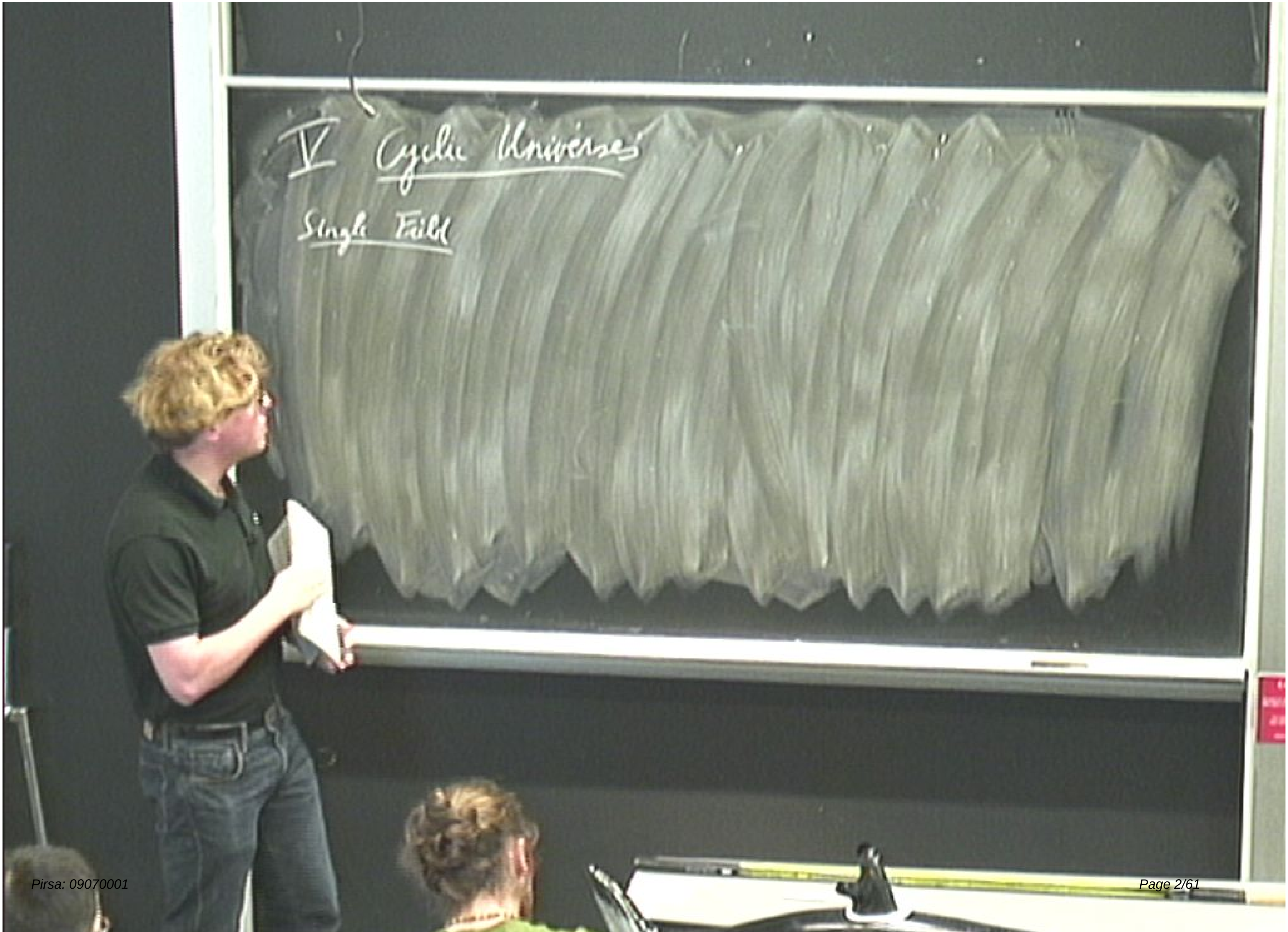
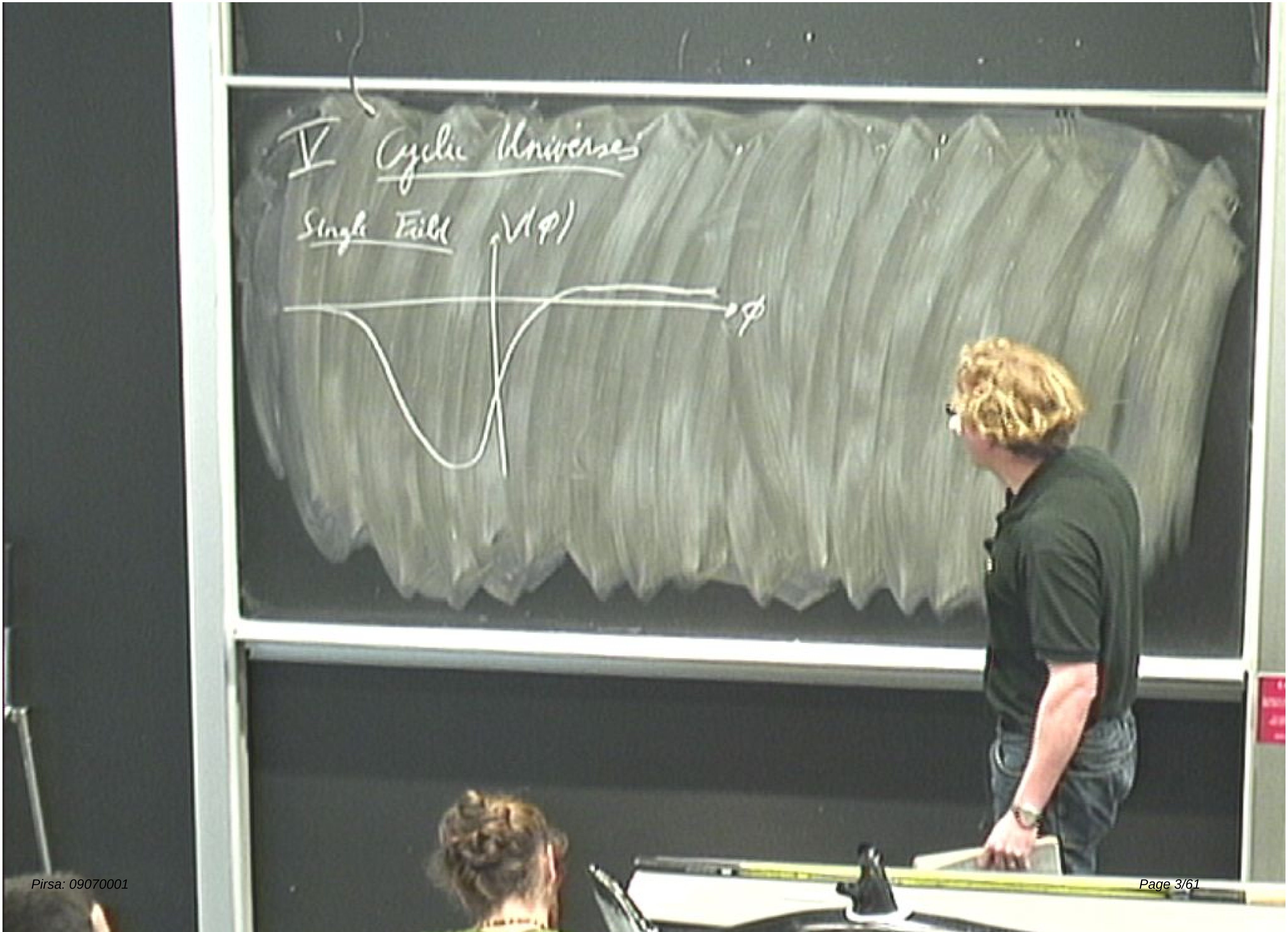
Title: Ekpyrotic/Cyclic Cosmology - Lecture 5

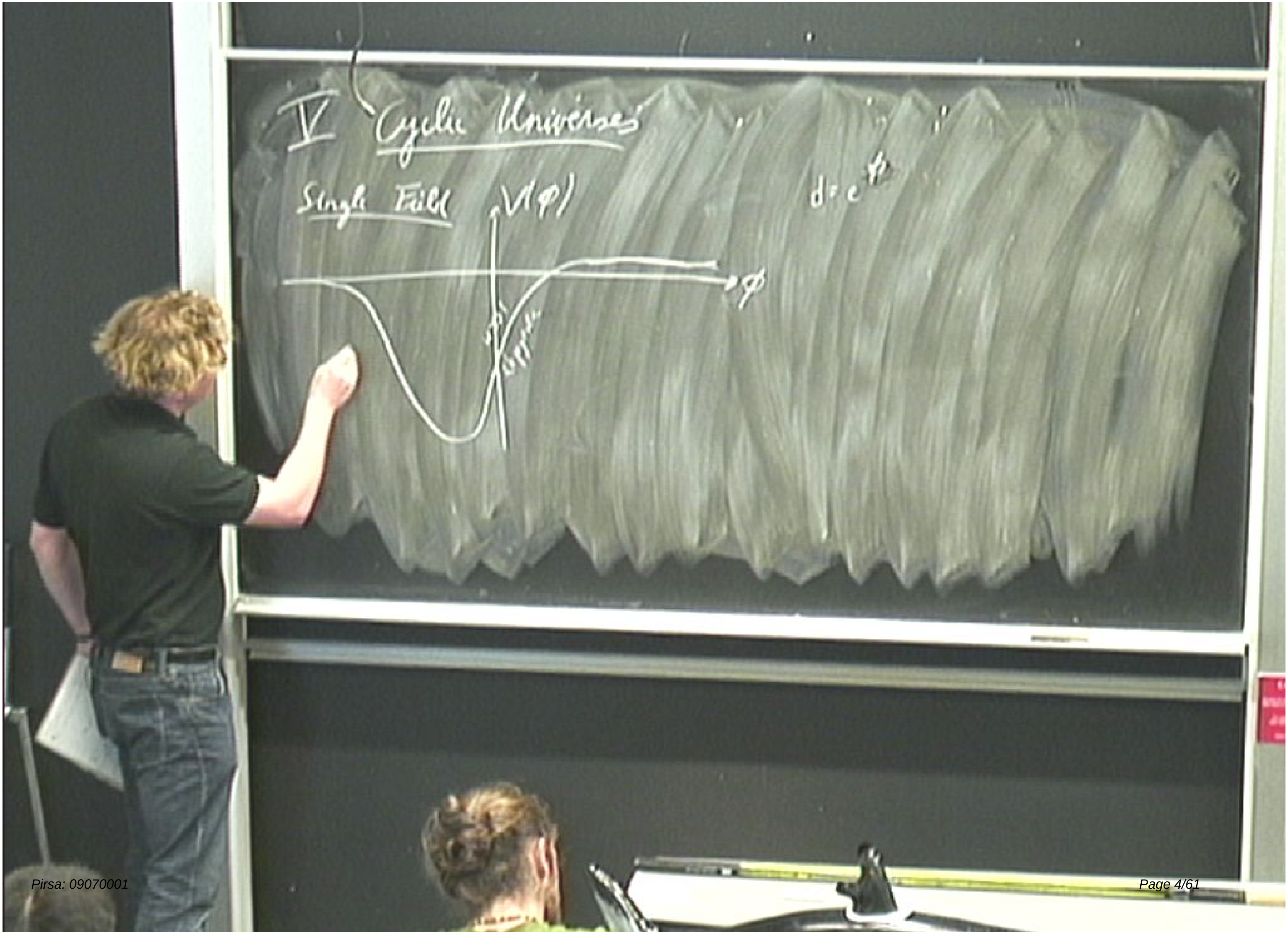
Date: Jul 01, 2009 09:00 AM

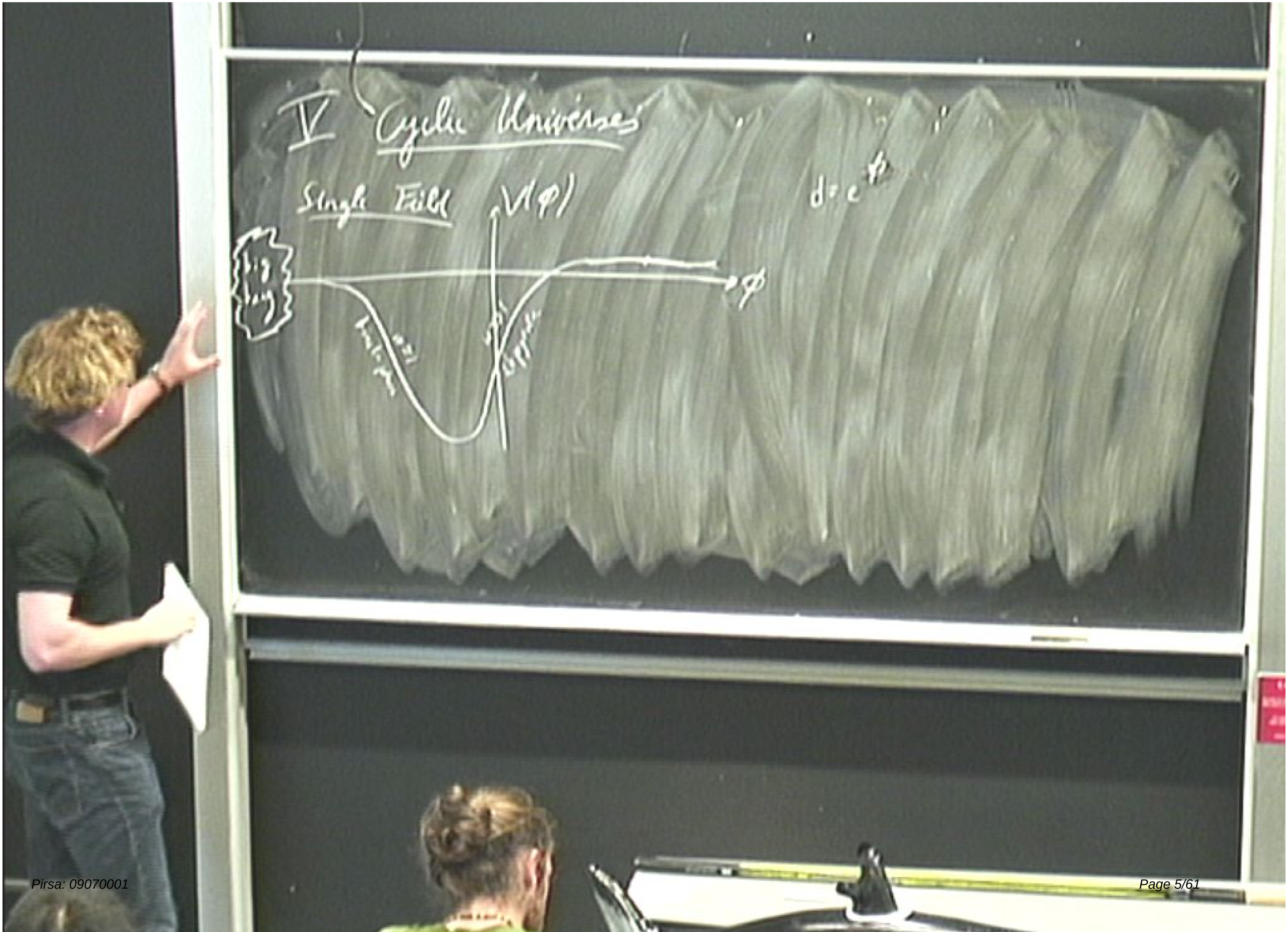
URL: http://pirsa.org/09070001

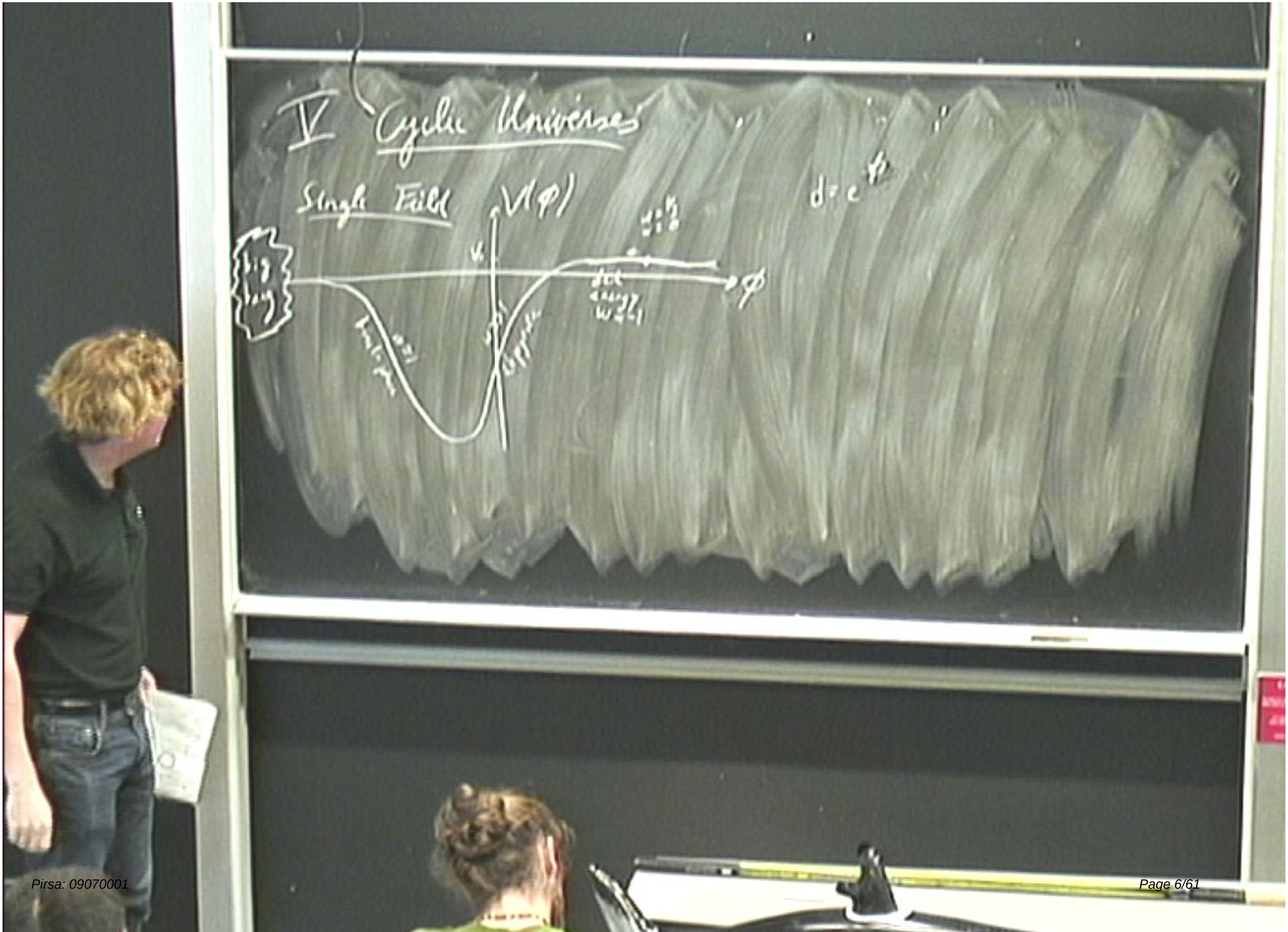
Abstract:

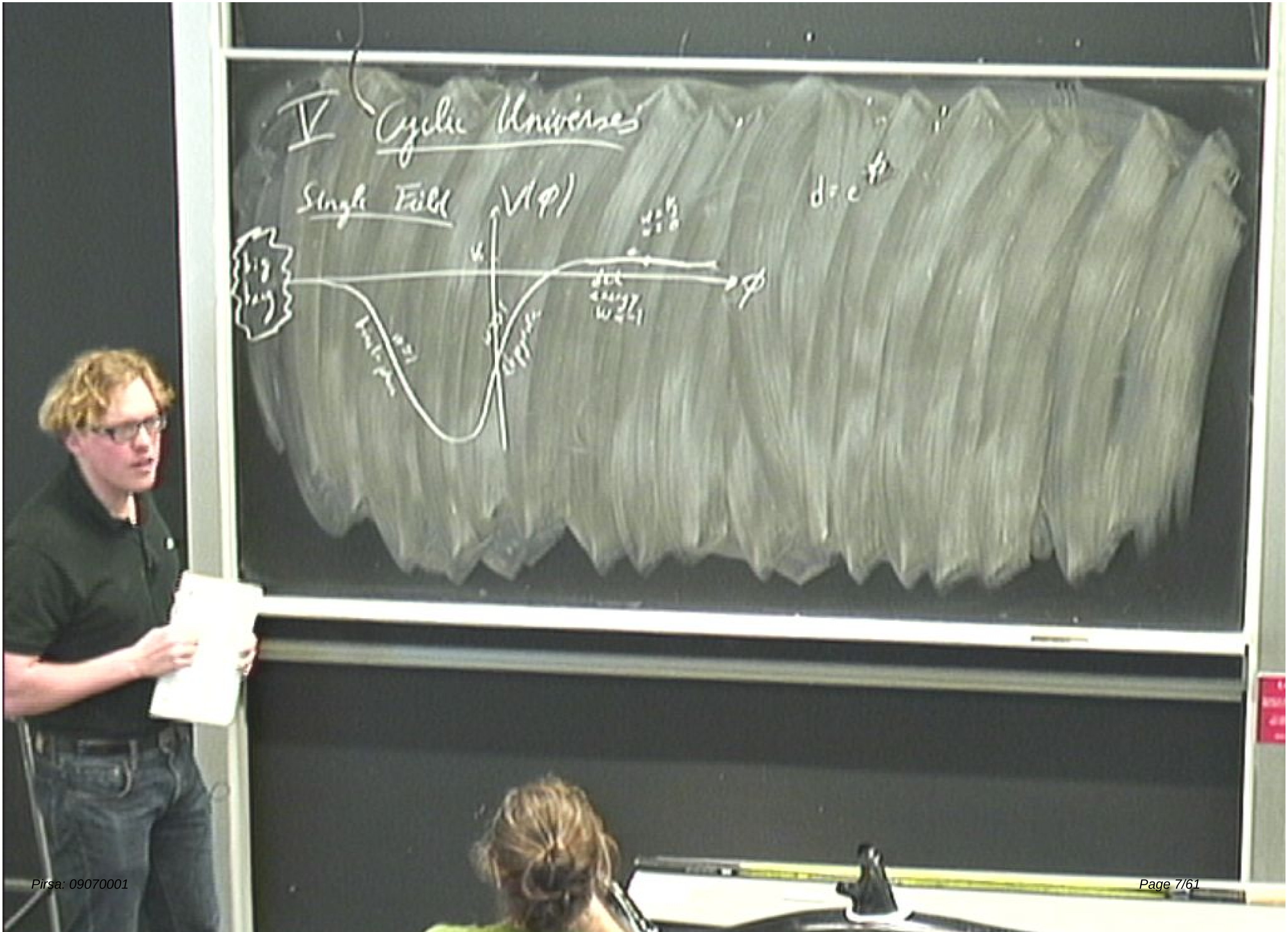

V Cyclic Universes
Single Field

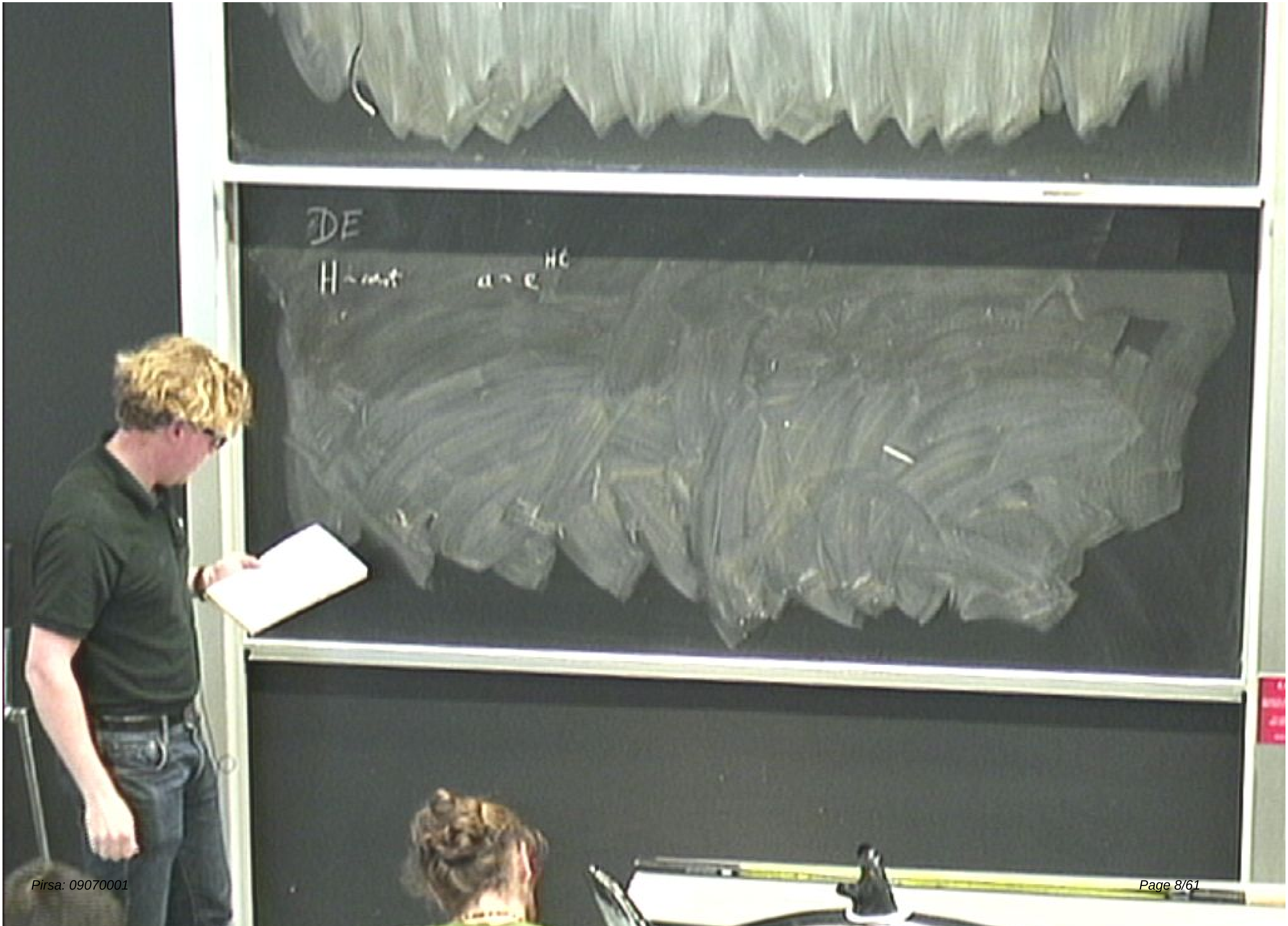

V Cyclic Universes
Single Field
V(φ)
φ

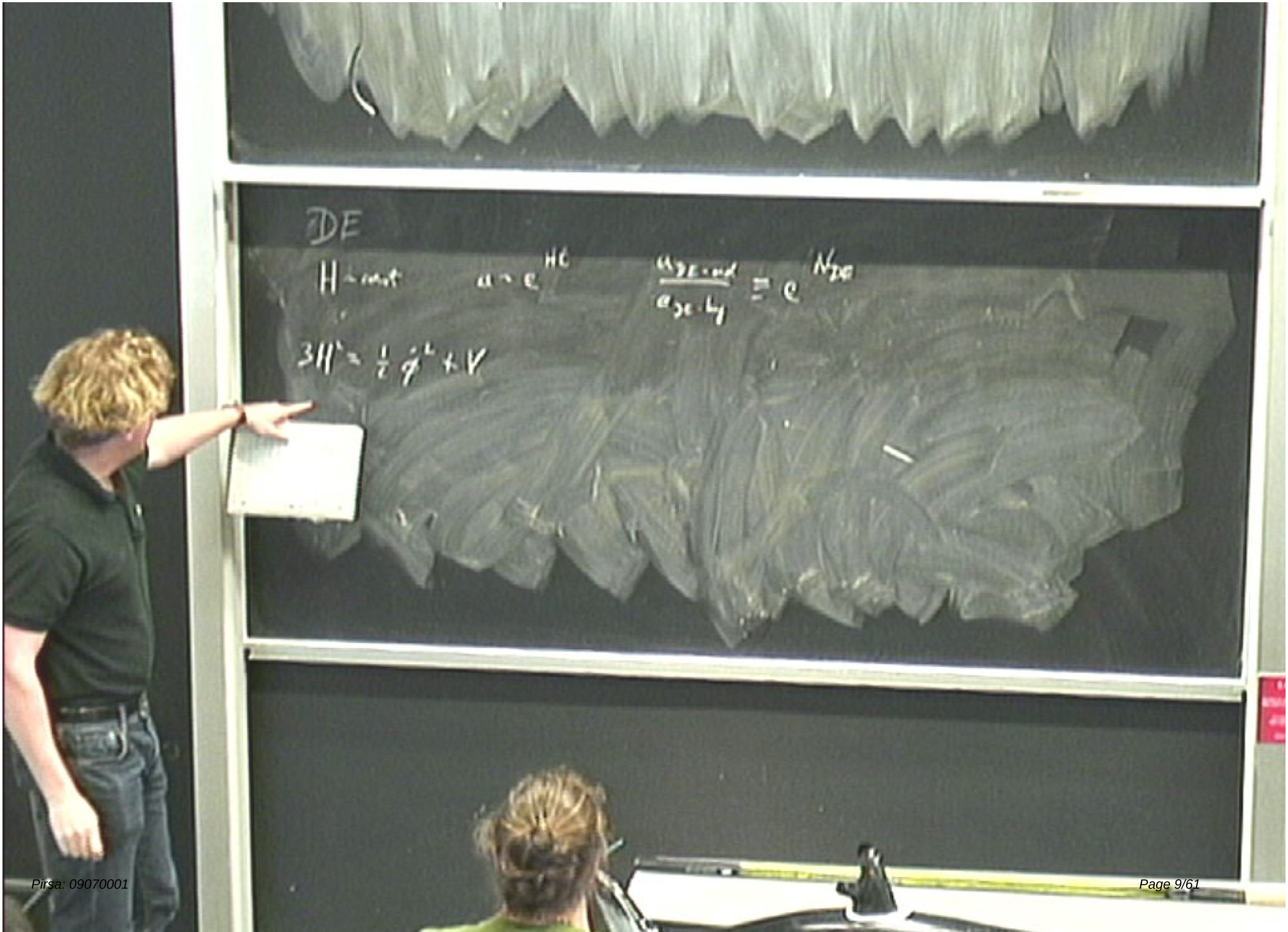

V Cyclic Universes
Single Field
V(φ)
φ

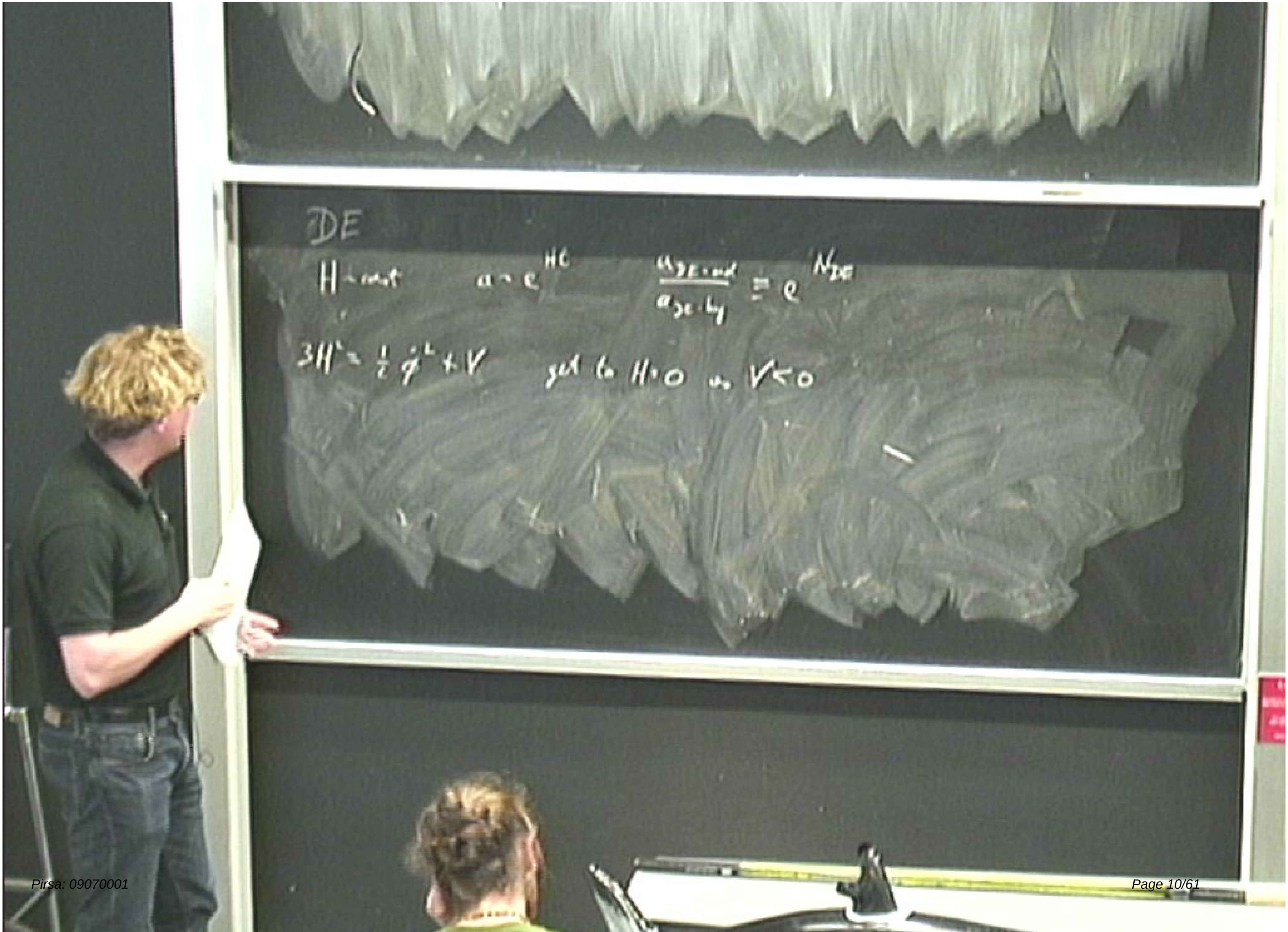

V Cyclic Universes
Single Field
V(φ)
φ
big bang

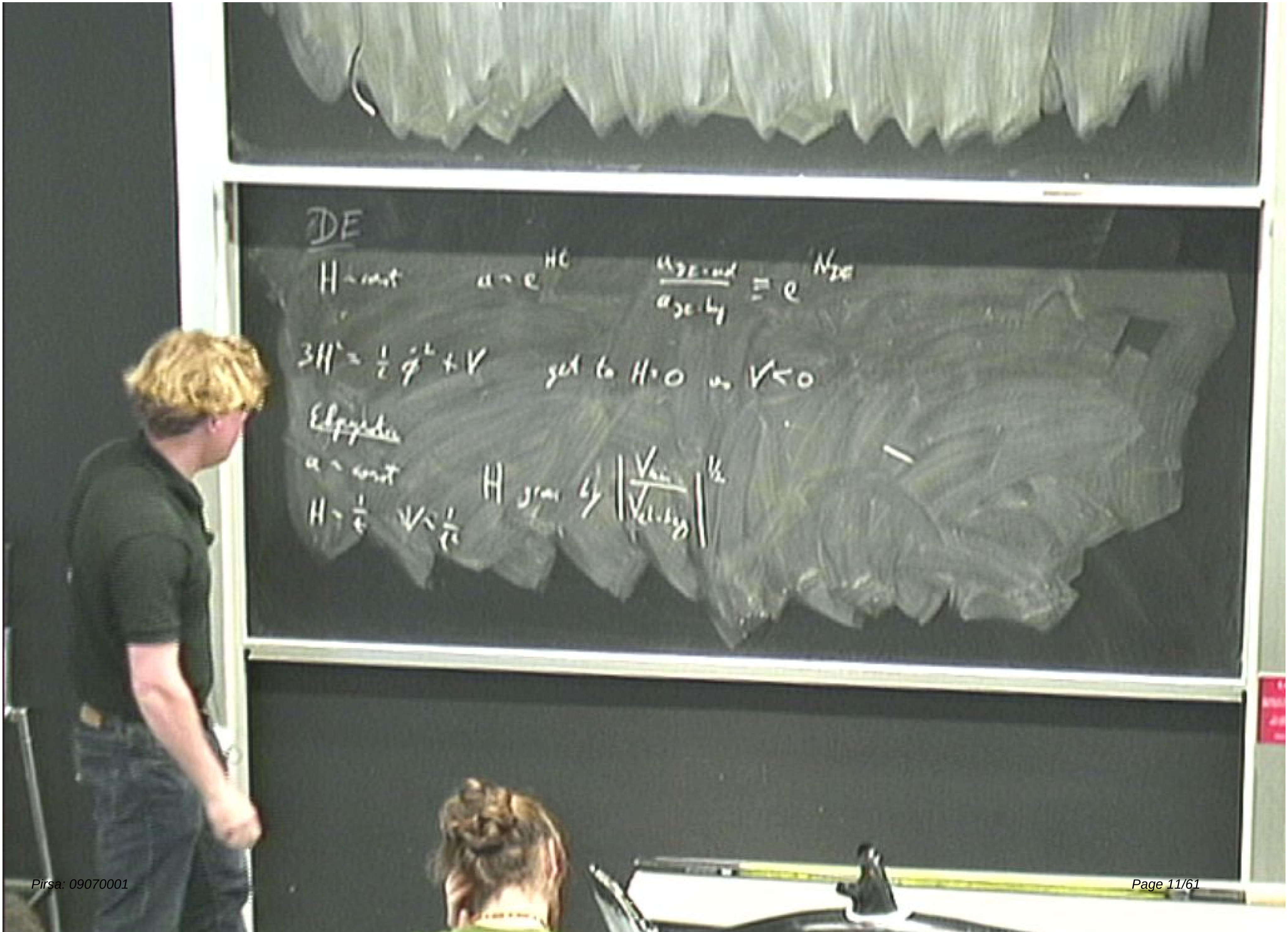

V Cyclic Universes
Single Field
V(φ)

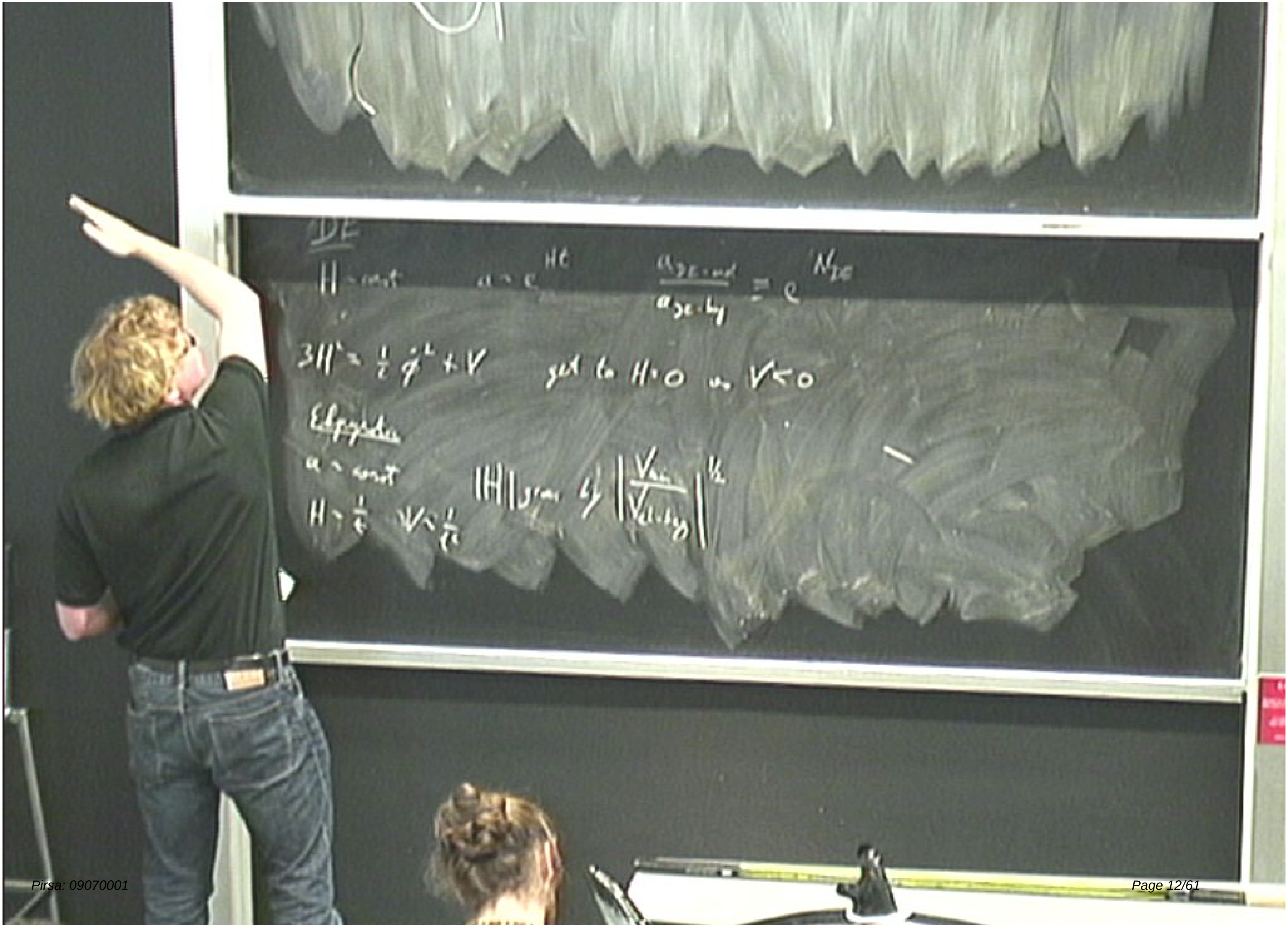

V Cyclic Universes
Single Field
V(φ)
φ

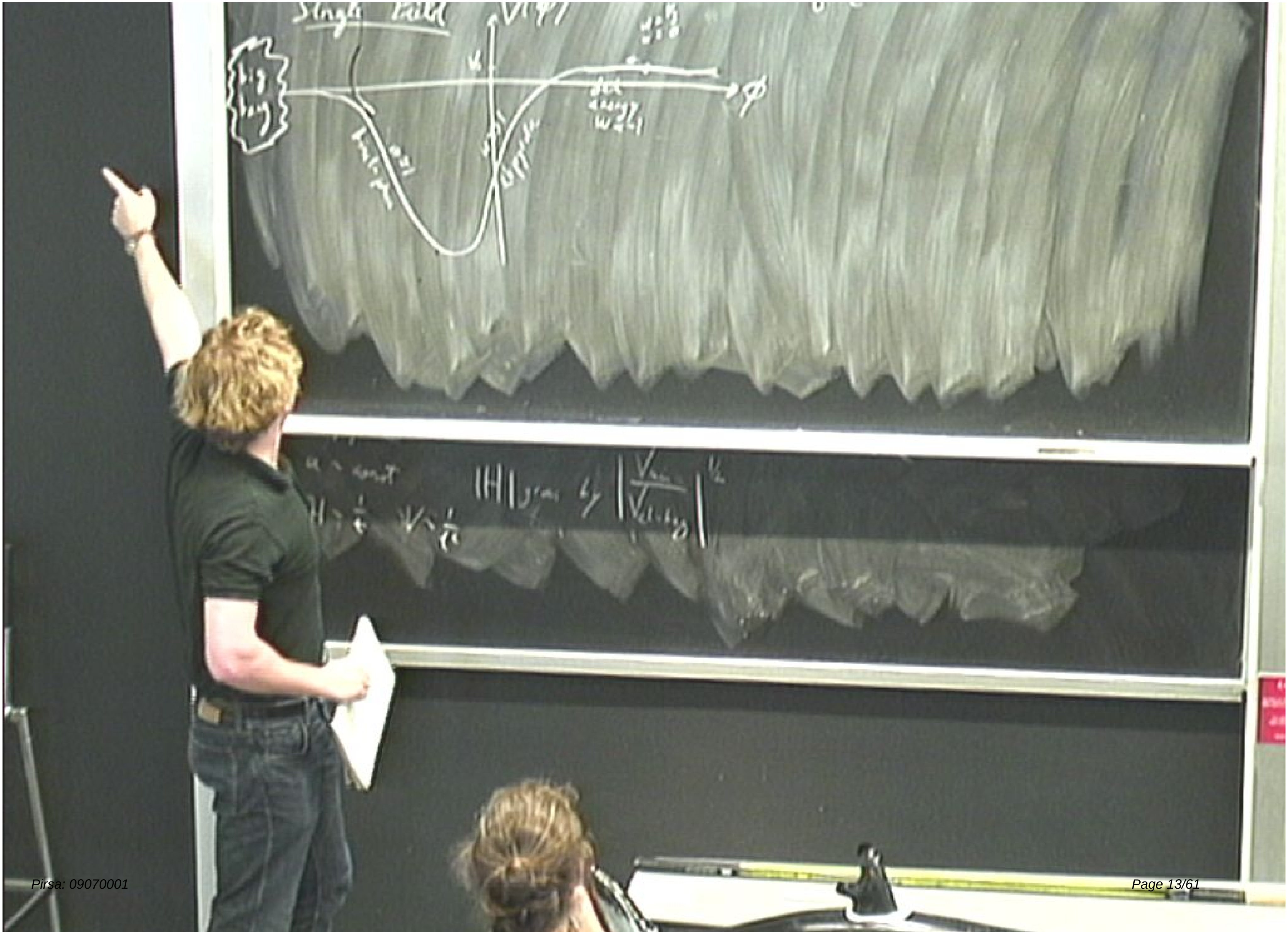

DE
H ~ const
a ~ e^Ht

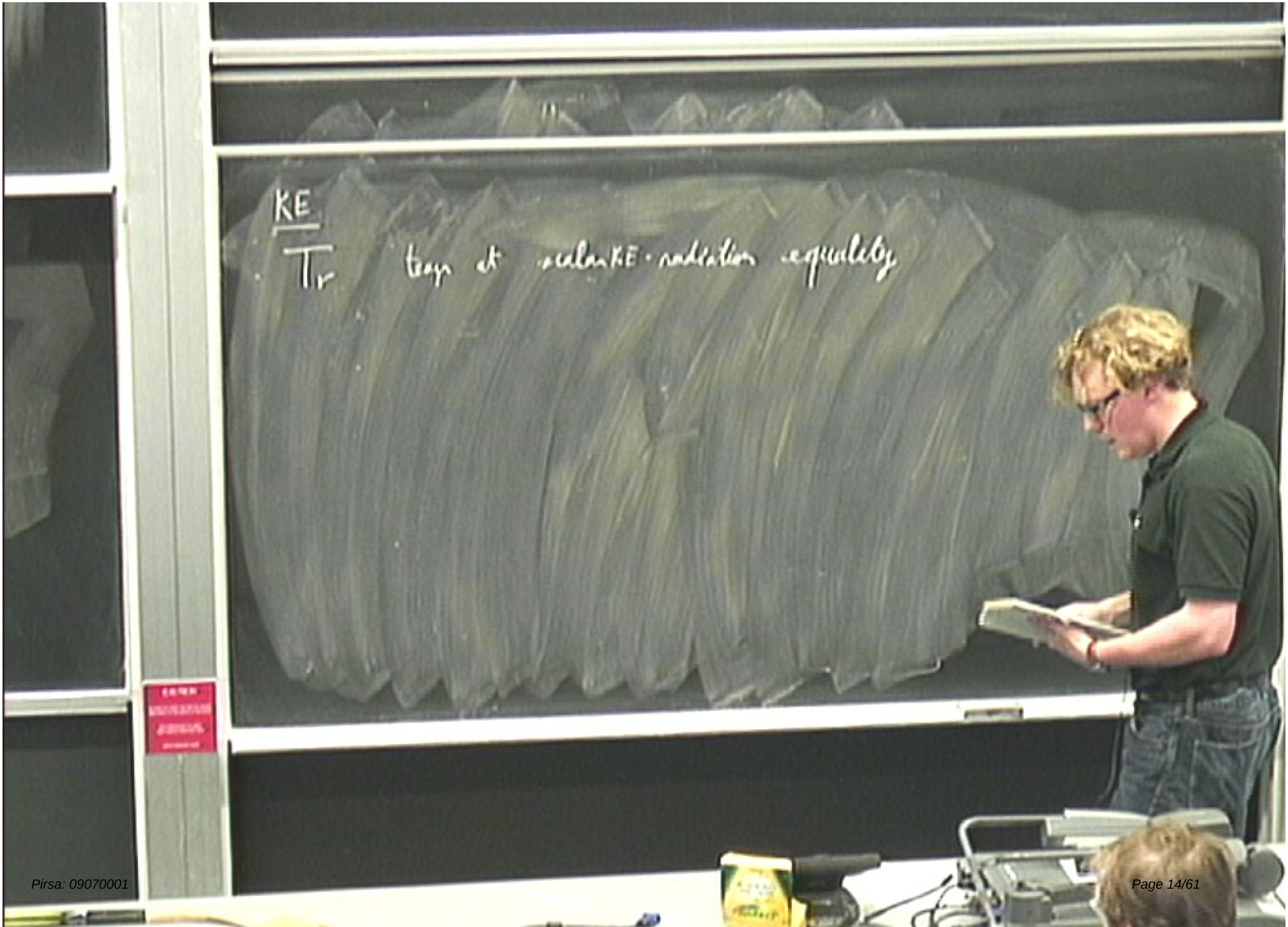

DE
H ~ const
a ~ e^Ht
a_DE,end / a_DE,beg = e^N_DE
3H² = ½ φ̇² + V

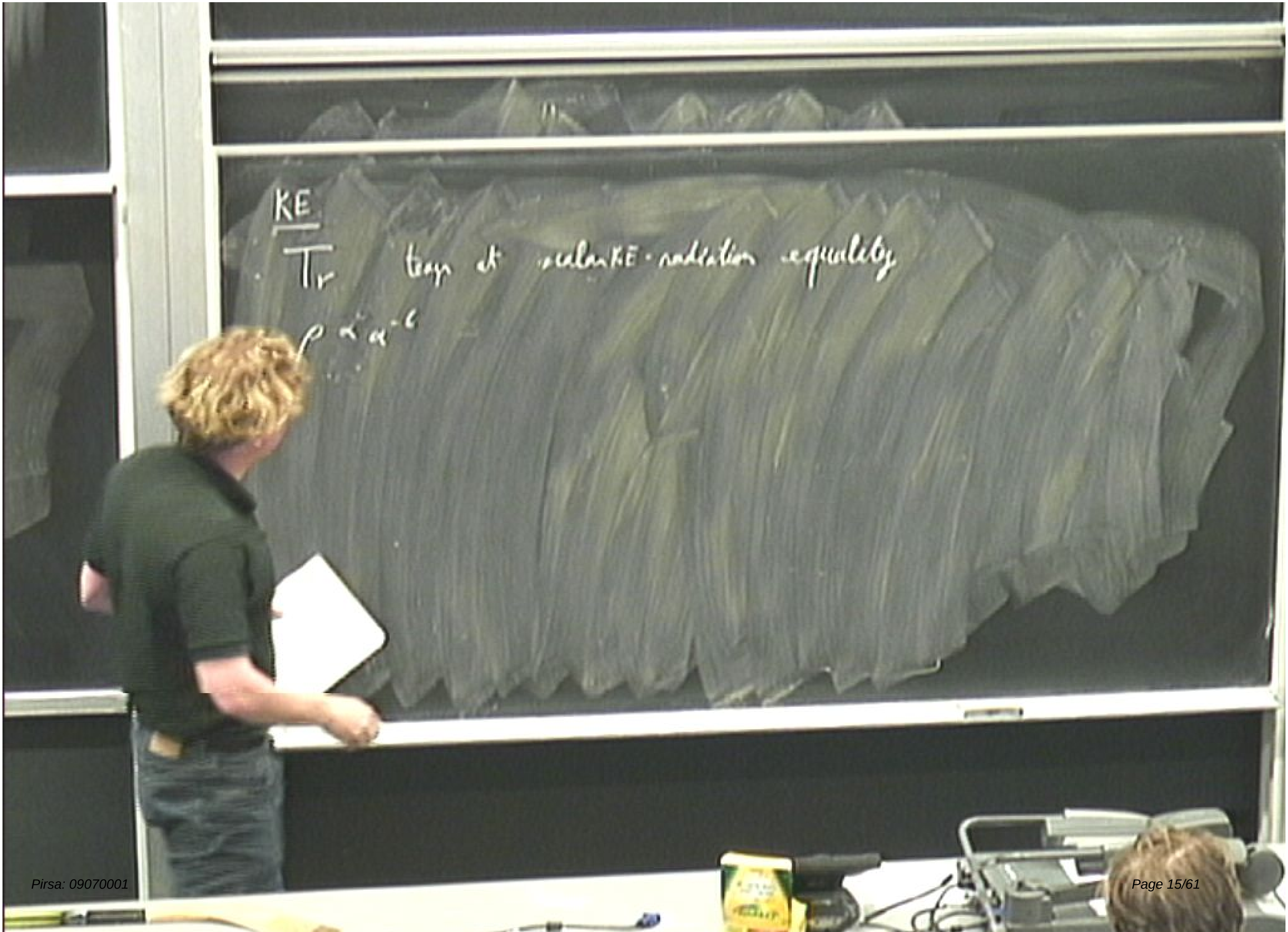

DE
H ~ const   a ~ e^{Ht}   a_{DE,end} / a_{DE,beg} = e^{N_{DE}}
3H^2 = ½ φ̇^2 + V   get to H=0 iff V<0

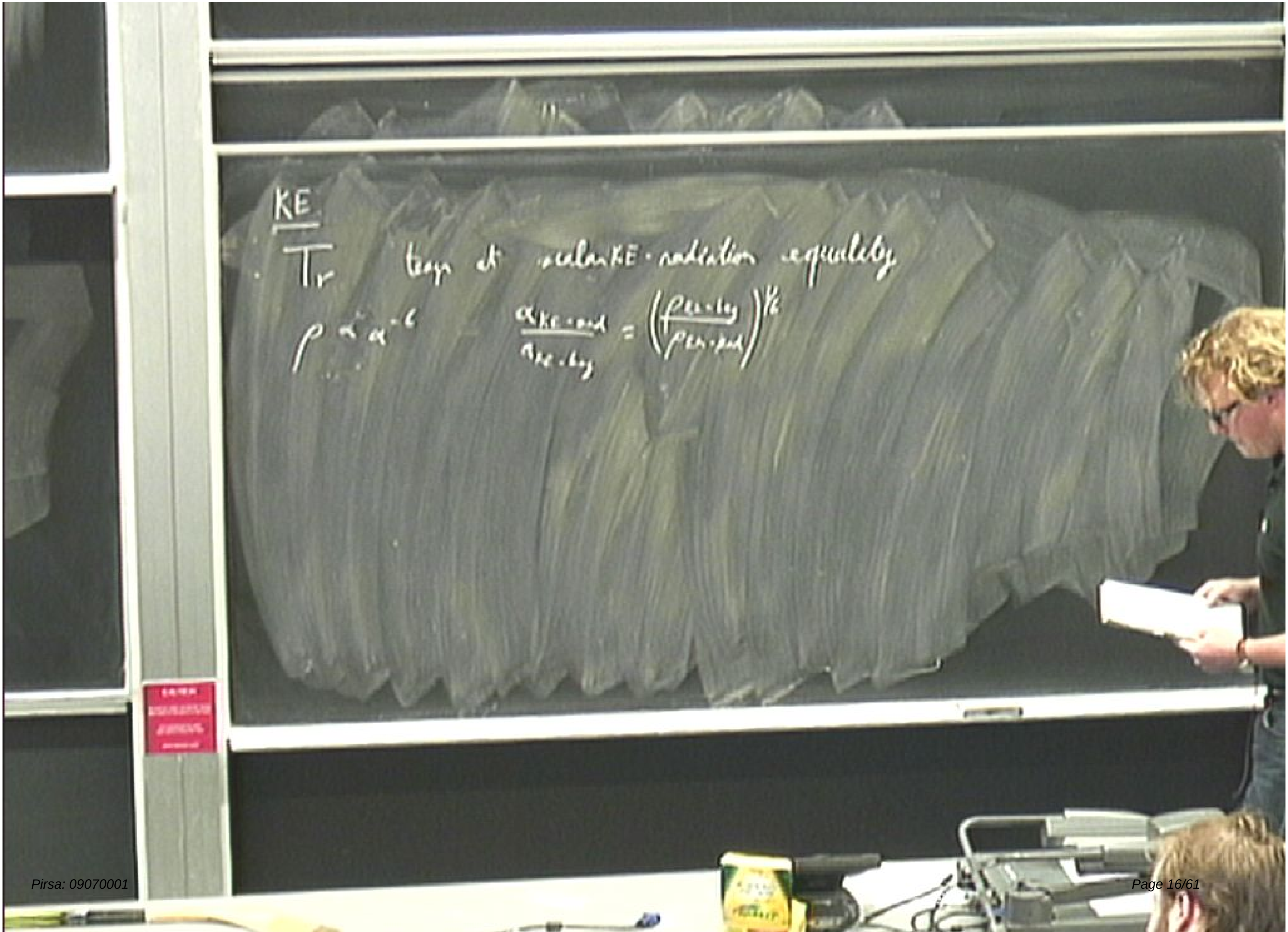

DE
H ~ const   a ~ e^Ht   a_DE end / a_DE beg = e^N_DE
3H^2 = 1/2 φ̇^2 + V   get to H=0 w/ V<0
Ekpyrotic
a ~ const   H grows by |V_end / V_beg|^1/2
H ~ 1/t   V ~ 1/t^2

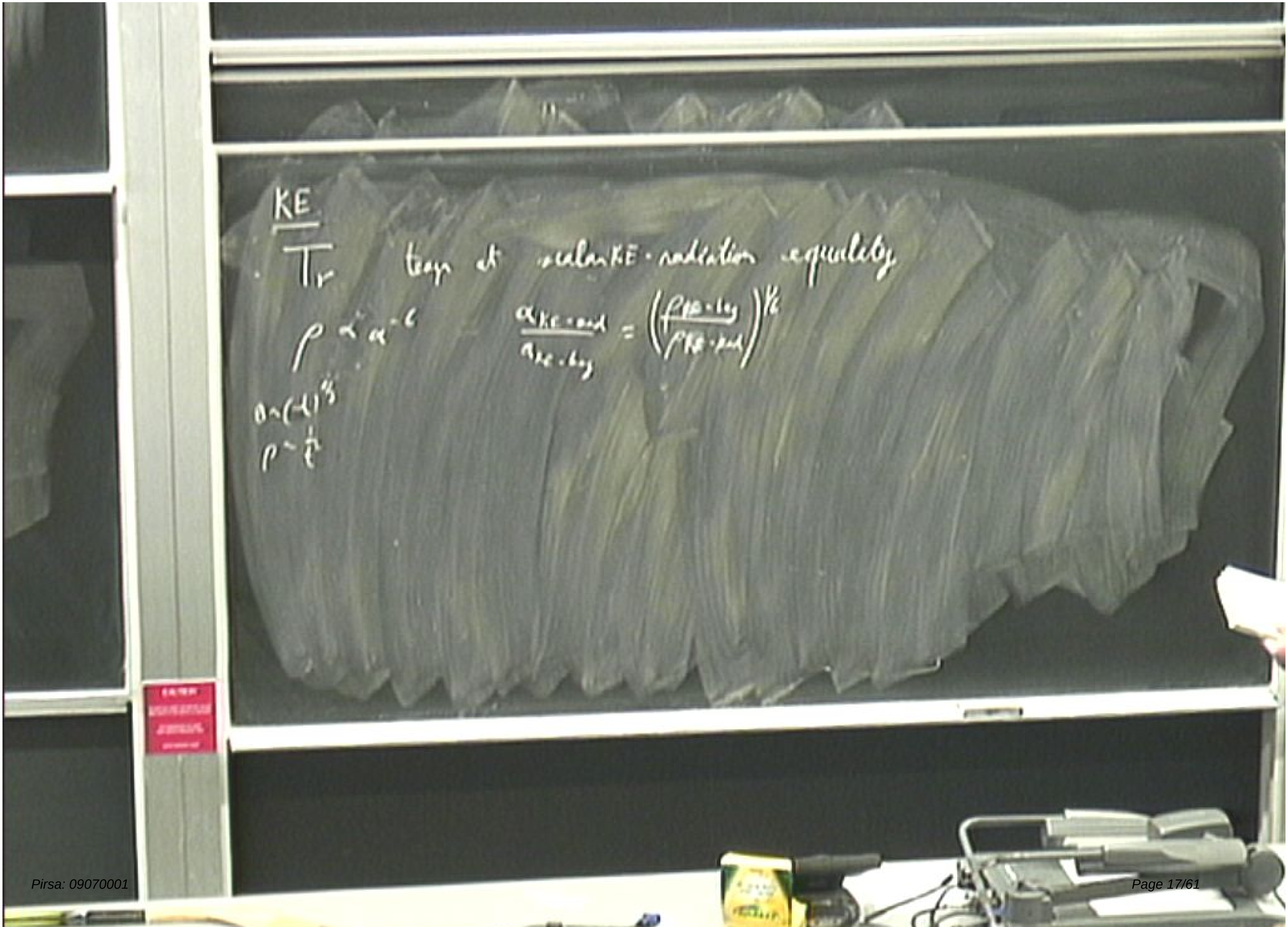

DE
H = const
get to H = 0 as V < 0
a ~ const

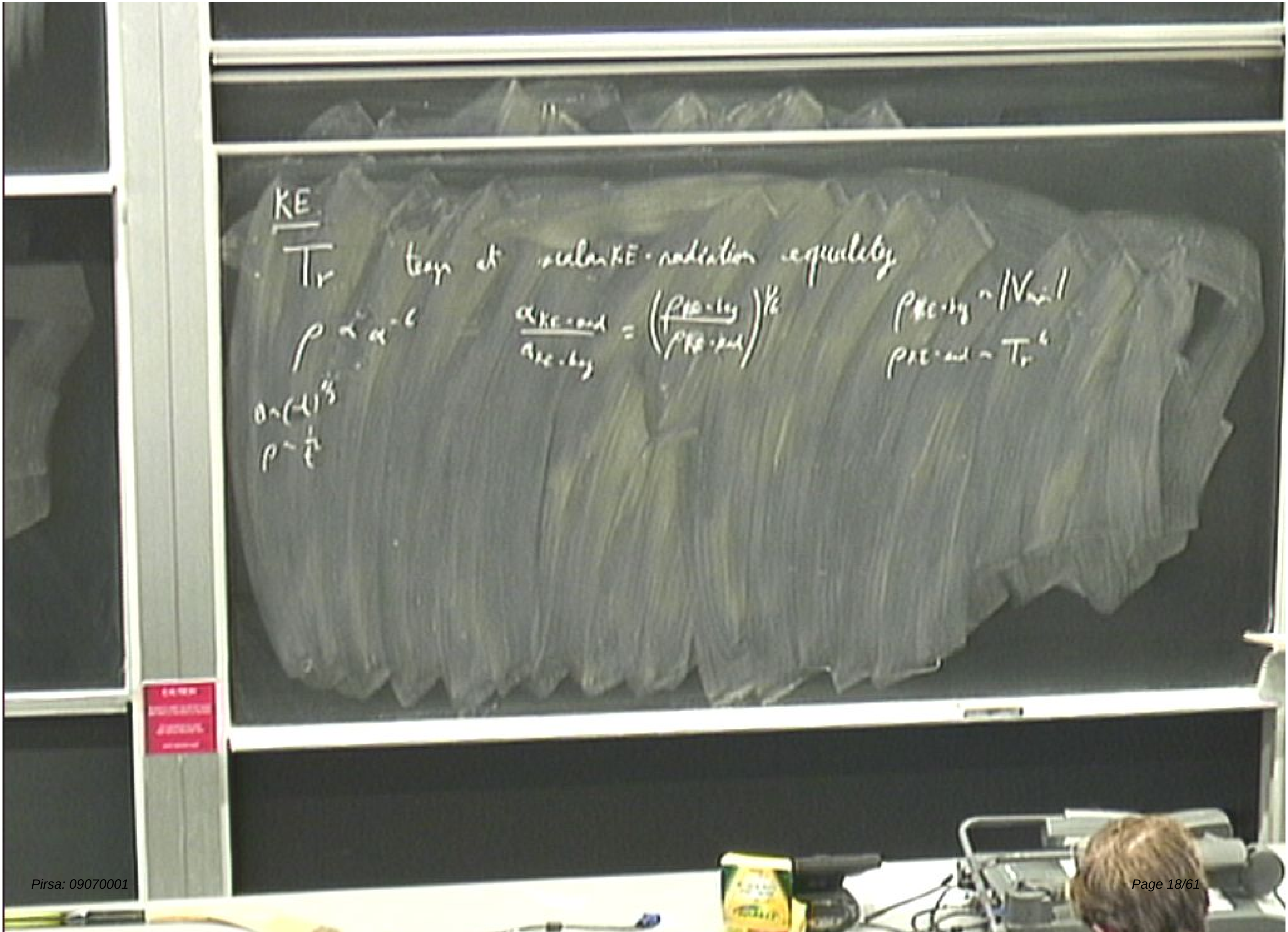


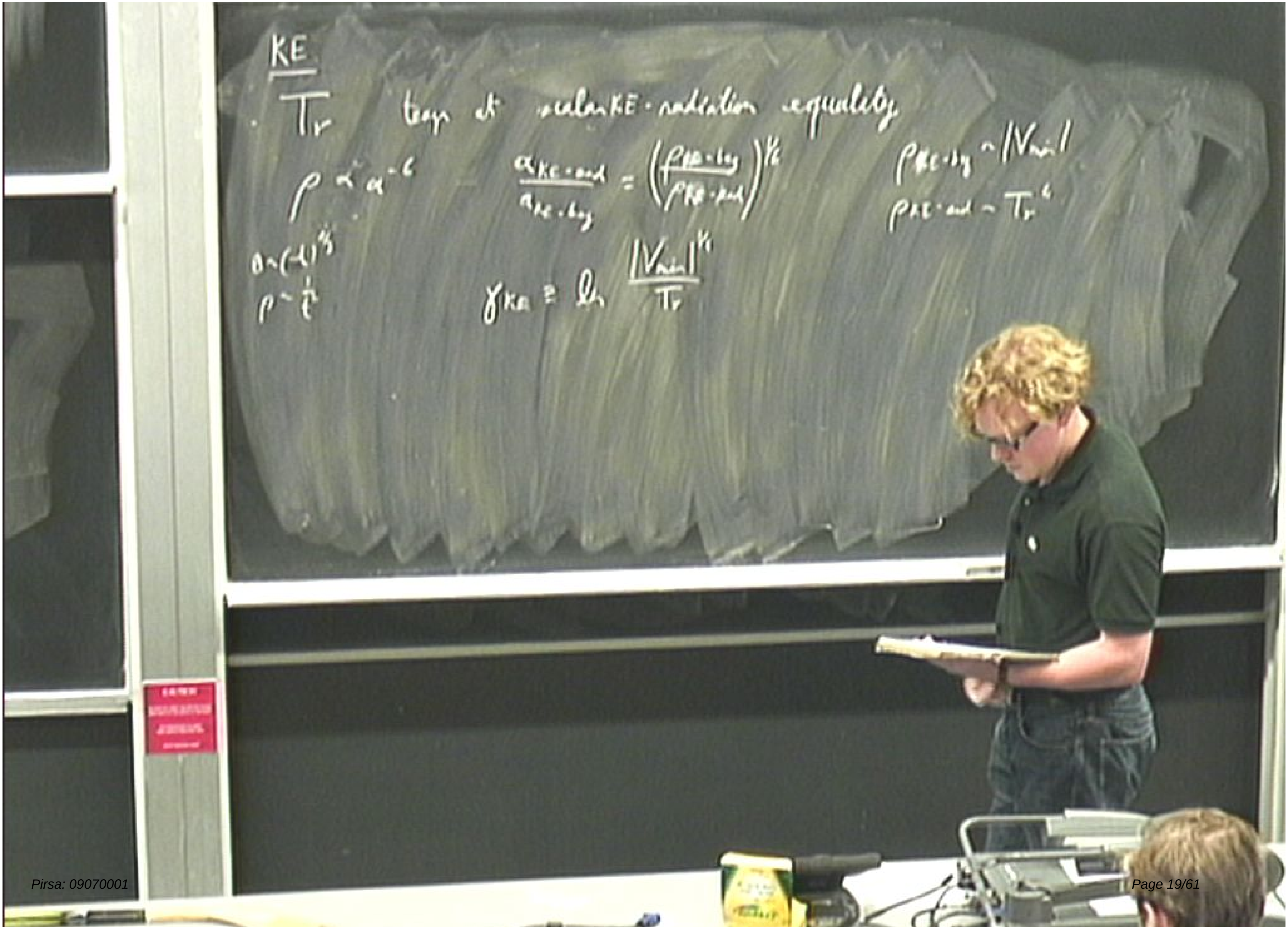

KE
Tr
temp at scalar KE-radiation equality

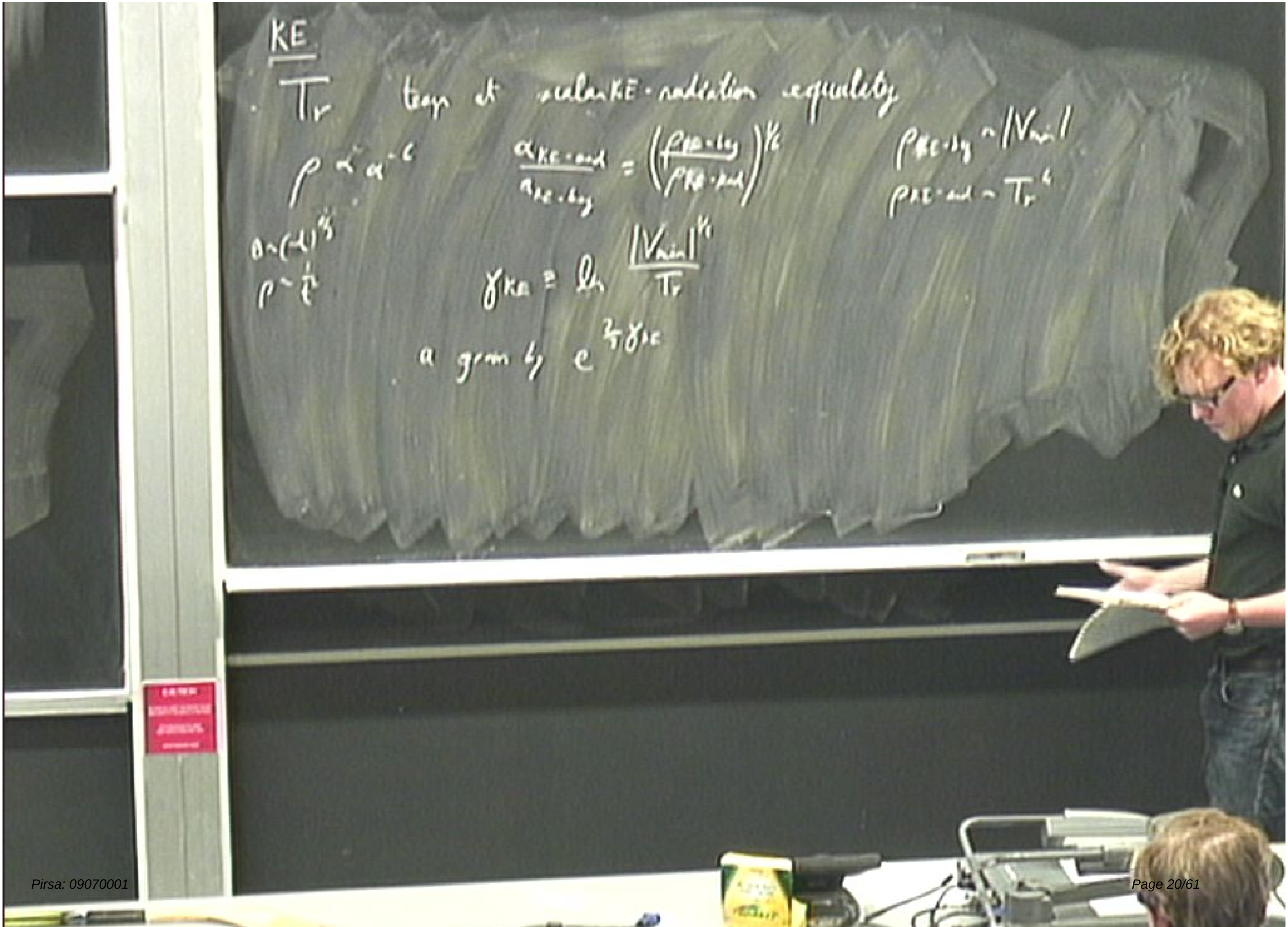

KE
Tr temp at scalarKE - radiation equality
$\rho \propto a^{-6}$

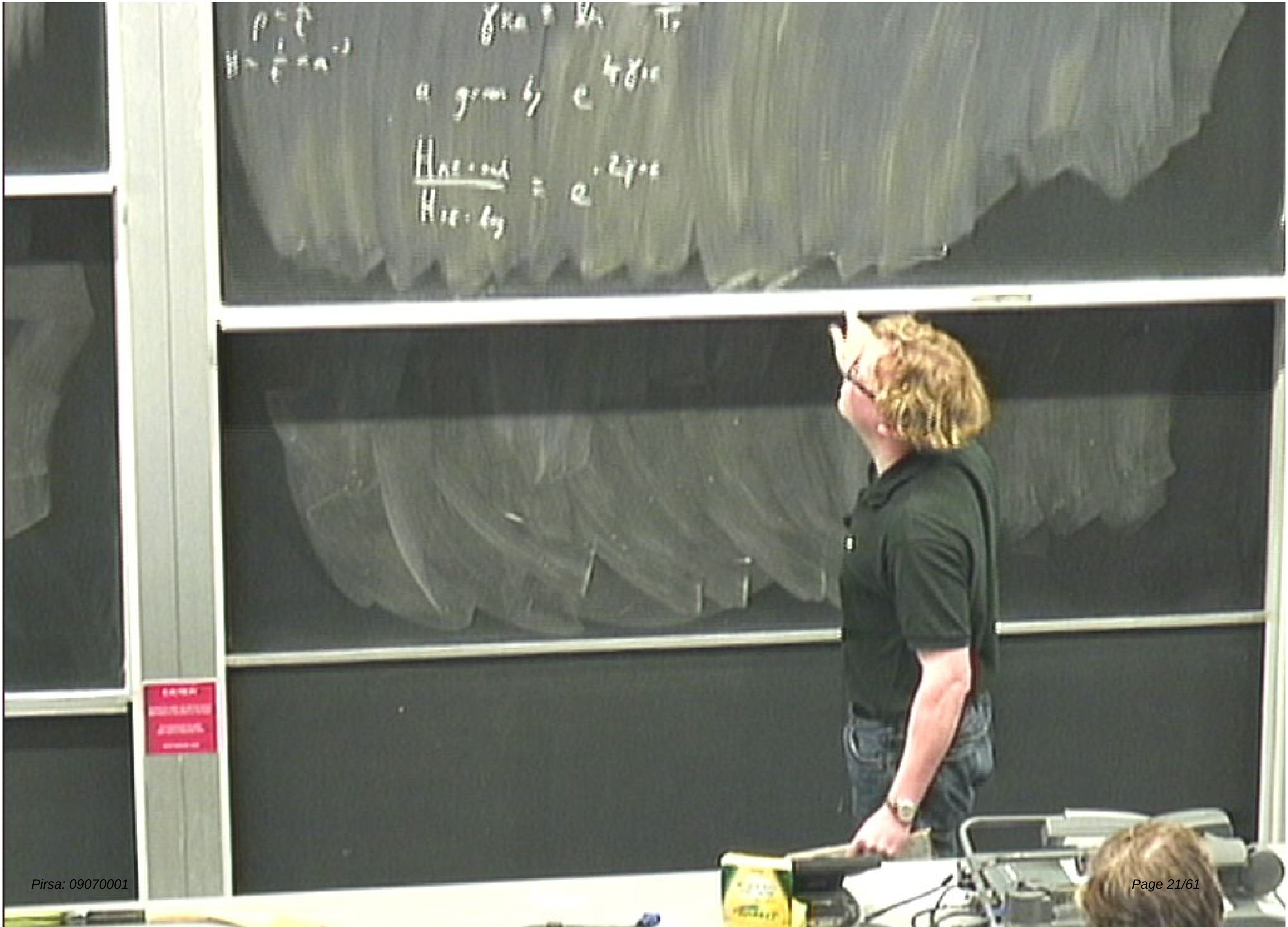

KE
Tr temp at scalarKE - radiation equality

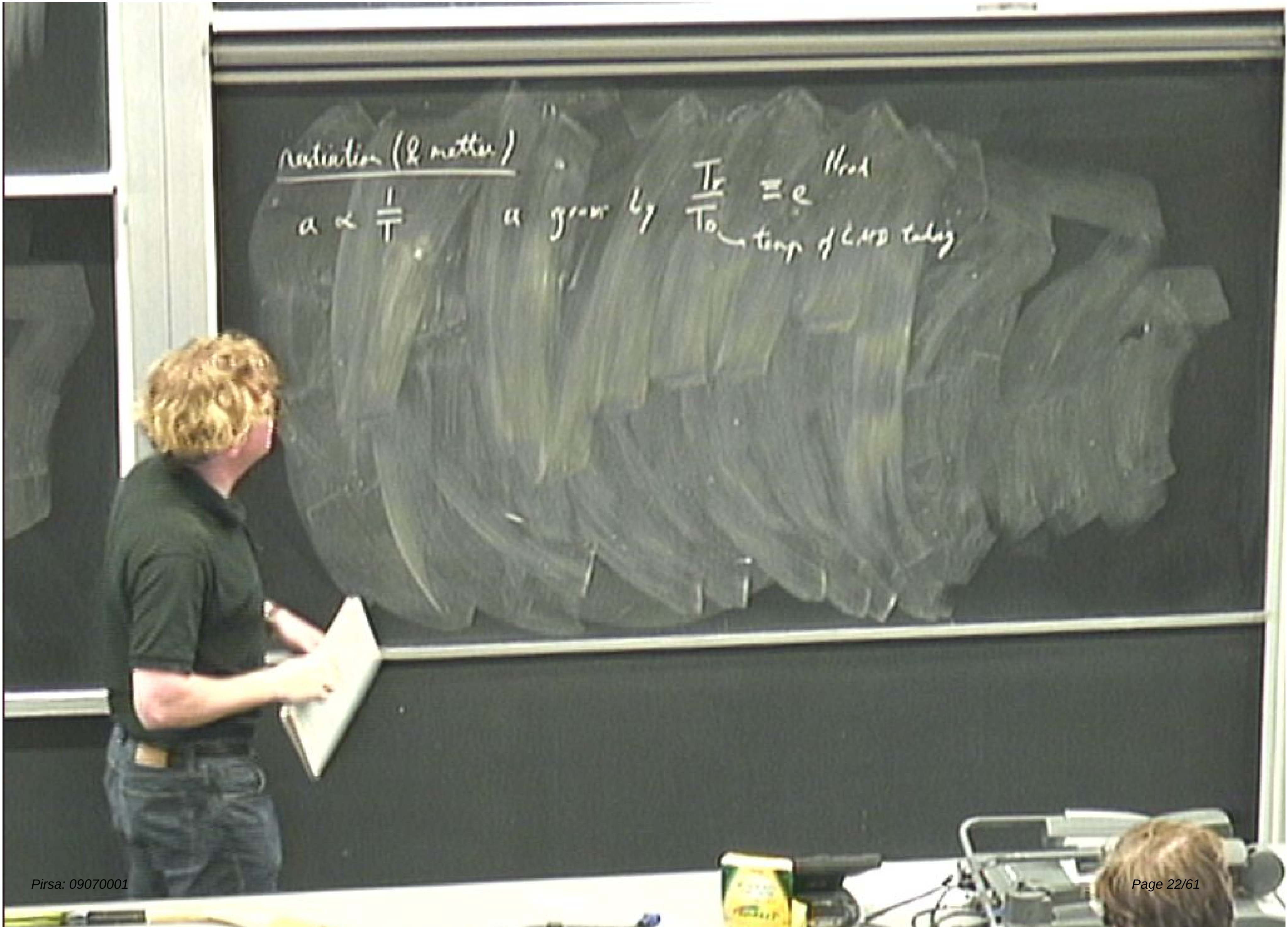

KE
Tr temp at scalarKE - radiation equality
ρ ∝ a^-6
a_KE-rad / a_KE-bg = (ρ_KE-bg / ρ_KE-rad)^1/6
a ~ (-t)^1/3
ρ ~ 1/t²

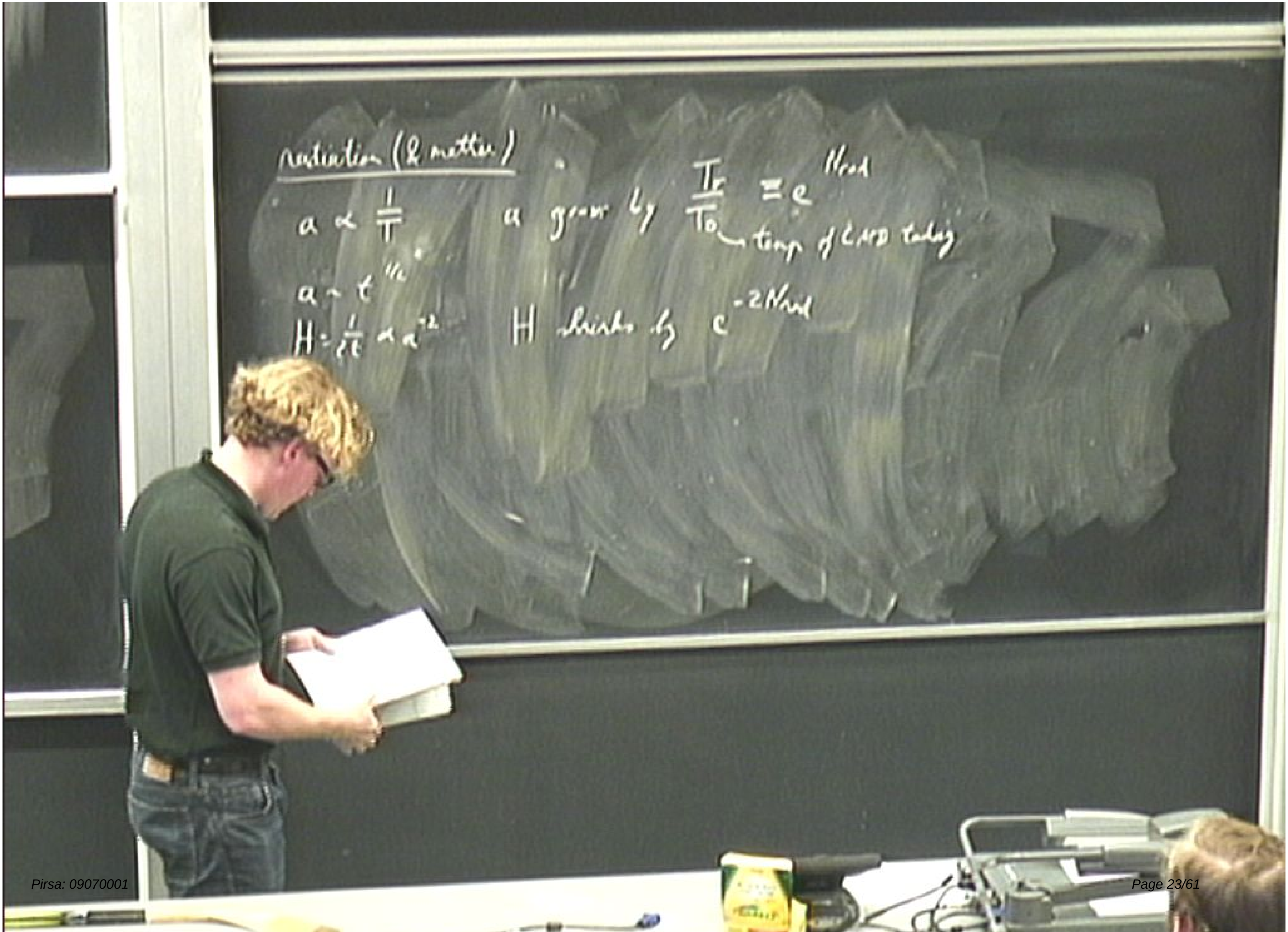

KE
Tr
temp at scalarKE-radiation equality

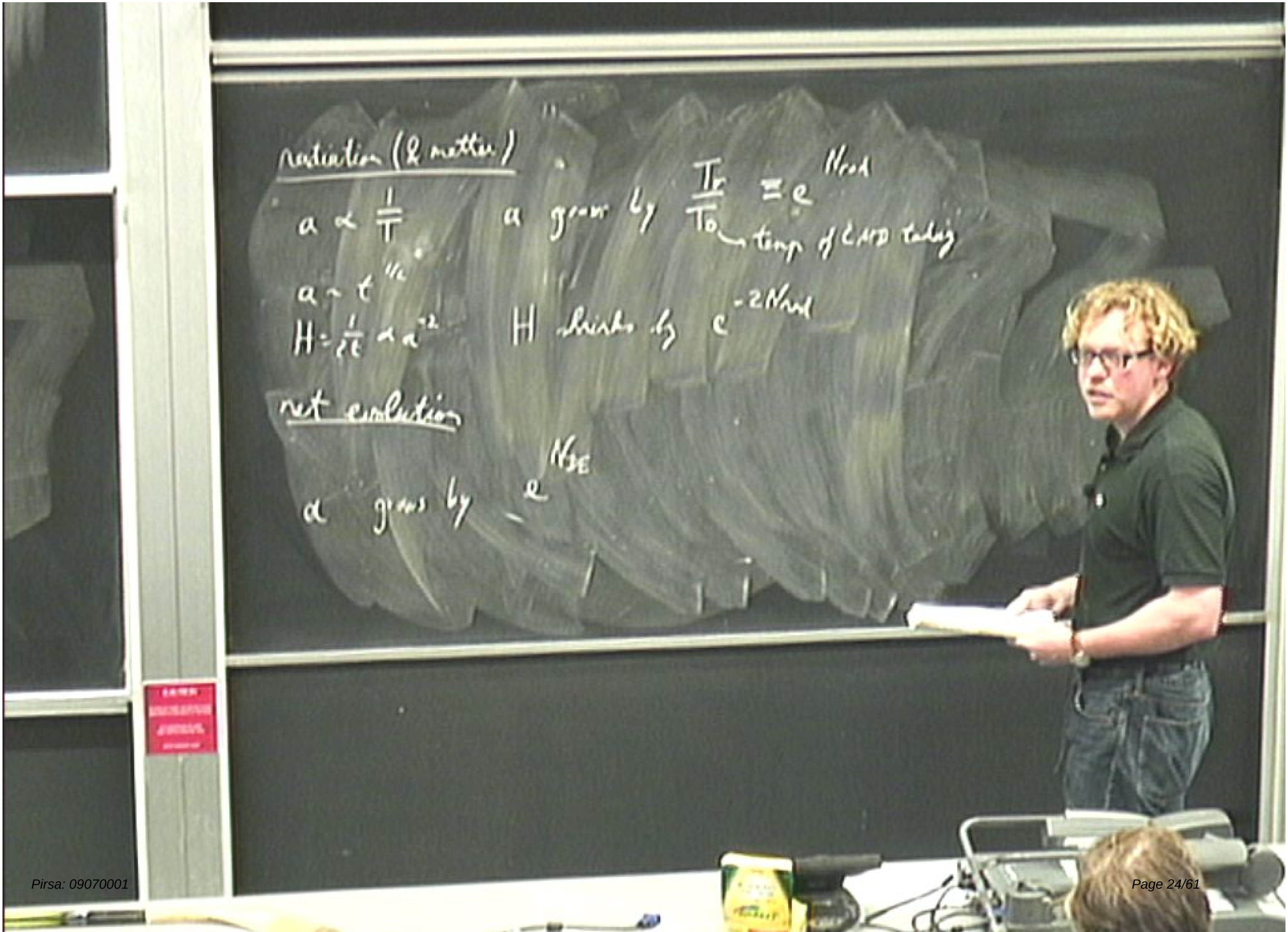

KE
Tr
equality

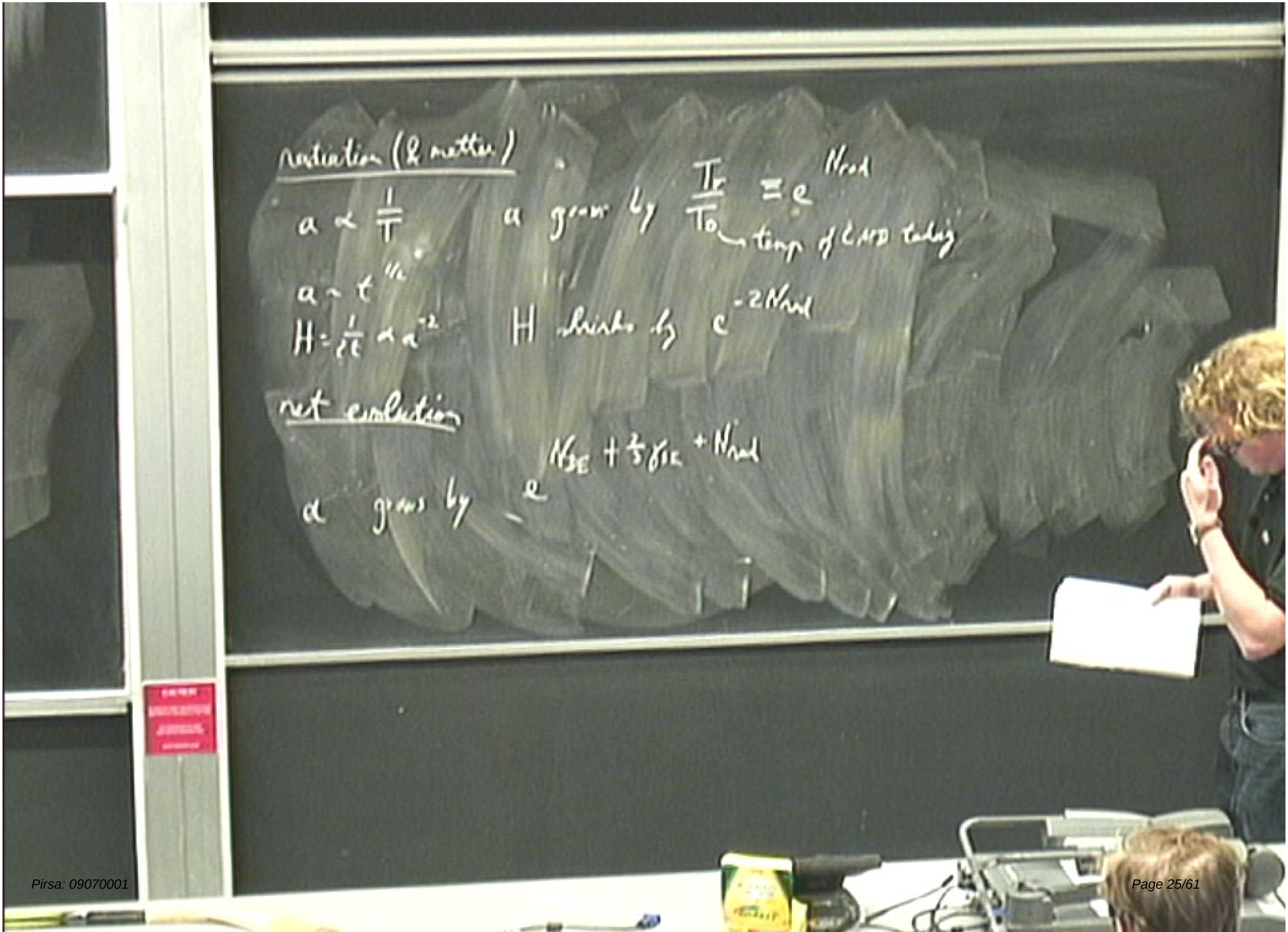

KE
T_r temp at scalar KE - radiation equality
$\rho \propto a^{-6}$
$\frac{a_{KE-rad}}{a_{KE-beg}} = \left(\frac{\rho_{KE-beg}}{\rho_{KE-rad}}\right)^{1/6}$
$\rho_{KE-beg} \sim |V_{min}|$
$\rho_{KE-rad} \sim T_r^4$
$a \sim (-t)^{1/3}$
$\rho \sim \frac{1}{t^2}$
$\gamma_{KE} = \ln \frac{|V_{min}|^{1/4}}{T_r}$
a grows by $e^{\frac{2}{3}\gamma_{KE}}$

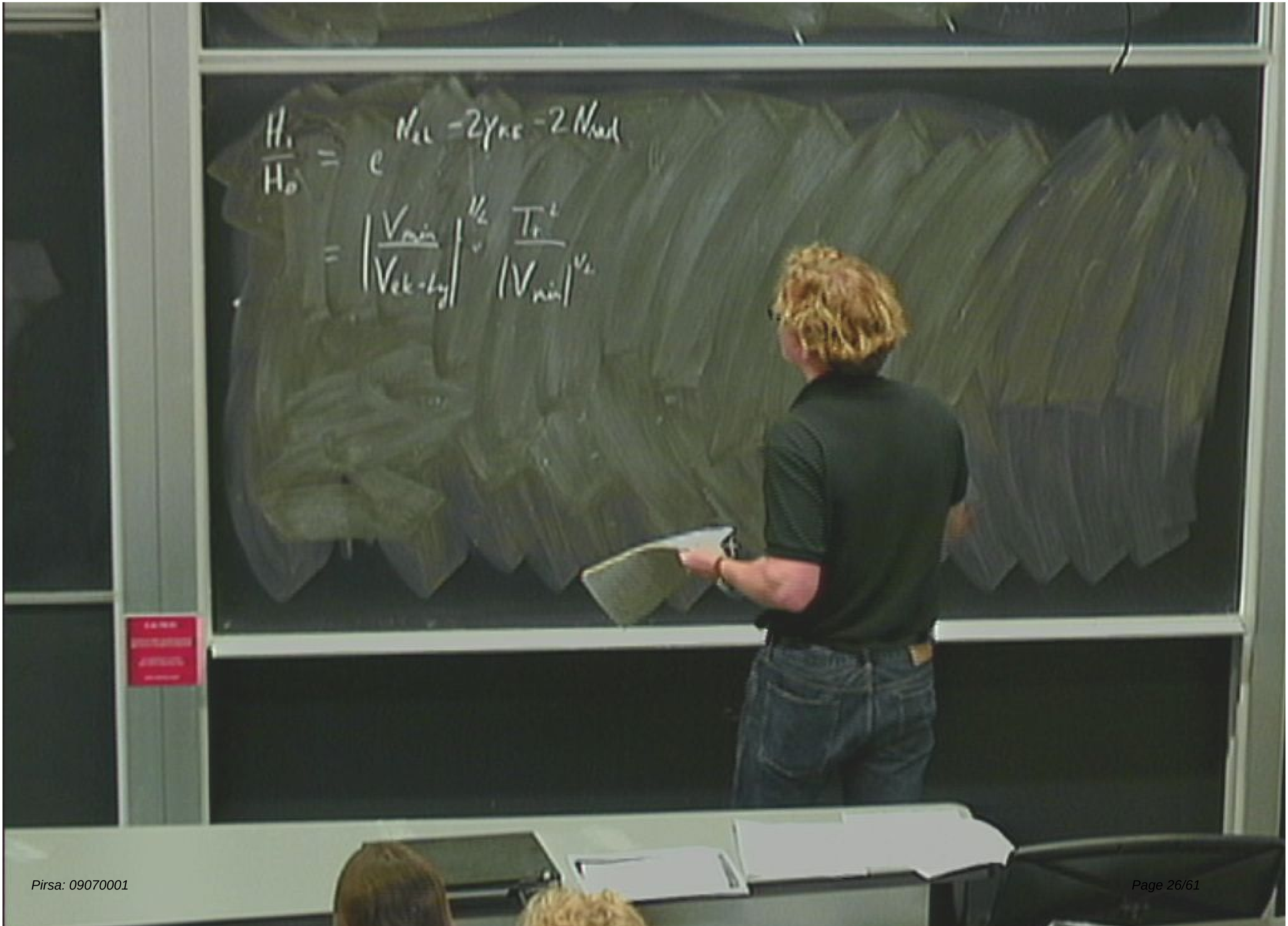



radiation (& matter)
$a \propto \frac{1}{T}$
a grows by $\frac{T_r}{T_0} \equiv e^{N_{rad}}$
temp of CMB today

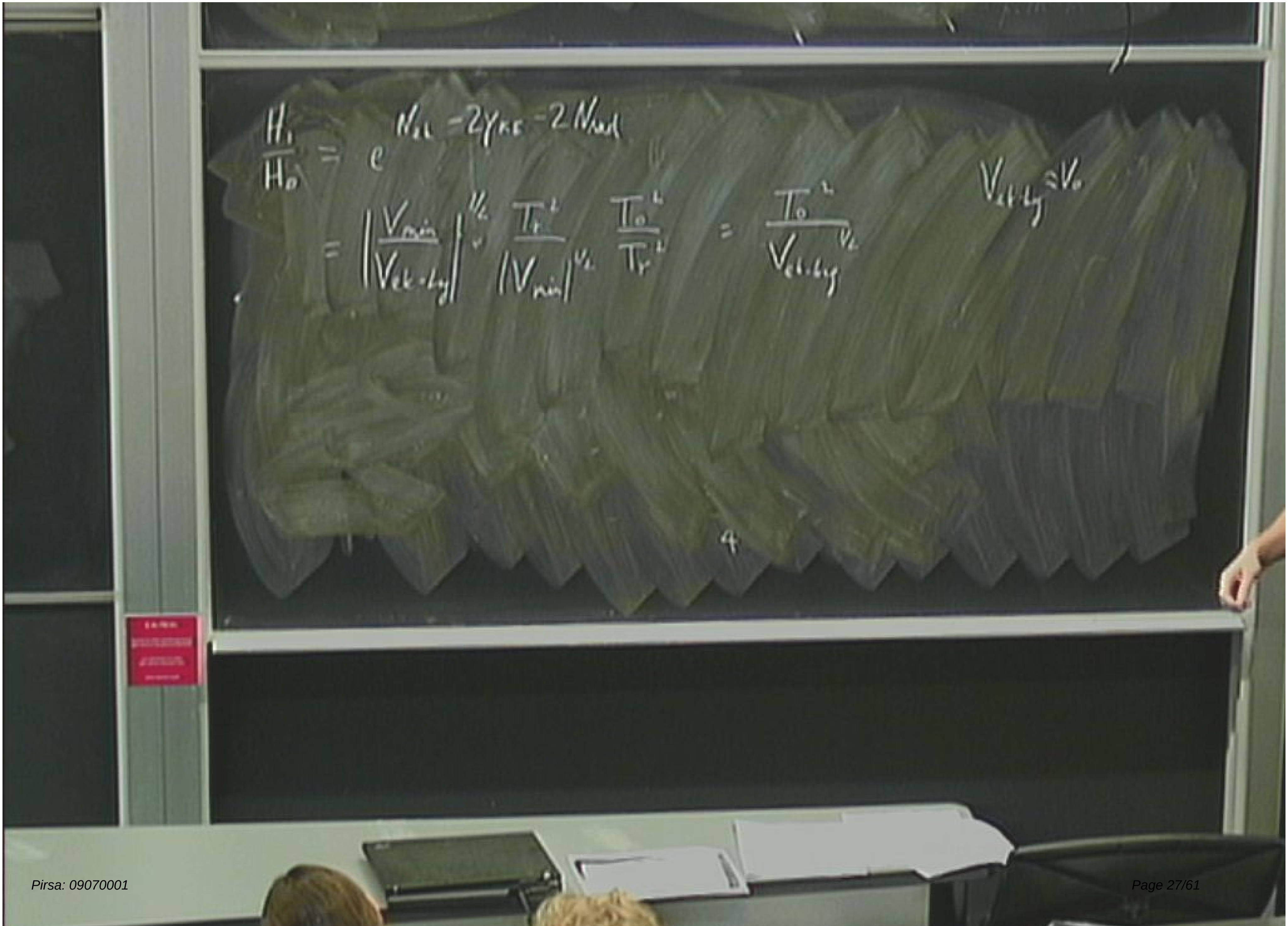

radiation (& matter)
a ∝ 1/T
a grows by T_r/T_0 ≃ e^{N_rad}
temp of CMB today
a ~ t^{1/2}
H = 1/2t ∝ a^{-2}
H shrinks by e^{-2N_rad}

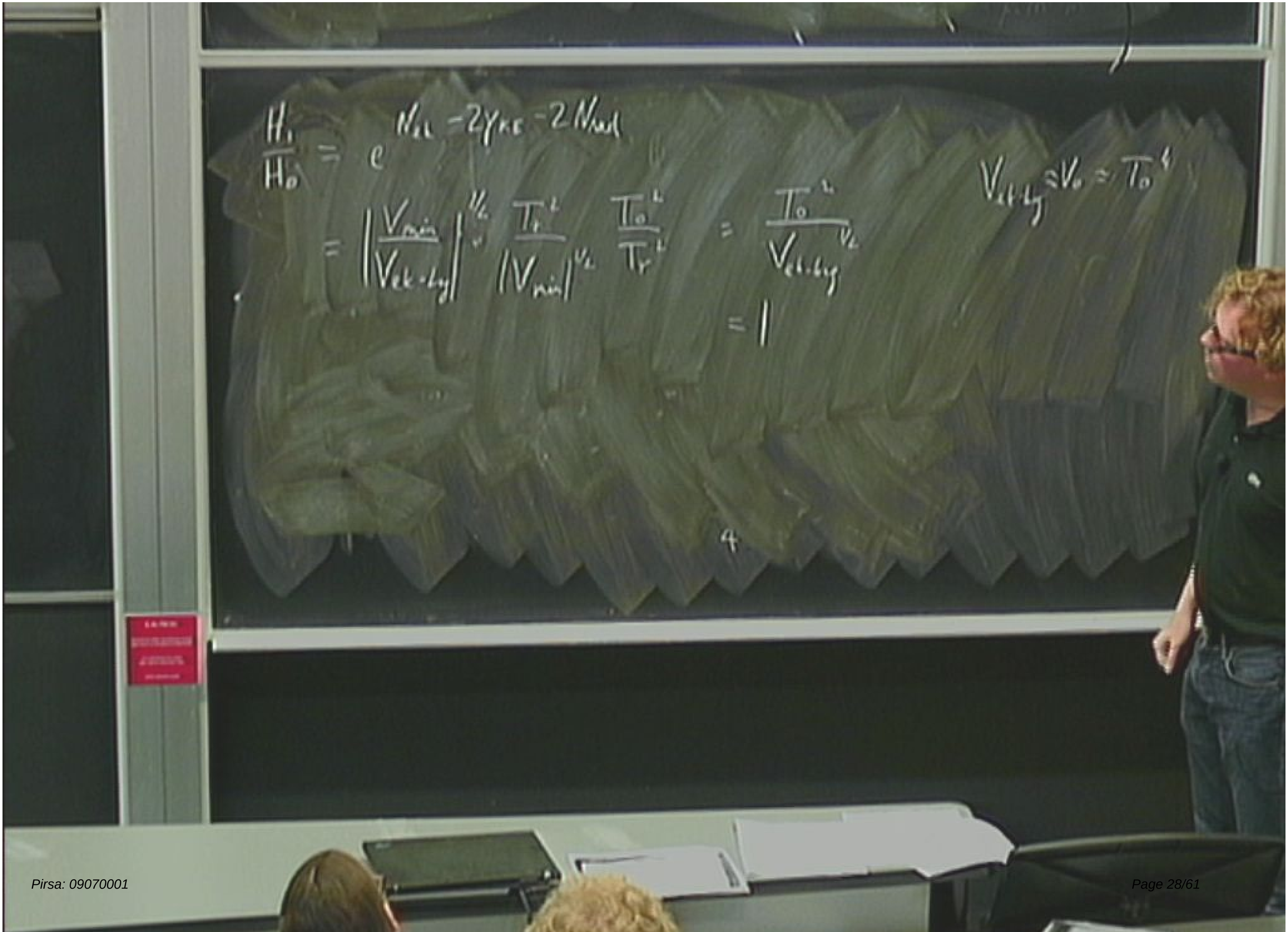

radiation (& matter)
a ∝ 1/T
a grows by Tr/T0 ≡ e^Nrad
temp of CMB today
a ~ t^1/2
H = 1/2t ∝ a^-2
H shrinks by e^-2Nrad
net evolution
a grows by e^NDE


radiation (& matter)
$a \propto \frac{1}{T}$
a grows by $\frac{T_r}{T_0} \equiv e^{N_{rad}}$
temp of CMB today
$a \sim t^{1/2}$
$H = \frac{1}{2t} \propto a^{-2}$
H shrinks by $e^{-2N_{rad}}$
net evolution
a grows by $e^{N_{SE} + \frac{2}{3}\gamma_{SE} + N_{rad}}$



H₁/H₀ = e^(N_tot − 2γ_KE − 2N_rad)
= |V_min / V_ek-ky|^(1/2) T_r² / |V_min|^(1/2)


$\frac{H_1}{H_0} = e^{N_{kk} - 2y_{KS} - 2N_{rad}}$
$= \left|\frac{V_{min}}{V_{ek-by}}\right|^{1/2} \frac{T_r^2}{|V_{min}|^{1/2}} \frac{T_0^2}{T_r^2} = \frac{T_0^2}{V_{ek-by}^{1/2}}$
$V_{ek-by} \simeq V_0$
4


$\frac{H_1}{H_0} = e^{N_{kk} - 2y_{KE} - 2N_{rad}}$
$= \left|\frac{V_{min}}{V_{kk-lg}}\right|^{1/2} \frac{T_r^2}{|V_{min}|^{1/2}} \frac{T_0^2}{T_r^2} = \frac{T_0^2}{V_{kk-lg}^{1/2}}$
$= 1$
$V_{kk-lg} \approx V_0 \approx T_0^4$

$$\frac{H_1}{H_0} = e^{N_{ek} - 2\gamma_{KE} - 2N_{rad}}$$

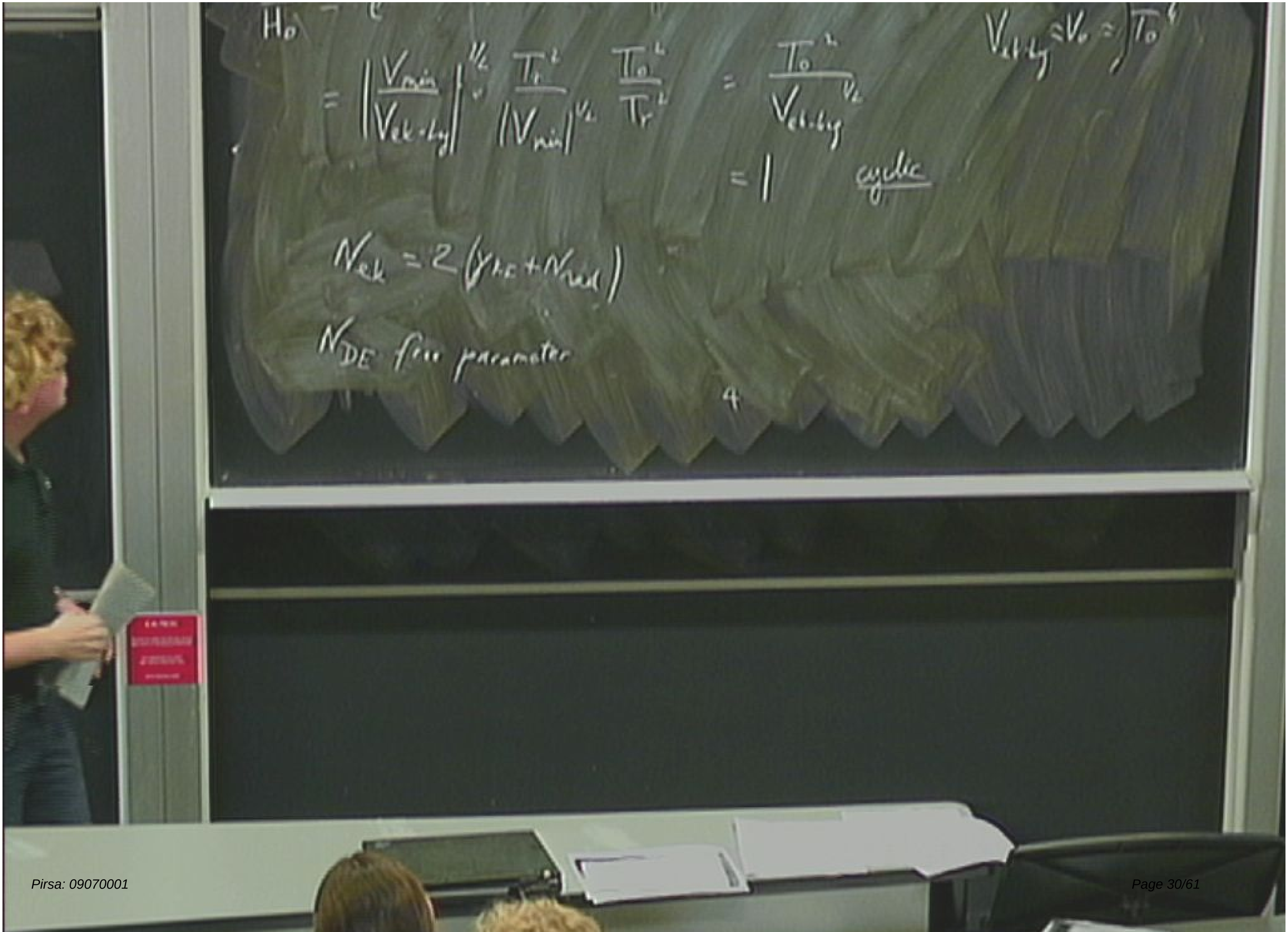
$$= \left|\frac{V_{min}}{V_{ek\text{-}by}}\right|^{1/2} \frac{T_r^4}{|V_{min}|^{1/2}} \frac{T_0^4}{T_r^4} = \frac{T_0^4}{V_{ek\text{-}by}^{1/2}}$$

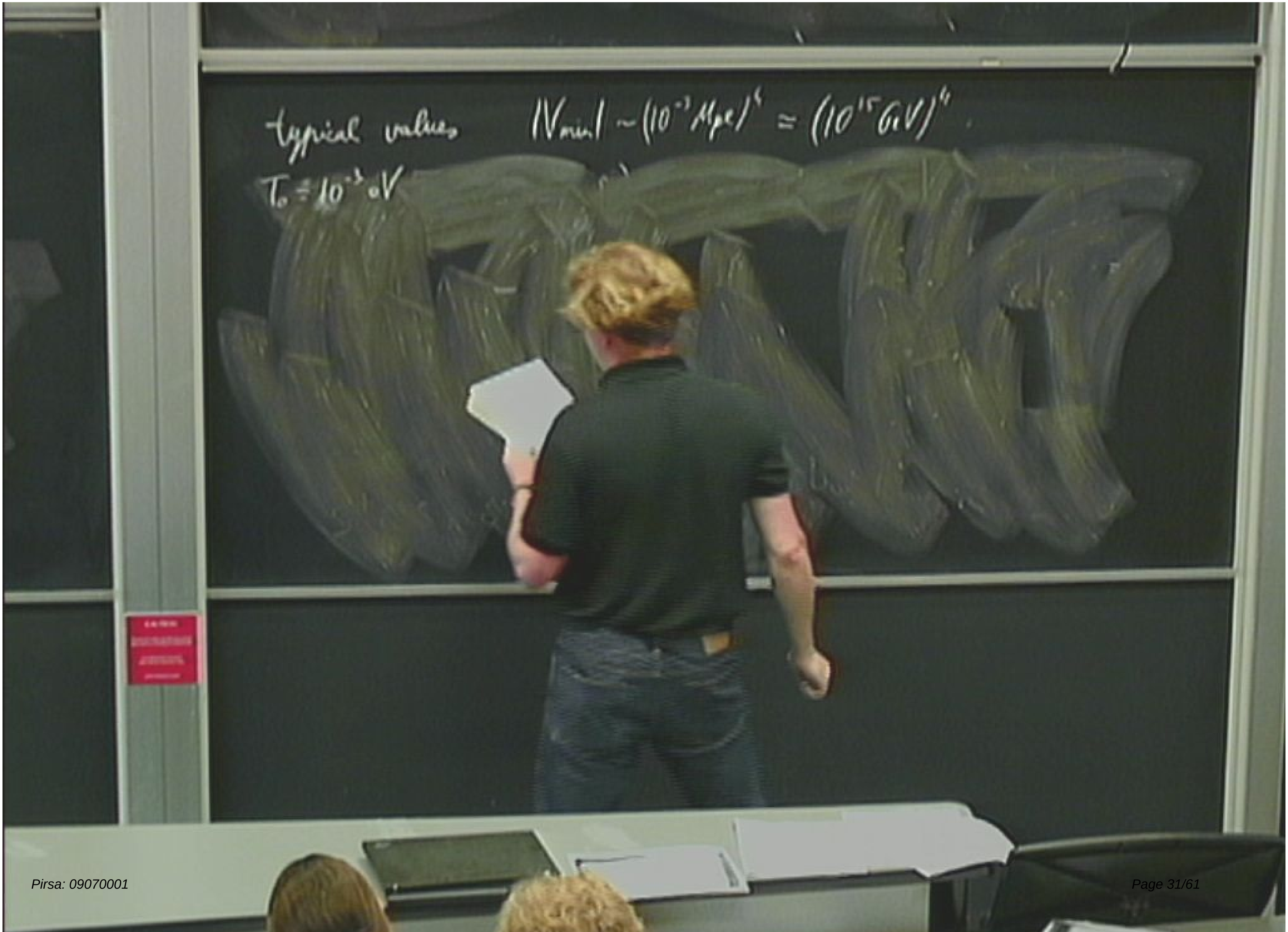
$$V_{ek\text{-}by} \approx V_0 \approx T_0^4$$

$$= 1 \qquad \underline{\text{cyclic}}$$

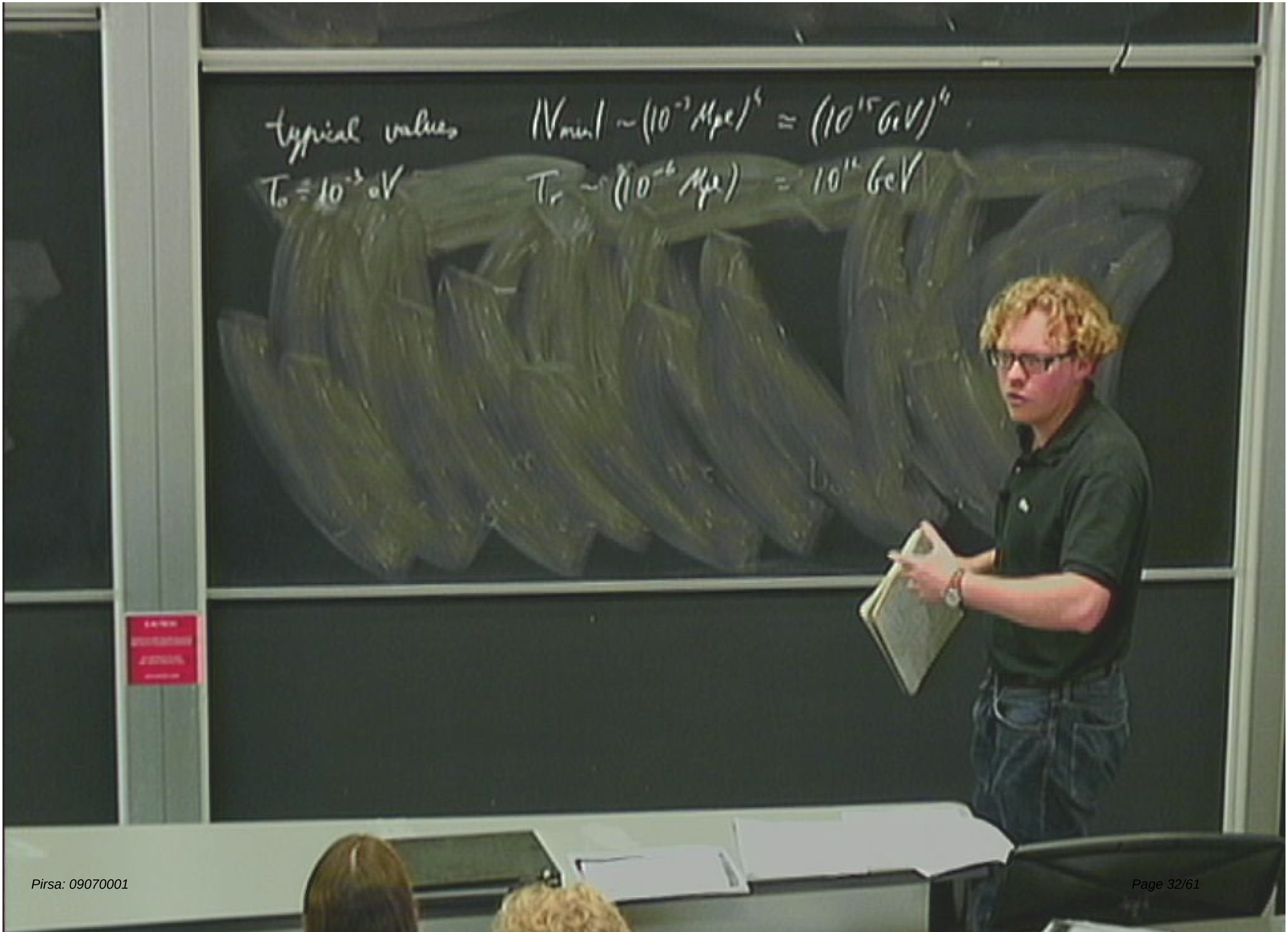
$$N_{ek} = 2(\gamma_{KE} + N_{rad})$$

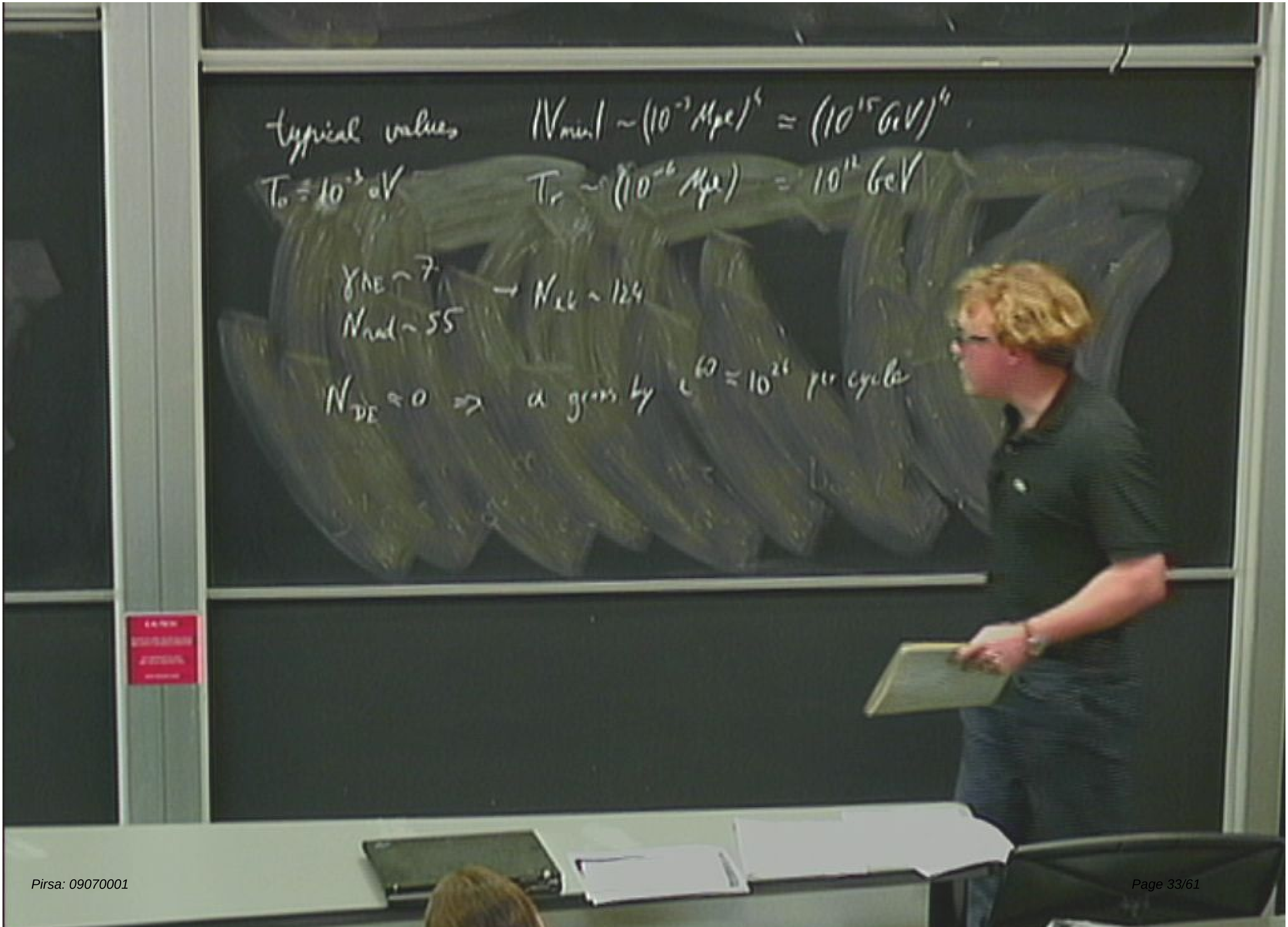
4

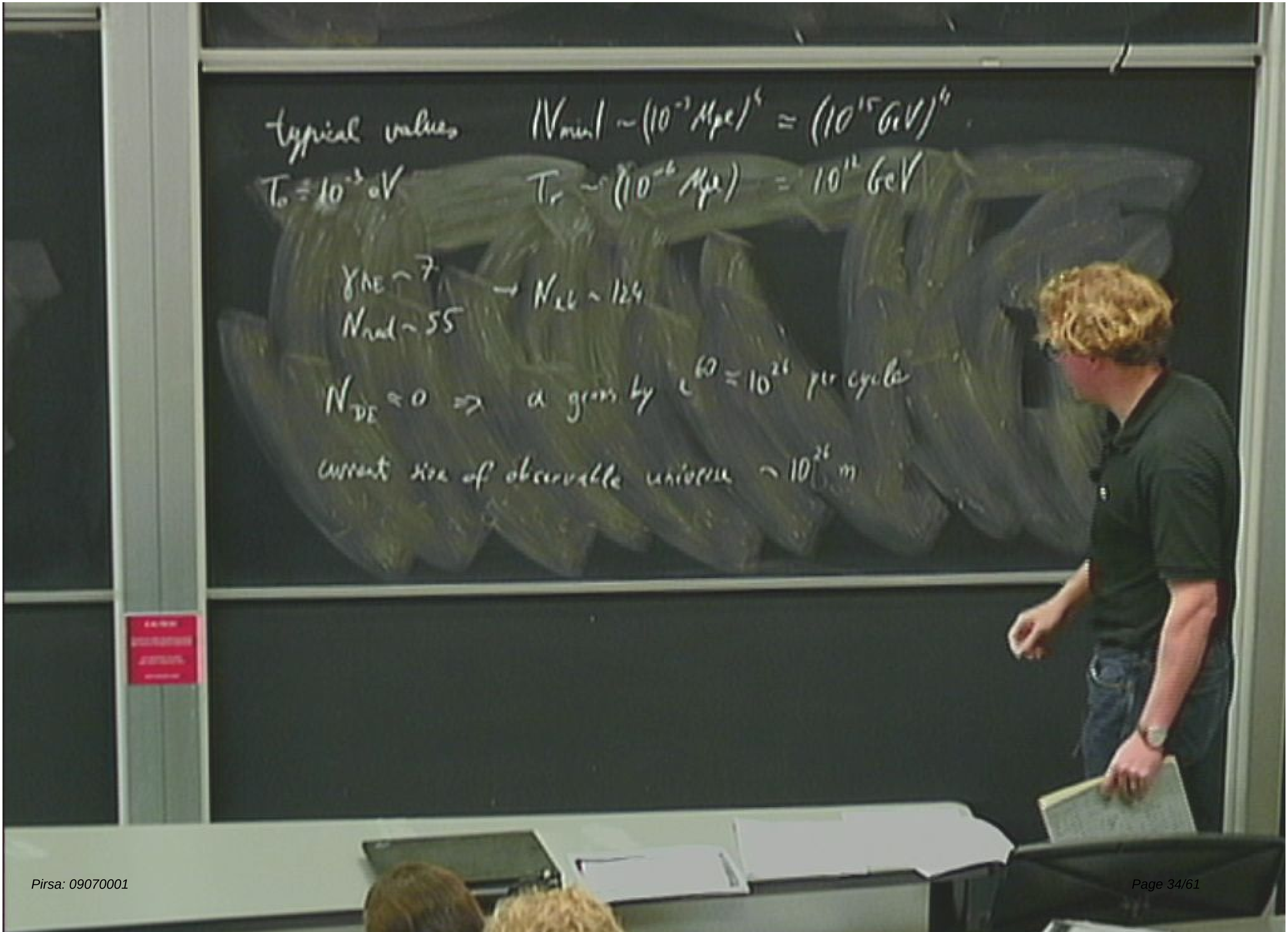

=1 cyclic
N_DE free parameter

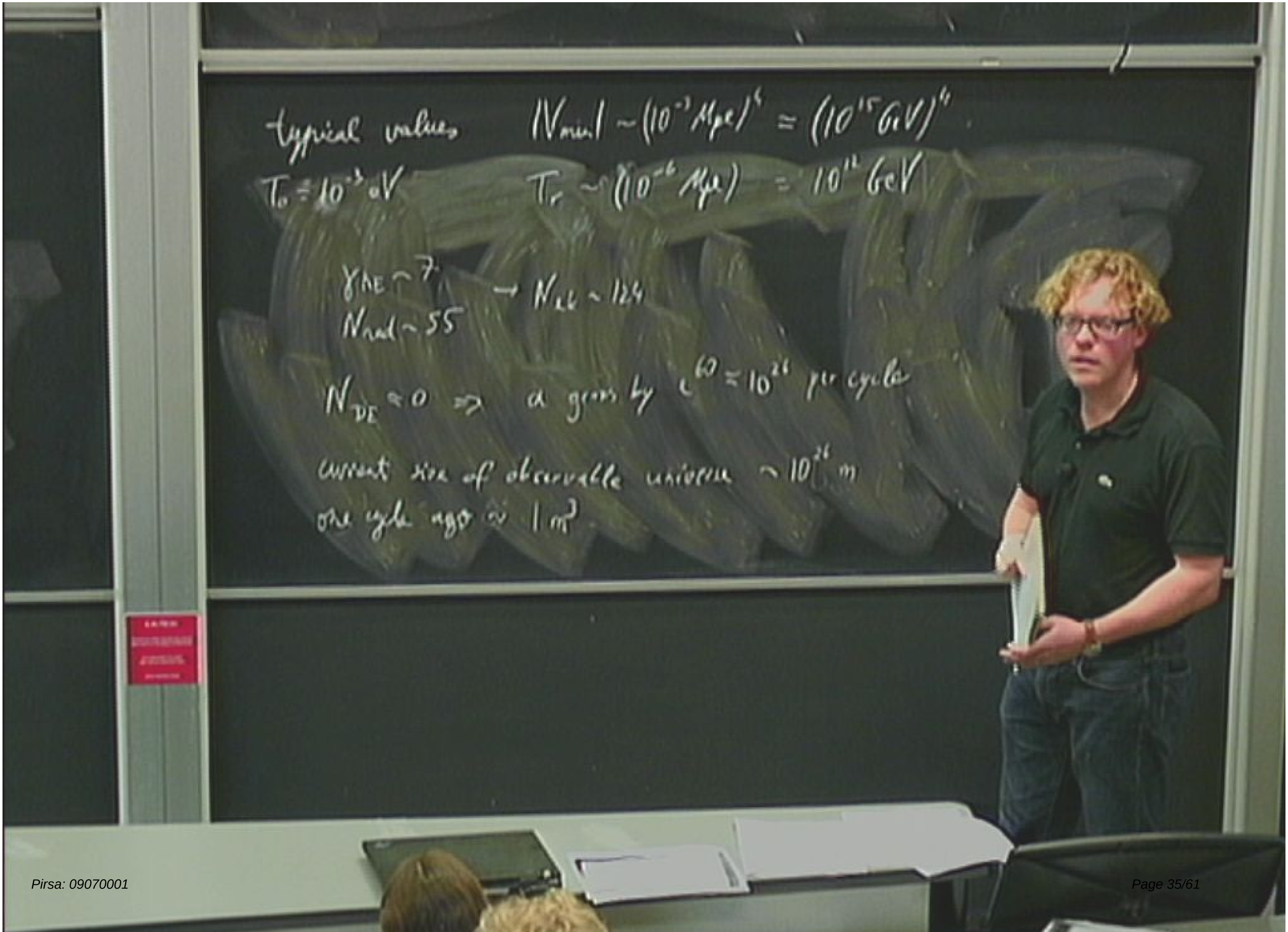


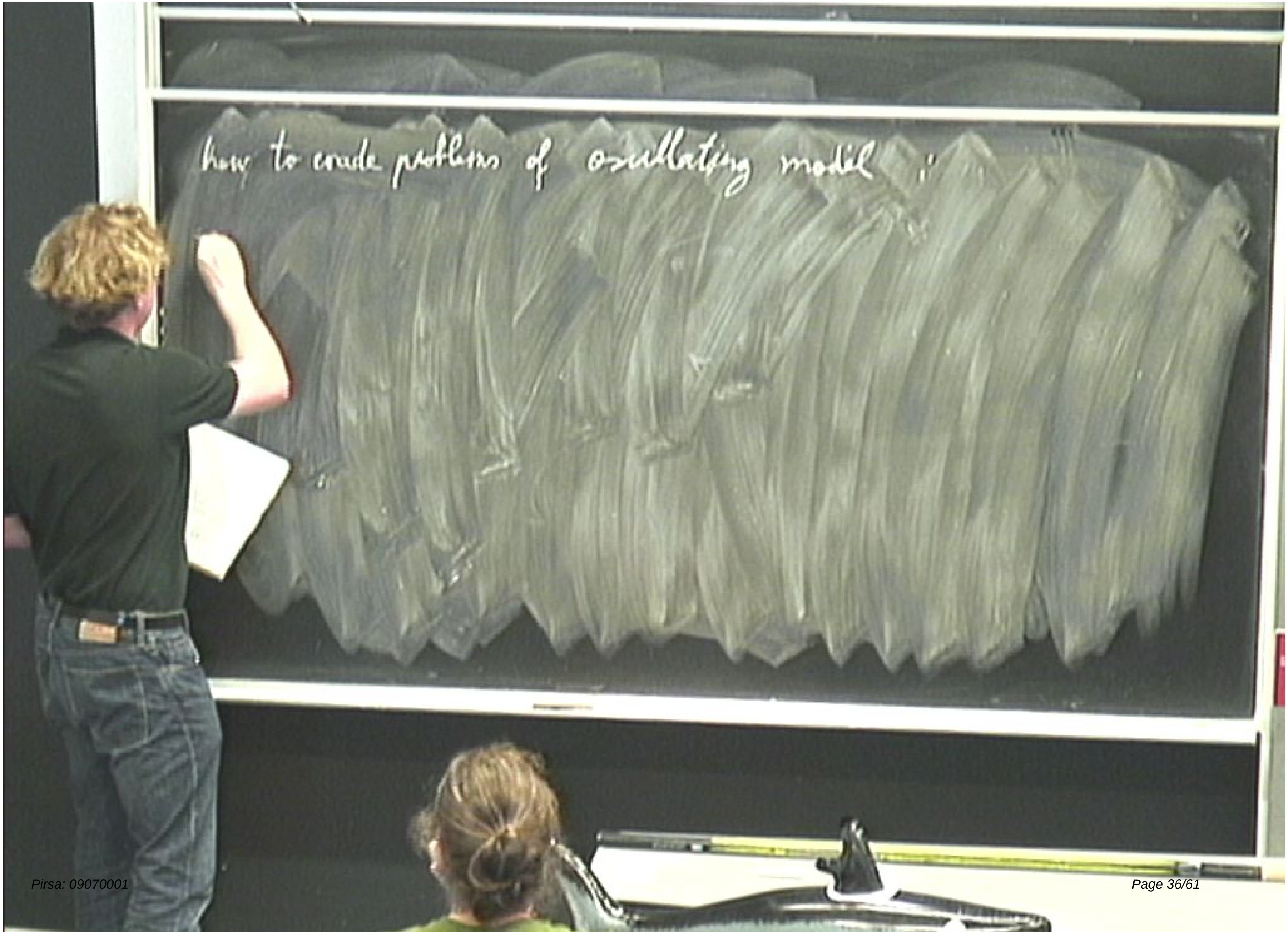
typical values $|V_{min}| \sim (10^{-3}\,\mathrm{Mpc})^4 \simeq (10^{15}\,\mathrm{GeV})^4$
$T_0 \doteq 10^{-3}\,\mathrm{eV}$

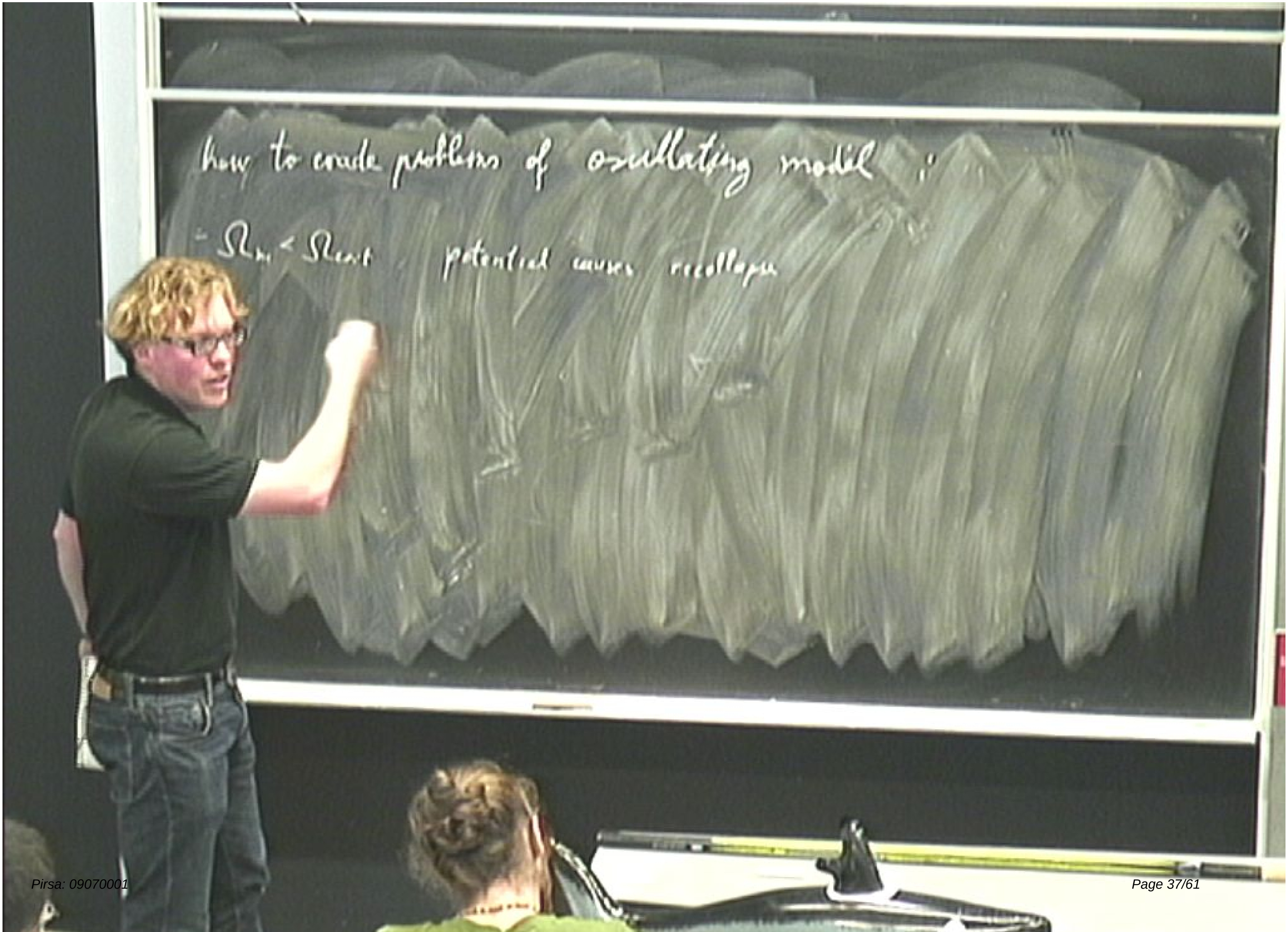

typical values |V_min| ~ (10^-3 Mpl)^4 ≃ (10^15 GeV)^4
T_0 ≃ 10^-3 eV T_r ~ (10^-6 Mpl) ≃ 10^12 GeV

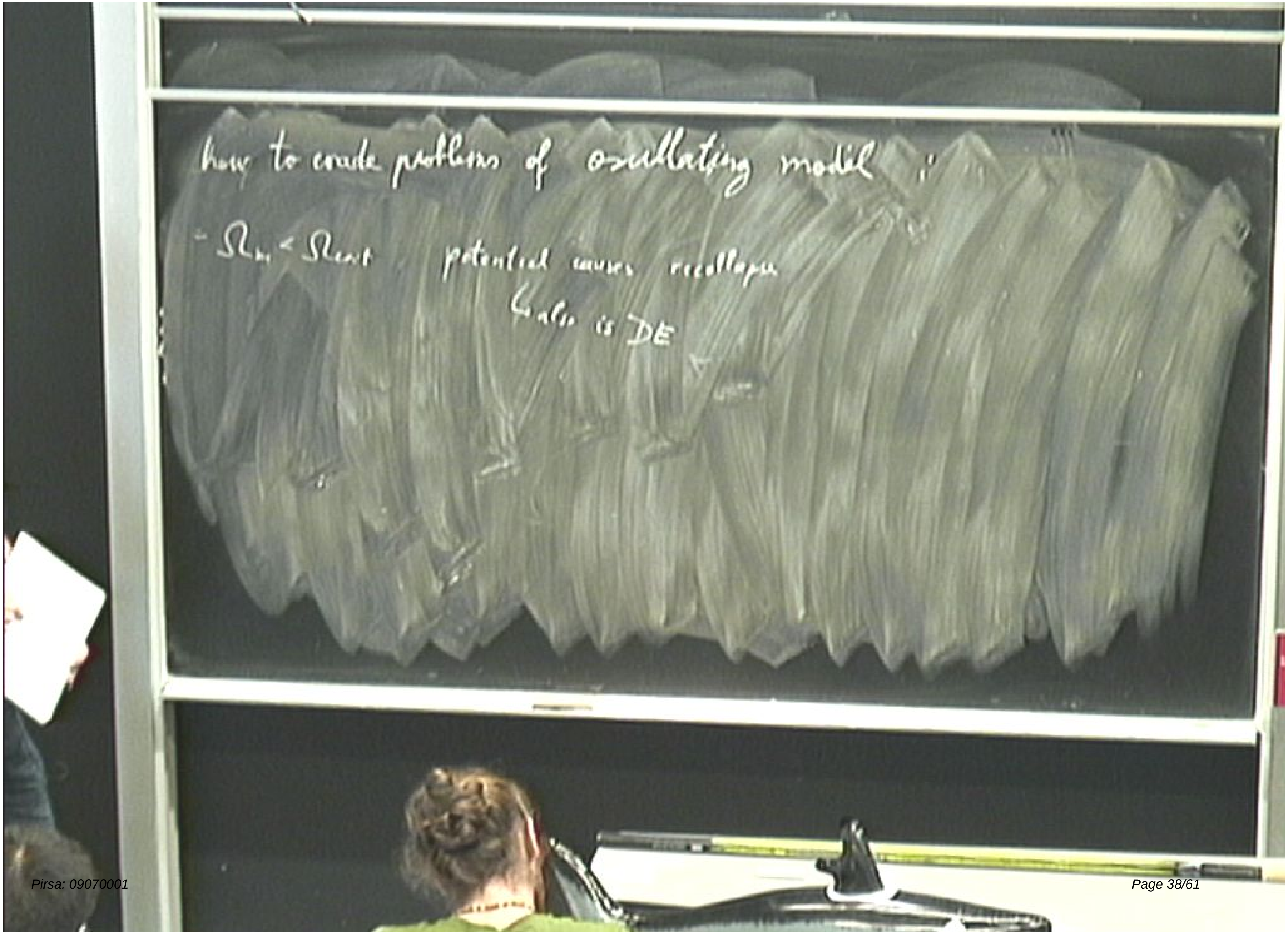

typical values |V_min| ~ (10^-3 Mpc)^4 ≃ (10^15 GeV)^4
T_0 ≃ 10^-3 eV T_r ~ (10^-6 Mpc) ≃ 10^12 GeV
γ_DE ~ 7 → N_KE ~ 124
N_rad ~ 55
N_DE ≈ 0 ⇒ a grows by e^60 ≈ 10^26 per cycle

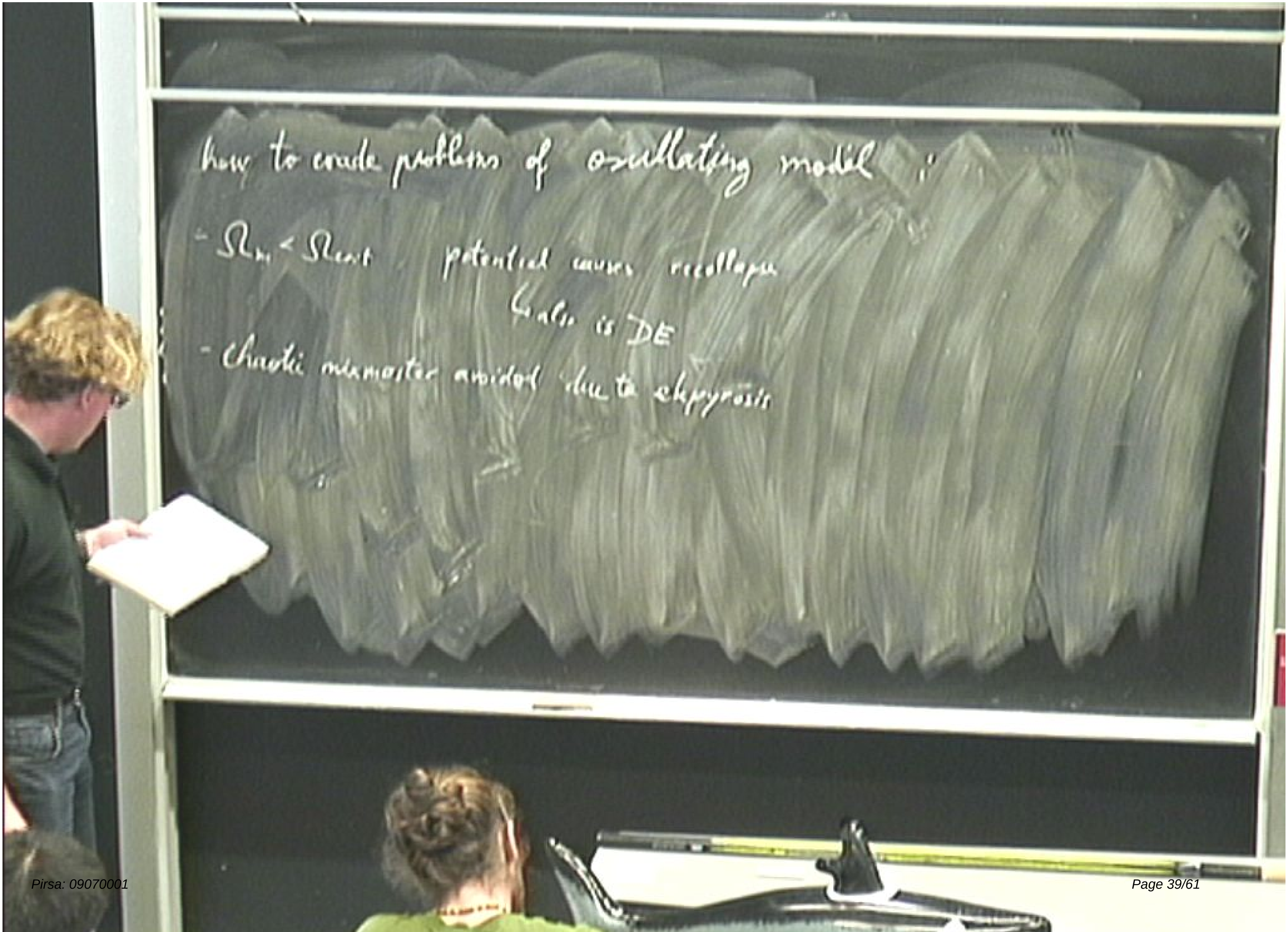

typical values $|V_{min}| \sim (10^{-3}\,\mathrm{Mpc})^4 \simeq (10^{15}\,\mathrm{GeV})^4$
$T_0 \doteq 10^{-3}\,\mathrm{eV}$ $T_r \sim (10^{-6}\,\mathrm{Mpc}) = 10^{12}\,\mathrm{GeV}$
$\gamma_{NE} \sim 7$ $\rightarrow N_{cl} \sim 124$
$N_{rad} \sim 55$
$N_{DE} \approx 0 \Rightarrow$ a grows by $e^{60} \approx 10^{26}$ per cycle
current size of observable universe $\sim 10^{26}\,\mathrm{m}$

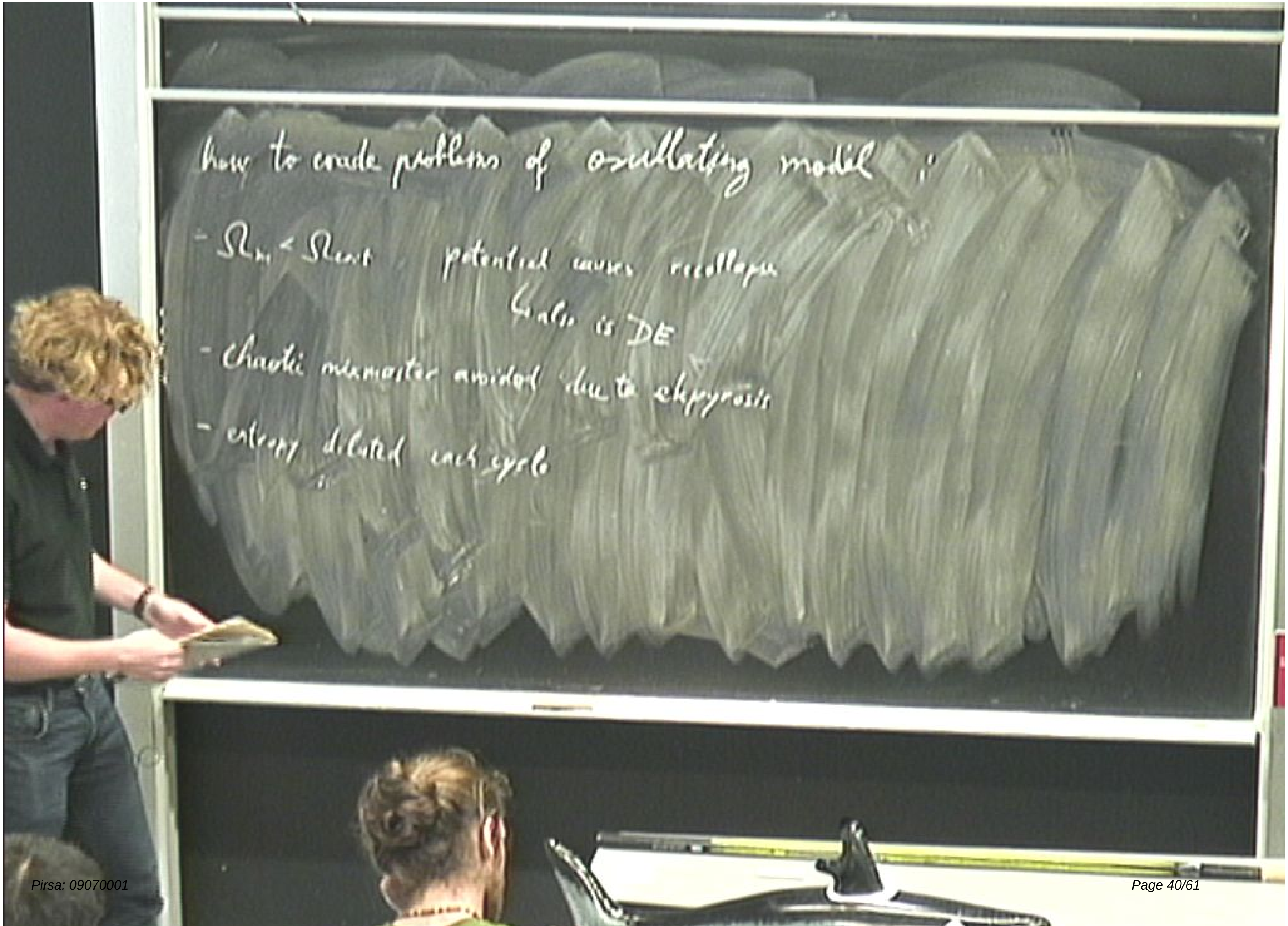

typical values |V_min| ~ (10^-3 Mpc)^4 ≈ (10^15 GeV)^4
T_0 ≈ 10^-3 eV
T_r ~ (10^-6 Mpc) ≈ 10^12 GeV
N_rad ~ 55
N_DE ≈ 0 ⇒ a grows by e^60 ≈ 10^26 per cycle
current size of observable universe ~ 10^26 m
one cycle ago ≈ 1 m

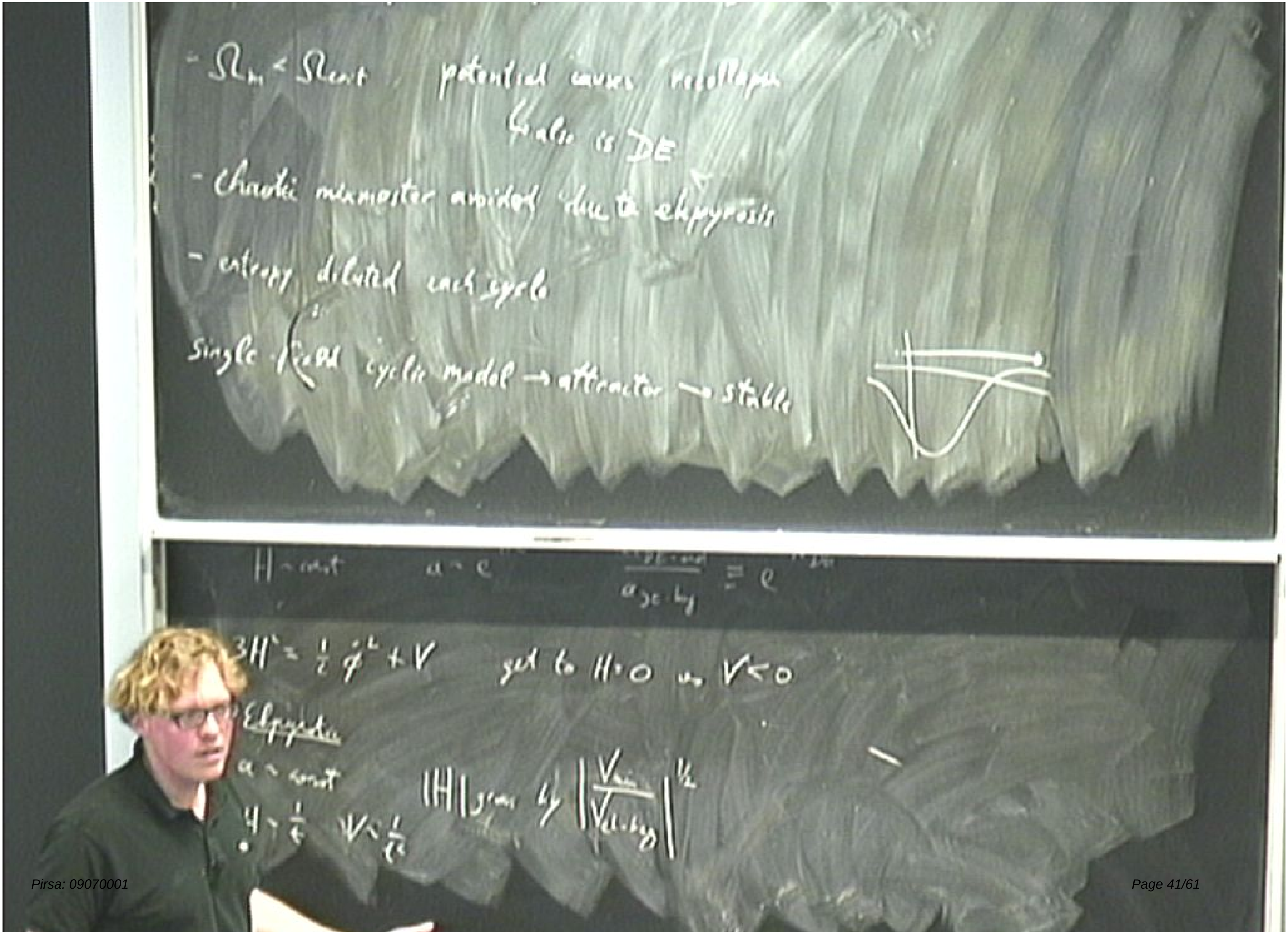

how to evade problems of oscillating model :

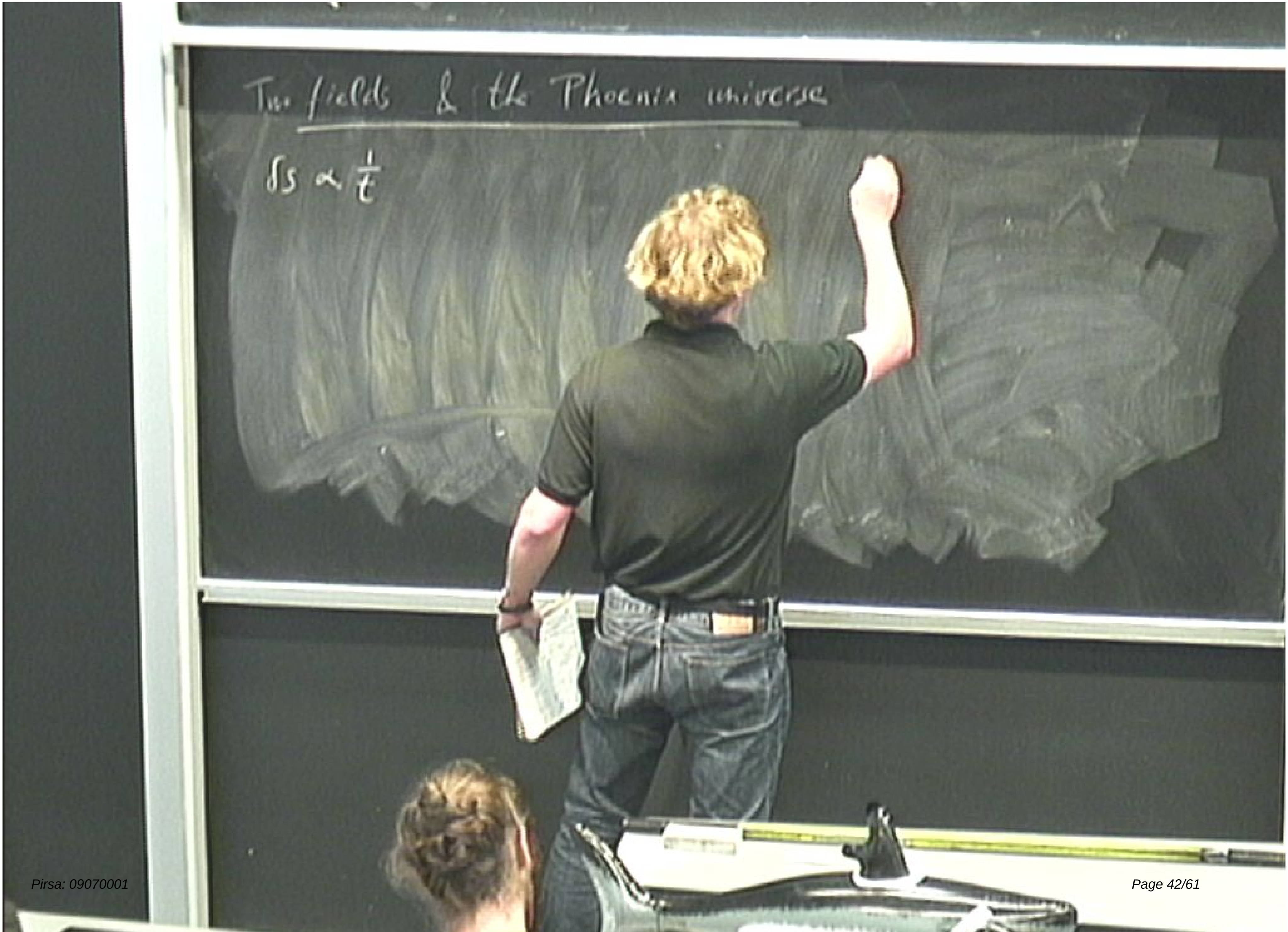

how to evade problems of oscillating model :
- Ωm < Ωcrit potential causes recollapse

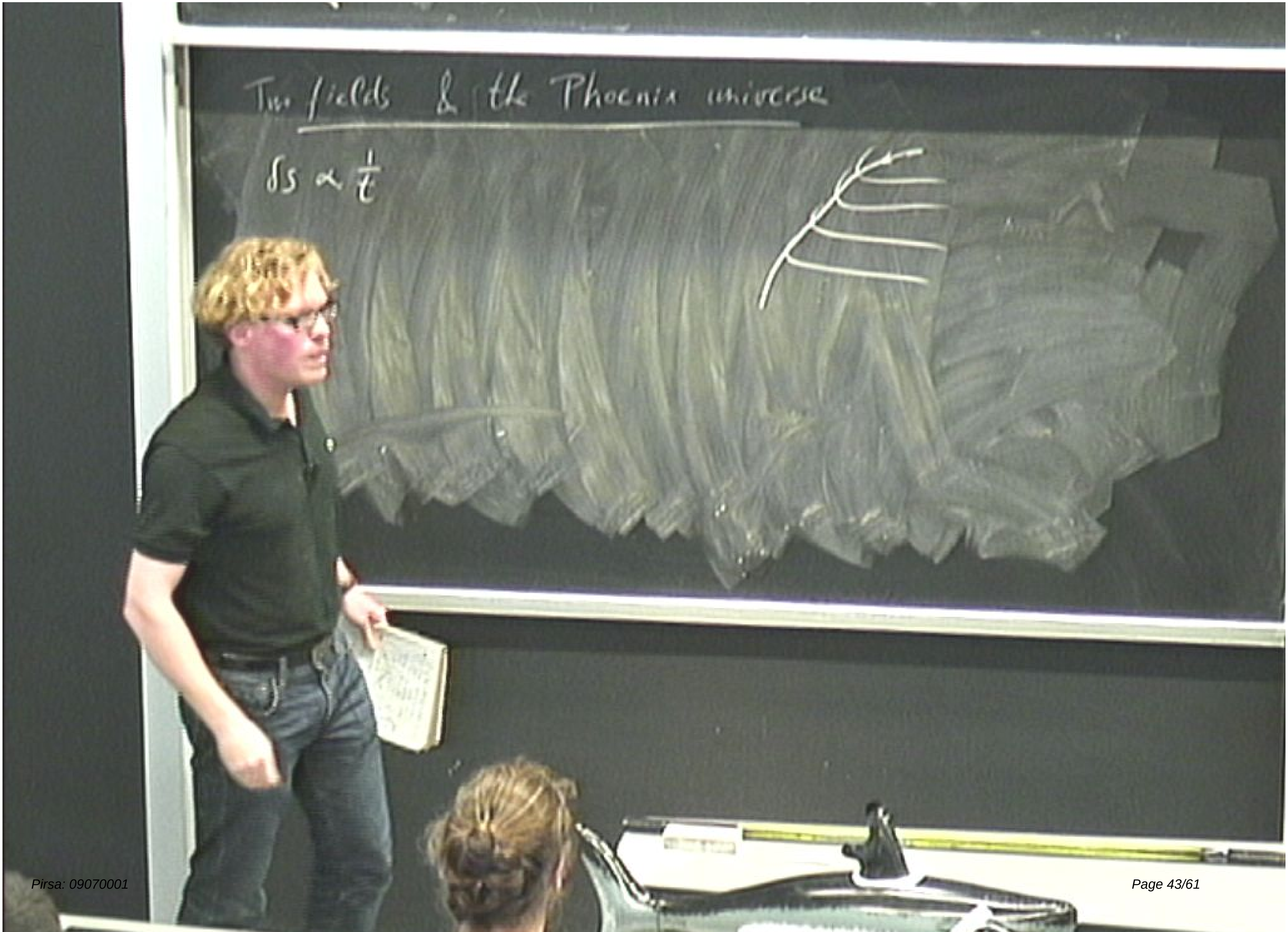

how to evade problems of oscillating model :
- Ωm < Ωcrit potential causes recollapse
↳ also is DE

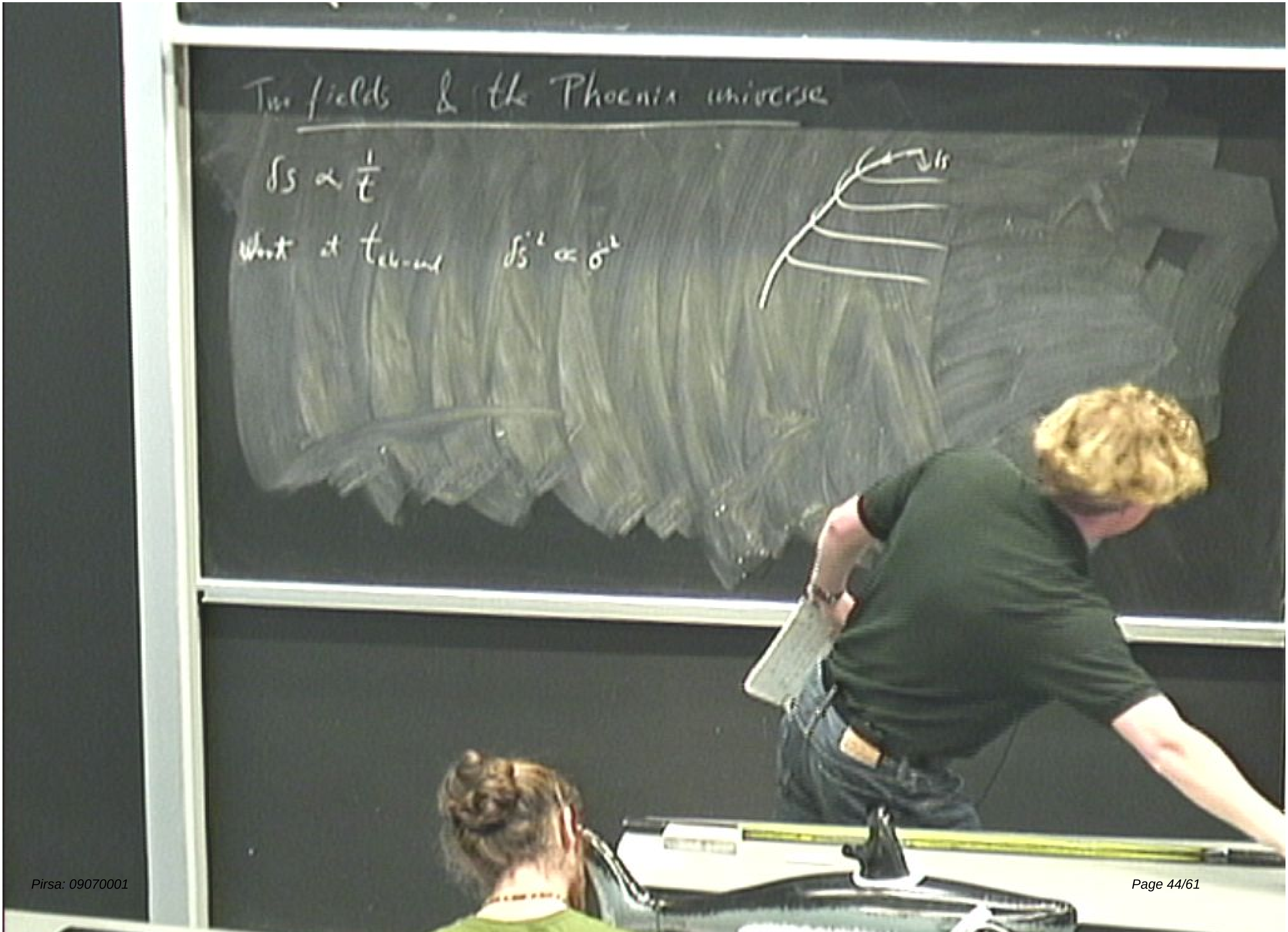

how to evade problems of oscillating model :
- Ωm < Ωcrit potential causes recollapse
↳ also is DE
- chaotic mixmaster avoided due to ekpyrosis

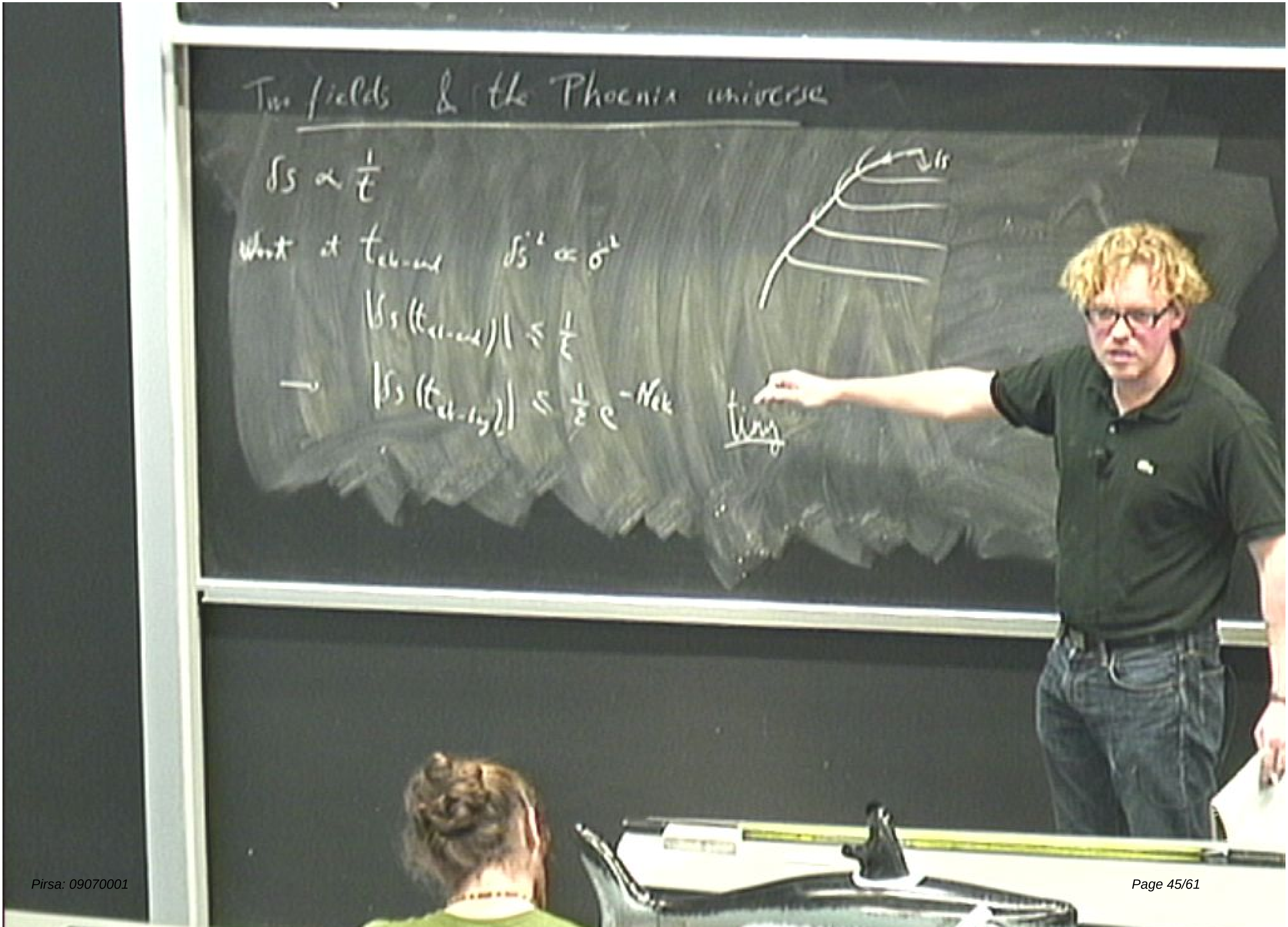

how to evade problems of oscillating model :
- Ωm < Ωcrit potential causes recollapse
↳ also is DE
- chaotic mixmaster avoided due to ekpyrosis
- entropy diluted each cycle

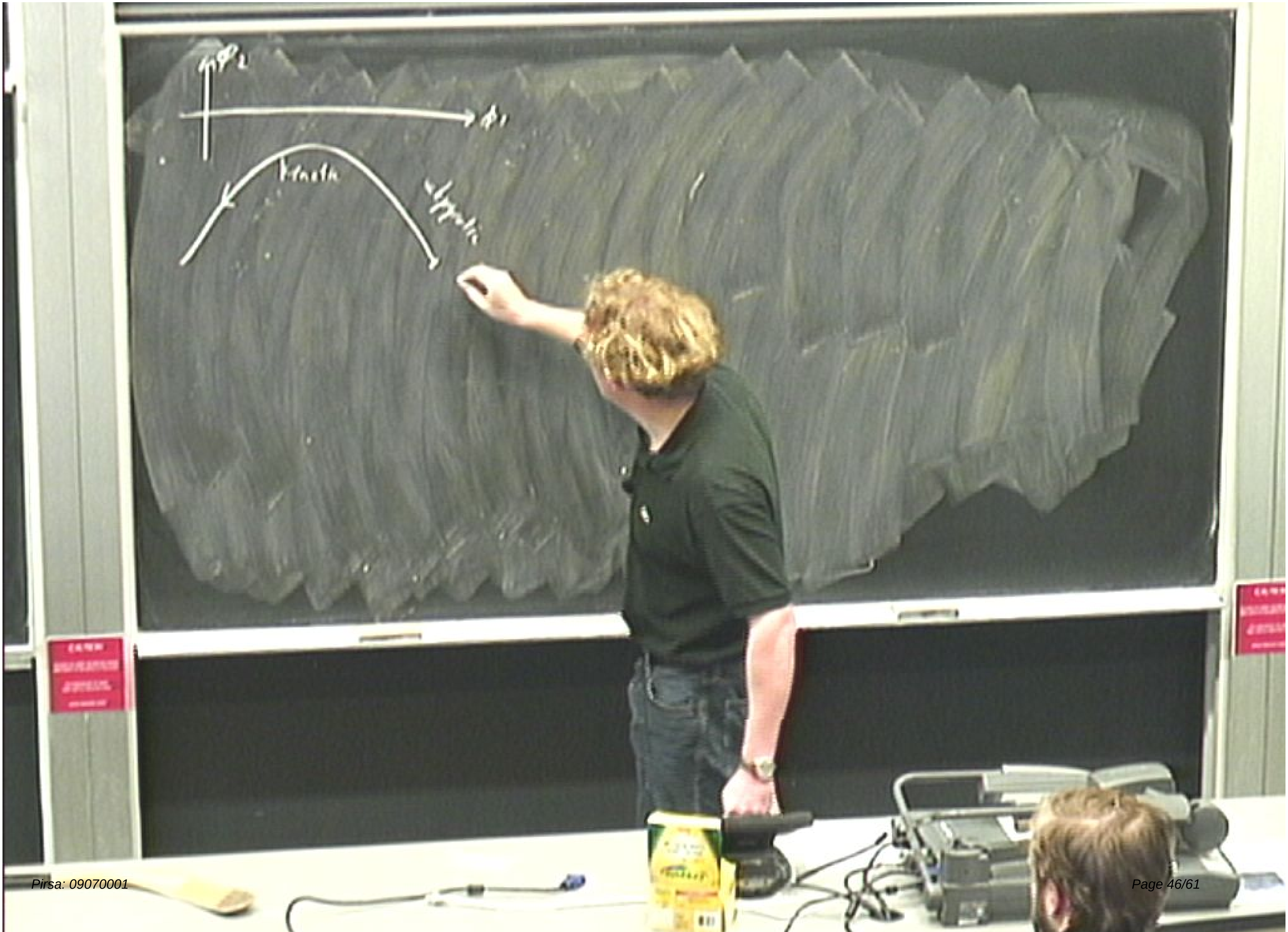

- Ω_m < Ω_crit potential causes recollapse
& also is DE
- Chaotic mixmaster avoided due to ekpyrosis
- entropy diluted each cycle
Single field cyclic model → attractor → stable
H ~ const a ~ e
3H² = ½ φ̇² + V get to H=0 as V<0
Ekpyrotic
a ~ const |H| grows by |V_min / V_today|^½
H ~ 1/t V ~ 1/t²

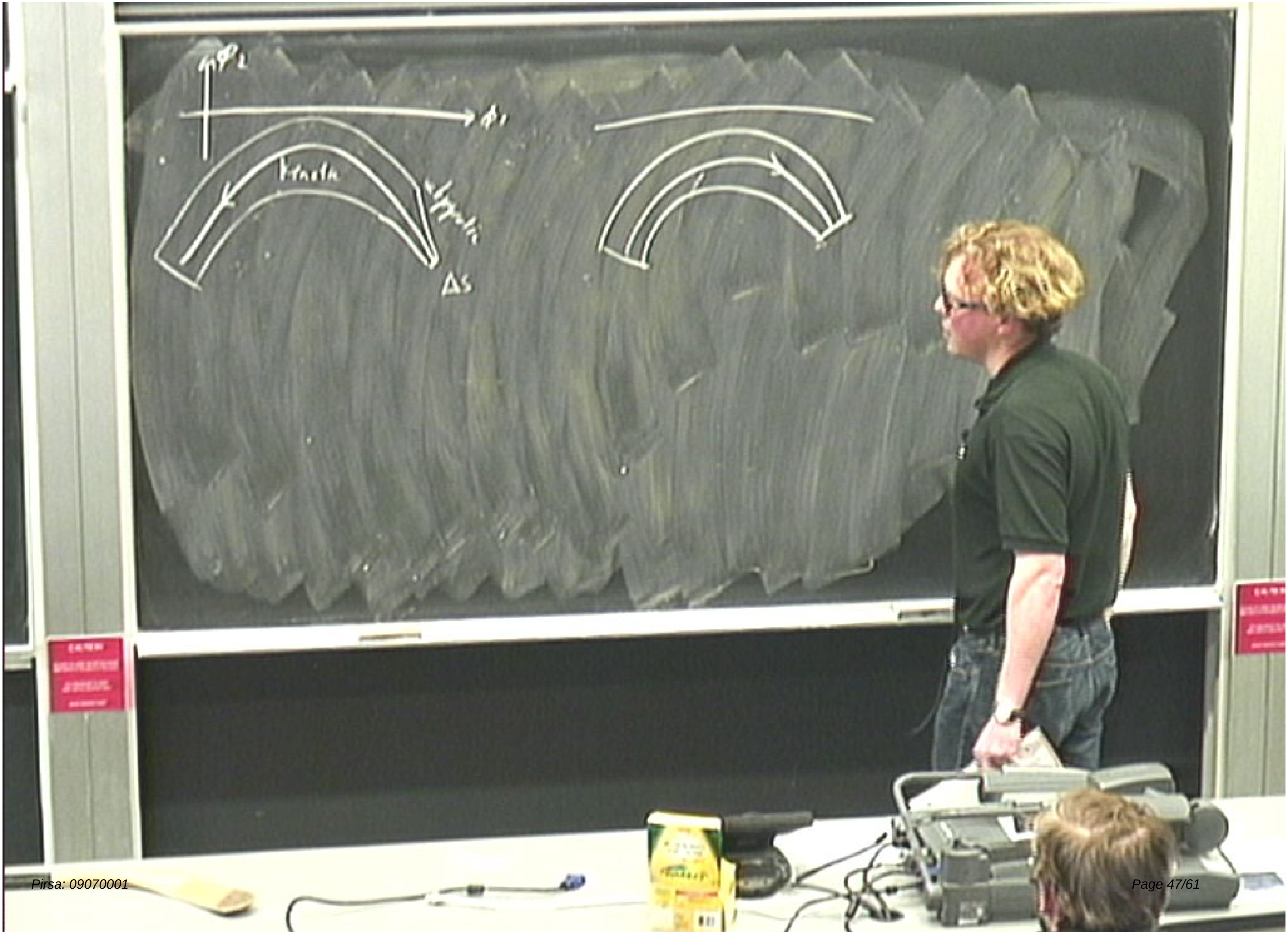

Two fields & the Phoenix universe
$\delta s \propto \frac{1}{t}$

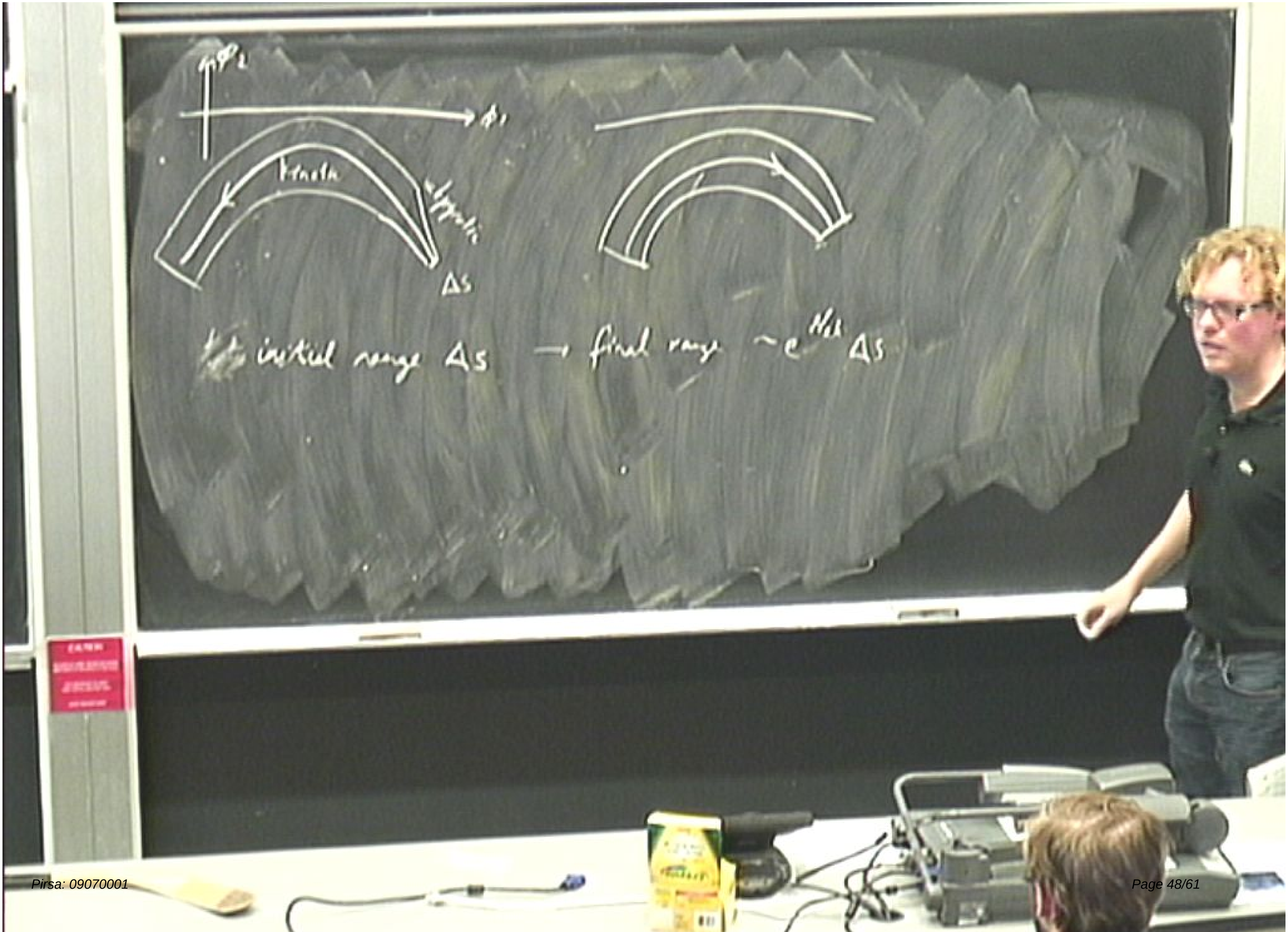

Two fields & the Phoenix universe
δs ∝ 1/t


Two fields & the Phoenix universe
δs ∝ 1/t
What at t_ek-end δs'² ∝ σ'²

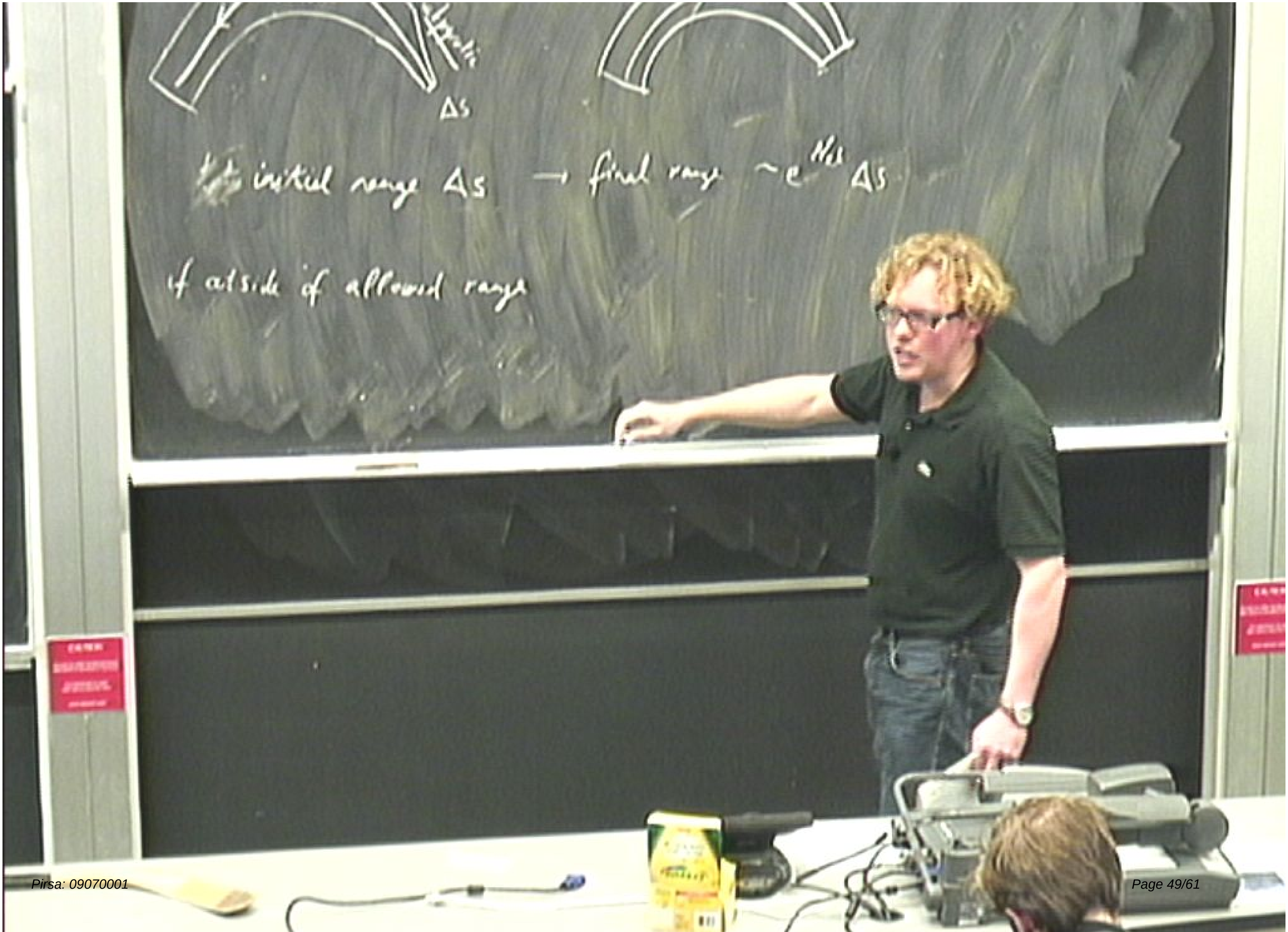

Two fields & the Phoenix universe
δs ∝ 1/t
Wait at t_ek-end δs² ∝ σ²
|δs(t_ek-end)| ≲ 1/ε
→ |δs(t_ek-beg)| ≲ 1/ε e^-Nek tiny

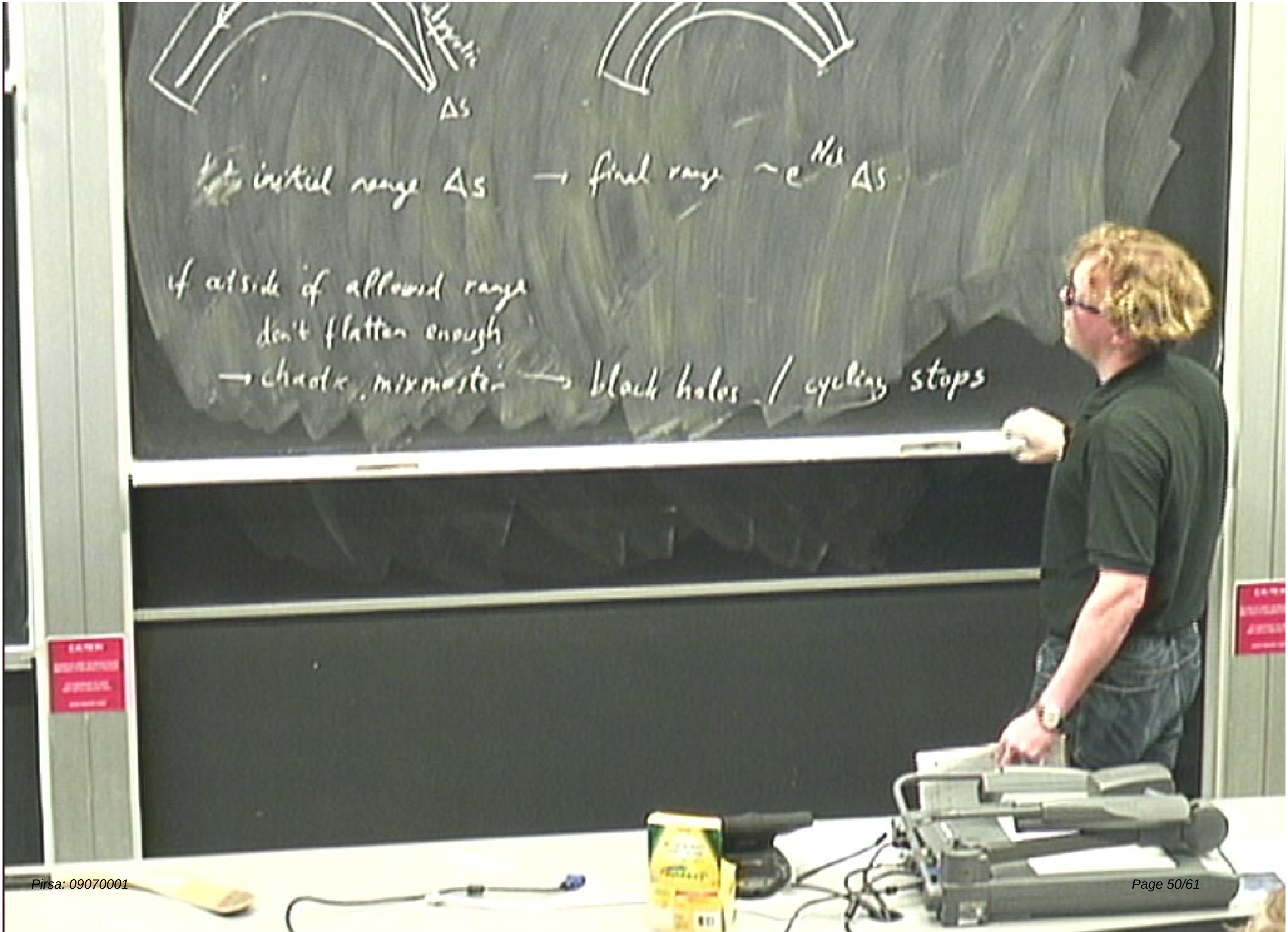


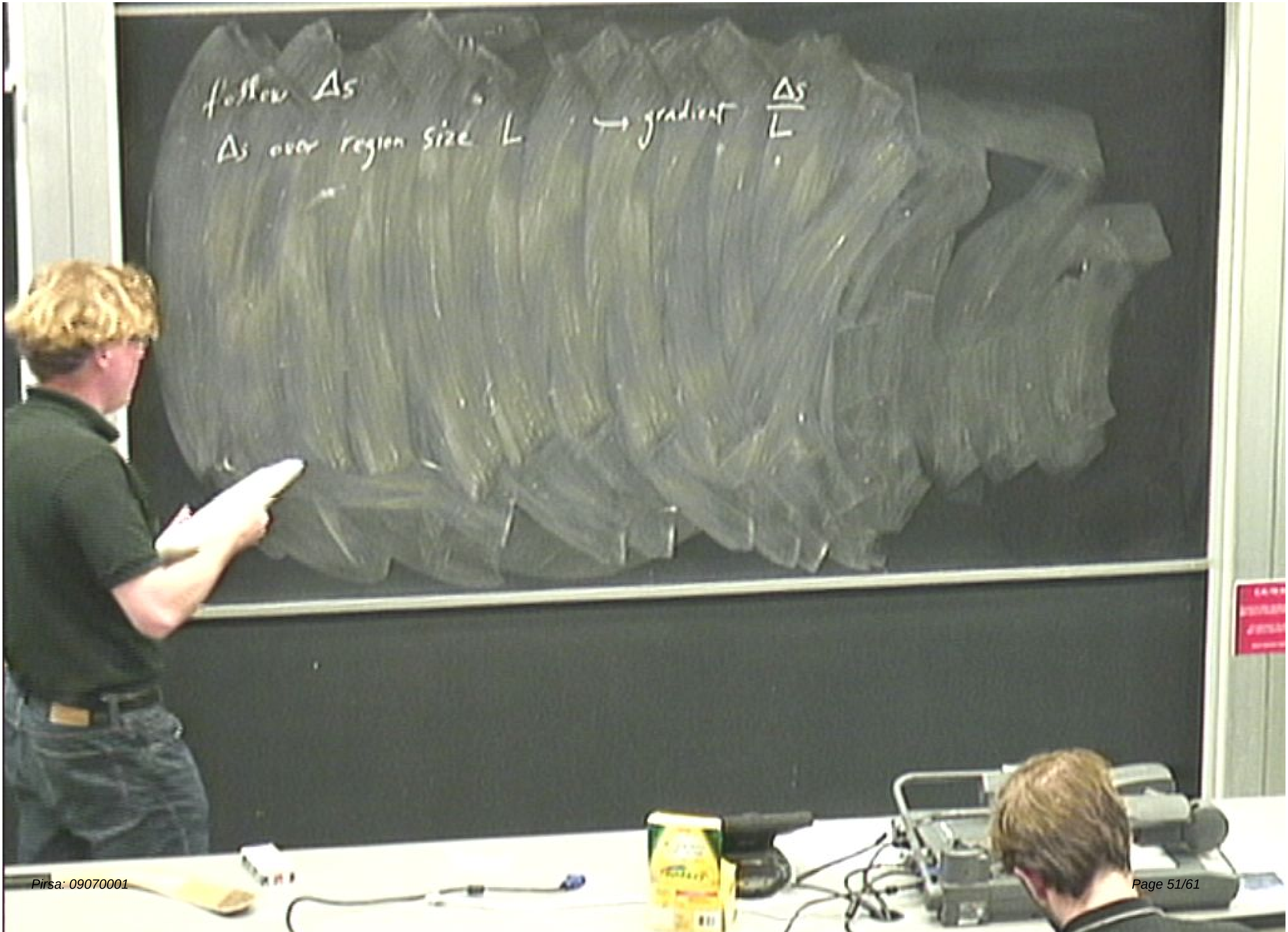


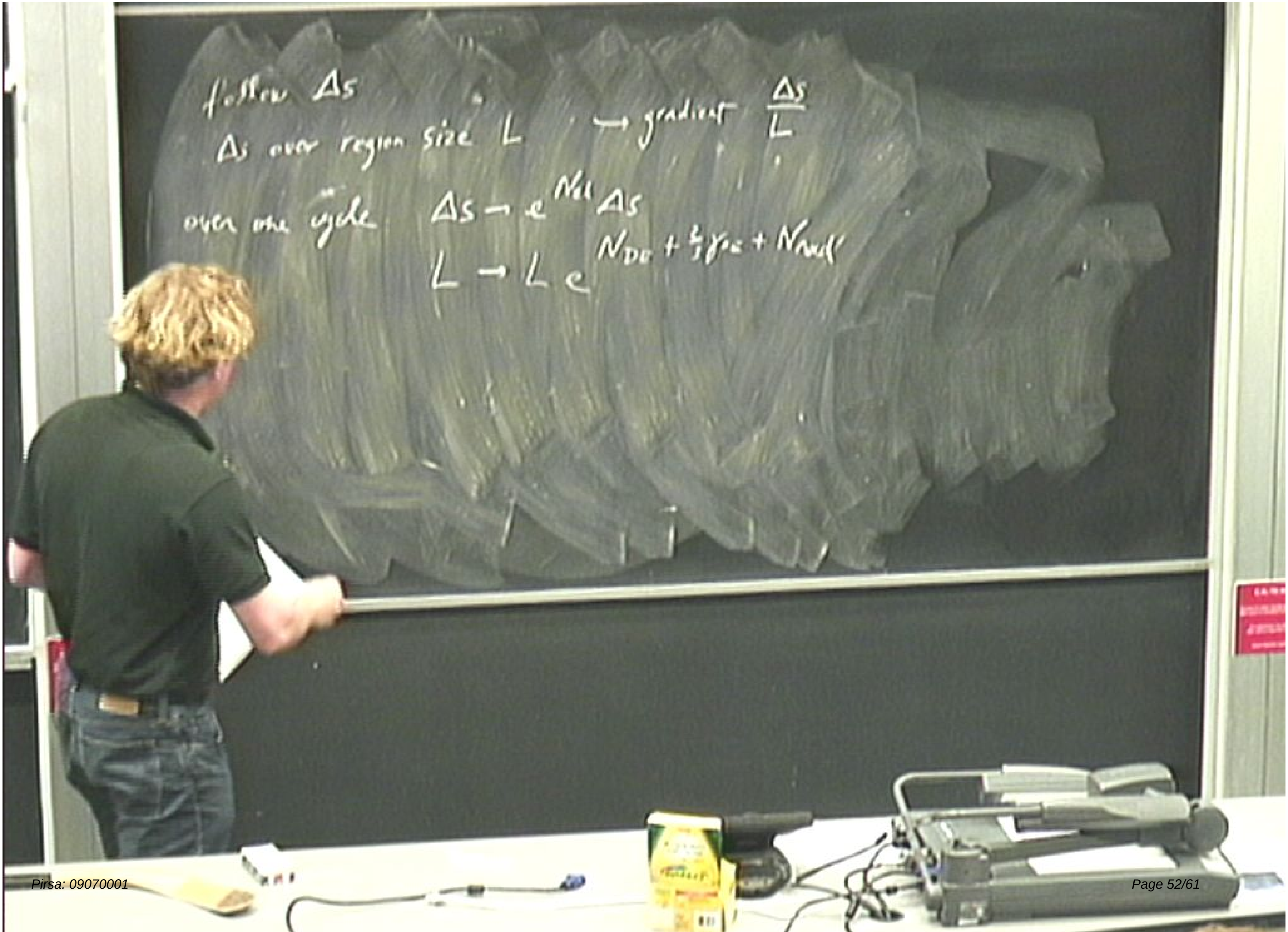


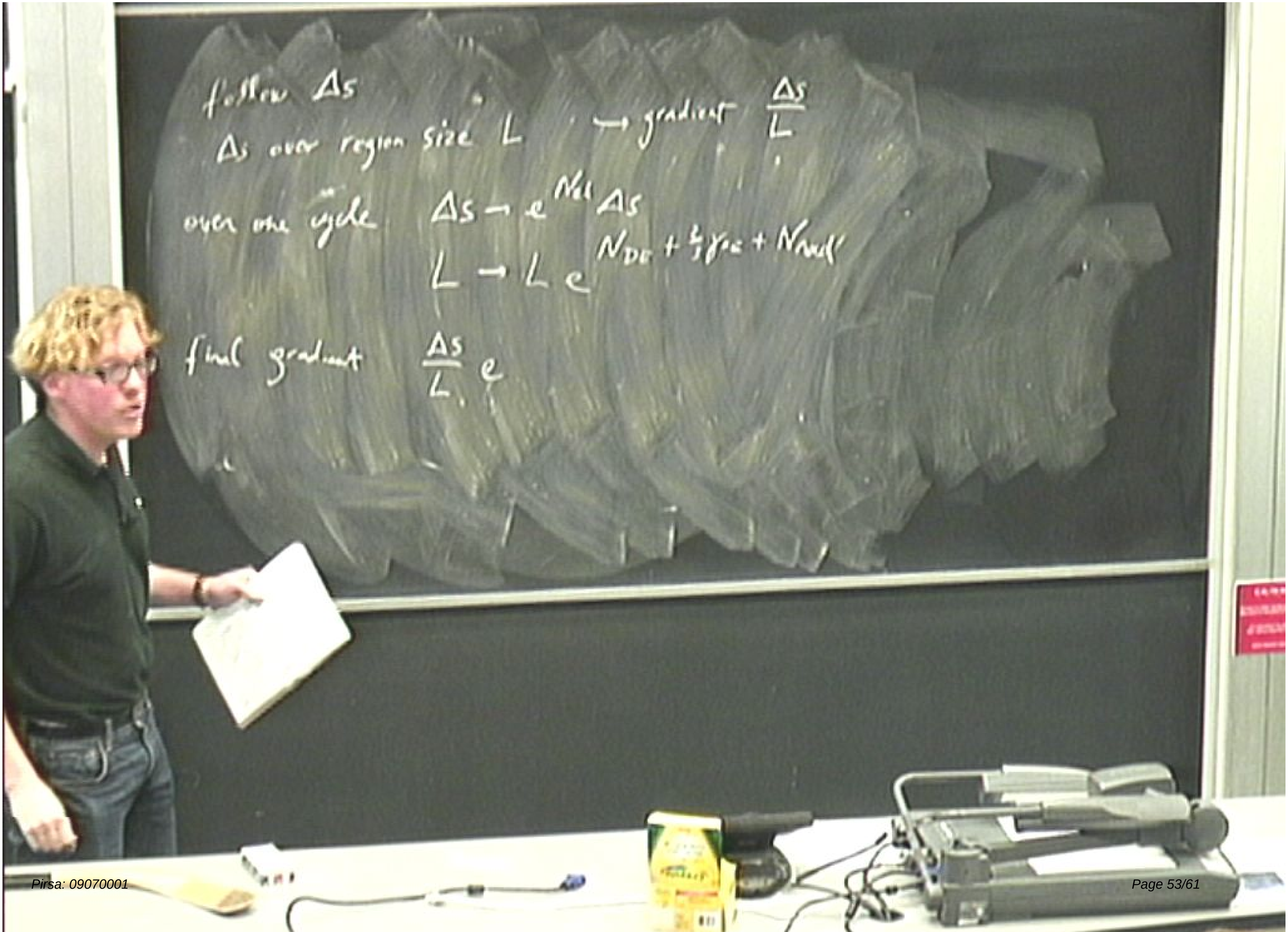
ΔS
initial range ΔS → final range


ΔS
initial range ΔS → final range ~e^λt ΔS
if outside of allowed range


Δs
initial range Δs → final range ~e^Hs Δs
if outside of allowed range
don't flatten enough
→ chaotic, mixmaster → black holes / cycling stops


follow Δs
Δs over region size L → gradient Δs/L


follow Δs
Δs over region size L $\rightarrow$ gradient $\frac{\Delta s}{L}$
over one cycle $\Delta s \rightarrow e^{N_{tl}} \Delta s$
$L \rightarrow L\, e^{N_{DE} + \frac{4}{3} y_{re} + N_{rad}}$


follow Δs
Δs over region size L → gradient Δs/L
over one cycle Δs → e Δs
L → L e
final gradient Δs/L e

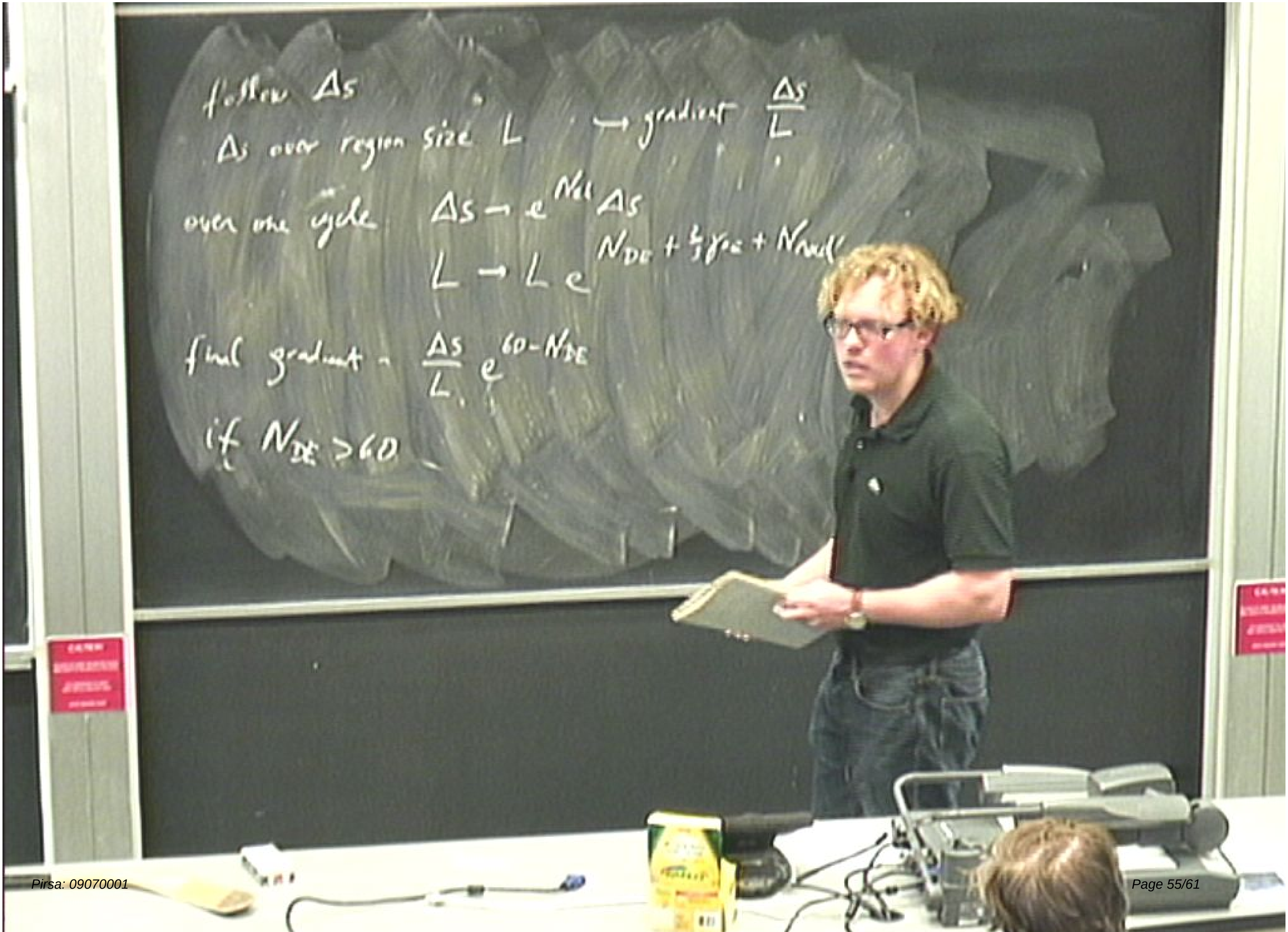
follow Δs

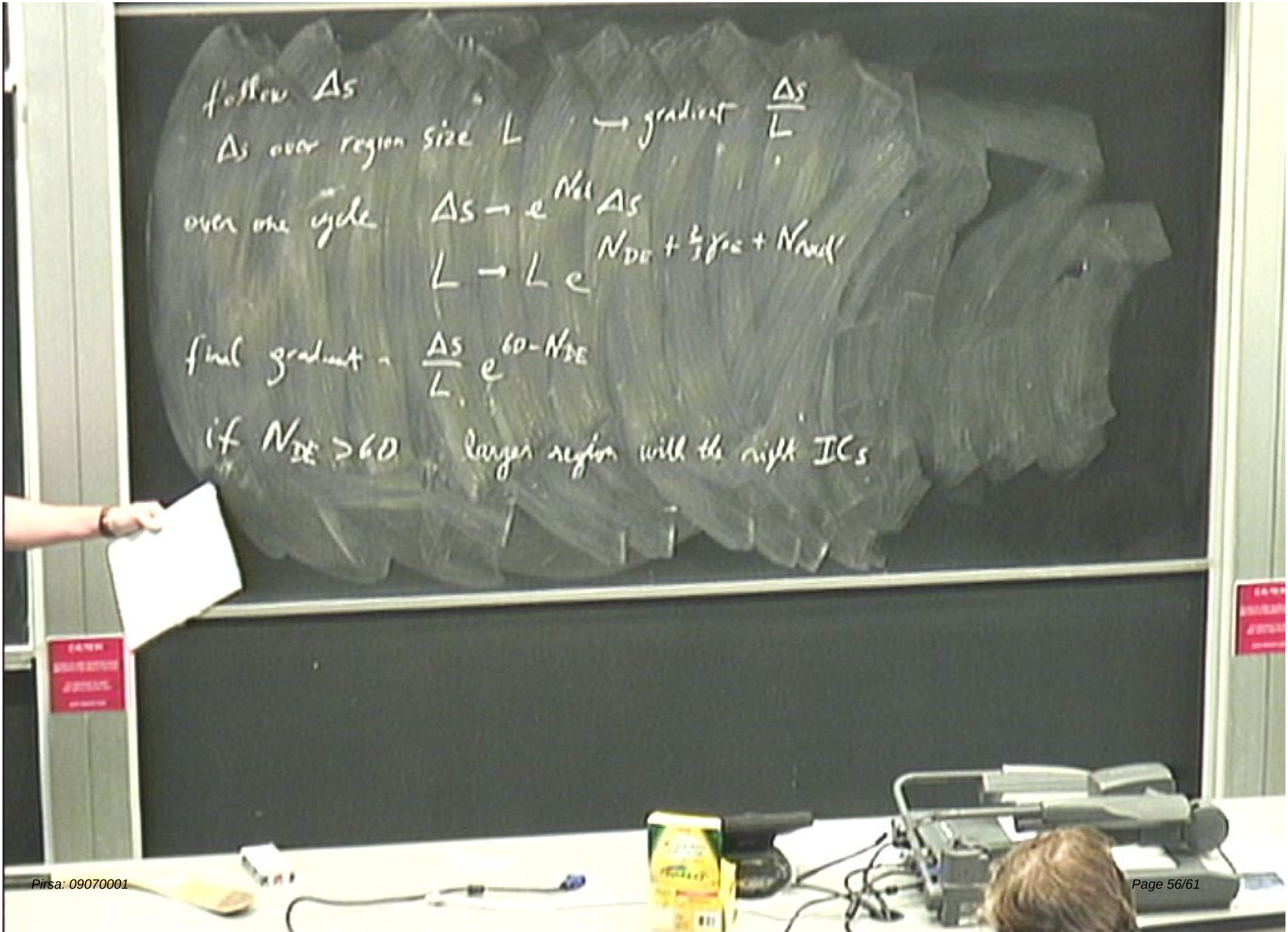
Δs over region size L $\rightarrow$ gradient $\frac{\Delta s}{L}$

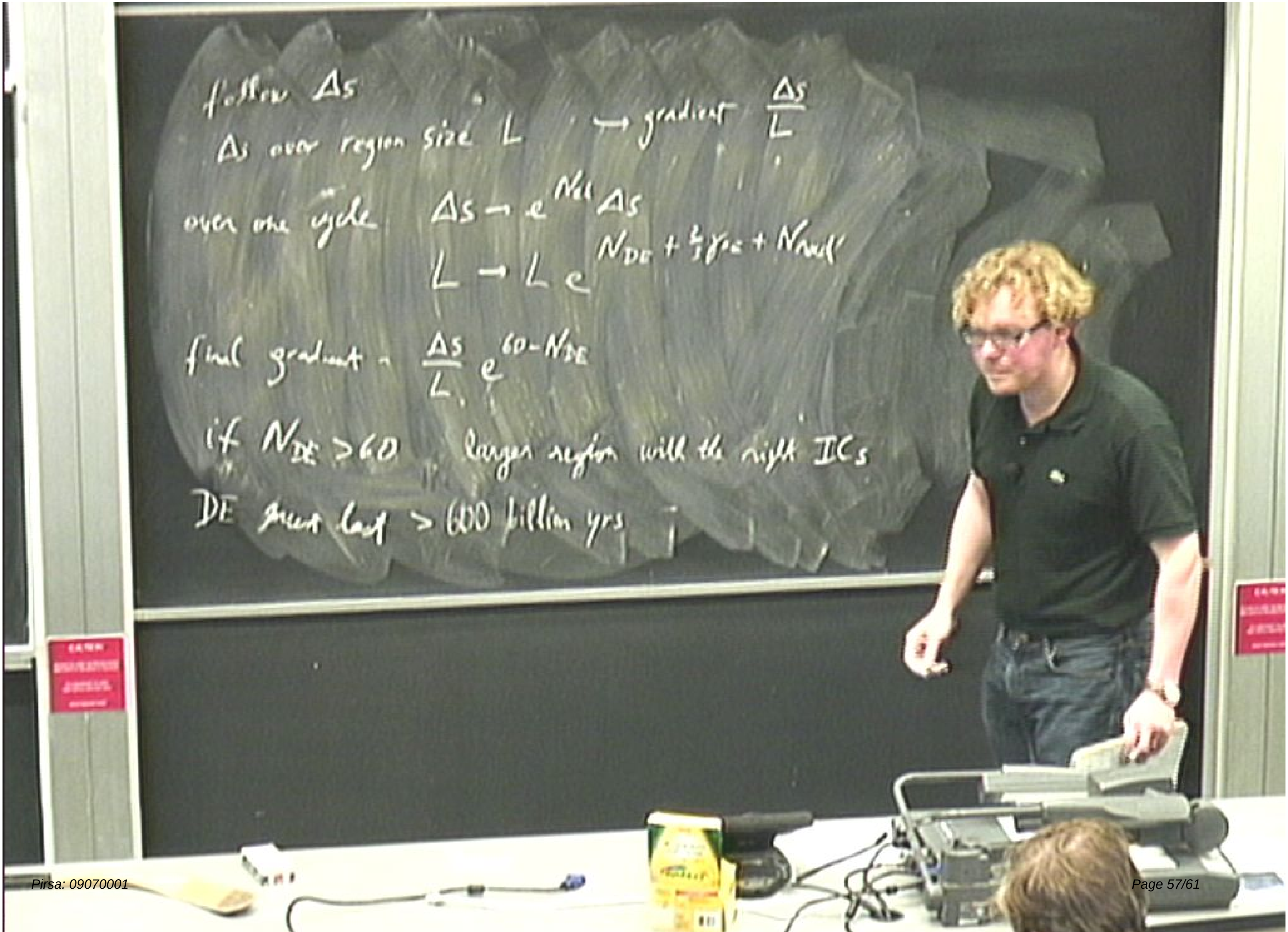
over one cycle $\Delta s \rightarrow e^{N_{tot}} \Delta s$

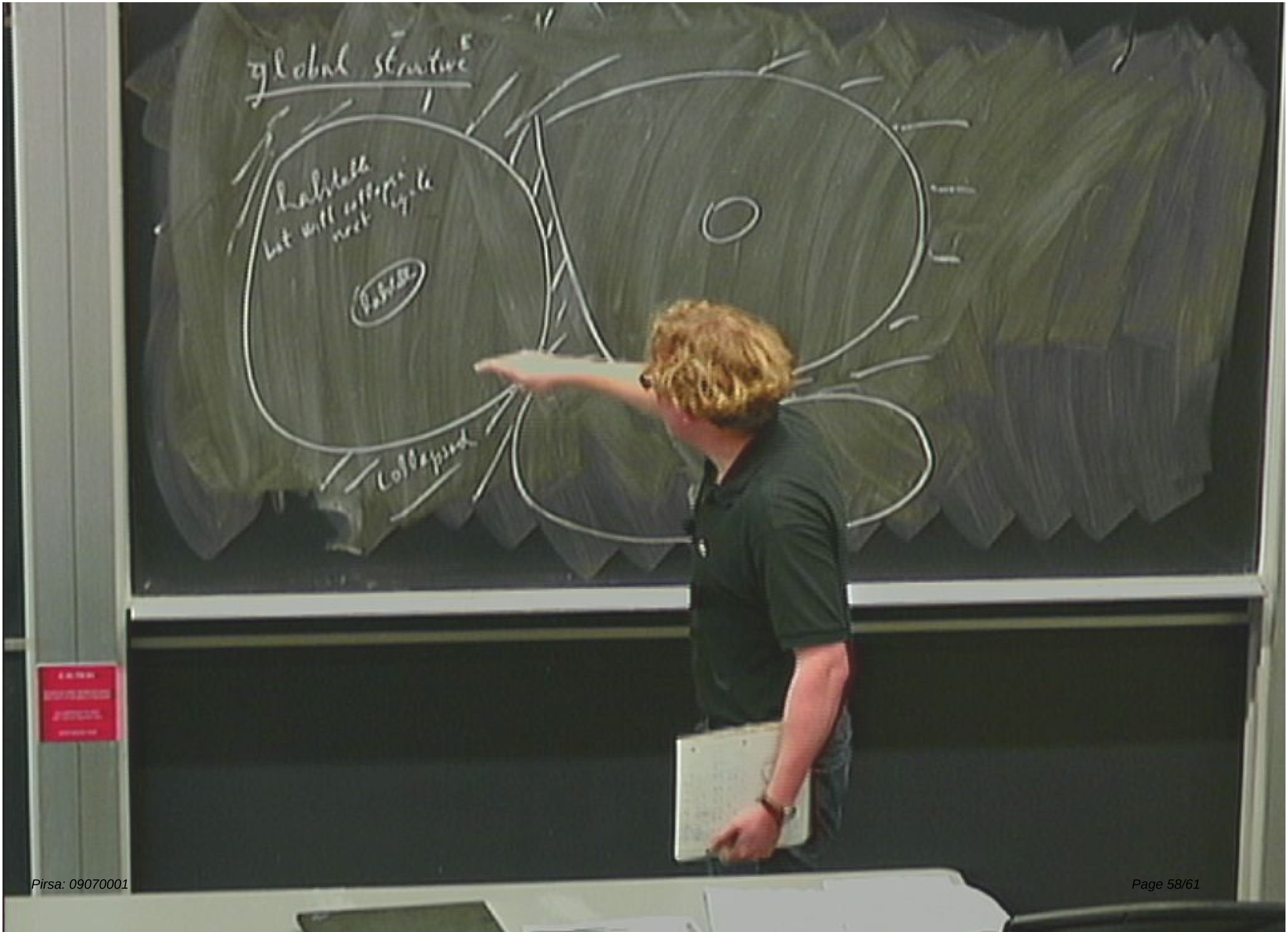
$L \rightarrow L\, e^{N_{DE} + \frac{1}{3}\gamma_{re} + N_{radl}}$

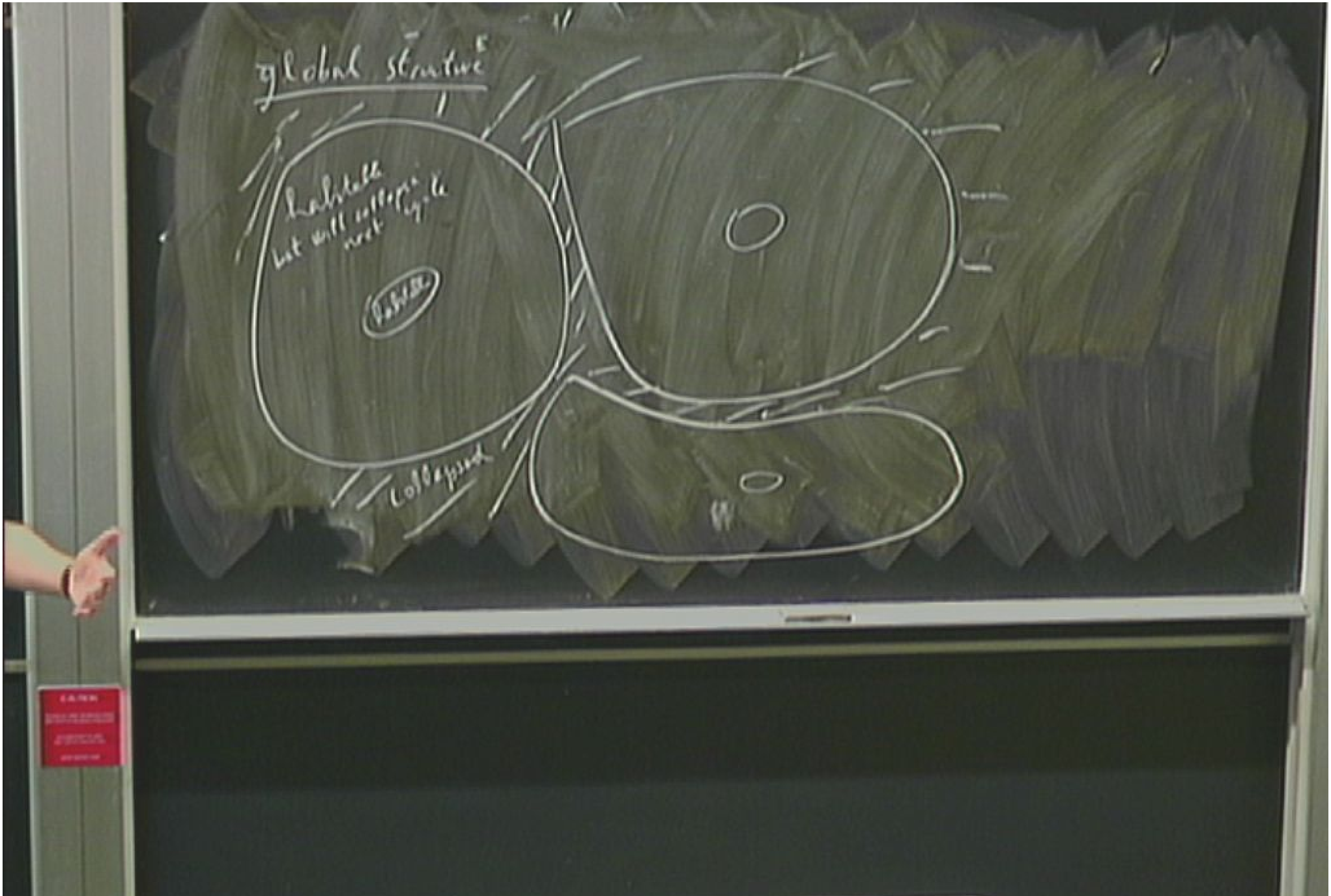
final gradient $\sim \frac{\Delta s}{L}\, e^{60 - N_{DE}}$

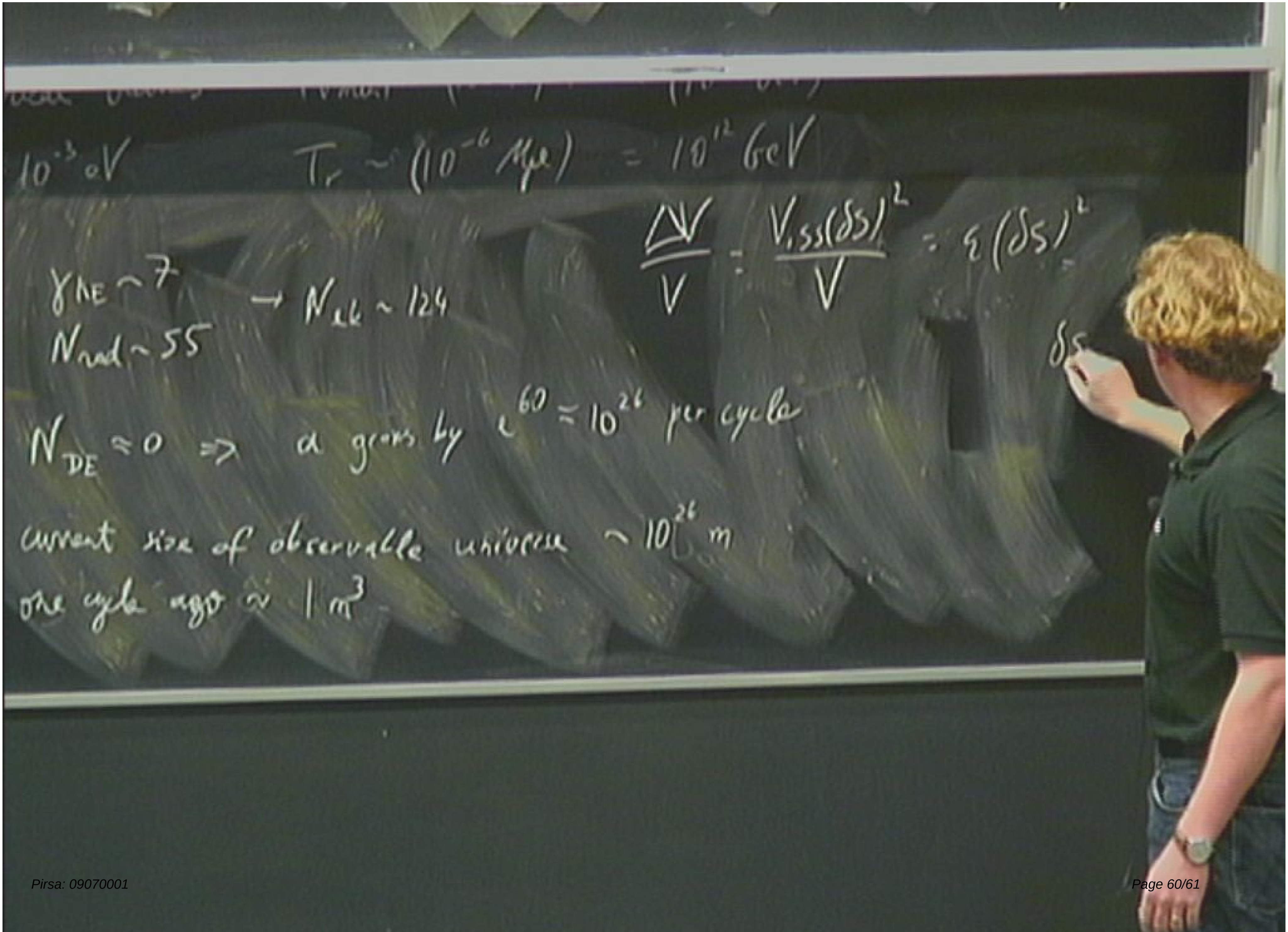

follow Δs
Δs over region size L → gradient Δs/L
over one cycle Δs → e Δs
L → L e
final gradient ~ Δs/L e^60-N_DE
if N_DE > 60

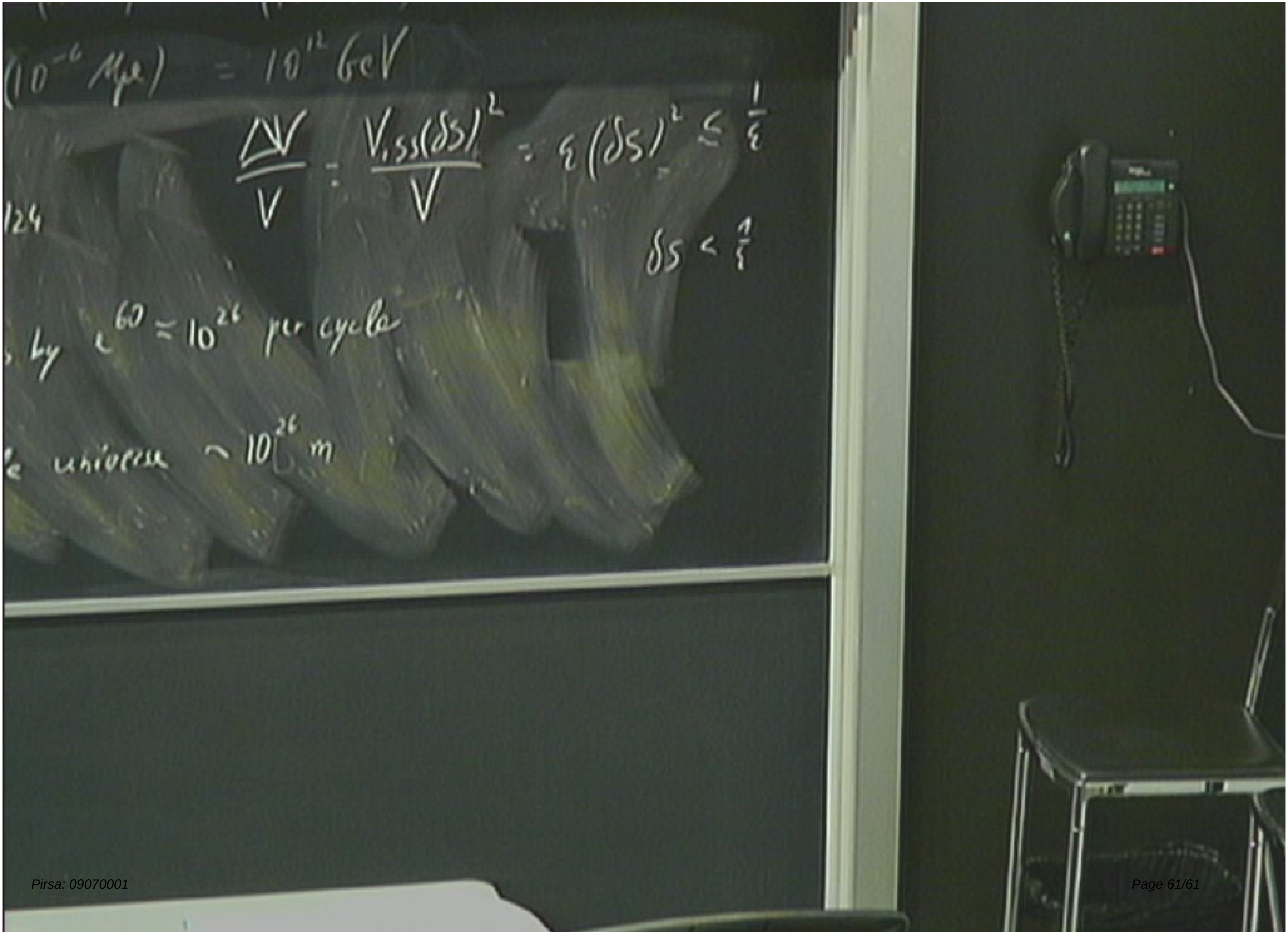

follow Δs
Δs over region size L → gradient $\frac{\Delta s}{L}$
over one cycle $\Delta s \to e^{N_{dS}} \Delta s$
$L \to L\, e^{N_{DE} + \frac{2}{3} N_{osc} + N_{rad}}$
final gradient ~ $\frac{\Delta s}{L} e^{60 - N_{DE}}$
if $N_{DE} > 60$ larger region with the right ICs


follow Δs
Δs over region size L → gradient Δs/L
over one cycle Δs → e^{N_tot} Δs
L → L e^{N_DE + ... + N_infl}
final gradient ~ Δs/L e^{60 - N_DE}
if N_DE > 60 larger region with the right ICs
DE must last > 600 billion yrs


global structure
collapsed


global structure
habitable
collapsed


10^-3 eV
T_r ~ (10^-6 M_pl) = 10^12 GeV
ΔV/V = V,ss(δs)^2/V = ε(δs)^2
γ_KE ~ 7
N_rad ~ 55
→ N_ek ~ 124
δs
N_DE ≈ 0 ⇒ a grows by e^60 ≈ 10^26 per cycle
current size of observable universe ~ 10^26 m
one cycle ago ≈ 1 m^3



$(10^{-6} M_{pl}) = 10^{12}$ GeV
$\frac{\Delta V}{V} = \frac{V_{,ss}(\delta s)^2}{V} = \epsilon (\delta s)^2 \leq \frac{1}{\epsilon}$
124
$\delta s < \frac{1}{\epsilon}$
by $e^{60} \simeq 10^{26}$ per cycle
universe $\sim 10^{26}$ m