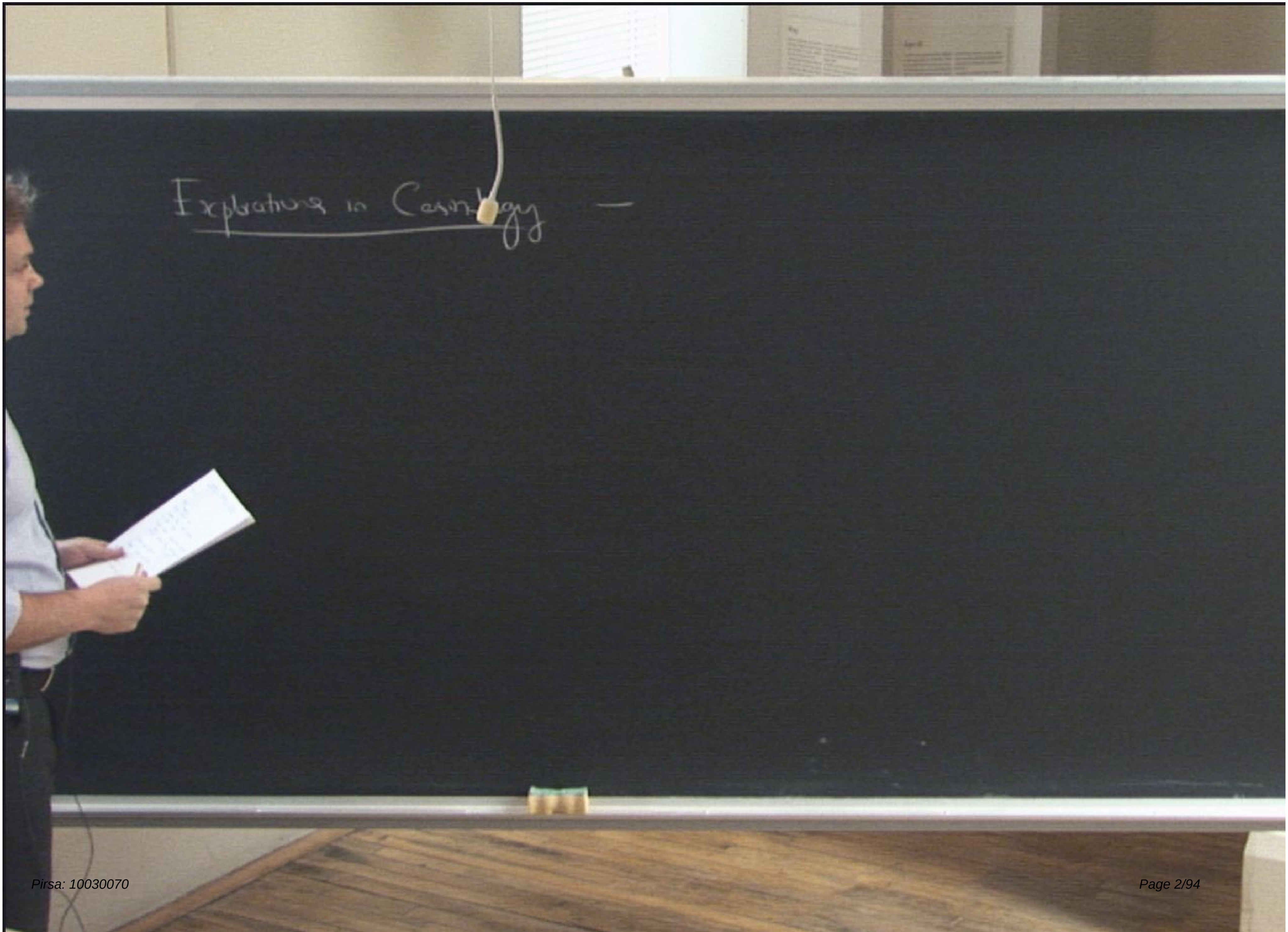
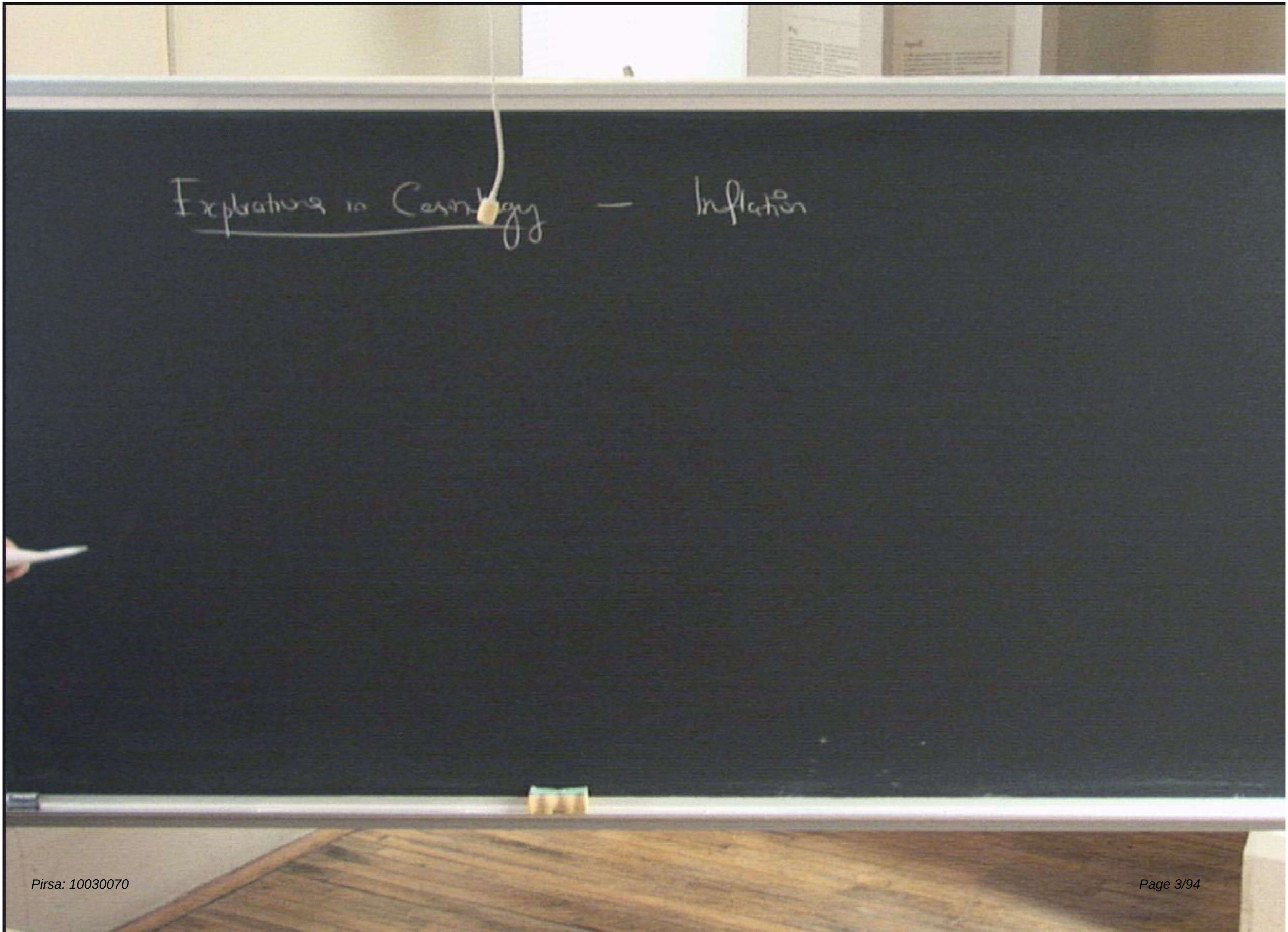
Title: Explorations in Cosmology (PHYS 649) - Lecture 1

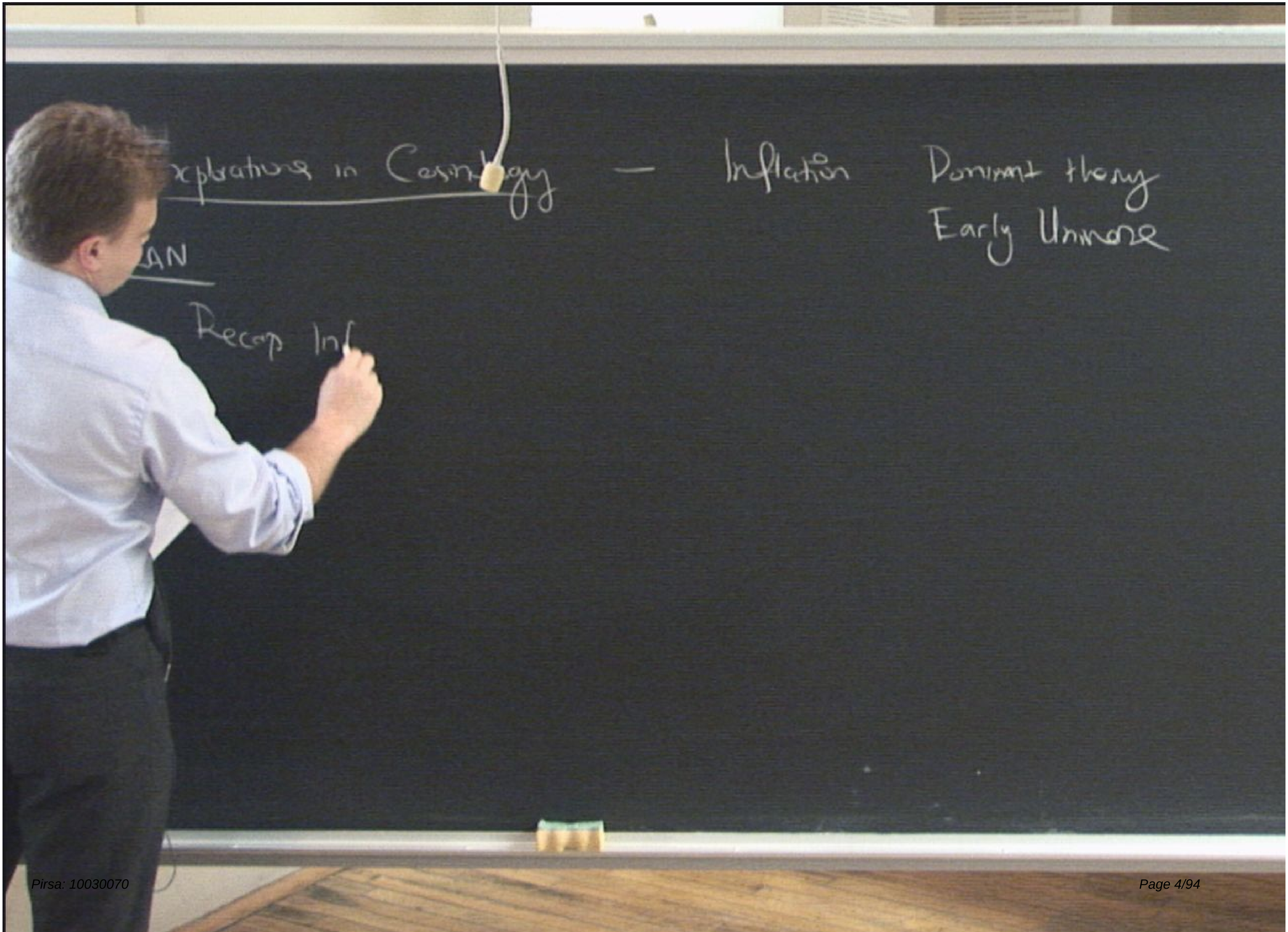
Date: Mar 15, 2010 09:00 AM

URL: http://pirsa.org/10030070

Abstract:


Explorations in Cosmology —


Explorations in Cosmology — Inflation


Inflation
Dominant theory
Early Universe
Recap Inf

Explorations in Cosmology — Inflation Dominant theory Early Universe

PLAN

Recap Inflation

Explorations in Cosmology — Inflation

Dominant theory
Early Universe

PLAN

- Recap Inflation
- Quantum field theory in curved spacetimes

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PLAN

- Recap Inflation
- Quantum field theory in curved spacetimes
  - De Sitter spacetime
  - FRW

Explorations in Cosmology — Inflation

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- Recap Inflation
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  - particle creation.

Explorations in Cosmology — Inflation Dominant theory Early Universe

PLAN

- Recap Inflation
- Quantum field theory in curved spacetimes
  - De Sitter spacetime
  - FRW
- particle creation.
- Squeezed states & coherent states

Cosmological Perturbation Theory
(Quantum fields AND gravity)

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Comoving gauge

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Inflationary Power Spectrum

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Inflationary Power Spectrum

Non-gaussianity
Stringy motivated models of inflation

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Inflationary Power Spectrum

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Stringy motivated models of inflation

Recap Inflation

Recap Inflation

Introduced 'initial conditions problems'

Horizon problem

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Horizon problem - Why is it

Recap Inflation

Introduced 'initial conditions problems'

Horizon problem - Why is it

al conditions problems'

– Why is the universe appears highly correlated over length scales that would have been out of causal contact (outside each others horizon)

Recap Inflation

Introduced 'initial conditions problems'

Horizon problem — Why is the universe appears highly correlat[ed]
that would have been out of causal contac[t]

Flatness problem

Recap Inflation

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Horizon problem – Why is it universe appears highly correlat[...] that would have been out of causal contac[...]

Flatness problem

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

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Horizon problem – Why is it universe appears highly correlat[ed] that would have been out of causal contac[t]

Flatness problem

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Matter $\rho \sim \frac{1}{a^3}$

Radiation $\rho \sim \frac{1}{a^4}$

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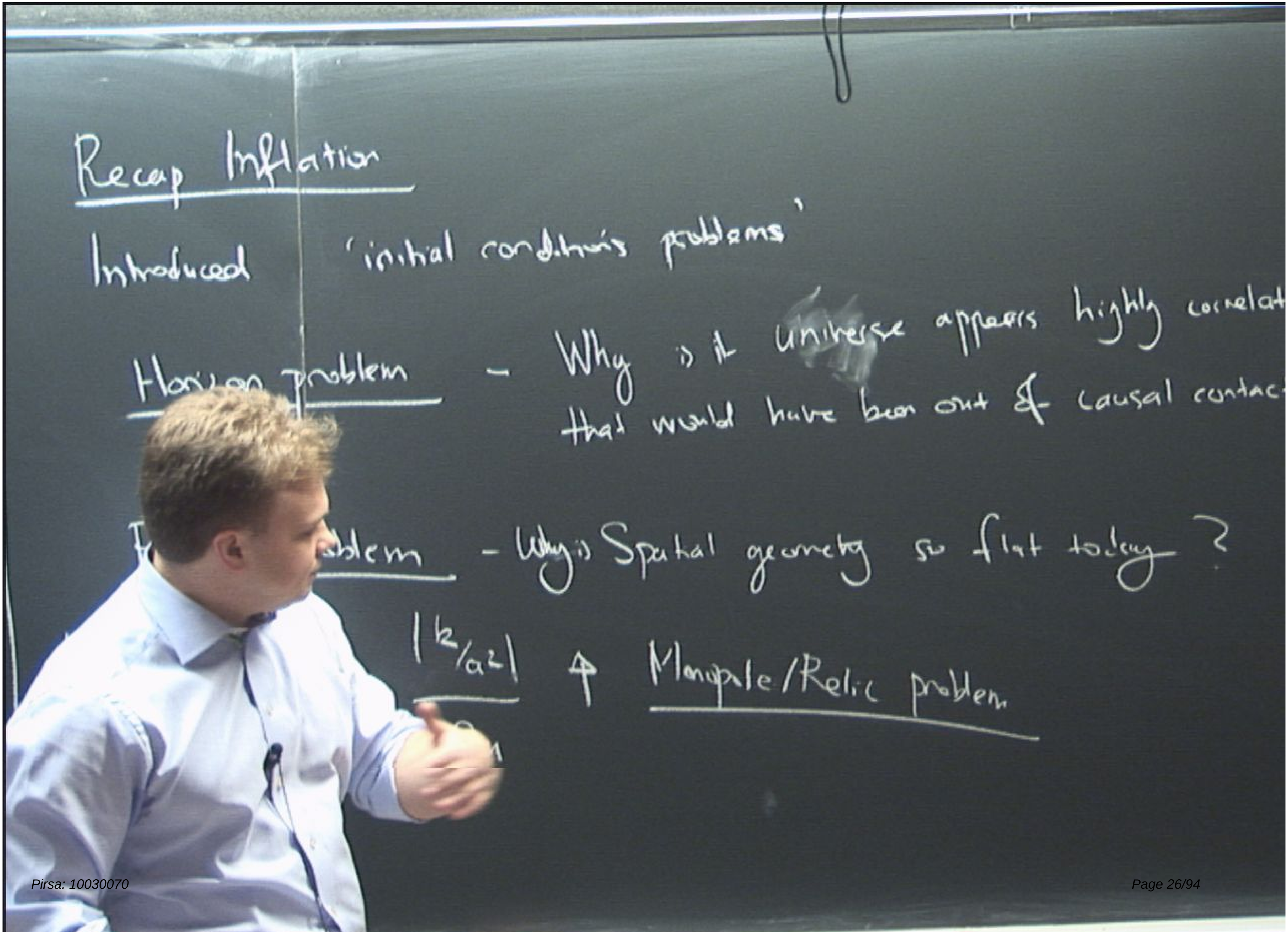
Flatness problem

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad \frac{|k/a^2|}{\rho_H} \uparrow$$

Matter $\rho \sim \frac{1}{a^3}$

Radiation $\rho \sim \frac{1}{a^4}$


Recap Inflation
Introduced 'initial conditions problems'
Horizon problem - Why is it universe appears highly correlat
that would have been out of causal contac
oblem - Why is Spatial geometry so flat today ?
|k/a²| ↑ Monopole/Relic problem

Recap Inflation

Introduced 'initial conditions problems'

Horizon problem - Why is the universe appears highly correlat[ed] that would have been out of causal contac[t]

Flatness problem - Why is spatial geometry so flat today?

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\frac{|k/a^2|}{\rho_H}\uparrow$$

Matter $\rho \sim \frac{1}{a^3}$

Radiation $\rho \sim \frac{1}{a^4}$

Monopole/Relic problem - Why don't [...] from early u[niverse] r

'initial conditions problems'

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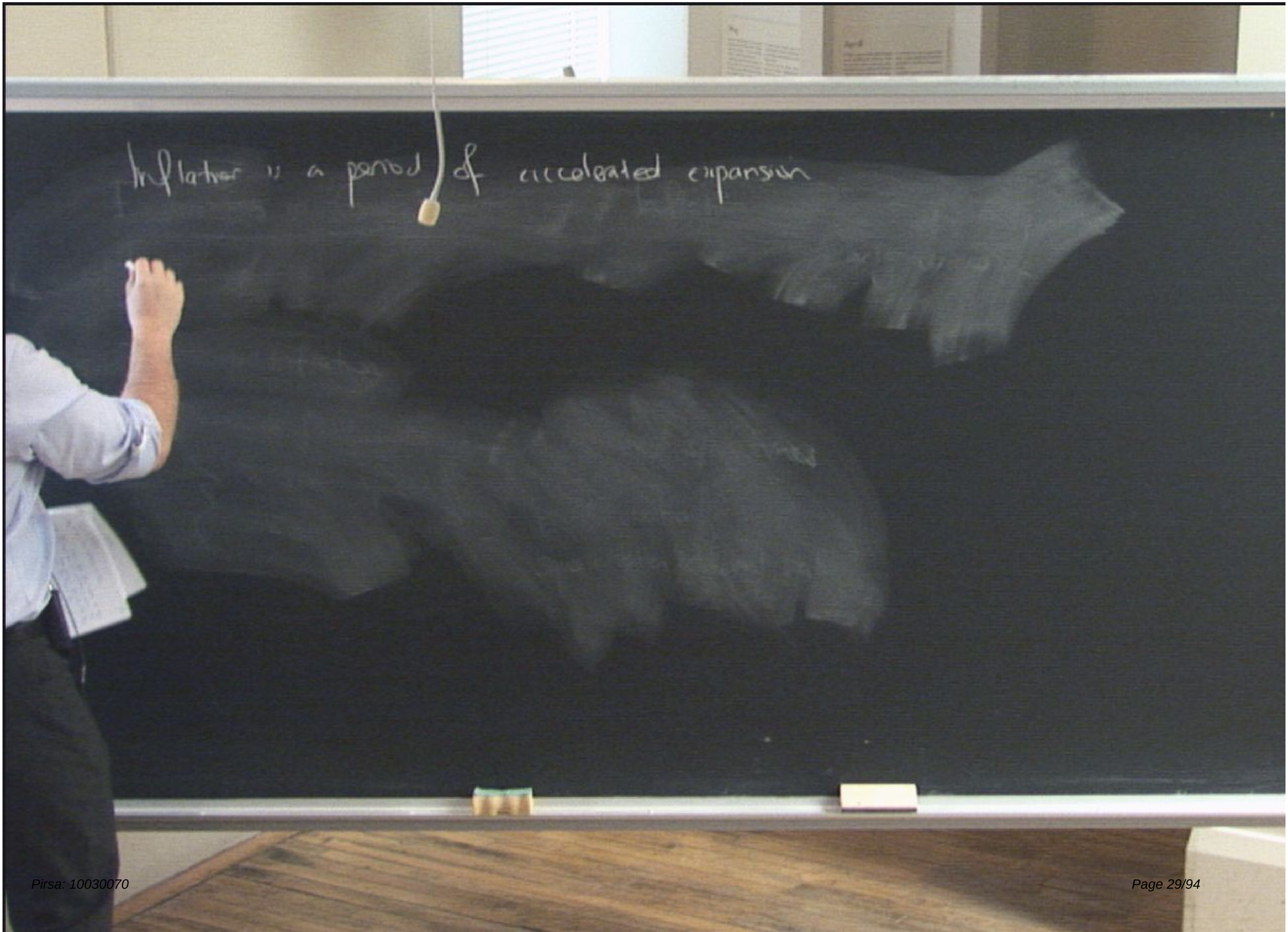
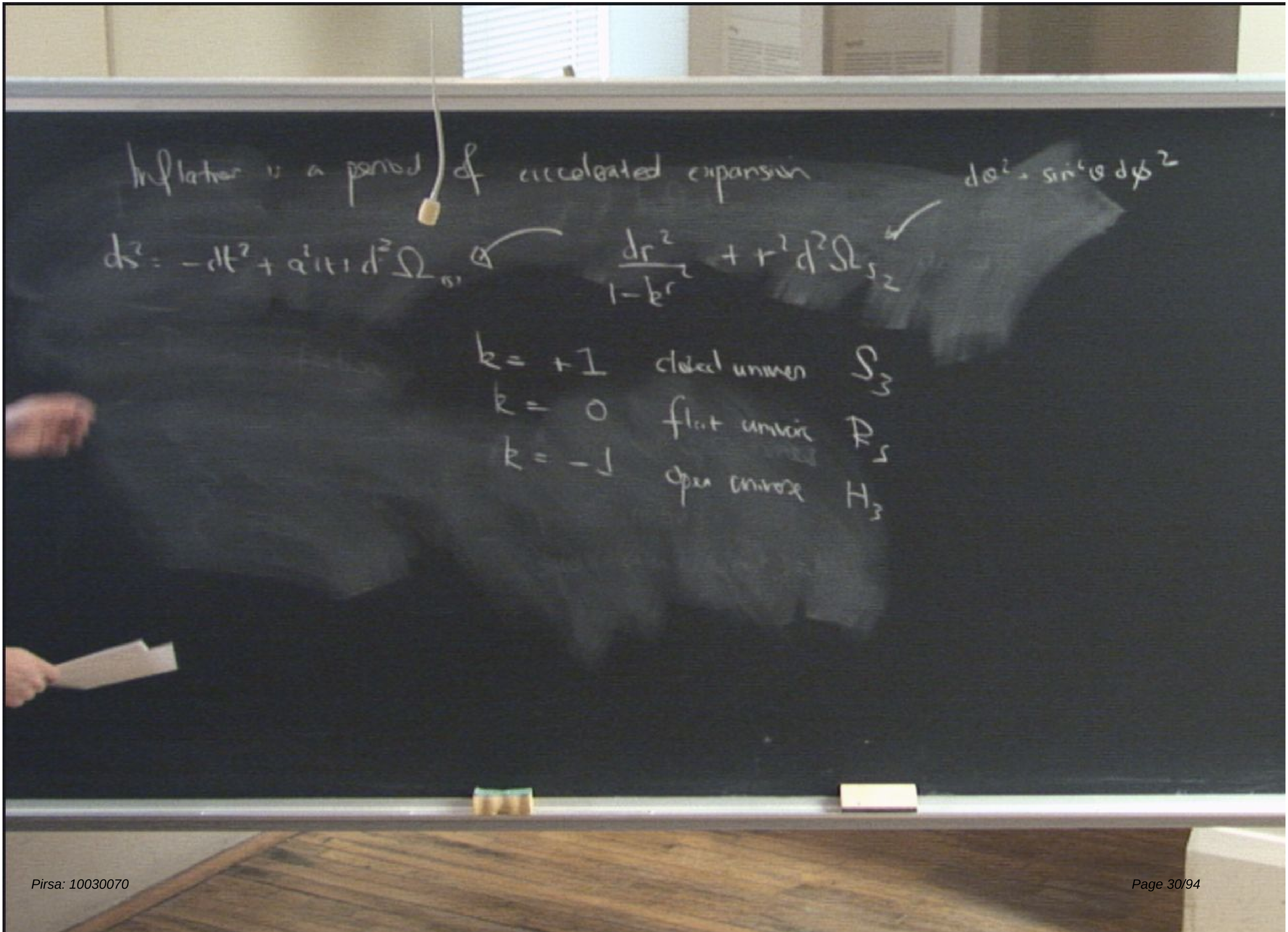
$$\frac{|k/a^2|}{\rho_M} \uparrow$$

Monopole/Relic problem — Why don't we see left overs from early universe?


Inflation is a period of accelerated expansion


Inflation is a period of accelerated expansion
$d\theta^2 + \sin^2\theta\, d\phi^2$
$ds^2 = -dt^2 + a^2(t)\, d^2\Omega_{S_3}$
$\frac{dr^2}{1-kr^2} + r^2 d^2\Omega_{S_2}$
$k = +1$ closed universe S_3
$k = 0$ flat universe R_3
$k = -1$ open universe H_3

Inflation is a period of accelerated expansion

$d\theta^2 + \sin^2\theta \, d\phi^2$

$$ds^2 = -dt^2 + a^2(t)\, d^2\Omega_{(3)} \qquad \frac{dr^2}{1-kr^2} + r^2 d^2\Omega_{S_2}$$

$$\ddot{a} > 0$$

$k = +1$	closed universe	S_3
$k = 0$	flat universe	R_3
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$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{1}{3M_{pl}^2}$$

$$\frac{1}{8\pi G}$$

Recap Inflation

Introduced 'in

Horizon problem

Flatness problem

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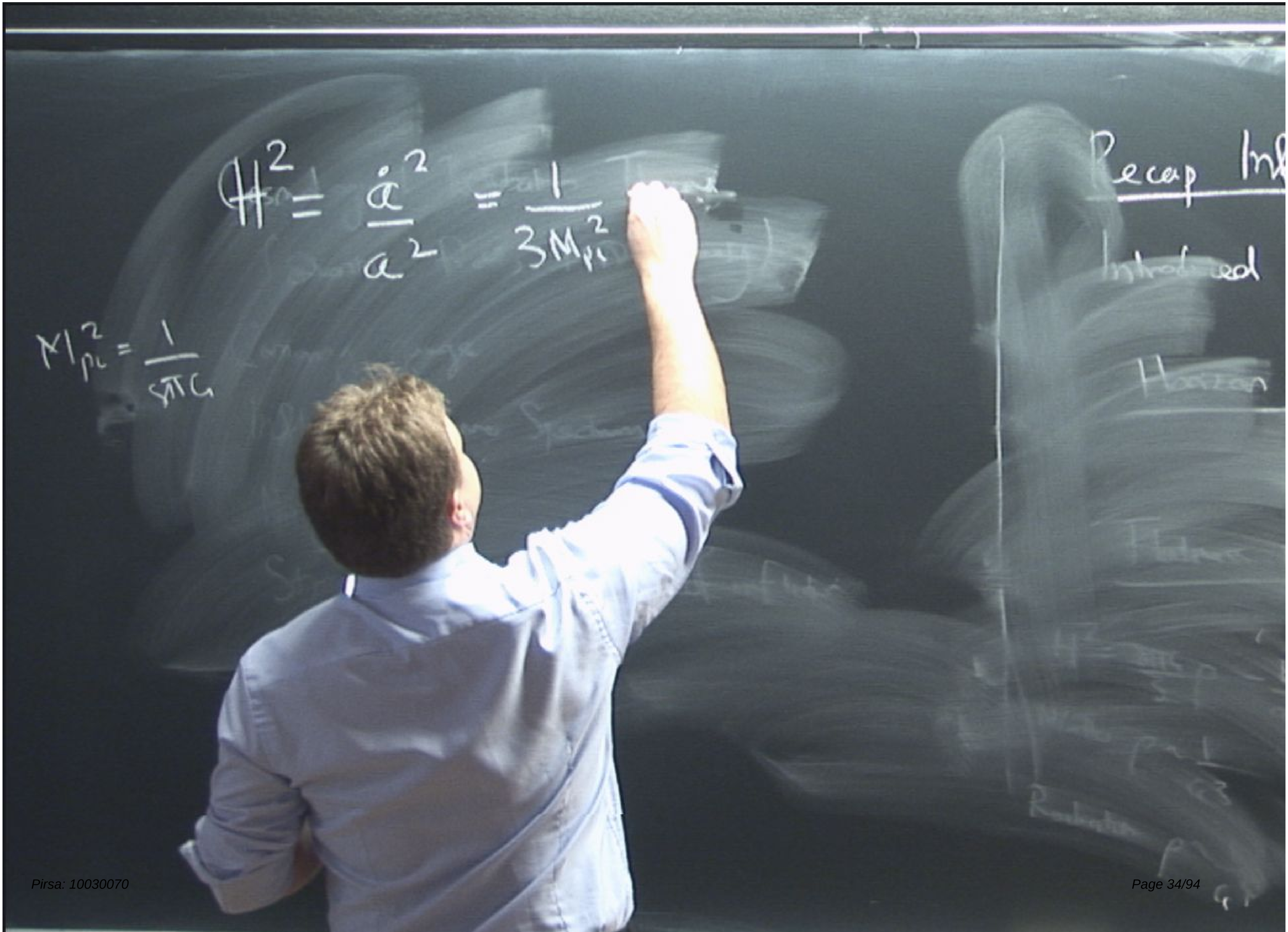
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Recap Inf
Introduced
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$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{1}{3M_{pl}^2}\rho - \frac{k}{a^2}$$

Recap Inf

Introduced

Horizon

$$M_{pl}^2 = \frac{1}{8\pi G}$$

$$k = 0$$

$$\dot{a}^2 = \frac{1}{3M_{pl}^2}\rho a^2$$

$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^3}\left(\dot{\rho} a^2 + 2a\dot{a}\rho\right)$$

$$\boxed{H^2 = \frac{\dot{a}^2}{a^2} = \frac{1}{3M_{pl}^2}\rho - \frac{k}{a^2}}$$

$M_{pl}^2 = \frac{1}{8\pi G}$ $k = 0$

$$\dot{a}^2 = \frac{1}{3M_{pl}^2}\rho a^2$$

$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^3}\left(\dot{\rho} a^2 + 2a\dot{a}\rho\right)$$

$$\dot{\rho} = -3\frac{\dot{a}}{a}(p+\rho)$$ $c = 1$

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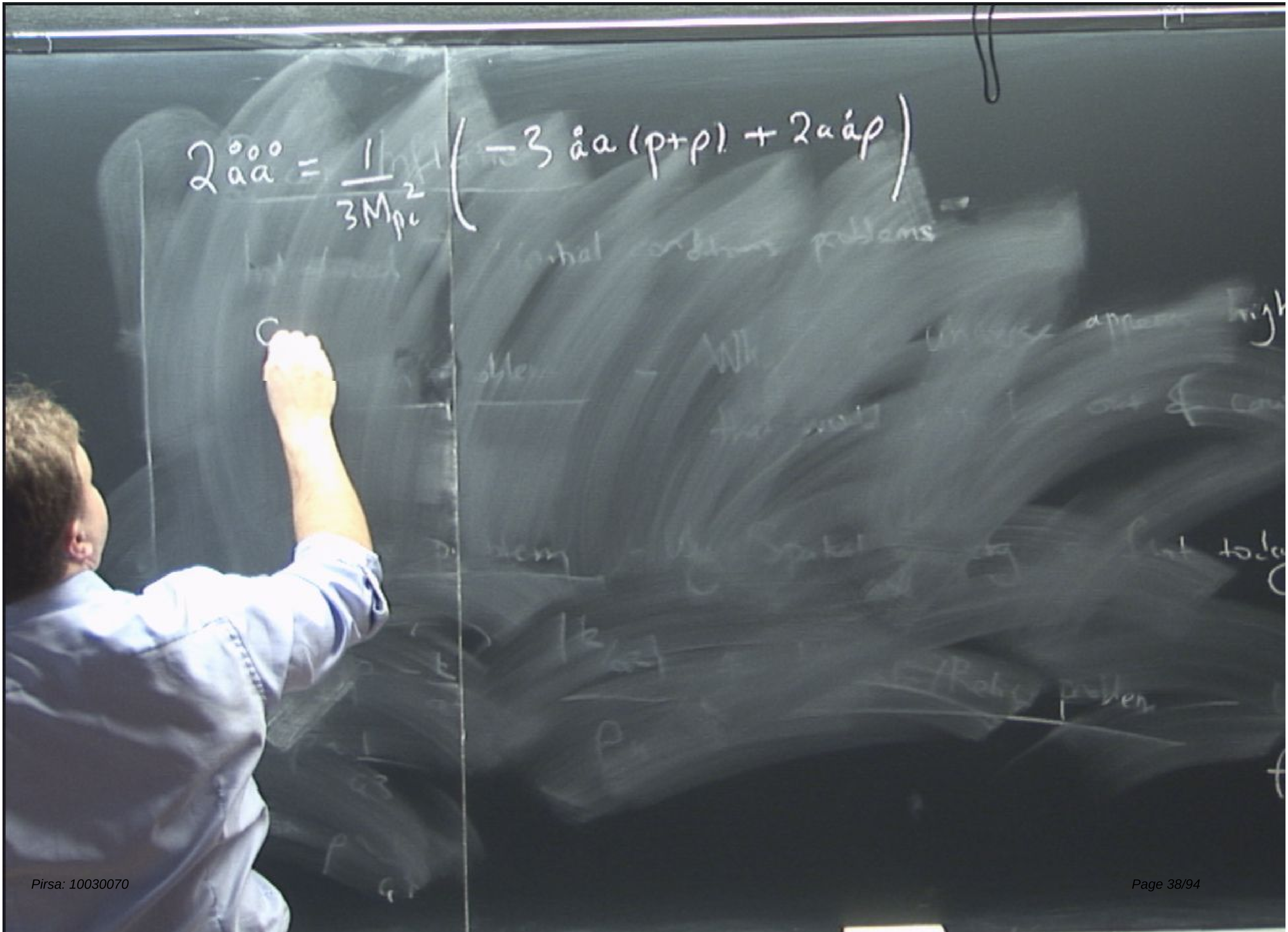
$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}$$


$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}\left(-3\dot{a}a(p+\rho) + 2a\dot{a}\rho\right)$

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$\rho)$

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$$\boxed{\ddot{a} = -\frac{1}{2M_{pl}^2}a\left(p+\frac{1}{3}\rho\right)}$$

$\rho)$ $\quad -\frac{1}{2}+\frac{1}{3} = -\frac{1}{6}(3-2)$

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$$\boxed{\ddot{a} = -\frac{1}{2M_{pl}^2}a\left(p + \frac{1}{3}\rho\right)}$$

$$p + \frac{1}{3}\rho <$$

$$p < -$$

$$\rho)$$

$$-\frac{1}{2} + \frac{1}{3} = -\frac{1}{6}(3-2)$$

$$= \frac{1}{3M_{pl}^2}\left(-3\dot{a}a(p+\rho) + 2a\dot{a}\rho\right)$$

$$\ddot{a} = -\frac{1}{2M_{pl}^2}\, a(p+\rho) + \frac{1}{3M_{pl}^2}\, a\rho$$

$$\boxed{\ddot{a} = -\frac{1}{2M_{pl}^2}\, a\left(p + \frac{1}{3}\rho\right)}$$

$$p + \frac{1}{3}\rho < 0$$

$$p < -\frac{1}{3}\rho$$

$$+\frac{1}{3} = -\frac{1}{6}(3-2)$$

$$w = \frac{p}{\rho}$$

$$= \frac{1}{3M_{pl}^2}\left(-3\dot{a}a(p+\rho) + 2a\dot{a}\rho\right)$$

$$\mathring{a} = -\frac{1}{2M_{pl}^2}a(p+\rho) + \frac{1}{3M_{pl}^2}a\rho$$

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$$w = \frac{p}{\rho}$$

$$\boxed{w < -\frac{1}{3}}$$

$(p+\rho) + 2a\dot{a}\rho\Big)$

$a(p+\rho) + \frac{1}{3M_{pl}^2} a\rho$

$\boxed{a\left(p + \frac{1}{3}\rho\right)}$

$-2\Big)$

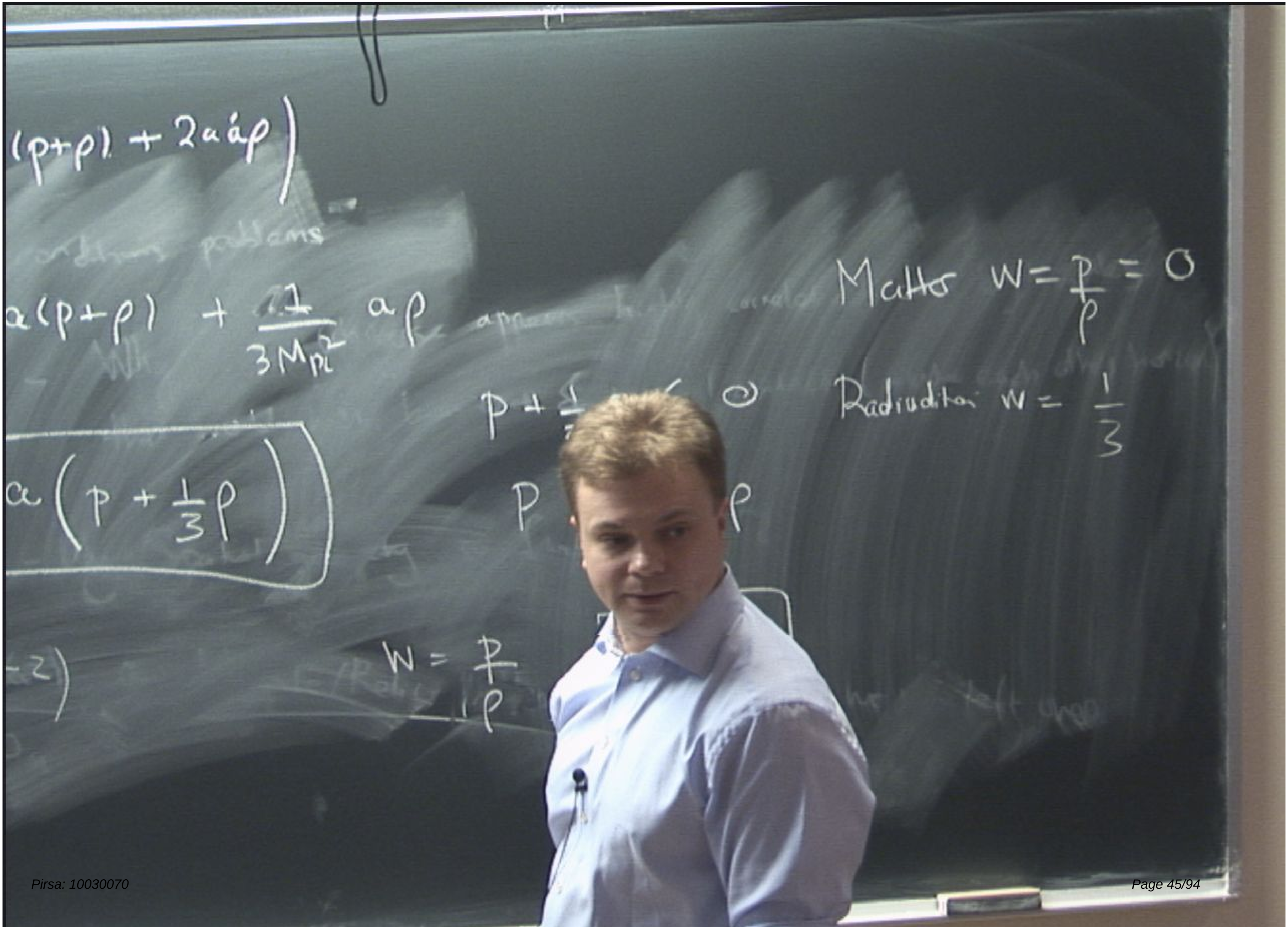
$p + \frac{1}{3}\rho < 0$

$p < -\frac{1}{3}\rho$

$w = \frac{p}{\rho}$ $\boxed{w < -\frac{1}{3}}$

Matter $w = \frac{p}{\rho} = 0$

Radiation $w = \frac{1}{3}$



(p+ρ) + 2aȧρ)
a(p+ρ) + 1/(3M_pl^2) aρ
Matter w = p/ρ = 0
Radiation w = 1/3
a(p + 1/3 ρ)
w = p/ρ

$\dot{a}a(p+\rho) + 2a\dot{a}\rho)$

$\frac{1}{M_{pl}^2} a(p+\rho) + \frac{1}{3M_{pl}^2} a\rho$

$p + \frac{1}{3}\rho < 0$

$p < -\frac{1}{3}\rho$

$\boxed{a\left(p + \frac{1}{3}\rho\right)}$

Matter $w = \frac{p}{\rho} = 0$

Radiation $w = \frac{1}{3}$

$(3^k - 2)$

$w = \frac{p}{\rho}$ $\boxed{w < -\frac{1}{3}}$

$$\boxed{H^2 = \frac{\dot{a}^2}{a^2} = \frac{1}{3M_{pl}^2}\rho - \frac{k}{a^2}}$$

$\frac{1}{8\pi G}$

$k = 0$

$$\dot{a}^2 = \frac{1}{3M_{pl}^2}\rho a^2$$

$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}\left(\dot{\rho} a^2 + 2a\dot{a}\rho\right)$$

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$c = 1$

$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}\Big(-$$

$$\ddot{a} = -\frac{}{2M}$$

$$\ddot{a} = -\frac{1}{2M_{p}}$$

$$-\frac{1}{2} + \frac{1}{3} = -\frac{1}{6}\Big($$

$+ 2a\dot{a}p \Big)$

problems

$) + \frac{1}{3M_{pl}^2} a\rho$

$\Big(+ \frac{1}{3}\rho \Big)$

$p + \frac{1}{3}\rho < 0$

$p < -\frac{1}{3}\rho$

Matter $w = \frac{p}{\rho} = 0$

Radiation $w = \frac{1}{3}$

$\Downarrow$

deceleration

$w = \frac{p}{\rho}$

$\boxed{w < -\frac{1}{3}}$

$+ 2a\dot{a}\rho)$

problems

$) + \frac{1}{3M_{pl}^2} a\rho$

Matter $w = \frac{p}{\rho} = 0$

$p + \frac{1}{3}\rho < 0$

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$$\boxed{+\frac{1}{3}\rho\Big)}$$

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Inflation is a period of accelerated expansion

$d\theta^2 + \sin^2\theta\, d\phi^2$

$$ds^2 = -dt^2 + a^2(t)\, d^2\Omega_{(3)}$$

$$\frac{dr^2}{1-kr^2} + r^2 d^2\Omega_{S_2}$$

$$\ddot{a} > 0$$

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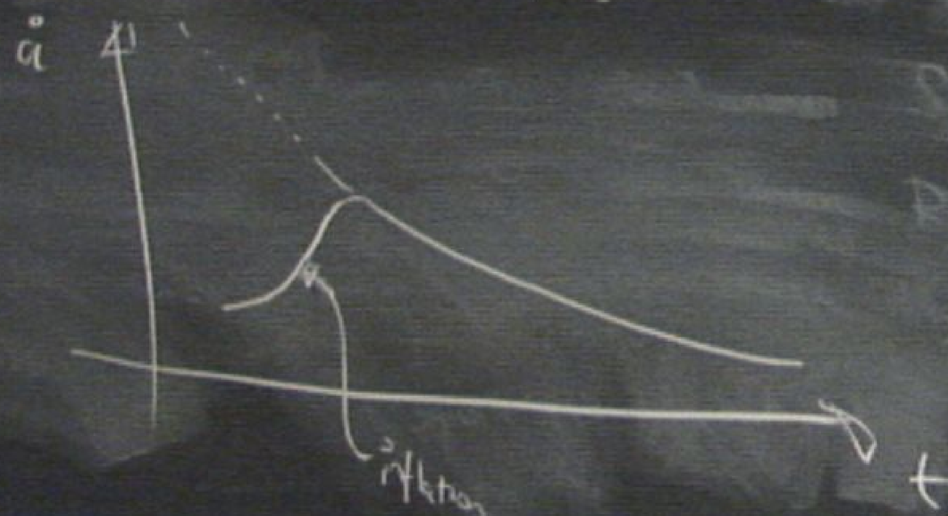

Horizon problem

$$d_H^{(t_{today})} = a(t_{today}) \int_{t_{beg}}^{t_{today}} \frac{1}{a(t)}\, dt$$

$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}\Big(-$$

$$\ddot{a} = -\frac{}{12}$$

$$\boxed{\ddot{a} = -\frac{1}{2M}}$$

Horizon problem

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$$\ddot{a} = -\frac{\quad}{2M}$$

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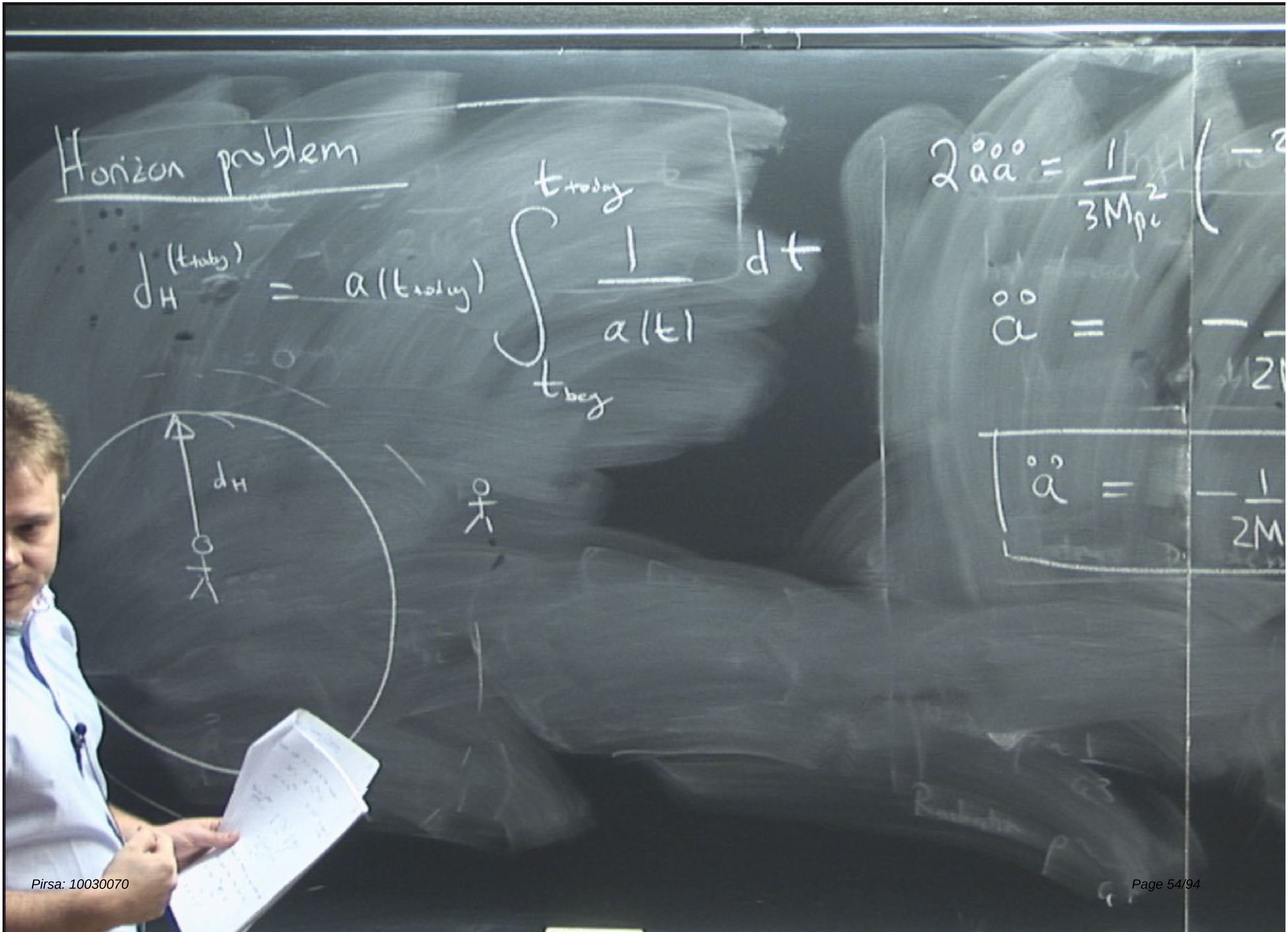
Horizon problem
$d_H^{(t_{today})} = a(t_{today}) \int_{t_{beg}}^{t_{today}} \frac{1}{a(t)} dt$
d_H
$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}($
$\ddot{a} =$
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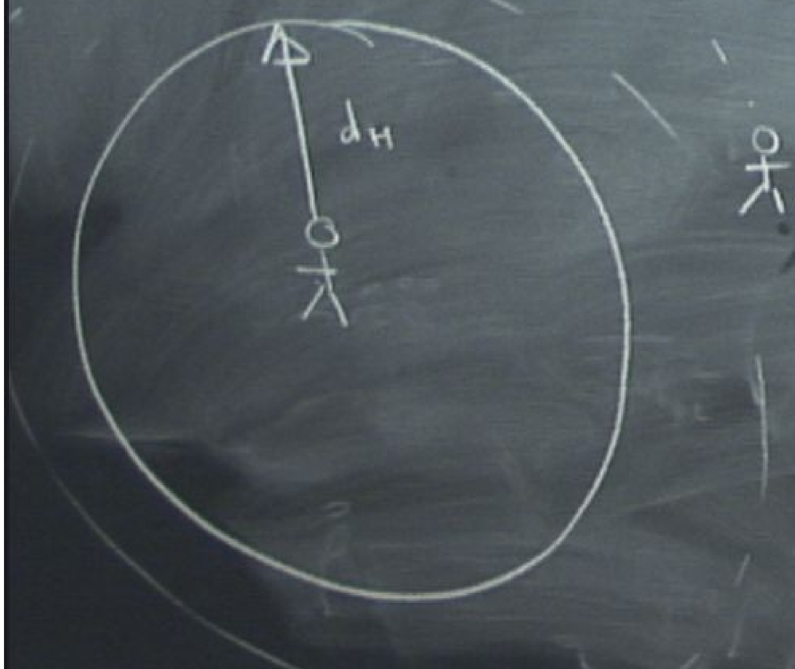
Horizon problem

$$d_H^{(t_{today})} = a(t_{today}) \int_{t_{beg}}^{t_{today}} \frac{1}{a(t)}\, dt$$



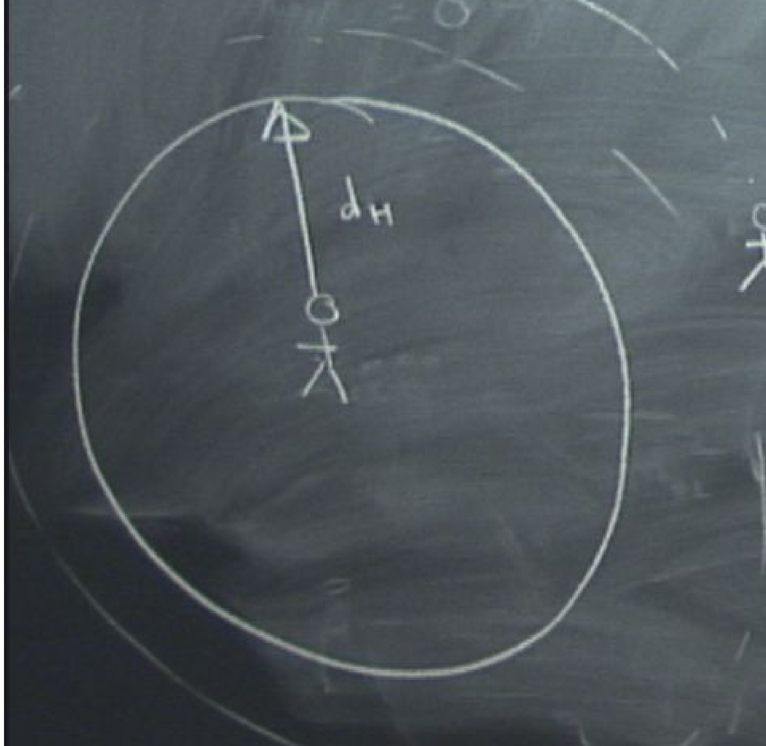
$$2\dot{a}\ddot{a} = \frac{1}{3M_{pl}^2}\Big(- \ldots$$

$$\ddot{a} = - \frac{\ldots}{2\ldots}$$

$$\boxed{\ddot{a} = - \frac{1}{2M\ldots}}$$

Horizon problem

$$d_H^{(t_{today})} = a(t_{today}) \int_{t_{beg}}^{t_{today}} \frac{1}{a(t)}\, dt$$



de Sitter
spacetime
Event horizon

global

local

curvature scale $d_c = H^{-1}$

global

local

curvature scale $d_c = cH^{-1}$

global

local

curvature scale $d_c = cH^{-1}$

Hubble radius

Hubble horizon

horizon

global

local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

global | local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

d_H

global

matter, radiation

local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

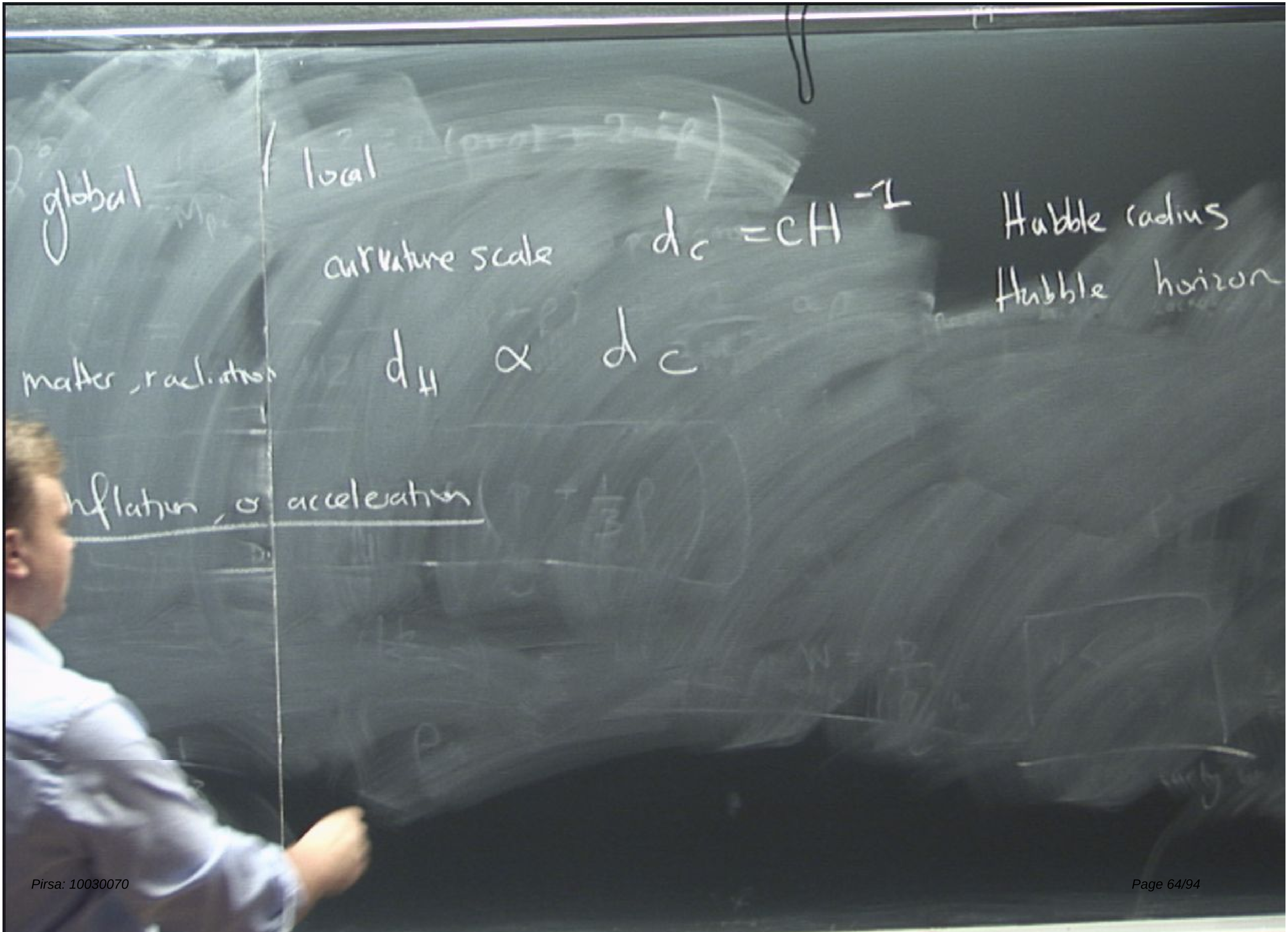
$d_H \propto d_c$

global | local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

matter, radiation $d_H \propto d_c$


global
local
curvature scale
$d_c = cH^{-1}$
Hubble radius
Hubble horizon
matter, radiation
$d_H \propto d_c$
inflation, or acceleration

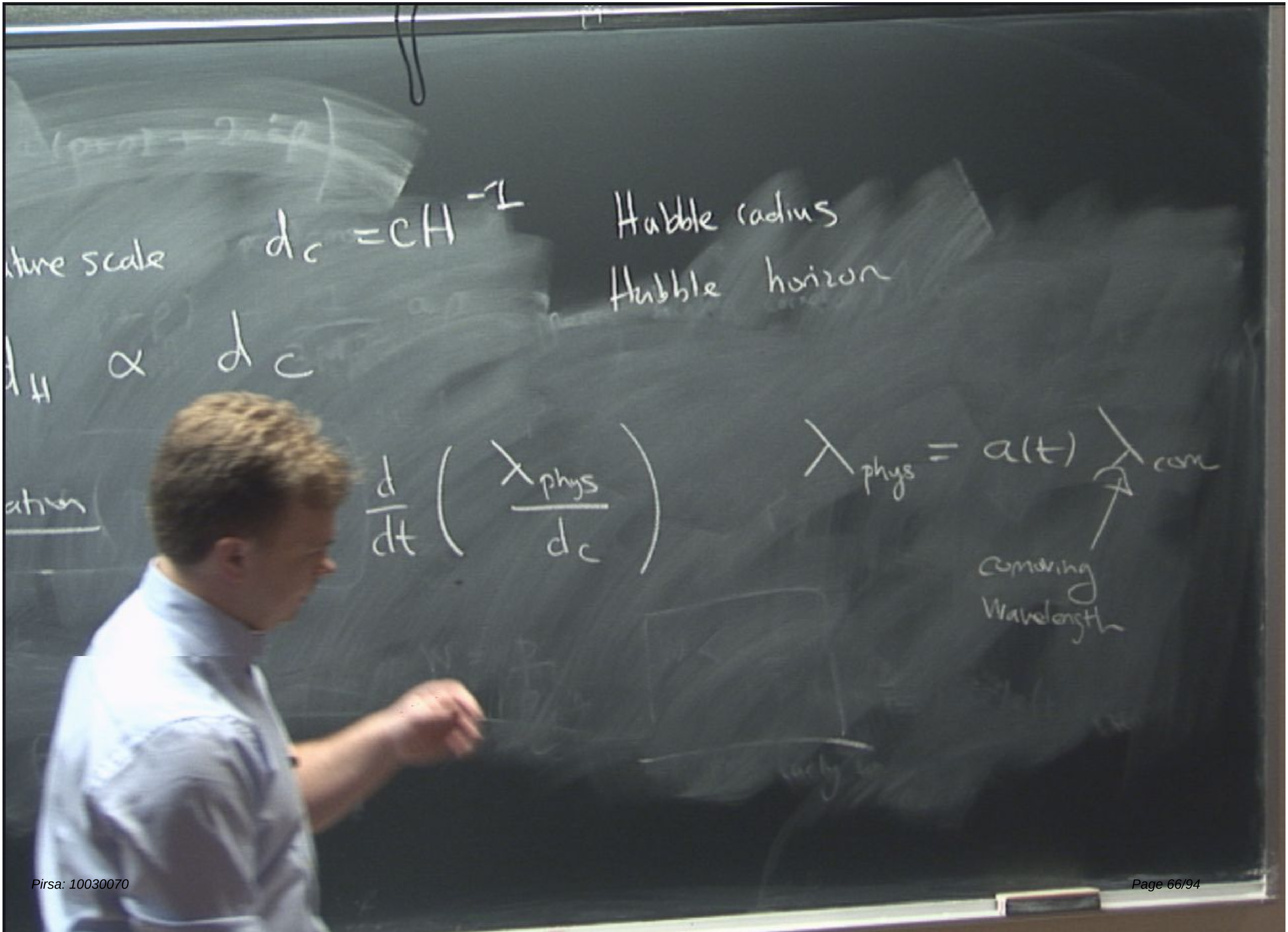
global | local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

matter, radiation $d_H \propto d_c$

<u>Inflation, or acceleration</u> $\longrightarrow \dfrac{d}{dt}\left(\dfrac{\lambda_{phys}}{d_c}\right)$


ture scale
$d_c = cH^{-1}$
Hubble radius
Hubble horizon
$d_H \propto d_c$
ation
$\frac{d}{dt}\left(\frac{\lambda_{phys}}{d_c}\right)$
$\lambda_{phys} = a(t)\,\lambda_{com}$
comoving wavelength

$d_c = cH^{-1}$ Hubble radius

...ture scale

Hubble horizon

$d_H \propto d_c$

...ation $\rightarrow$ $\frac{d}{dt}\left(\frac{\lambda_{phys}}{d_c}\right)$

$\lambda_{phys} = a(t)\,\lambda_{com}$

comoving wavelength

$\lambda_{phys}(t) = \frac{a(t)}{a(t_0)}\lambda_{phys}(t_0)$

$= a(t)\,\lambda_{com}$

...ture scale $\quad d_c = cH^{-1}$ Hubble radius

Hubble horizon

$d_H \propto d_c$

...ation $\rightarrow$ $\dfrac{d}{dt}\left(\dfrac{\lambda_{phys}}{d_c}\right) > 0 \qquad \lambda_{phys} = a(t)\,\lambda_{com}$

comoving wavelength

$\dfrac{\dot a}{a}$

$\dfrac{d}{dt}\left(aH\lambda_{com}\right)$

$\ddot a\,\lambda_{com}$

$$\lambda_{phys}(t) = \frac{a(t)}{a(t_0)}\lambda_{phys}(t_0) = a(t)\,\lambda_{com}$$

local

curvature scale $d_c = cH^{-1}$ Hubble radius

Hubble horizon

acl.ation $d_H \propto d_c$

...on, or acceleration $\longrightarrow$ $\frac{d}{dt}\left(\frac{\lambda_{phys}}{d_c}\right) > 0$ $\lambda_{phys} = a(t$

$\frac{\dot{a}}{a}$

comov

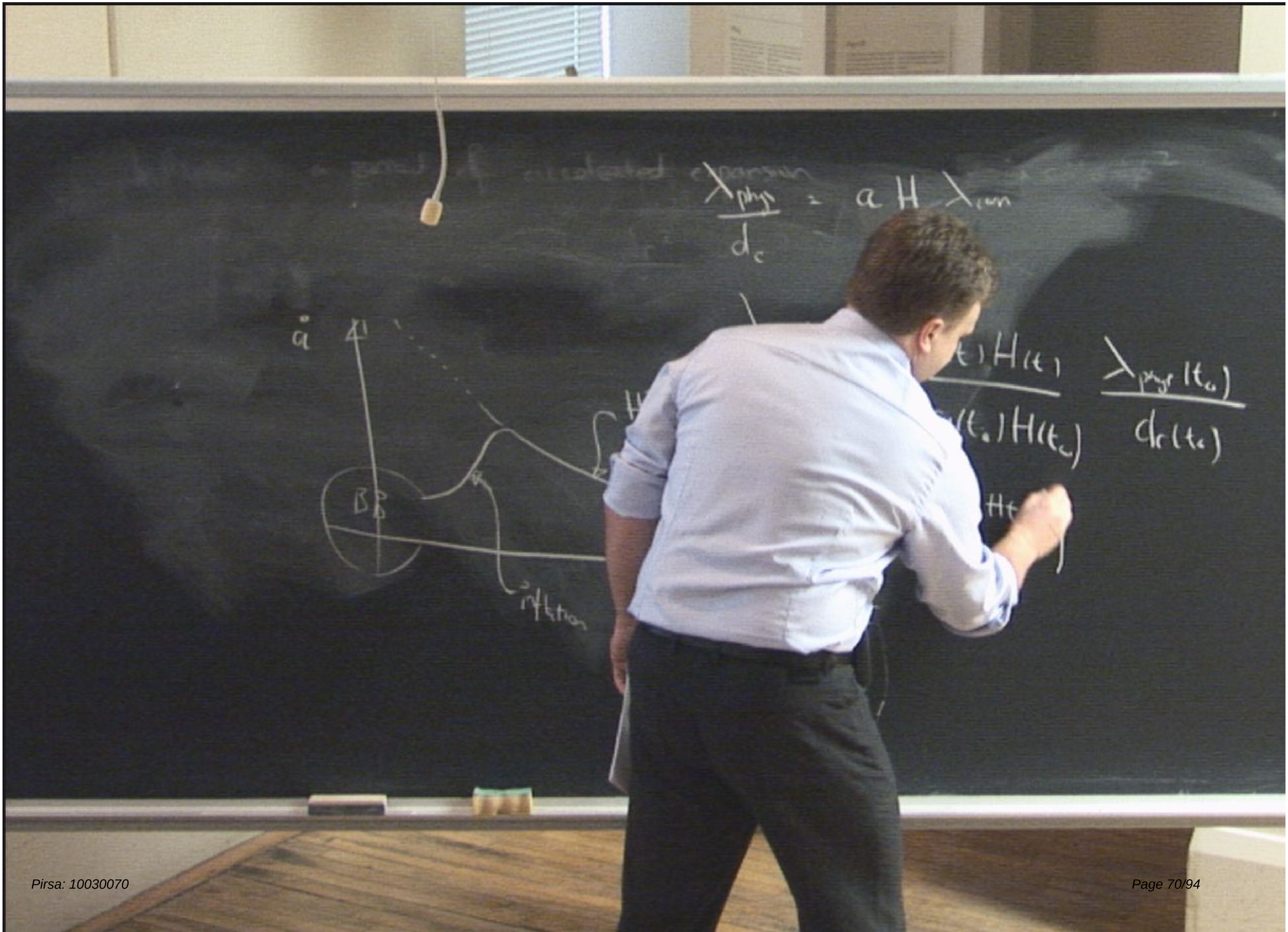
Wavel

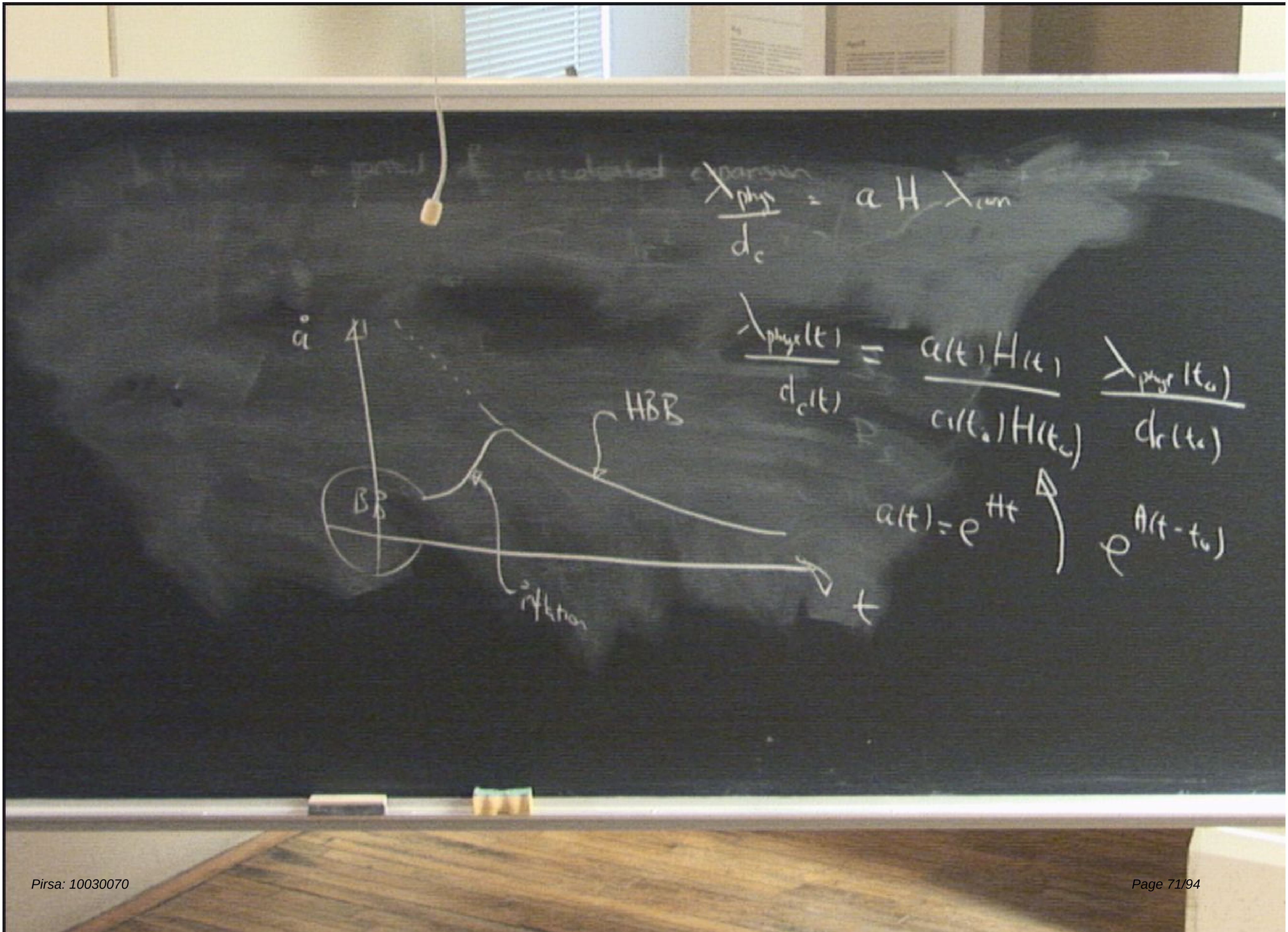
$\left(\frac{\ldots \lambda_{com}}{\ldots^{-1}}\right) = \frac{d}{dt}\left(aH\lambda_{com}\right)$

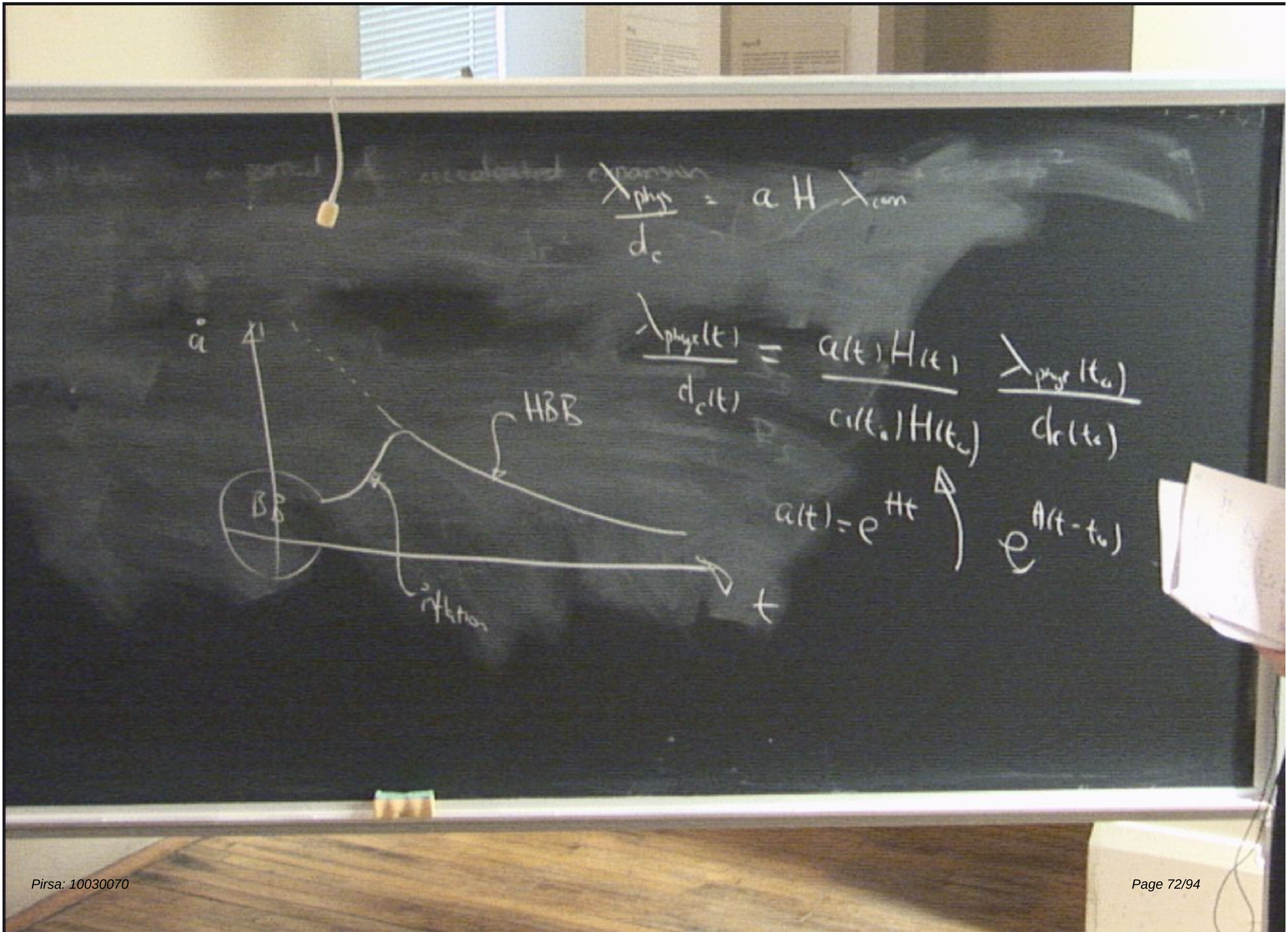
$\lambda_{phys}(t) = \frac{a(t)}{a(t_0)}\lambda_{phys}(t_0$

$= \ddot{a}\,\lambda_{com} > 0$

$= a(t)\,\lambda_{com}$



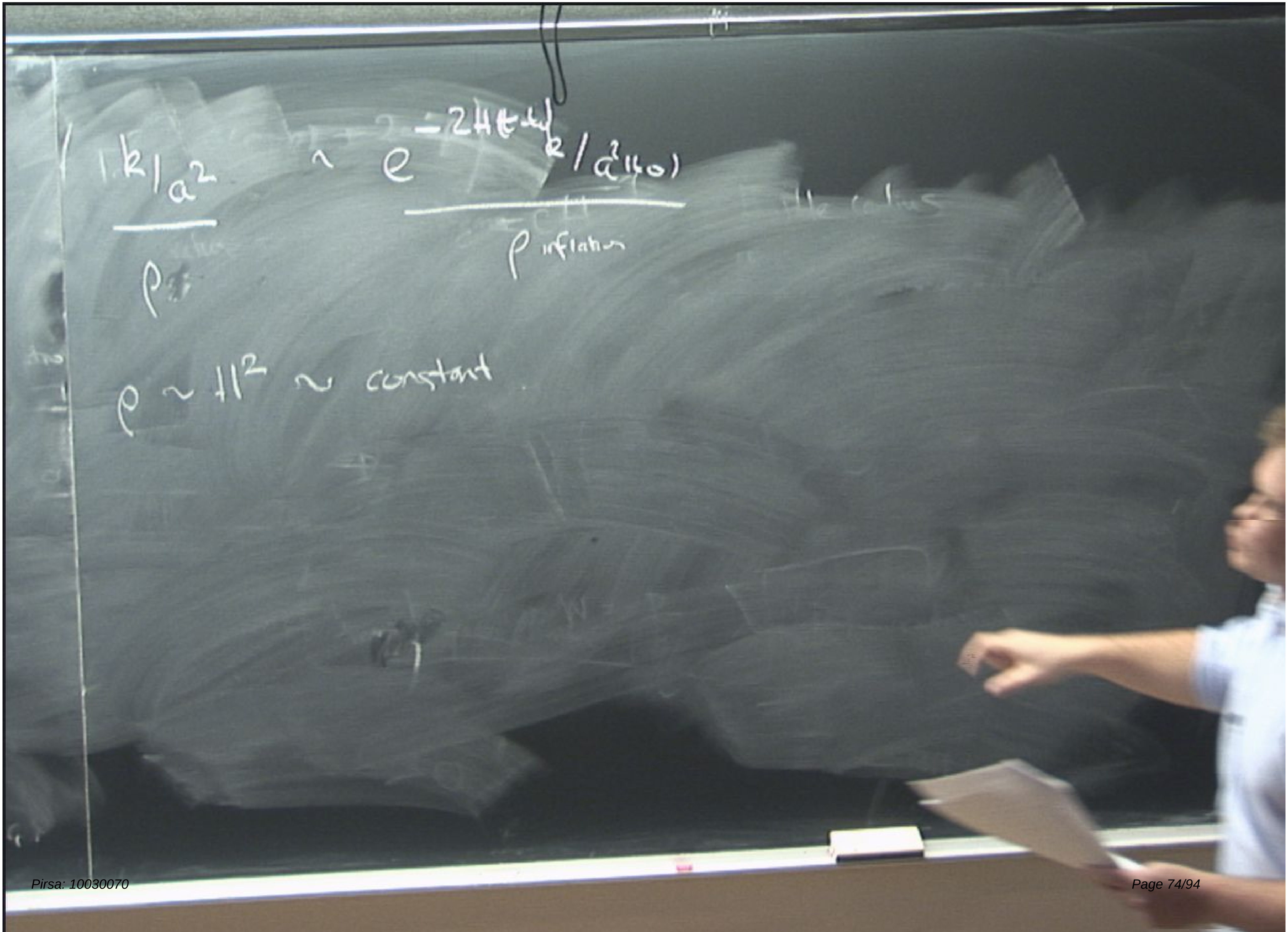

λphys / dc = a H λcom
λphys(t) / dc(t) = a(t) H(t) / a(t0) H(t0) · λphys(t0) / dc(t0)
a(t) = e^Ht
e^H(t - t0)
ȧ
HBB
BB
inflation
t

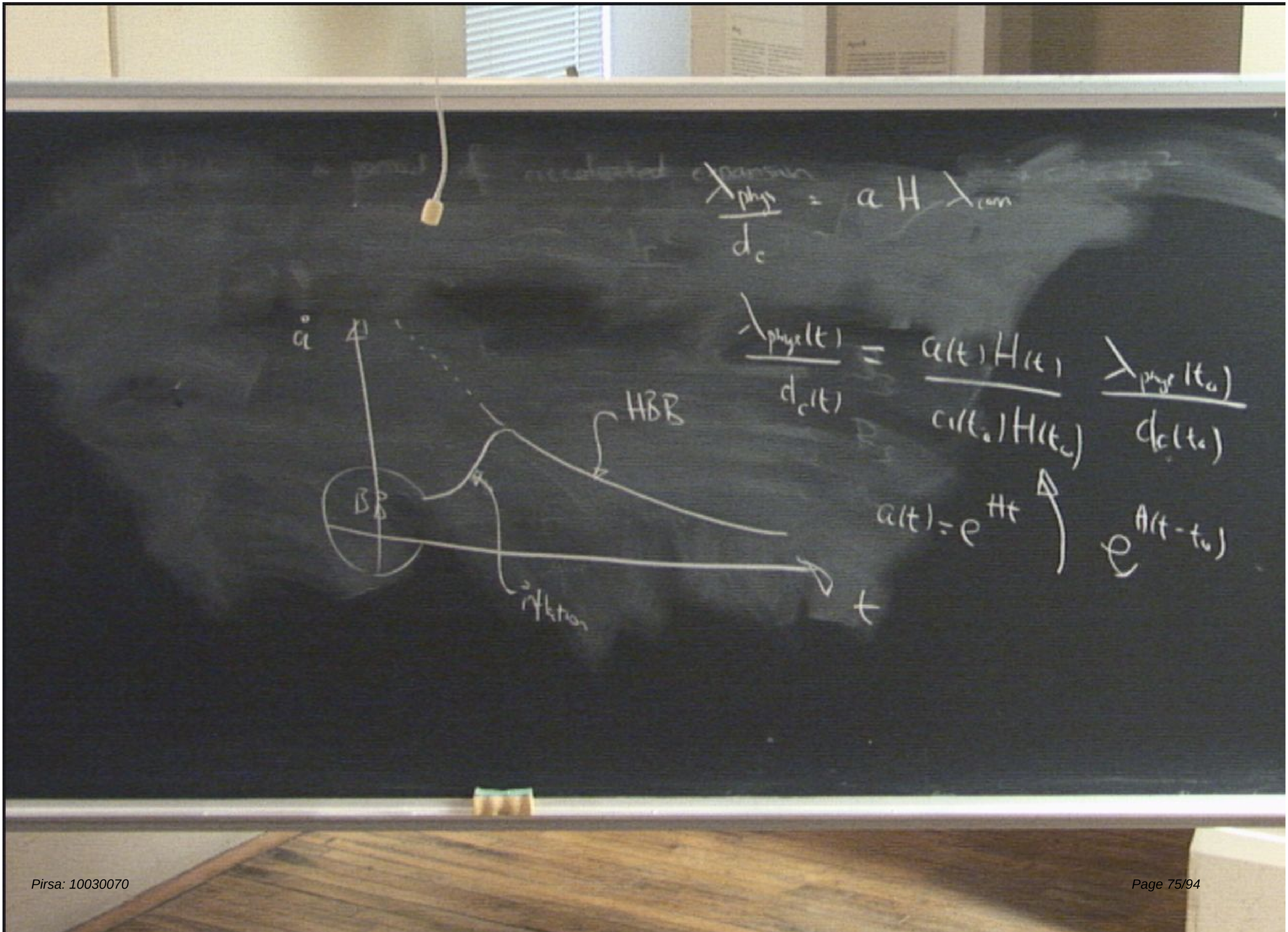


$\frac{\lambda_{phys}}{d_c} = a H \lambda_{com}$
$\frac{\lambda_{phys}(t)}{d_c(t)} = \frac{a(t)H(t)}{a(t_0)H(t_0)} \frac{\lambda_{phys}(t_0)}{d_c(t_0)}$
$a(t) = e^{Ht}$
$e^{H(t-t_0)}$
$\dot{a}$
HBB
BB
inflation
t

$$\frac{|k|/a^2}{\rho}$$

$\rho \sim H^2 \sim$ constant


|k|/a² / ρ ~ e^(−2H(t−t_i)) k/a²(t_0) / ρ inflation
ρ ~ H² ~ constant


$\frac{\lambda_{phys}}{d_c} = aH\lambda_{com}$
$\frac{\lambda_{phys}(t)}{d_c(t)} = \frac{a(t)H(t)}{a(t_0)H(t_0)} \frac{\lambda_{phys}(t_0)}{d_c(t_0)}$
$a(t) = e^{Ht}$
$e^{H(t-t_0)}$
$\dot{a}$
HBB
BB
inflation
t

$$\frac{|k|/a^2}{\rho} \sim \frac{e^{-2H(t-t_0)}\, k/a^2(t_0)}{\rho_{\text{inflation}}}$$

$$\rho \sim H^2 \sim \text{constant}$$

Monopoles

$$\rho \sim \frac{1}{a^3}$$

$$\frac{1/a^3}{\rho} \sim e^{-3H(t-t_0)}$$

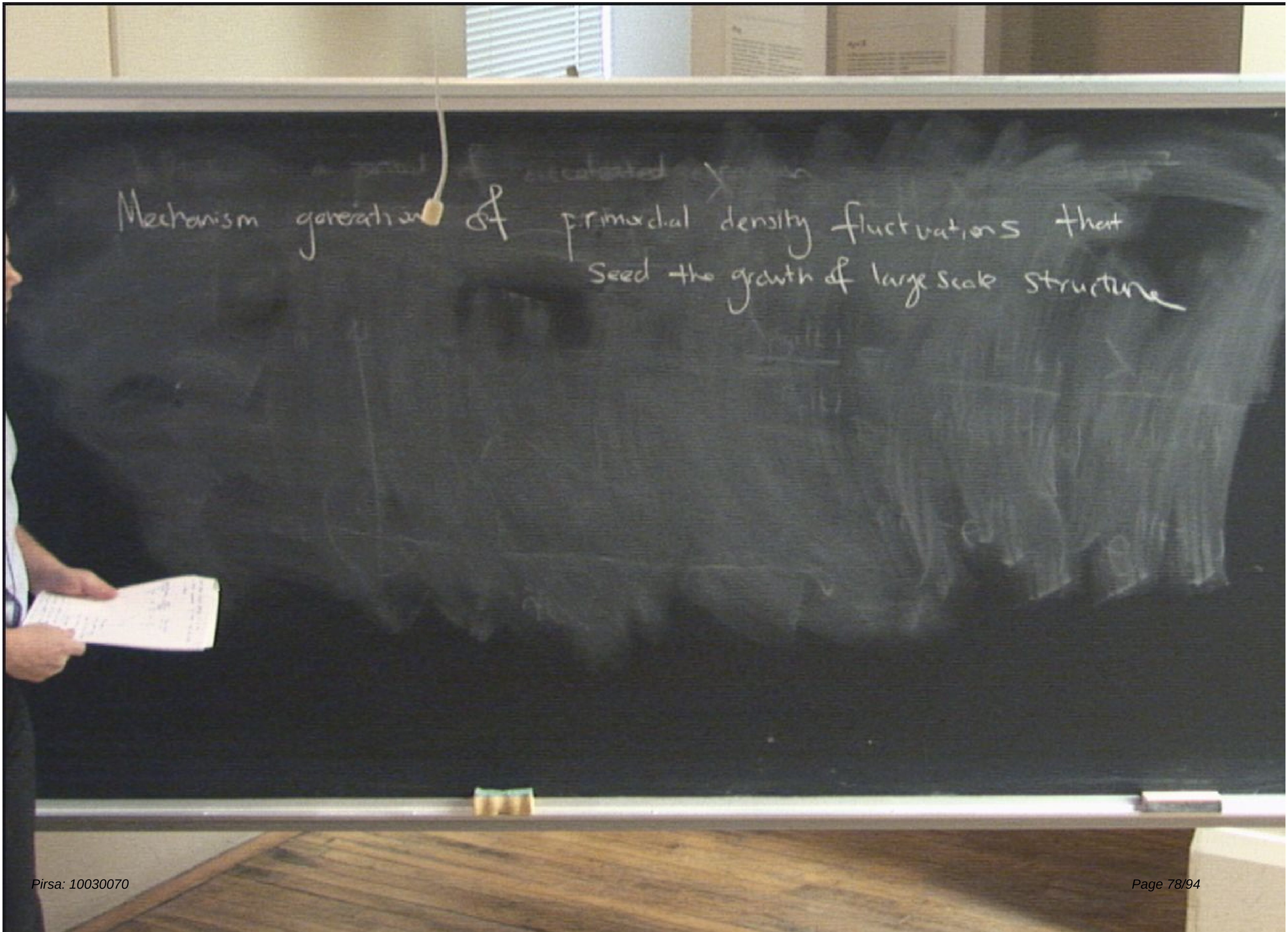
$$\frac{|k|/a^2}{\rho} \sim e^{-2H(t-t_0)} \frac{k/a^2(t_0)}{\rho_{\text{inflation}}}$$

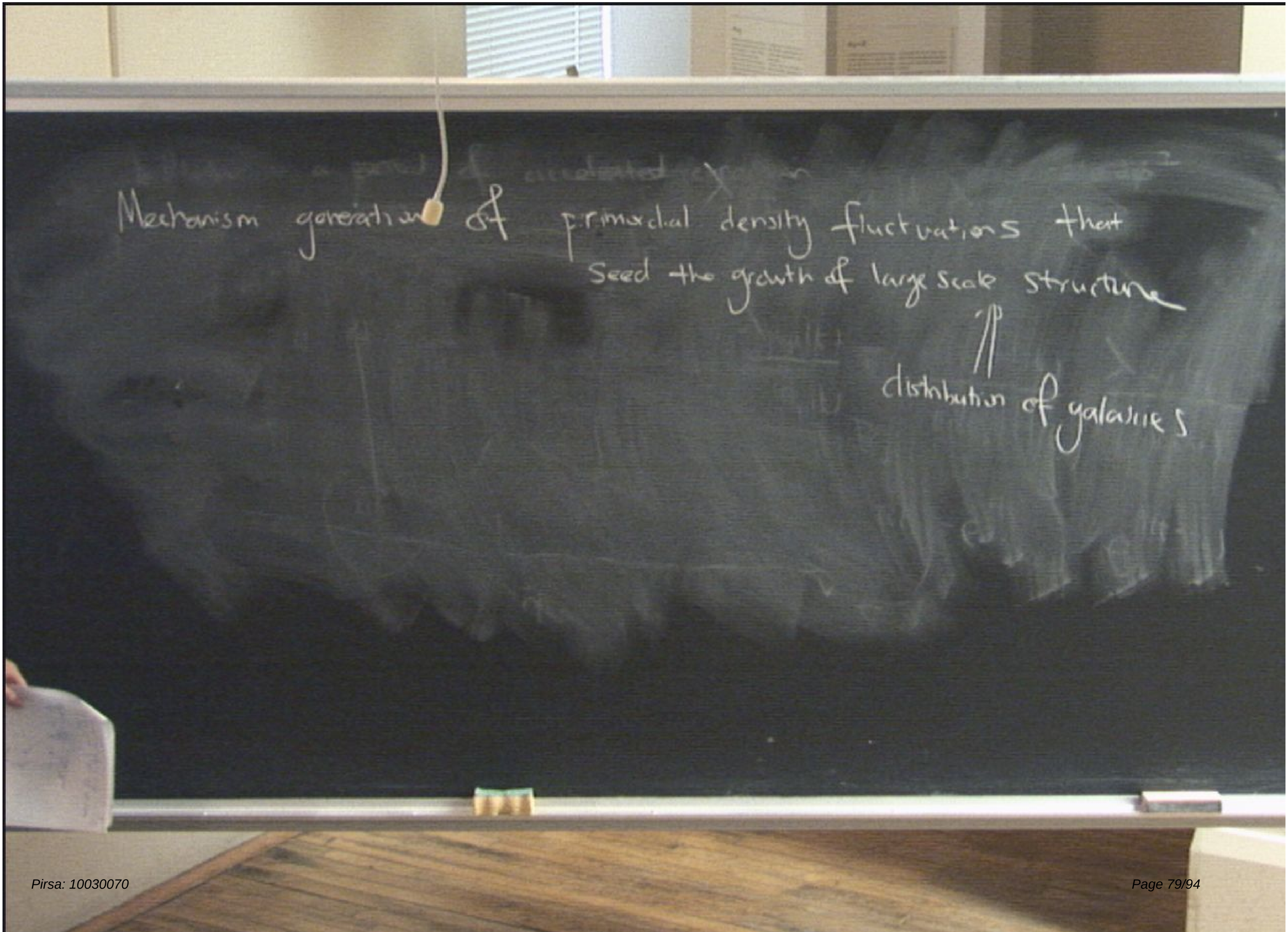
$$\rho_{\text{inflation}} \sim H^2 \sim \text{constant}$$

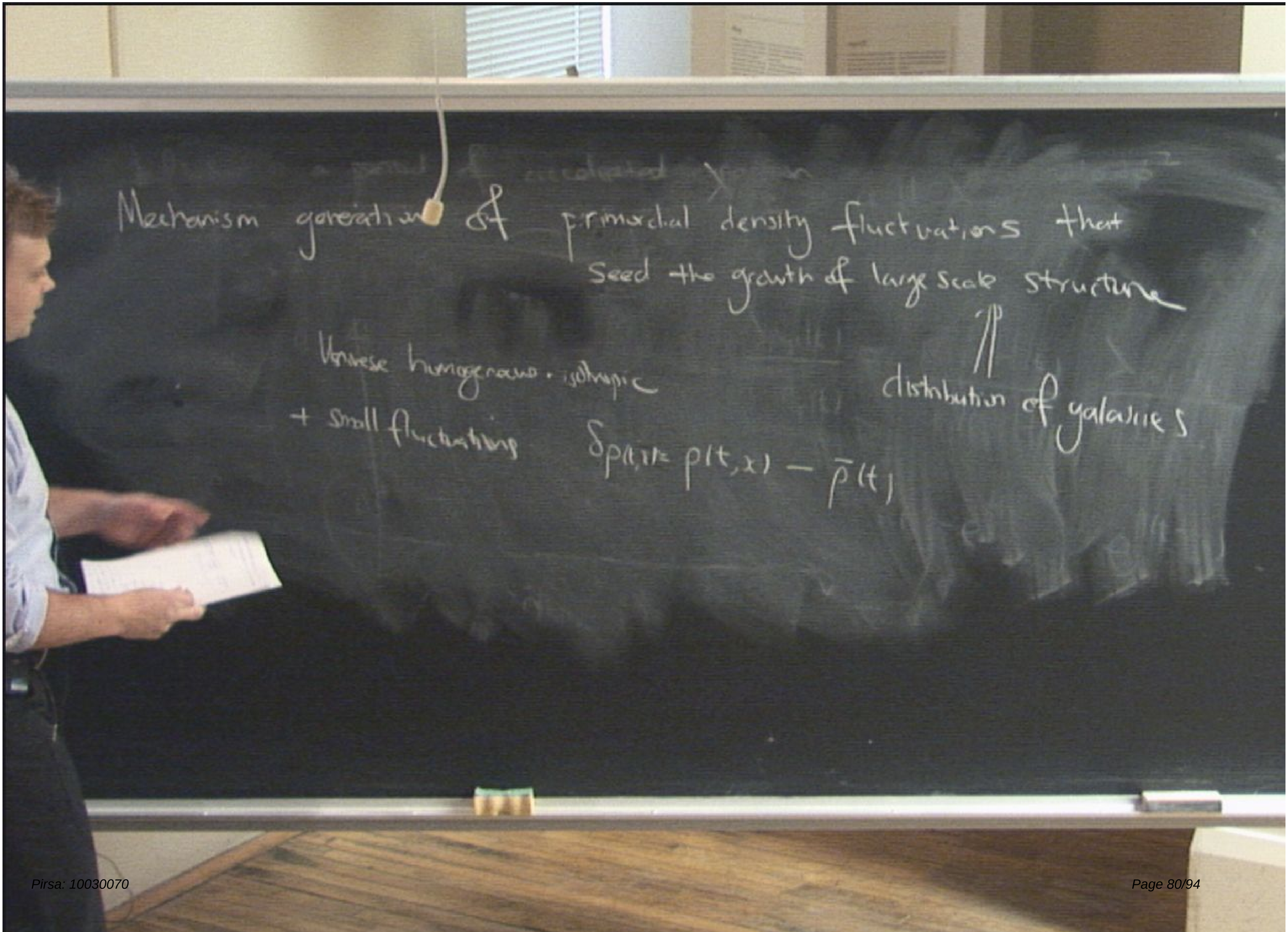
$$\frac{1/a^3}{\rho} \sim e^{-3H(t-t_0)}$$

Monopoles

$$\rho \sim \frac{1}{a^3}$$


Mechanism generation of primordial density fluctuations that
seed the growth of large scale structure


Mechanism generation of primordial density fluctuations that
seed the growth of large scale structure
distribution of galaxies


Mechanism generation of primordial density fluctuations that
seed the growth of large scale structure
distribution of galaxies
Universe homogeneous + isotropic
+ small fluctuations
δρ(t,x) = ρ(t,x) − ρ̄(t)

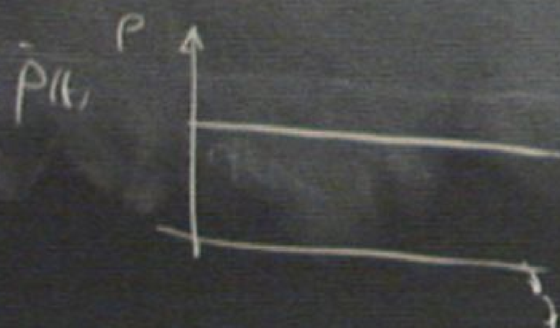
Mechanism generation of primordial density fluctuations that seed the growth of large scale structure

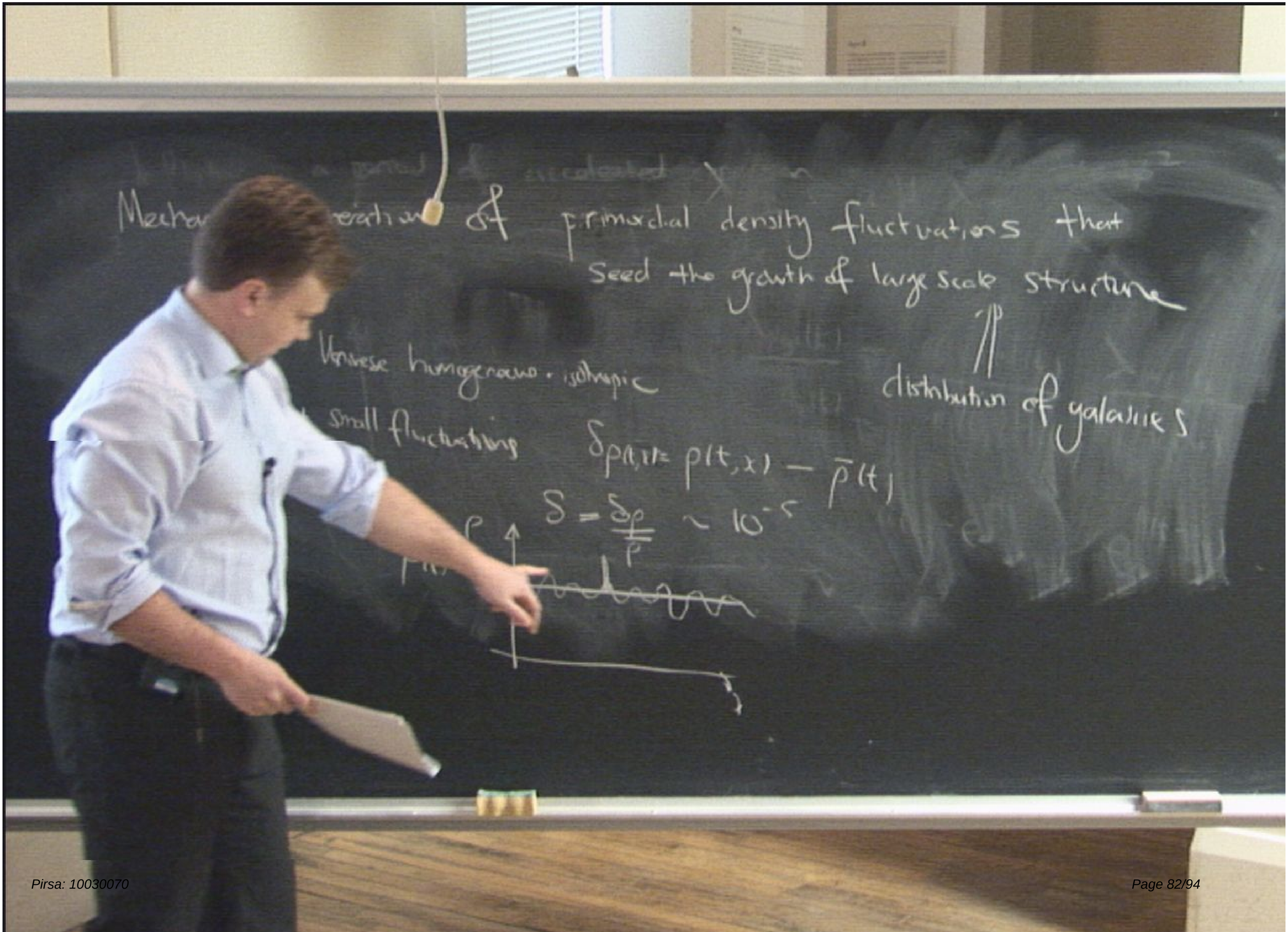
$\Uparrow$

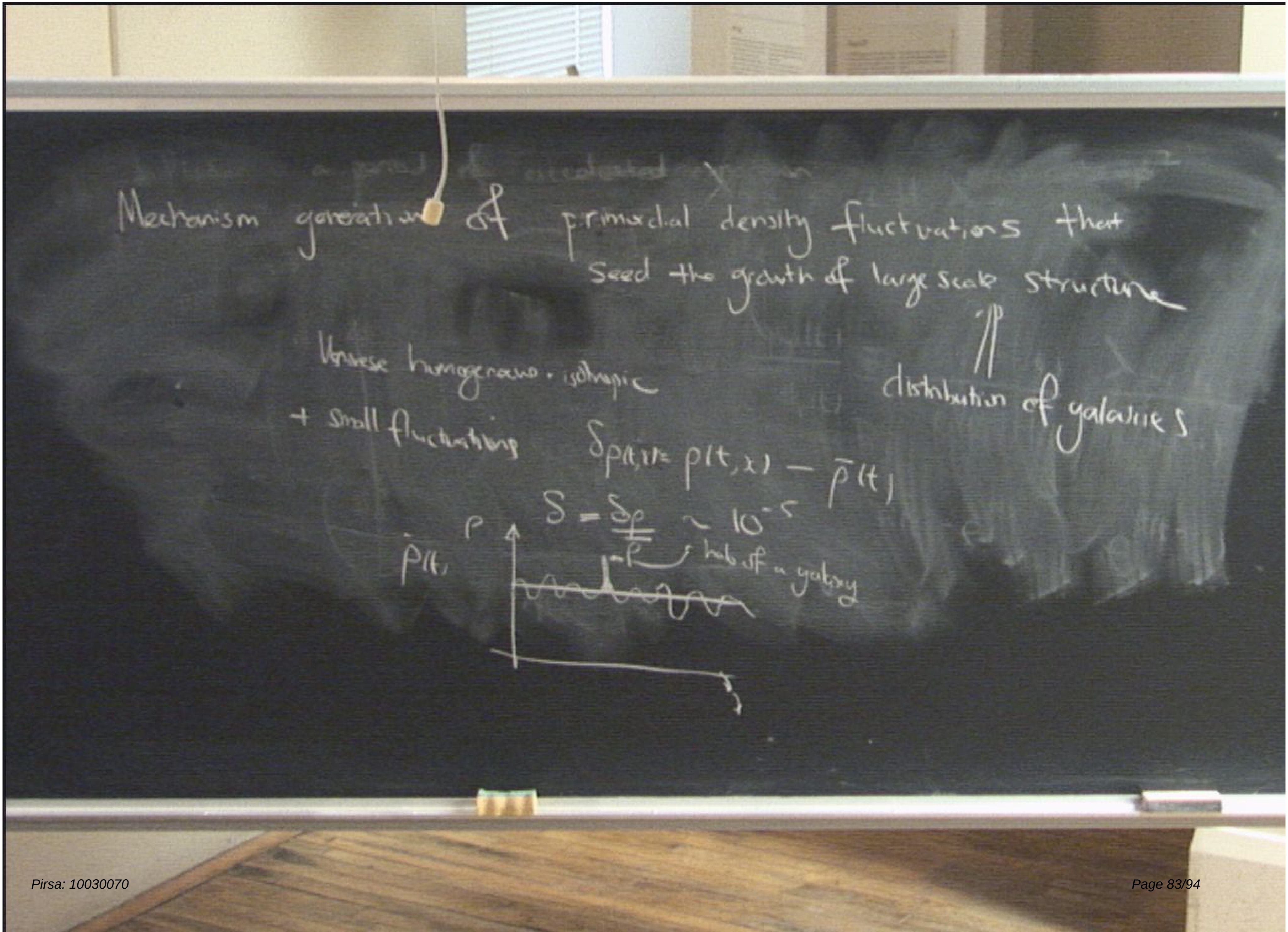
distribution of galaxies

Universe homogeneous + isotropic

+ small fluctuations $\delta\rho(t,x) = \rho(t,x) - \bar{\rho}(t)$




primordial density fluctuations that
seed the growth of large scale structure
distribution of galaxies
Universe homogeneous + isotropic
small fluctuations
$\delta\rho(t,x) = \rho(t,x) - \bar{\rho}(t)$
$\delta = \frac{\delta\rho}{\bar{\rho}} \sim 10^{-5}$


Mechanism generation of primordial density fluctuations that seed the growth of large scale structure
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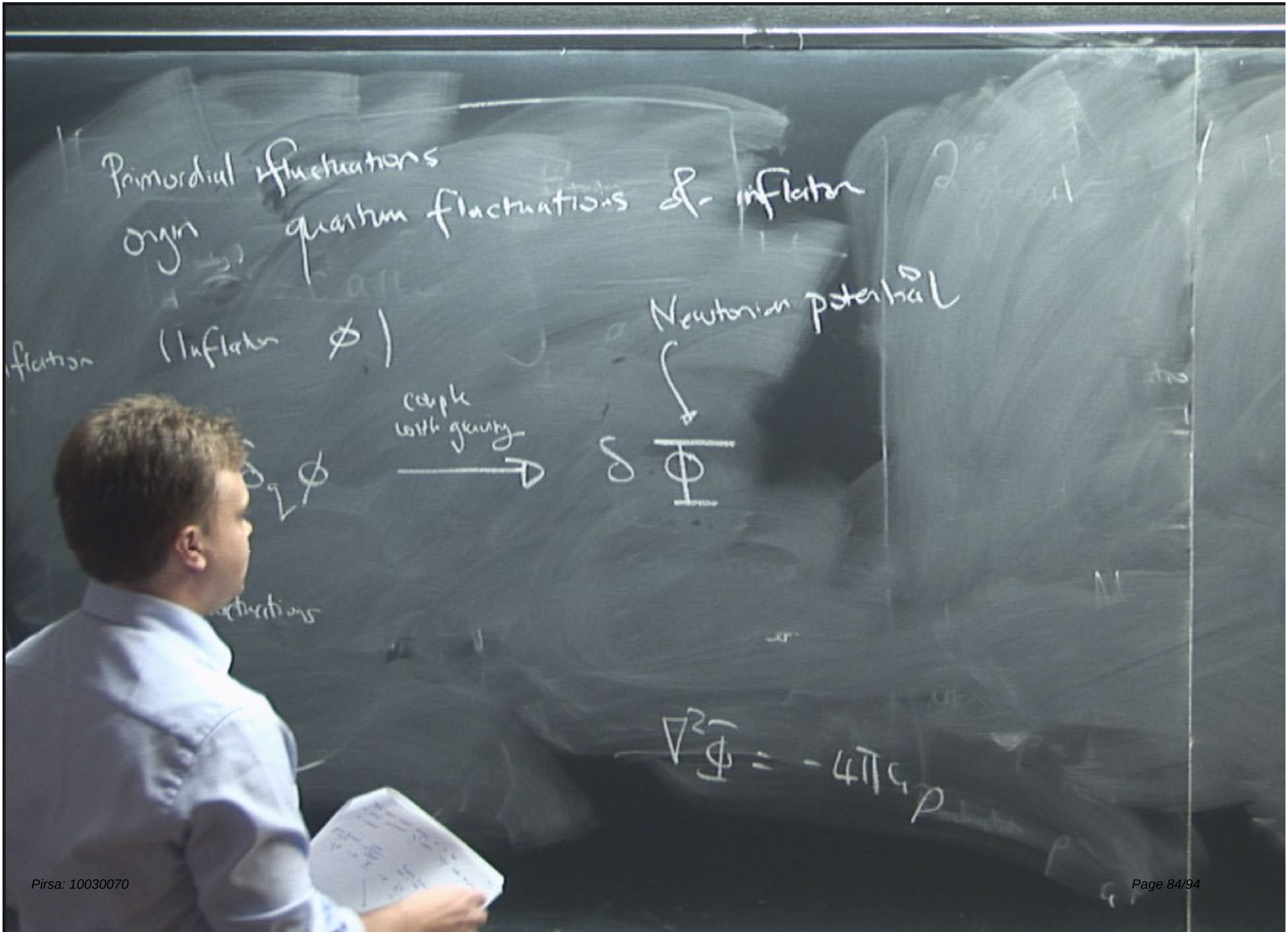
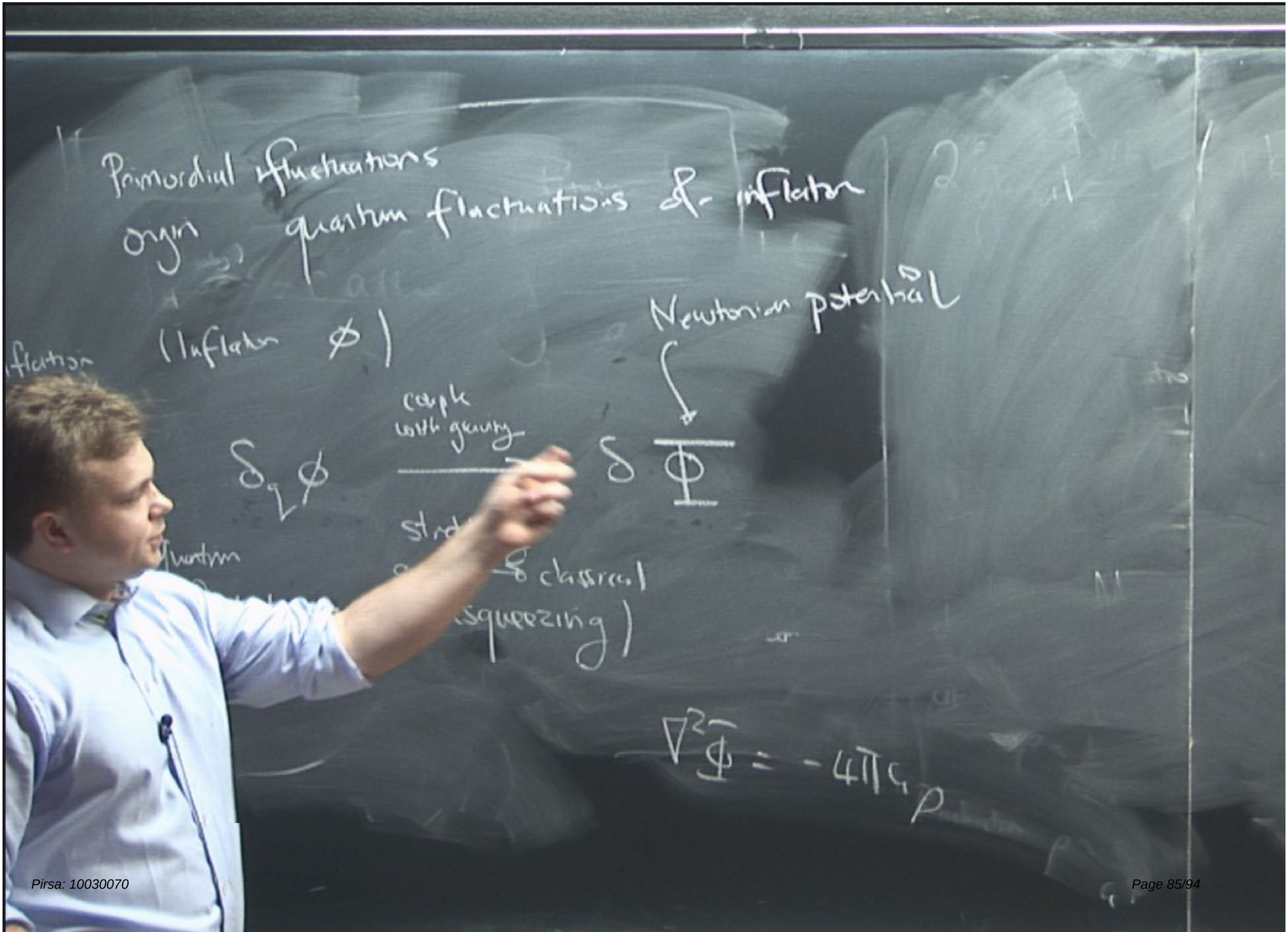
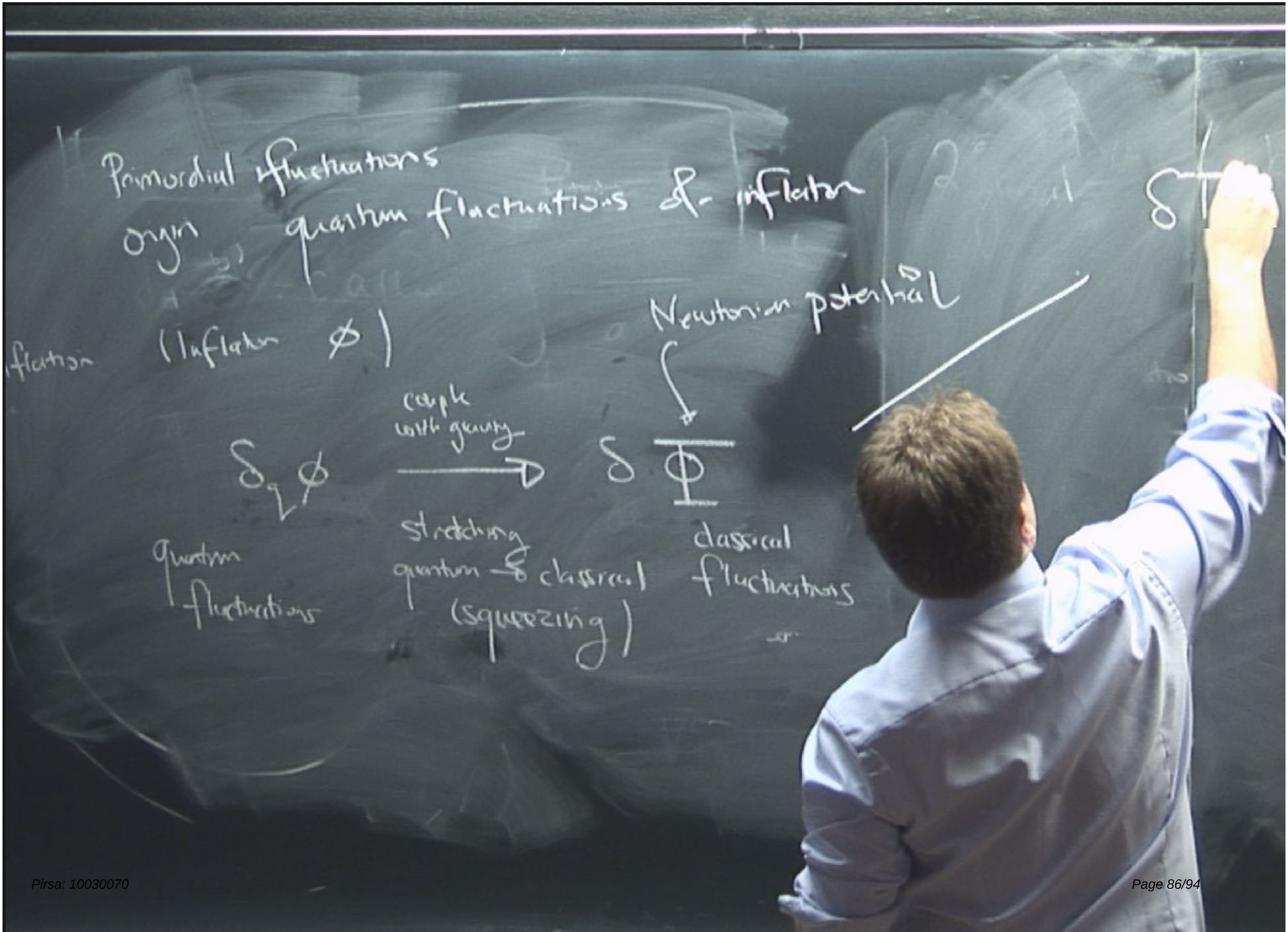
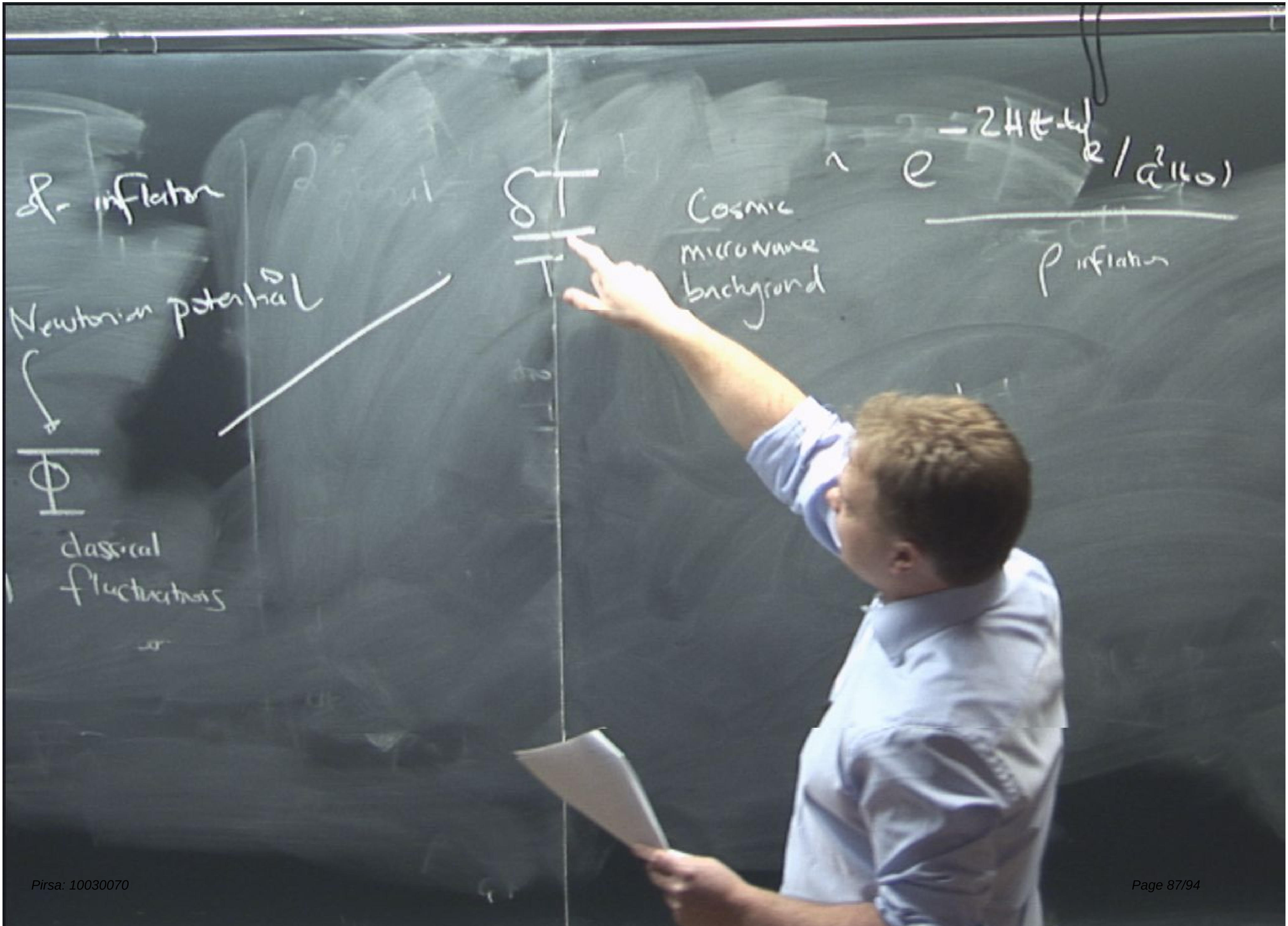
$\delta = \frac{\delta\rho}{\bar{\rho}} \sim 10^{-5}$
$\bar{\rho}(t)$
ρ
halo of a galaxy

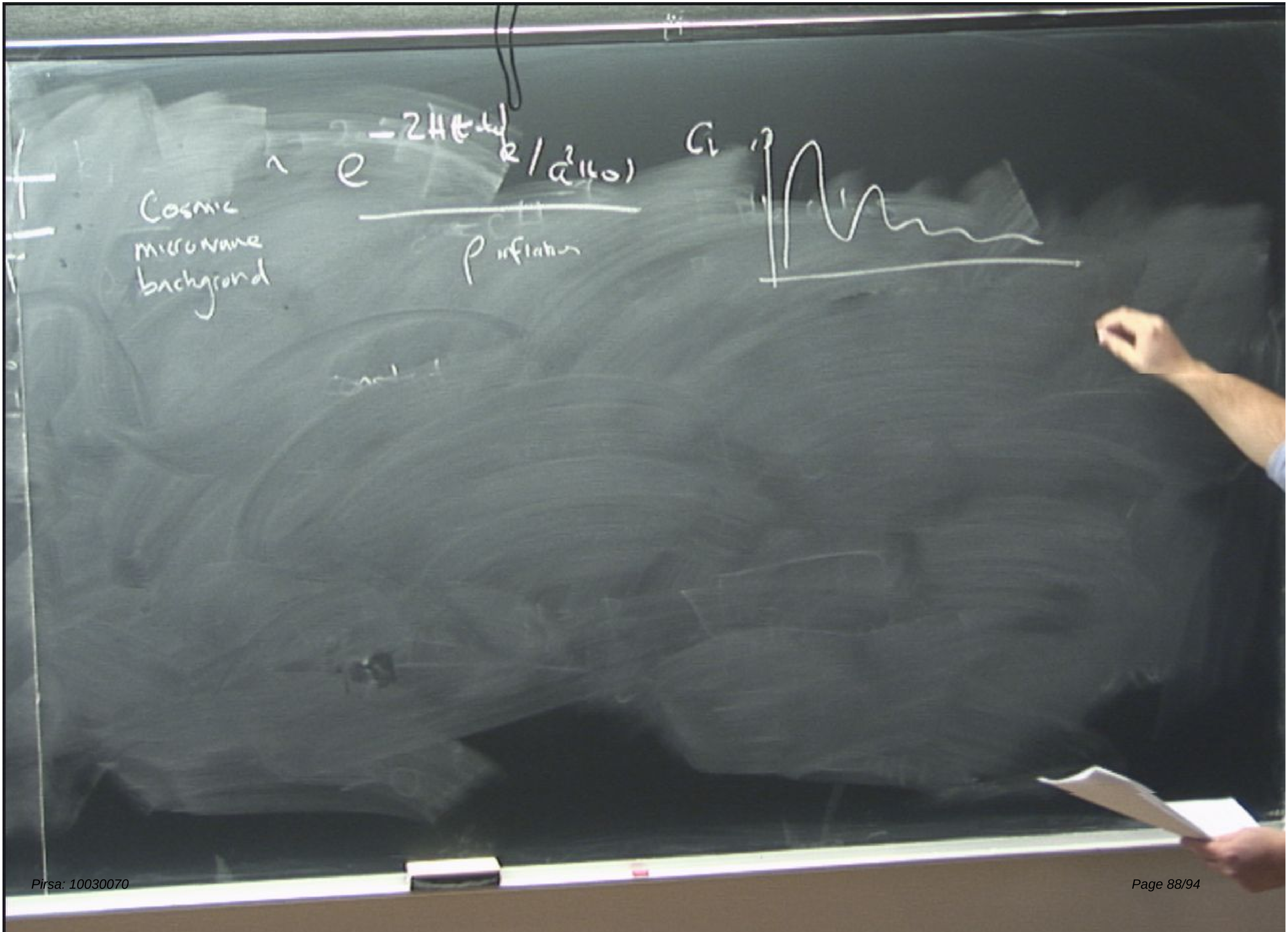

Primordial fluctuations
origin quantum fluctuations of inflaton
(Inflaton ϕ)
Newtonian potential
couple with gravity
δϕ → δΦ
∇²Φ = -4πGρ

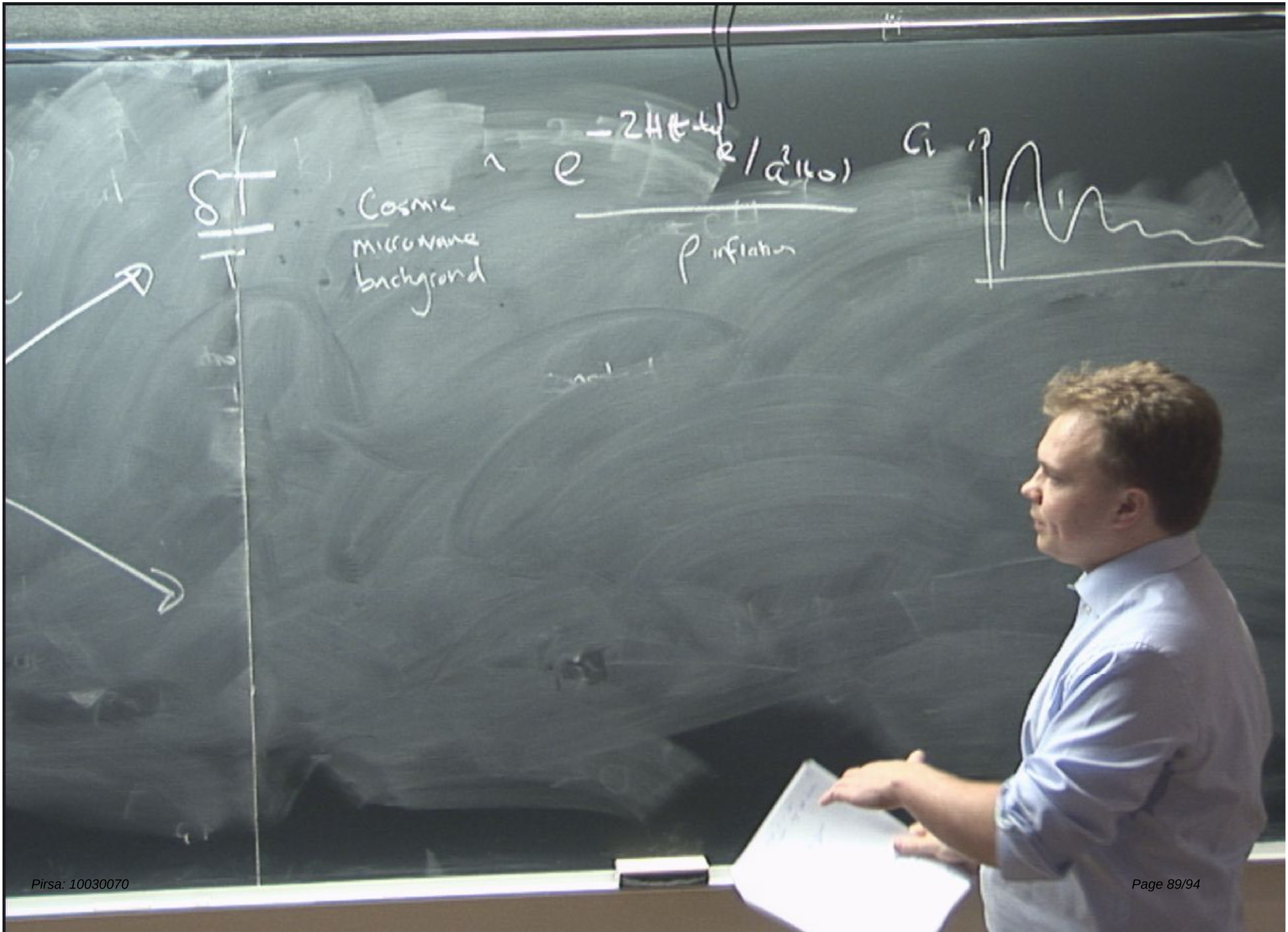

Primordial fluctuations
origin quantum fluctuations of inflaton
(Inflaton ϕ)
Newtonian potential
couple with gravity
$\delta_Q \phi$
$\delta \Phi$
classical
squeezing)
$\nabla^2 \Phi = -4\pi G \rho$



Primordial fluctuations
origin quantum fluctuations & inflaton
(Inflaton ϕ)
Newtonian potential
couple with gravity
$\delta_q \phi \longrightarrow \delta \Phi$
quantum fluctuations
stretching quantum → classical (squeezing)
classical fluctuations

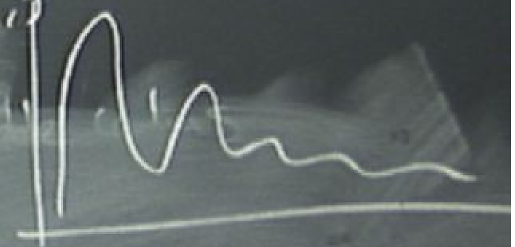

δ - inflaton
Newtonian potential
Φ
classical
fluctuations
δT
T
Cosmic
microwave
background
ρ inflaton


Cosmic
microwave
background
ρ inflation
C_l


Cosmic
microwave
background
ρ inflation

$\frac{\delta T}{T}$ Cosmic microwave background $\sim \dfrac{e^{-2H(t-t_0)}\, k/a^2(t_0)}{\rho_{\text{inflation}}}$

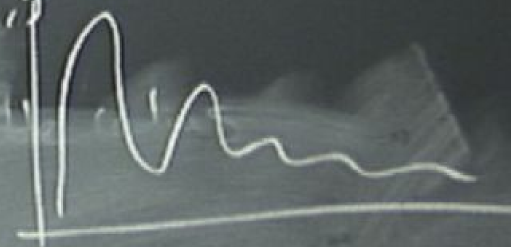
C_l



$\delta = \frac{\delta\rho}{\rho}$ primordial fluctuations $\Longrightarrow$ large scale structure

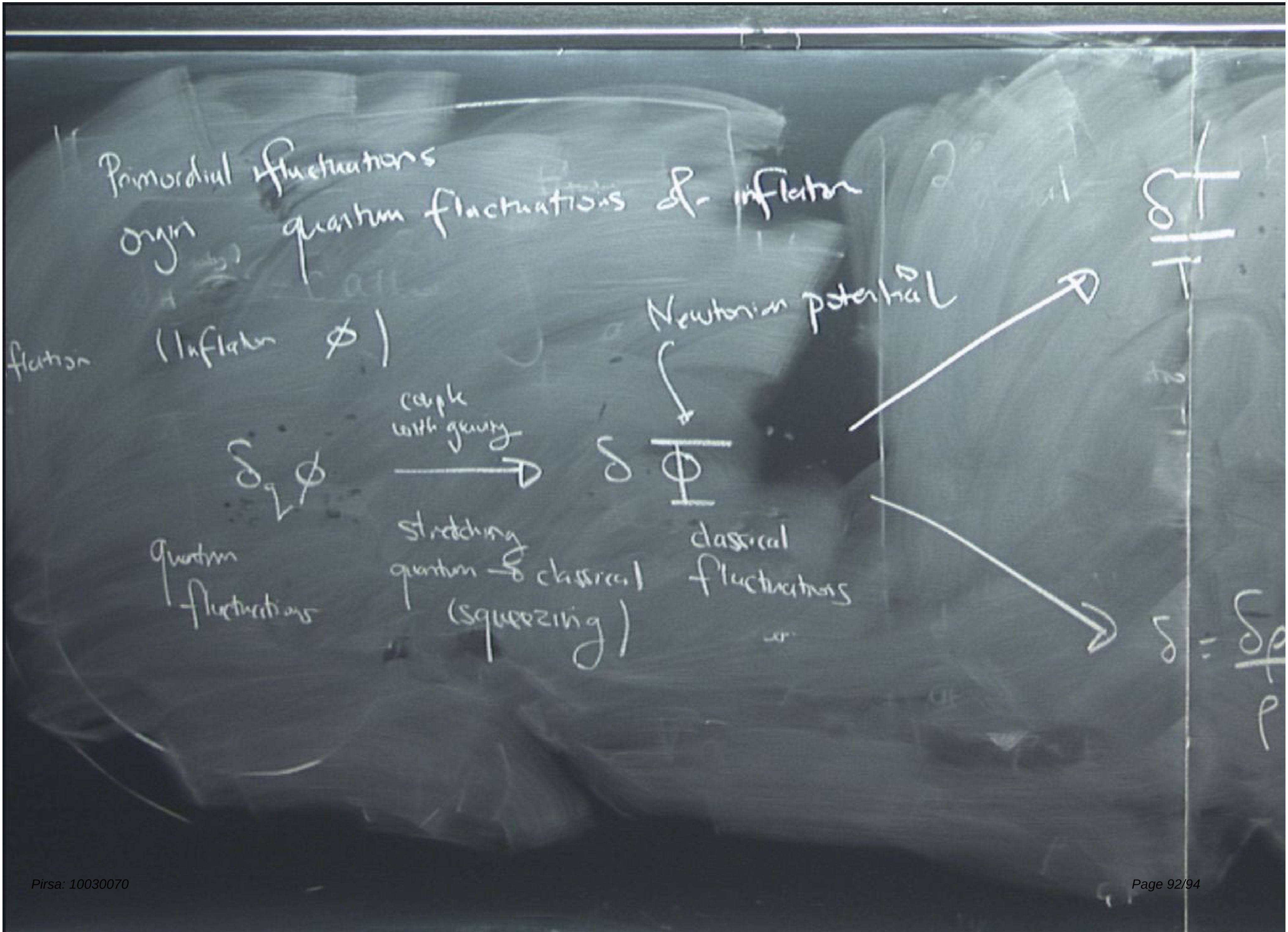
$\frac{\delta T}{T}$ Cosmic microwave background $\sim \frac{e^{-2H(t-t_0)} k/a^2(t_0)}{\rho_{\text{inflation}}}$

C_l



gravitational instability

$\delta = \frac{\delta\rho}{\rho}$ primordial fluctuations $\Longrightarrow$ large scale structure


Primordial fluctuations
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Newtonian potential
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$\delta_Q \phi \longrightarrow \delta \Phi$
stretching
quantum → classical
(squeezing)
quantum fluctuations
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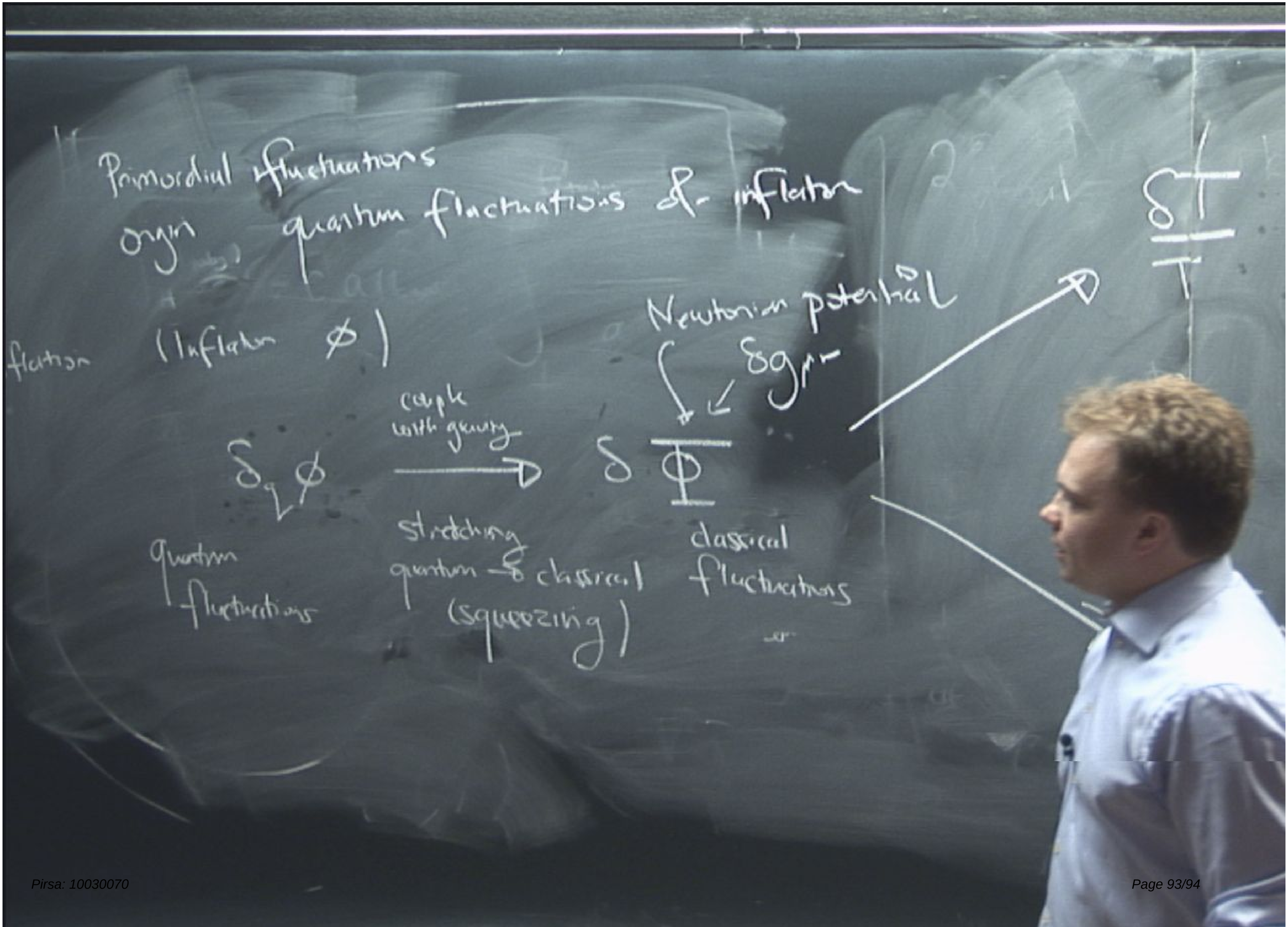
$\frac{\delta T}{T}$
$\delta = \frac{\delta \rho}{\rho}$


Primordial fluctuations
origin quantum fluctuations & inflaton
(Inflaton ϕ)
Newtonian potential
δg
couple with gravity
δ ϕ
δ Φ
δT
T
quantum fluctuations
stretching quantum → classical (squeezing)
classical fluctuations

Primordial fluctuations

origin quantum fluctuations & inflaton

flation (Inflaton ϕ)

Newtonian potential

$\delta g_{\mu\nu}$

$$\delta_q \phi \xrightarrow[\text{stretching}]{\text{couple with gravity}} \delta \Phi \longrightarrow \frac{\delta T}{T}$$

quantum fluctuations

stretching quantum → classical (squeezing)

classical fluctuations

$$\delta \Phi \longrightarrow \delta = \frac{\delta\rho}{\rho}$$