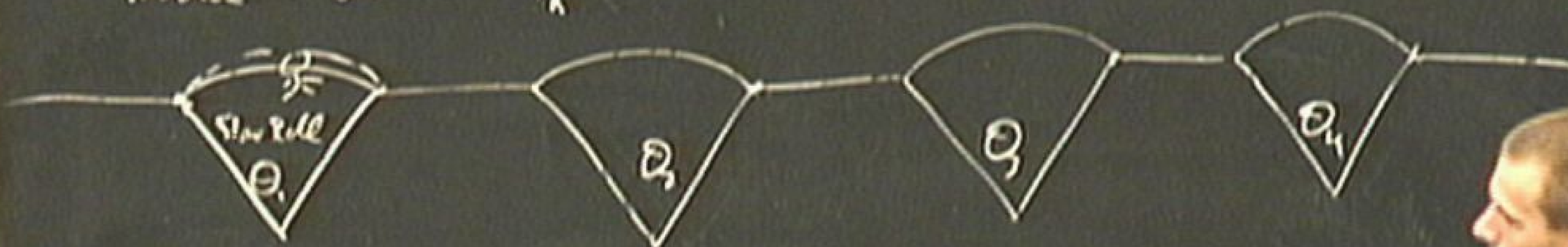

Eternal Inflation

Caveat: Need to regulate ∞'s of eternal inflation

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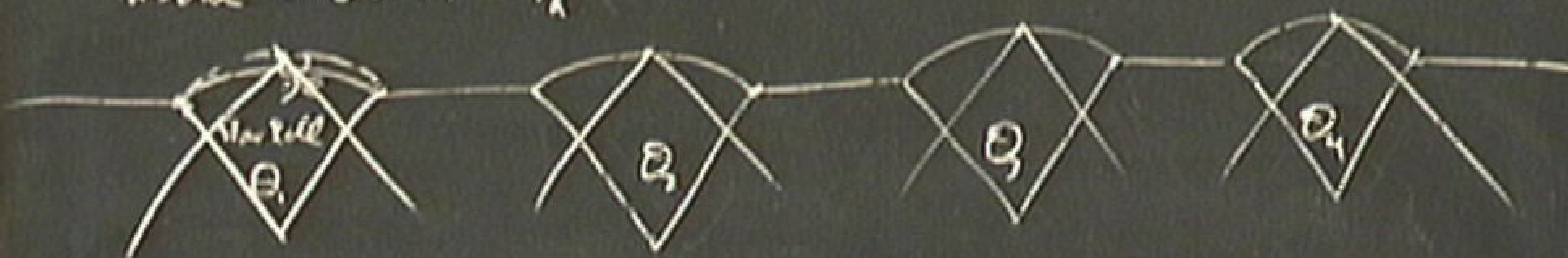

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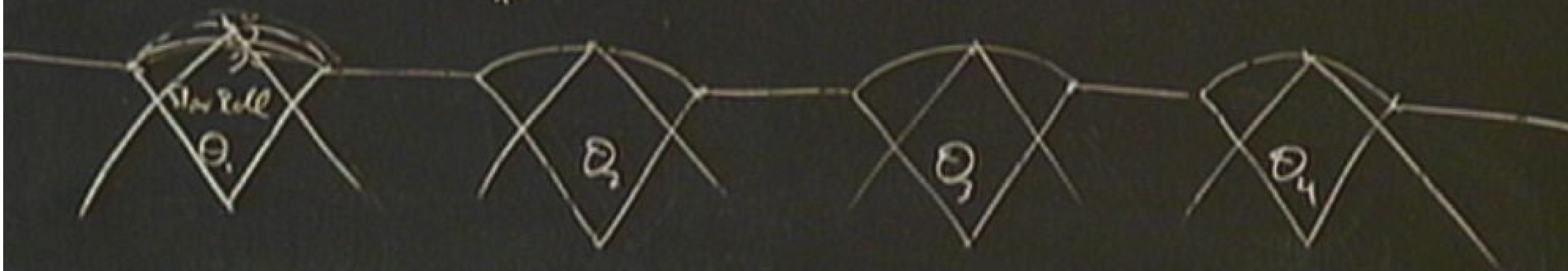

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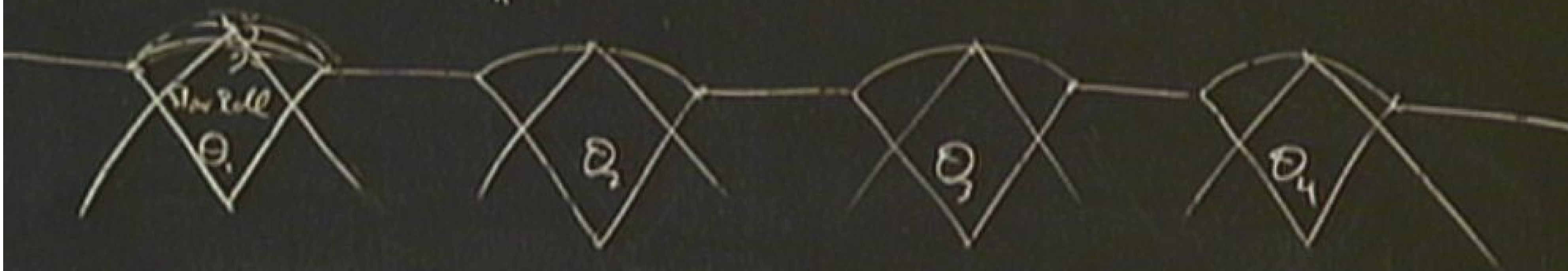

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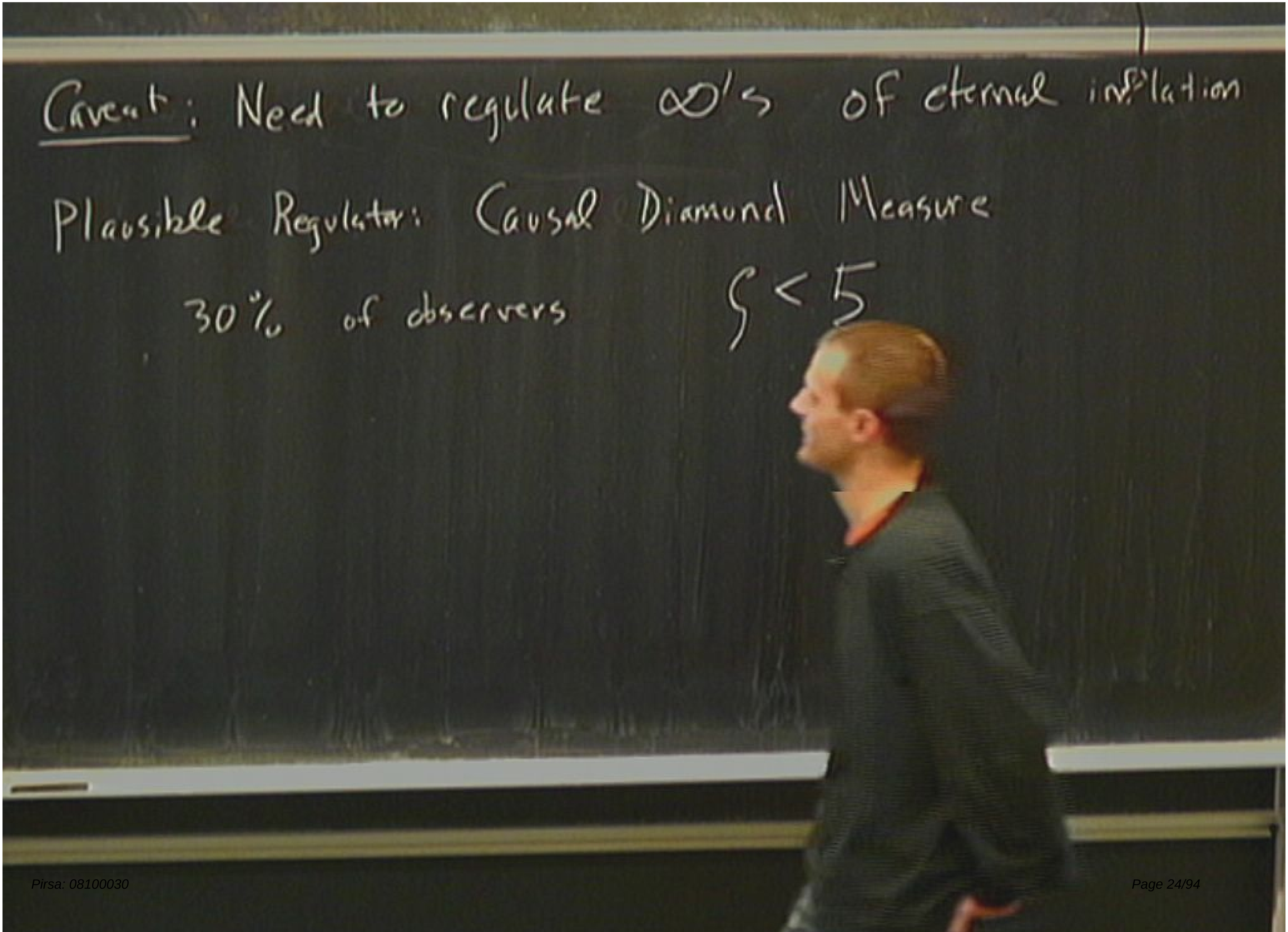
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Possible obs. confirmation

Strong CP problem

$$\Delta \mathcal{L}_{QCD} = \theta_0 \int F \wedge F$$

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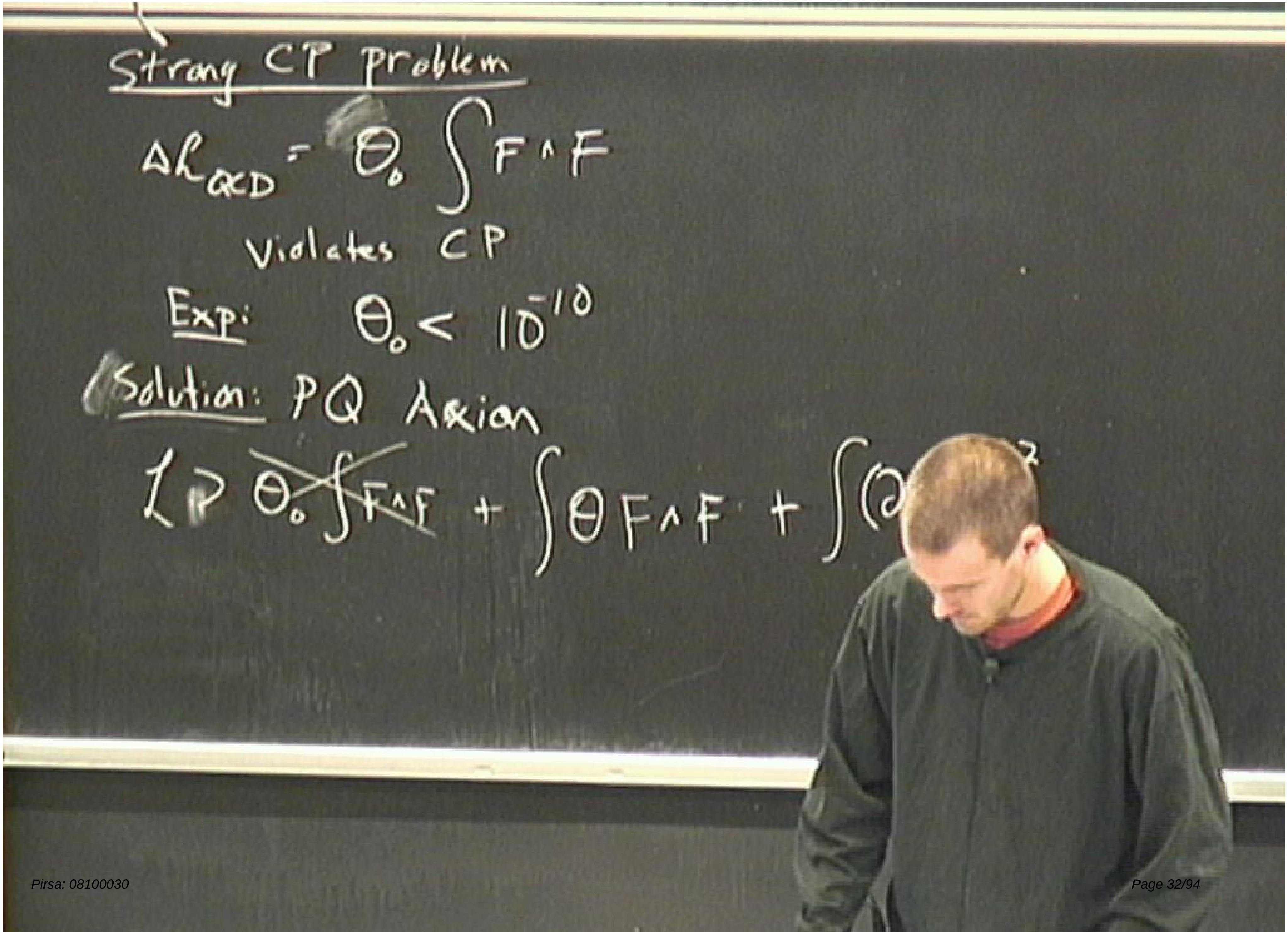
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Dynamically sets $\theta = 0$.

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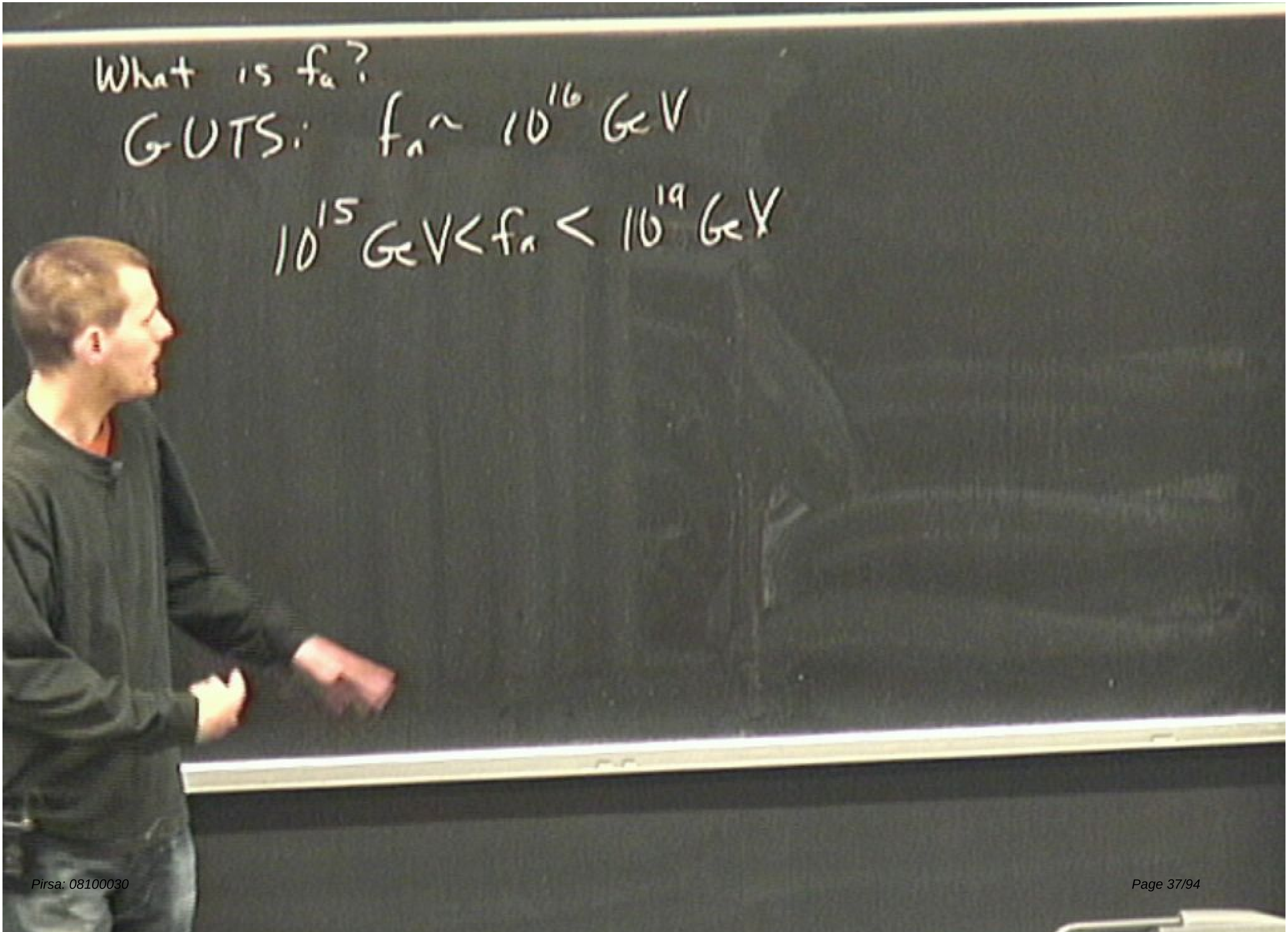
What is f_a?

GUTS: $f_a \sim 10^{16}$ GeV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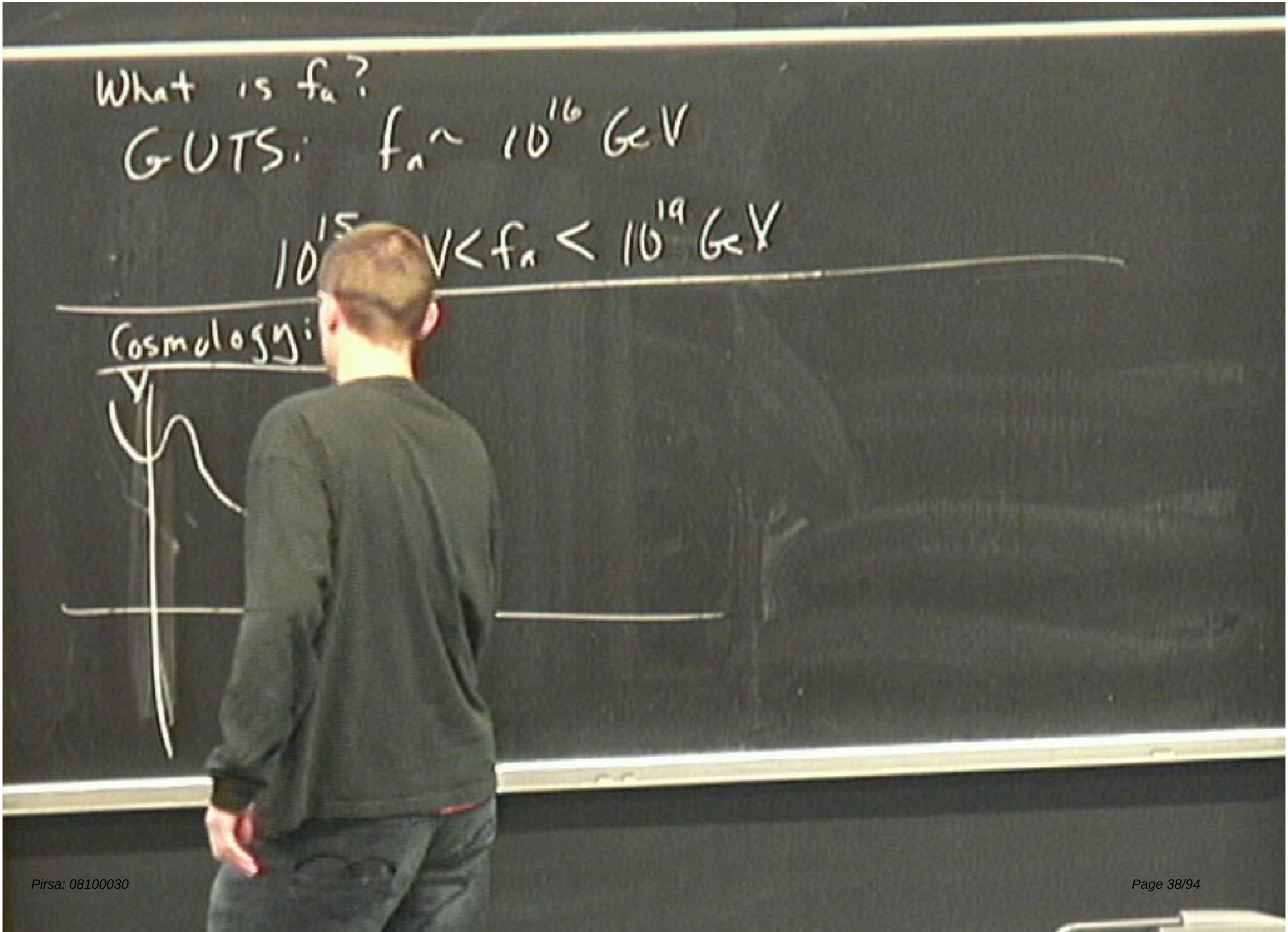
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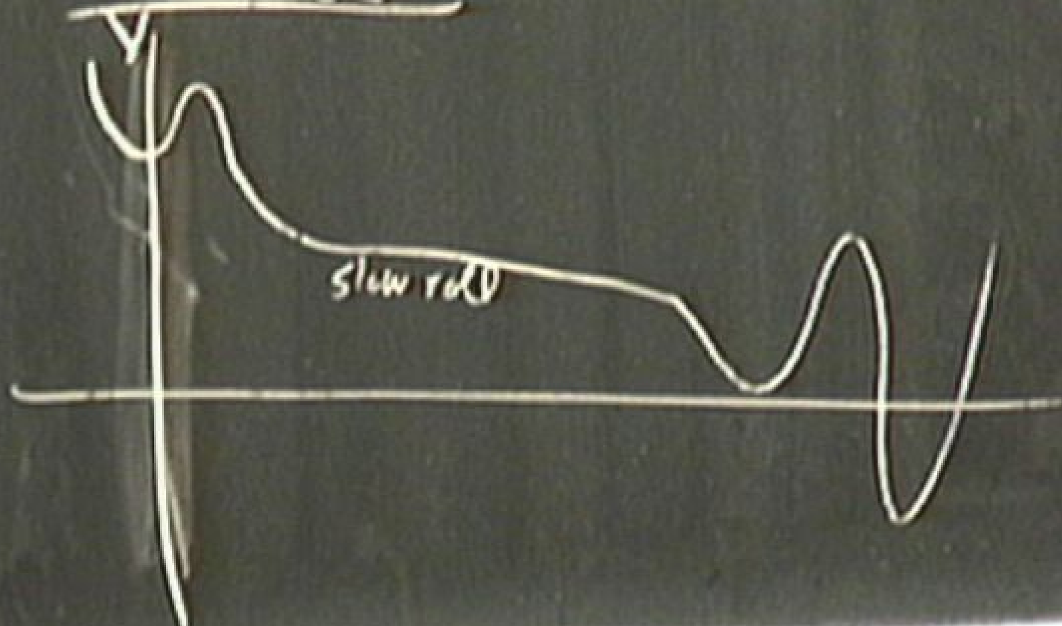

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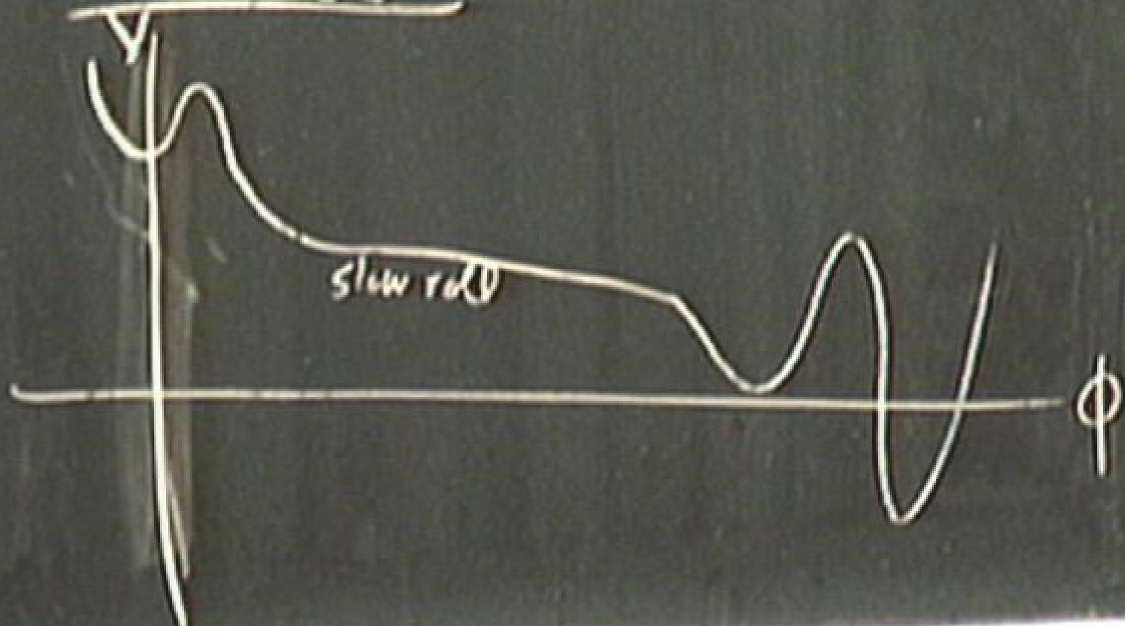

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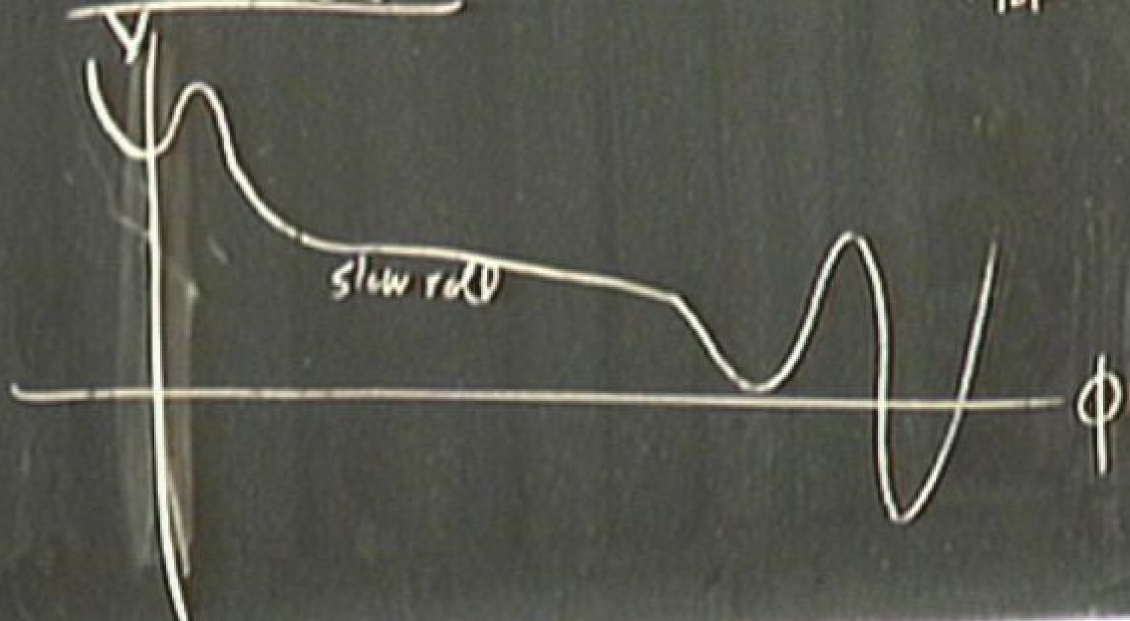
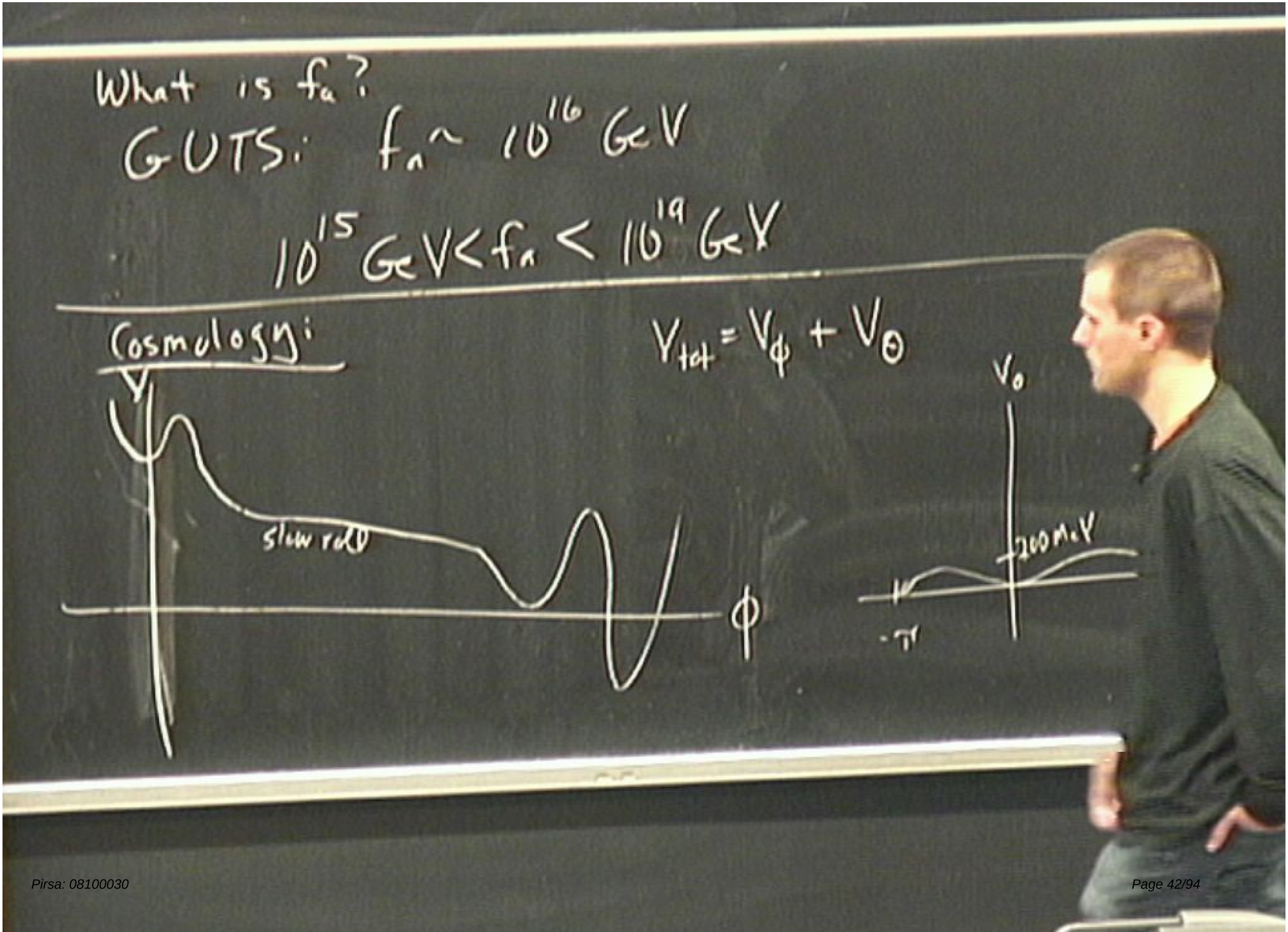
$V_{tot} = V_\phi + V_\Theta$

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ϕ
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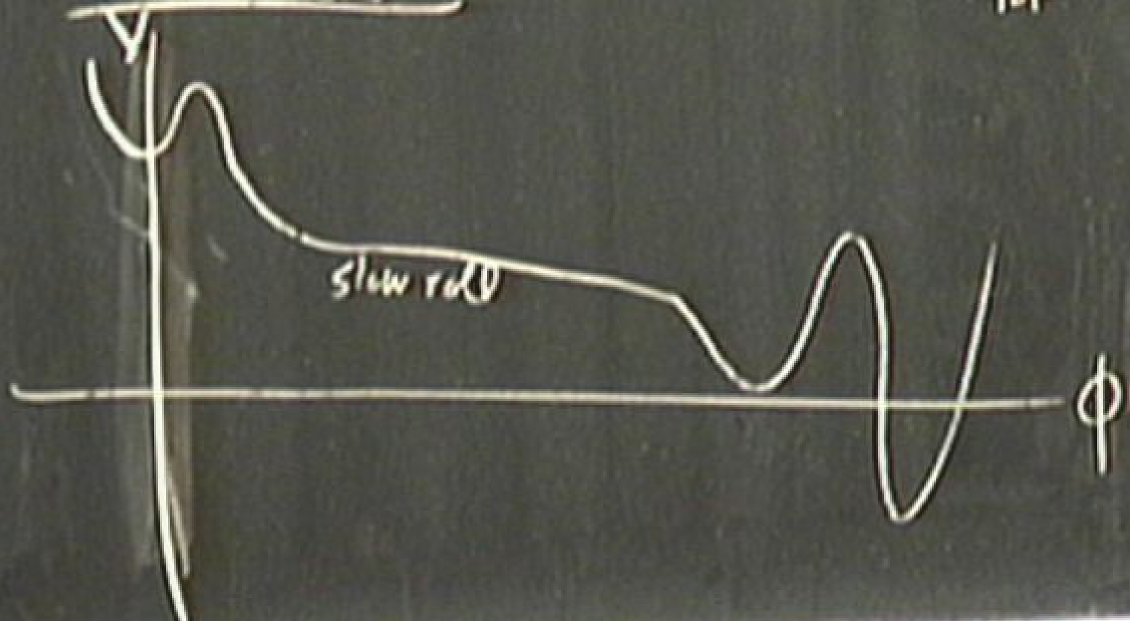

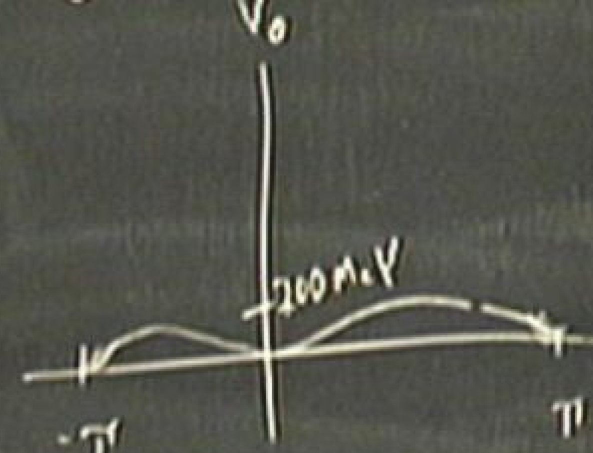

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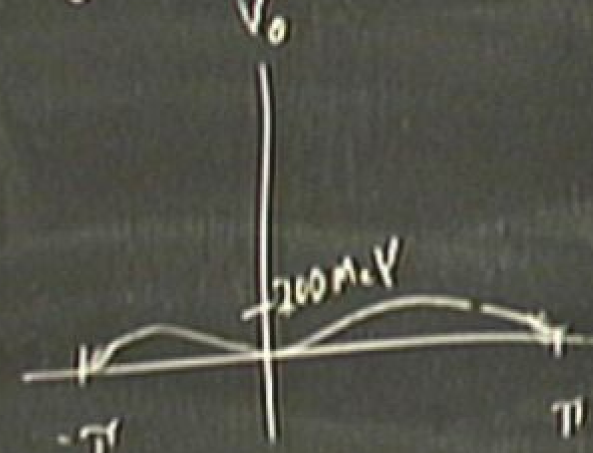

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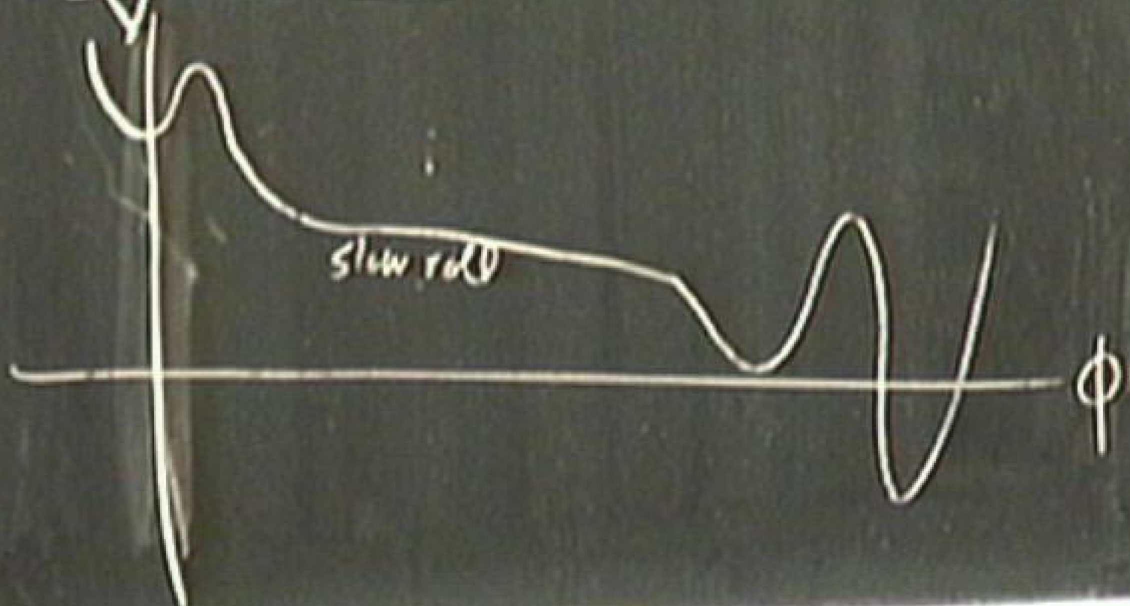

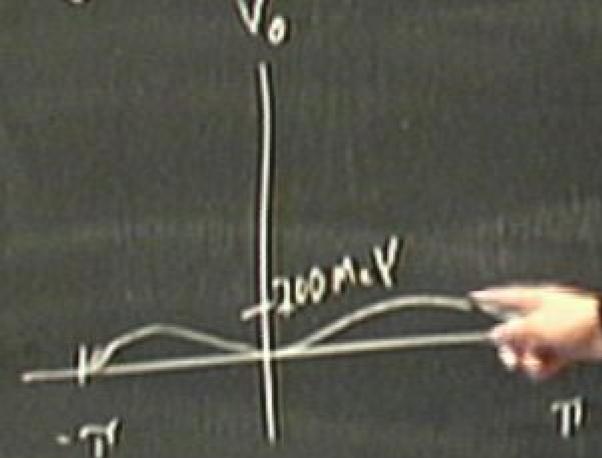

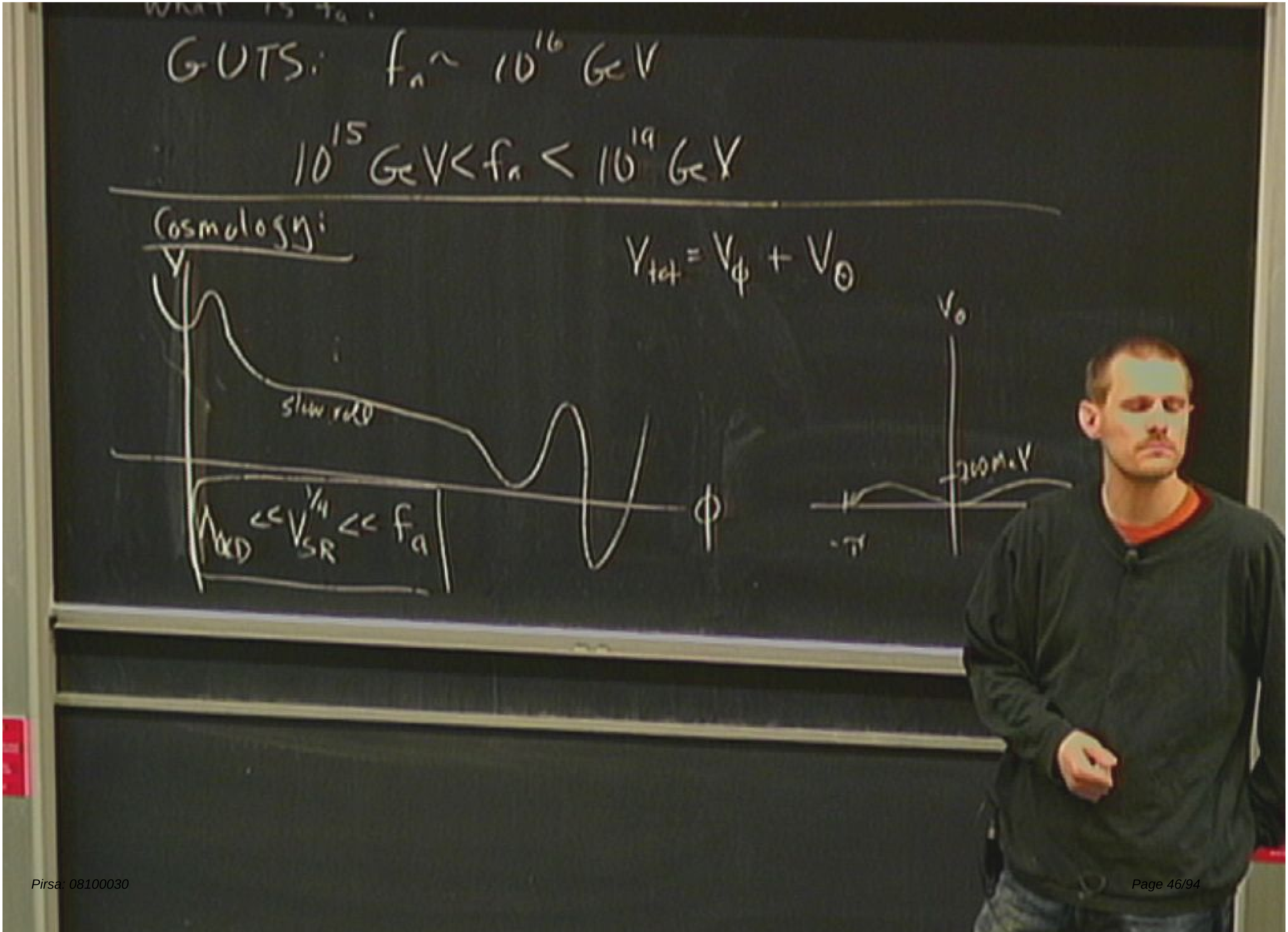
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slow roll
$\Lambda_{QCD} \ll V_{SR}^{1/4} \ll f_a$
ϕ
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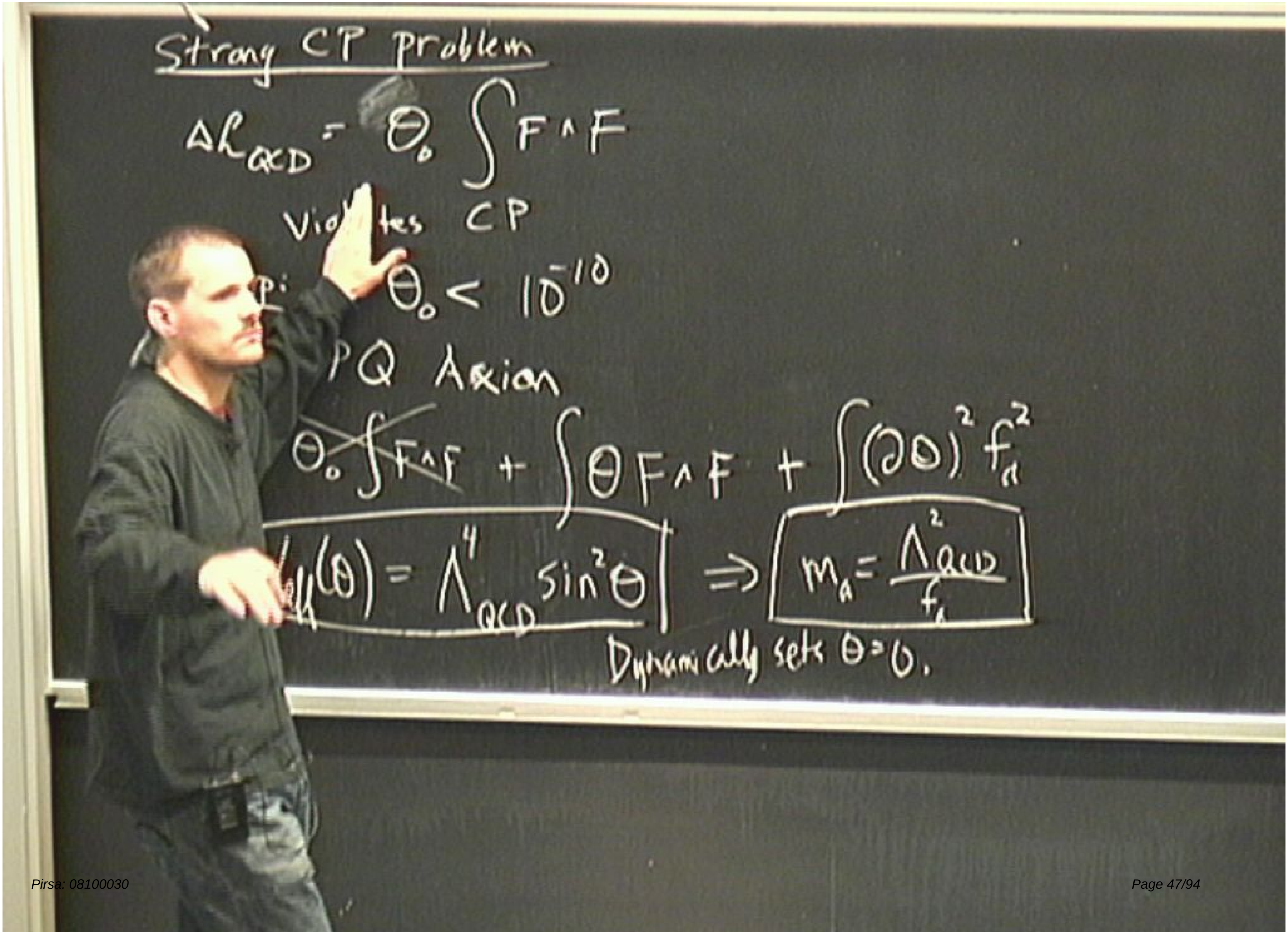
Strong CP problem
$\Delta \mathcal{L}_{QCD} = \Theta_0 \int F \wedge F$
CP
$\Theta_0 < 10^{-10}$
PQ Axion
$\cancel{\Theta_0 \int F \wedge F} + \int \Theta F \wedge F + \int (\partial \Theta)^2 f_a^2$
$(\Theta) = \Lambda_{QCD}^4 \sin^2 \Theta$
$\Rightarrow \boxed{m_a = \frac{\Lambda_{QCD}^2}{f_a}}$
Dynamically sets $\Theta = 0$.

Strong CP problem

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Violates CP

Exp: $\Theta_0 < 10^{-10}$

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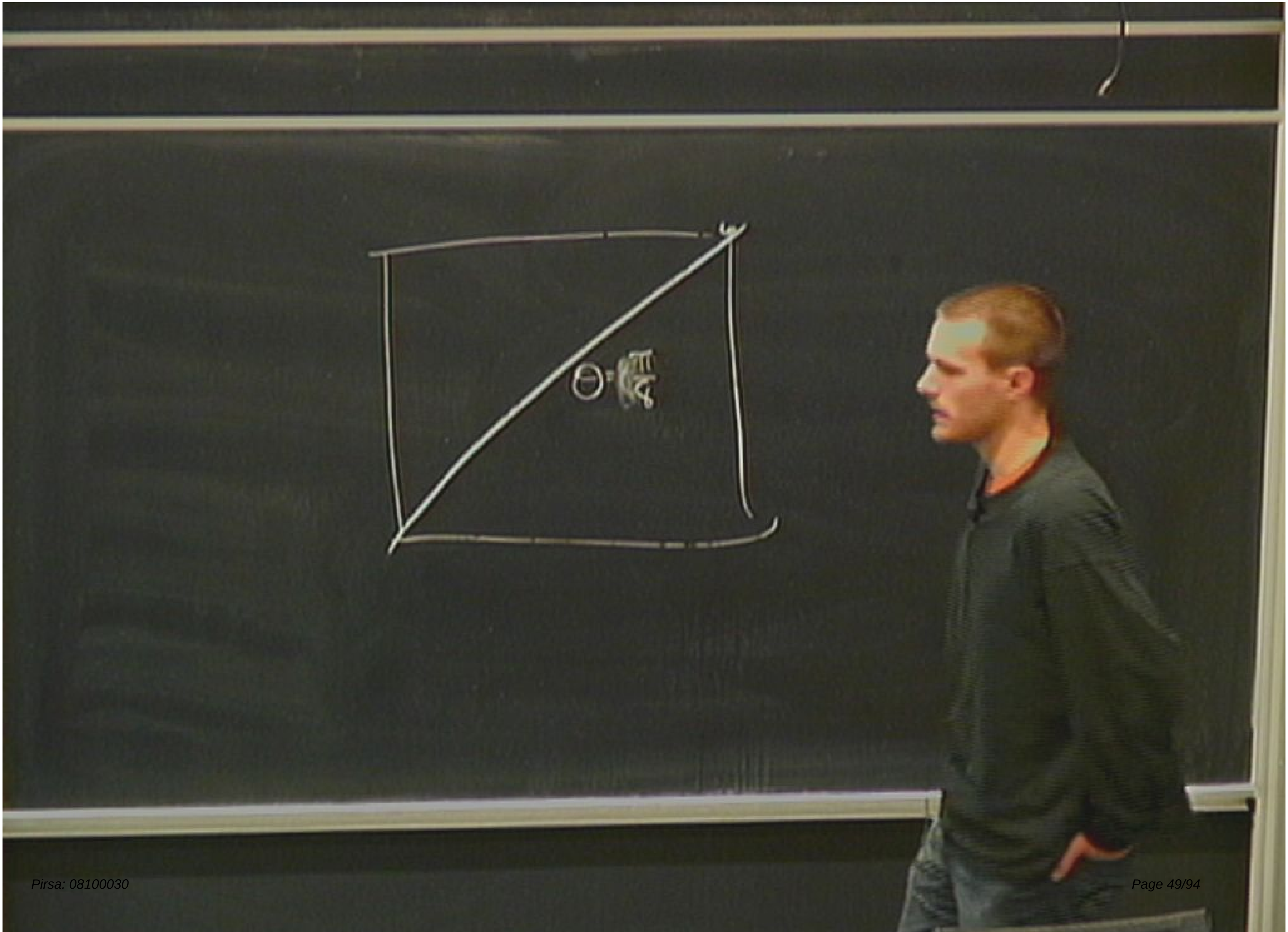
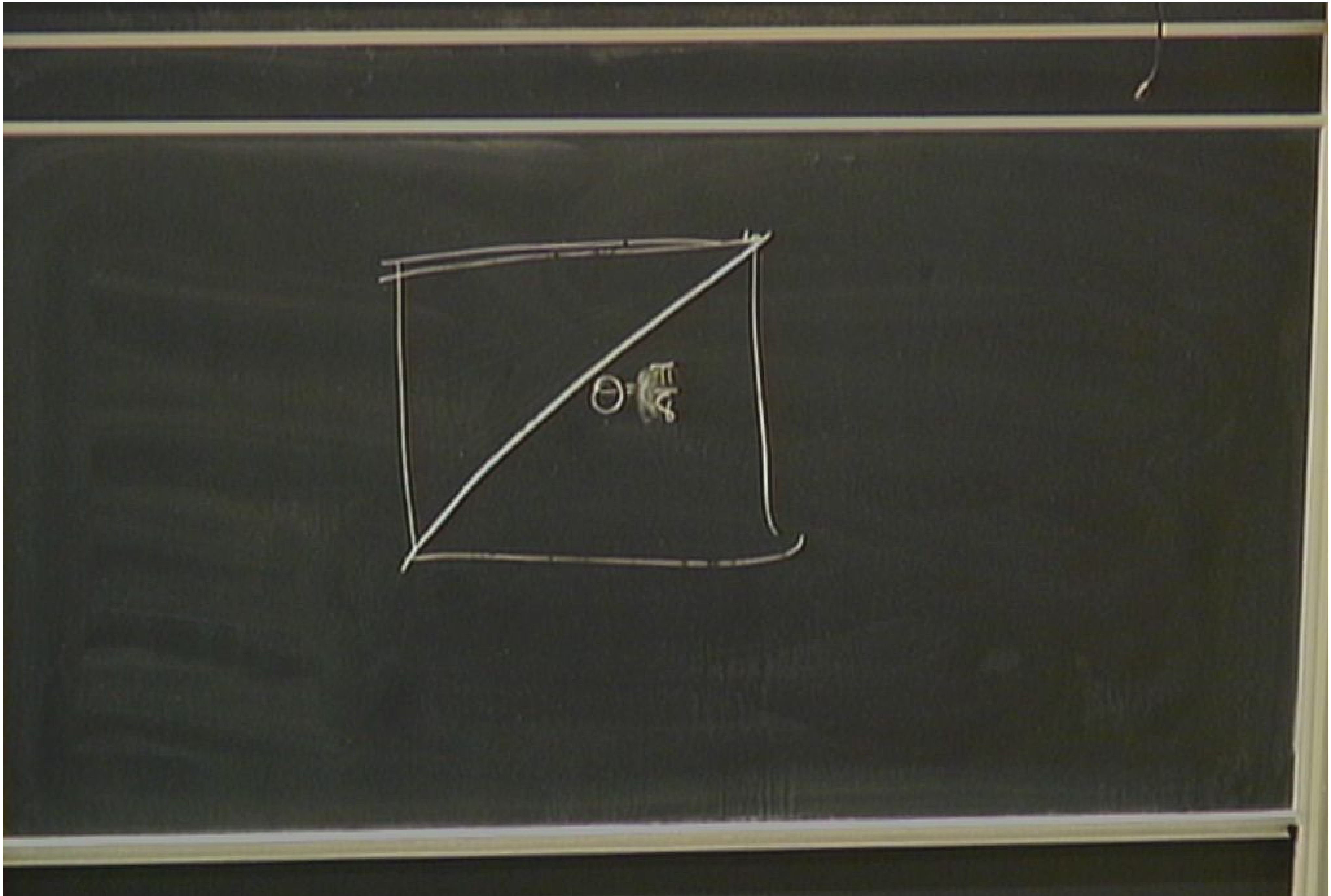

$\Theta = \frac{\pi}{4}$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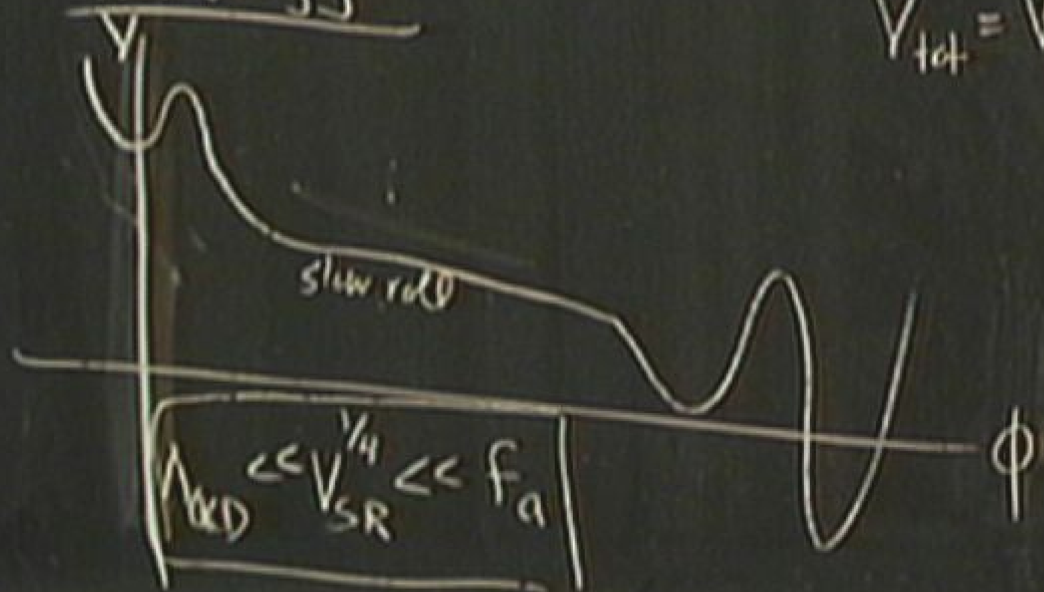
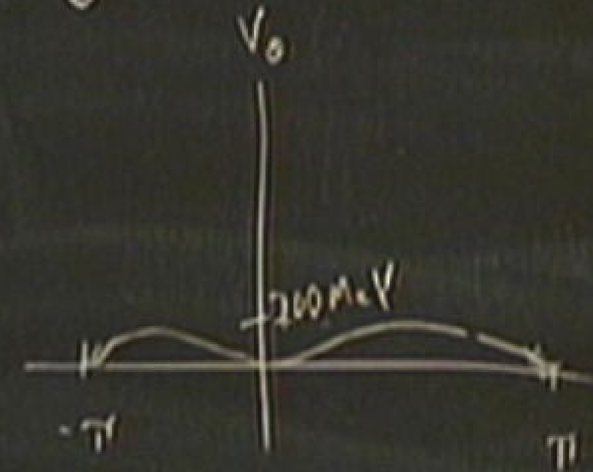
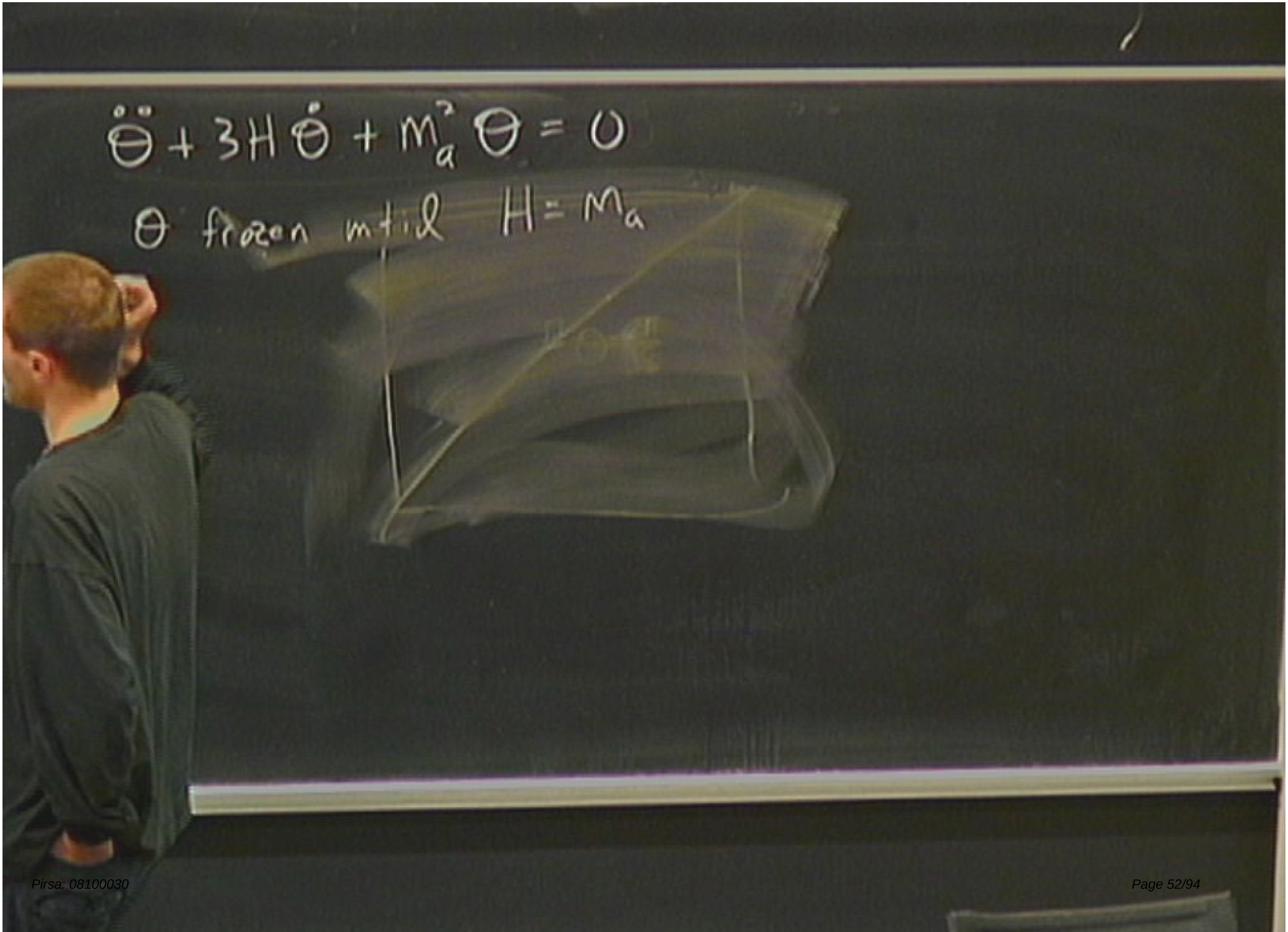
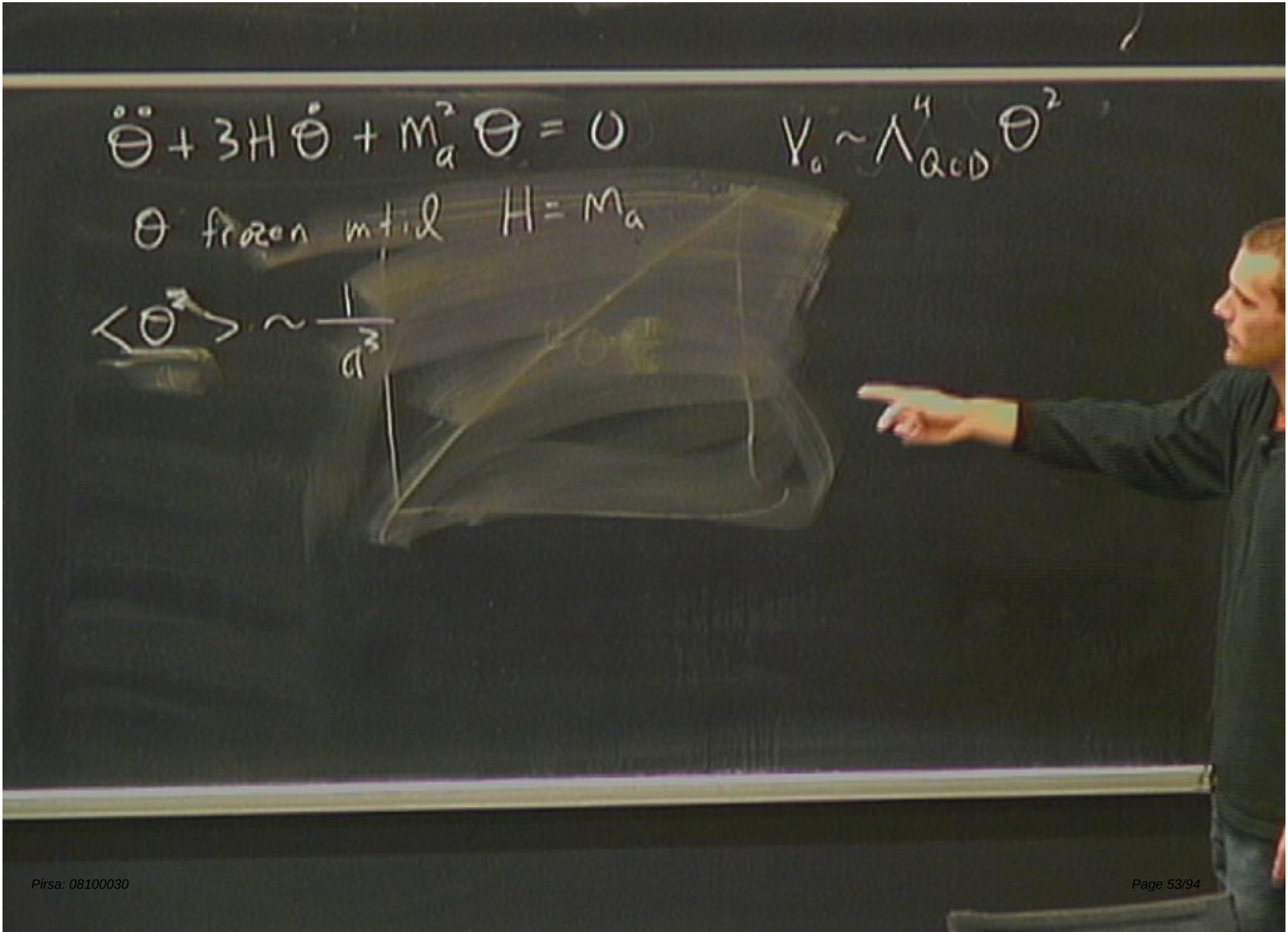


$$\boxed{\Lambda_{QCD} << V_{SR}^{1/4} << f_a}$$




$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$
θ frozen until $H = m_a$


$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$
$V_a \sim \Lambda_{QCD}^4 \theta^2$
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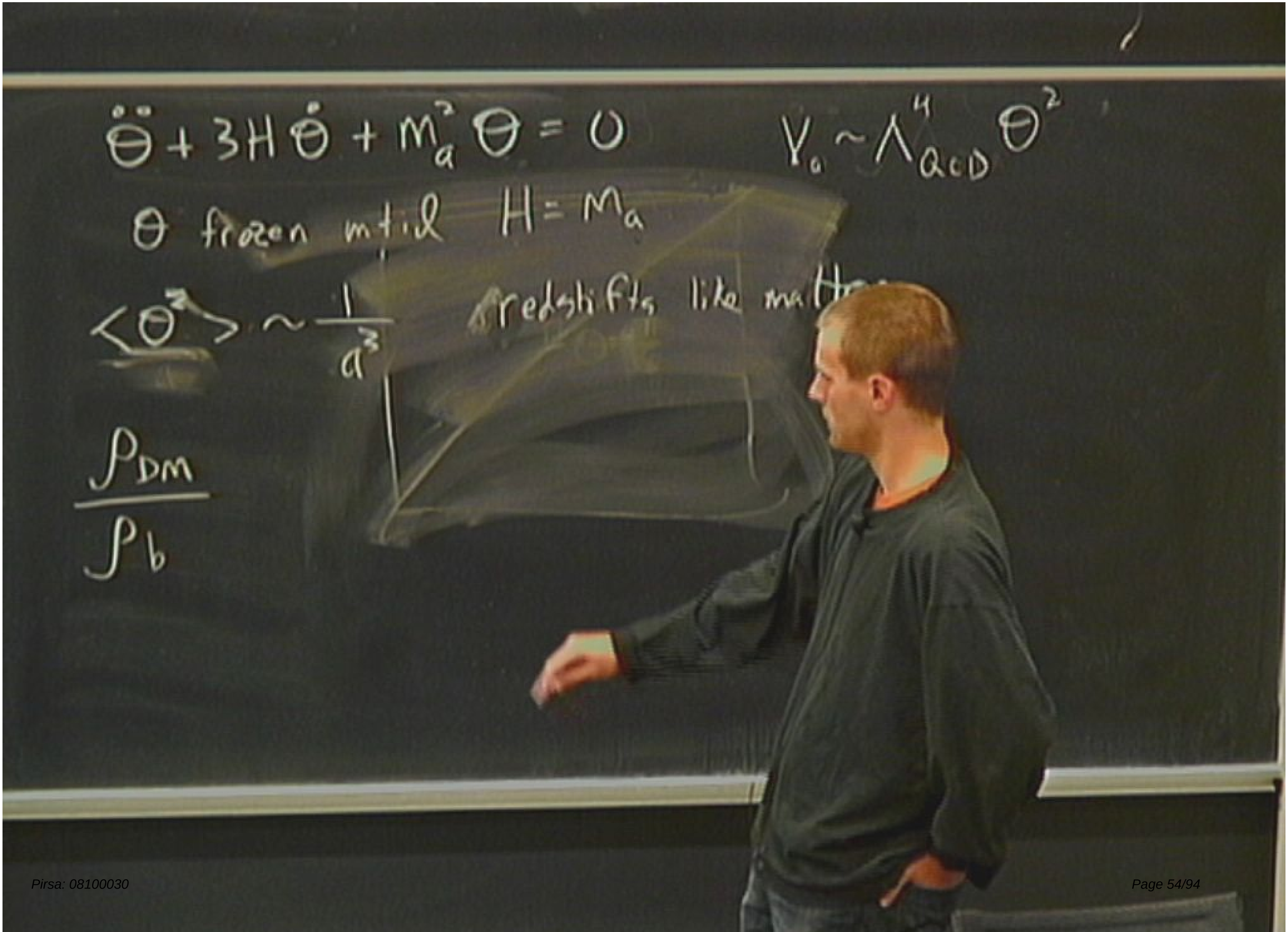
$\langle \theta^2 \rangle \sim \frac{1}{a^3}$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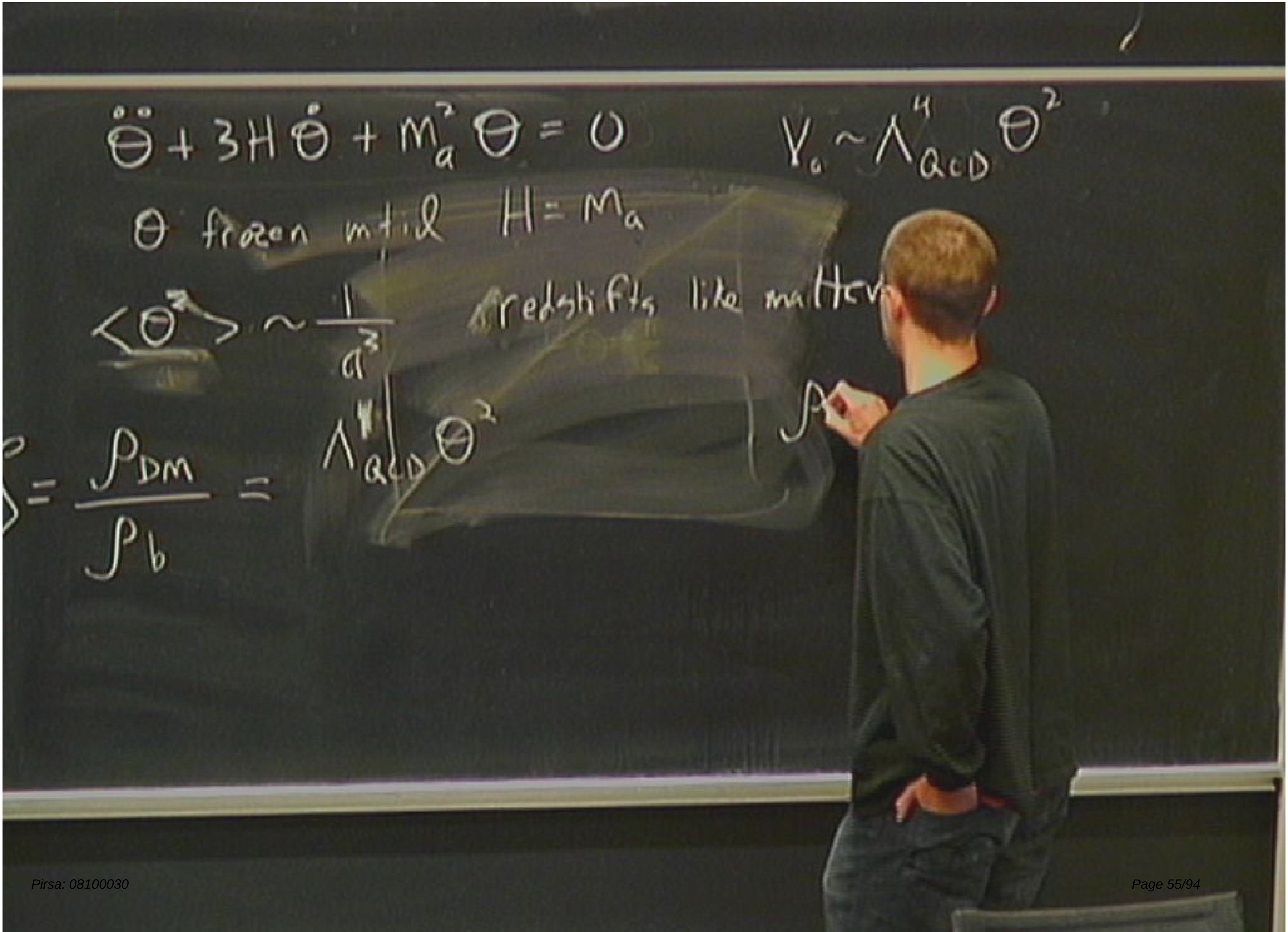
redshifts like ma
$\frac{\rho_{DM}}{\rho_b}$



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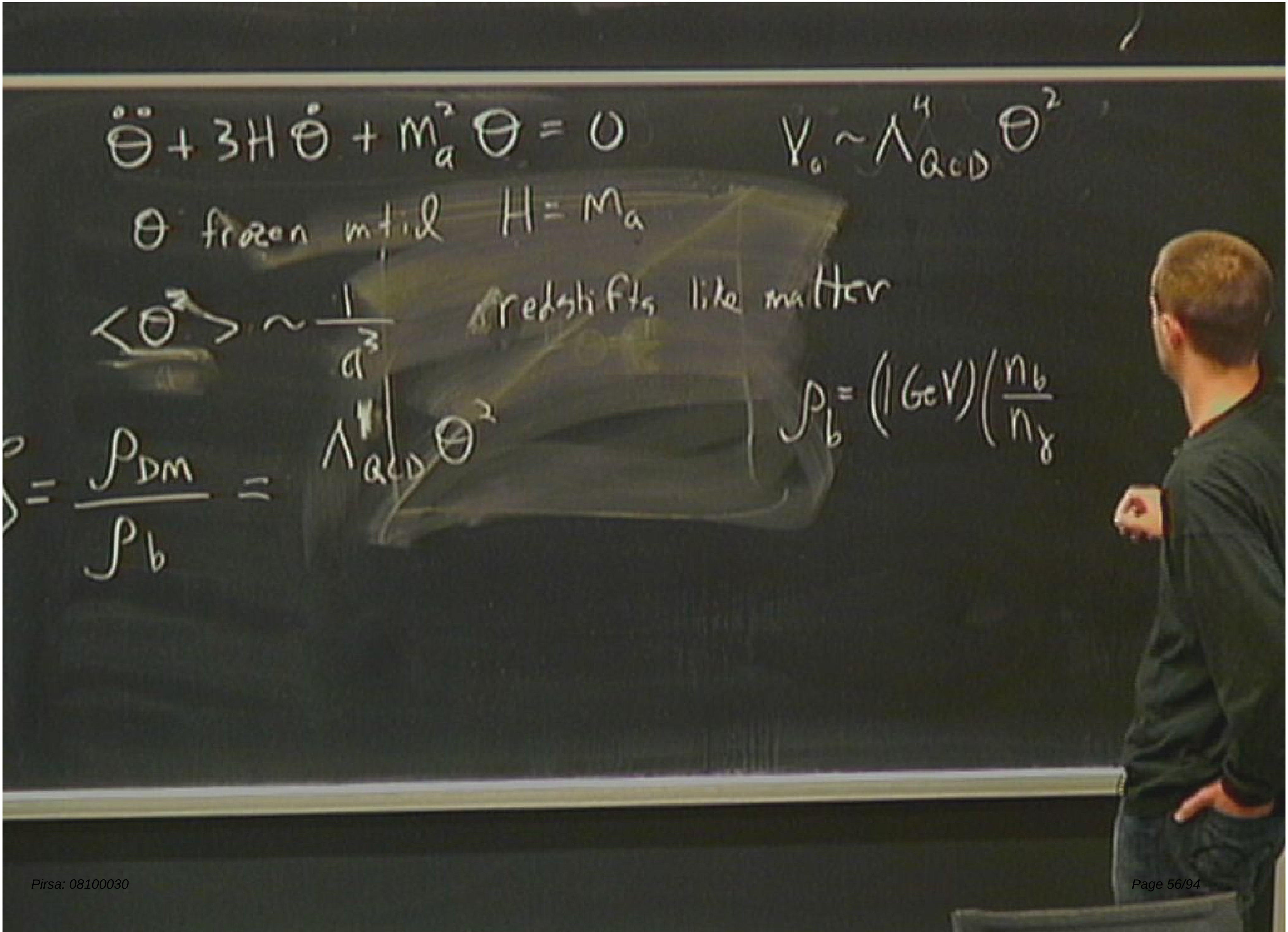
redshifts like matter
ρ
$= \frac{\rho_{DM}}{\rho_b} = \Lambda_{QCD}^4 \Theta^2$



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$V_a \sim \Lambda_{QCD}^4 \theta^2$
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redshifts like matter
$\rho_b = (1\,\mathrm{GeV})\left(\frac{n_b}{n_\gamma}\right.$
$\Lambda_{QCD}^4\theta^2$
$\Omega = \frac{\rho_{DM}}{\rho_b} =$

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\,\theta = 0 \qquad V_a \sim \Lambda_{QCD}^4\,\theta^2$$

θ frozen until $H = m_a$

$$\langle \theta^2 \rangle \sim \frac{1}{a^3}$$ redshifts like matter

$$\rho_b = (1\,\mathrm{GeV})\left(\frac{n_b}{n_\gamma}\right) n_\gamma$$

$$(1\,\mathrm{GeV})\, 10^{-9}\, T^3$$

$$S = \frac{\rho_{DM}}{\rho_b} = \qquad \Lambda_{QCD}^4\,\theta^2$$

θ frozen until $H = m_a$

$\langle \theta^2 \rangle \sim \frac{1}{a^3}$ redshifts like matter

$\Omega = \frac{\rho_{DM}}{\rho_b} = \Lambda^4_{QCD} \theta^2$

$\rho_b = (1\,GeV)\left(\frac{n_b}{n_\gamma}\right) n_\gamma$

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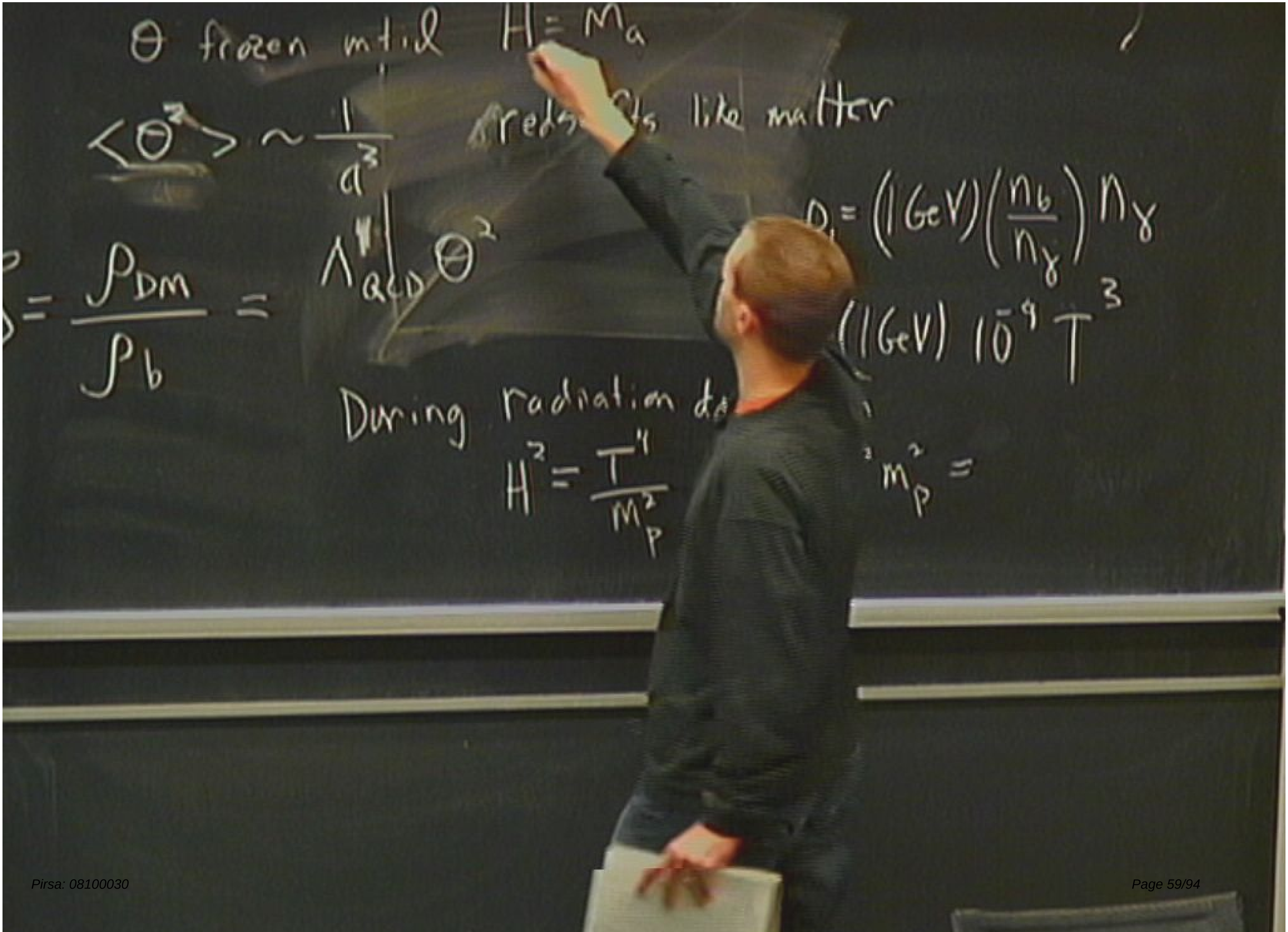
During radiation domination

$$H^2 = \frac{T^4}{M_p^2}$$


θ frozen until H = m_a
⟨θ²⟩ ~ 1/a³
like matter
Λ⁴_QCD θ²
= ρ_DM / ρ_b =
= (1 GeV)(n_b/n_γ) n_γ
(1 GeV) 10⁻⁹ T³
During radiation
H² = T⁴/M_p²
m_p² =

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0 \qquad V_a \sim \Lambda_{QCD}^4\,\theta^2$$

θ frozen until $H = m_a$

$$\langle\theta^2\rangle \sim \frac{1}{a^3}$$ redshifts like matter

$$\Lambda_{QCD}^4\,\theta^2$$

$$\rho_b = (1\,\text{GeV})\left(\frac{n_b}{n_\gamma}\right) n_\gamma$$

$$= \frac{\rho_{DM}}{\rho_b} =$$

$$((1\,\text{GeV})\,10^{-9}\,T^3$$

During radiation domination

$$H^2 = \frac{T^4}{M_p^2} \qquad T^4 = H^2 m_p^2 = m_a^2 M_p$$

$$\ddot{\Theta} + 3H\dot{\Theta} + m_a^2\,\Theta = 0 \qquad V_a \sim \Lambda_{QCD}^4\,\Theta^2$$

Θ frozen until $\underline{H = m_a}$

$$\langle \Theta^2 \rangle \sim \frac{1}{a^3}$$ redshifts like matter

$$\rho_b = (1\,\mathrm{GeV})\left(\frac{n_b}{n_\gamma}\right) n_\gamma$$

$$(1\,\mathrm{GeV})\,10^{-9}\,T^3$$

$$\frac{\rho_{DM}}{\rho_b} = \frac{\Lambda_{QCD}^4\,\Theta^2}{(1\,\mathrm{GeV})\,10^{-9}}$$

During radiation domination

$$H^2 = \frac{T^4}{M_p^2} \qquad T^4 = H^2 m_p^2 = m_a^2 m_p^2$$

$$=$$

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0 \qquad V_0 \sim \Lambda_{QCD}^4\theta^2$$

θ frozen until $H = m_a$

$$\langle\theta^2\rangle \sim \frac{1}{a^3}$$ redshifts like matter

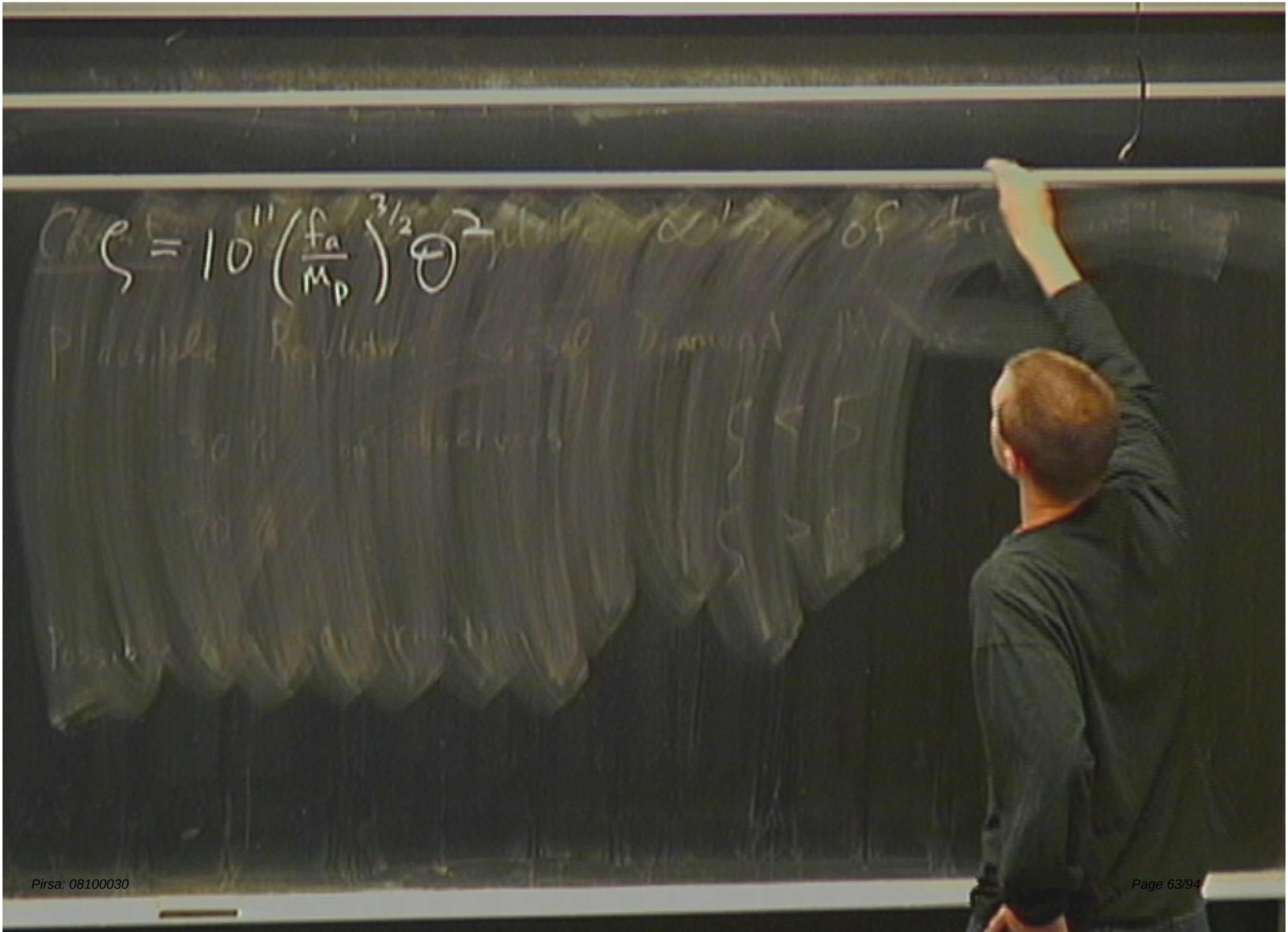
$$\rho_b = (1\,\mathrm{GeV})\left(\frac{n_b}{n_\gamma}\right)n_\gamma$$

$$\frac{\rho_{DM}}{\rho_b} = \frac{\Lambda_{QCD}^4\theta^2}{(1\,\mathrm{GeV})\,10^{-9}\,\Lambda_{QCD}^3\left(\frac{m_p}{f_a}\right)^{3/2}} \qquad (1\,\mathrm{GeV})\,10^{-9}\,T^3$$

During radiation domination

$$H^2 = \frac{T^4}{M_p^2} \qquad T^4 = H^2 m_p^2 = m_a^2 M_p^2$$

$$T^4 = \frac{\Lambda_{QCD}^4 m_p^2}{f_a^2}$$

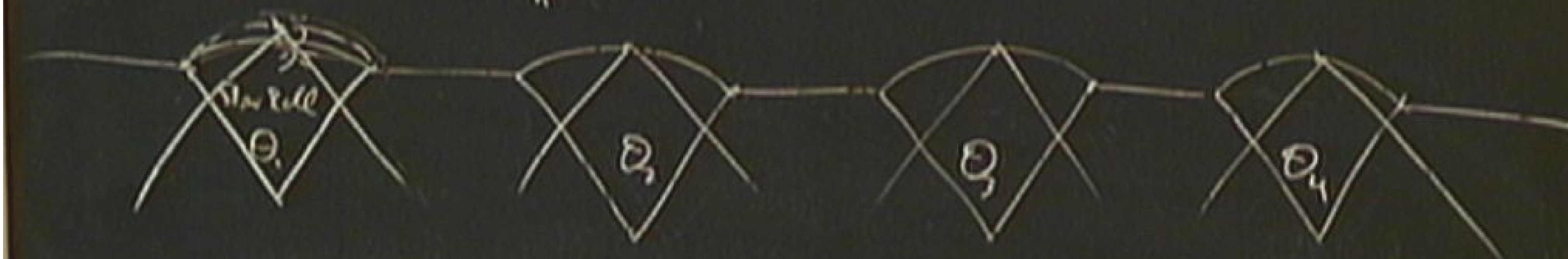

$\zeta = 10^{11} \left(\frac{f_a}{M_p}\right)^{3/2} \theta^2$

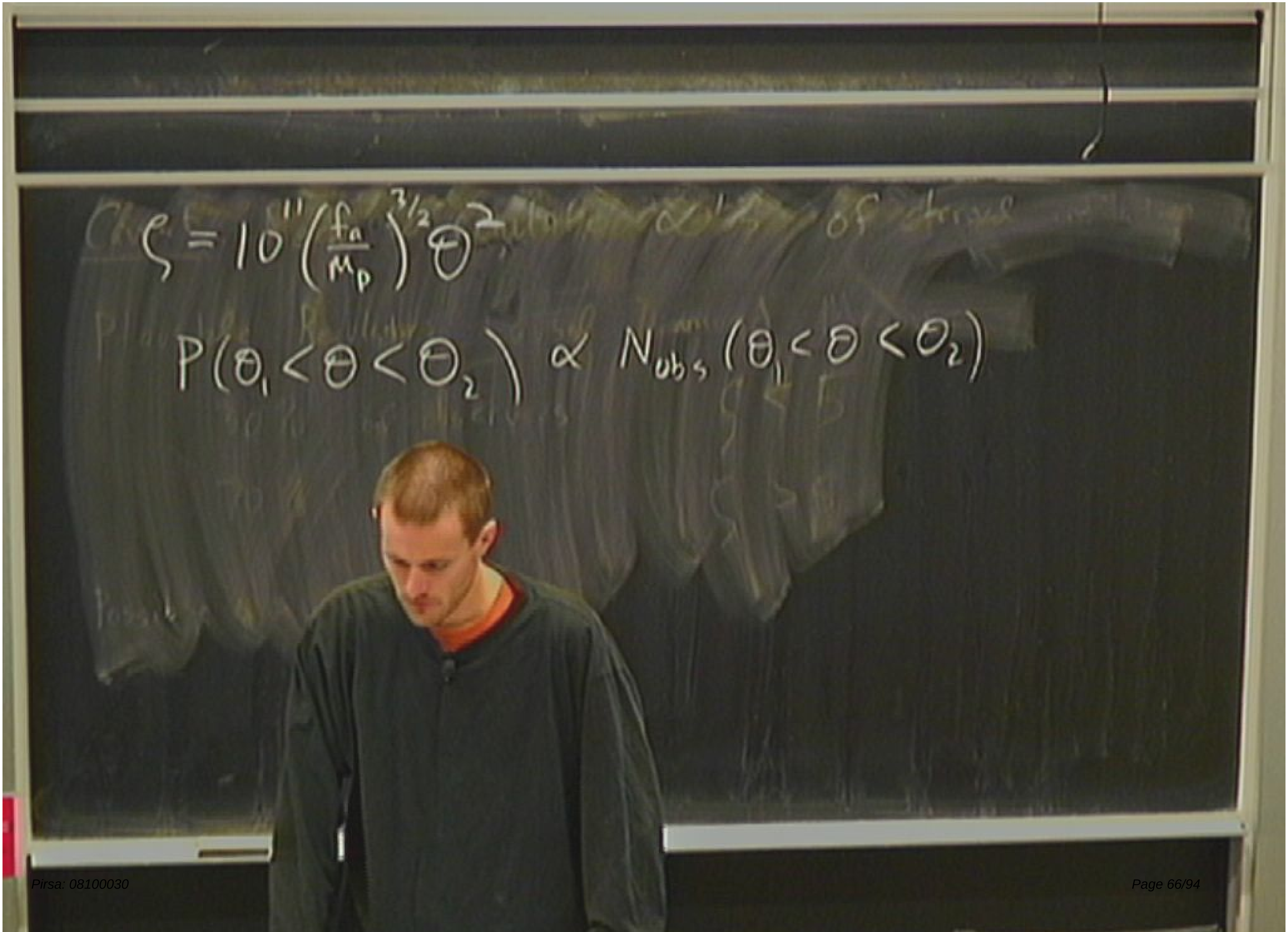
$$\varsigma = 10^{11}\left(\frac{f_a}{M_p}\right)^{3/2}\theta^2$$

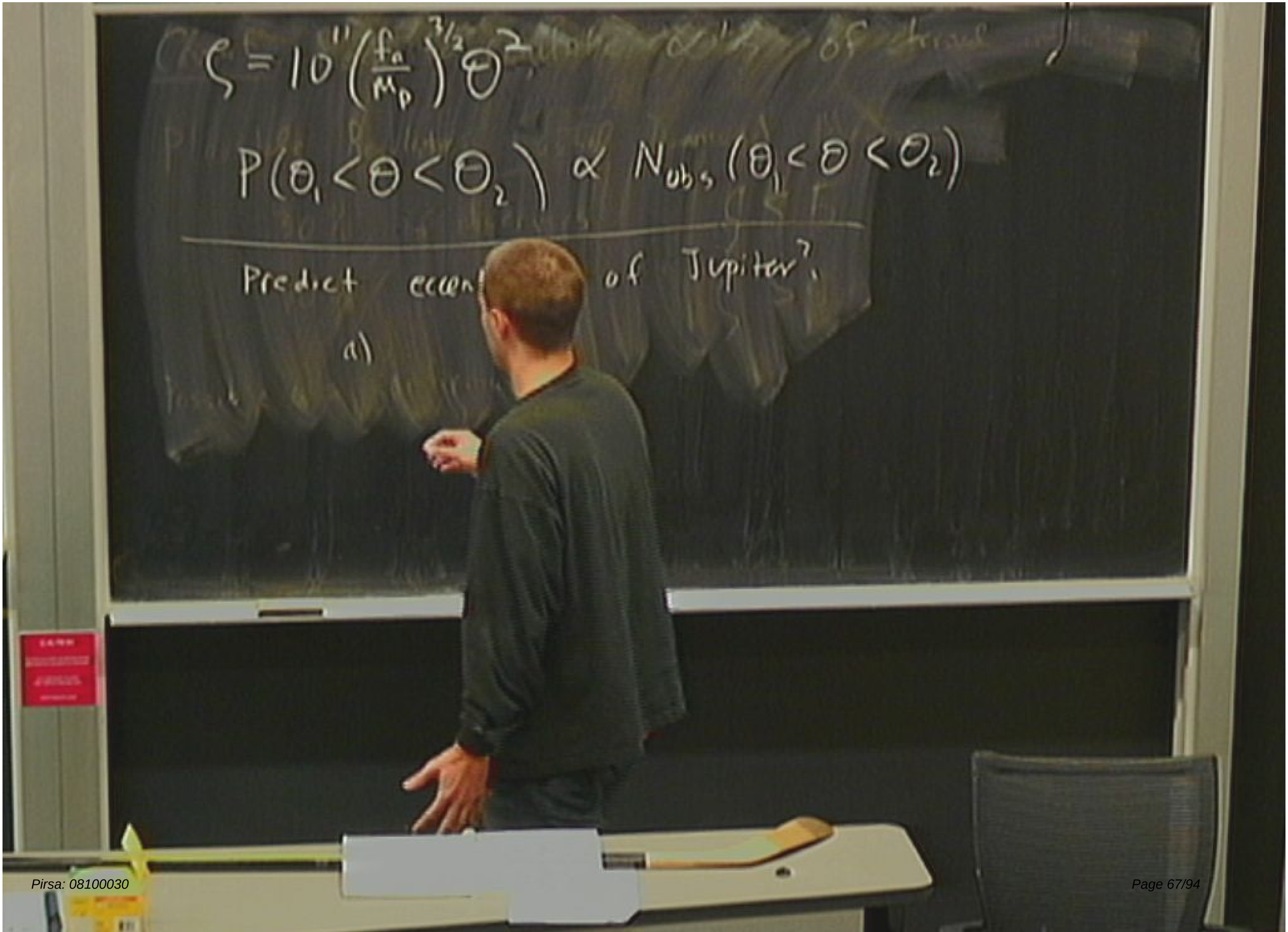
② Axion acts like DM

$$\rho = 10^{11}\left(\frac{f_a}{M_p}\right)^{3/2}\theta^2$$

Usual conclusion: $f_a < 10^{12}$ GeV




$\zeta = 10^{11}\left(\frac{f_a}{M_p}\right)^{3/2}\theta^2$
$P(\theta_1 < \theta < \theta_2) \propto N_{obs}(\theta_1 < \theta < \theta_2)$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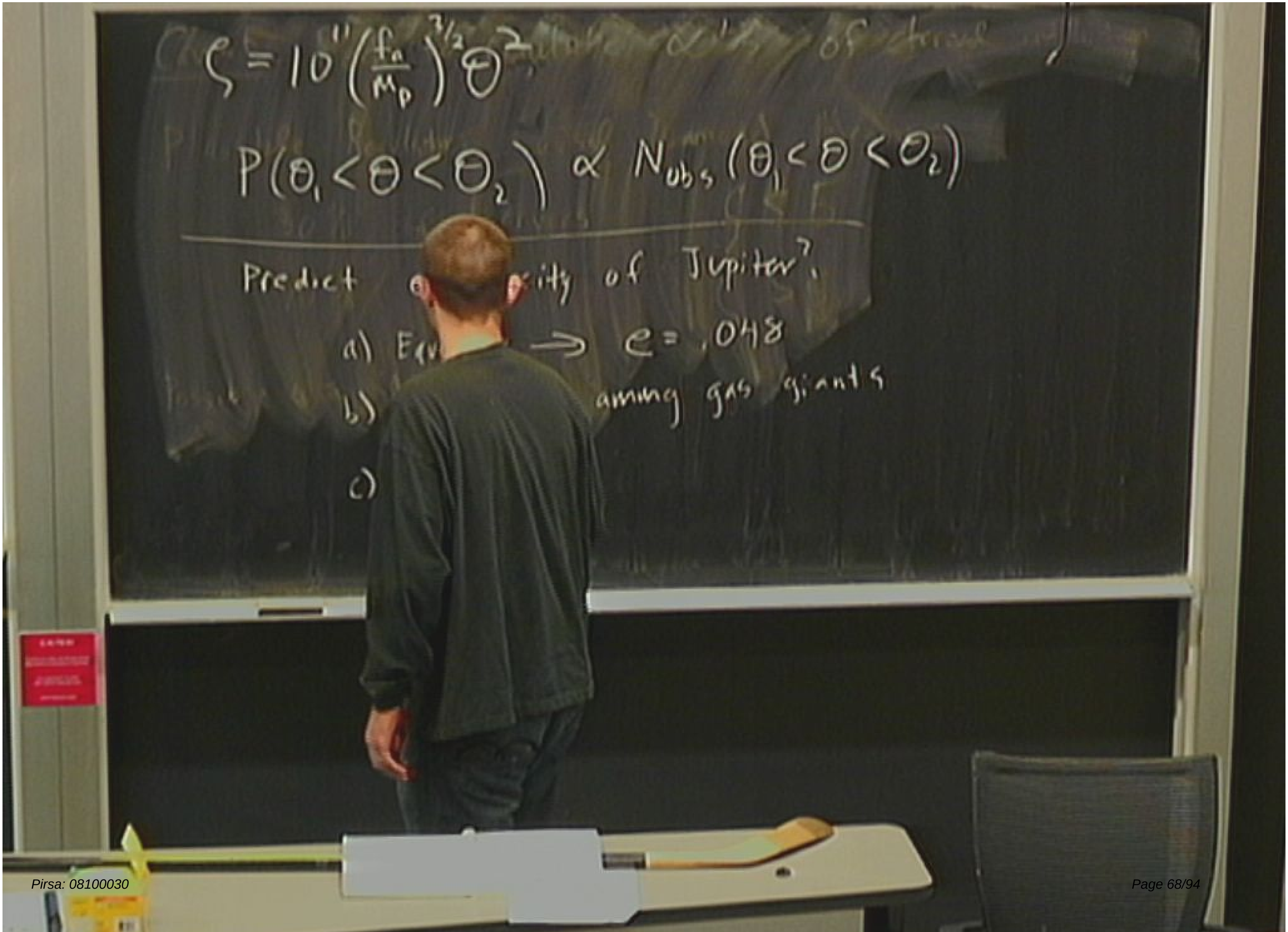
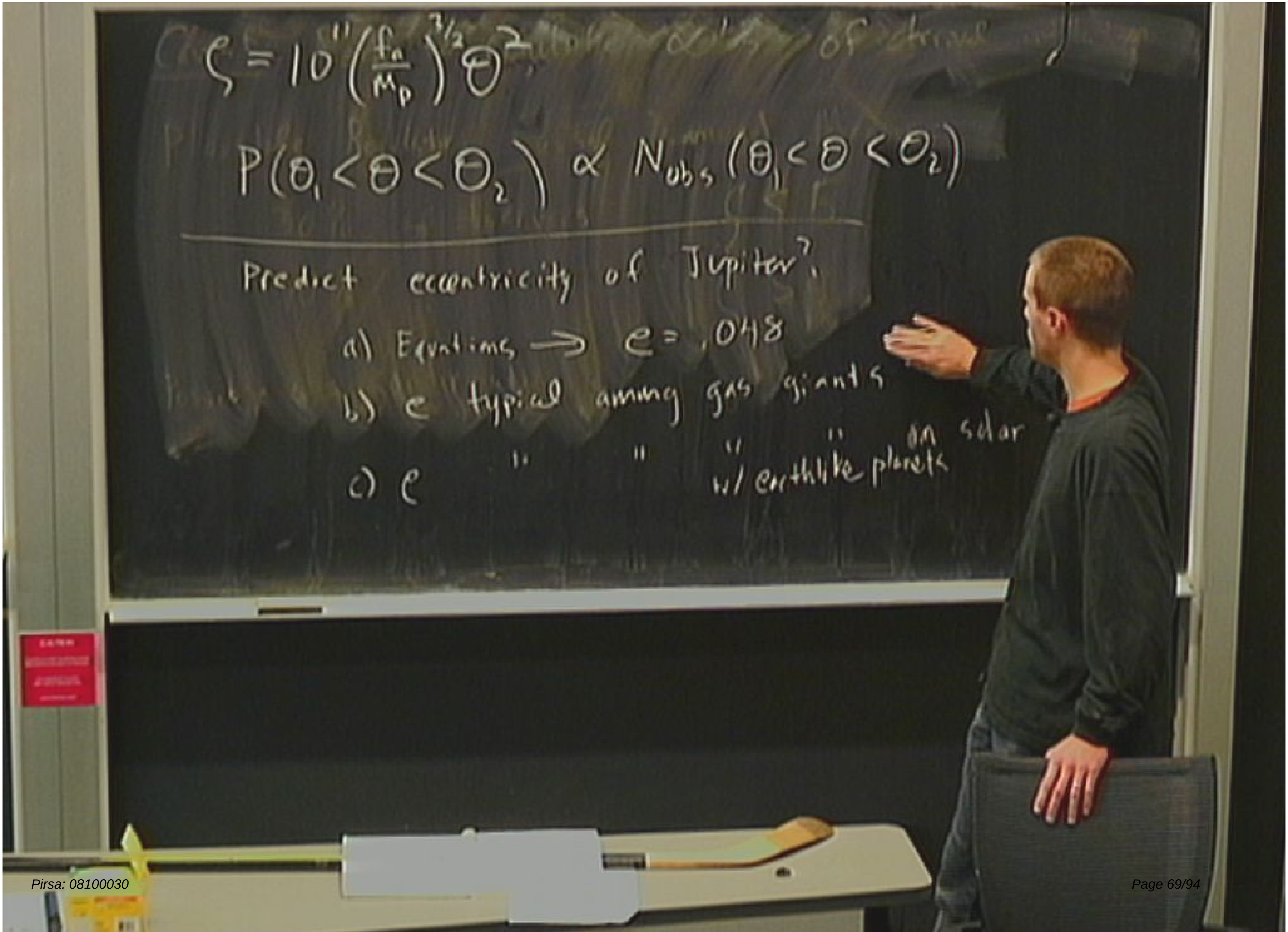
Predict eccen of Jupiter?
a)


$\rho = 10^{11}\left(\frac{f_a}{M_p}\right)^{3/2}\theta^2$
$P(\theta_1 < \theta < \theta_2) \propto N_{obs}(\theta_1 < \theta < \theta_2)$
Predict
of Jupiter?
a)
$\Rightarrow e = .048$
b)
among gas giants
c)


$\varsigma = 10^{11} \left(\frac{f_n}{M_p}\right)^{3/2} \Theta^2$
$P(\Theta_1 < \Theta < \Theta_2) \propto N_{obs}(\Theta_1 < \Theta < \Theta_2)$
Predict eccentricity of Jupiter?
a) Equations → e = .048
b) e typical among gas giants
" " " in solar
c) e " " " w/ earthlike planets

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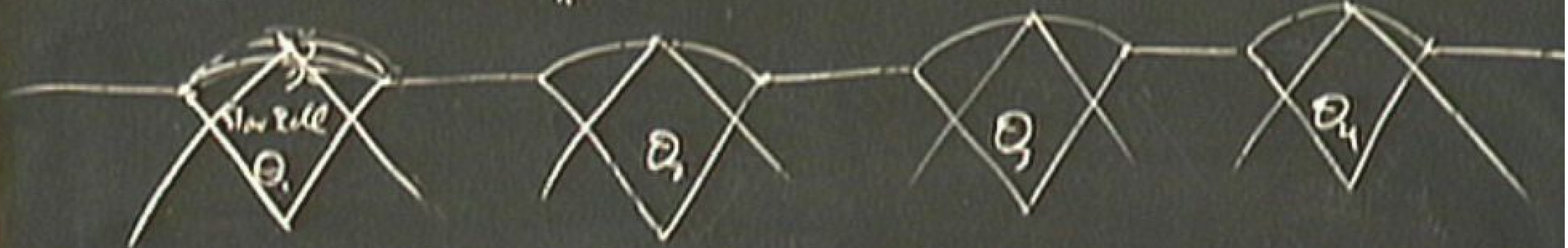

$$\frac{dP}{d\theta} = \frac{dP}{d\theta}\Big|_{prior} N_{obs}(\theta)$$

② Axion acts like DM

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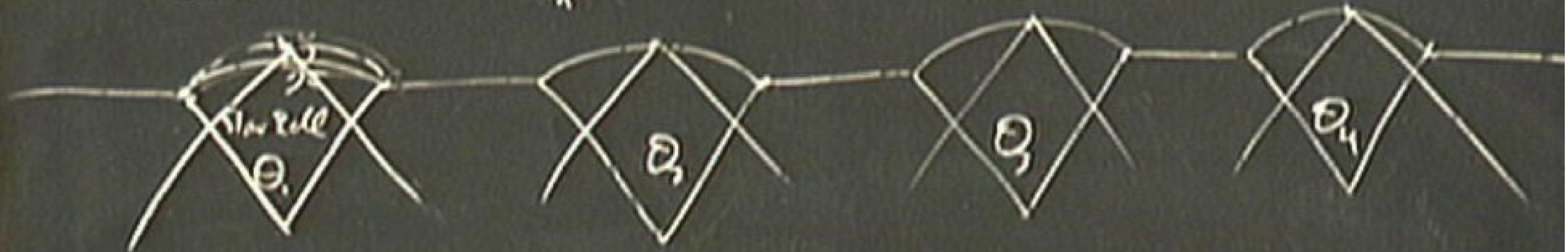
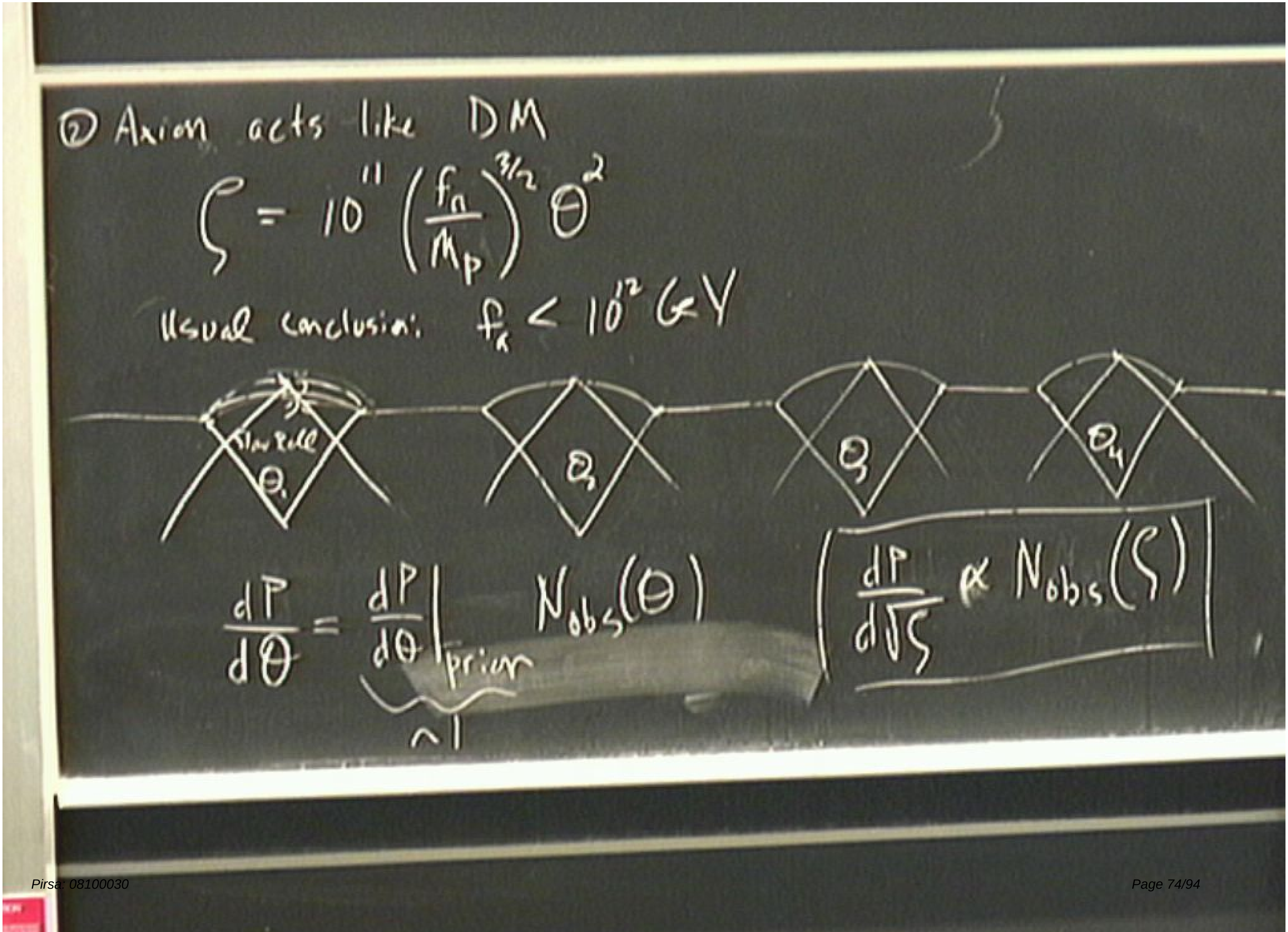


$$\frac{dP}{d\theta} = \left.\frac{dP}{d\theta}\right|_{prior} N_{obs}(\theta)$$

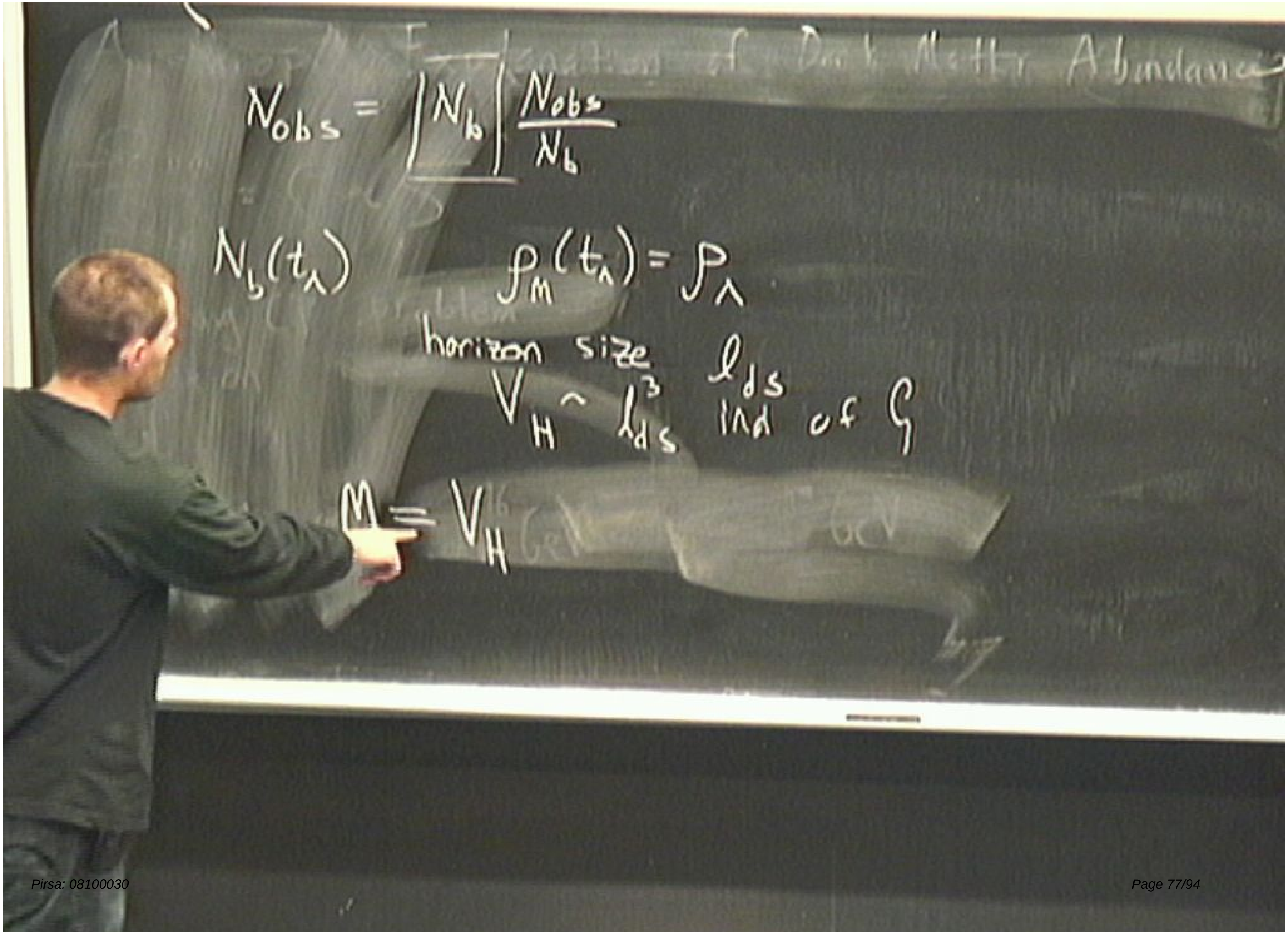

② Axion acts like DM
$\rho = 10^{11} \left(\frac{f_a}{M_p}\right)^{3/2} \theta^2$
Usual conclusion: $f_a < 10^{12}$ GeV
slow roll
θ_1
θ_2
θ_3
θ_4
$\frac{dP}{d\theta} = \frac{dP}{d\theta}\Big|_{prior} N_{obs}(\theta)$
$\frac{dP}{d\sqrt{\rho}} \propto N_{obs}(\rho)$

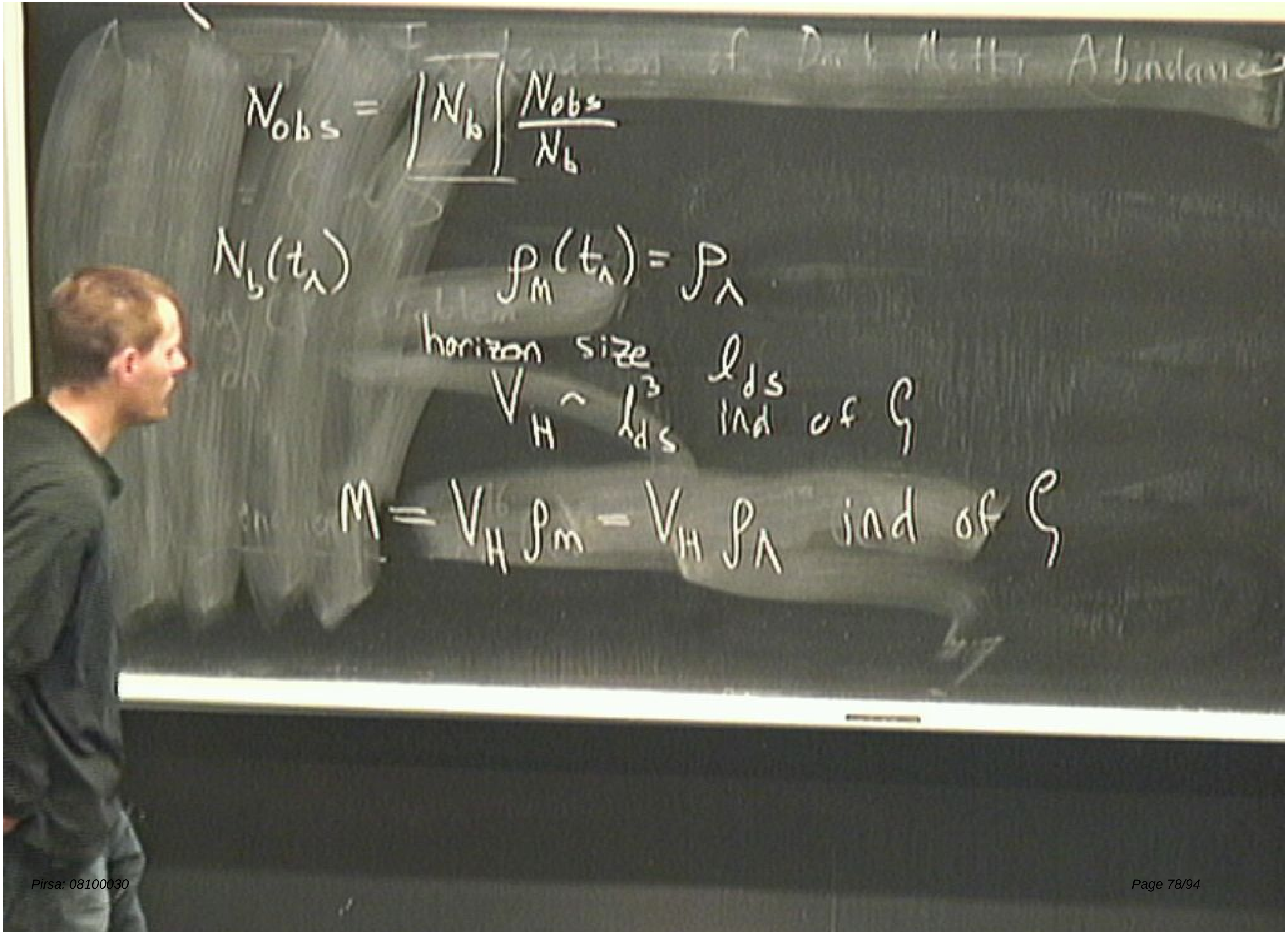
... Explanation of Dark Matter Abundance

$$N_{obs} = N_b \cdot \frac{N_{obs}}{N_b}$$

$$N_{obs} = \boxed{N_b} \frac{N_{obs}}{N_b}$$

$$N_b(t_\Lambda)$$


Abundance
N_obs = N_b N_obs / N_b
N_b(t_Λ)
ρ_m(t_Λ) = ρ_Λ
horizon size l_ds
V_H ~ l_ds^3 ind of ζ
M = V_H


of Dark Matter Abundance
$N_{obs} = \boxed{N_b} \frac{N_{obs}}{N_b}$
$N_b(t_\Lambda)$ $\rho_m(t_\Lambda) = \rho_\Lambda$
horizon size l_{dS}
$V_H \sim l_{dS}^3$ ind of ζ
$M = V_H \rho_m = V_H \rho_\Lambda$ ind of ζ

... of Dark Matter Abundance

$$N_{obs} = \boxed{N_b}\,\frac{N_{obs}}{N_b}$$

$$N_b(t_\Lambda) \qquad \rho_m(t_\Lambda) = \rho_\Lambda$$

horizon size ℓ_{ds}

$$V_H \sim \ell_{ds}^3 \quad \text{ind of } \zeta$$

$$M = V_H\,\rho_m = V_H\,\rho_\Lambda \quad \text{ind of } \zeta$$

$$\propto M_b = \frac{M}{1+\zeta}$$

Explanation of Dark Matter Abundance

$$N_{obs} = \boxed{N_b} \frac{N_{obs}}{N_b}$$

$N_b(t_\Lambda)$ $\qquad \rho_m(t_\Lambda) = \rho_\Lambda$

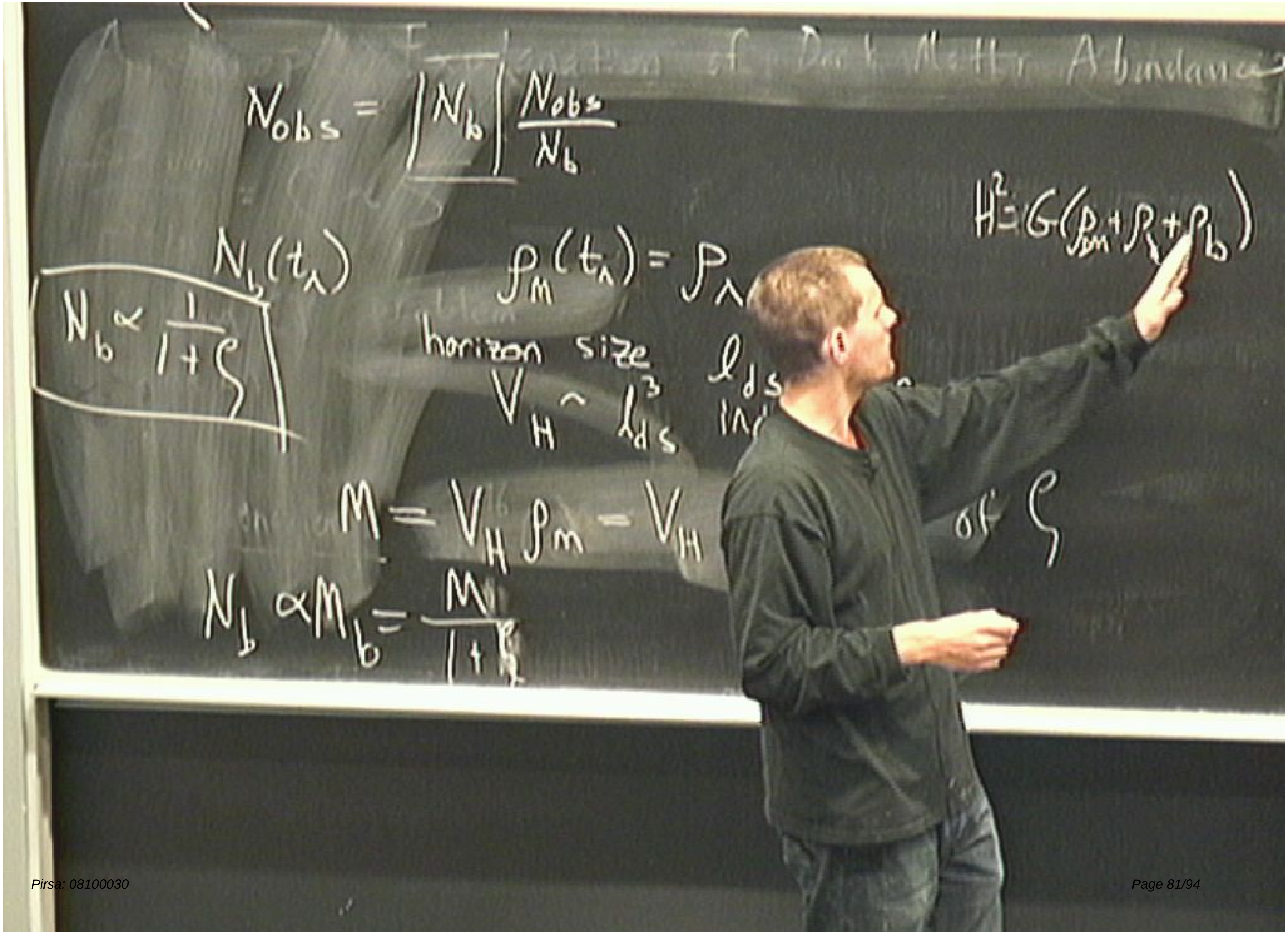
$$\boxed{N_b \propto \frac{1}{1+\zeta}}$$

horizon size ℓ_{ds}

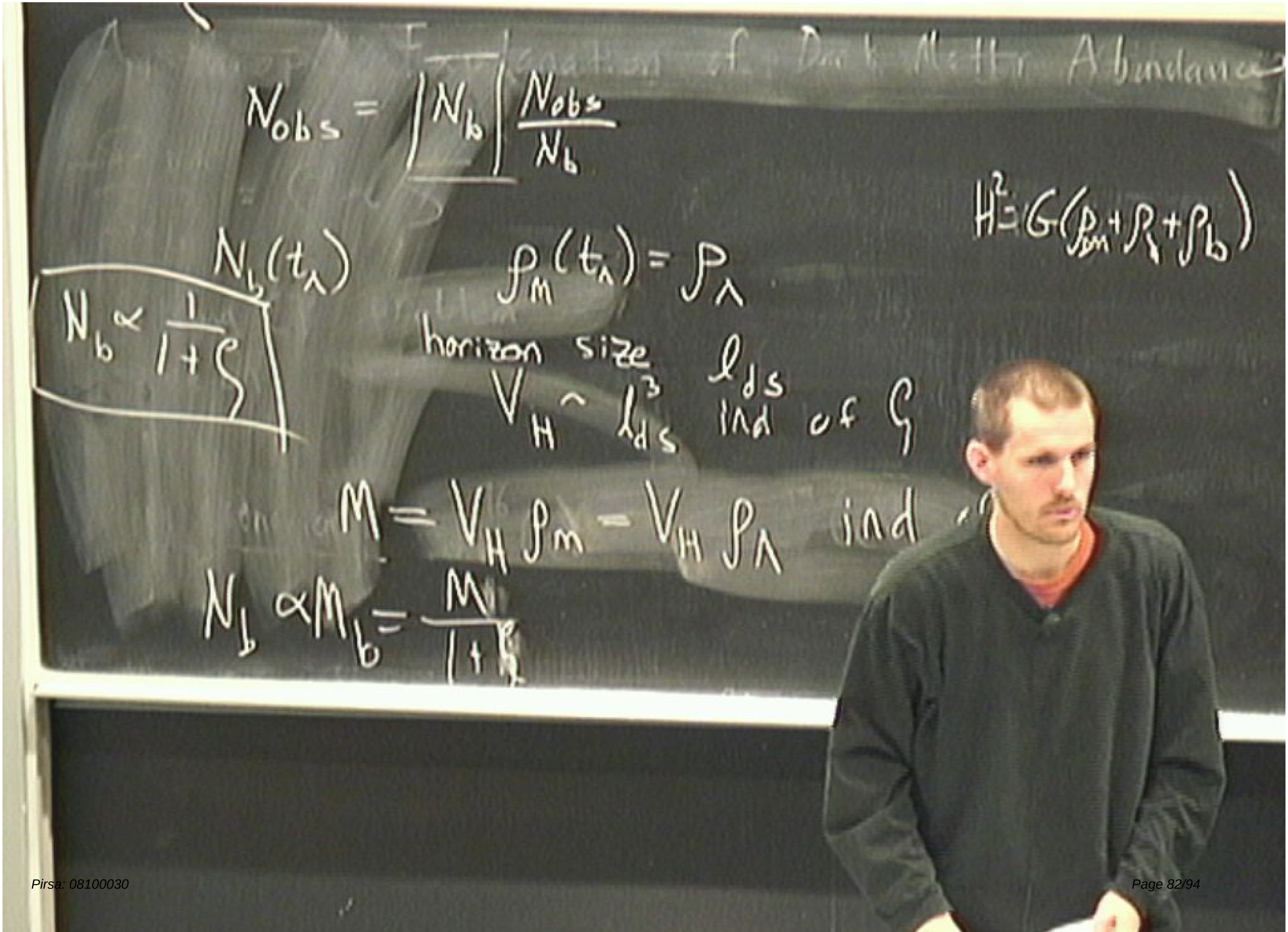
$V_H \sim \ell_{ds}^3$ ind of ζ

$M = V_H \rho_m = V_H \rho_\Lambda$ ind of ζ

$$N_b \propto M_b = \frac{M}{1+\zeta}$$



Explanation of Dark Matter Abundance
$N_{obs} = \boxed{N_b} \frac{N_{obs}}{N_b}$
$H^2 = G(\rho_m + \rho_r + \rho_b)$
$N_b(t_\Lambda)$
$\rho_m(t_\Lambda) = \rho_\Lambda$
$\boxed{N_b \propto \frac{1}{1+\zeta}}$
horizon size l_{ds}
$V_H \sim l_{ds}^3$ ind
$M = V_H \rho_m = V_H$
of ζ
$N_b \propto M_b = \frac{M}{1+\zeta}$


Dark Matter Abundance
N_obs = N_b N_obs/N_b
N_b(t_Λ)
ρ_m(t_Λ) = ρ_Λ
N_b ∝ 1/(1+ζ)
horizon size l_ds
V_H ~ l_ds^3 ind of ζ
M = V_H ρ_m = V_H ρ_Λ ind of
N_b ∝ M_b = M/(1+ζ)
H^2 = G(ρ_m + ρ_r + ρ_b)

Explanation of Dark Matter Abundance

$$N_{obs} = \boxed{N_b} \frac{N_{obs}}{N_b}$$

$$H^2 = G(\rho_m + \rho_r + \rho_b)$$

$N_b(t_\Lambda)$ $\qquad \rho_m(t_\Lambda) = \rho_\Lambda$

$$\boxed{N_b \propto \frac{1}{1+\zeta}}$$

horizon size ℓ_{ds}

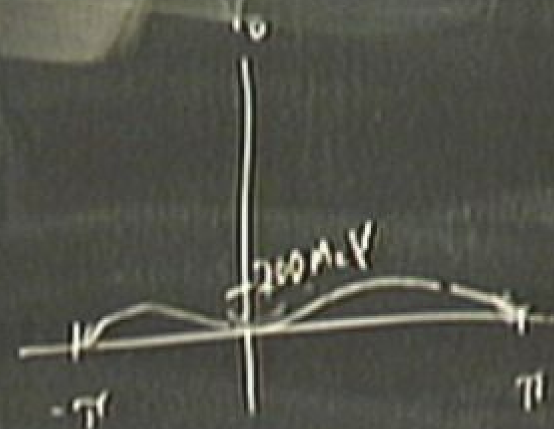
$V_H \sim \ell_{ds}^3$ ind of ζ

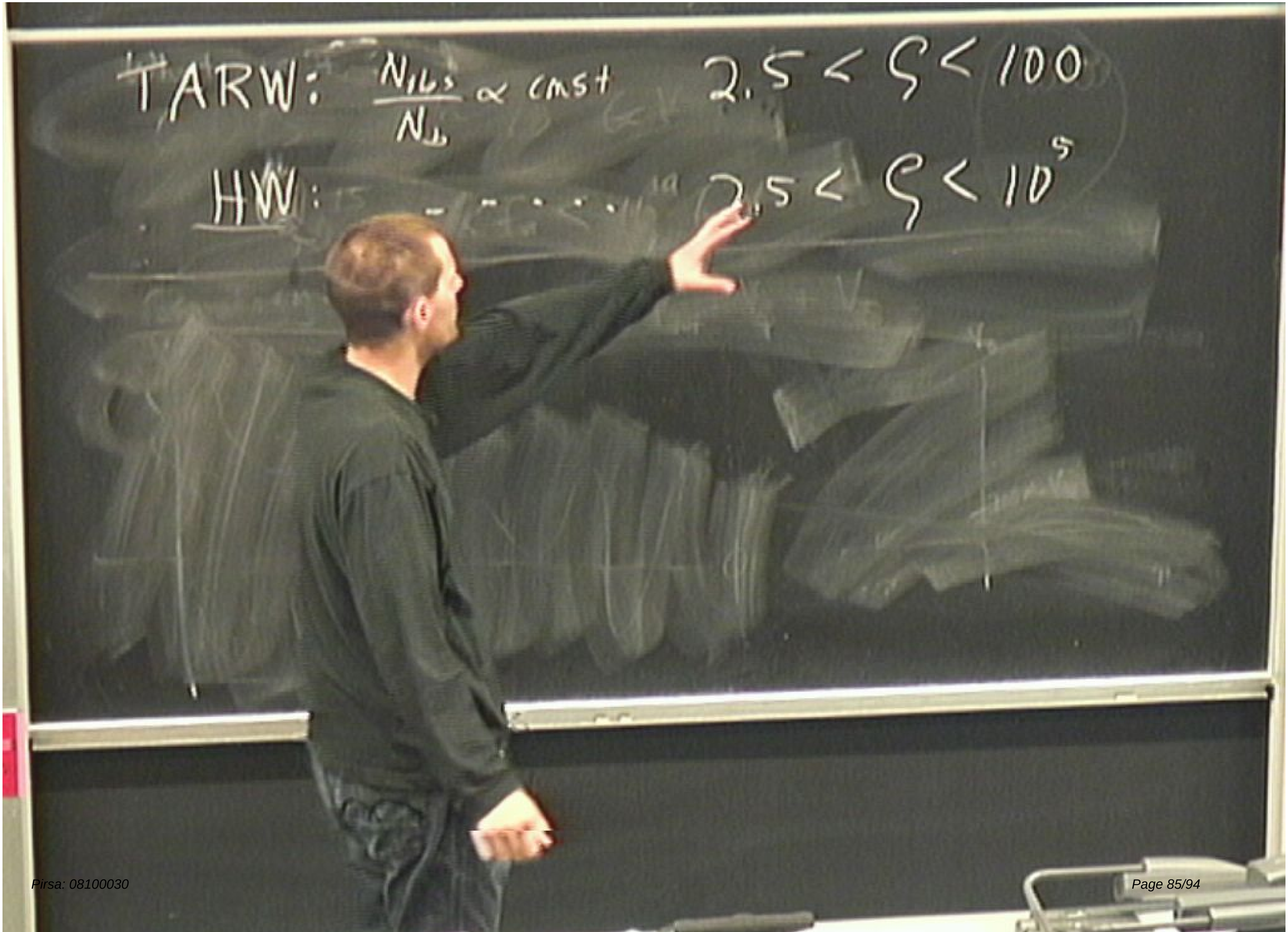
$$\boxed{\rho_b \propto \frac{1}{1+\zeta}}$$

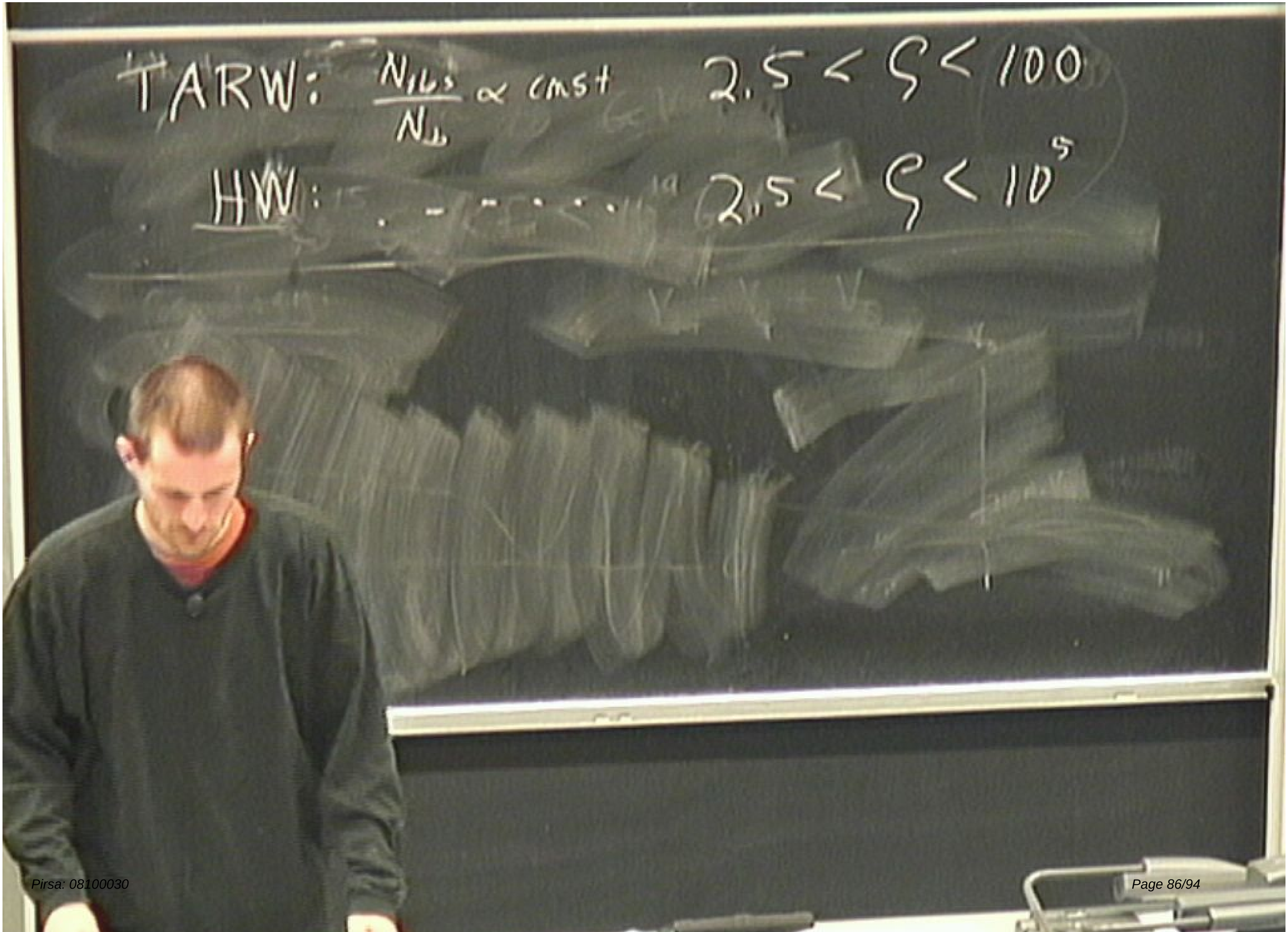
$M = V_H \rho_m = V_H \rho_\Lambda$ ind of ζ

$$N_b \propto M_b = \frac{M}{1+\zeta}$$

TARW: $\frac{N_{ibs}}{N_{ib}} \propto \text{const} \quad 2.5 < \xi < 100$

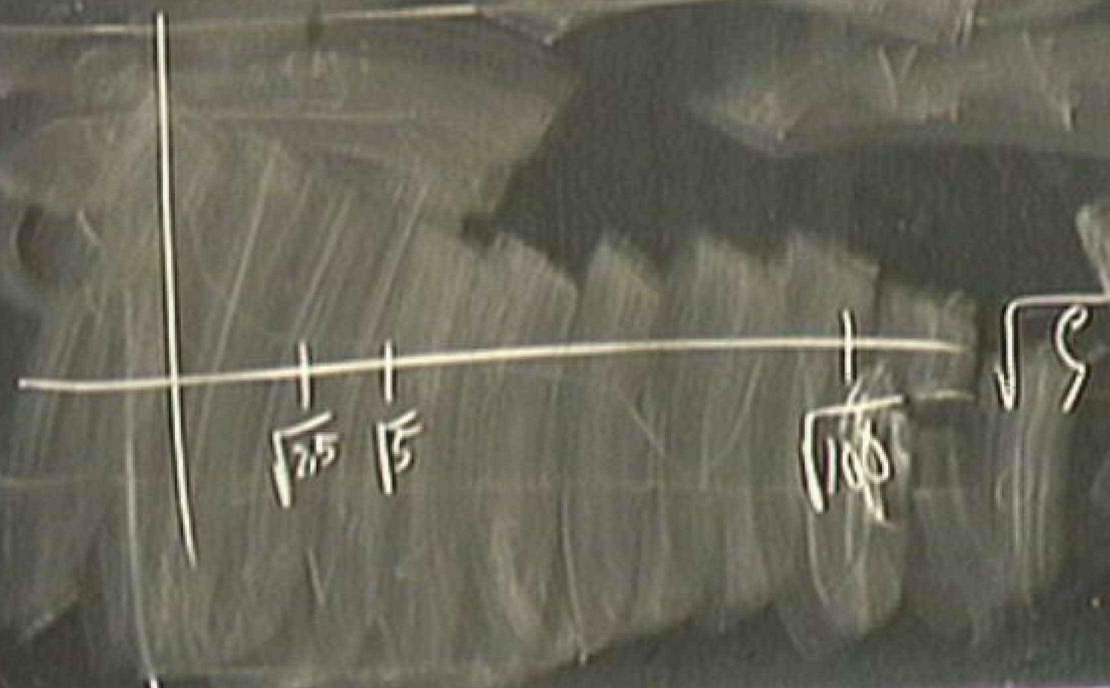


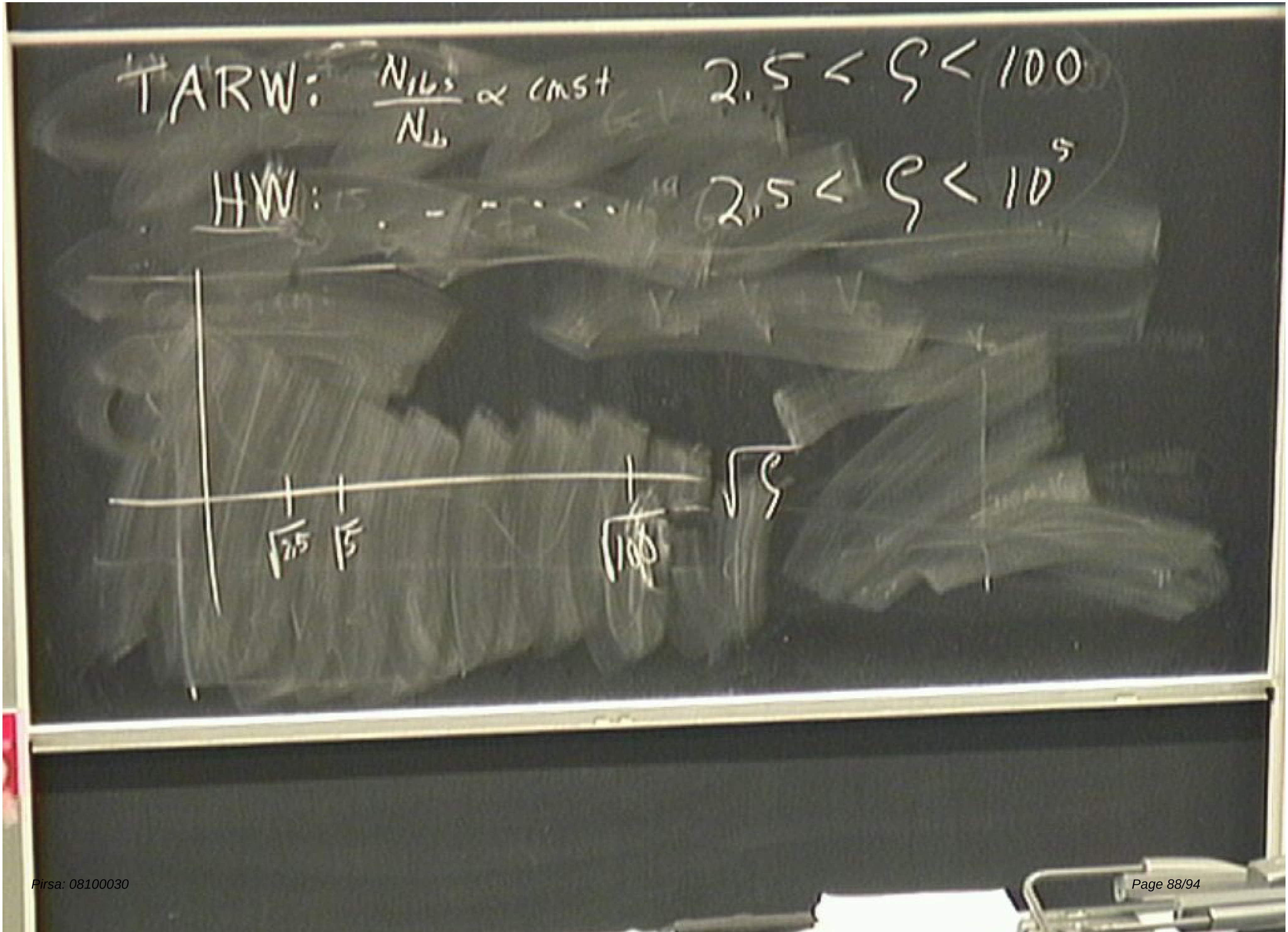

TARW: $\frac{N_{ibs}}{N_{ib}} \propto$ cnst $2.5 < \varsigma < 100$
HW: $2.5 < \varsigma < 10^5$

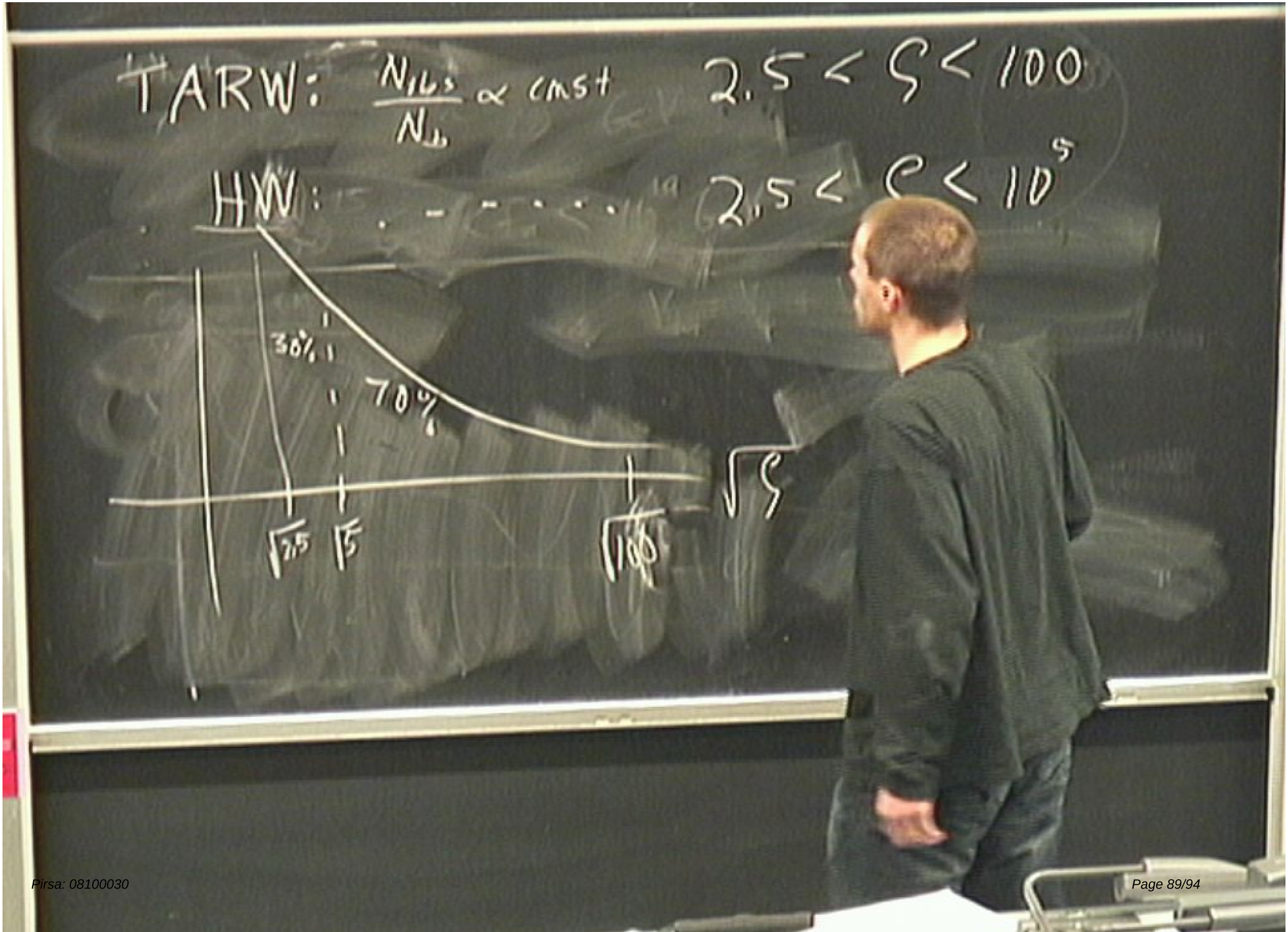

TARW: $\frac{N_{ibs}}{N_{b}} \propto$ const $2.5 < \varsigma < 100$
HW: $2.5 < \varsigma < 10^5$

TARW: $\frac{N_{1bs}}{N_{b}} \propto \text{cnst}$ $\quad 2.5 < \rho < 100$

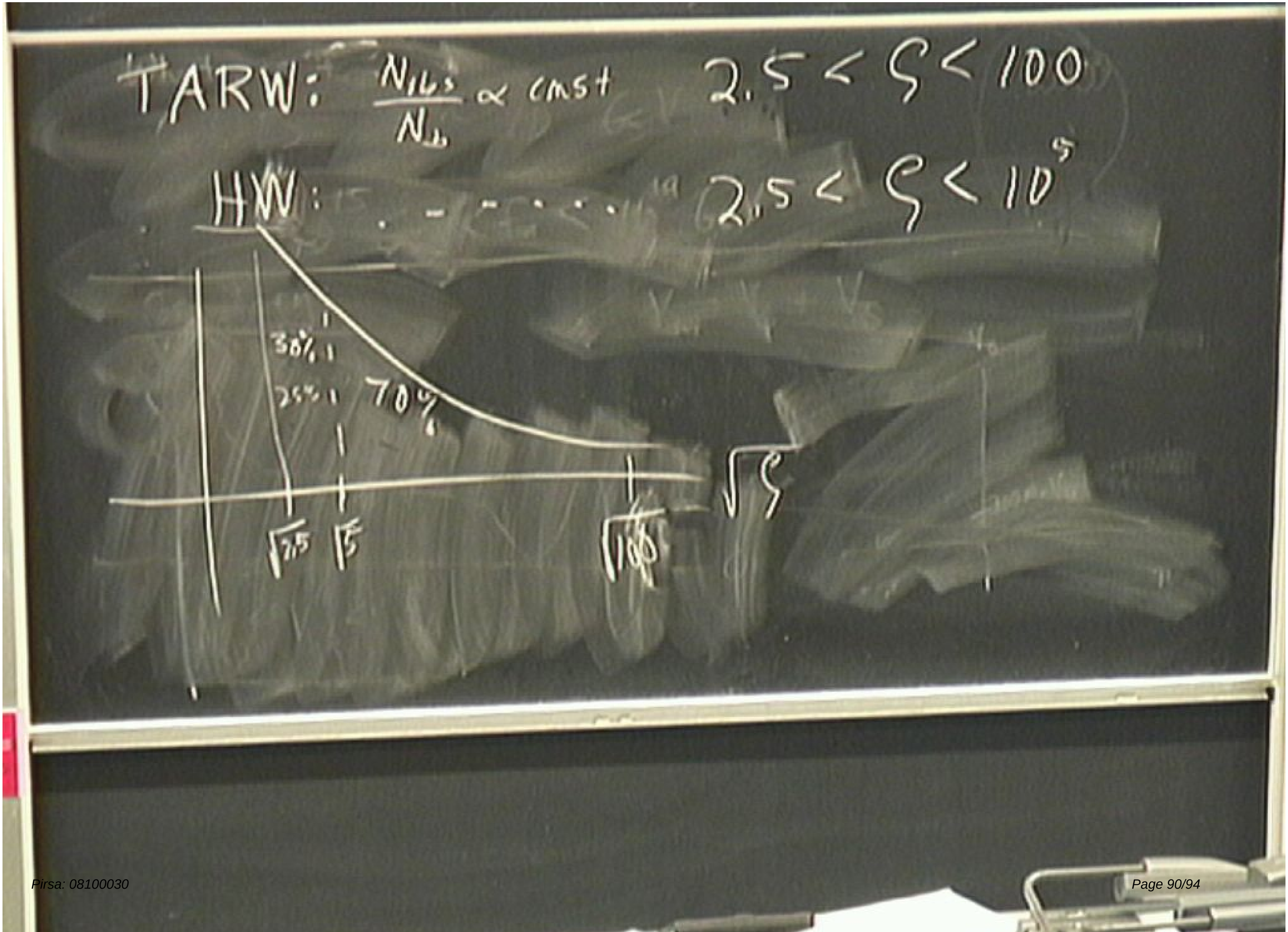
HW: . . . . . . $\quad 2.5 < \rho < 10^{5}$




TARW: $\frac{N_{lbs}}{N_{b}} \propto$ cnst
$2.5 < \varsigma < 100$
HW:
$2.5 < \varsigma < 10^5$
$\sqrt{2.5}$ $\sqrt{5}$ $\sqrt{100}$ $\sqrt{\varsigma}$



TARW: $\frac{N_{lbs}}{N_{b}} \propto$ const
$2.5 < \varsigma < 100$
HW:
$2.5 < \varsigma < 10^{5}$
30%
70%
$\sqrt{2.5}$
$\sqrt{5}$
$\sqrt{100}$
$\sqrt{\varsigma}$


TARW: N14s / N1s ∝ const
2.5 < ς < 100
HW:
2.5 < ς < 10^5
30%
25%
70%
√ς
√2.5
√5
√100

$$\rho = 10^{11}\left(\frac{f_a}{M_p}\right)^{3/2}\theta^2$$

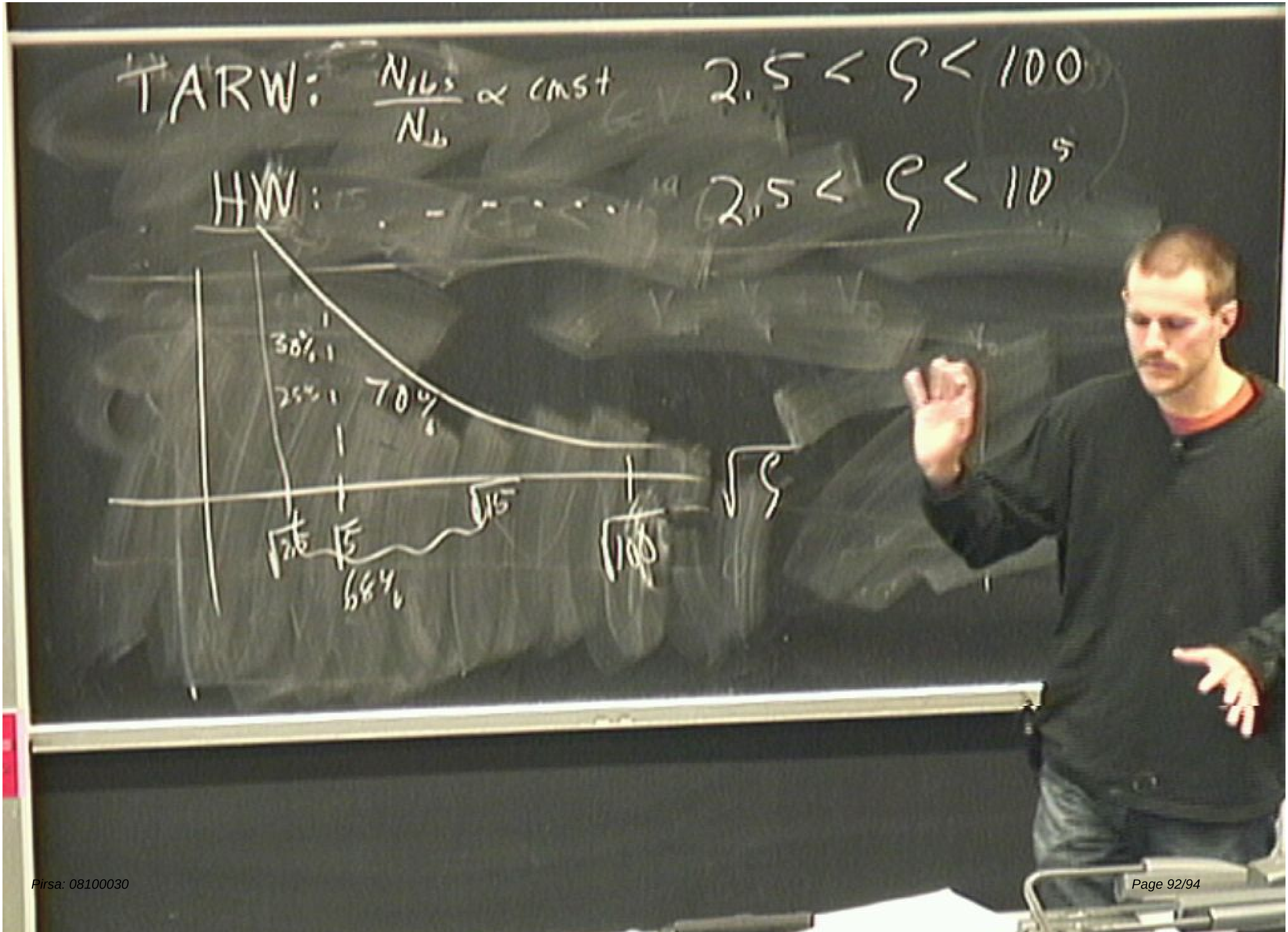
$$P(\theta_1 < \theta < \theta_2) \propto N_{obs}(\theta_1 < \theta < \theta_2)$$

Predict eccentricity of Jupiter?

a) Equations $\rightarrow$ $e = .048$

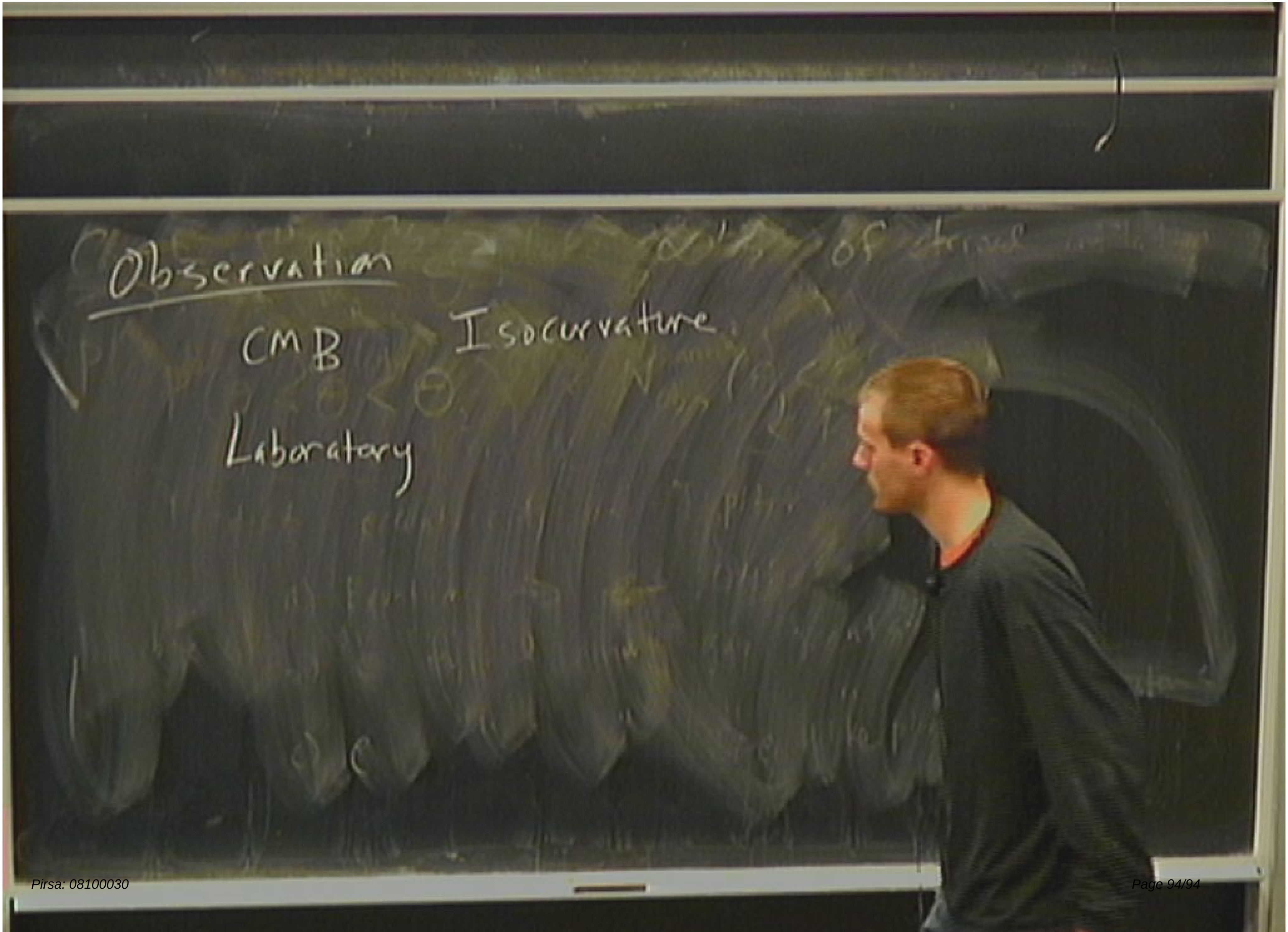
b) e typical among gas giants

c) e " " " " in solar systems w/ earthlike planets


TARW: $\frac{N_{lbs}}{N_b} \propto$ const
$2.5 < \varsigma < 100$
HW:
$2.5 < \varsigma < 10^5$
30%
25%
70%
$\sqrt{2.5}$
$\sqrt{5}$
$\sqrt{15}$
$\sqrt{100}$
$\sqrt{\varsigma}$
68%

Observation

Isocurvature.


Observation
CMB
Isocurvature
Laboratory