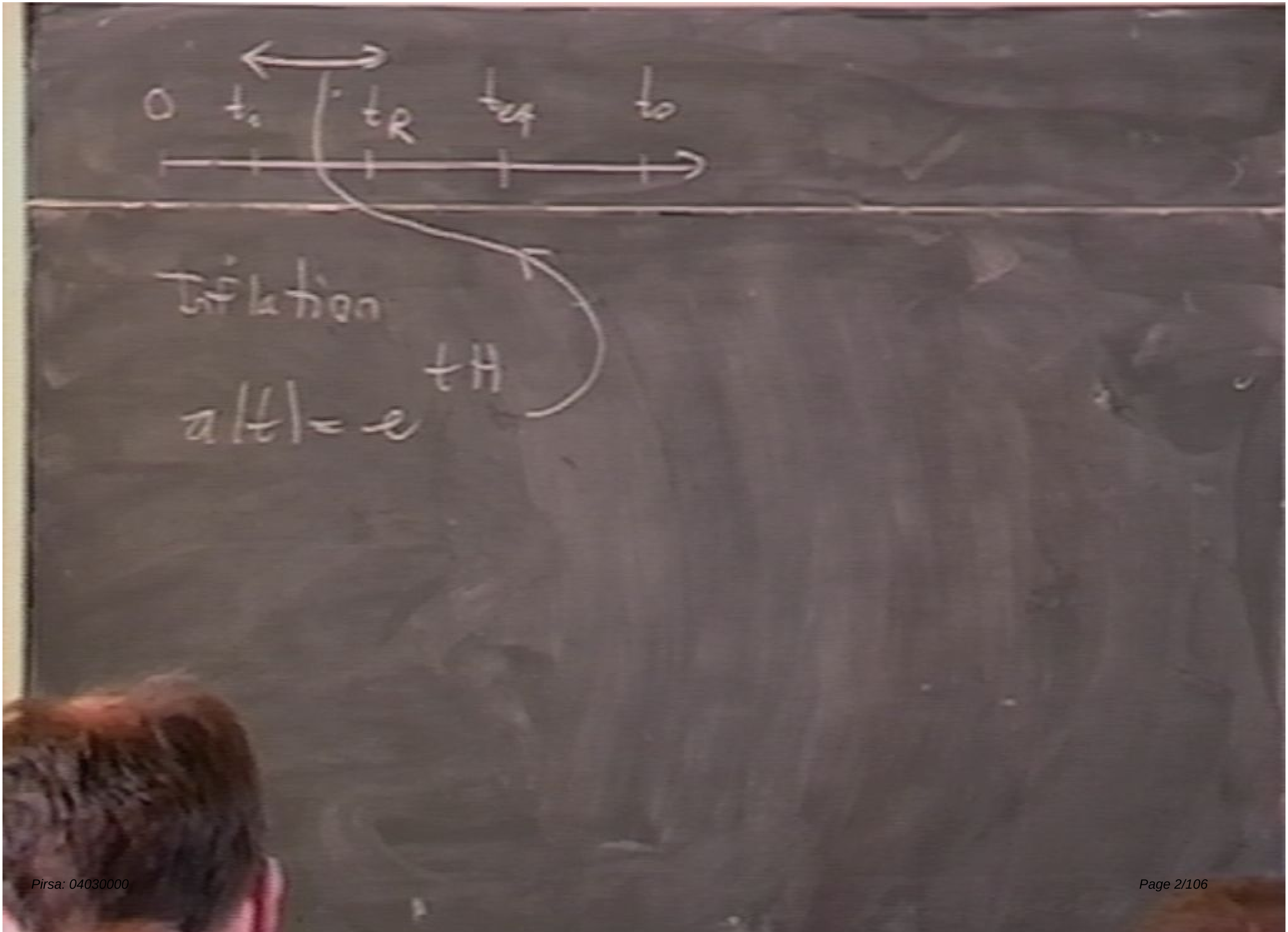
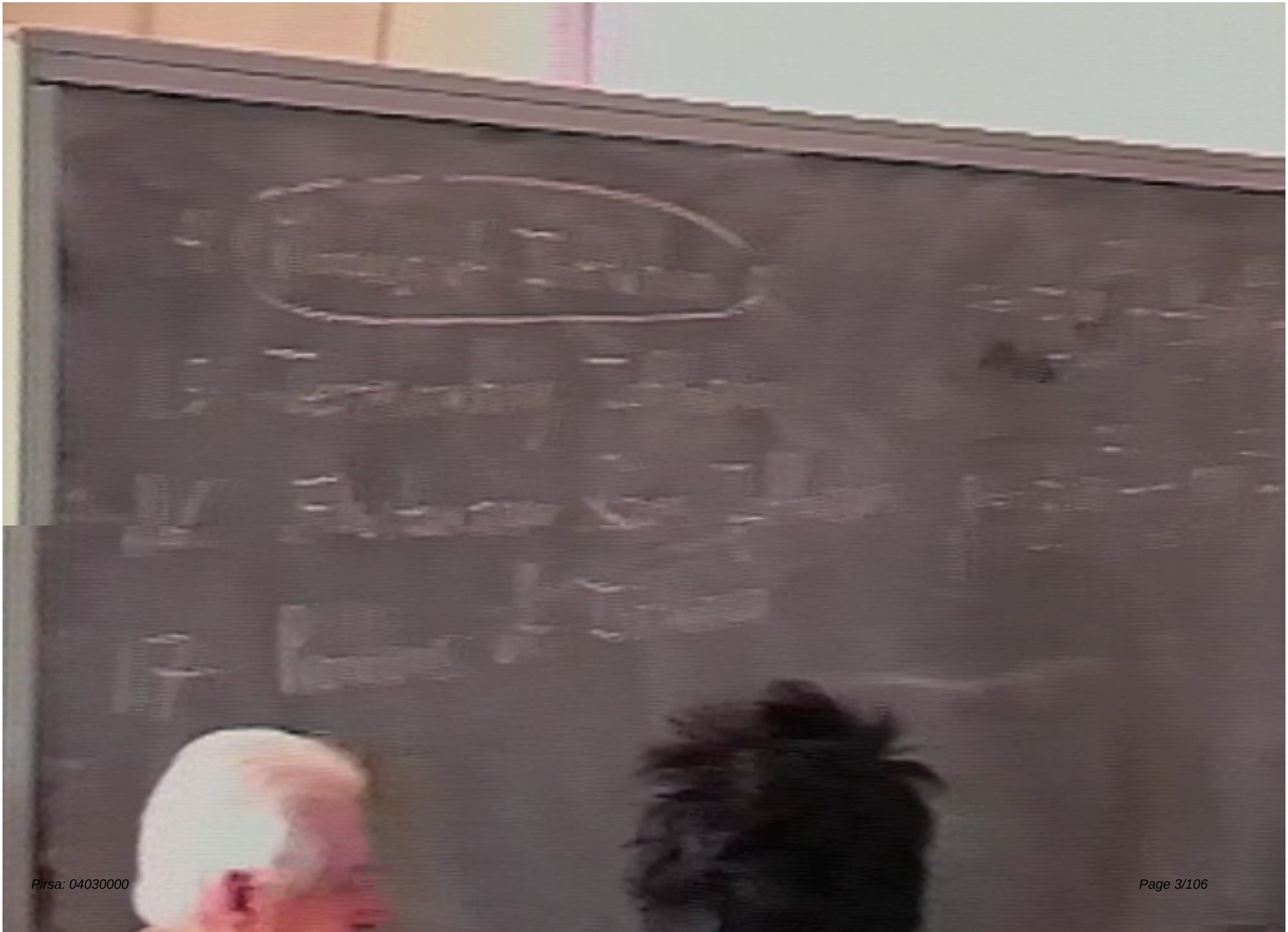
Title: Challenges for Theories of Fundamental Physics from Cosmology

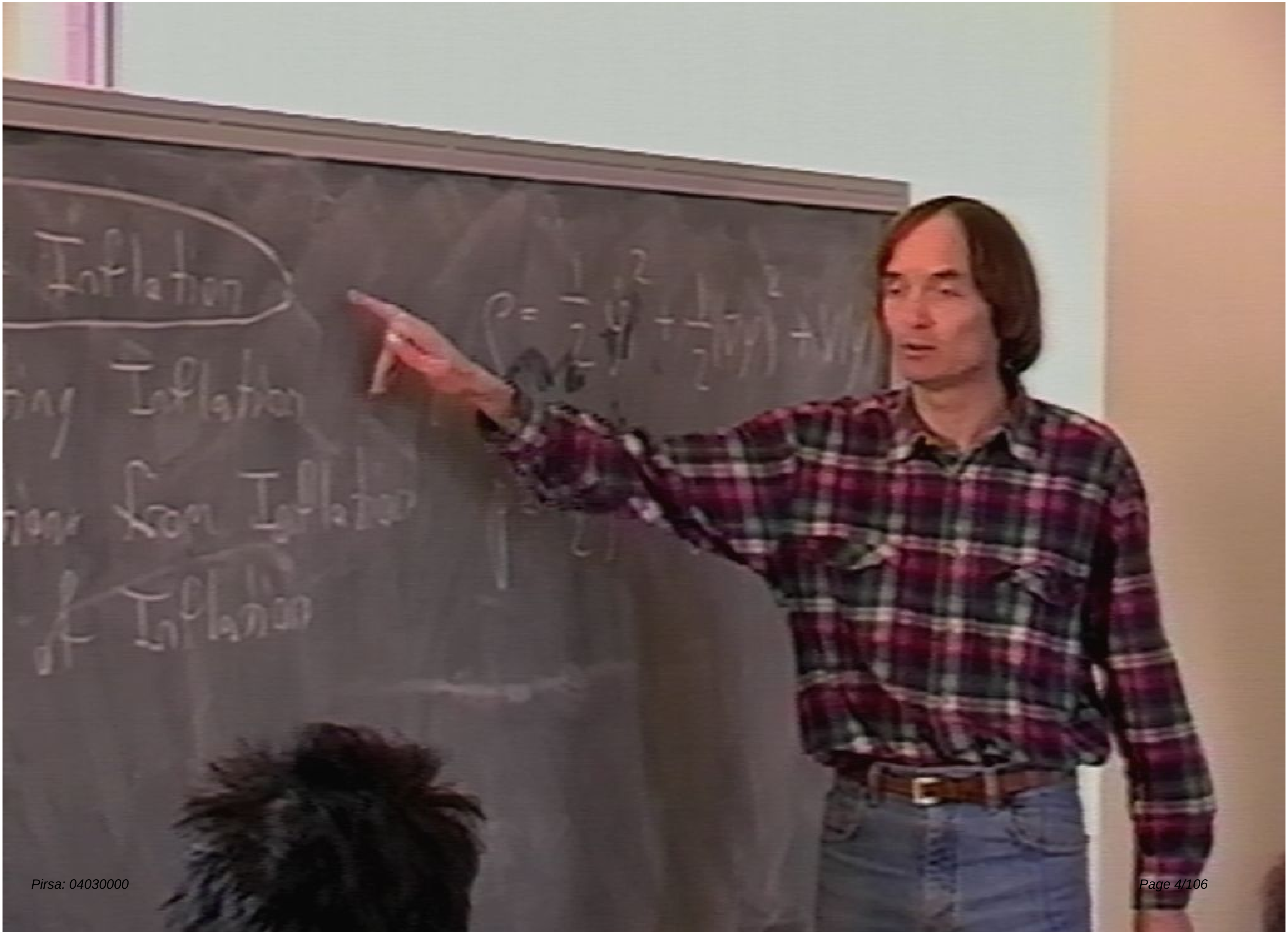
Date: Mar 09, 2004 12:00 PM

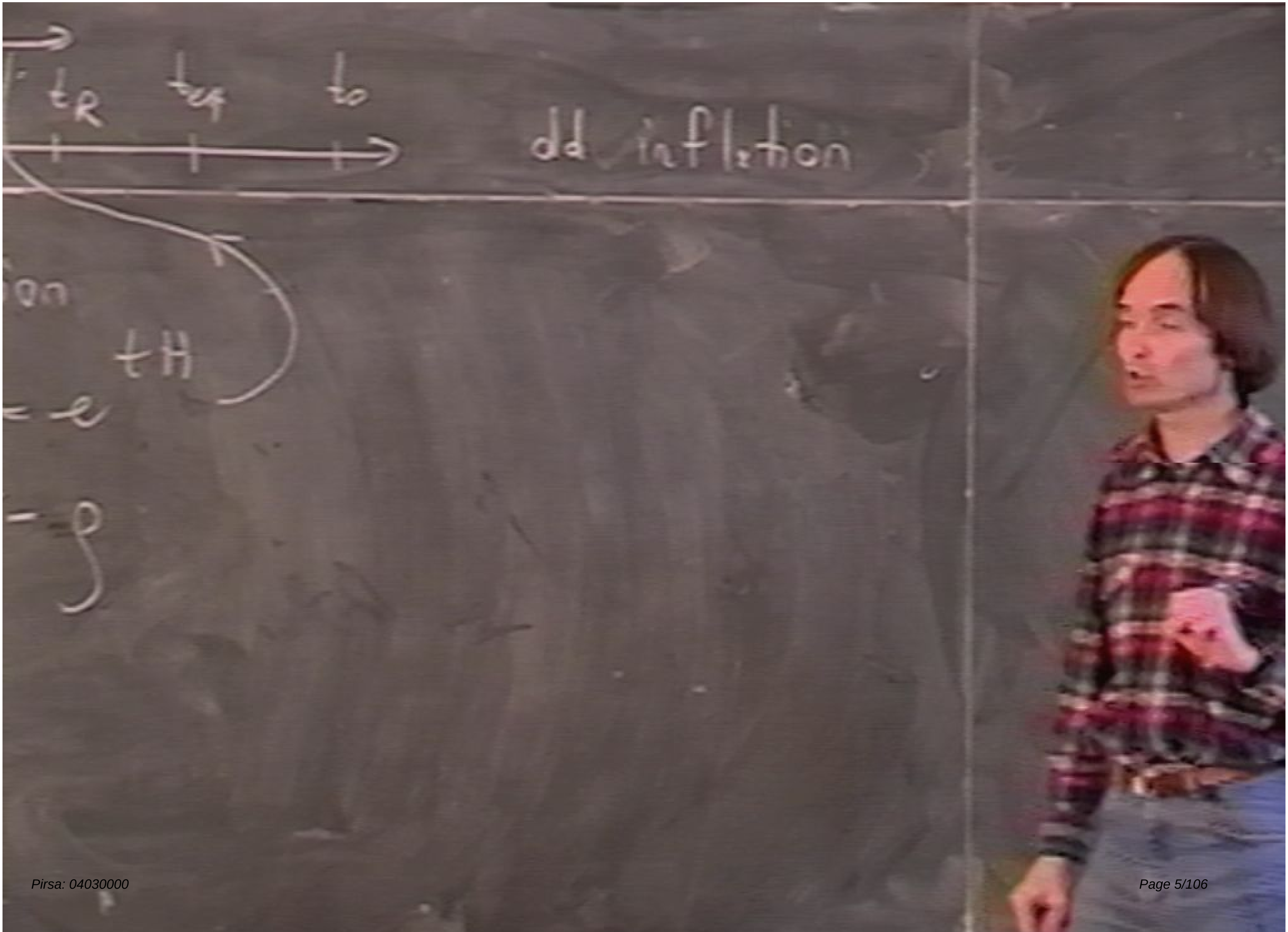
URL: http://pirsa.org/04030000

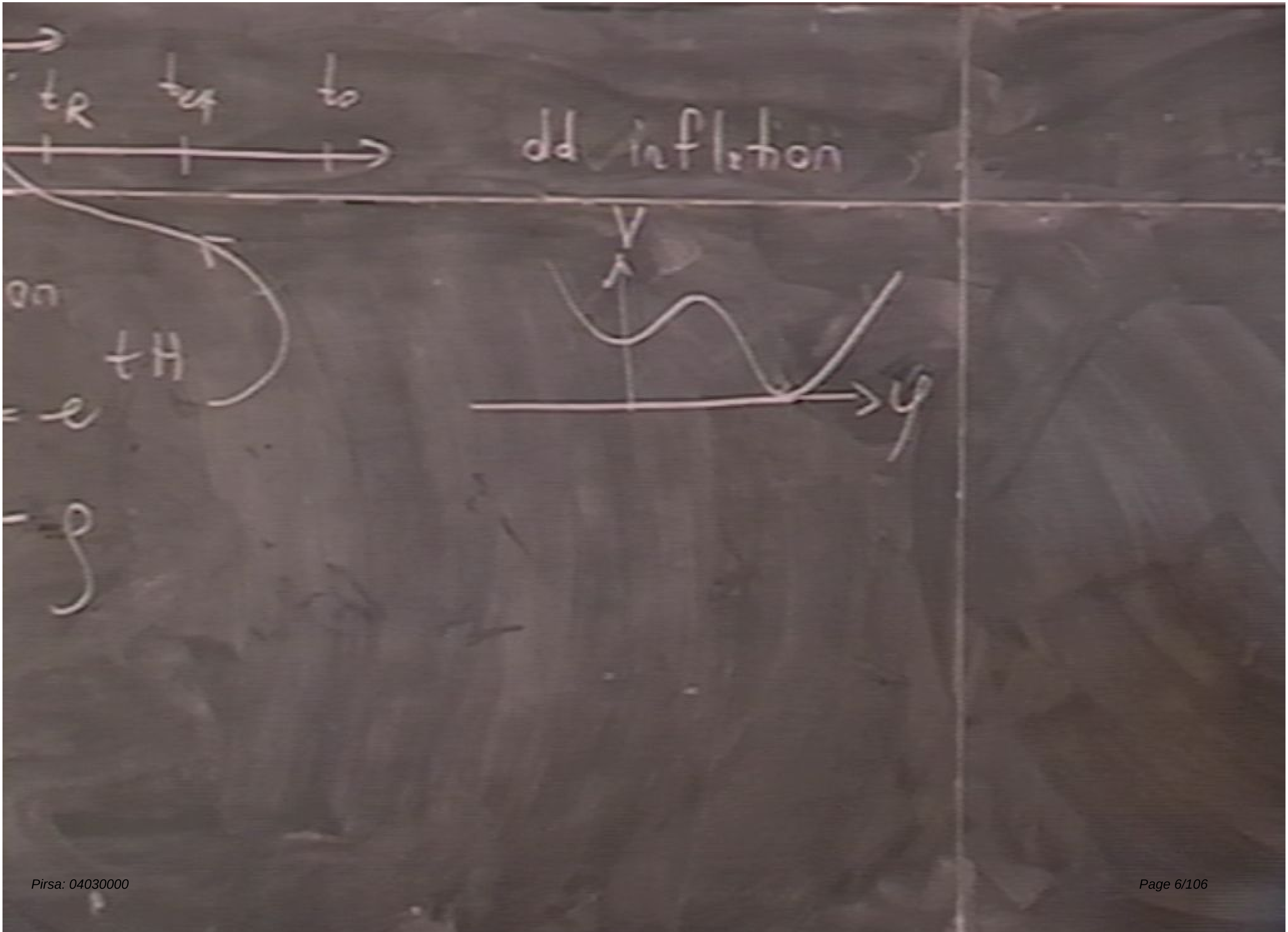
Abstract:


0 t_i t_R t_{eq} t_0
Inflation
$a(t) = e^{tH}$

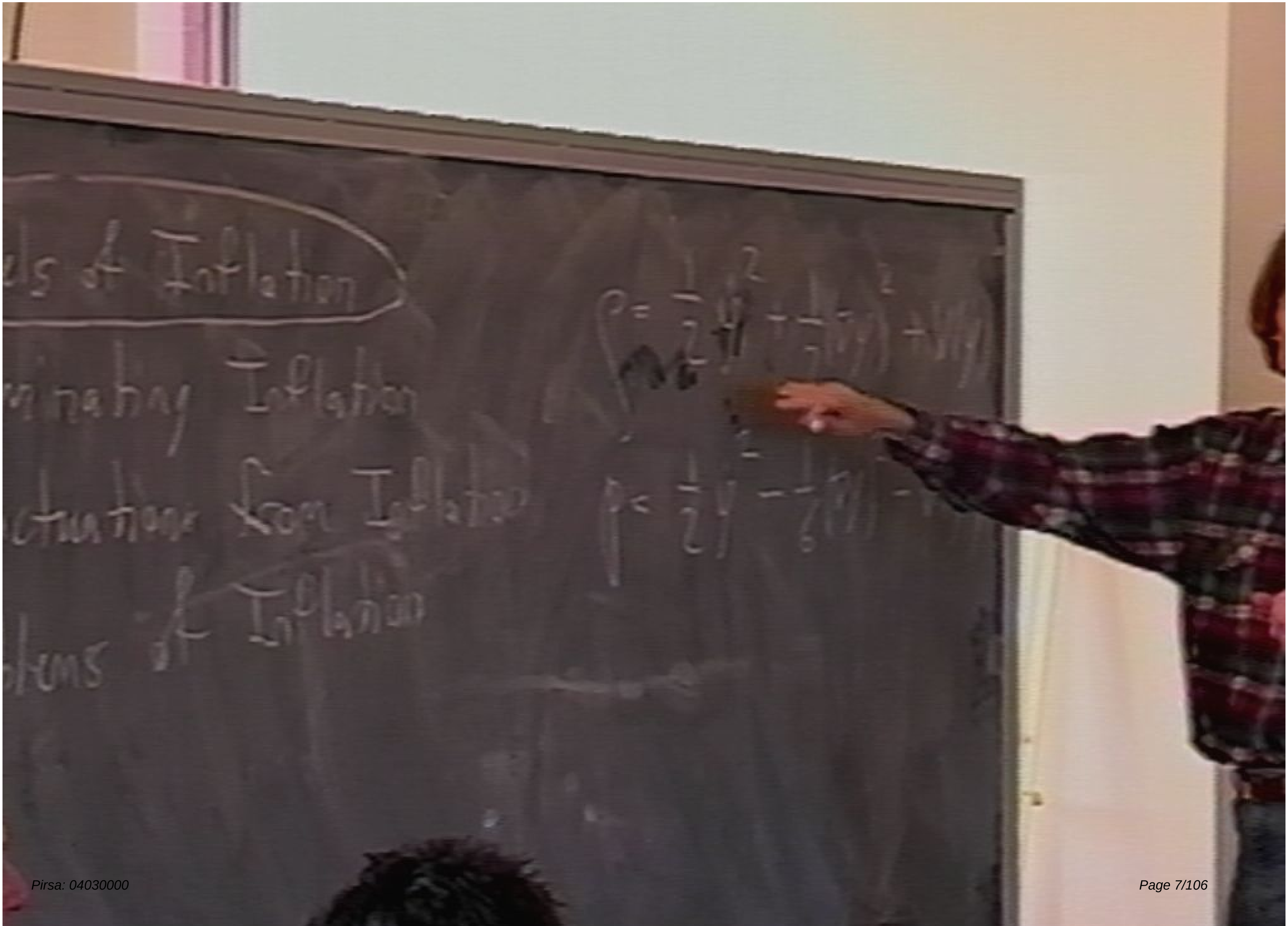


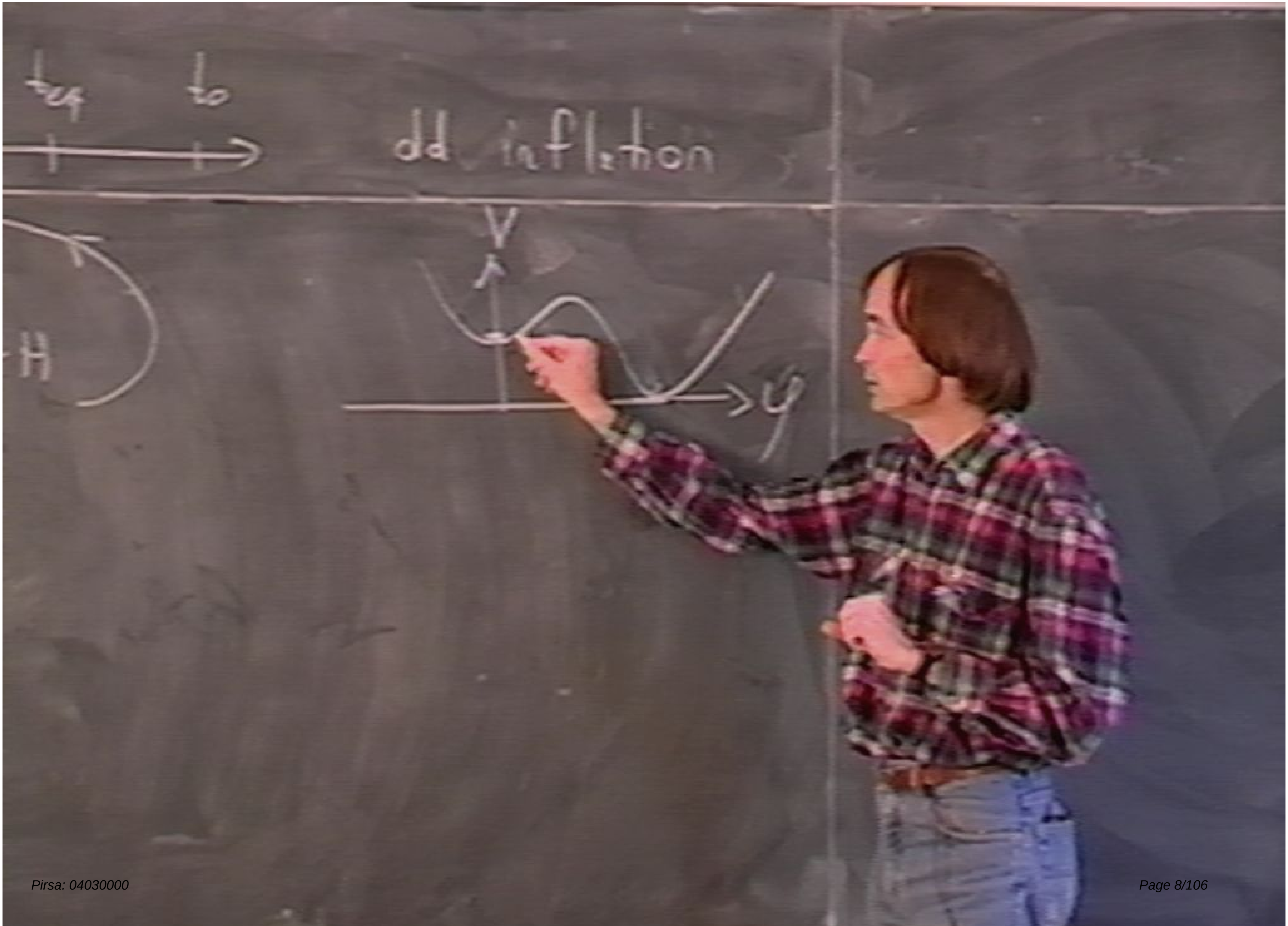

Inflation
Inflation
from Inflation
Inflation
$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$

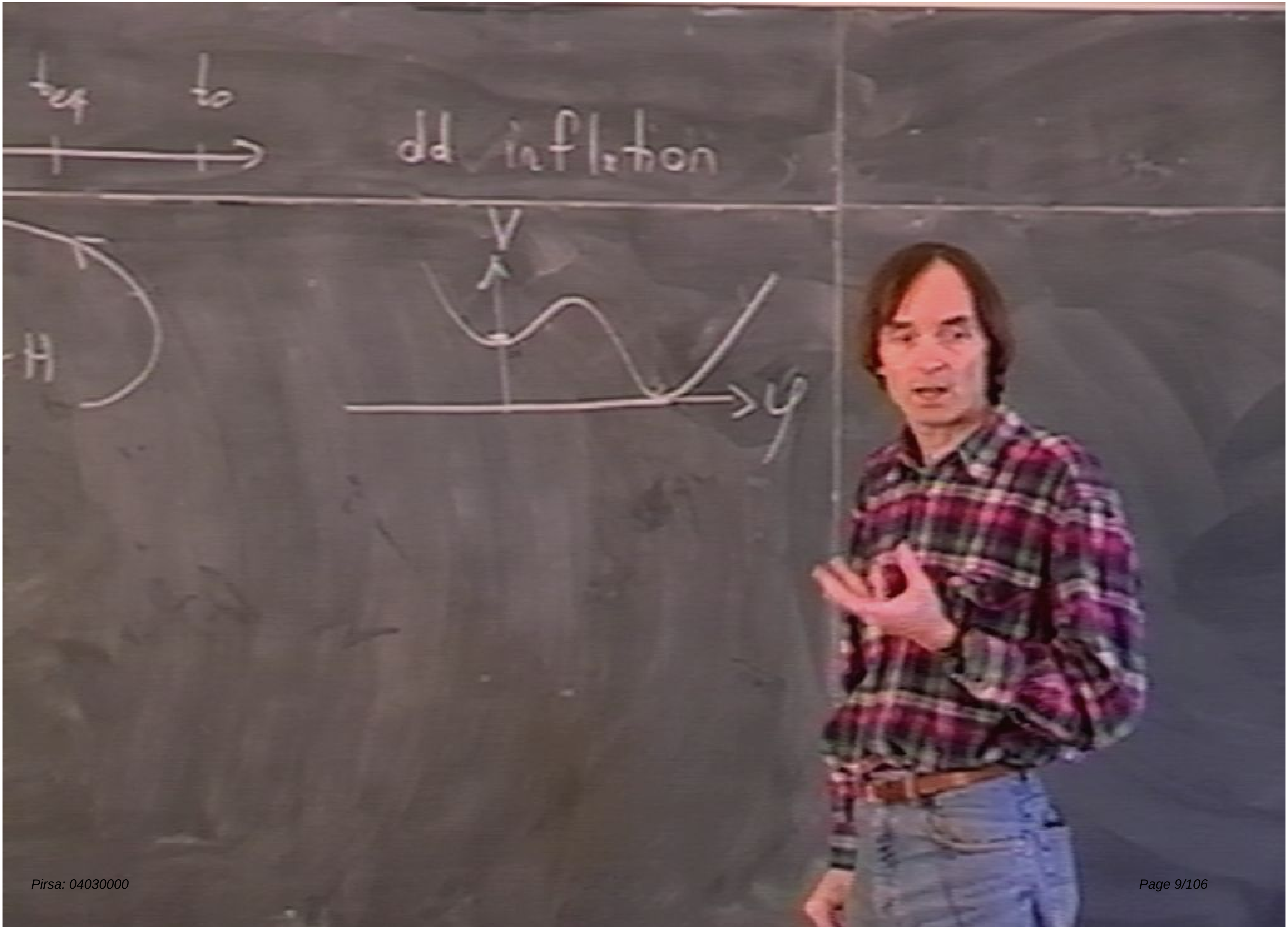

t_R
t_eq
t_0
inflation
tH



t_R
t_{eq}
t_0
inflation
V
φ
tH


els of Inflation
Inflation
ctuations from Inflation
blems of Inflation

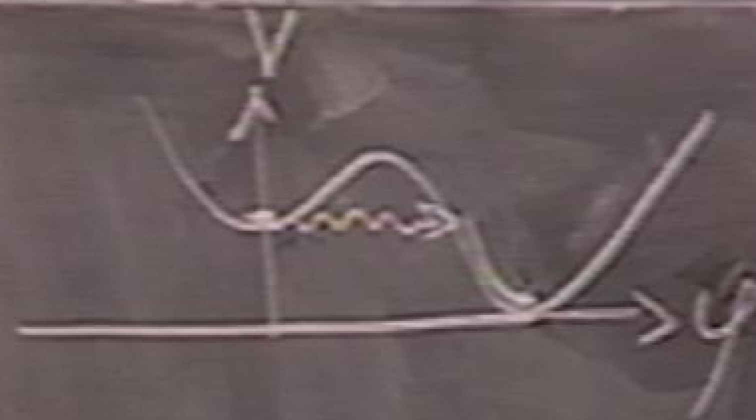

old inflation
V
H



V
φ
H

$0 \quad t_i \quad t_R \quad t_{eq} \quad t_0$

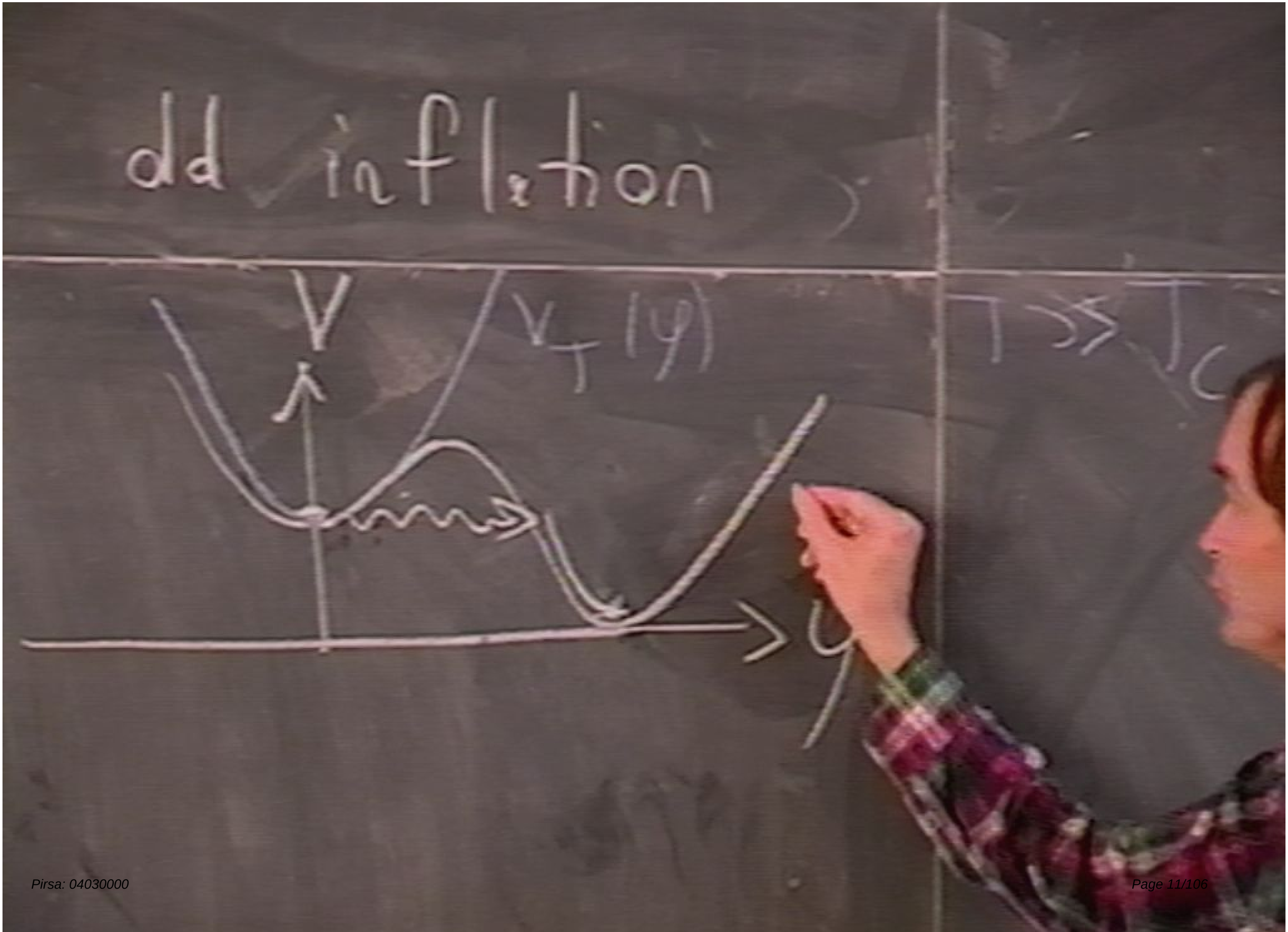
old inflation

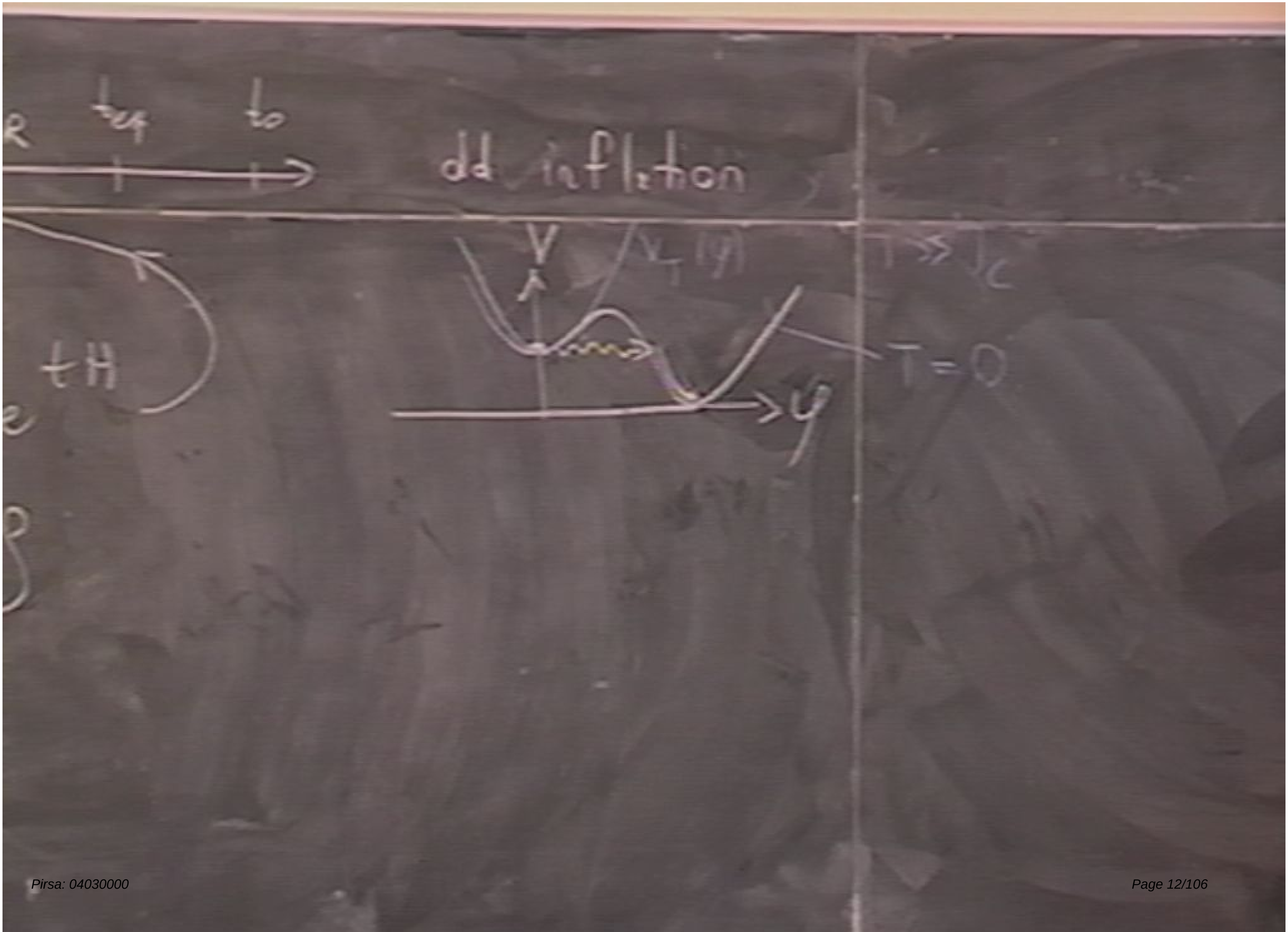


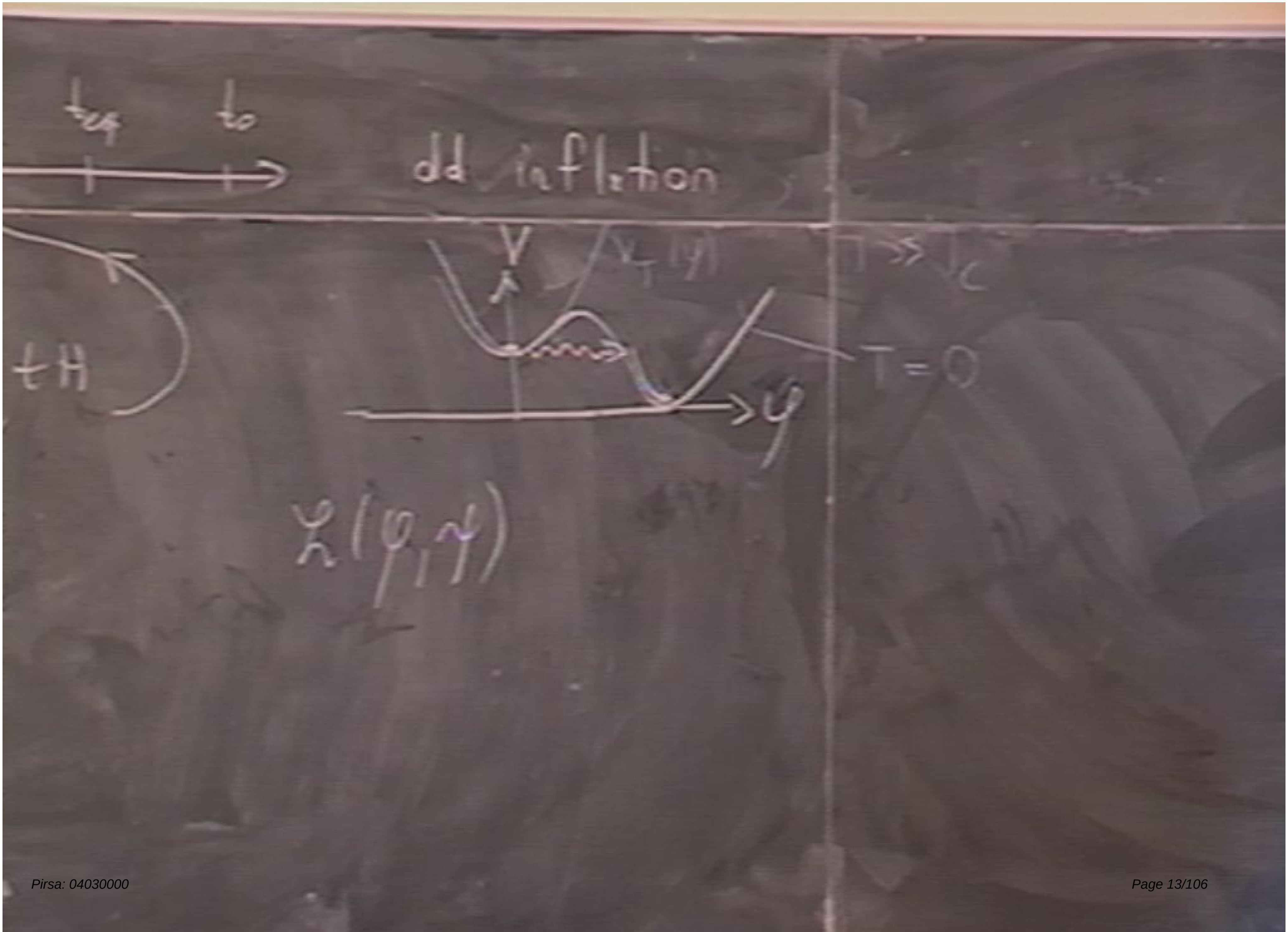
inflation

$a(t) \simeq e^{tH}$

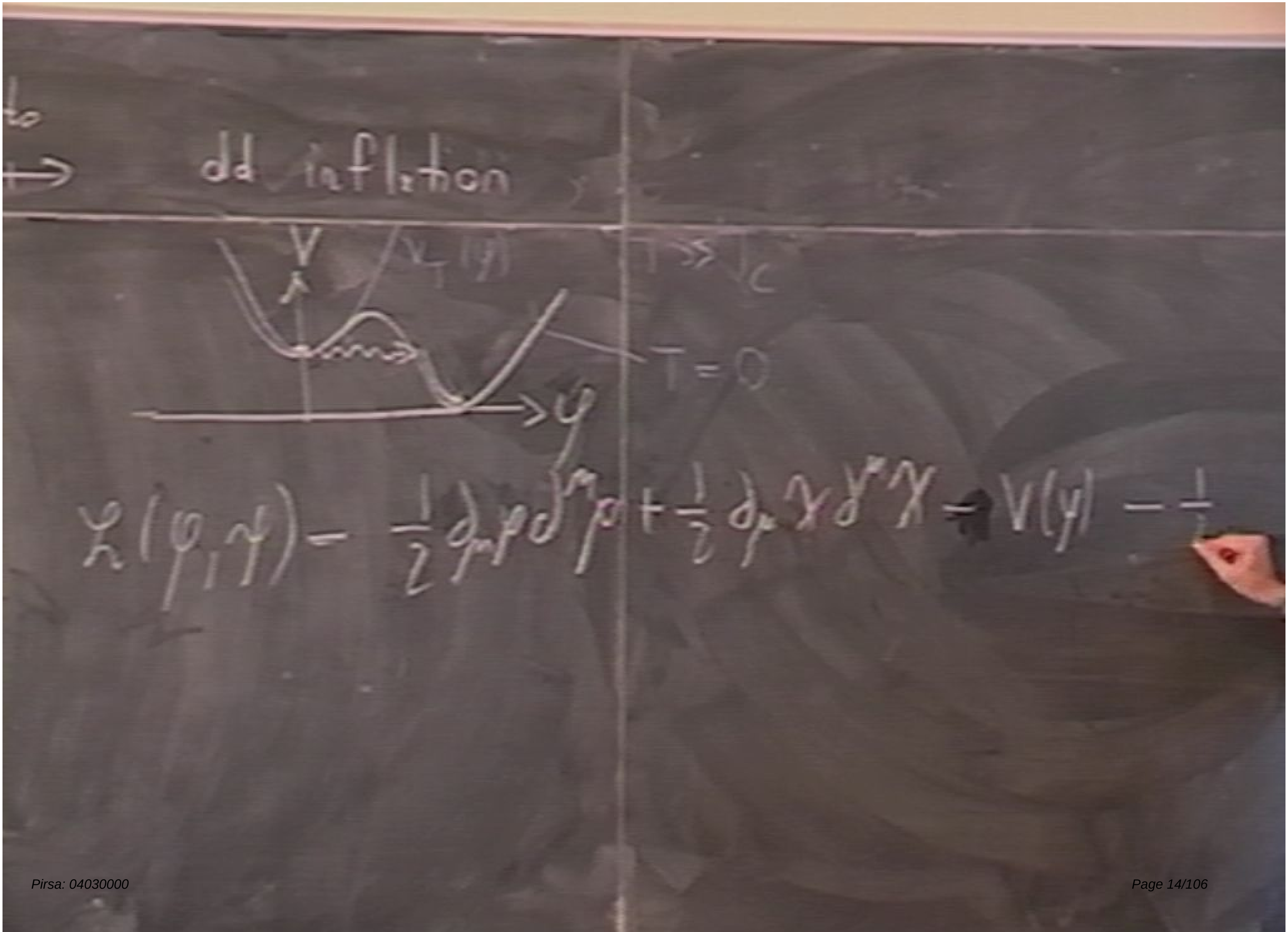
$p \tilde{=} -\rho$

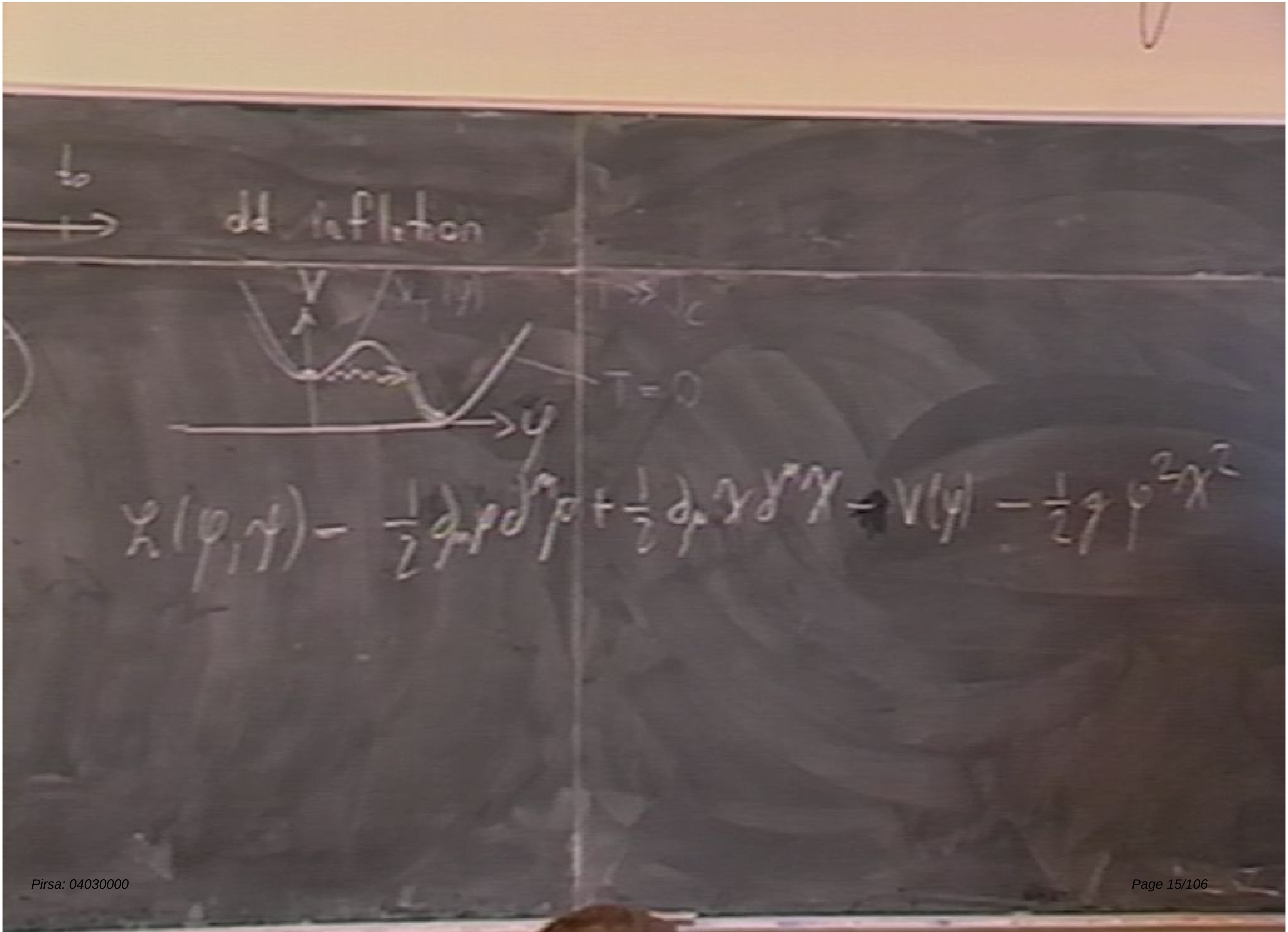

inflation
V
V_T(φ)
T >> T_c
φ


t_eq
t_0
old inflation
V
V_T(φ)
T >> T_c
T = 0
φ
tH



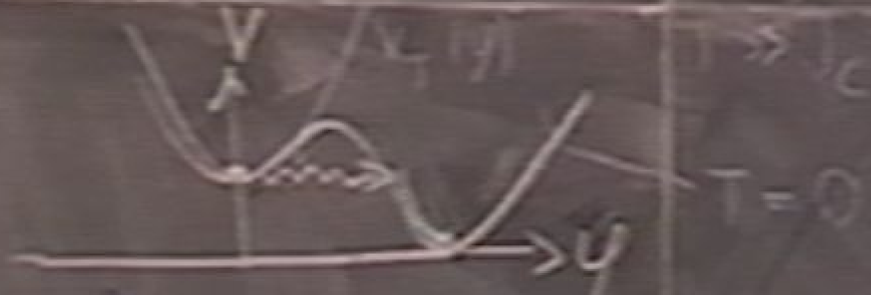
t_{eq}
t_0
old inflation
V
$V_T(\varphi)$
$T \gg T_c$
$T = 0$
φ
tH
$\mathcal{L}(\varphi, \psi)$


to
old inflation
V
T = 0
φ


old inflation
V
T > T_c
T = 0
φ
$\mathcal{L}(\varphi,\chi) = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - V(\varphi) - \frac{1}{2}g\varphi^2\chi^2$

to

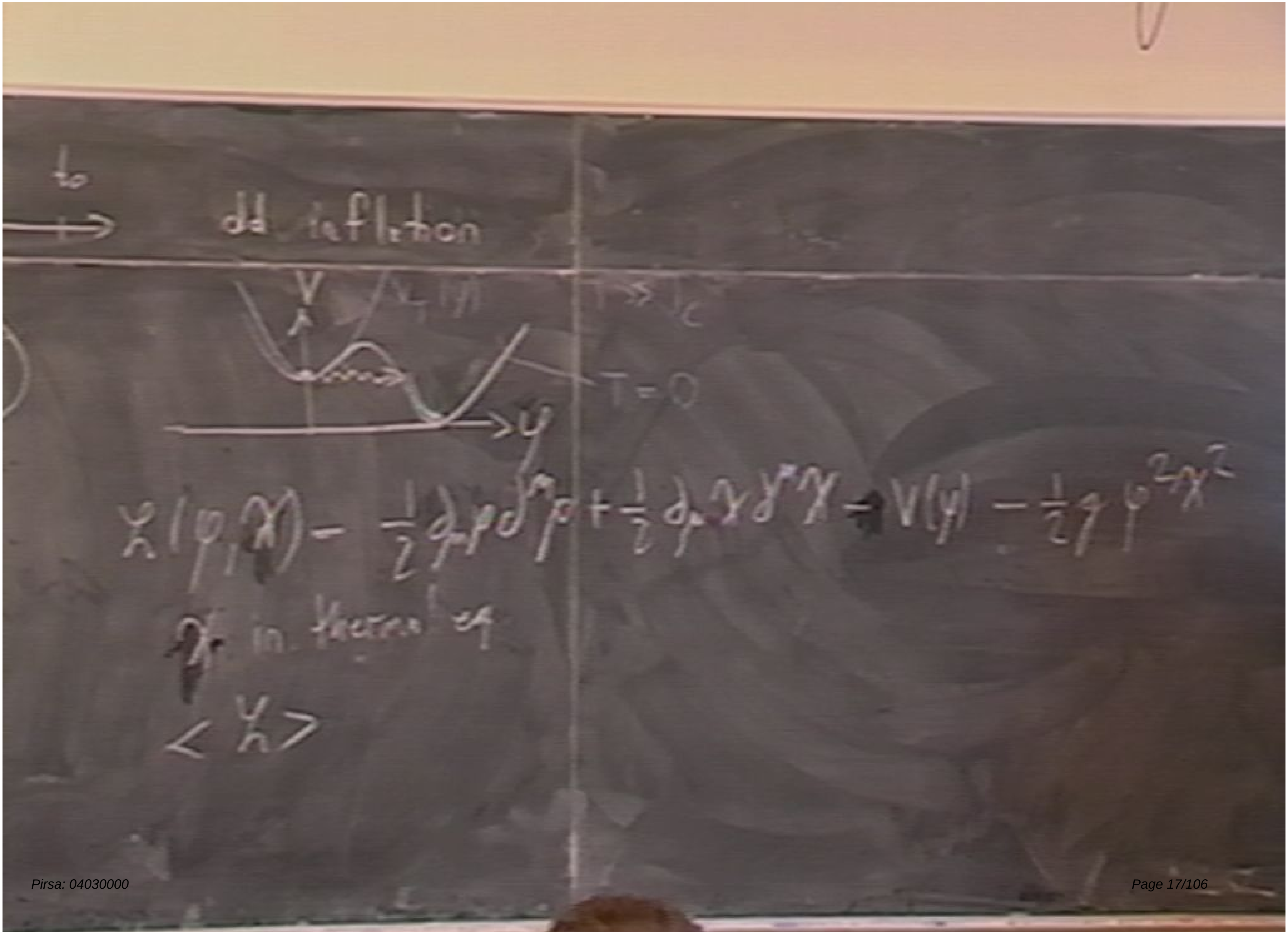
$\Longrightarrow$ old inflation



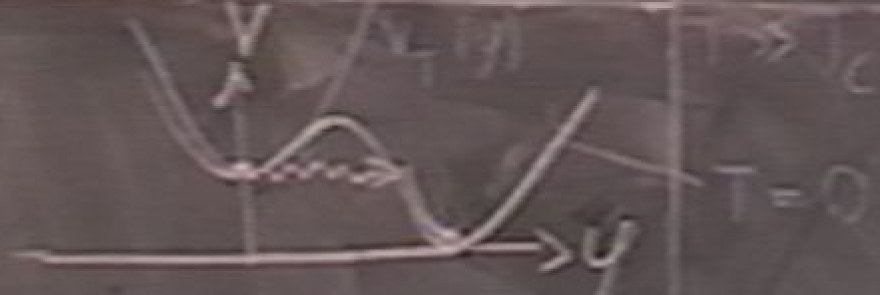
$$\mathcal{L}(\varphi,\chi) = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi + \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - V(\varphi) - \frac{1}{2}g\,\varphi^2\chi^2$$

φ in thermal eq

$\langle \mathcal{L} \rangle$


to
old inflation
V
T > T_c
T = 0
$\mathcal{L}(\varphi,\chi) = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi + \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - V(\varphi) - \frac{1}{2}g\,\varphi^2\chi^2$
χ in thermal eq
$\langle \mathcal{L} \rangle$

→ old inflation

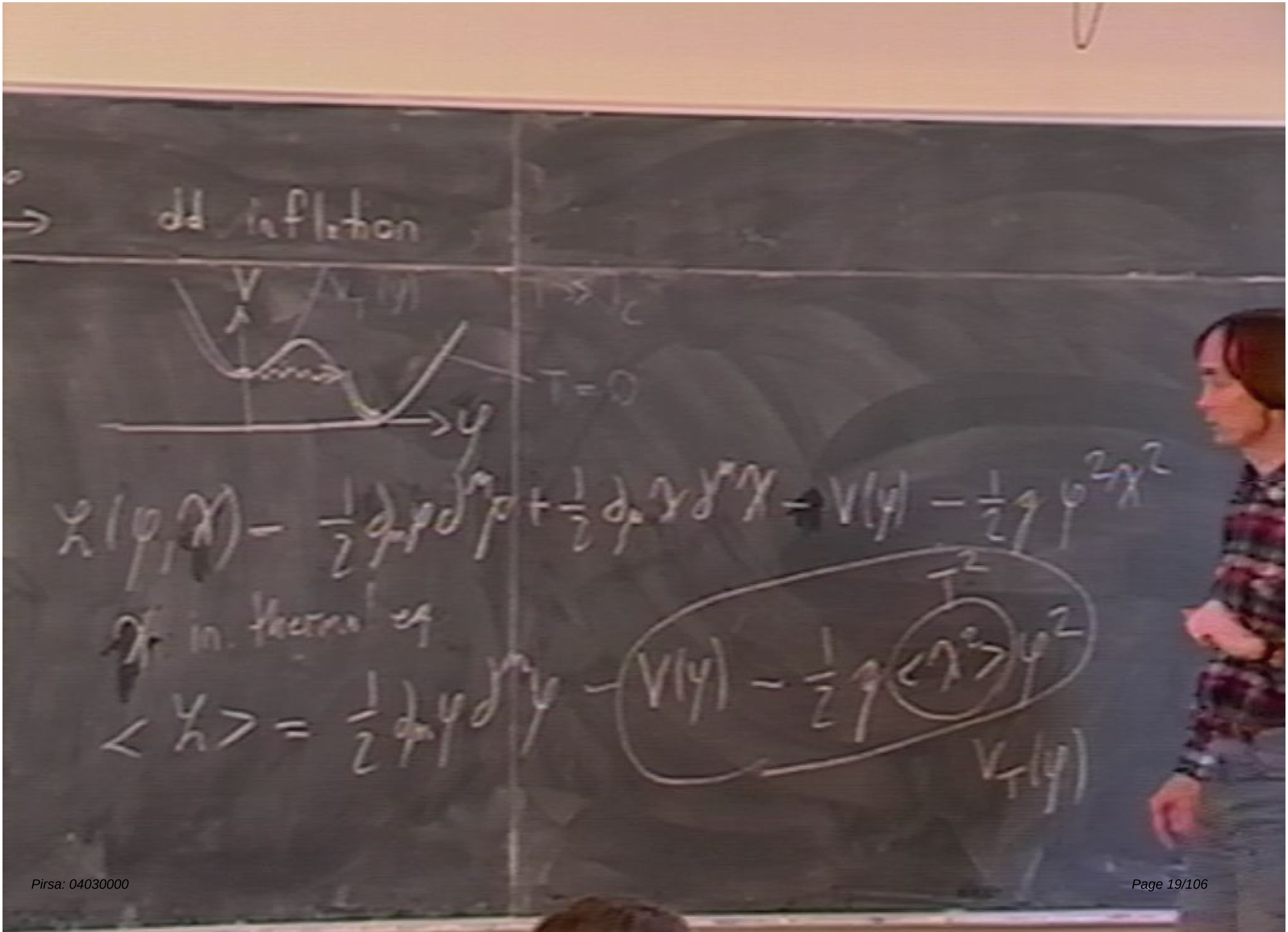


$$\mathcal{L}(\varphi,\chi) = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi + \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - V(\varphi) - \frac{1}{2}g\,\varphi^2\chi^2$$

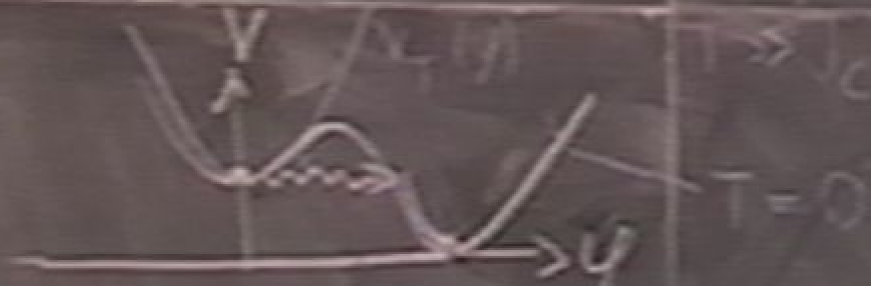
χ in thermal eq

$$\langle\mathcal{L}\rangle = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{2}g\langle\chi^2\rangle\varphi^2$$

$\langle\chi^2\rangle \sim T^2$


old inflation
V
V_T(φ)
T > T_c
T = 0
φ
L(φ, χ) = − 1/2 ∂_μ φ ∂^μ φ + 1/2 ∂_μ χ ∂^μ χ − V(φ) − 1/2 g φ^2 χ^2
χ in thermal eq
<L> = 1/2 ∂_μ φ ∂^μ φ − V(φ) − 1/2 g <χ^2> φ^2
T^2
V_T(φ)

$\Rightarrow$ old inflation

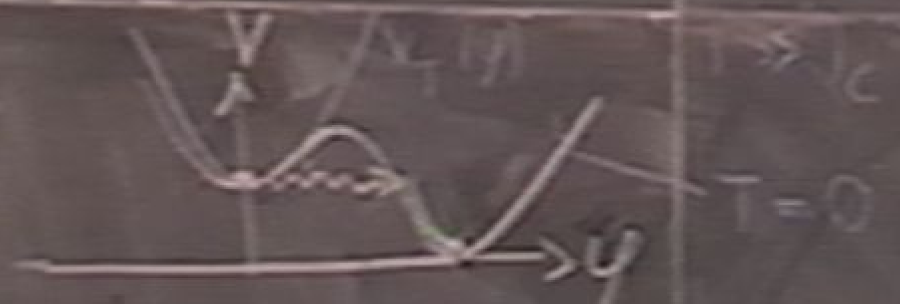


$$\mathcal{L}(\varphi, \chi) = -\frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - V(\varphi) - \frac{1}{2} g \varphi^2 \chi^2$$

χ in thermal eq

$$\langle \mathcal{L} \rangle = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \underbrace{V(\varphi) - \frac{1}{2} g \underbrace{\langle \chi^2 \rangle}_{T^2} \varphi^2}_{V_T(\varphi)}$$

old inflation



$$\mathcal{L}(\varphi,\chi) = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi + \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - V(\varphi) - \frac{1}{2}g\,\varphi^2\chi^2$$

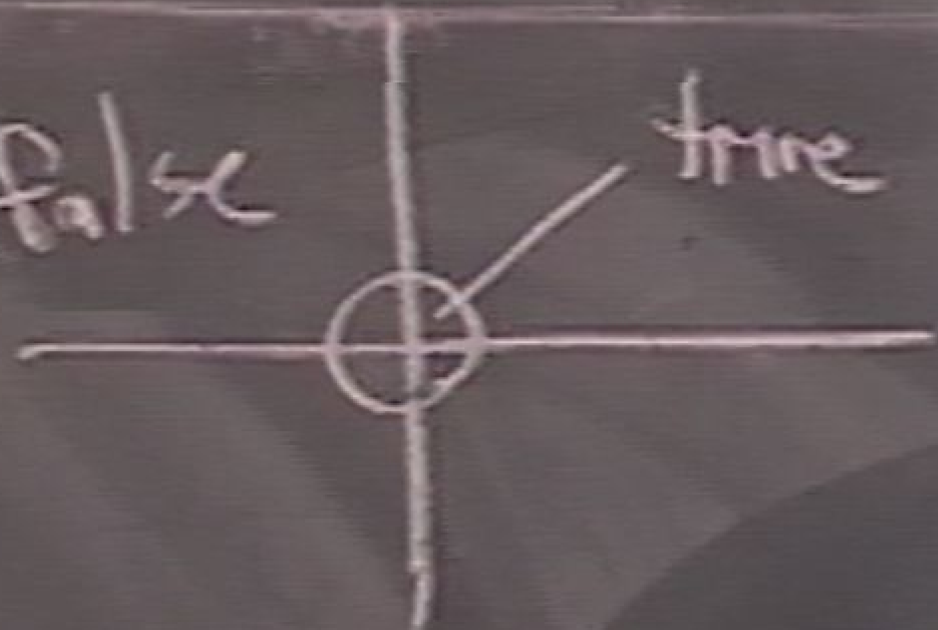
χ in thermal eq

$$\langle \mathcal{L} \rangle = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{2}g\langle\chi^2\rangle\varphi^2$$

$\langle\chi^2\rangle \sim T^2$

$V_T(\varphi)$

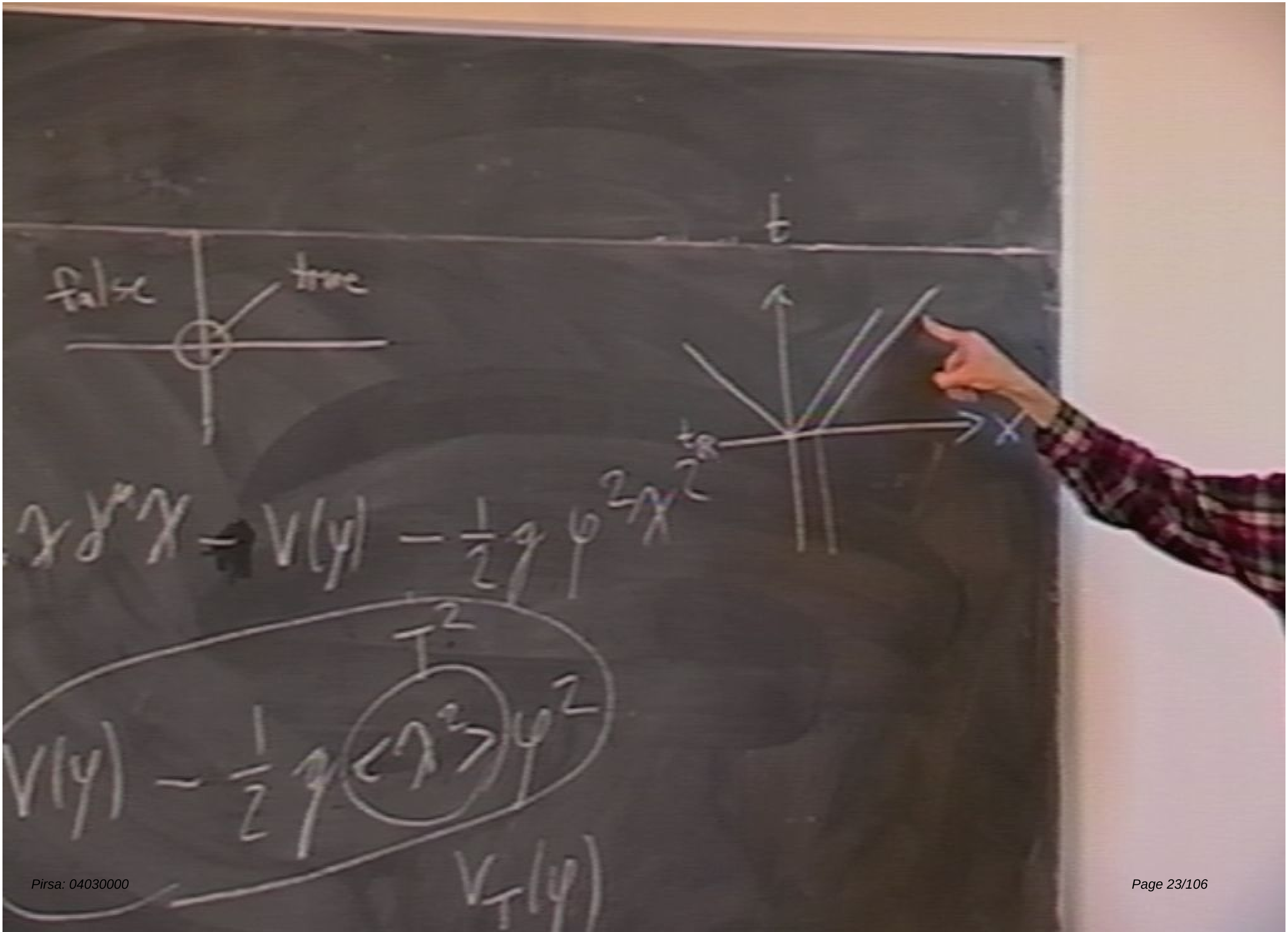
$| \gg |_c$

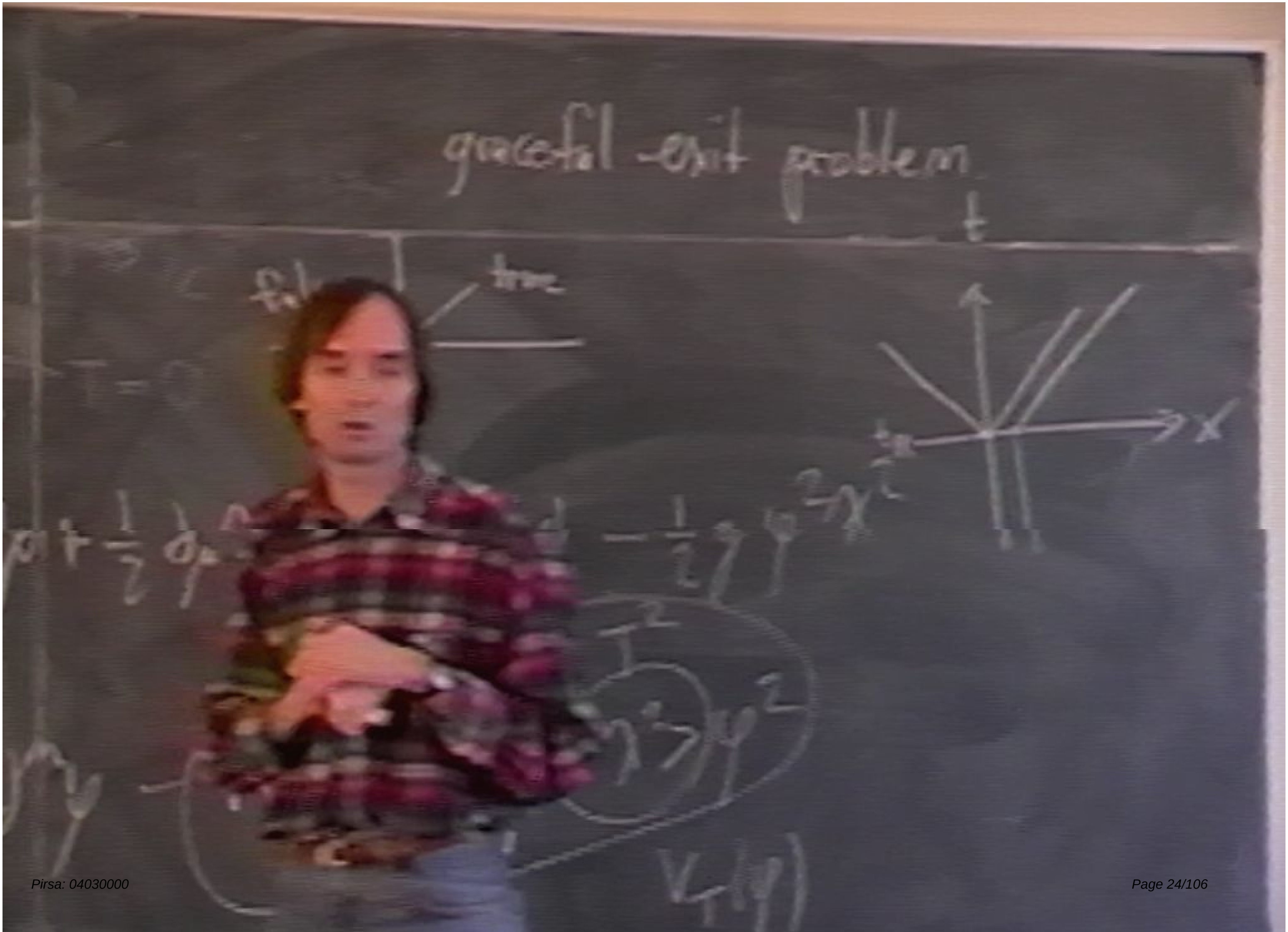


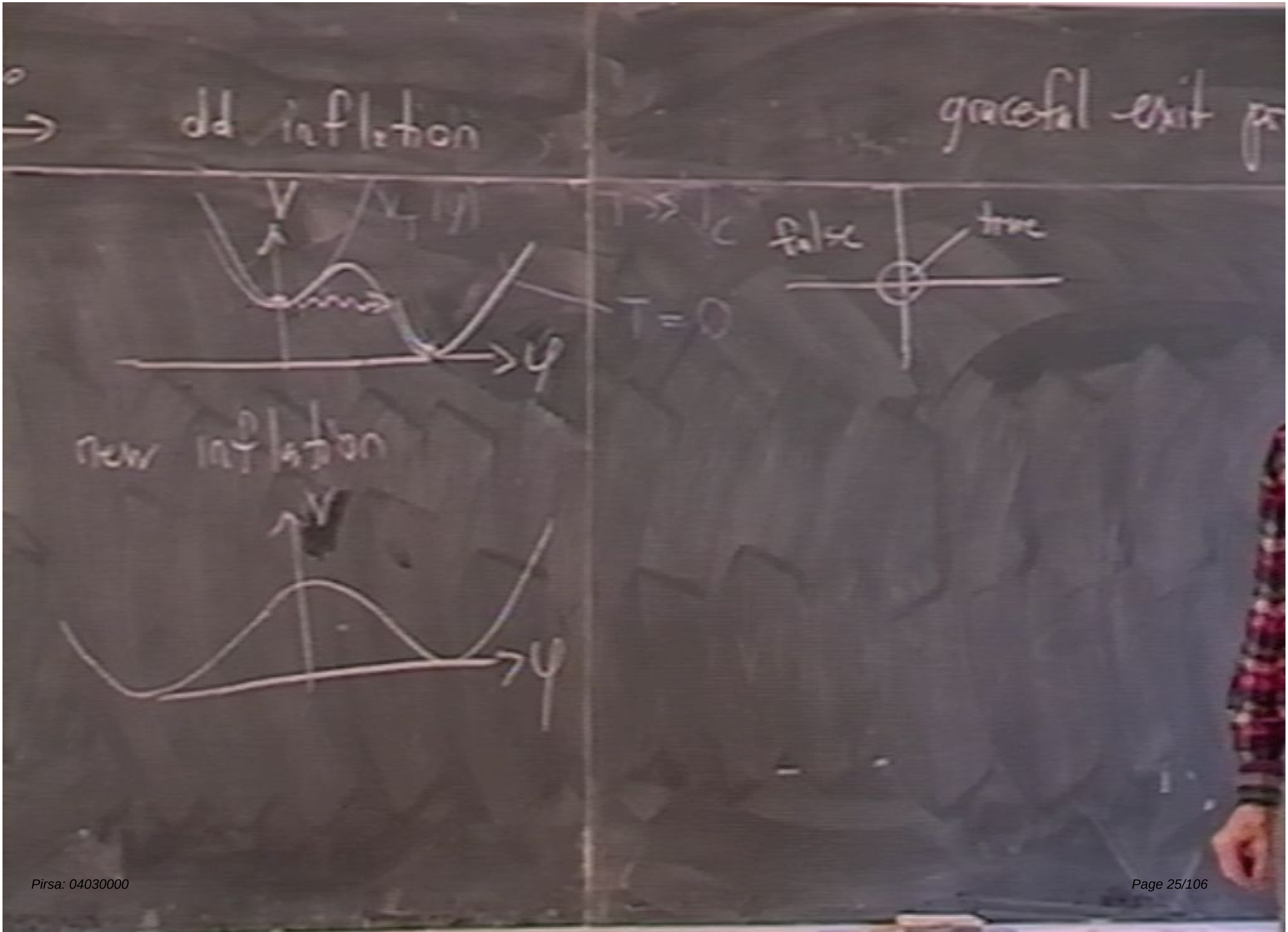
$T = 0$

$$+ \frac{1}{2} \partial_\mu \chi \gamma^\mu \chi - [illegible] V(\psi) - \frac{1}{2} g$$

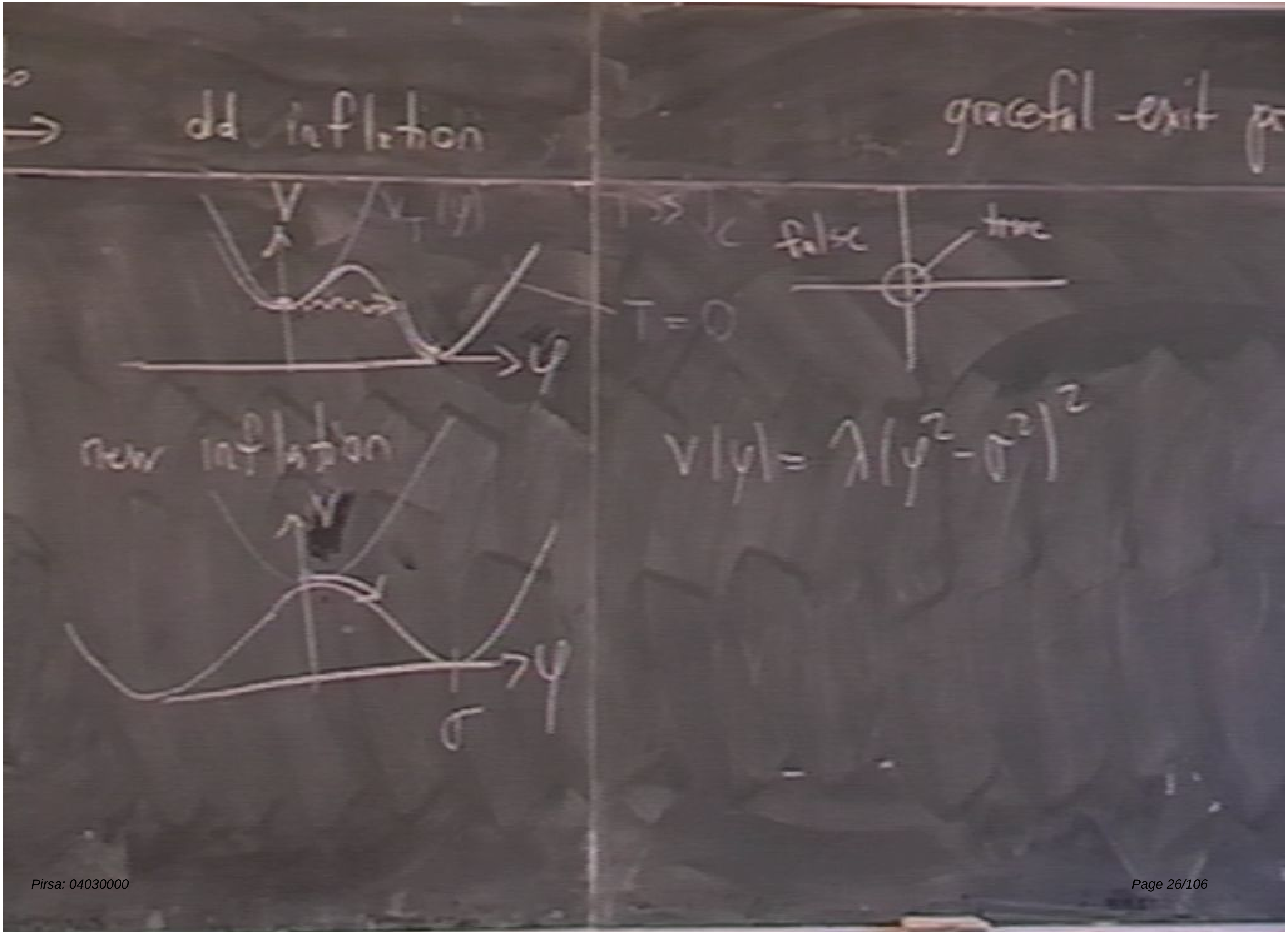
T^2

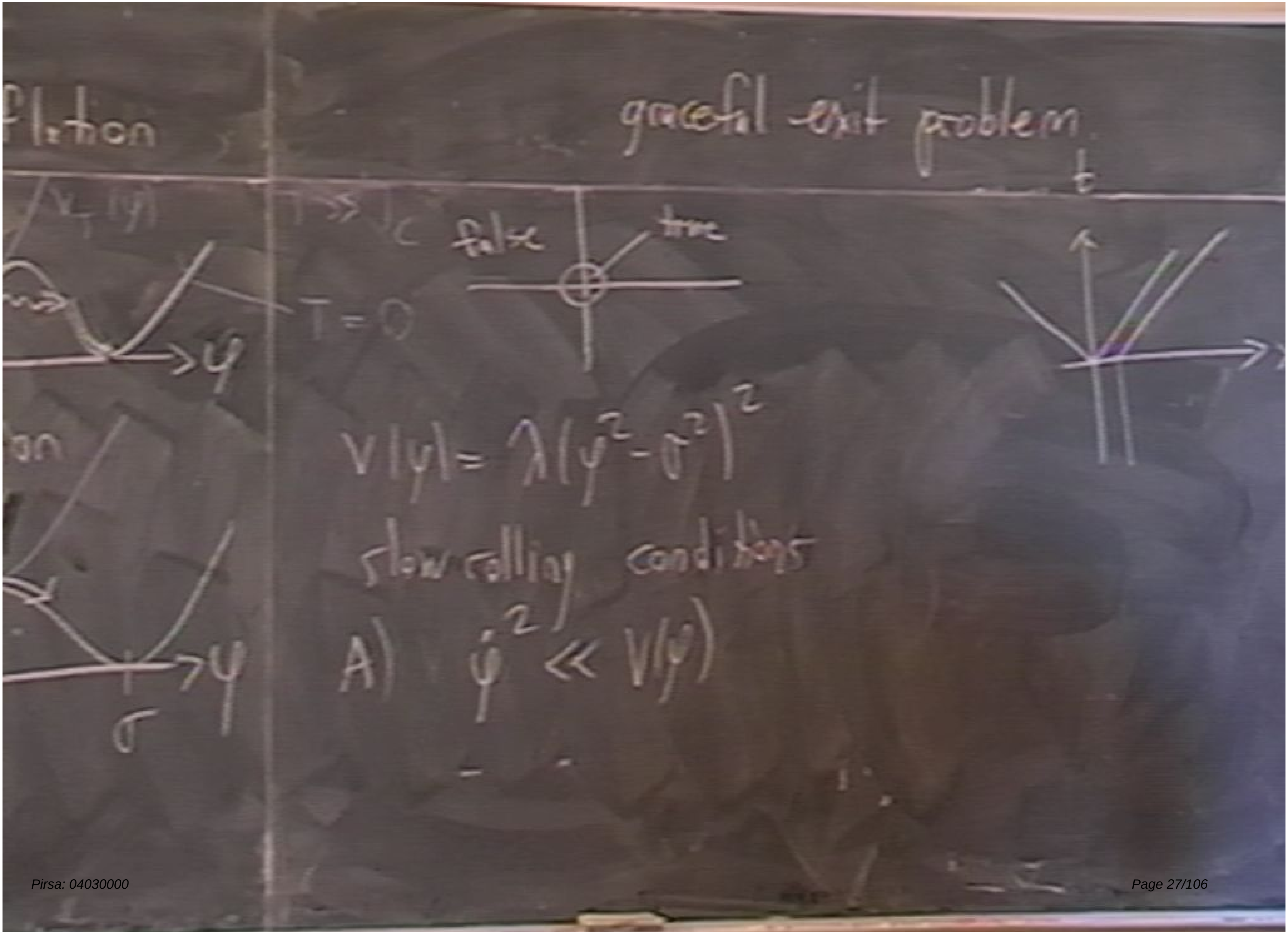

false
true
t
x
V(φ)
V_T(φ)

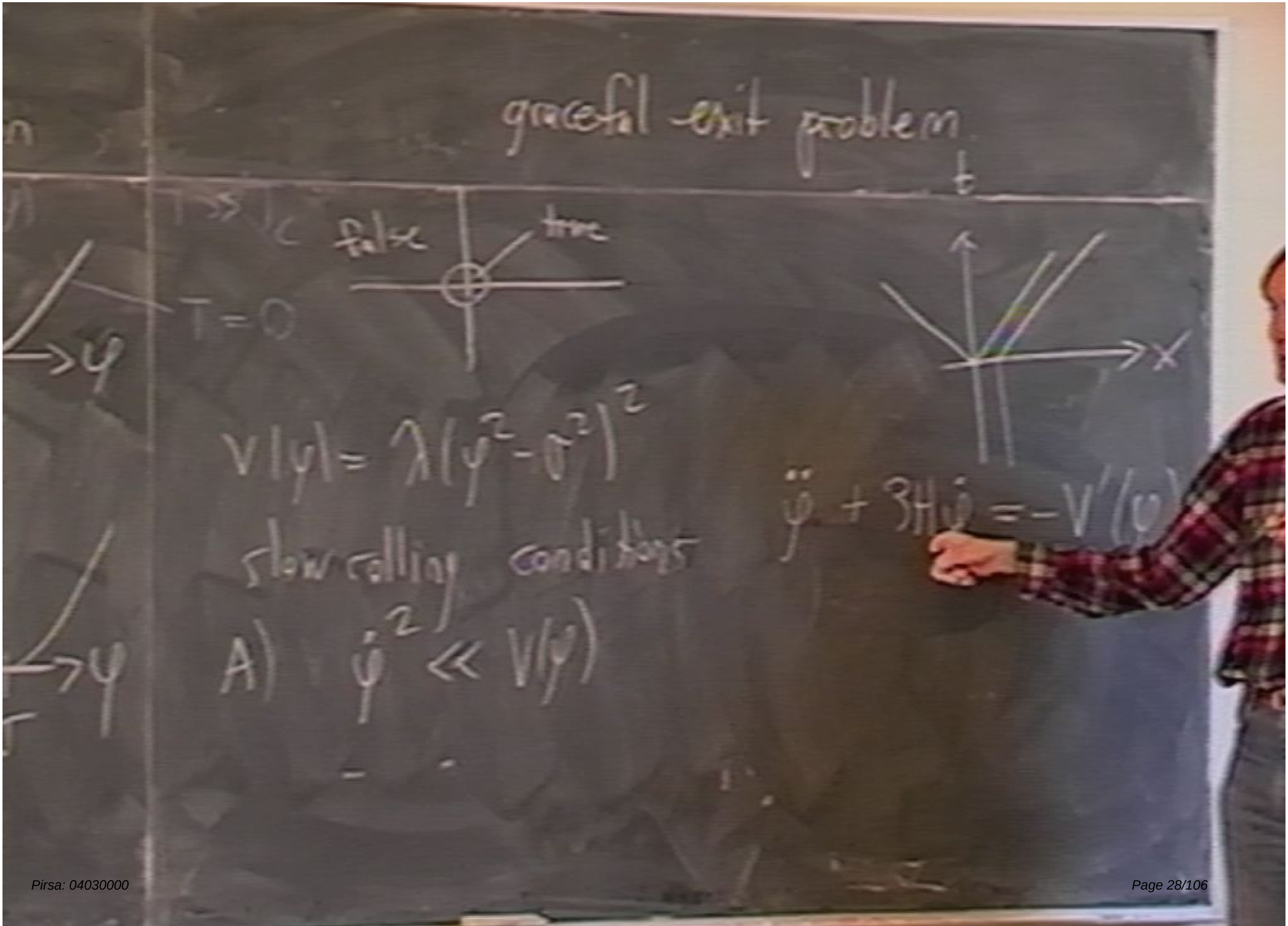

graceful exit problem

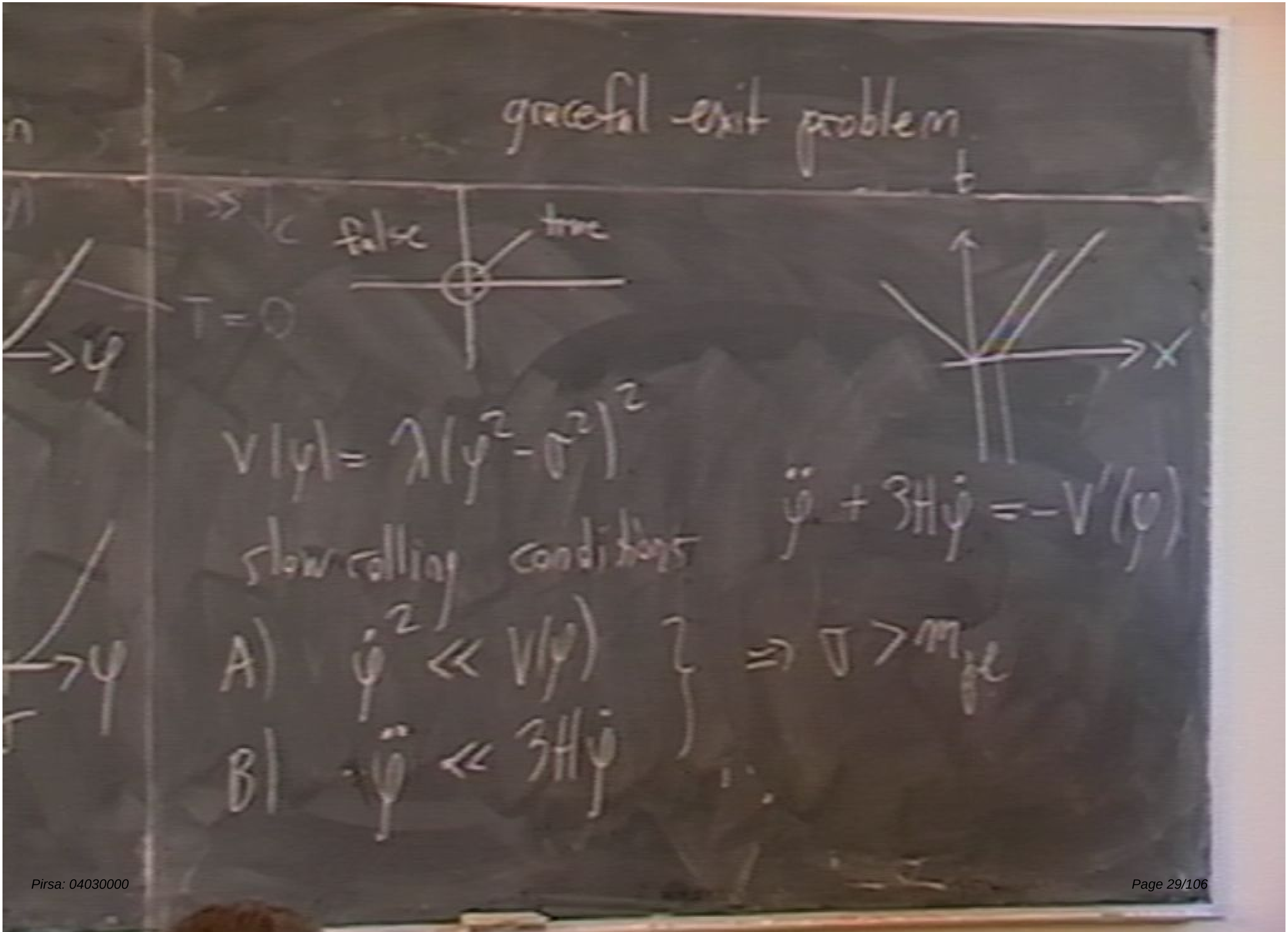


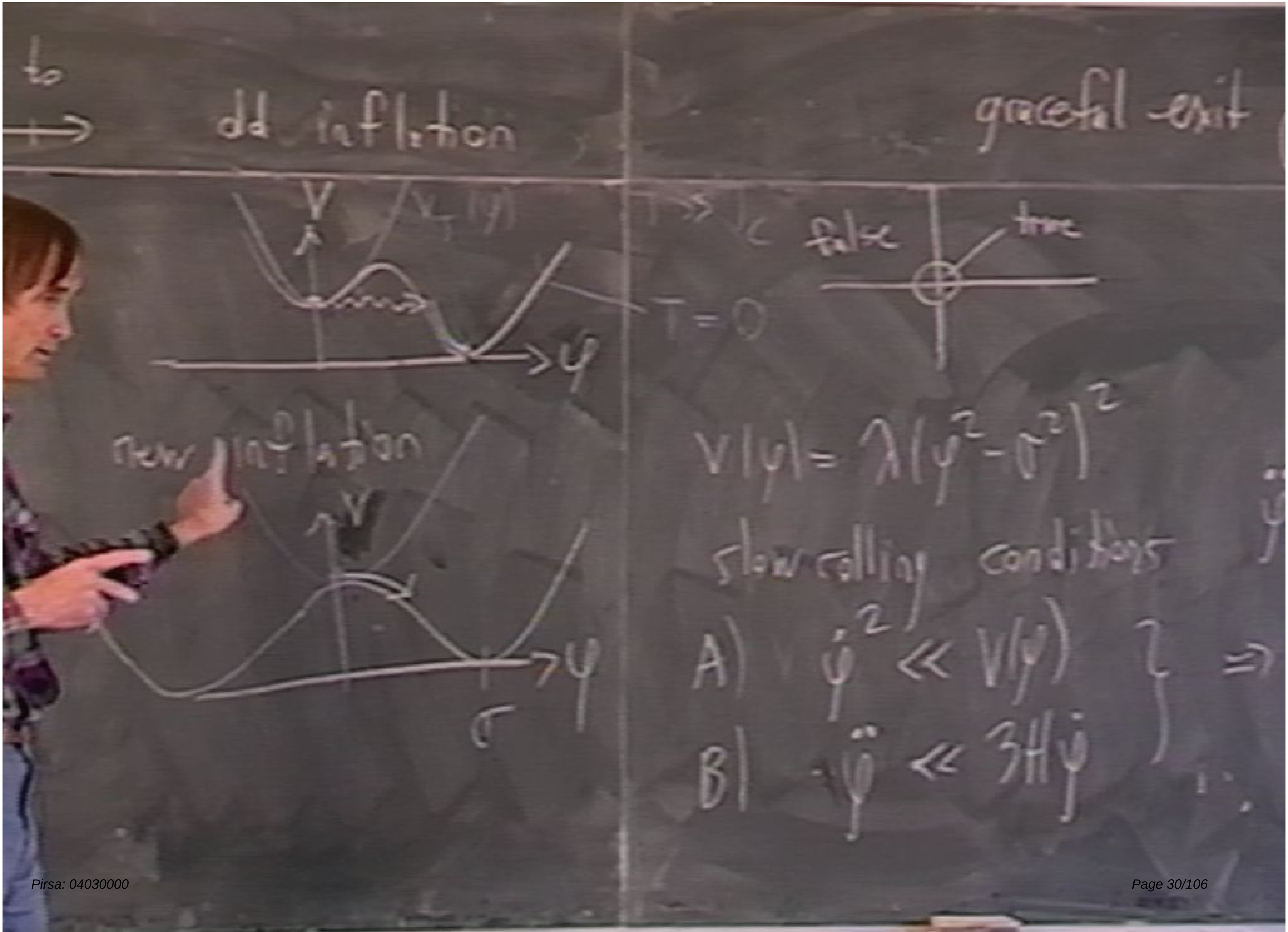
inflation
graceful exit
false
true
T = 0
new inflation


old inflation
graceful-exit
V
false
true
T = 0
new inflation
V
V(φ) = λ(φ² − σ²)²
σ


graceful exit problem
false
true
T = 0
V(φ) = λ(φ² − σ²)²
slow rolling conditions
A) φ̇² ≪ V(φ)


graceful exit problem
false
true
T = 0
t
x
V(φ) = λ(φ² − σ²)²
φ̈ + 3Hφ̇ = −V′(φ)
slow rolling conditions
A) φ̇² ≪ V(φ)


graceful exit problem
false
true
T = 0
t
x
V(φ) = λ(φ² − σ²)²
slow rolling conditions
φ̈ + 3Hφ̇ = −V′(φ)
A) φ̇² ≪ V(φ)
B) φ̈ ≪ 3Hφ̇
⇒ σ > m_pl



old inflation
graceful exit
false
true
T = 0
new inflation
V(φ) = λ(φ² − σ²)²
slow rolling conditions
A) φ̇² ≪ V(φ)
B) φ̈ ≪ 3Hφ̇

$\gg J_c$ false

true

$T = 0$

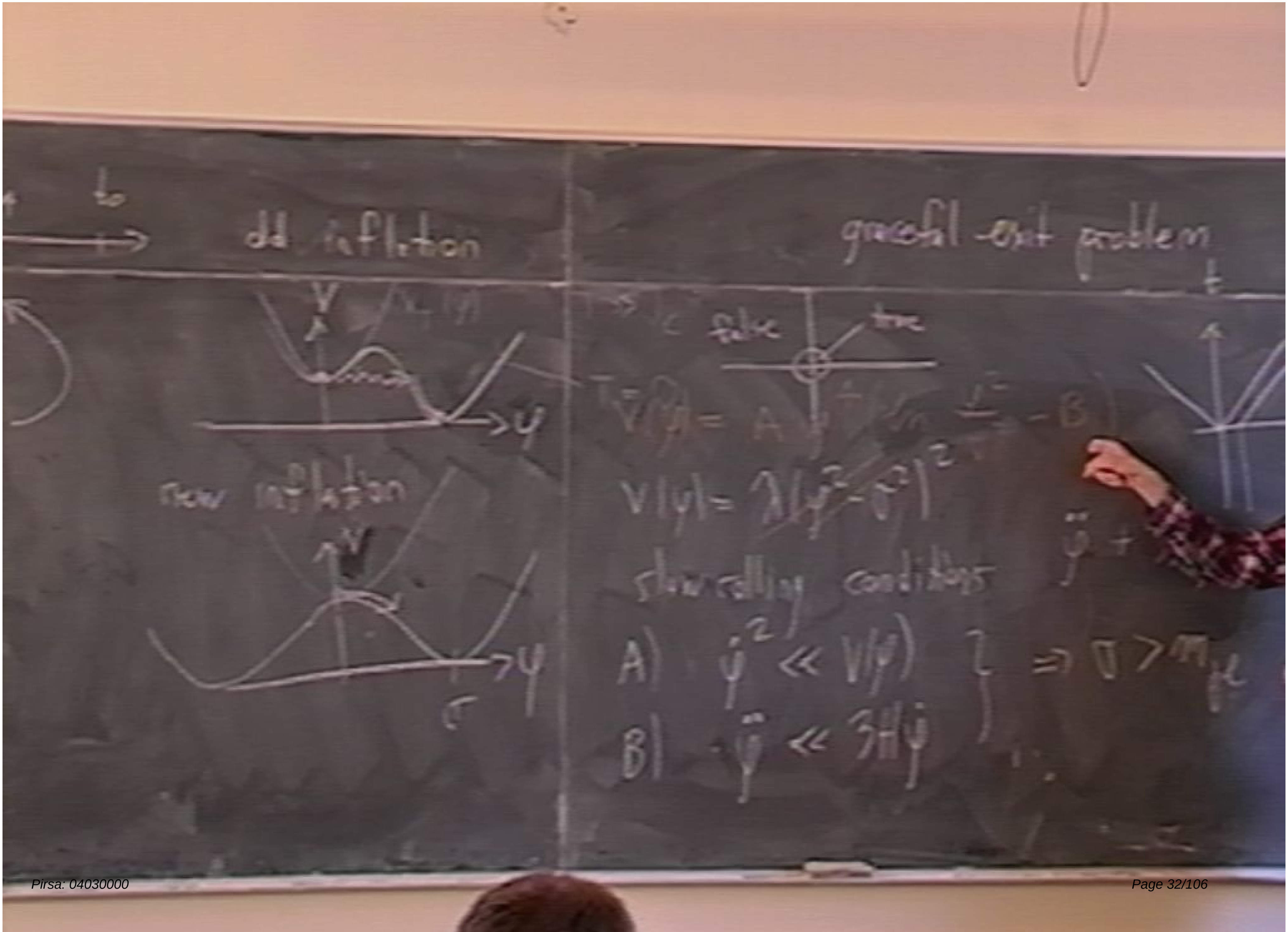
$A\varphi^4\left(\ln\frac{\varphi^2}{\sigma^2} - B\right)$

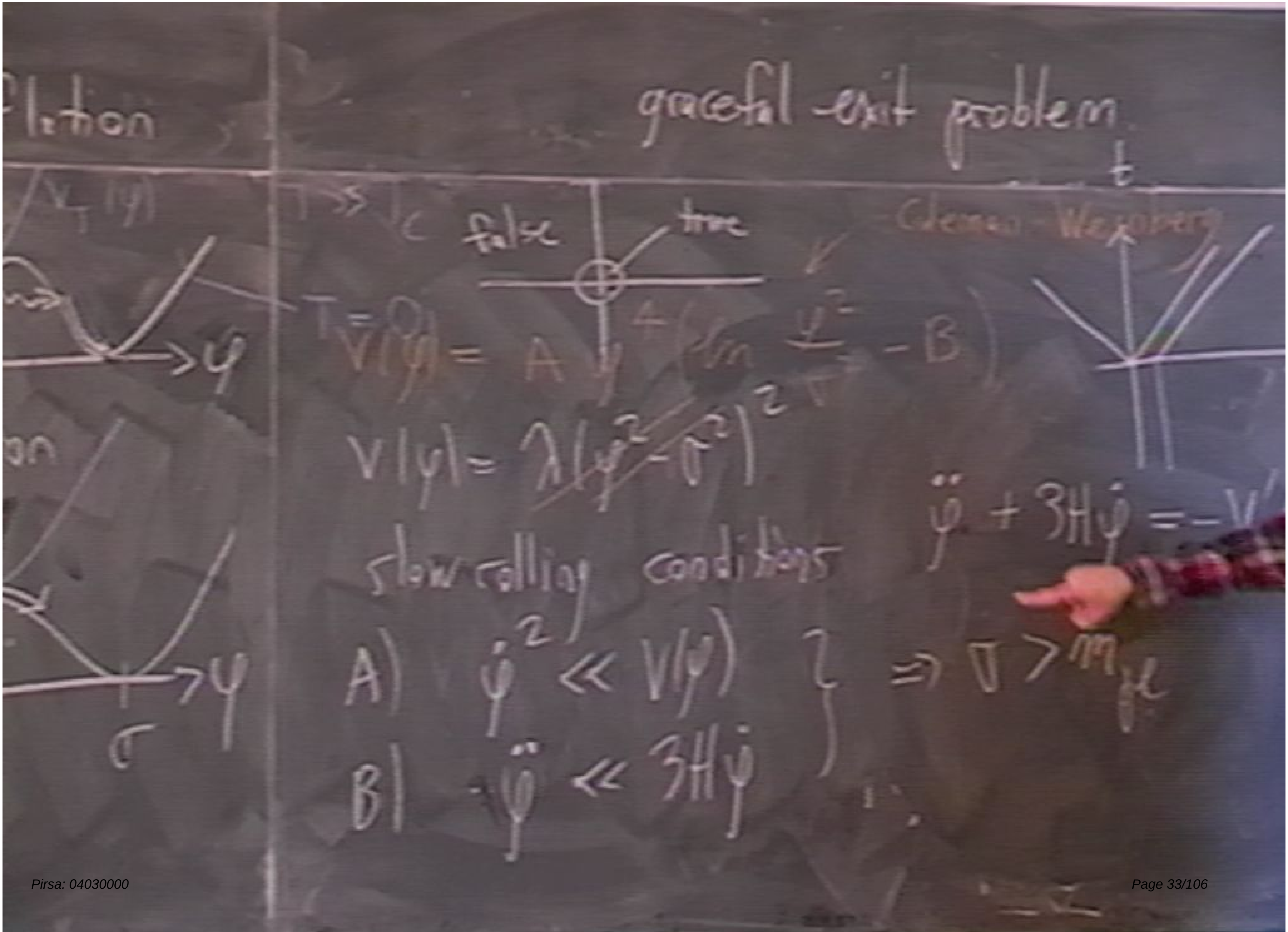
~~$V(\varphi) = \lambda(\varphi^2 - \sigma^2)^2$~~

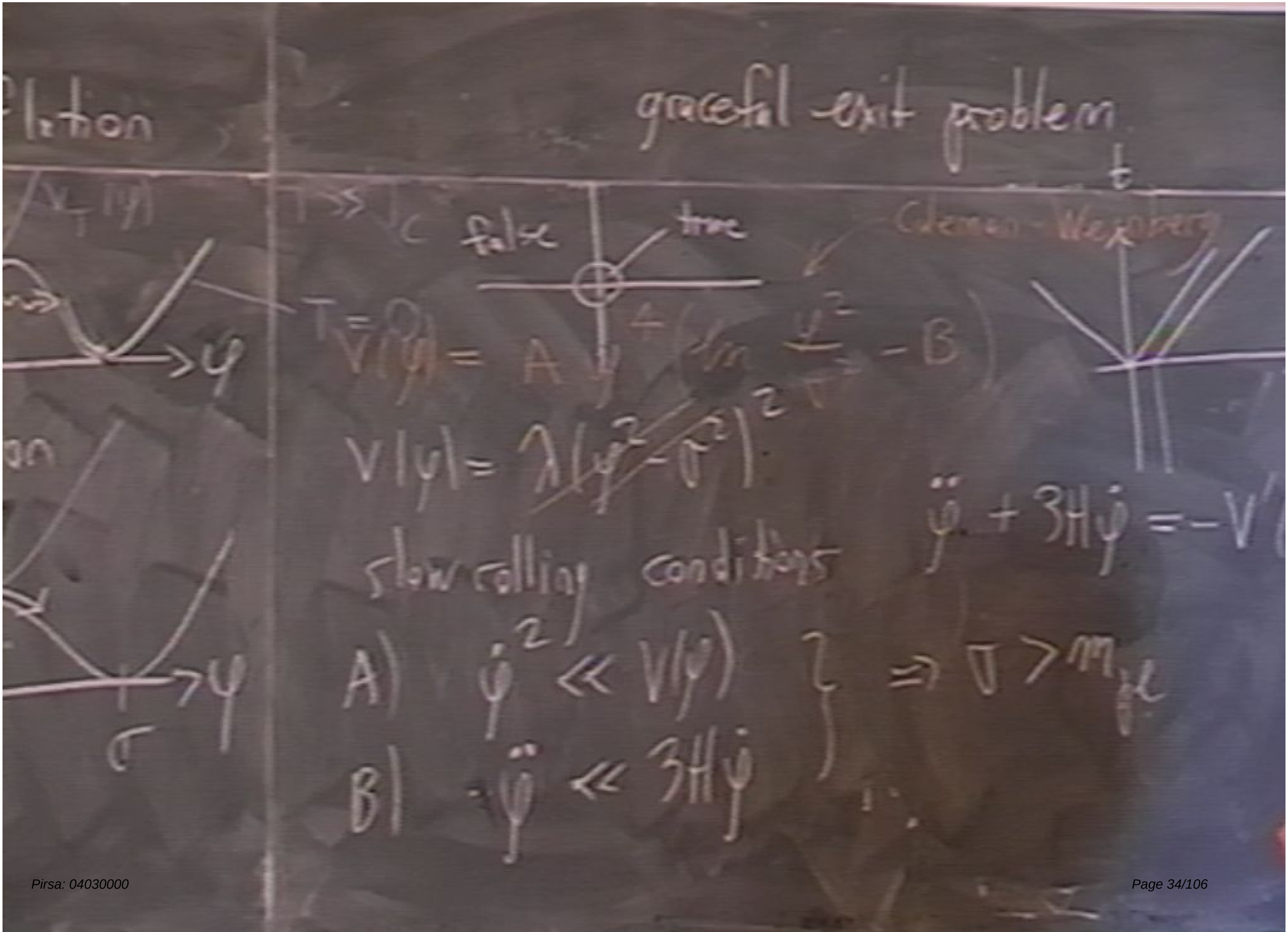
slow rolling conditions

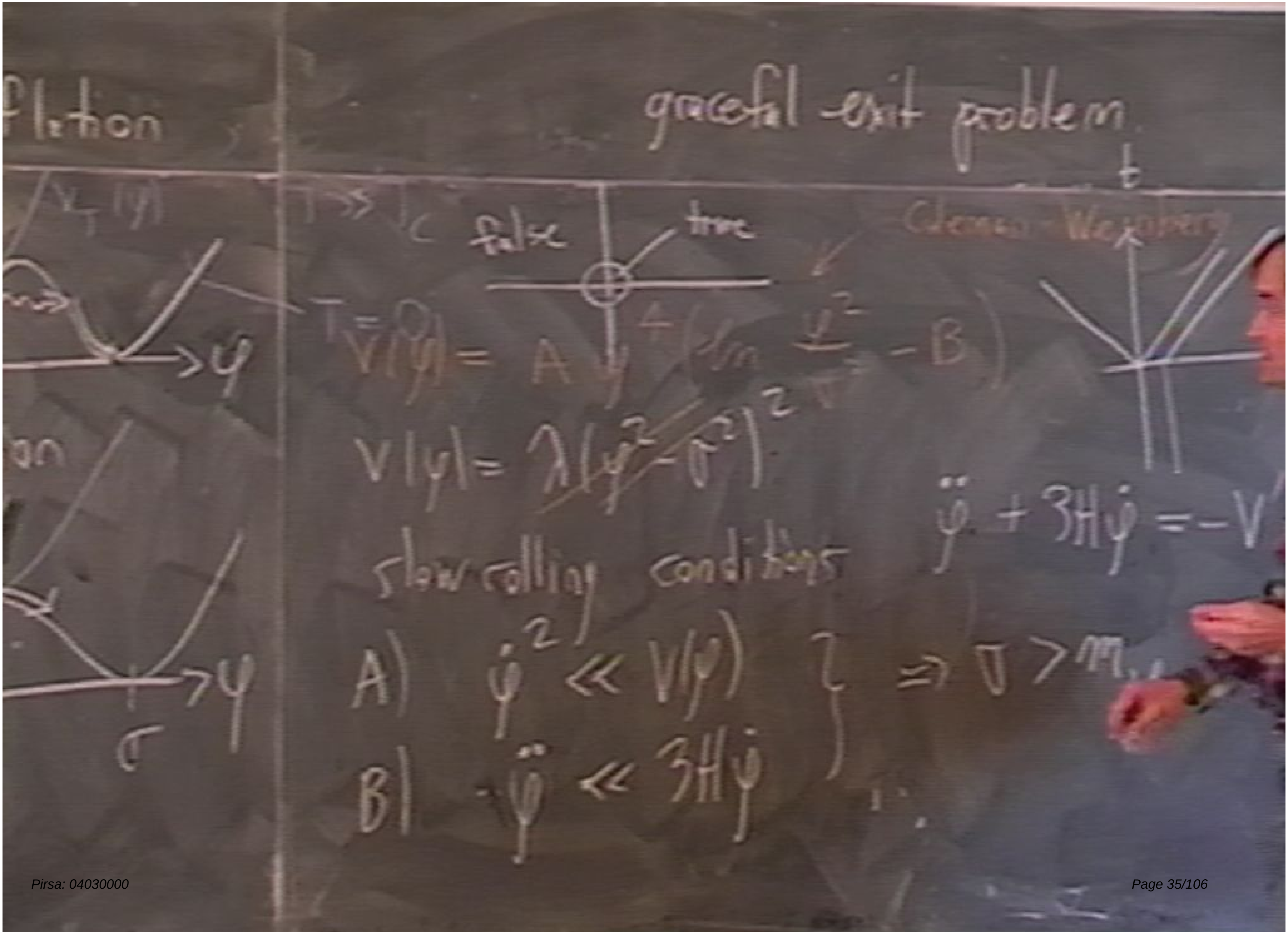
$\ddot{\varphi} + 3H\dot{\varphi}$

A) $\dot{\varphi}^2 \ll V(\varphi)$ $\Big\} \Rightarrow \sigma > m$

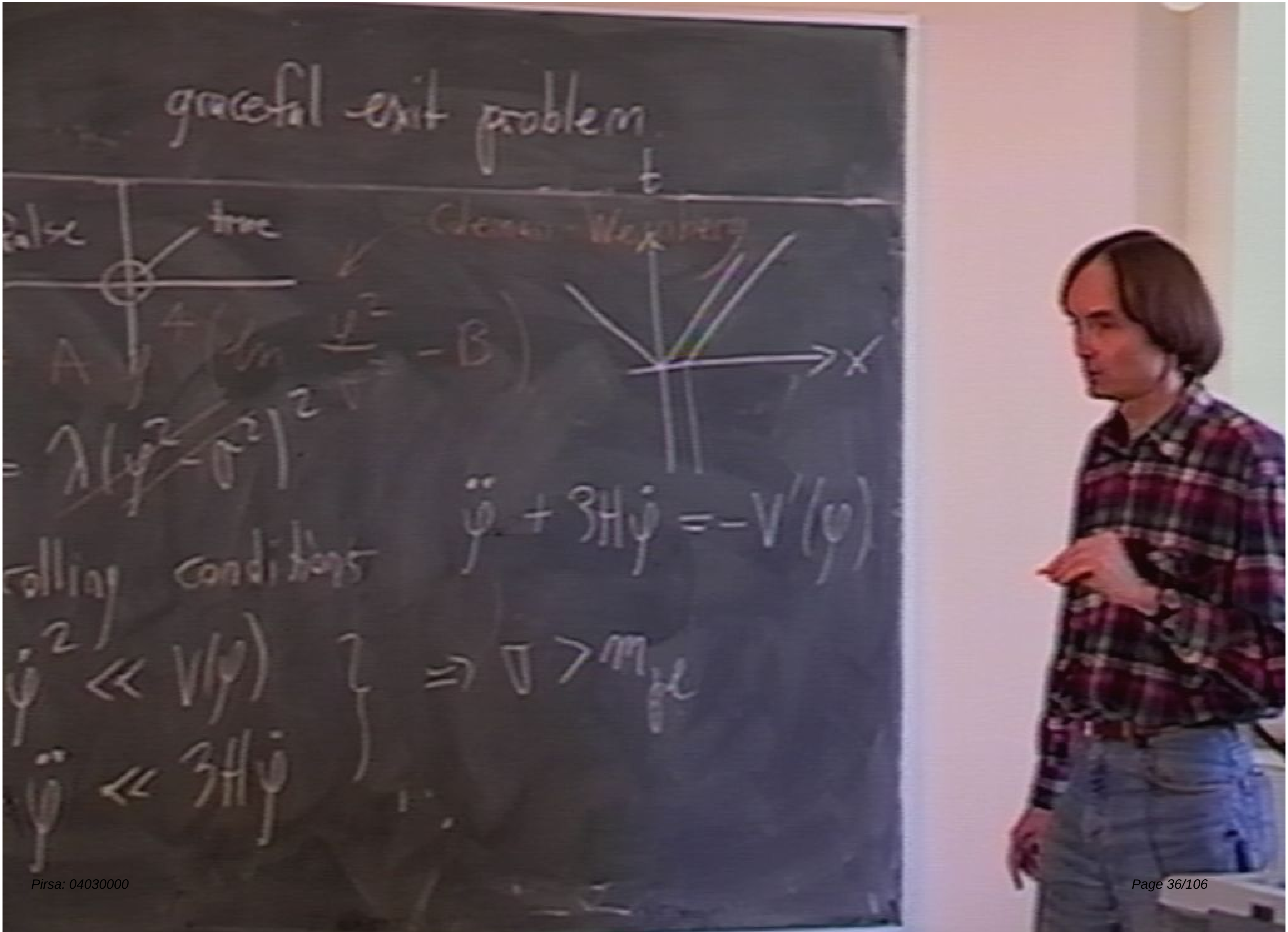

old inflation
graceful exit problem
false
true
new inflation
$V(\varphi) = \lambda(\varphi^2 - \sigma^2)^2$
slow rolling conditions
A) $\dot{\varphi}^2 \ll V(\varphi)$
B) $\ddot{\varphi} \ll 3H\dot{\varphi}$
$\Rightarrow \sigma > m_{pl}$

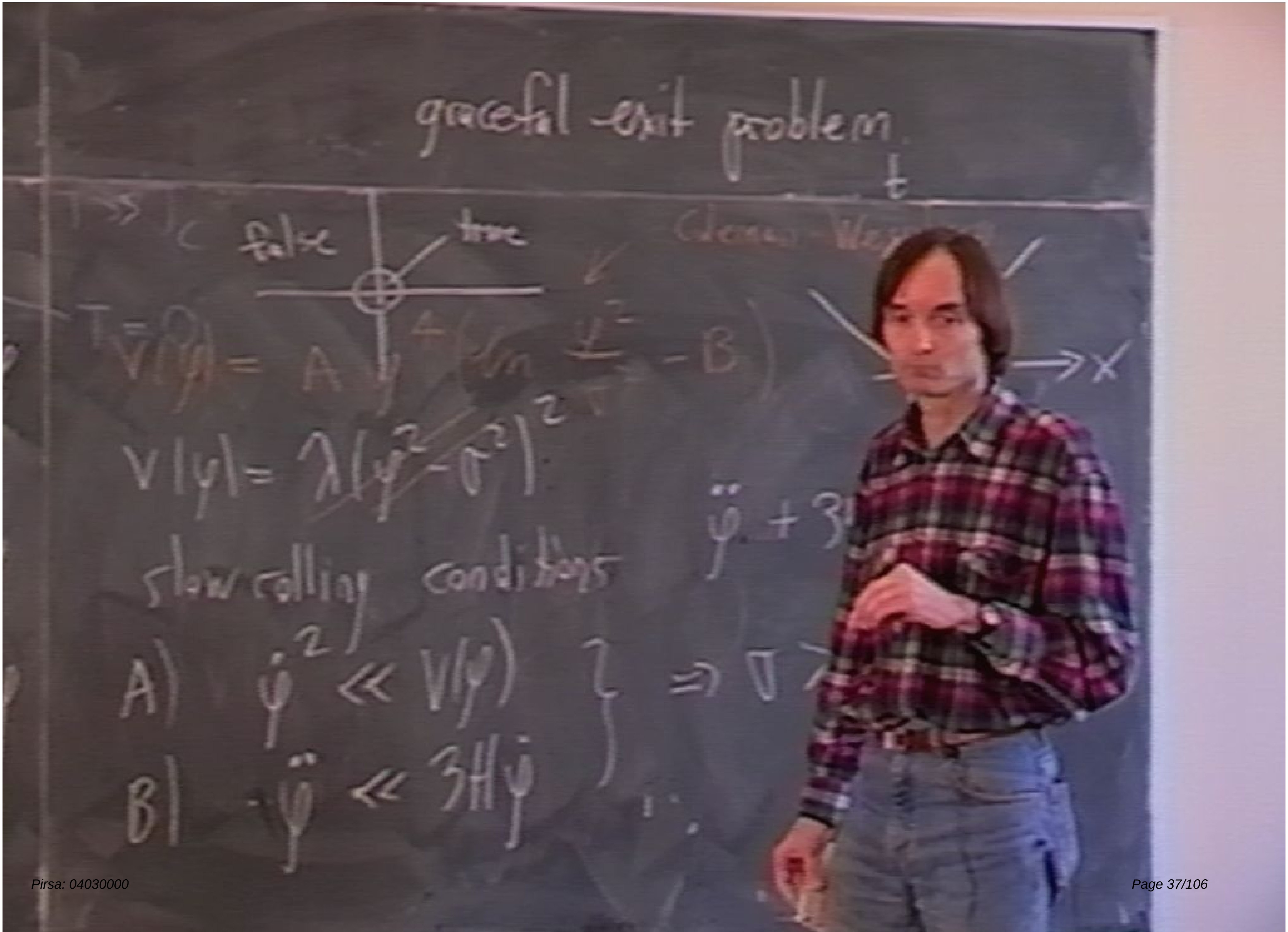

graceful exit problem
false
true
Coleman-Weinberg
V(φ) = λ(φ² − σ²)²
slow rolling conditions
φ̈ + 3Hφ̇ = −V′
A) φ̇² ≪ V(φ)
B) φ̈ ≪ 3Hφ̇
⇒ σ > m_pl

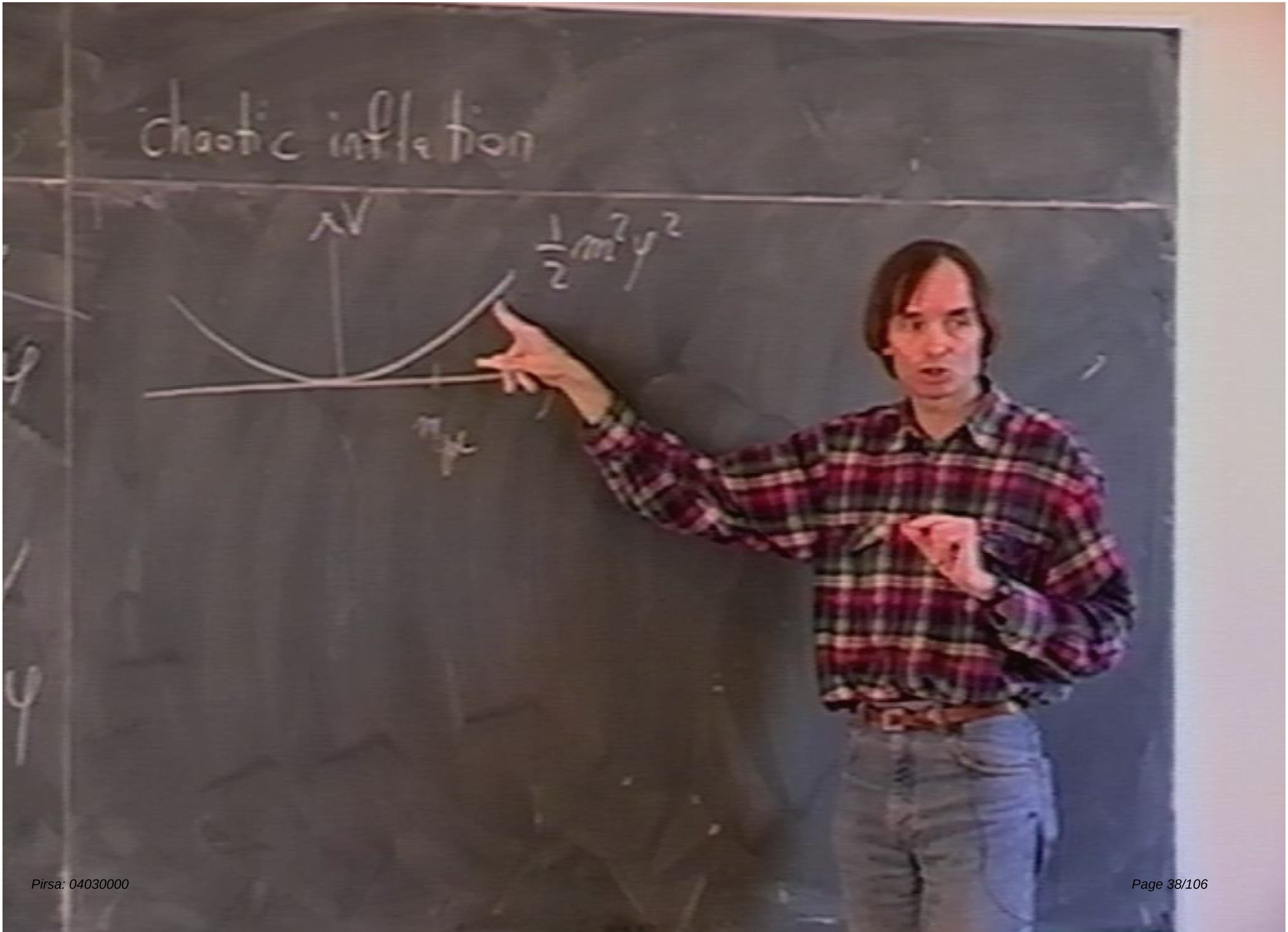

graceful exit problem
false
true
Coleman-Weinberg
V(φ) = λ(φ² − σ²)²
slow rolling conditions
φ̈ + 3Hφ̇ = −V′
A) φ̇² ≪ V(φ)
B) φ̈ ≪ 3Hφ̇
⇒ σ > m_pl



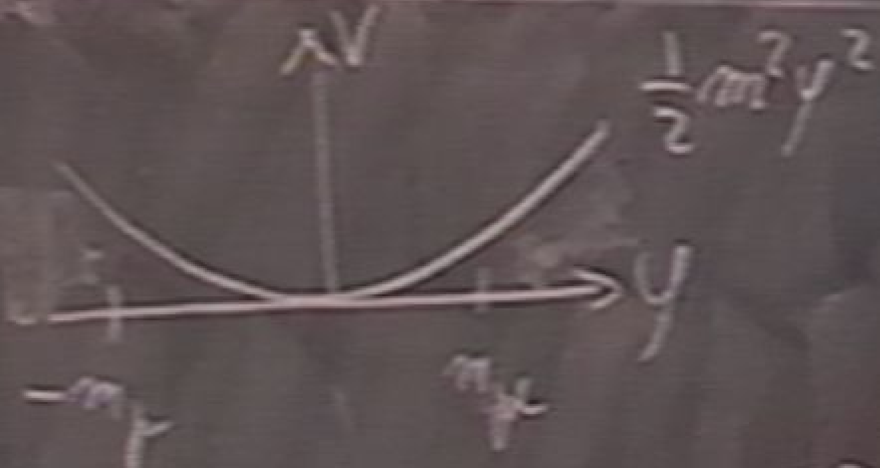
flation
graceful exit problem
T > Tc
false
true
Coleman-Weinberg
V(φ) = A φ⁴ (ln φ²/σ² − B)
V(φ) = λ(φ² − σ²)²
slow rolling conditions
φ̈ + 3Hφ̇ = −V′
A) φ̇² ≪ V(φ)
B) φ̈ ≪ 3Hφ̇
⇒ σ > m


graceful exit problem
false
true
t
x
conditions
φ̈ + 3Hφ̇ = −V′(φ)
φ̈ << 3Hφ̇

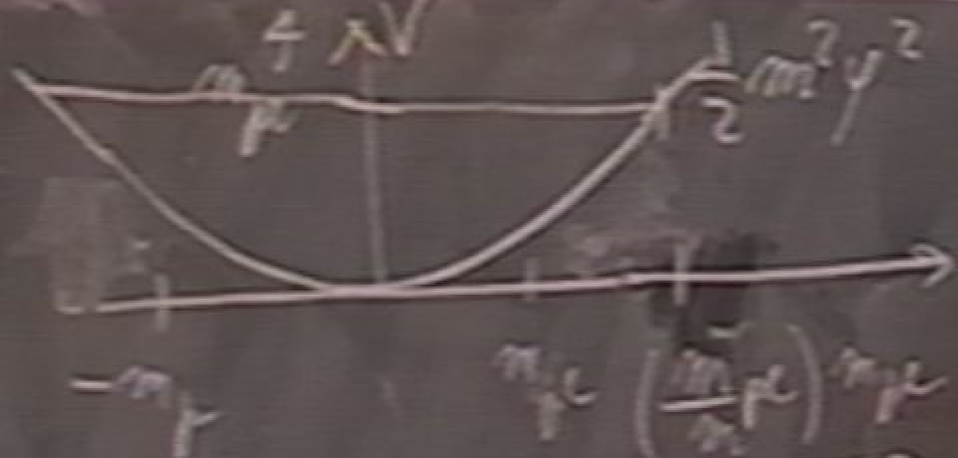

graceful exit problem
false
true
slow rolling conditions


chaotic inflation
V
$\frac{1}{2}m^2\varphi^2$

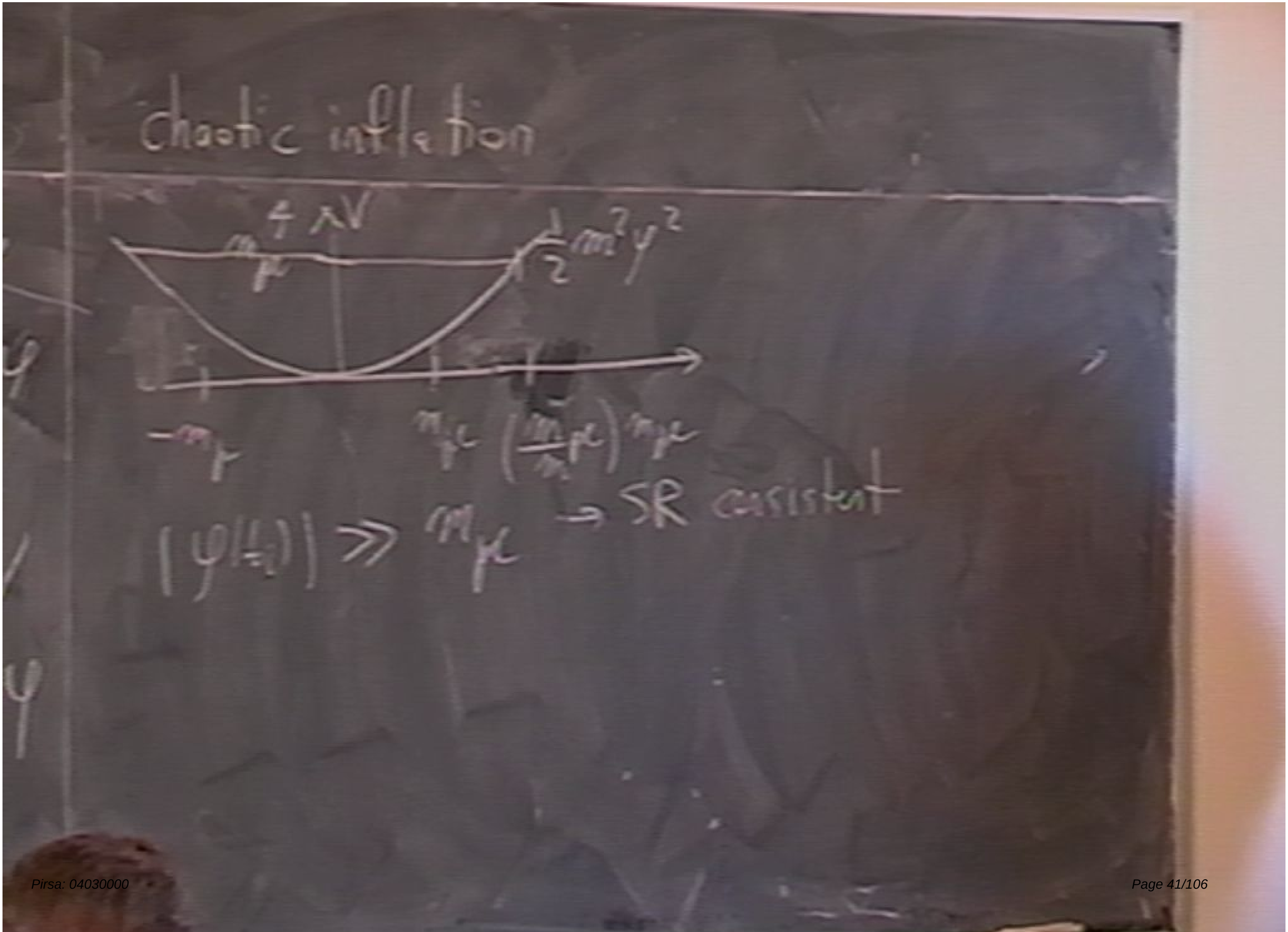
chaotic inflation

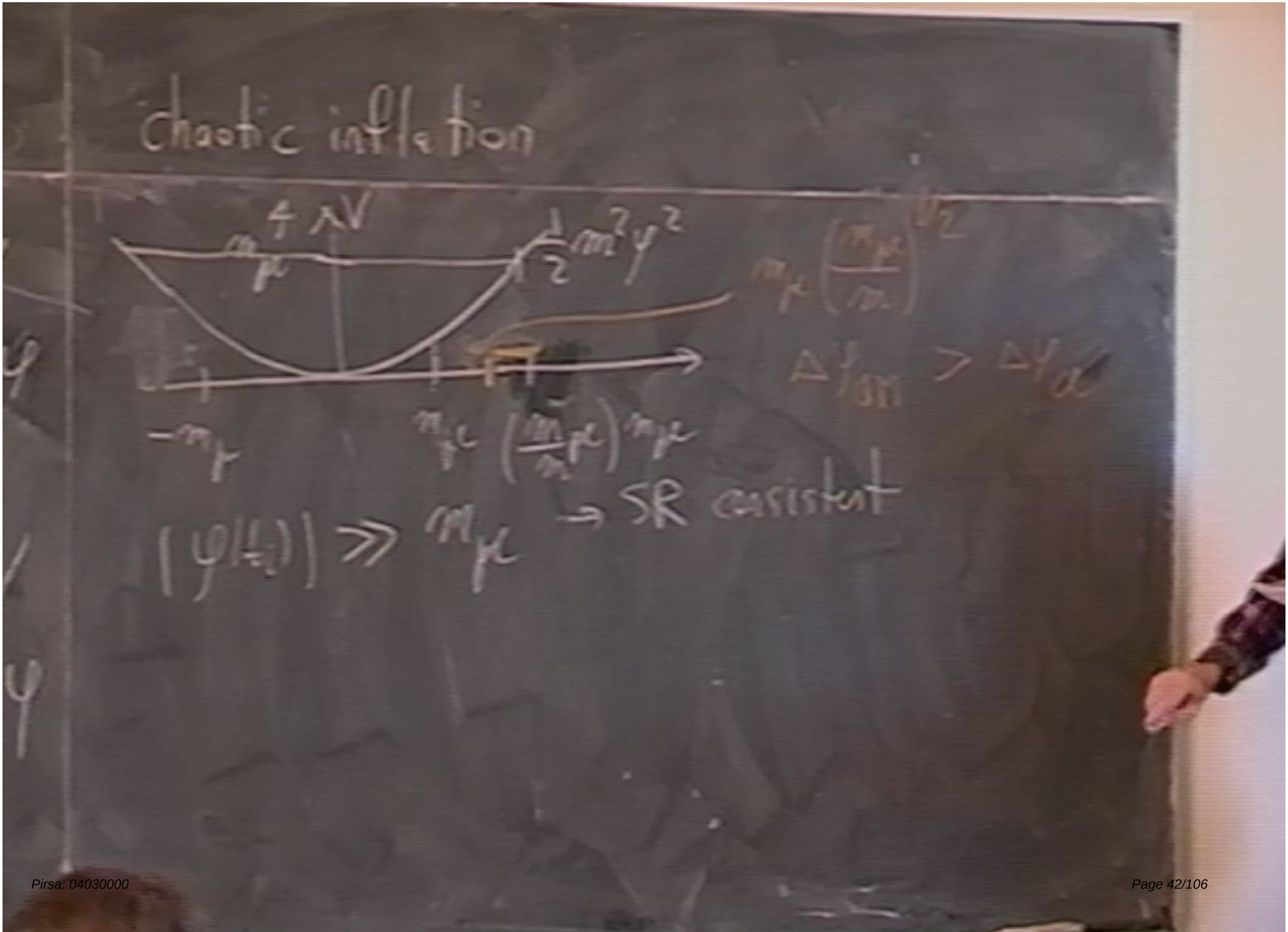


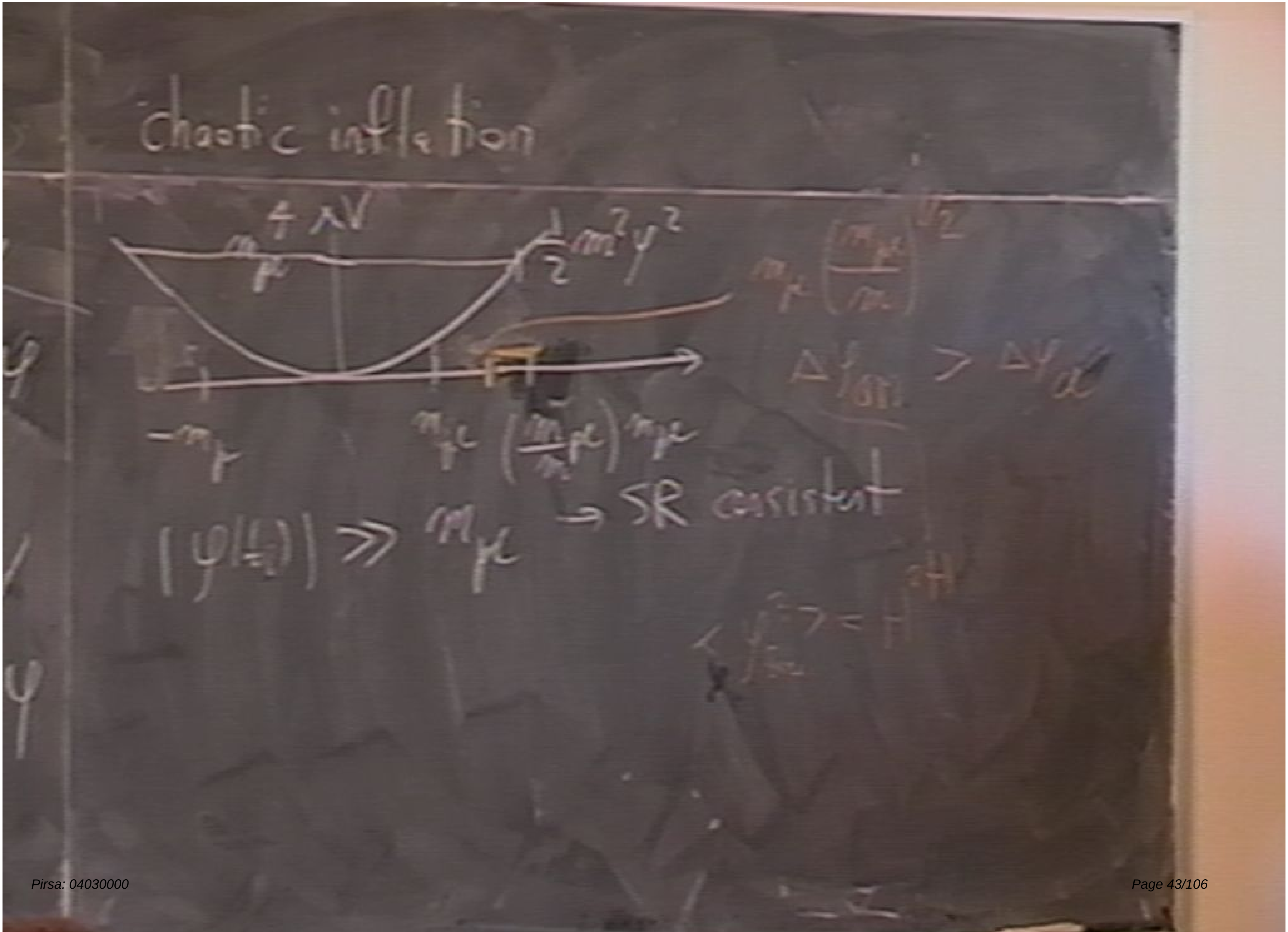
$|\varphi(t_i)| \gg m_P \rightarrow$ SR consistent chaotic inflation

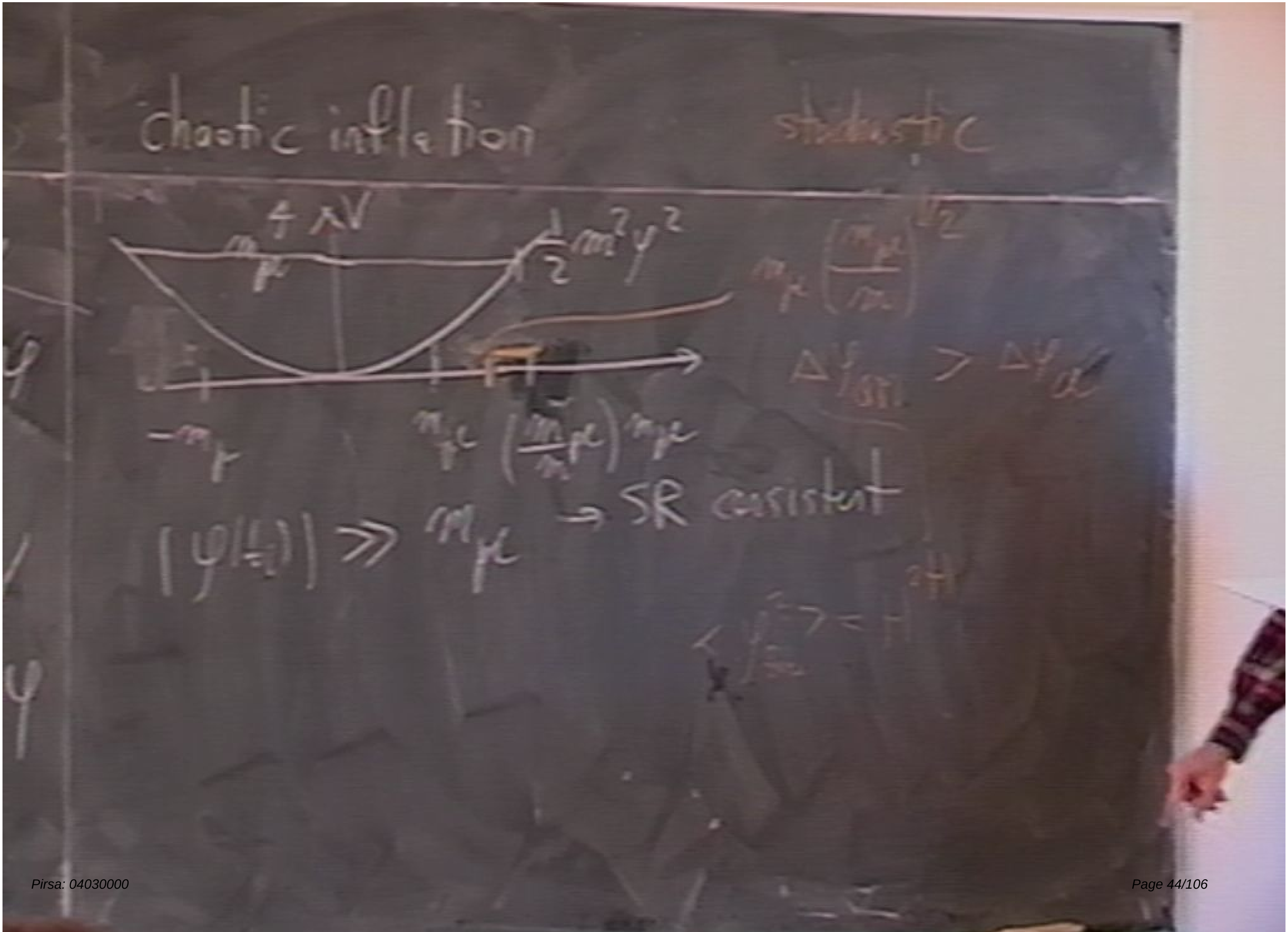


$|\varphi(t_i)| \gg m_p \rightarrow$ SR consistent

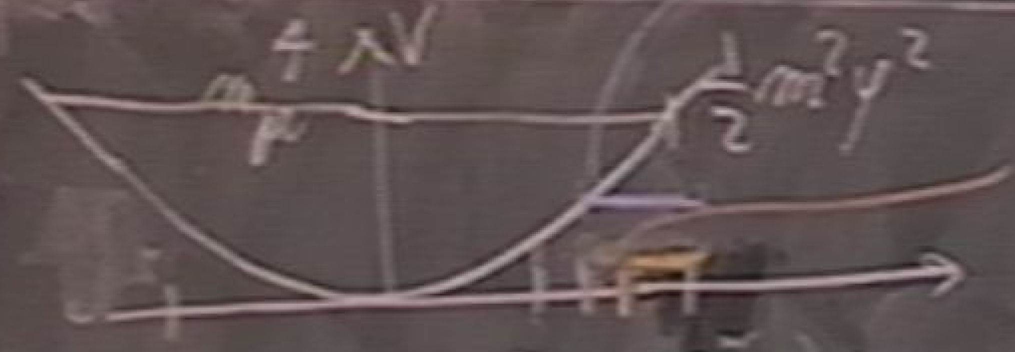

chaotic inflation
$\frac{1}{2}m^2\varphi^2$
$m_\mu^4 \quad \lambda V$
$-m_\mu \quad m_\mu \quad \left(\frac{m_\mu}{m}\right) m_\mu$
$|\varphi(t_i)| \gg m_\mu \rightarrow$ SR consistent


chaotic inflation
SR consistent


chaotic inflation
V
1/2 m² φ²
SR consistent


chaotic inflation
stochastic
V
1/2 m² φ²
SR consistent

chaotic inflation $\left(\frac{m_{pl}}{m}\right)^{1/3} m_{pl}$ stochastic



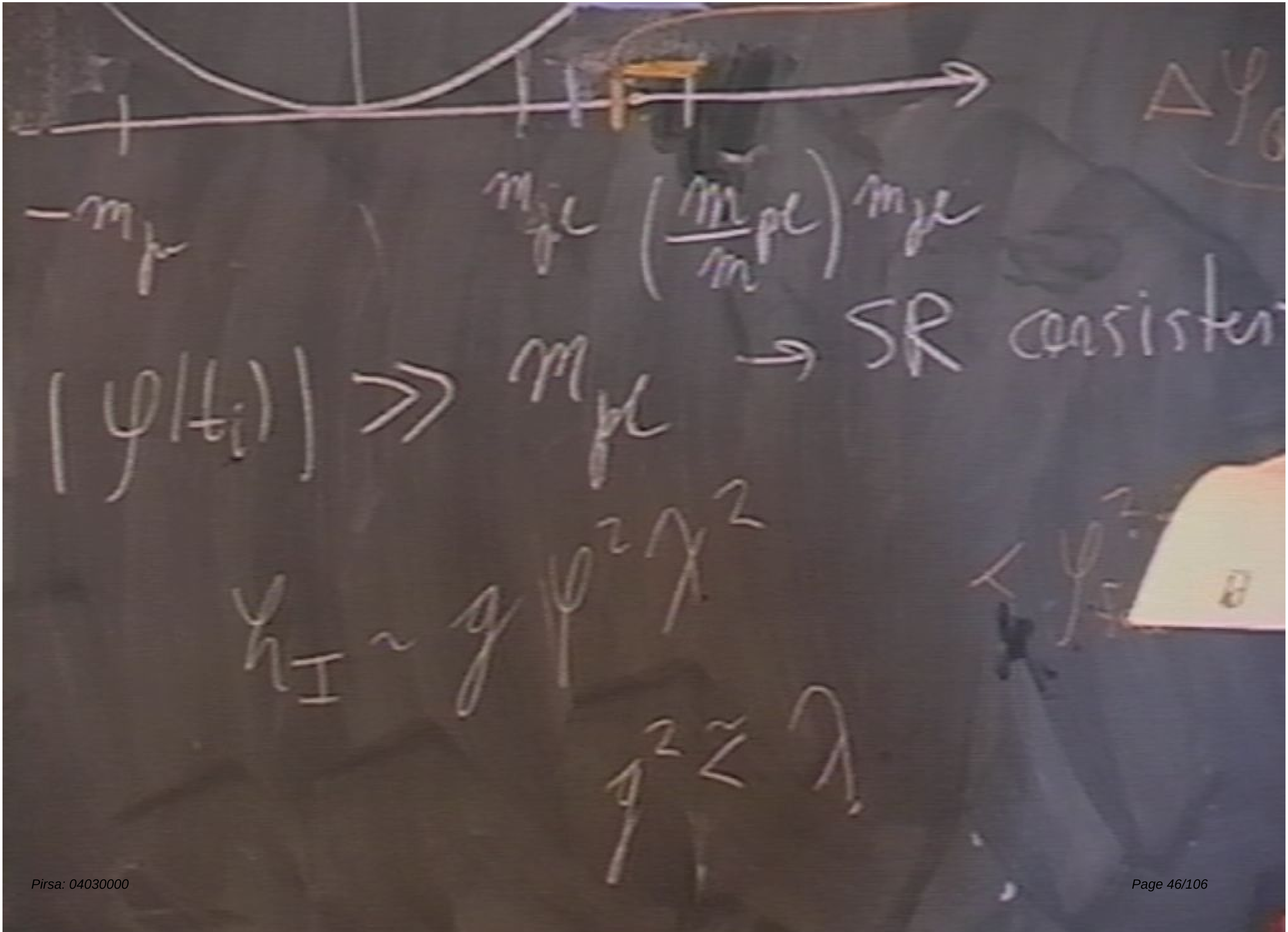
$m_{pl}\left(\frac{m_{pl}}{m}\right)^{1/2}$

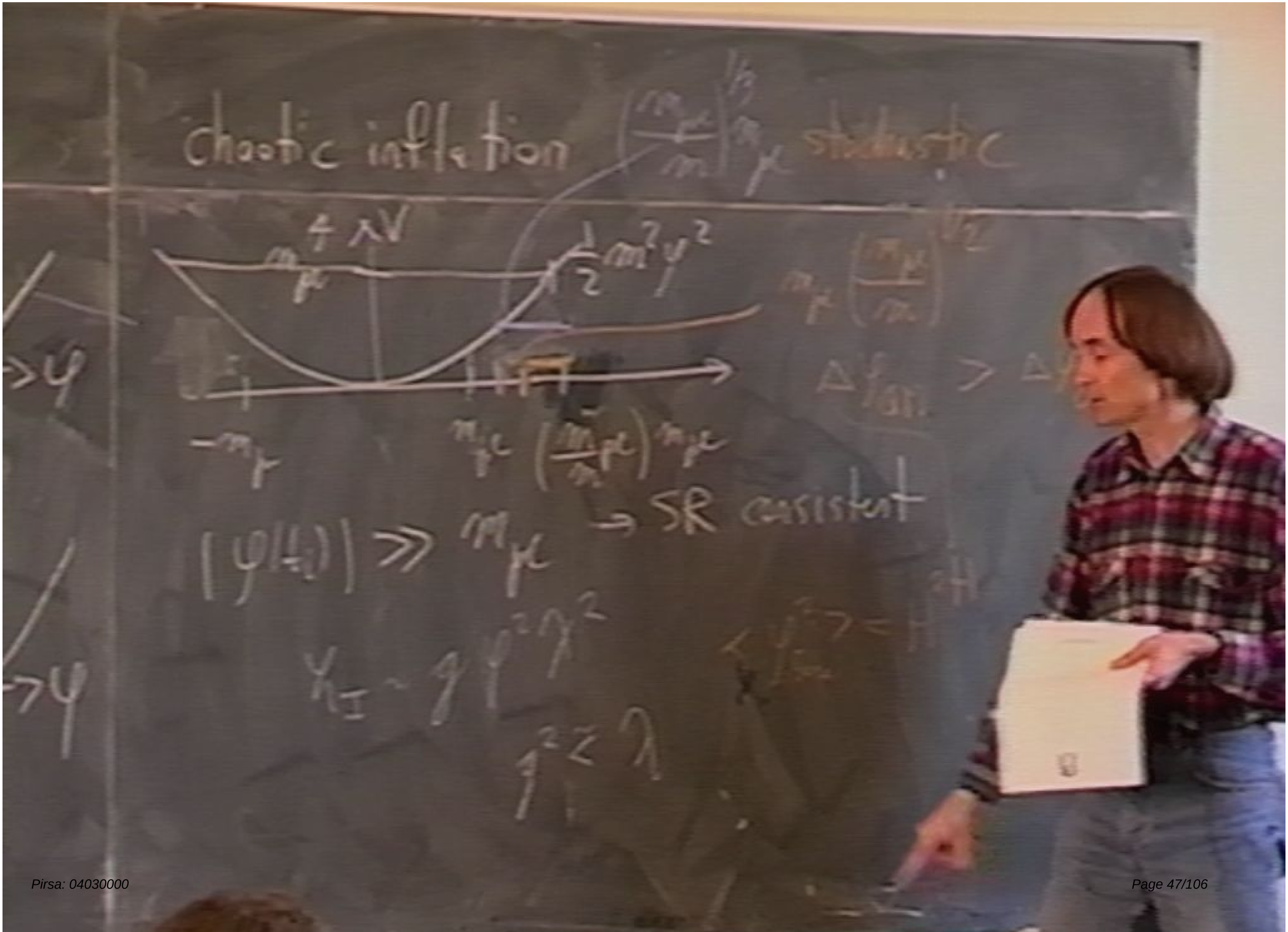
$\Delta\varphi_{cl} > \Delta\varphi_{q}$

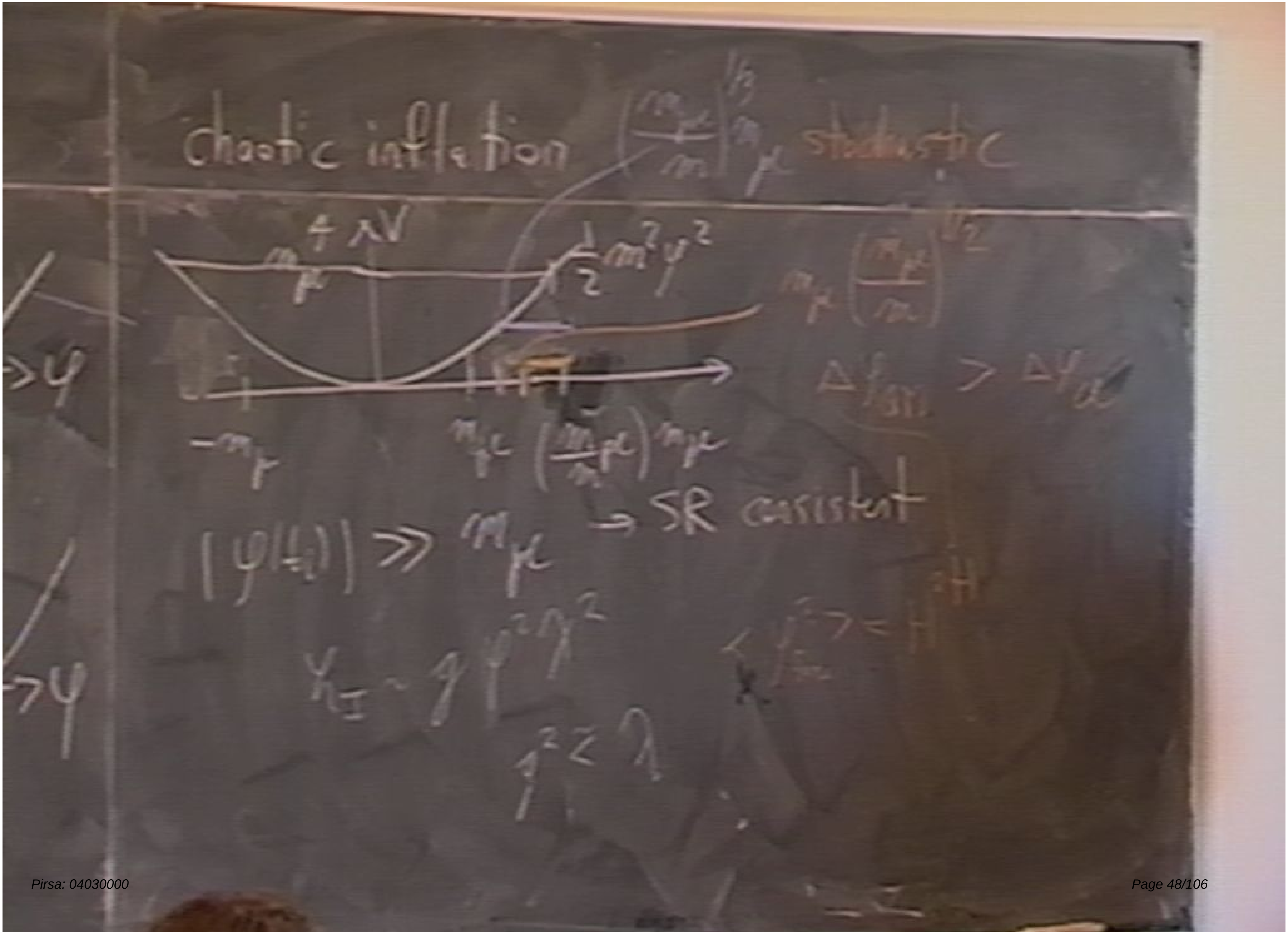
$m_{pl}\left(\frac{m_{pl}}{m}\right)m_{pl}$ → SR consistent

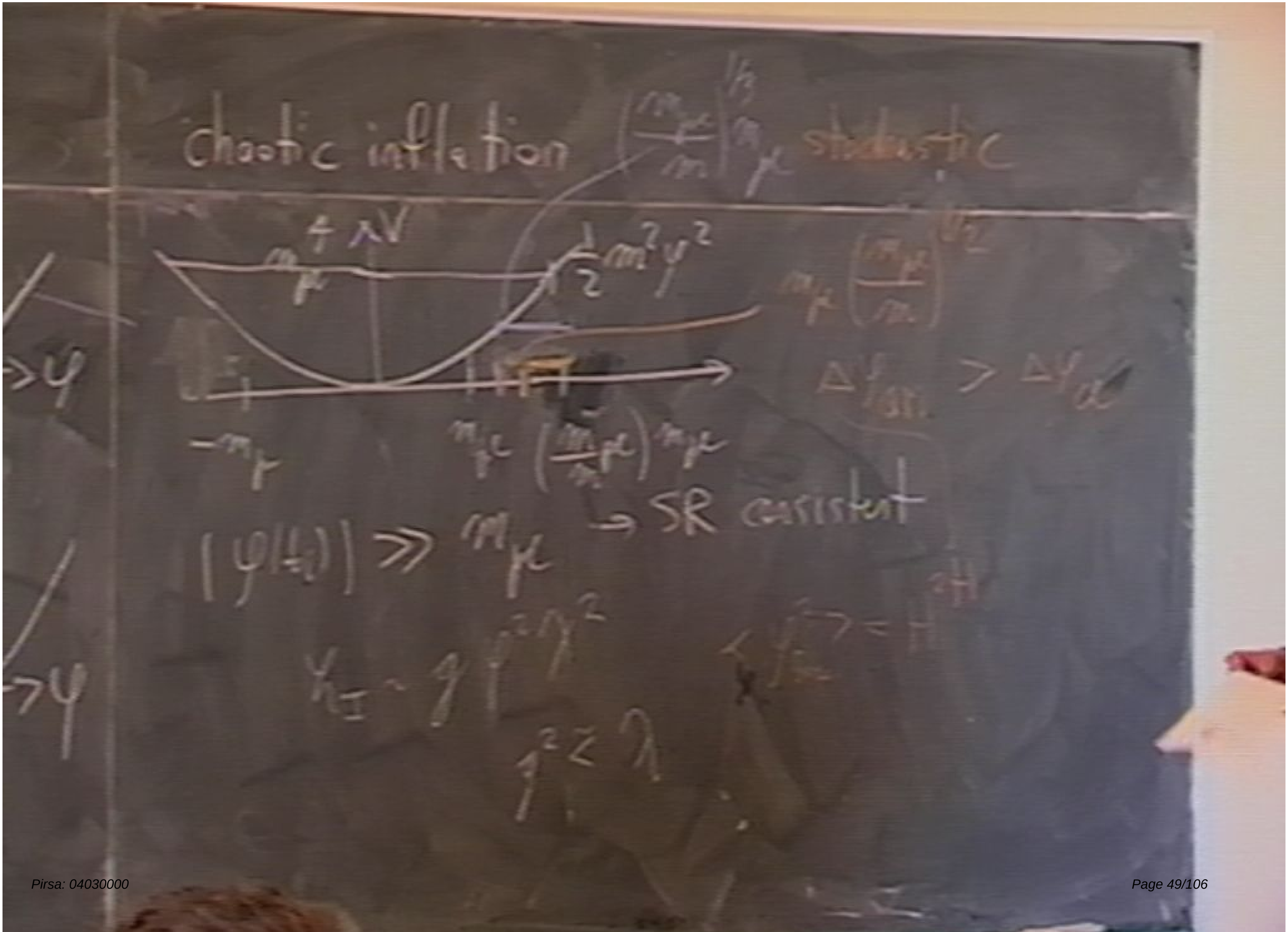
$|\varphi(t_i)| \gg m_{pl}$

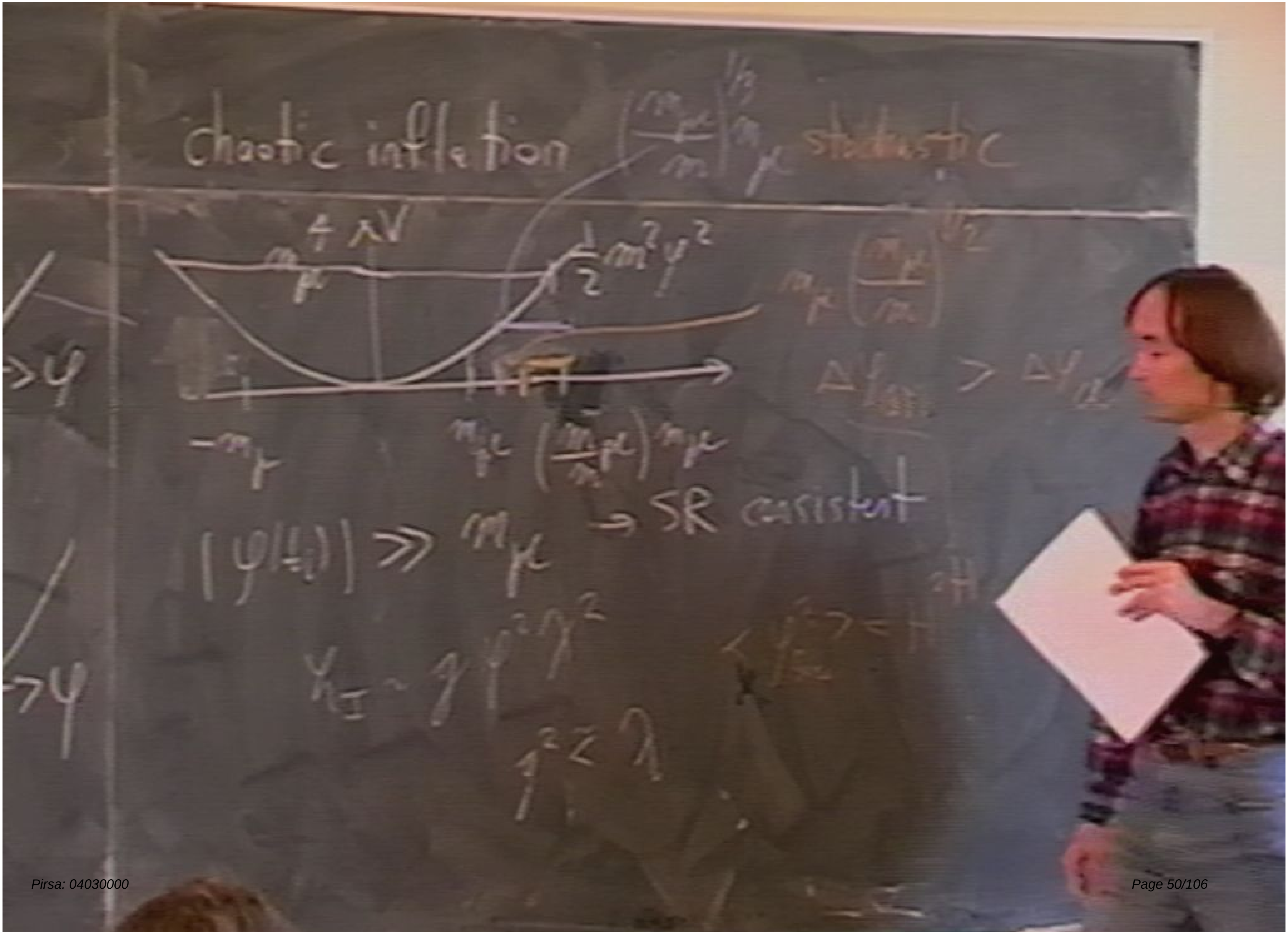
$\langle \varphi^2 \rangle = H^{2}H$

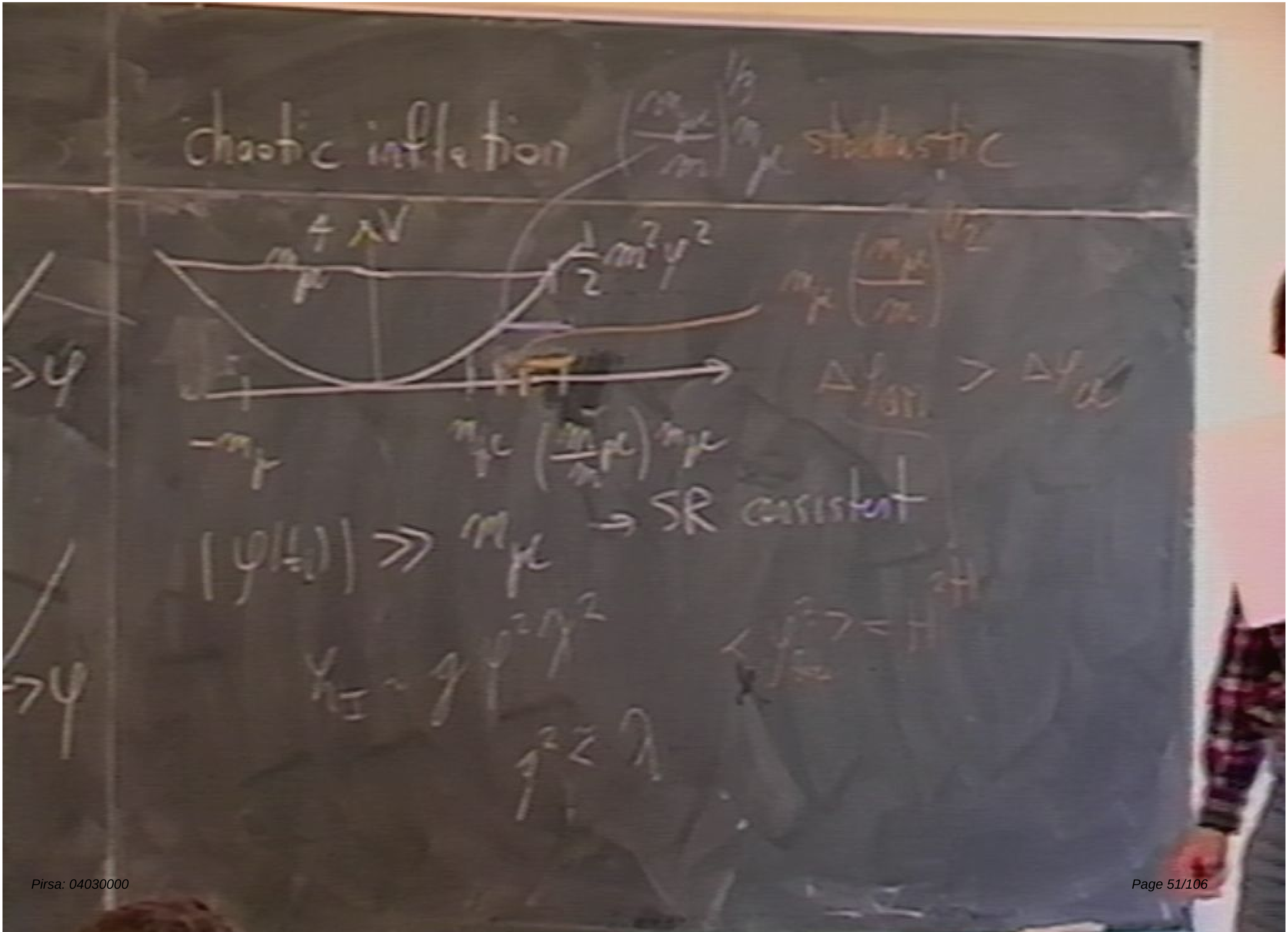

$-m_{pl}$
m_{pl} $\left(\frac{m}{m} m_{pl}\right)$ m_{pl}
$|\varphi(t_i)| \gg m_{pl}$ → SR consisten
$\mathcal{L}_I \sim g\,\varphi^2 \chi^2$
$g^2 \lesssim \lambda$

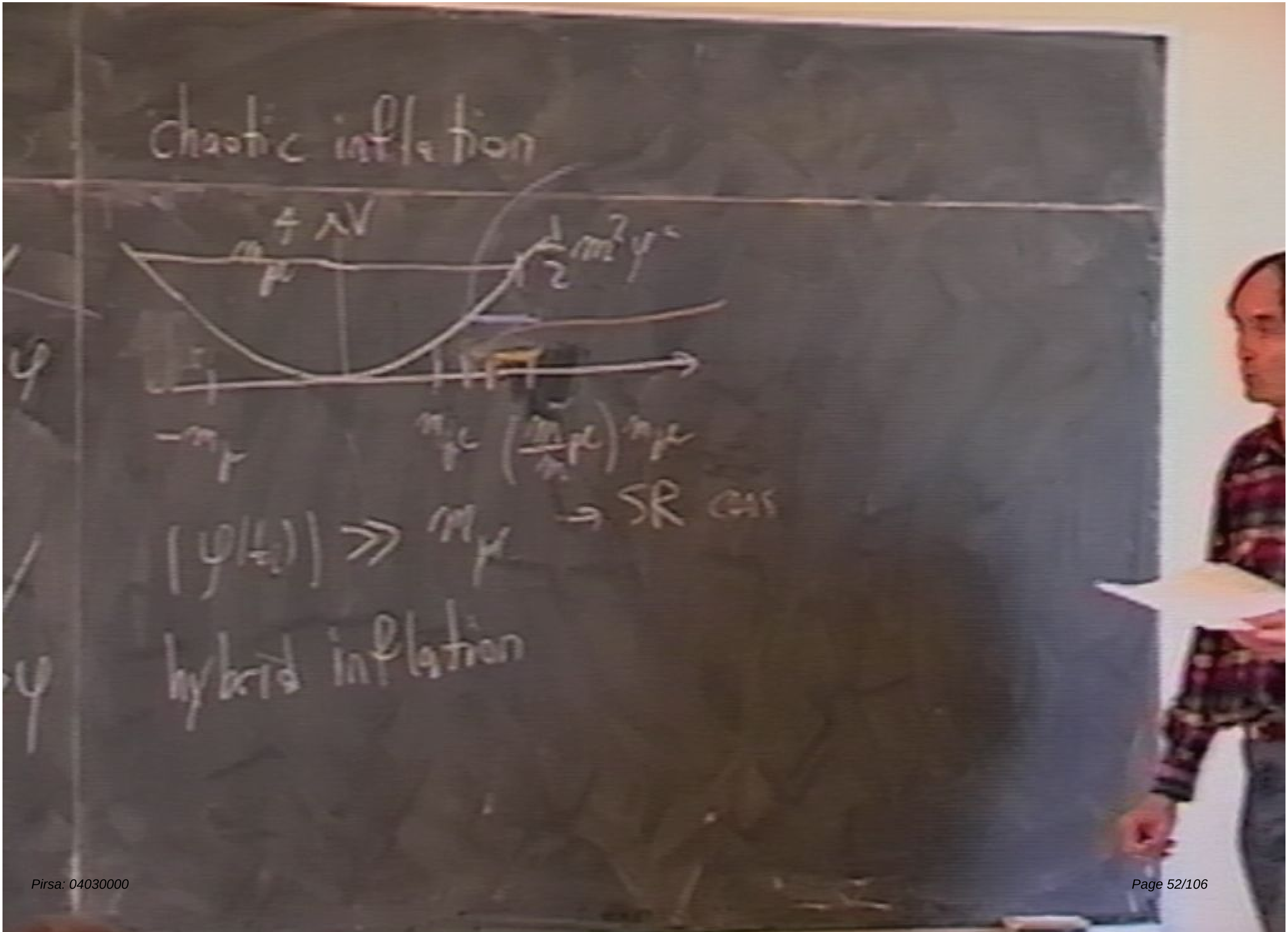

chaotic inflation
stochastic
SR consistent

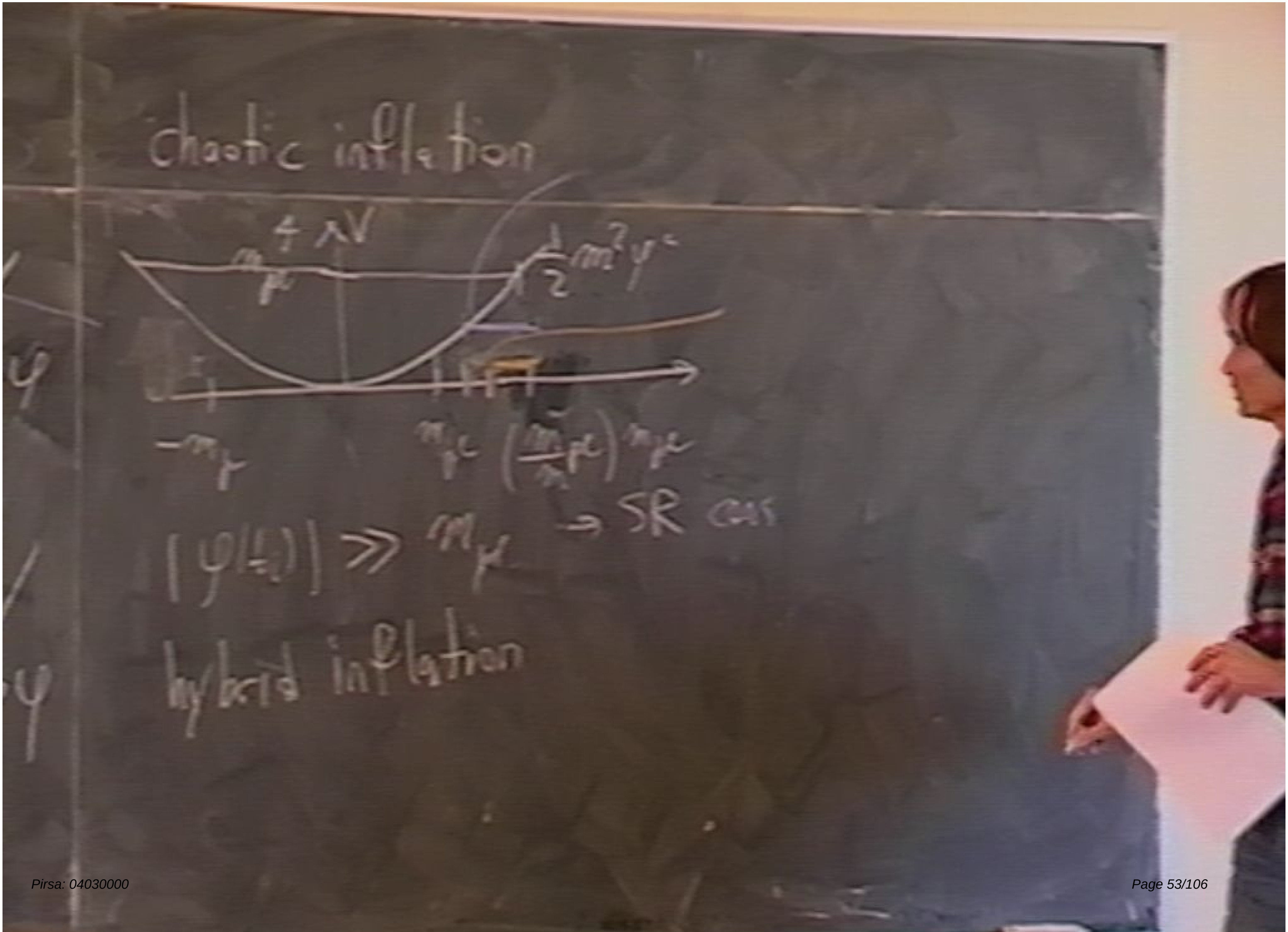

chaotic inflation
stochastic
$\frac{1}{2}m^2\varphi^2$
λV
SR consistent
$\langle \varphi^2 \rangle = H$
$g^2 < \lambda$

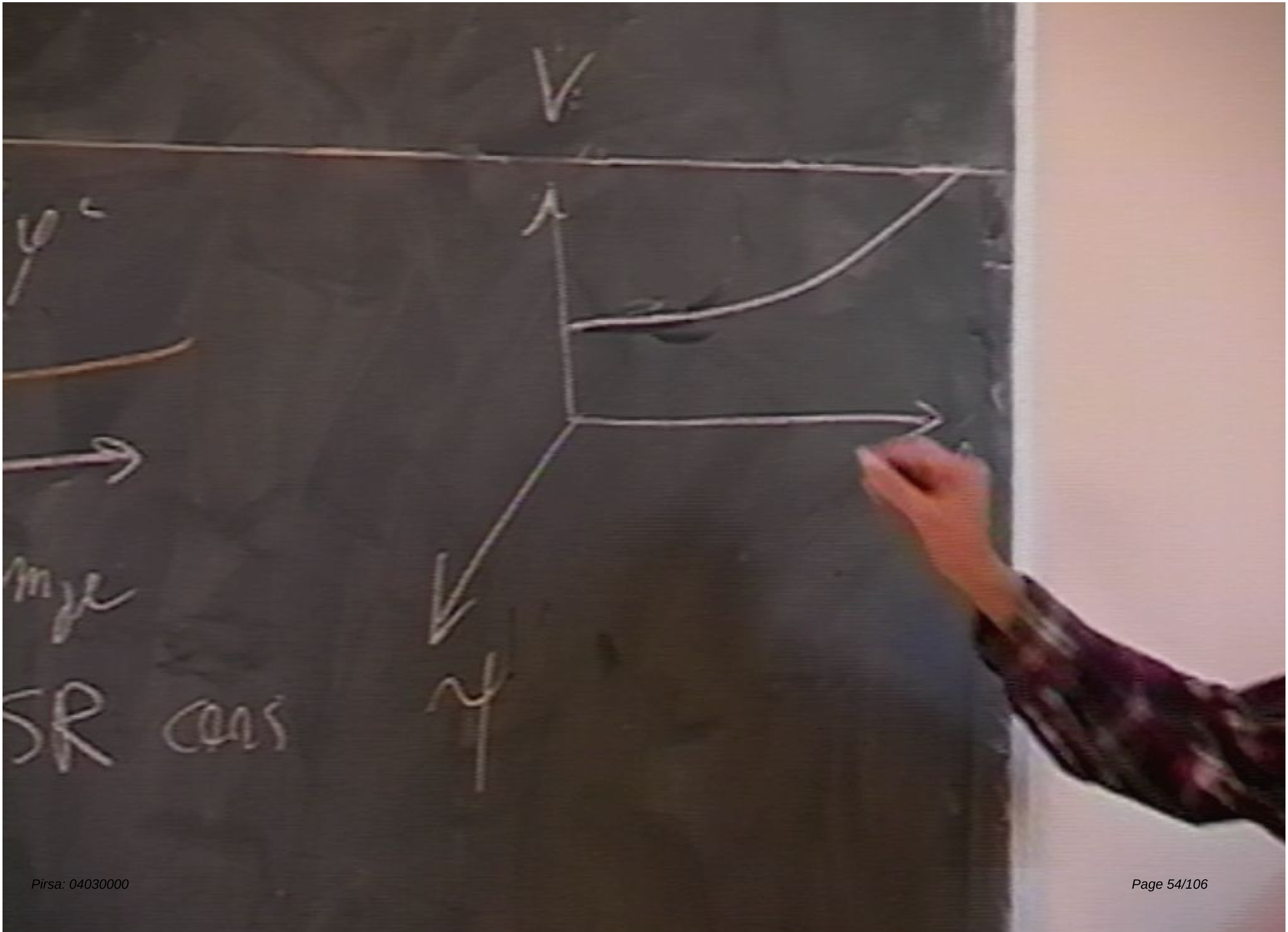

chaotic inflation
stochastic
SR consistent

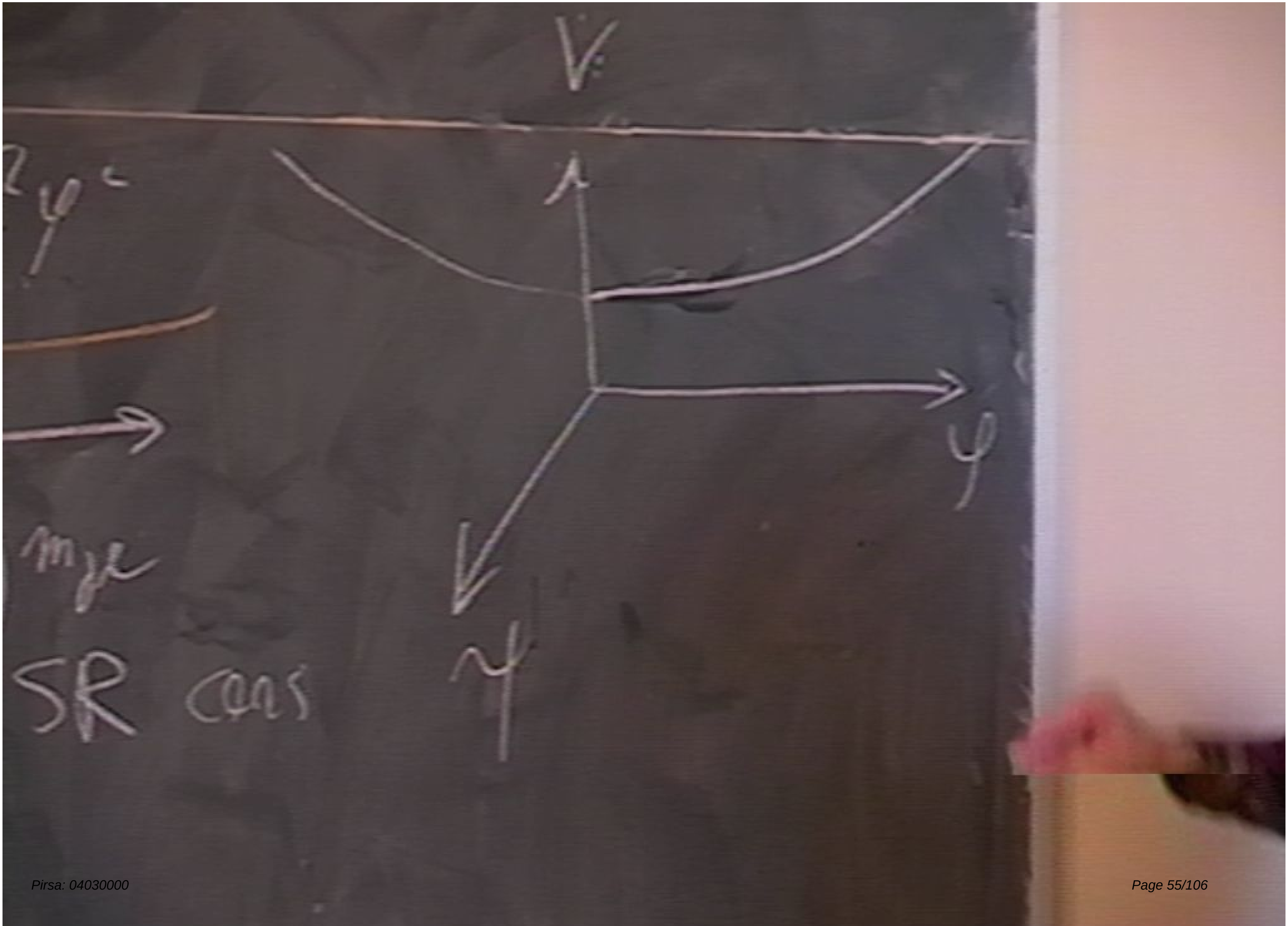

chaotic inflation
stochastic
SR consistent

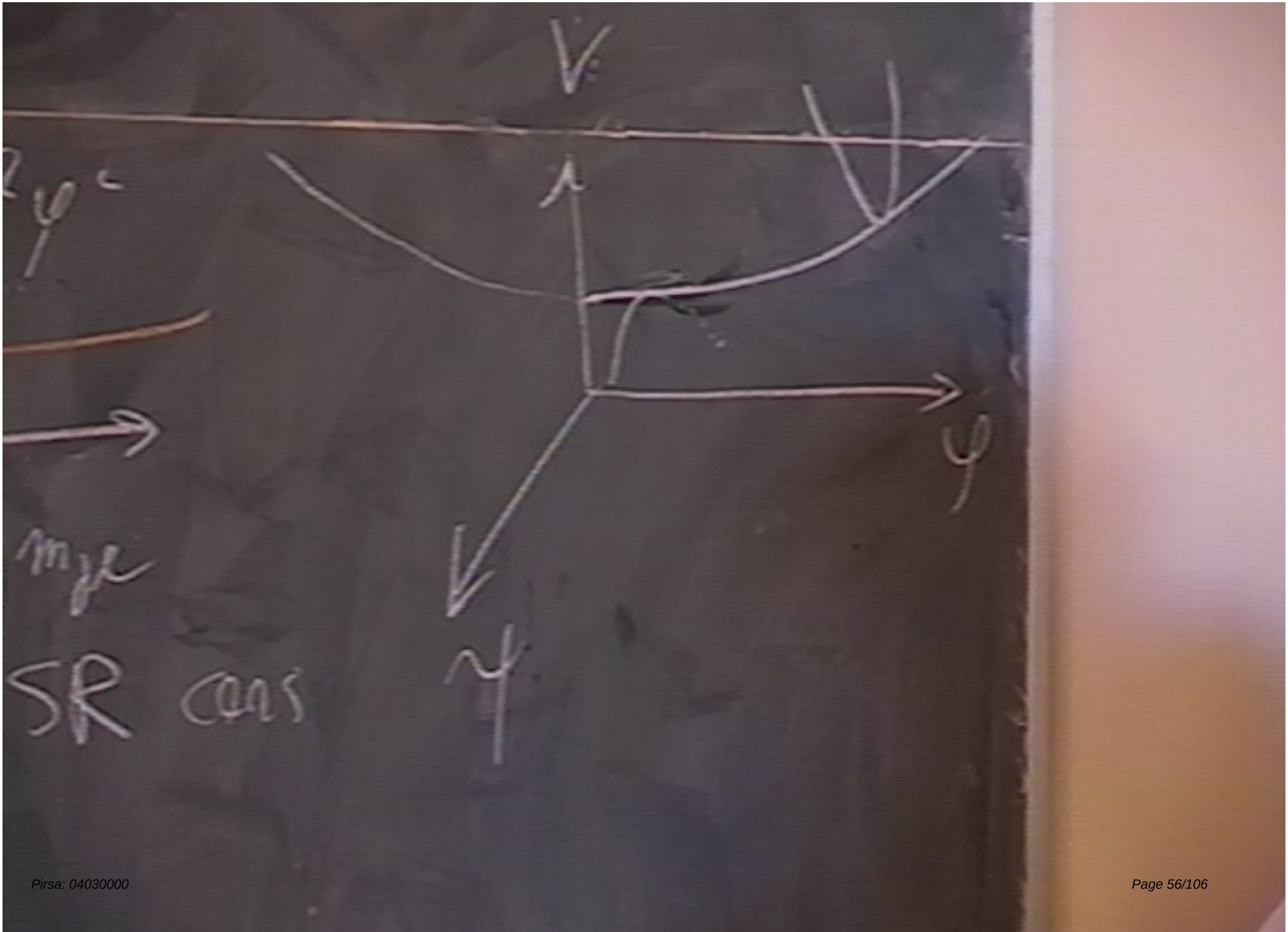

chaotic inflation
stochastic
SR consistent

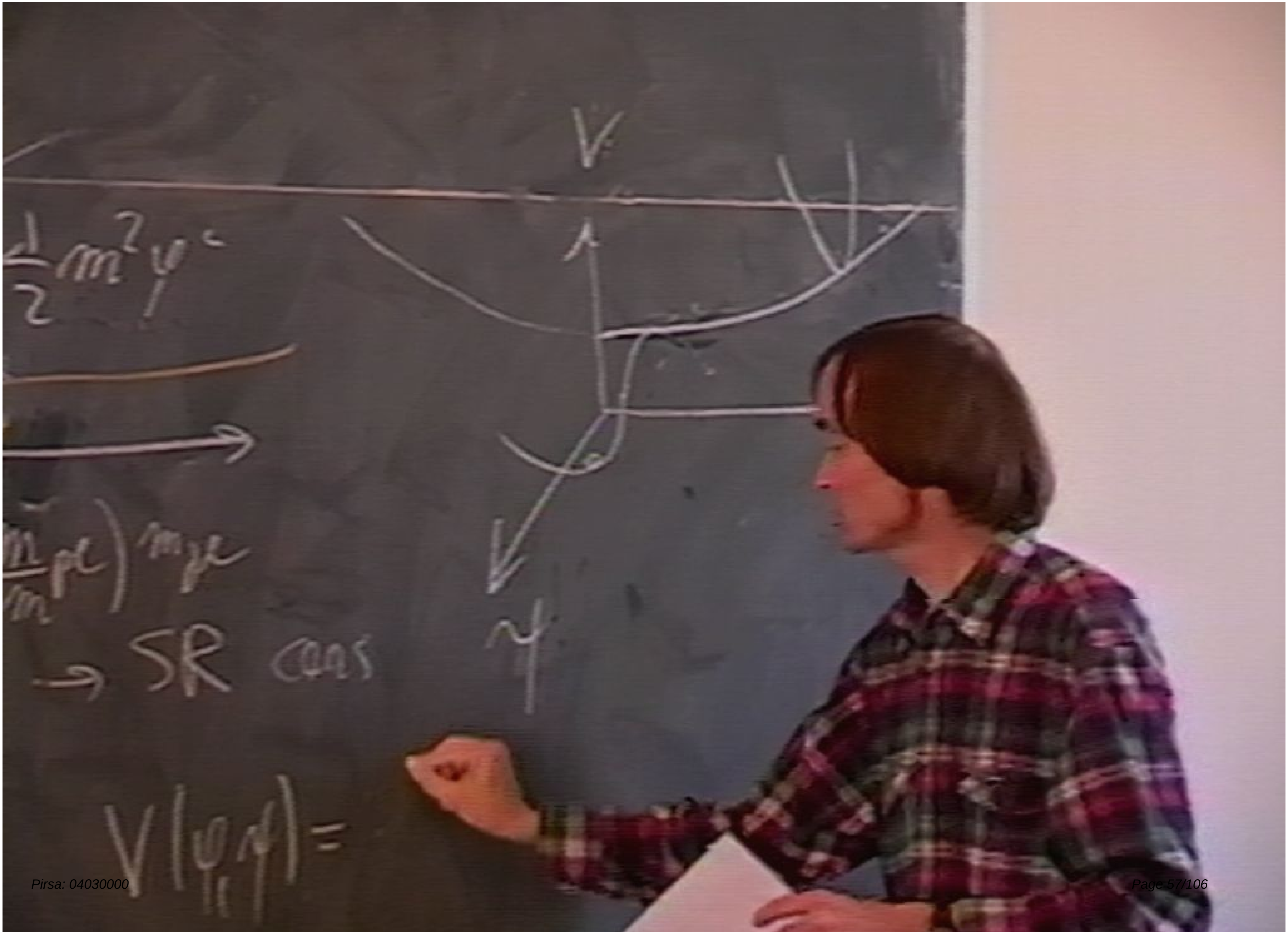

chaotic inflation
hybrid inflation

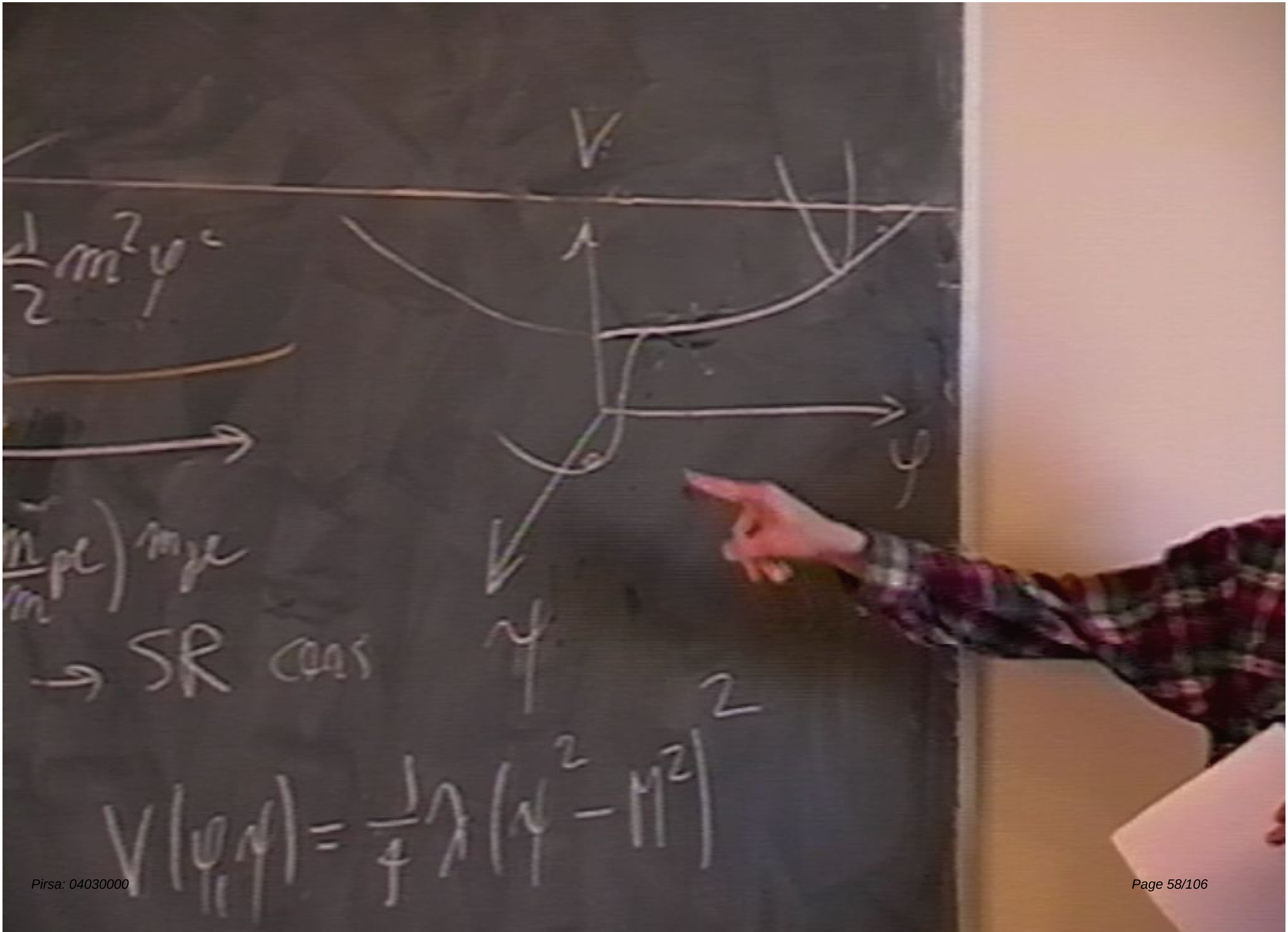

chaotic inflation
hybrid inflation


SR cons

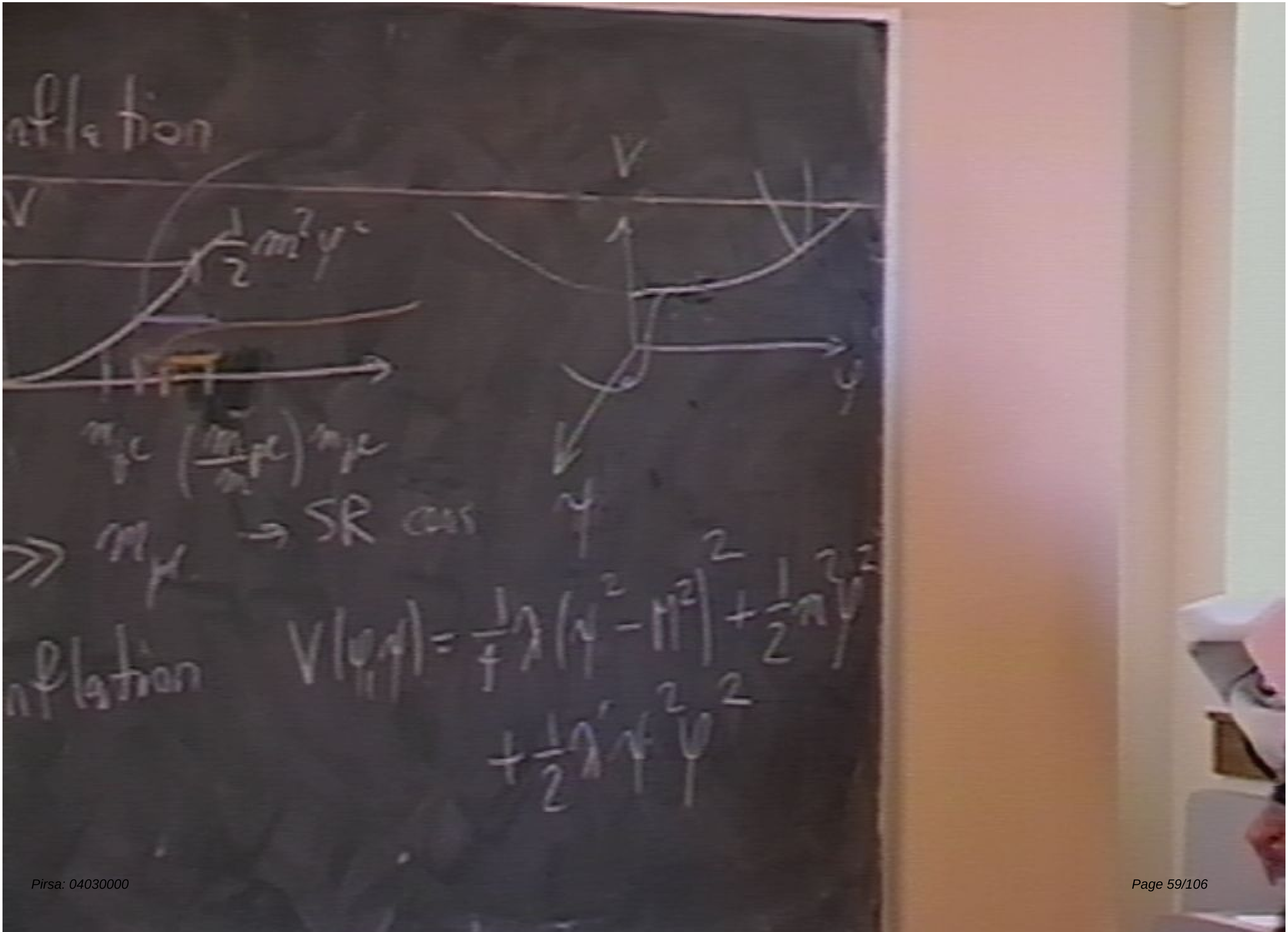

V
SR cons

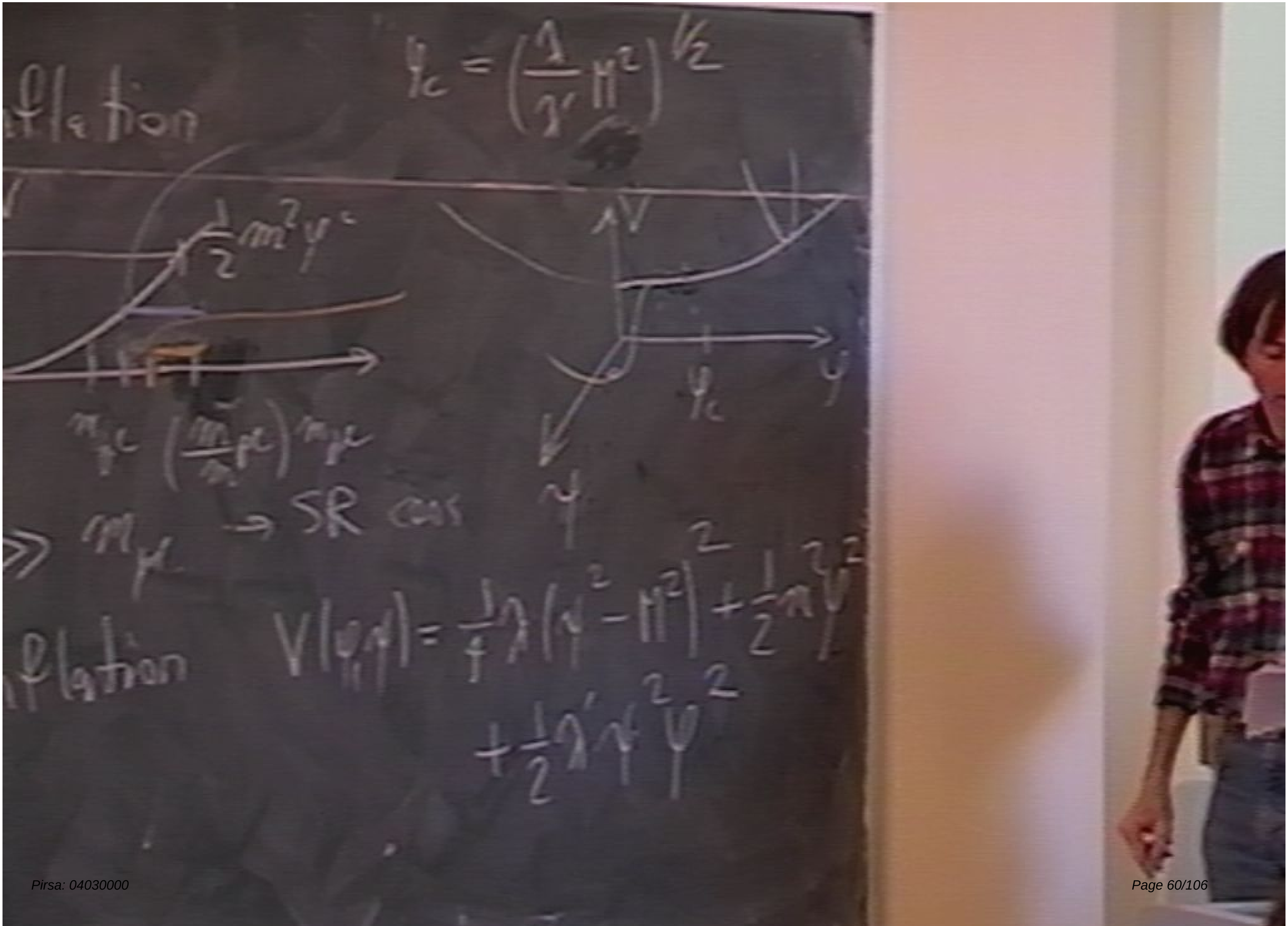

V
SR cons

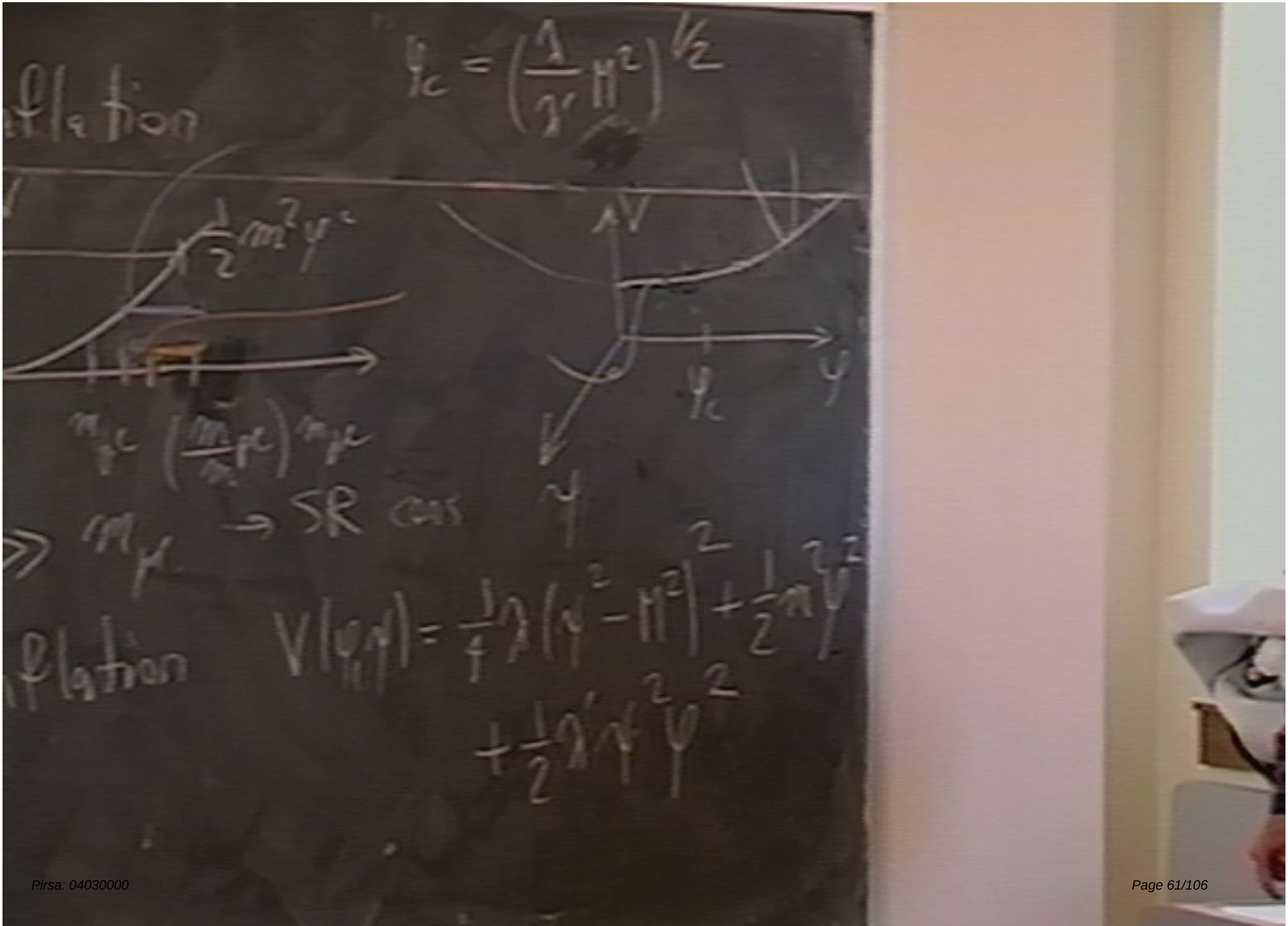

SR cons



V(φ,ψ) = 1/4 λ (ψ² − M²)²

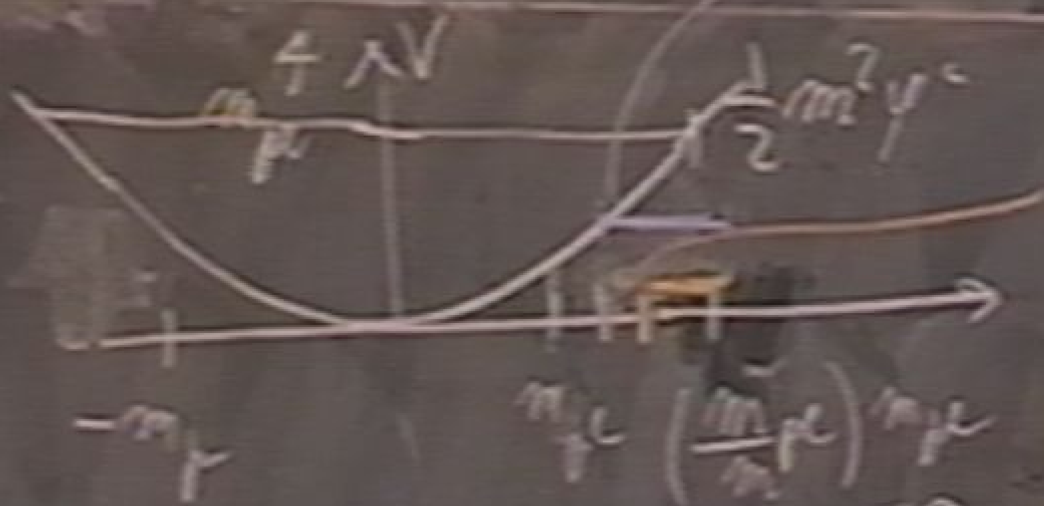

nflation
V
$\frac{1}{2}m^2\varphi^2$
SR
nflation
$V(\varphi,\psi) = \frac{1}{4}\lambda(\psi^2 - M^2)^2 + \frac{1}{2}m^2\varphi^2$
$+ \frac{1}{2}\lambda'\psi^2\varphi^2$

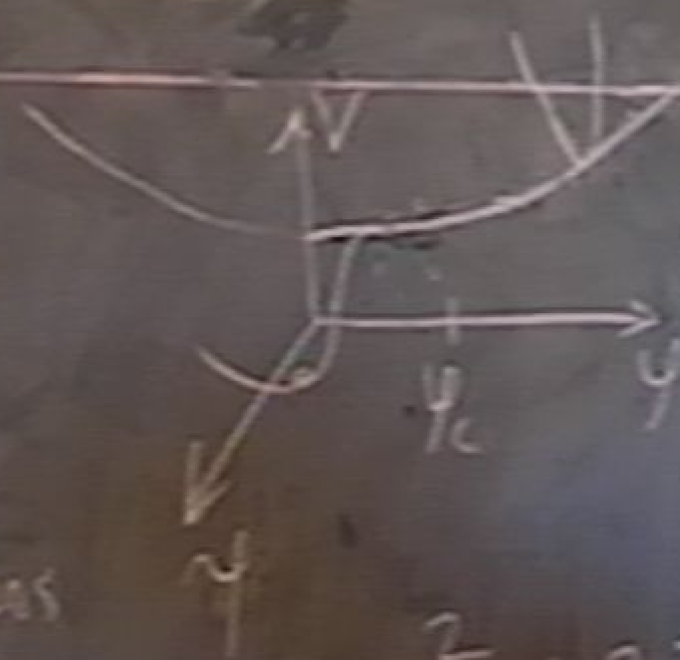

$\psi_c = \left(\frac{1}{\lambda'} M^2\right)^{1/2}$
flation
$\frac{1}{2} m^2 \varphi^2$
ψ_c
φ
SR cos
$\gg m_\varphi$
$V(\psi, \varphi) = \frac{1}{4}\lambda(\psi^2 - M^2)^2 + \frac{1}{2} m^2 \varphi^2 + \frac{1}{2}\lambda' \varphi^2 \psi^2$
flation


inflation
SR cons
inflation

Chaotic inflation

$$\psi_c = \left(\frac{\lambda}{\lambda'} M^2\right)^{1/2}$$

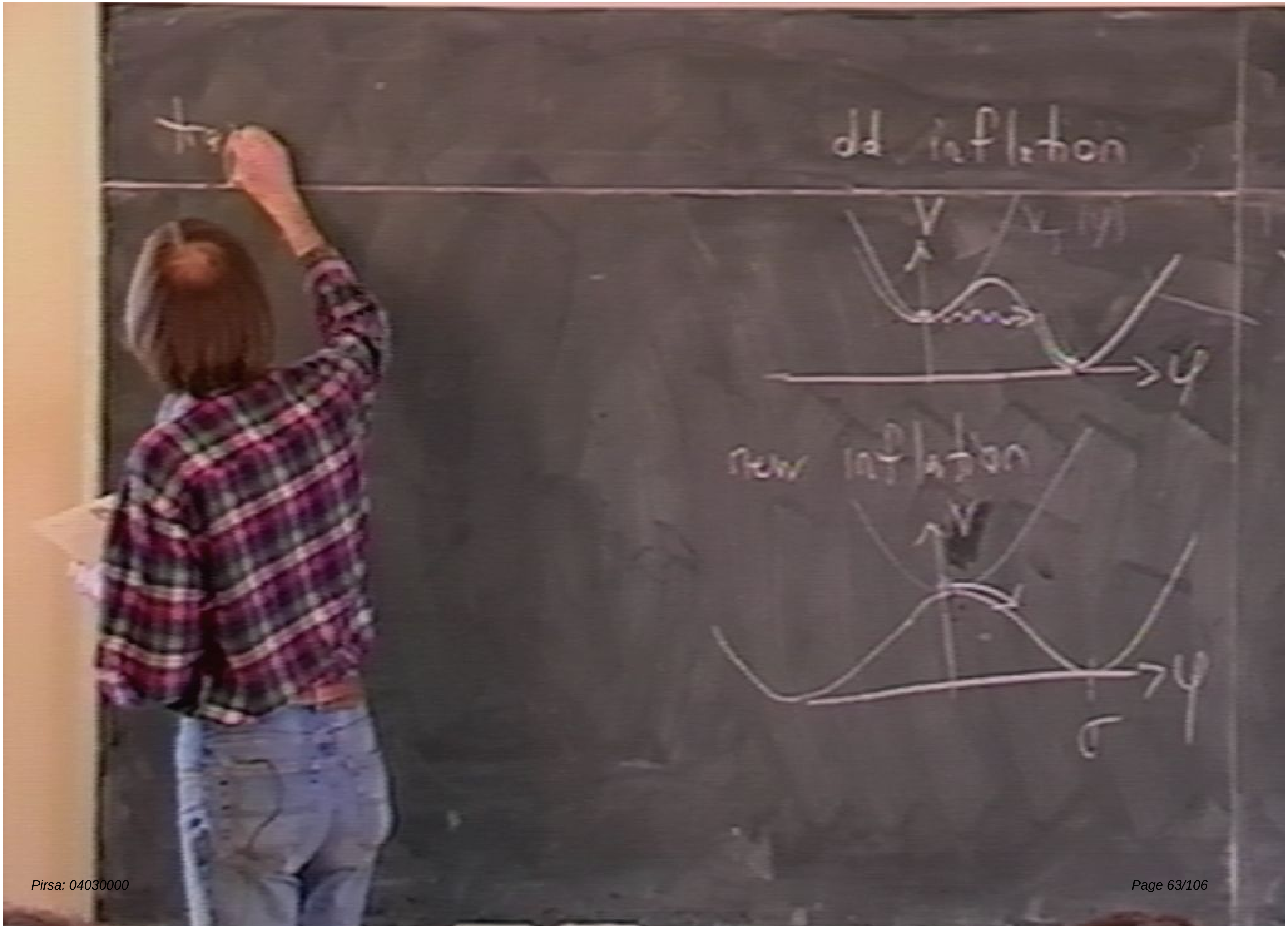




$|\varphi(t_i)| \gg m_{pl}$ → SR conds

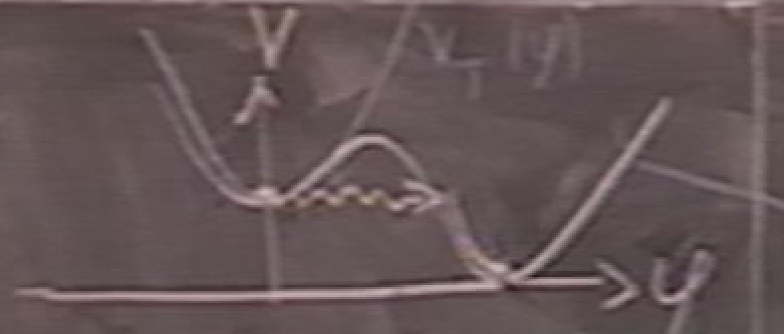
hybrid inflation $V(\varphi,\psi) = \frac{1}{4}\lambda(\psi^2 - M^2)^2 + \frac{1}{2}m^2\varphi^2 + \frac{1}{2}\lambda'\psi^2\varphi^2$

want: $\frac{1}{4}\lambda M^4 > \frac{1}{2} m^2 m_{pl}^2$


new inflation
V
ψ
σ

trapped inflation

old inflation

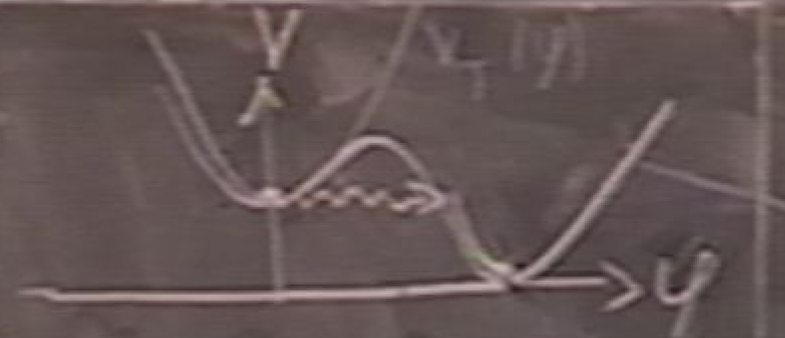


new inflation

trapped inflation

same as hybrid

old inflation



new inflation

trapped inflation

same as hybrid

φ oscillates about $\varphi = 0$

with large amplitude

↓

stabilizes $\psi = 0$

dd inflation

new inflation

trapped inflation

same as hybrid

ψ oscillates about $\psi = 0$

with large amplitude

↓

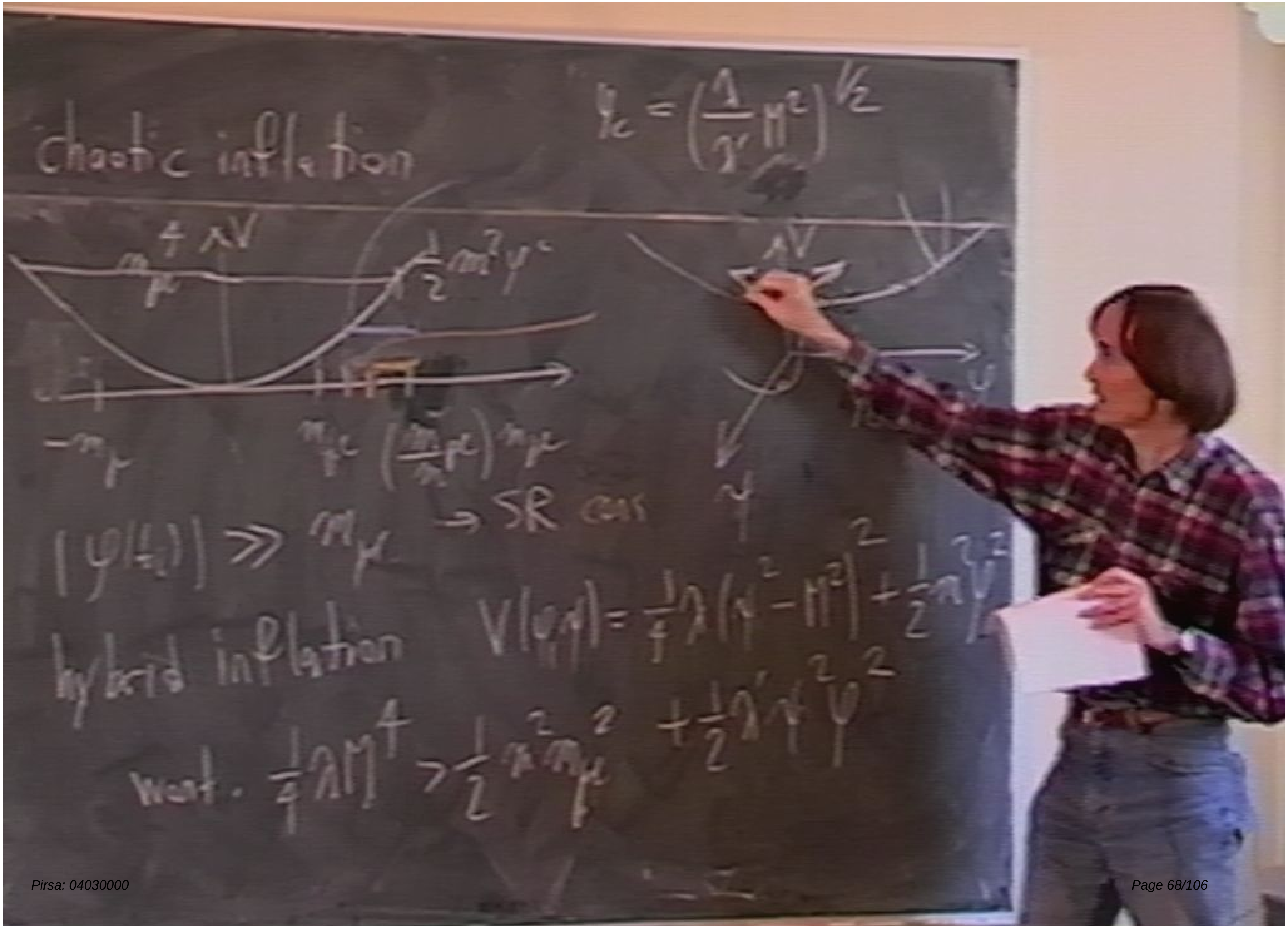
stabilizes $\psi = 0$

↓

new dd inflation

dd inflation

new inflation


chaotic inflation
$\psi_c = \left(\frac{\lambda}{\lambda'} M^2\right)^{1/2}$
$\frac{1}{2} m^2 \psi^2$
$|\psi(t_i)| \gg m_{pl}$
SR cons
hybrid inflation
$V(\psi,\phi) = \frac{1}{4}\lambda(\phi^2 - M^2)^2 + \frac{1}{2} m^2 \psi^2 + \frac{1}{2}\lambda' \phi^2 \psi^2$
want. $\frac{1}{4}\lambda M^4 > \frac{1}{2} m^2 m_{pl}^2$

trapped inflation

same as hybrid

φ oscillates about $\varphi = 0$

with large amplitude

↓

stabilizes $\psi = 0$

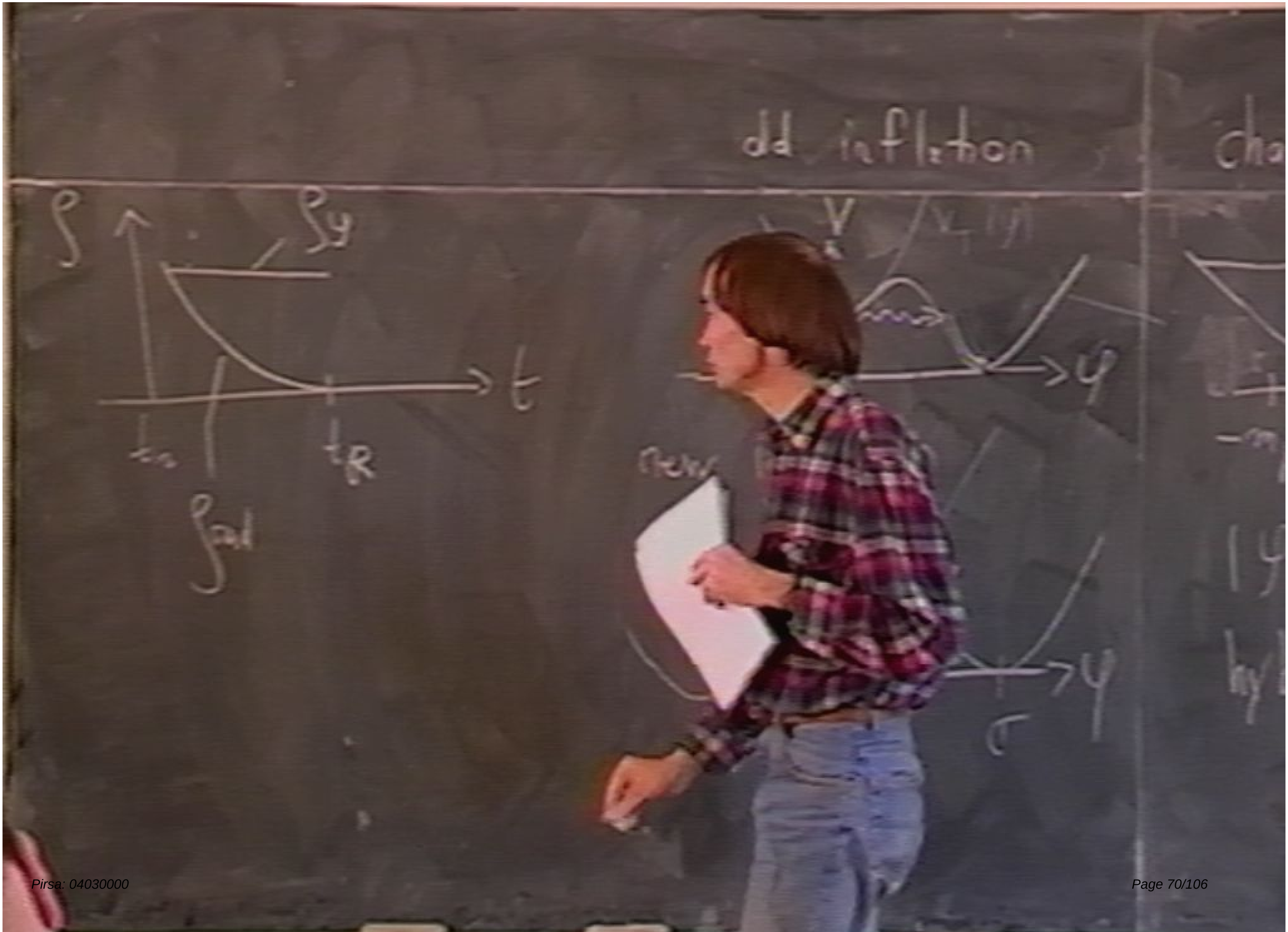
↓

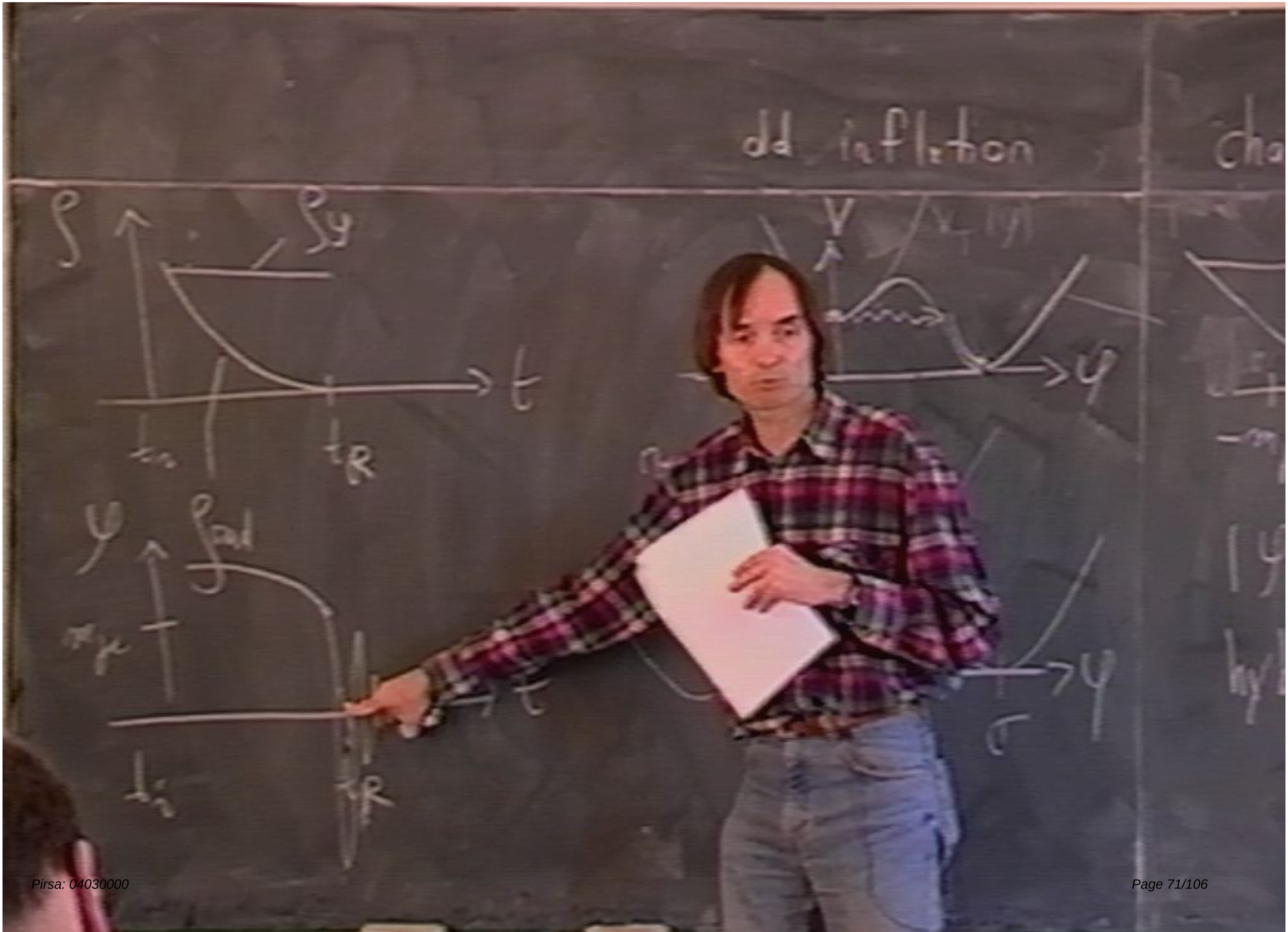
new dd inflation

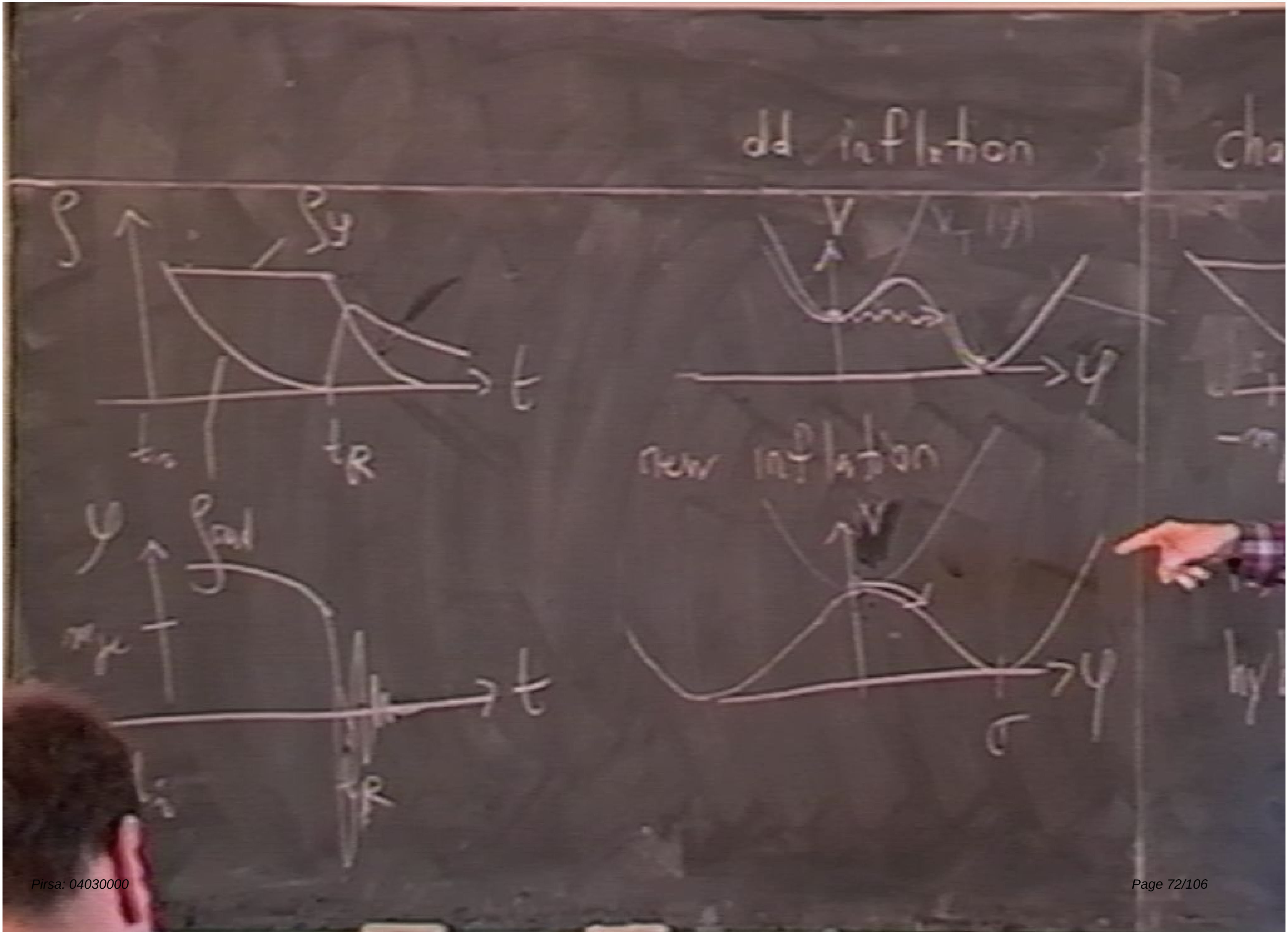
dd inflation

new inflation

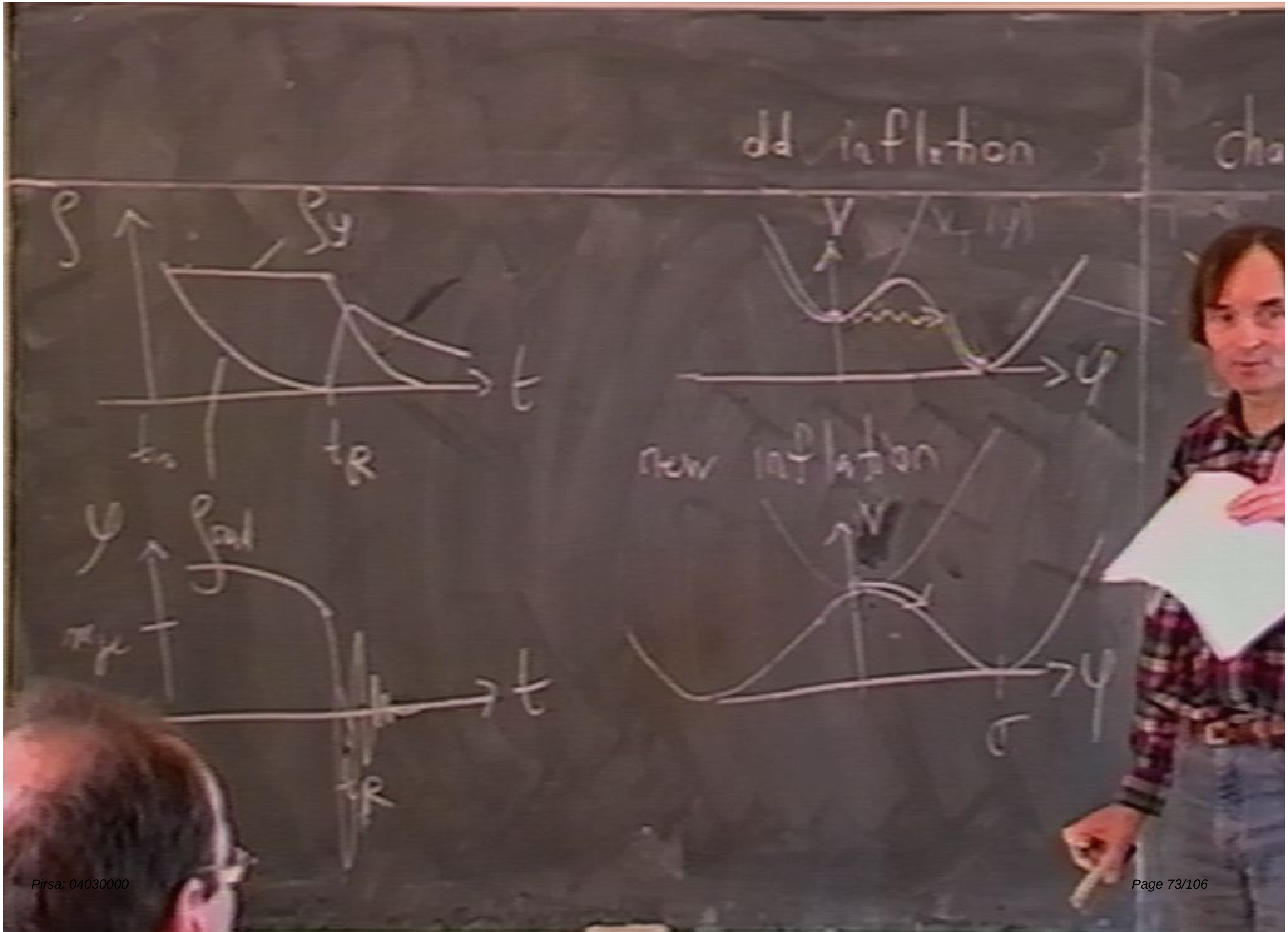
cha

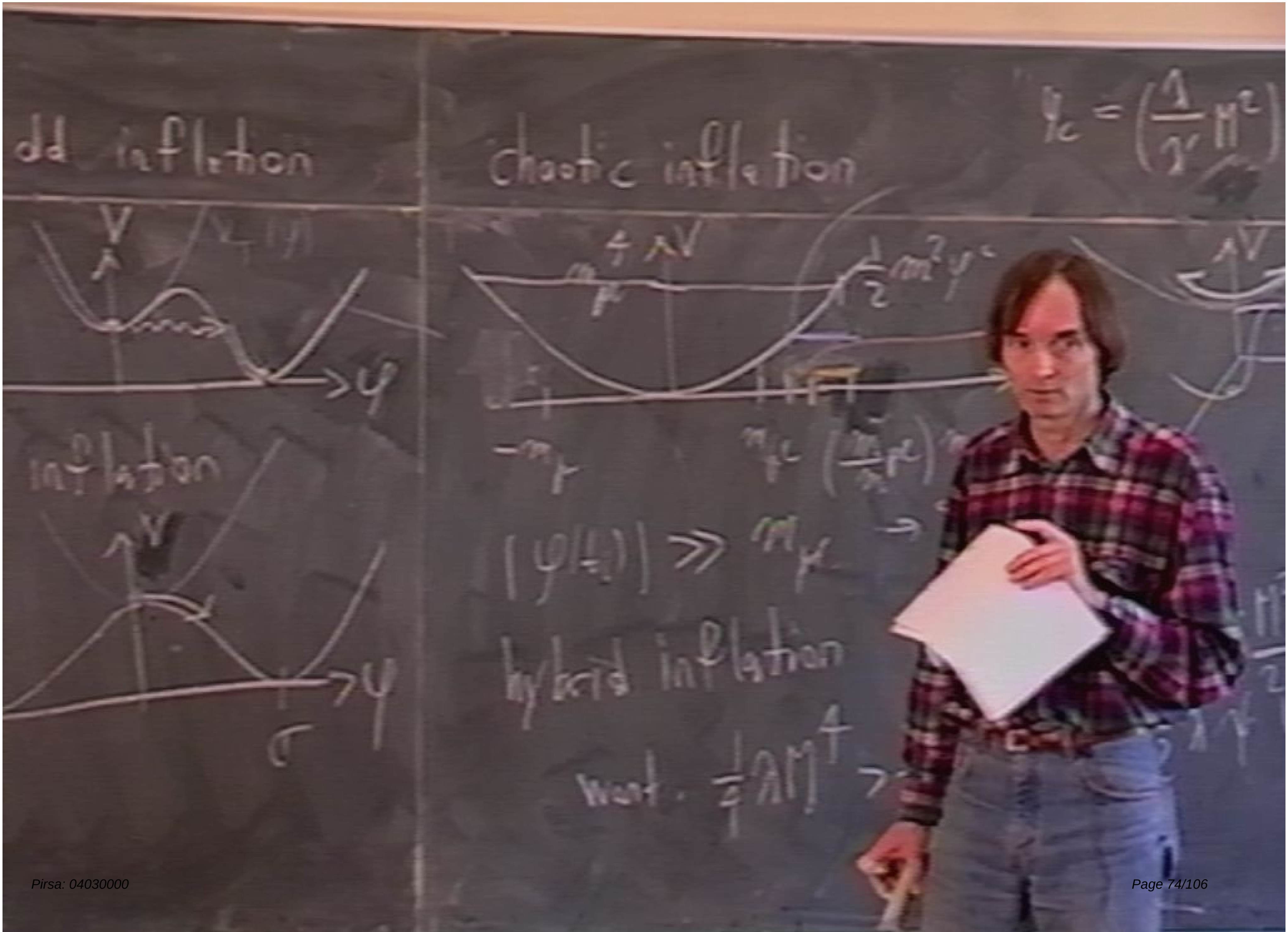

inflation
t
new

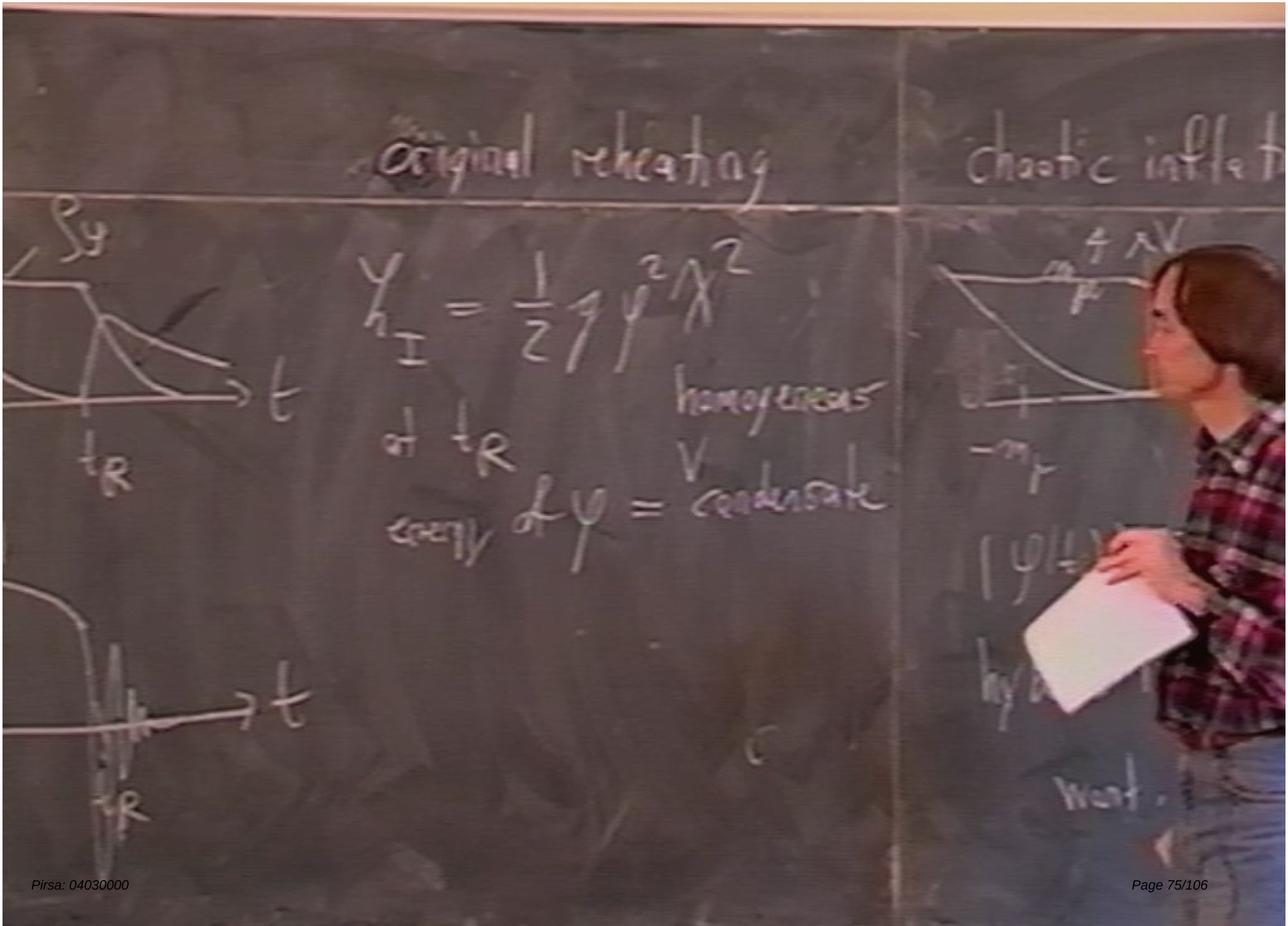

dd inflation

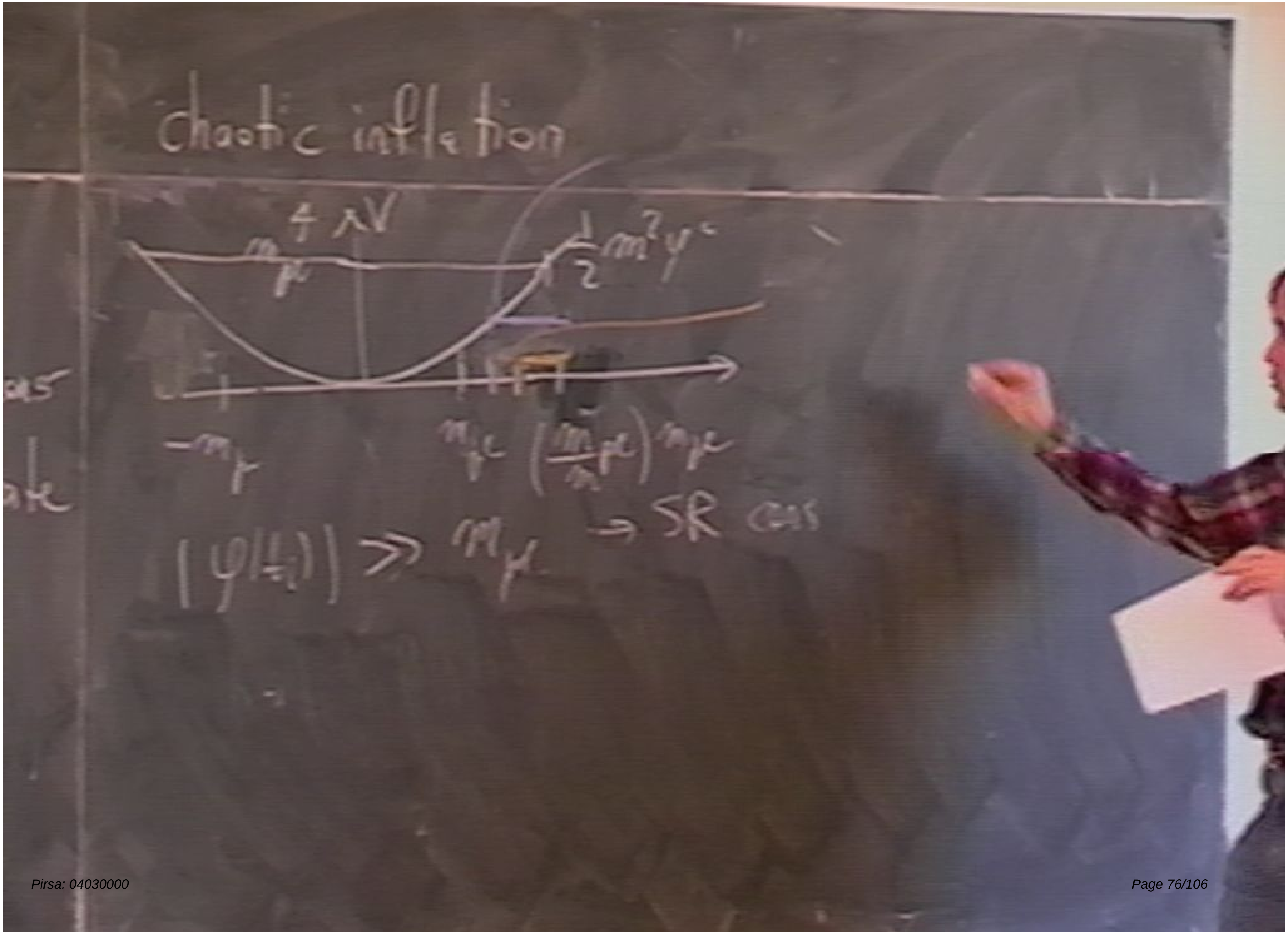


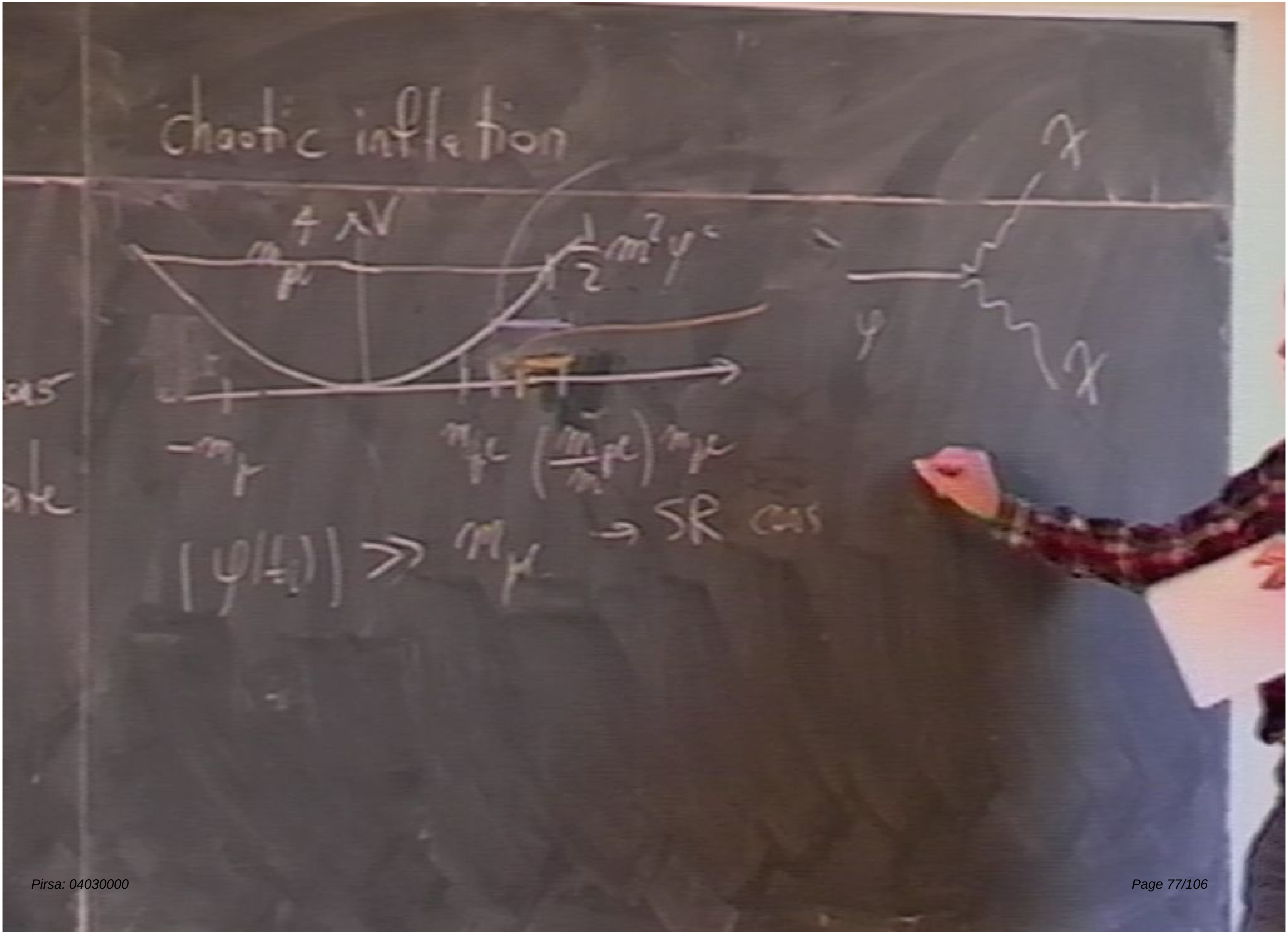
inflation
new inflation
t
t_R
V
σ

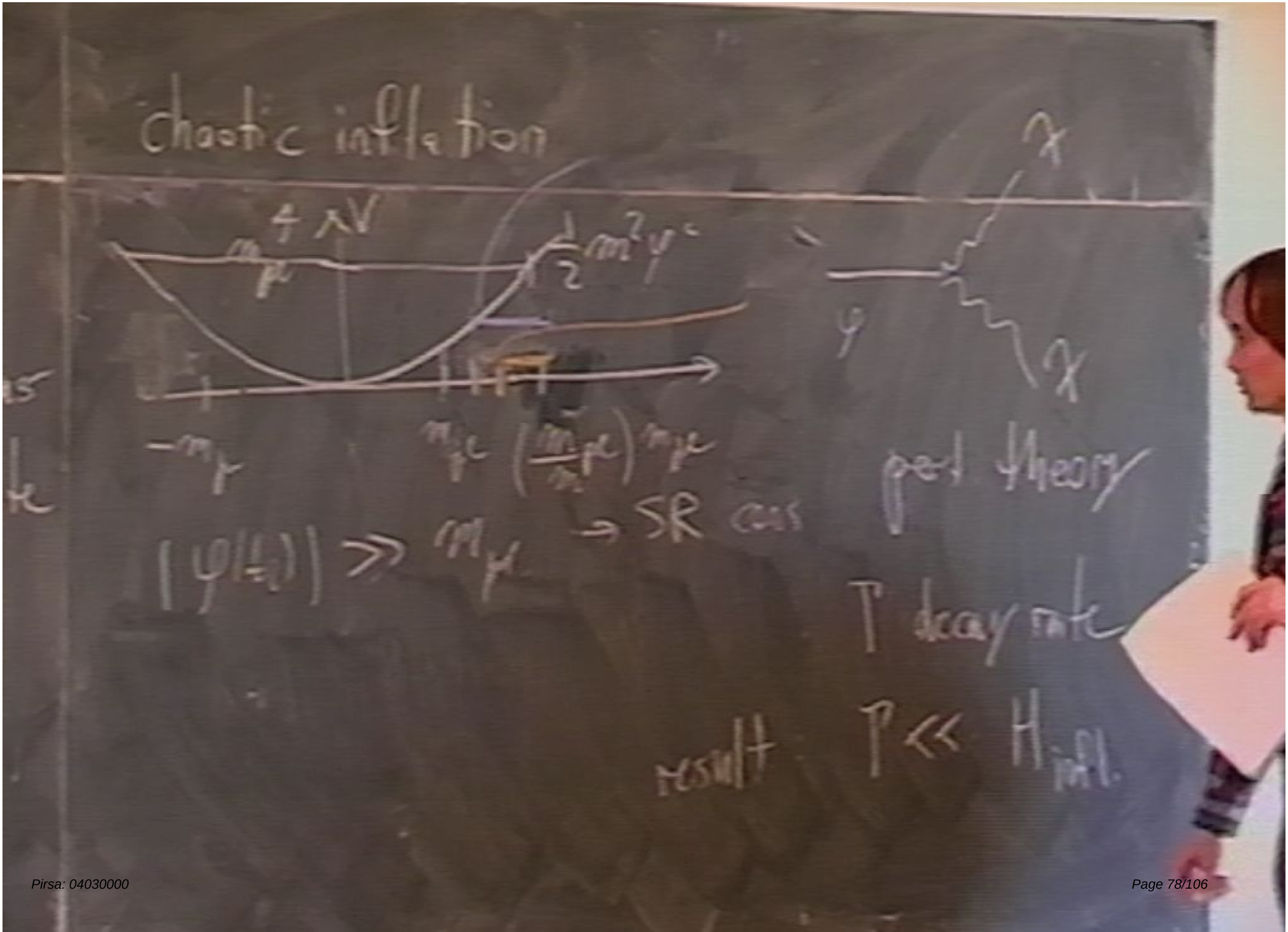

inflation
new inflation
t
t
tR
tR

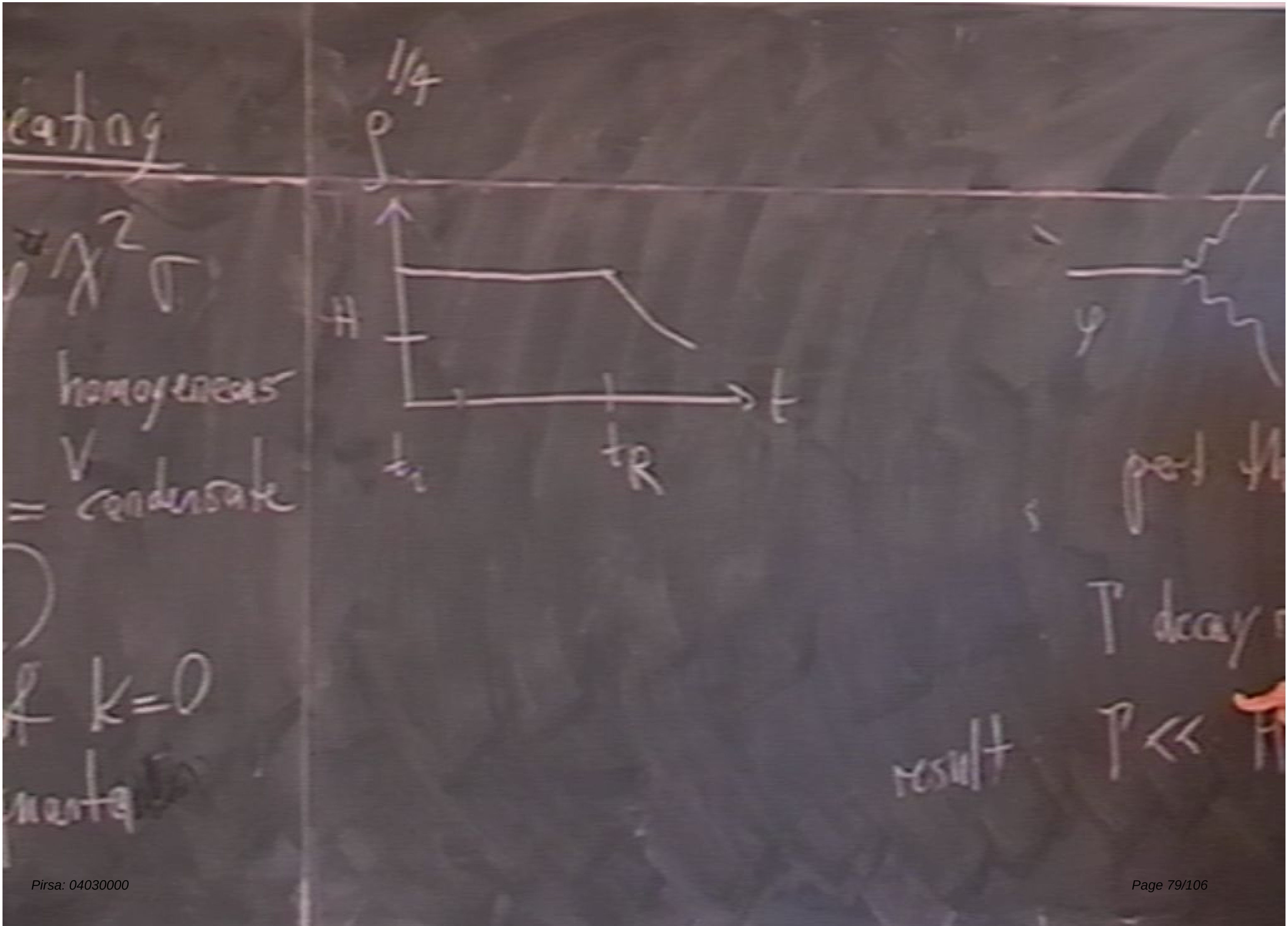

chaotic inflation
hybrid inflation

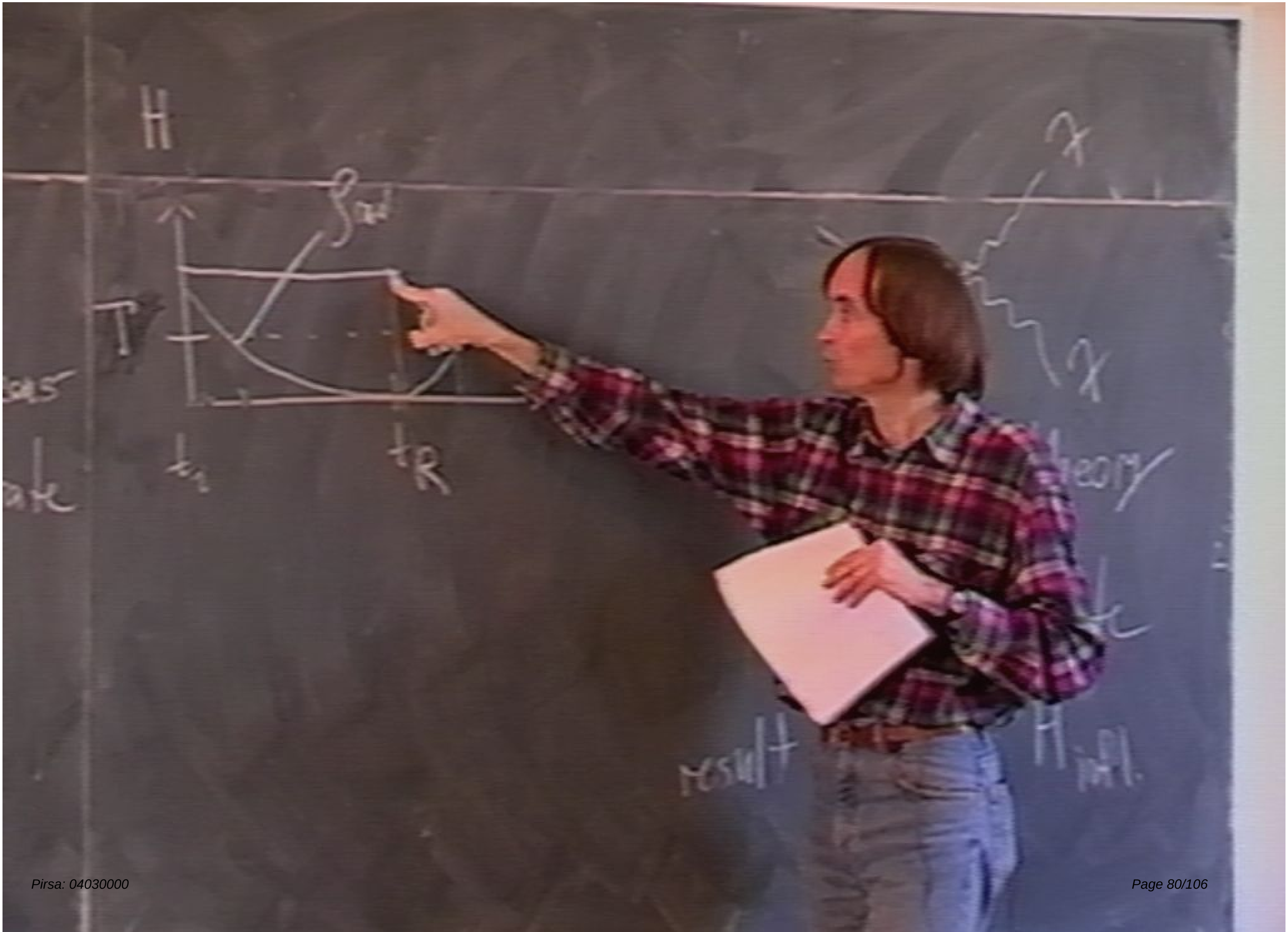

original reheating
chaotic infla
$\mathcal{L}_I = \frac{1}{2} g \varphi^2 \chi^2$
homogeneous
at t_R
energy of φ = condensate
t
t_R
t
t_R
Want

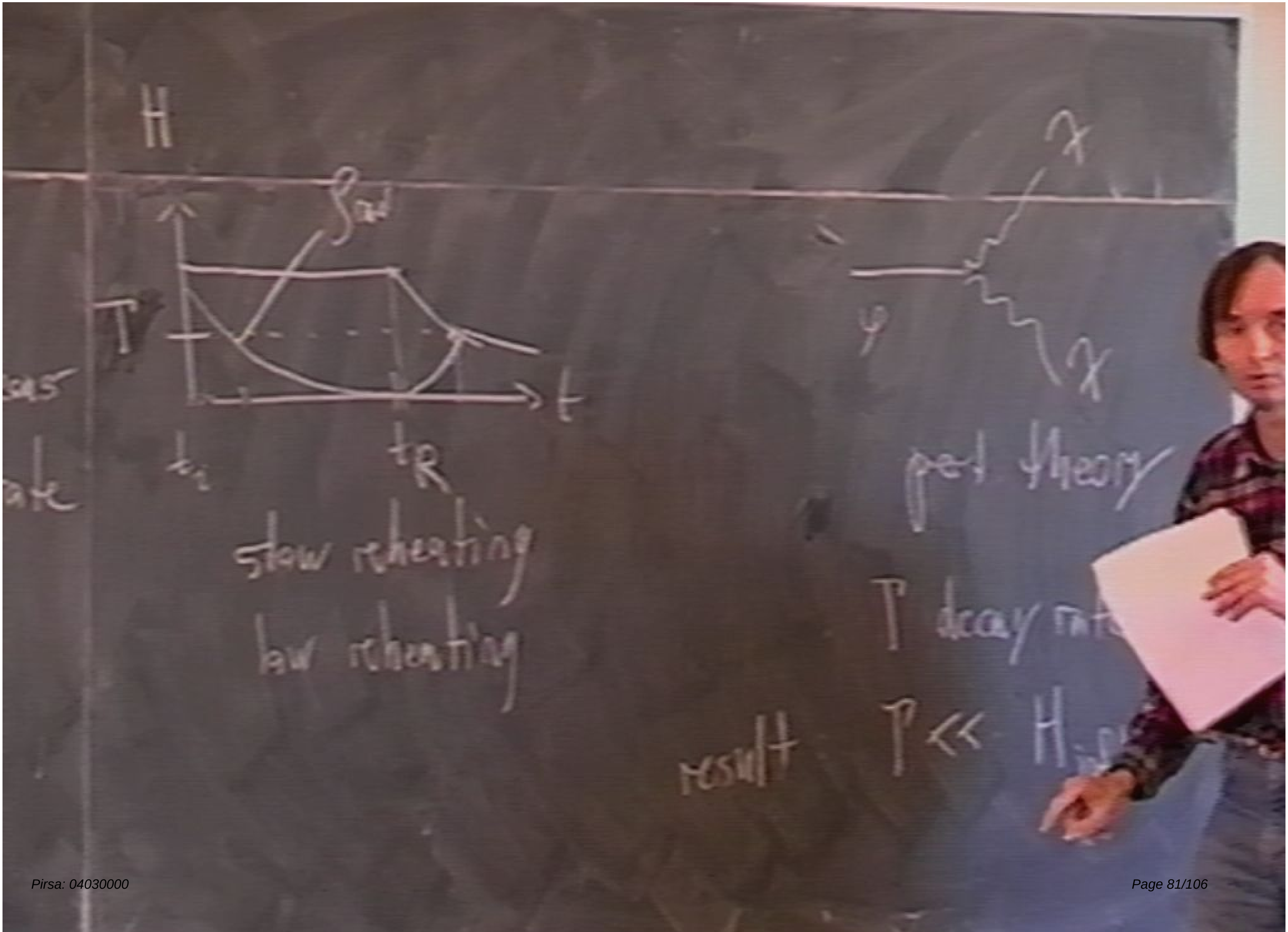

chaotic inflation
SR

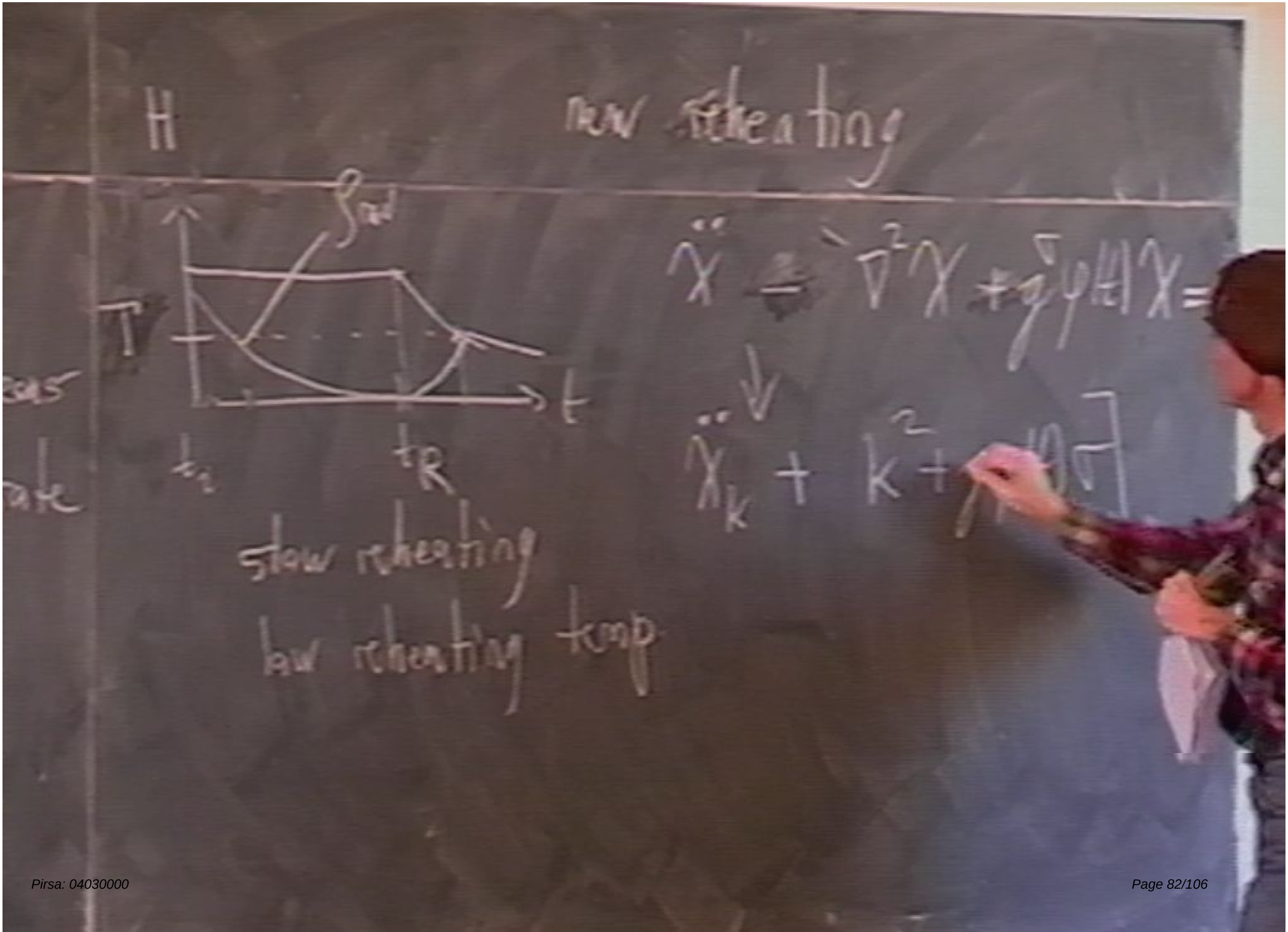

chaotic inflation
λV
½m²φ²
φ
χ
χ
→ SR


chaotic inflation
pert theory
SR cons
Γ decay rate
result Γ << H infl.


eating
homogeneous
condensate
k=0
H
t
t_R
result


H
T
ρ_{rad}
t_1
t_R
χ
χ
theory
result
$H_{infl.}$


H
t
tR
slow reheating
pert. theory
result


H
reheating
T
t
t_R
slow reheating
low reheating temp

$$\ddot{\chi} - \nabla^2 \chi + g\varphi(t)^2 \chi = 0$$

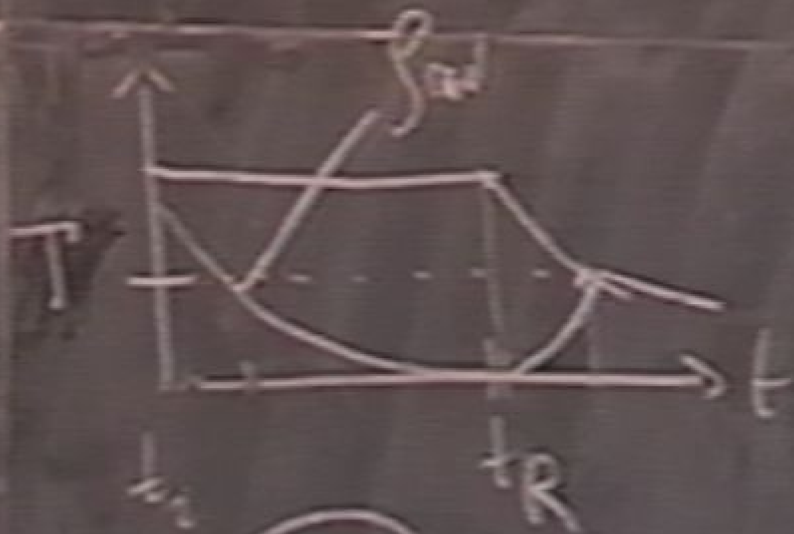
$$\downarrow$$

$$\ddot{\chi}_k + \left[k^2 + g\varphi(t)^2\right]\chi_k = 0$$

Mathieu eq.

H

new reheating



$$\ddot{\chi} - \nabla^2\chi + g^2\varphi(t)^2\chi = 0$$

$$\Downarrow$$

$$\ddot{\chi}_k + \left[k^2 + g^2\varphi(t)^2\right]\chi_k = 0$$

slow reheating

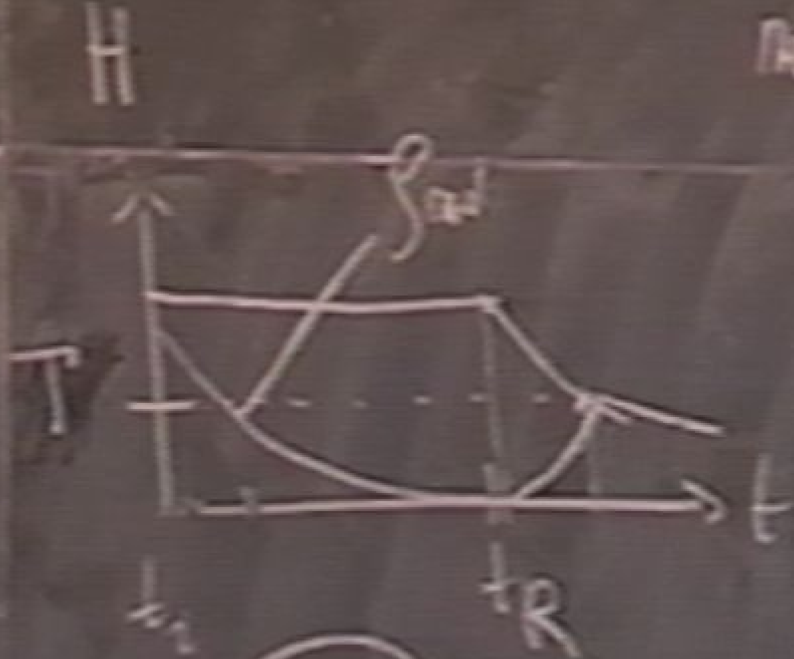
low reheating temp.

Mathieu eq

⇒ fast reheating

high " " temp

new reheating



ess

ate

slow reheating

low reheating temp

$$\ddot{\chi} - \nabla^2\chi + g\varphi(t)\chi = 0$$

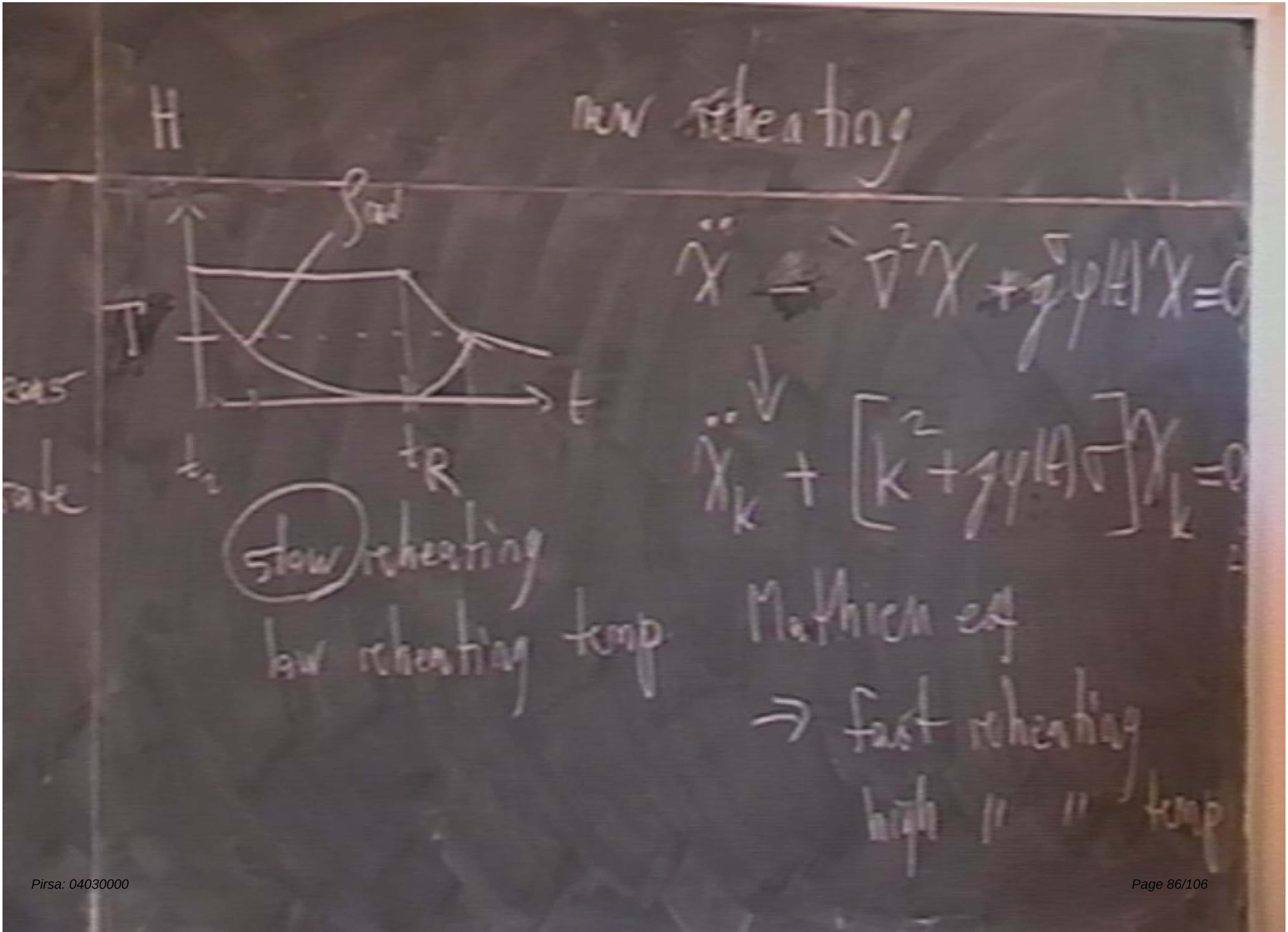
$\Downarrow$

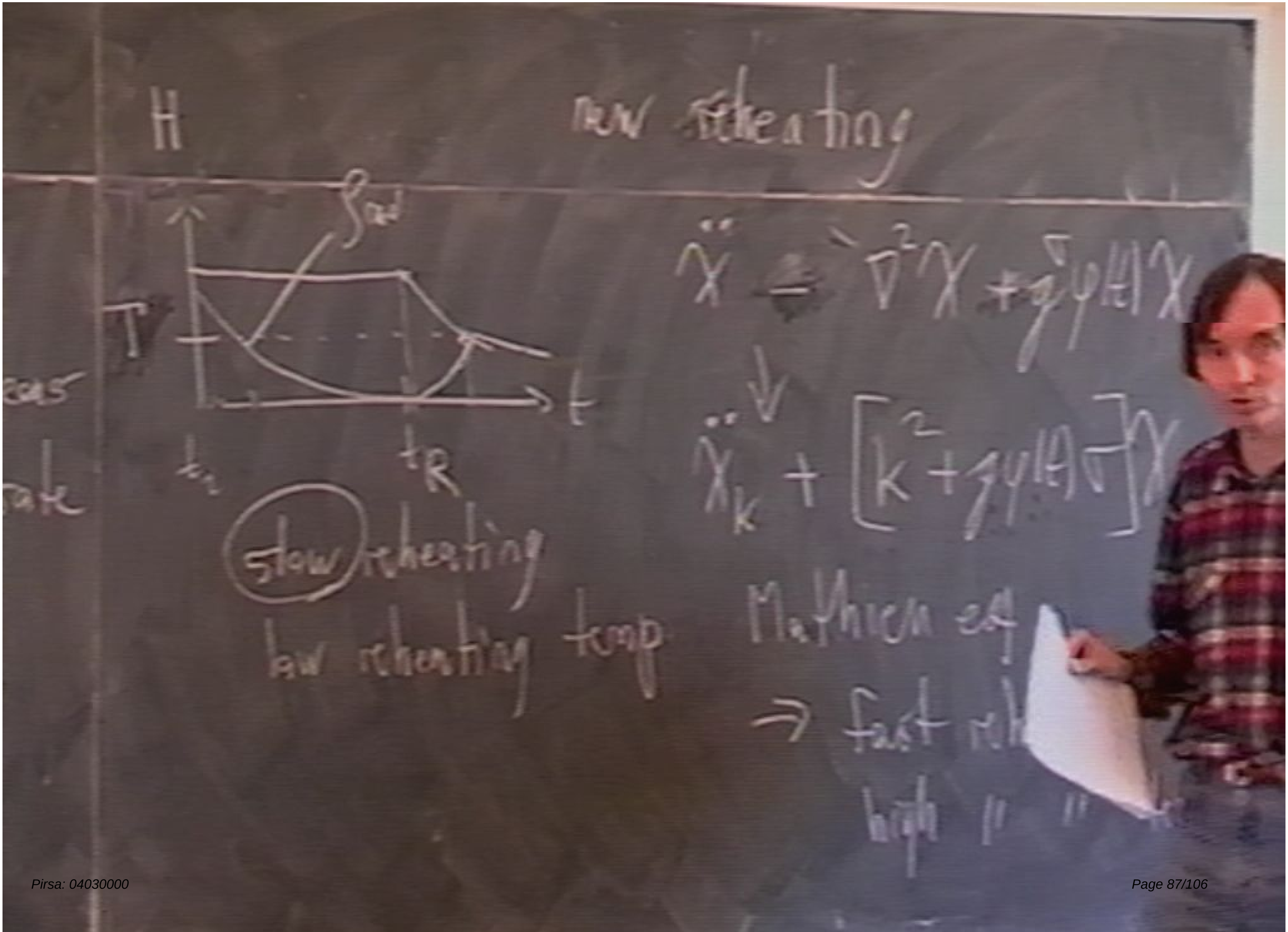
$$\ddot{\chi}_k + [k^2 + g\varphi(t)\sigma]\chi_k = 0$$

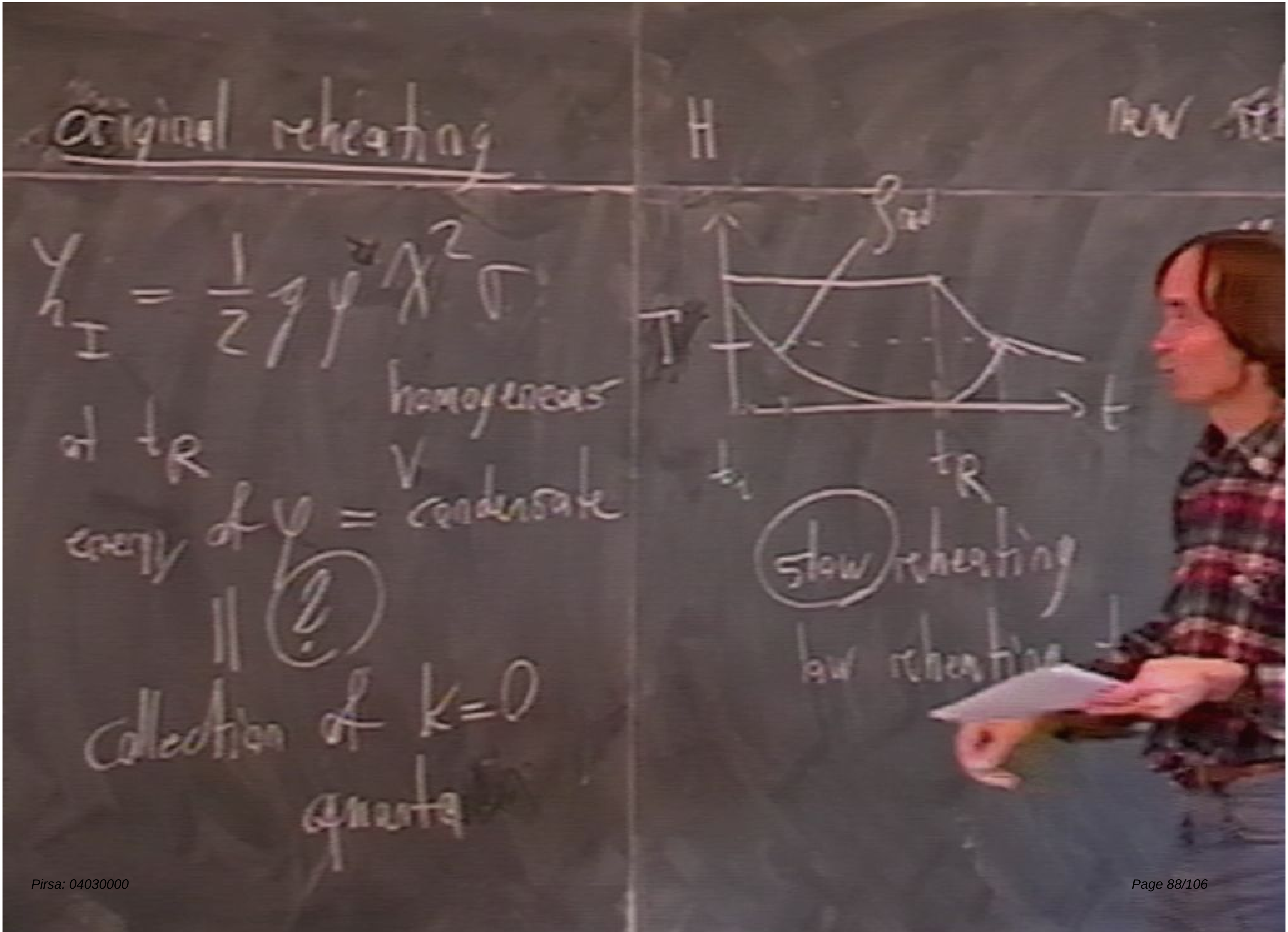
Mathieu eq

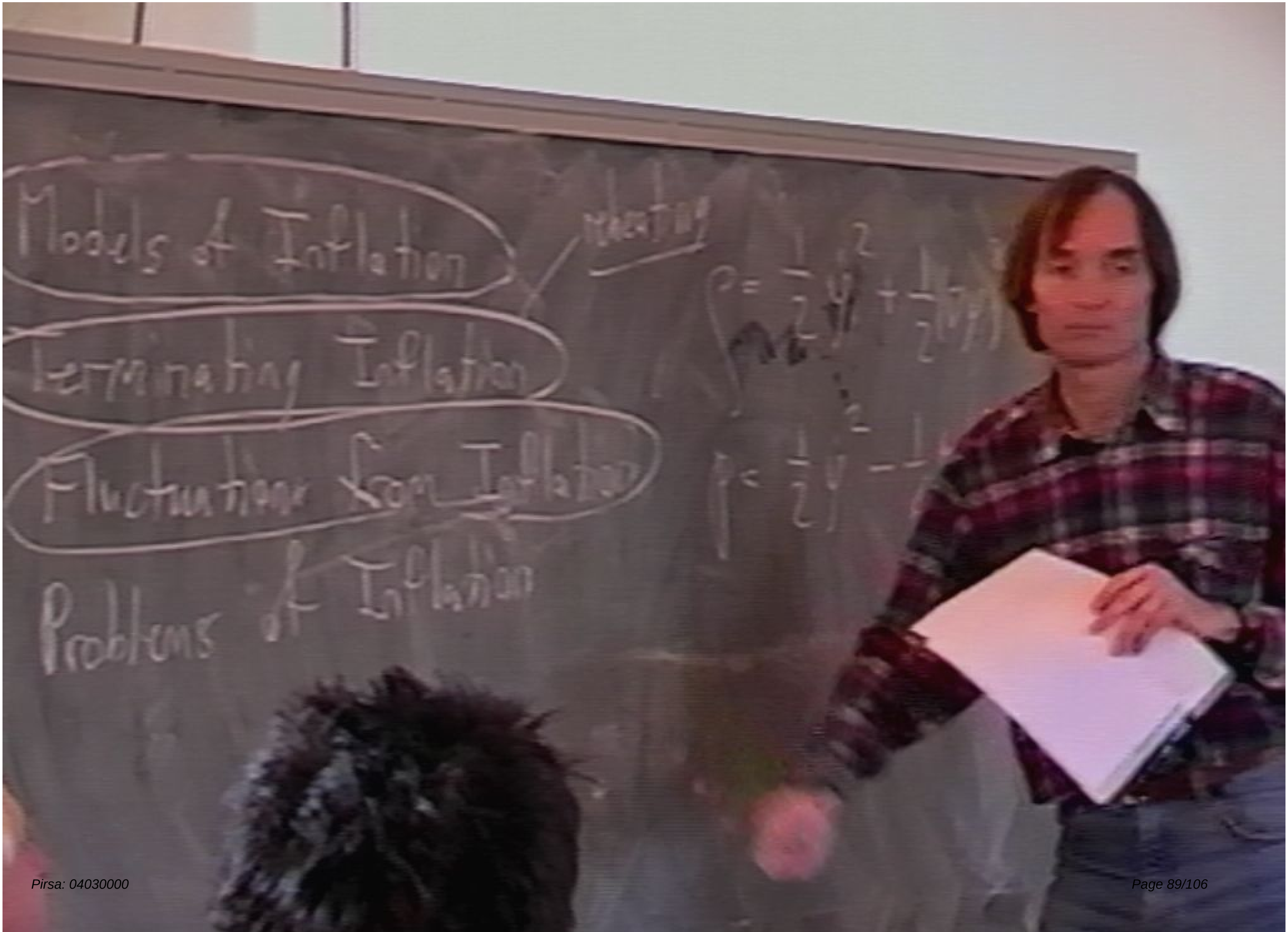
$\Rightarrow$ fast reheating

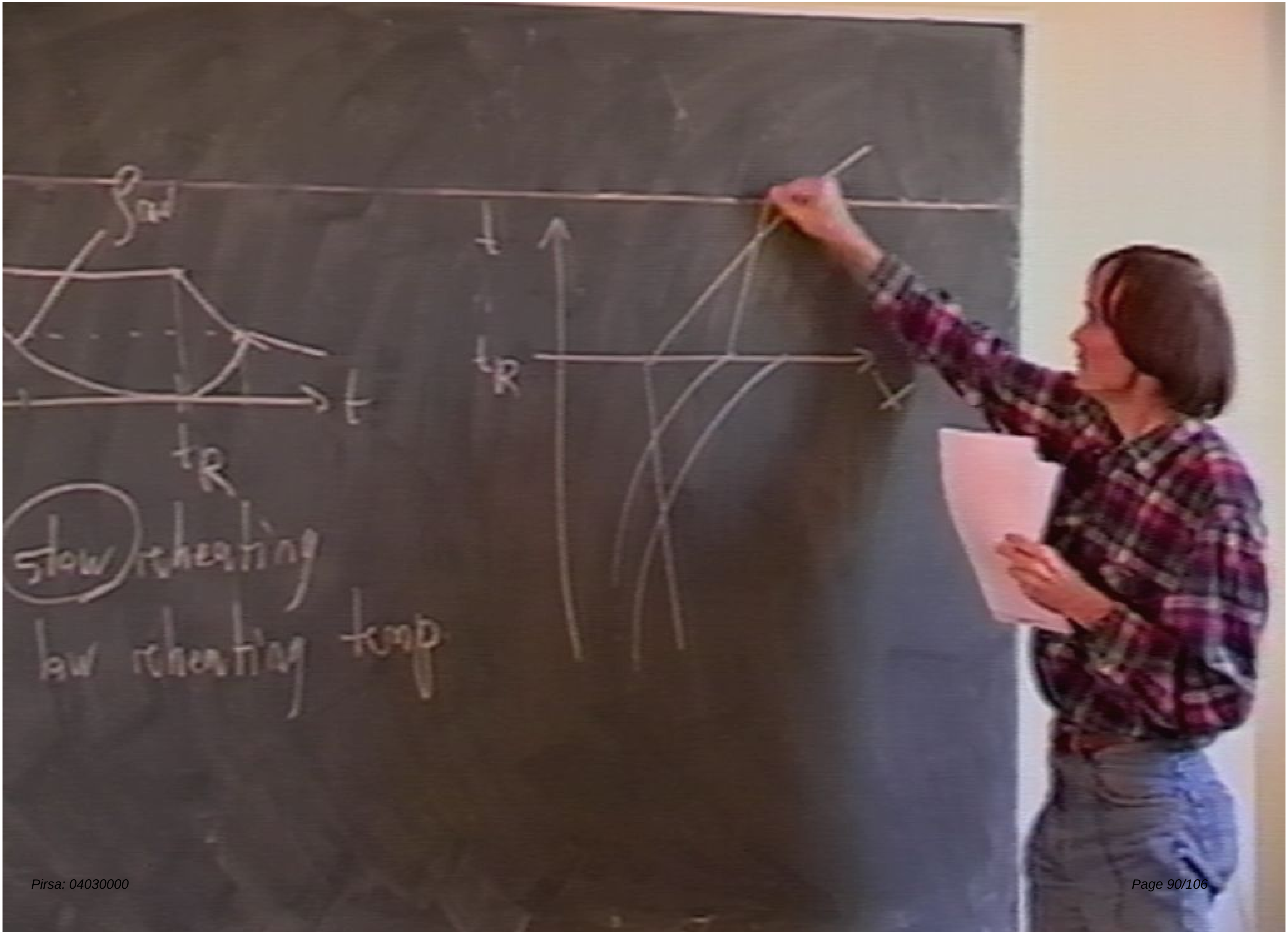
high " " temp

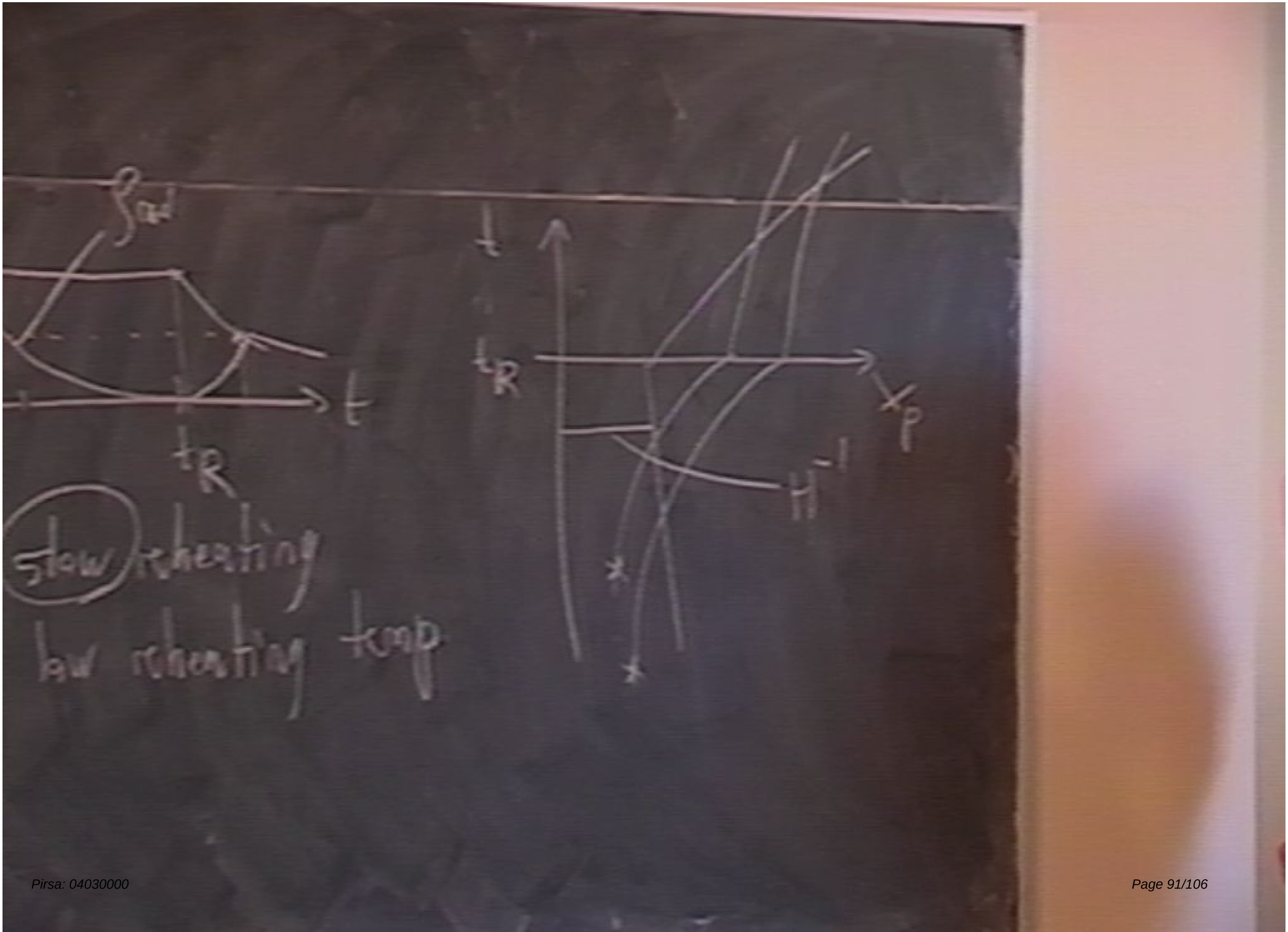

H
new reheating
T
t
t_R
slow reheating
low reheating temp
$\ddot{\chi}_k + [k^2 + g\varphi(t)\sigma]\chi_k = 0$
Mathieu eq
→ fast reheating
high " " temp

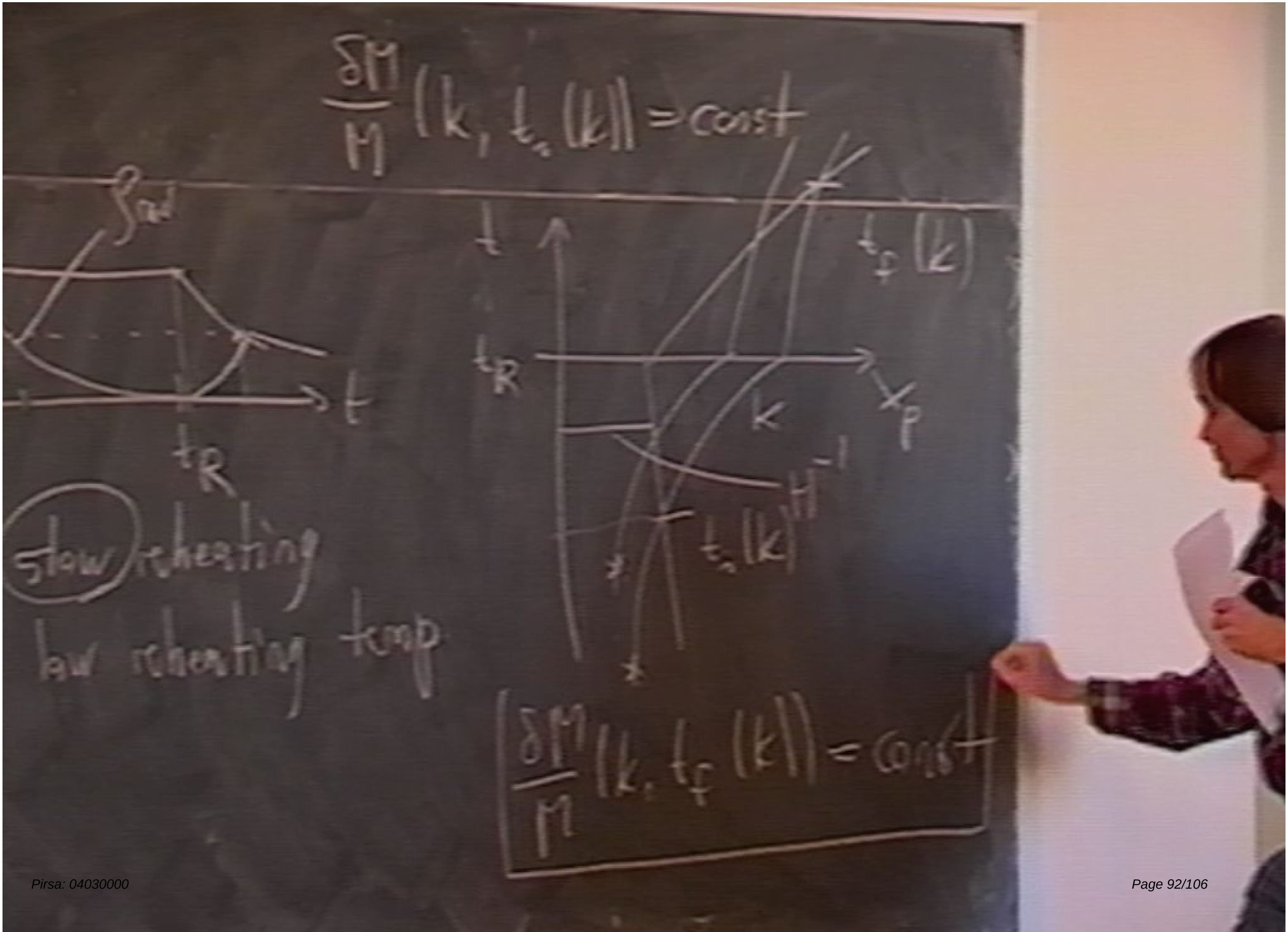

H
new reheating
ρ_{rad}
T
t
t_R
slow reheating
low reheating temp
Which eq

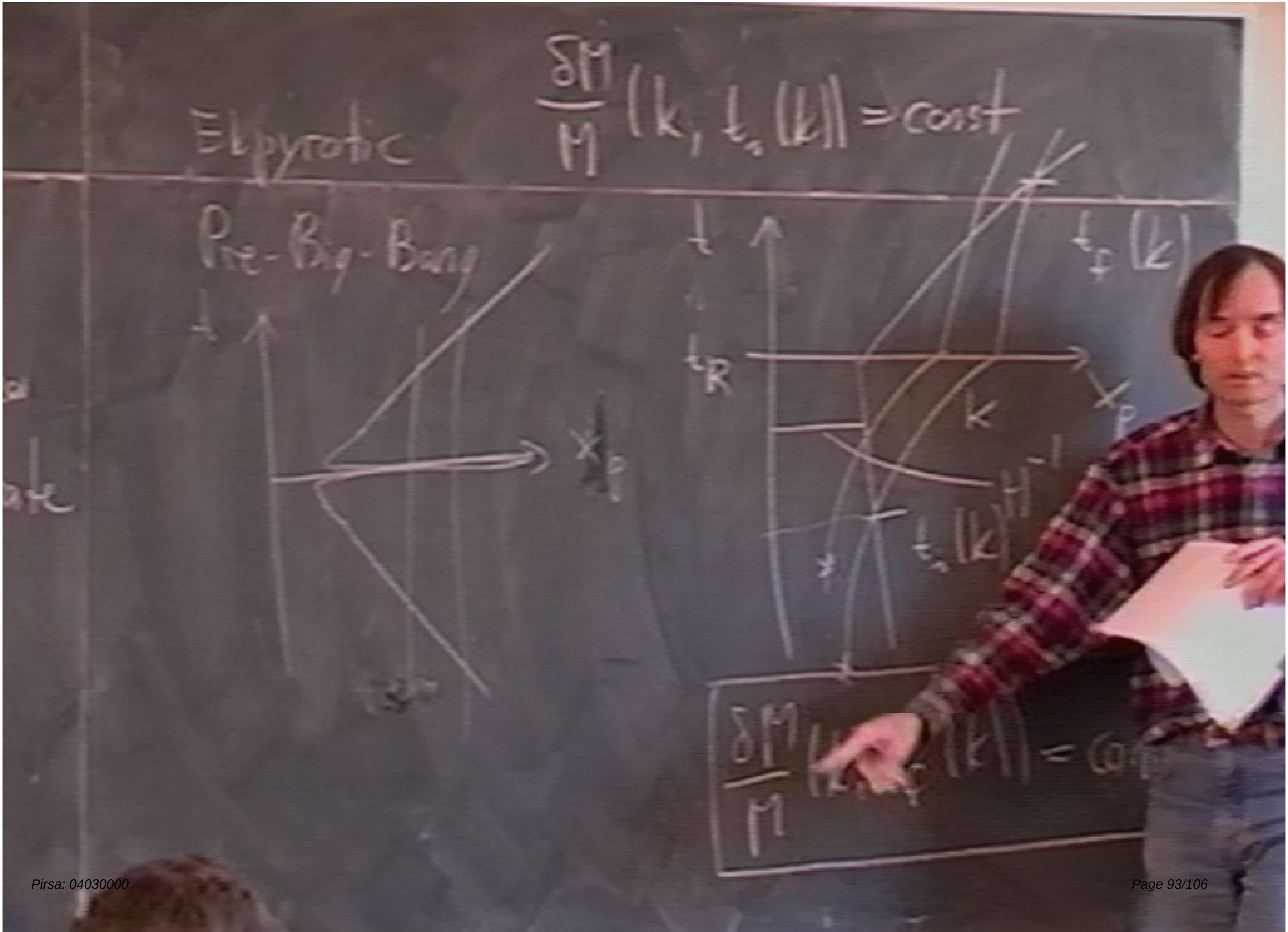

original reheating
H
new reh
$\mathcal{L}_I = \frac{1}{2} g \varphi \chi^2 \sigma$
homogeneous
at t_R
energy of φ = condensate
collection of k=0
quanta
ρ_{rad}
T
t
t_R
slow reheating
low reheating

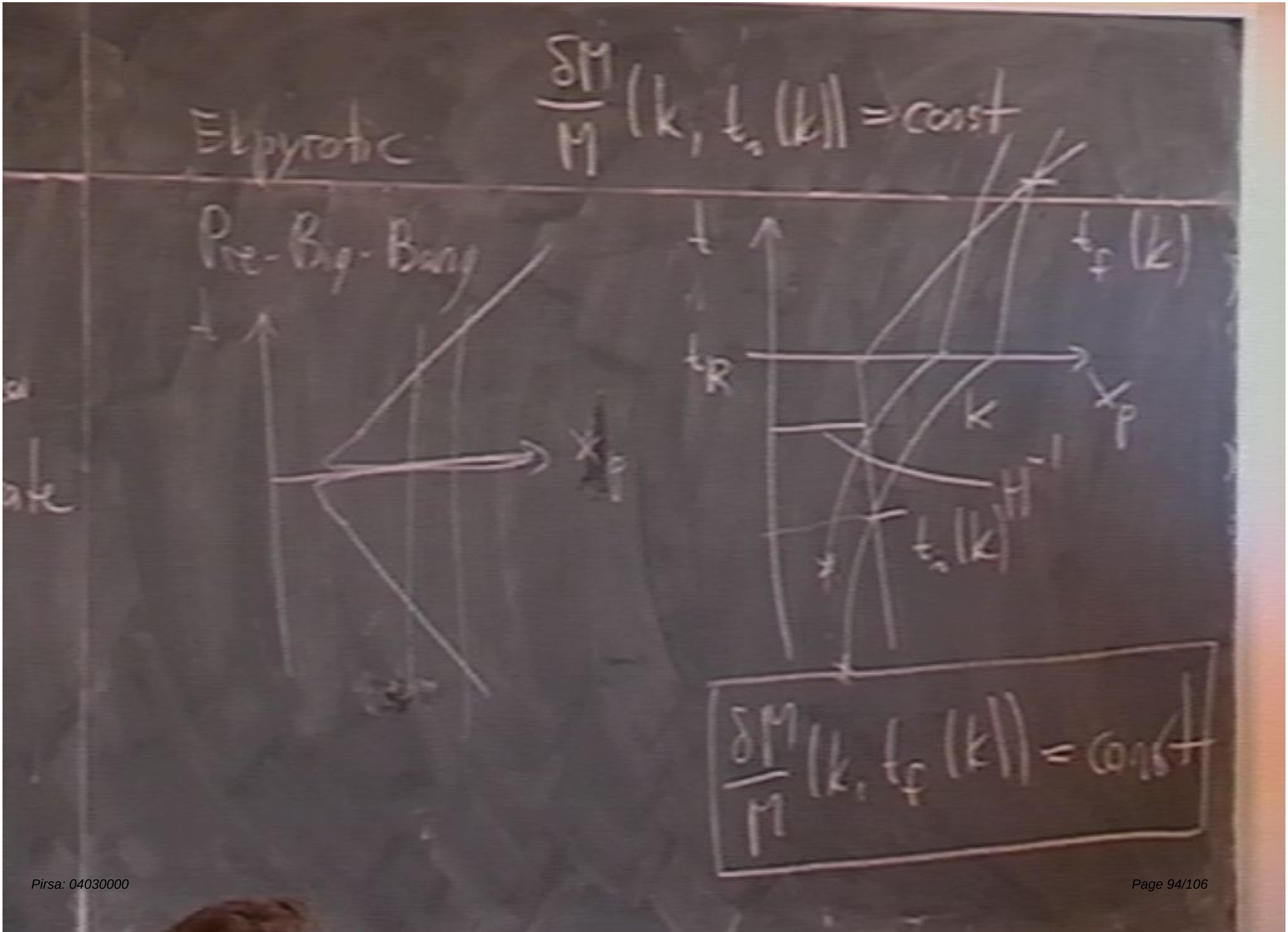

Models of Inflation
reheating
Terminating Inflation
Fluctuations from Inflation
Problems of Inflation


ρrad
t
tR
t
tR
slow reheating
low reheating temp

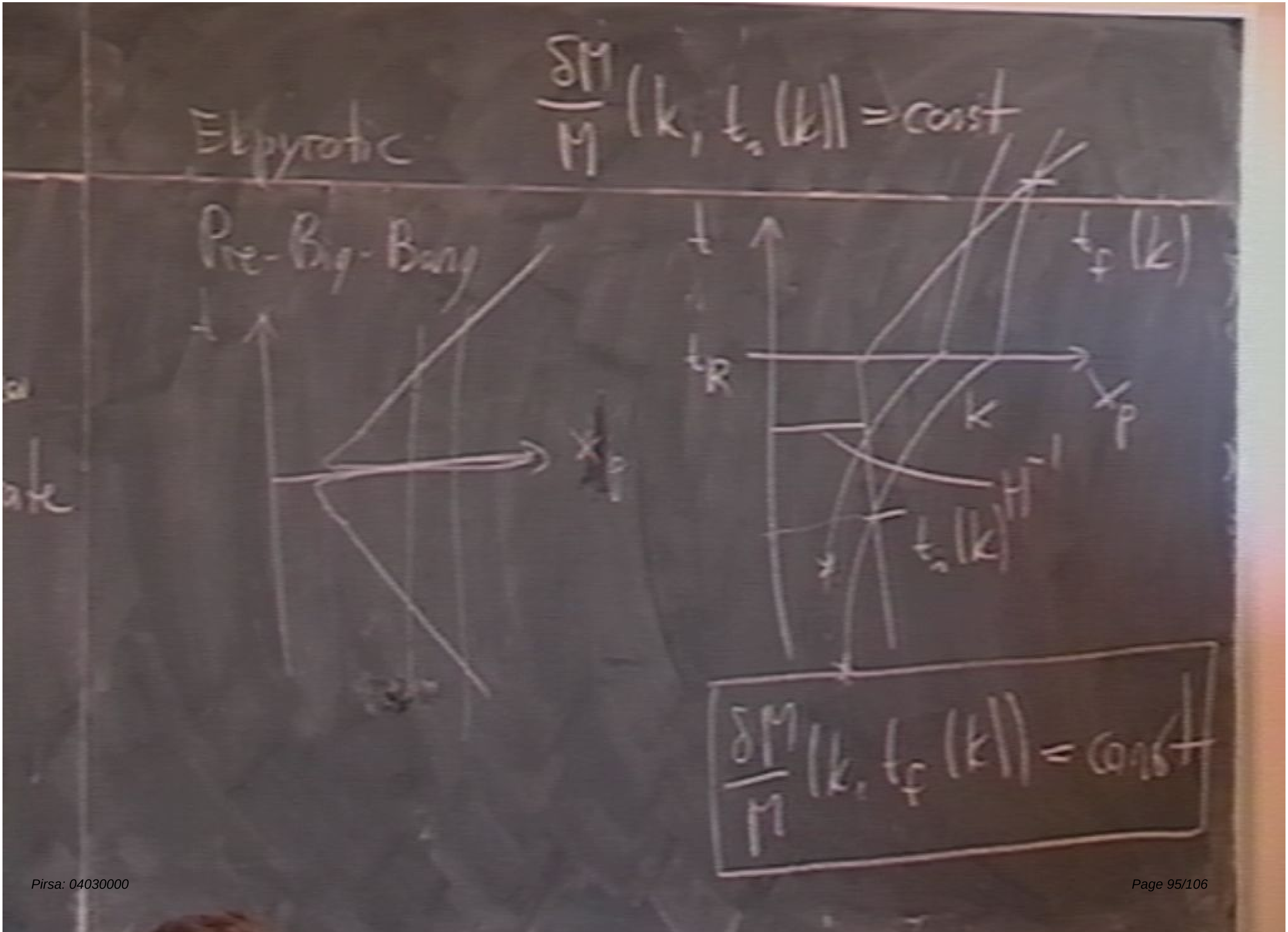

t
t_R
t
t_R
x_p
H^-1
slow reheating
low reheating temp

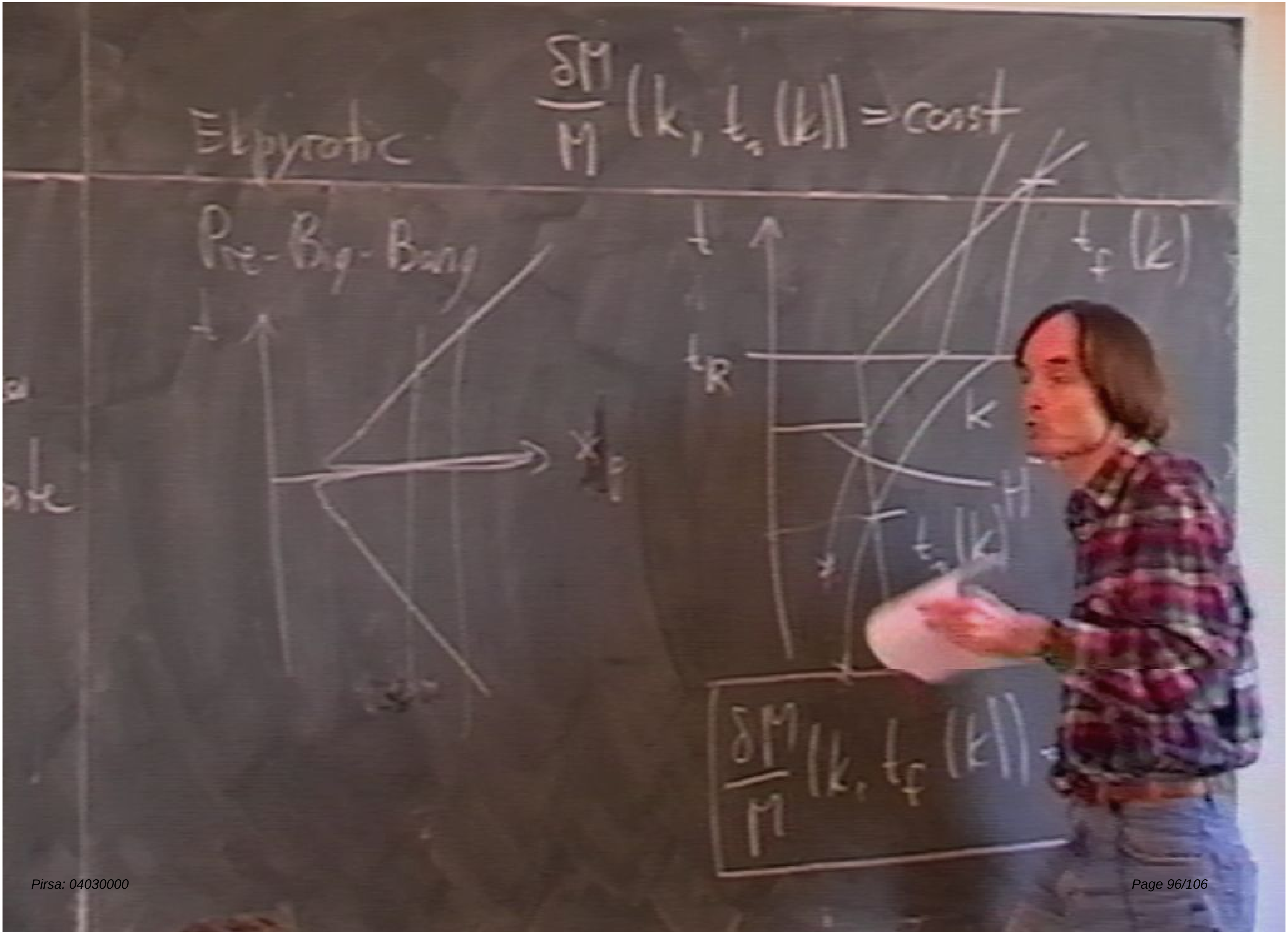

δM/M (k, t_x(k)) = const
ρ_rad
t
t_R
t_f(k)
k
p
H^-1
t_x(k)
slow reheating
low reheating temp
δM/M (k, t_f(k)) = const

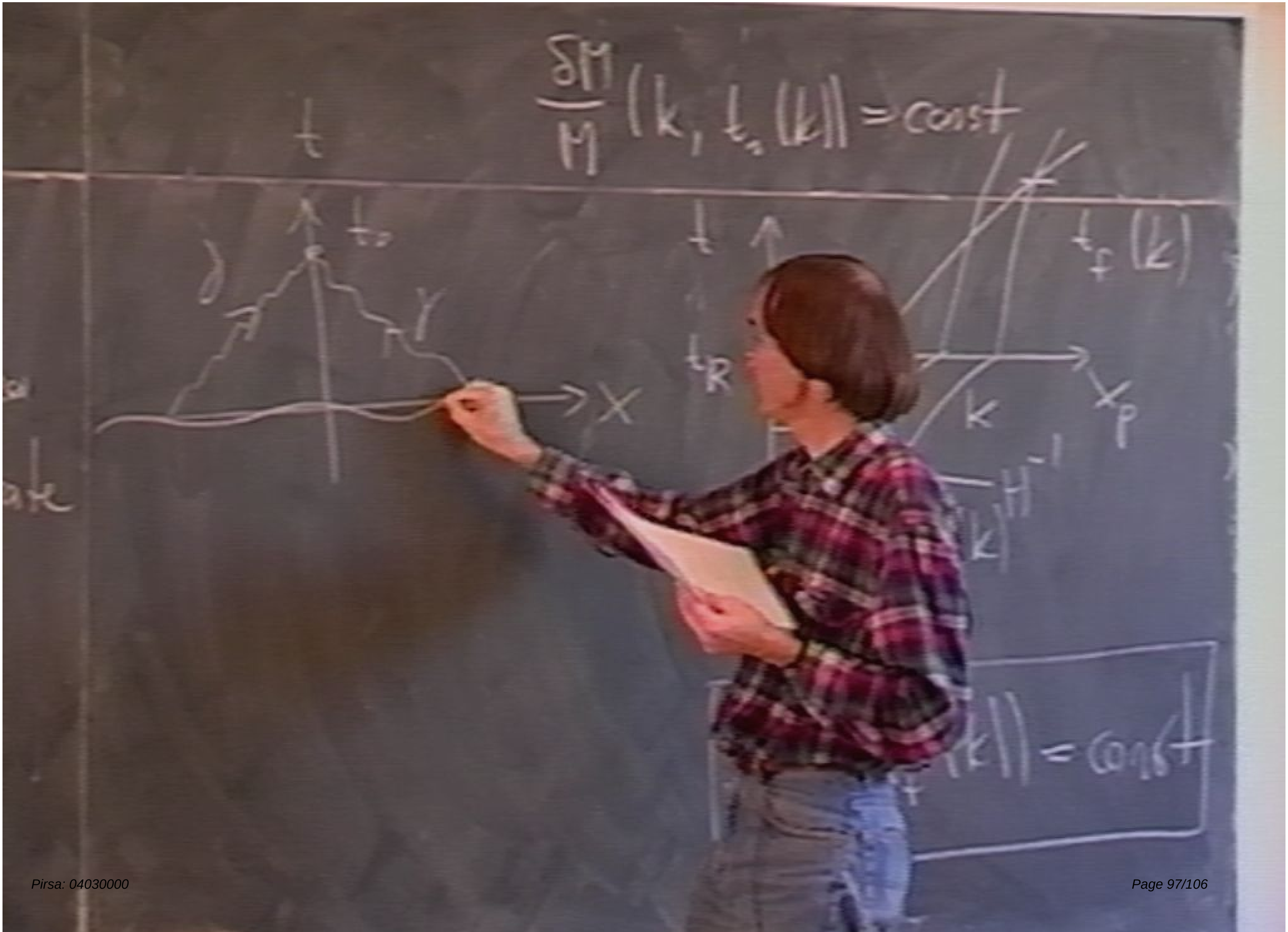

Ekpyrotic
δM/M (k, t(k)) = const
Pre-Big-Bang
t
t_R
k
H^-1
t_f (k)



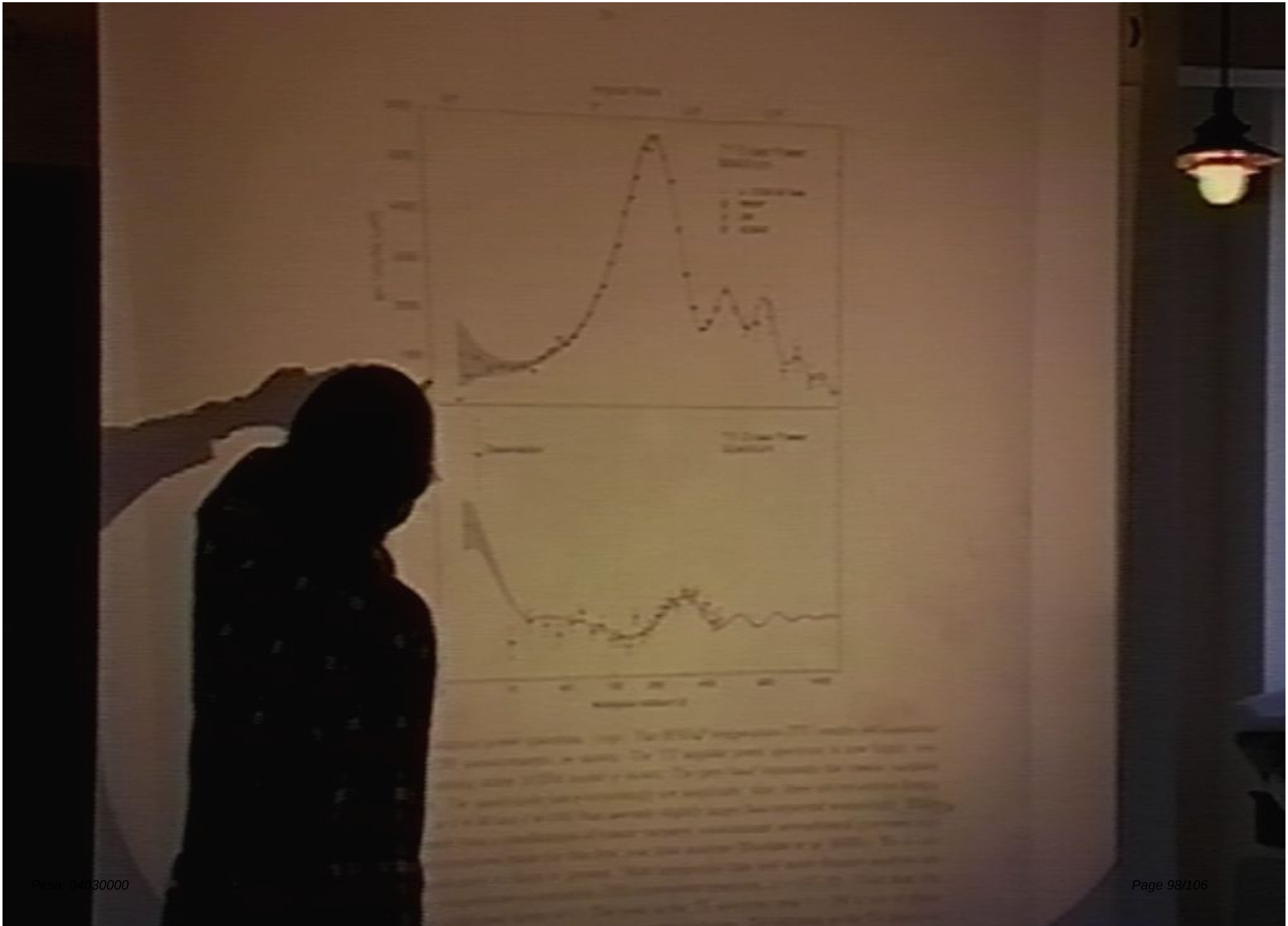
Ekpyrotic
$\frac{\delta M}{M}(k, t_a(k)) = const$
Pre-Big-Bang
t
x_p
t
$t_f(k)$
t_R
k
x_p
H^{-1}
$t_a(k)$
$\frac{\delta M}{M}(k, t_f(k)) = const$

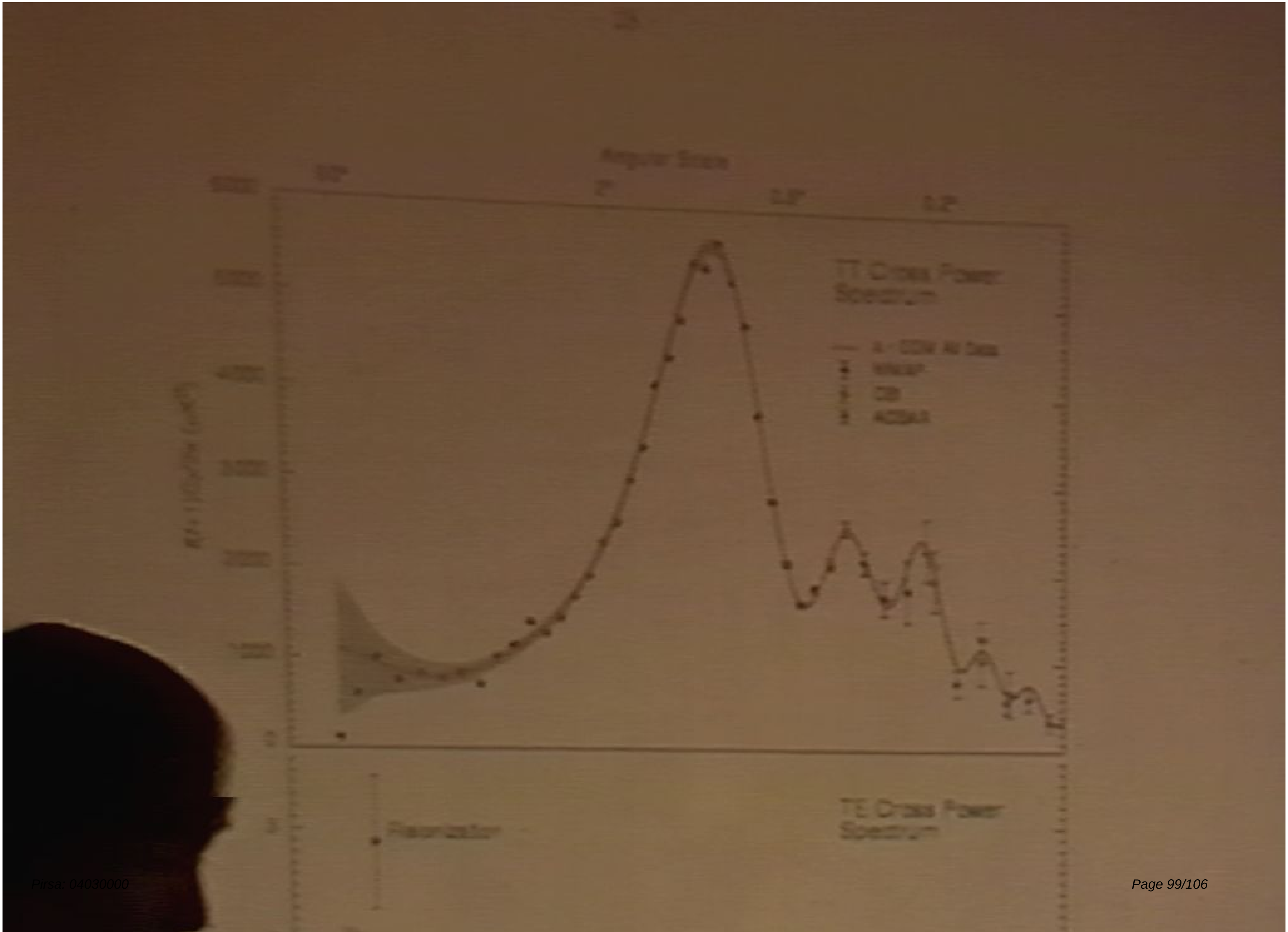

Ekpyrotic
δM/M (k, t_s(k)) = const
Pre-Big-Bang
t
x_p
t
t_R
t_f(k)
k
x_p
H^-1
t_s(k)
δM/M (k, t_f(k)) = const

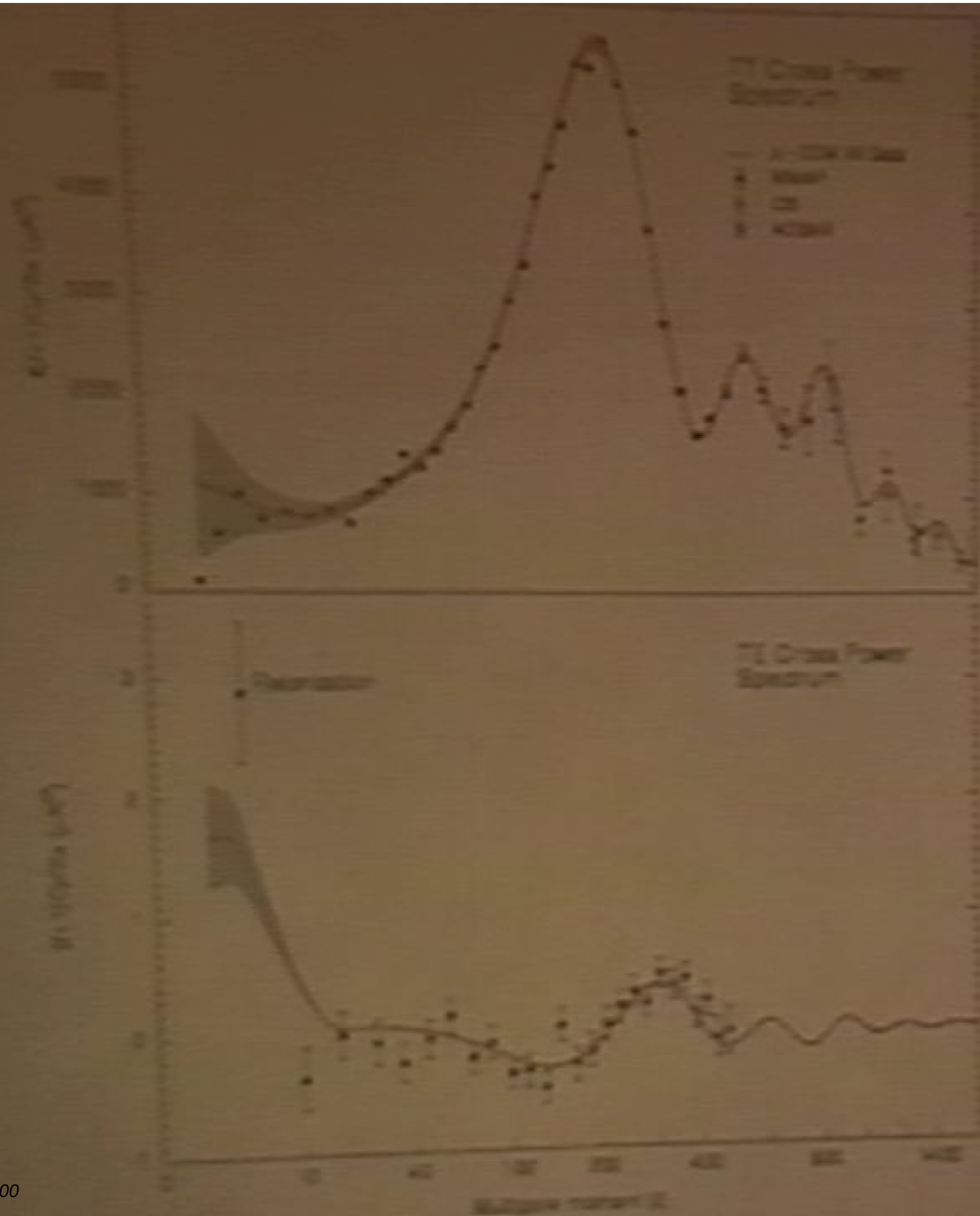

Ekpyrotic
Pre-Big-Bang
$\frac{\delta M}{M}(k, t_i(k)) \Rightarrow \text{const}$
t
t_R
$t_f(k)$
k
H
$t_i(k)$
x_p
$\frac{\delta M}{M}(k, t_f(k))$

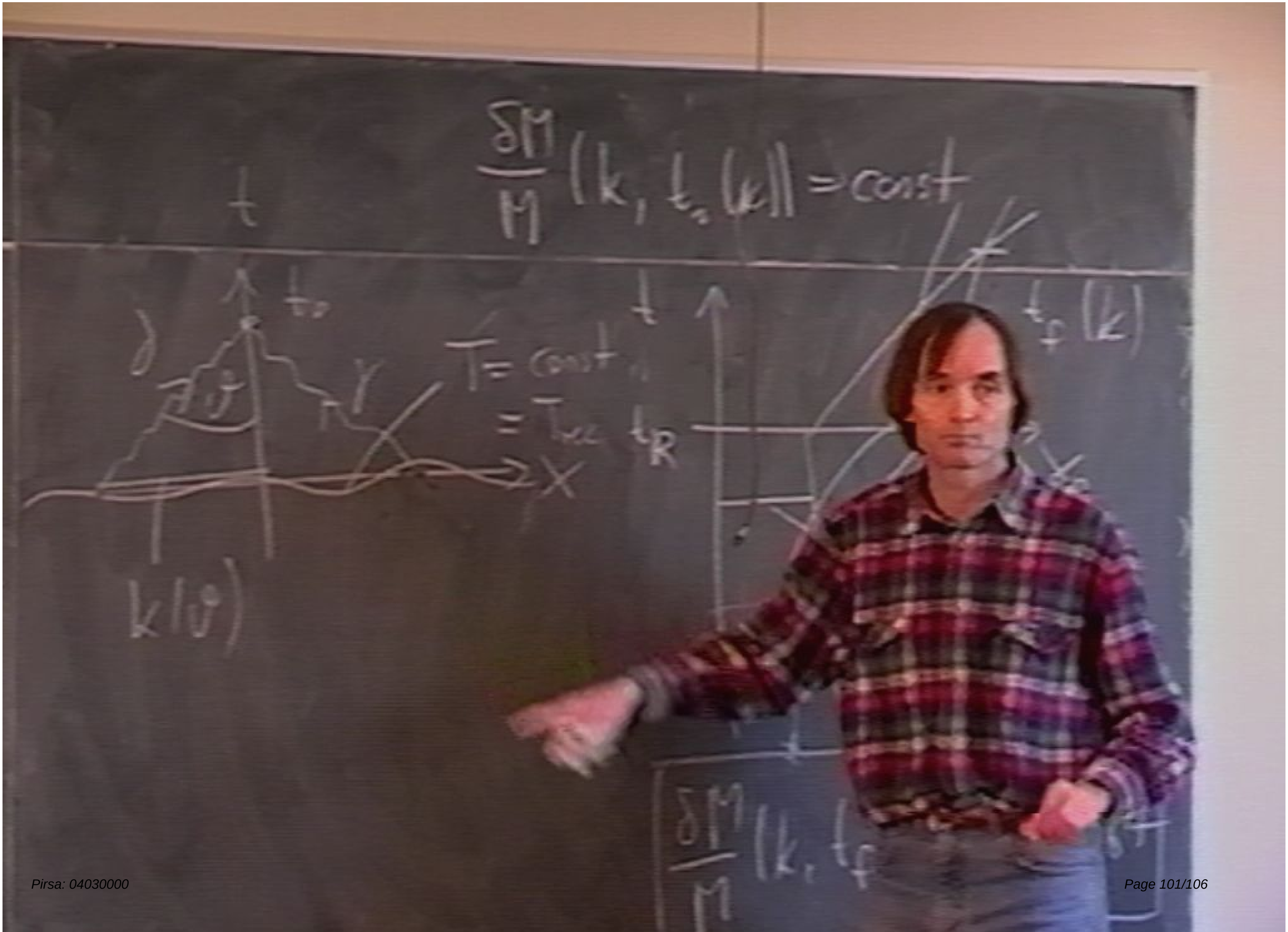


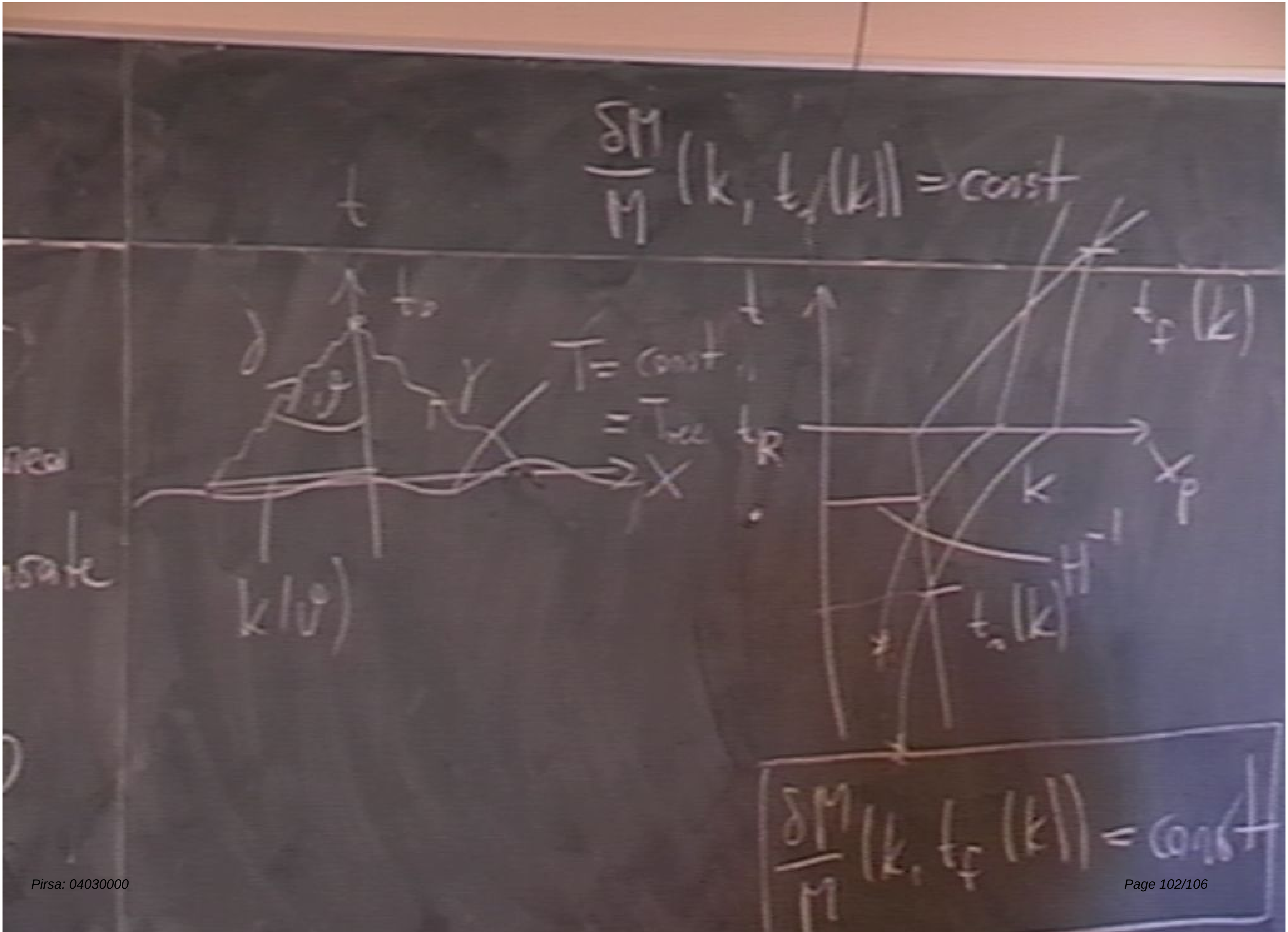
$\frac{\delta M}{M}(k, t_f(k)) = const$
t
t_0
X
t
t_R
$t_f(k)$
k
x_p
H^{-1}

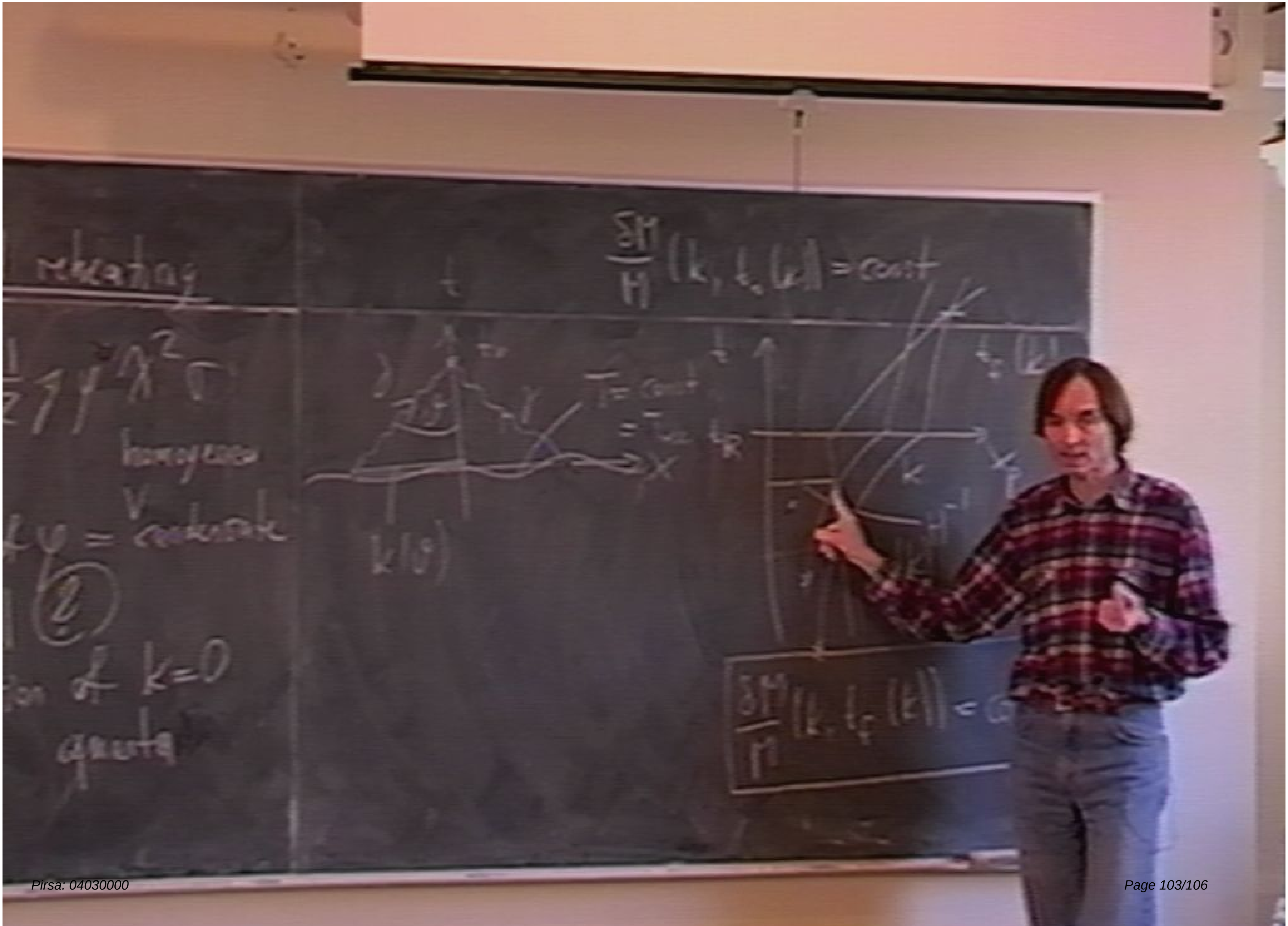


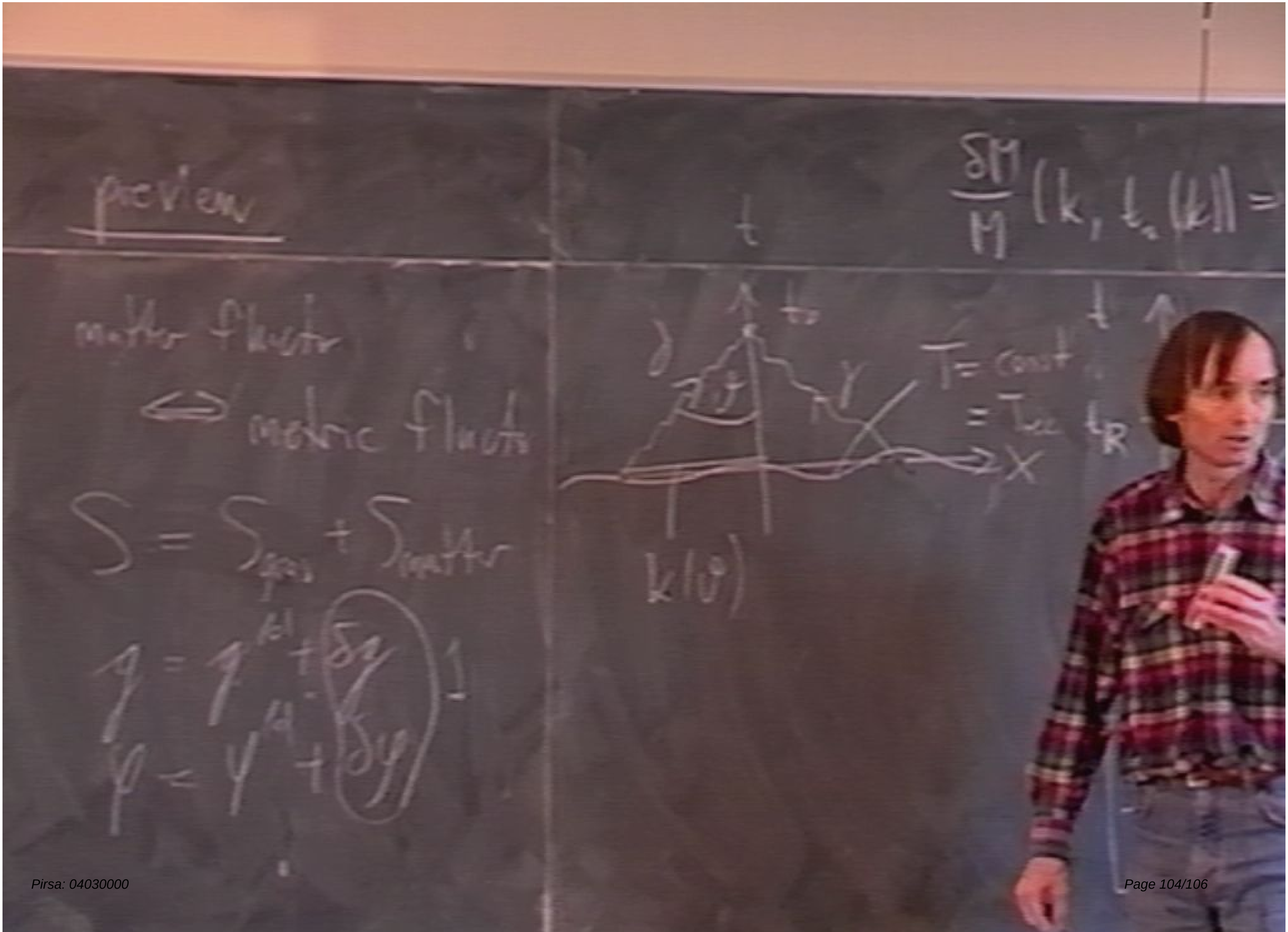

Angular Scale
TT Cross Power Spectrum
TE Cross Power Spectrum
Reionization

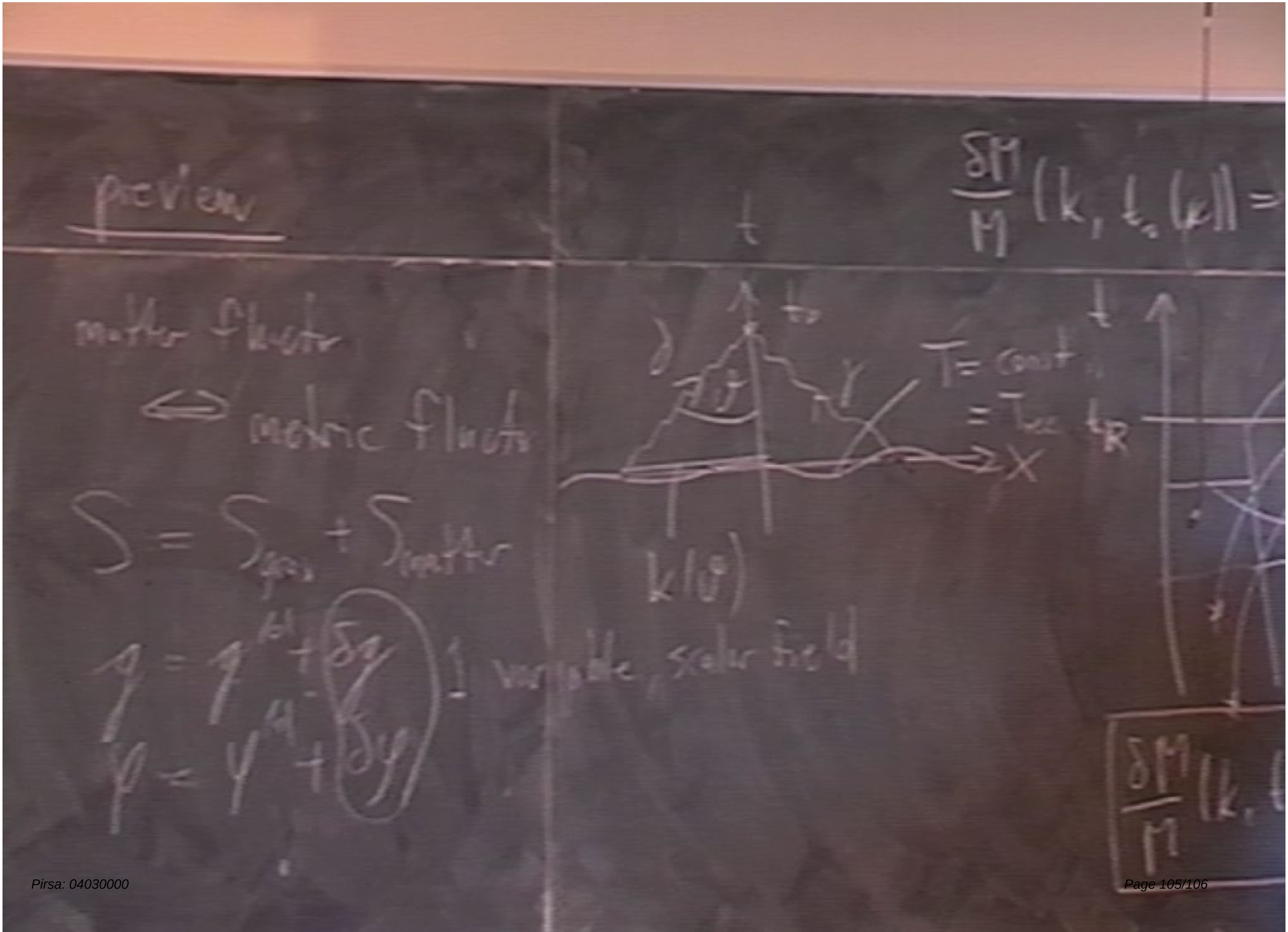

TT Cross Power Spectrum
TE Cross Power Spectrum

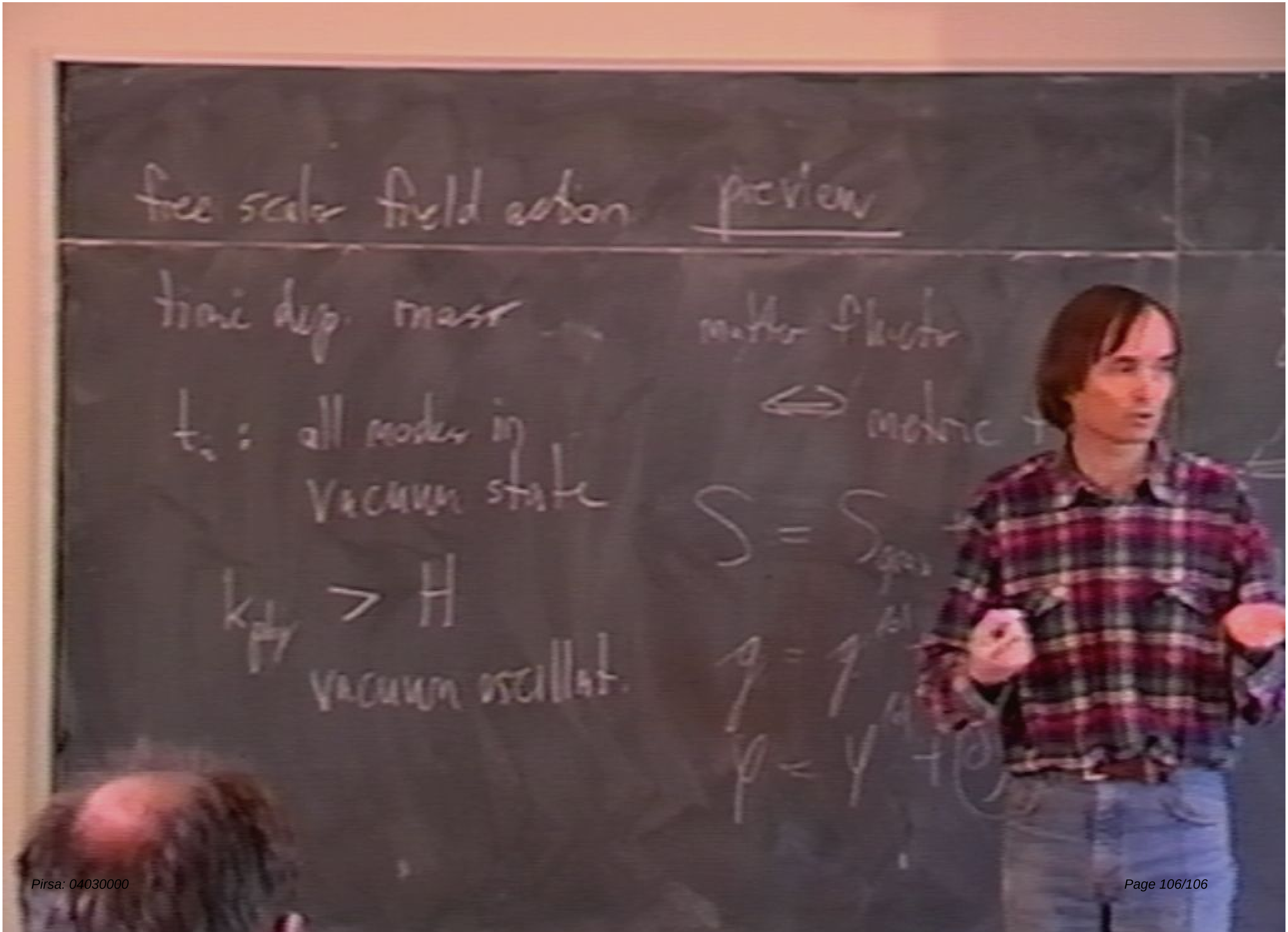

δM/M (k, t_f(k)) = const
t
t_f (k)
T = const
= T_rec t_R
k(θ)


δM/M (k, t_f(k)) = const
t
t_0
T = const
t_R
X
t_f (k)
k
H^-1
t_i (k)
δM/M (k, t_f (k)) = const


reheating
homogeneous
constant
k(t)
T = const
of k=0
quanta
δM/M (k, t_c(k)) = const
t_R
δM/M (k, t_f(k)) = c


preview
matter fluctn
⟺ metric fluctn
S = S_grav + S_matter
T = const
k(t)


preview
matter flucts
⟺ metric flucts
S = S_grav + S_matter
1 variable, scalar field
T = const
= T_rec t_R
k(θ)
δM/M (k, t_x(k)) =


free scalar field action
preview
time dep. mass
all modes in
vacuum state
vacuum oscillat.
metric