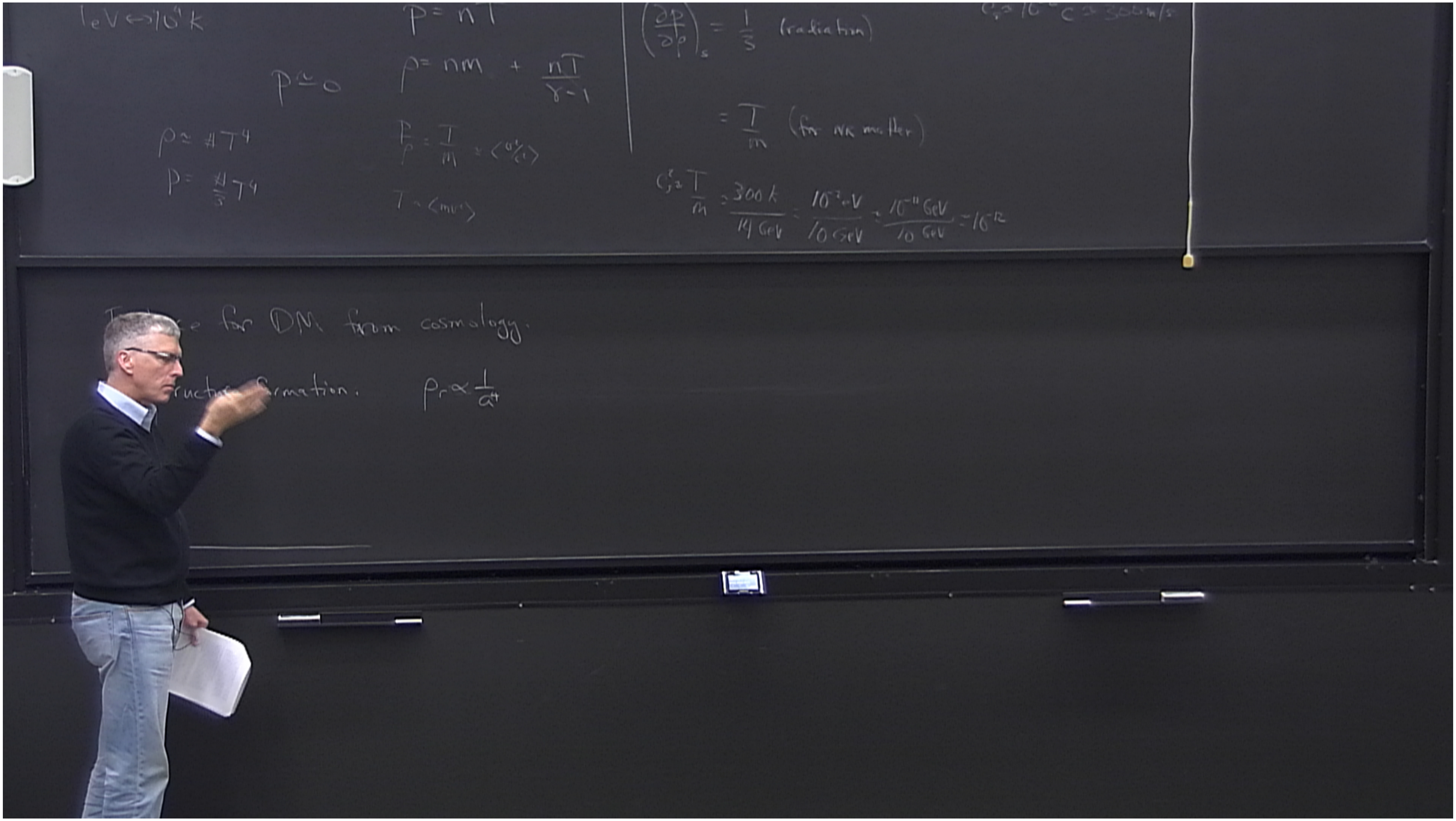
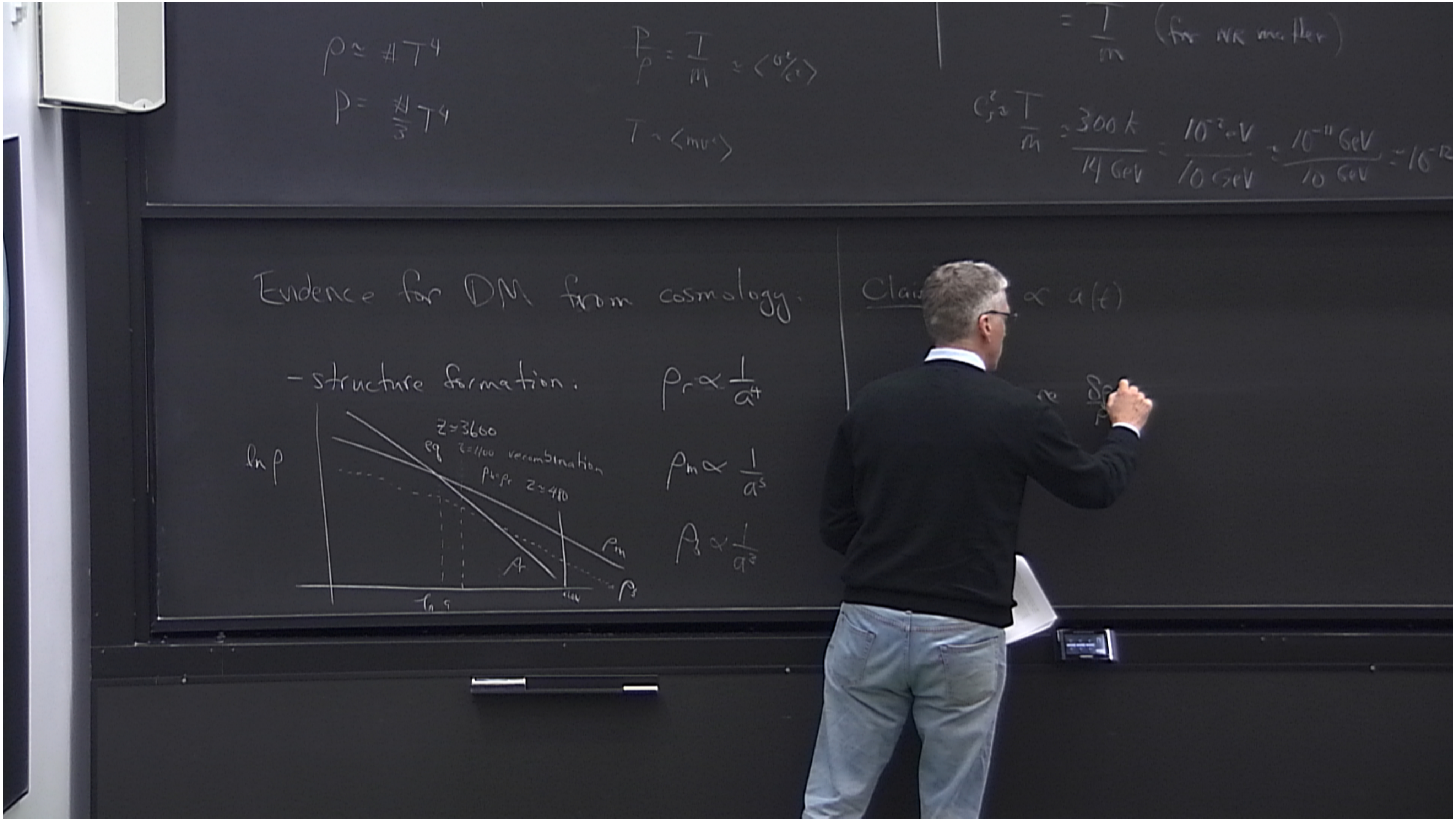
Title: PSI 2015/2016 Explorations in Particle Theory - Burgess - 3

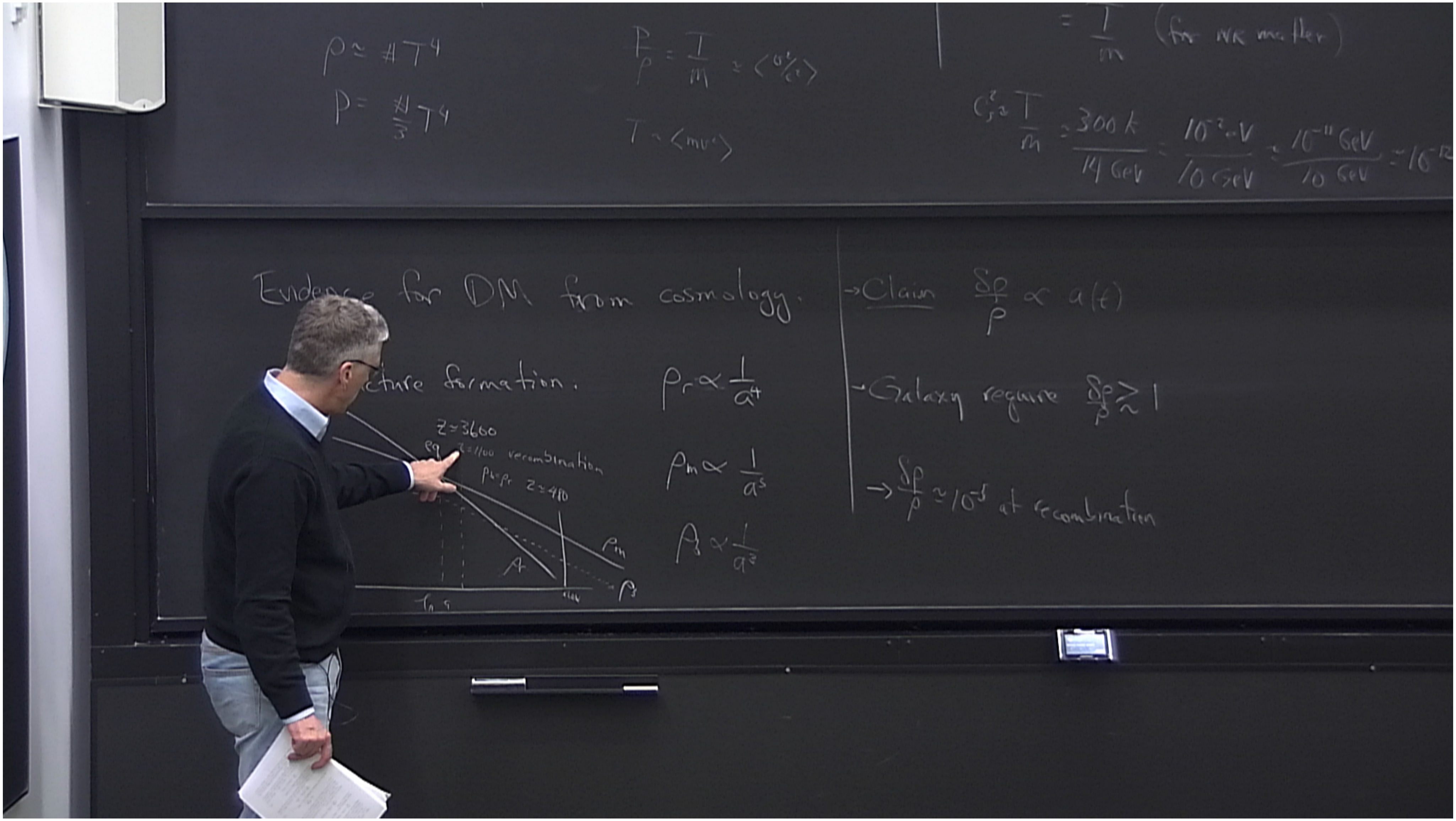
Date: Apr 13, 2016 09:00 AM

URL: http://pirsa.org/16040022

Abstract:


(radiation)
(for NR matter)
for DM from cosmology.
rmation.


ρ ≃ # T^4
P = #/3 T^4
P/ρ = T/m ≃ ⟨v²/c²⟩
T ~ ⟨mv²⟩
= T/m (for NR matter)
c_s² ≈ T/m ≈ 300 K / 14 GeV ≈ 10^-2 eV / 10 GeV ≈ 10^-11 GeV / 10 GeV ≈ 10^-12
Evidence for DM from cosmology.
- structure formation.
ρ_r ∝ 1/a^4
ρ_m ∝ 1/a^3
ln ρ
z ≈ 3600
eq
z ≈ 1100 recombination
ρ_m
Λ


Evidence for DM from cosmology.
cture formation.
z ≈ 3600
eq
z ≈ 1100 recombination
recombination
(for NR matter)
→ Claim δρ/ρ ∝ a(t)
→ Galaxy require δρ/ρ ≳ 1
→ δρ/ρ ≃ 10^-5 at recombination

$\frac{T}{m} \simeq \langle v^2/c^2 \rangle$

$= \frac{T}{m}$ (for NR matter)

$$c_s^2 \simeq \frac{T}{m} \simeq \frac{300\,K}{14\,GeV} \simeq \frac{10^{-2}\,eV}{10\,GeV} \simeq \frac{10^{-11}\,GeV}{10\,GeV} \simeq 10^{-12}$$

...smology:

$\rho_r \propto \frac{1}{a^4}$

$\rho_m \propto \frac{1}{a^3}$

$\rho_k \propto \frac{1}{a^2}$

→ Claim $\frac{\delta\rho}{\rho} \propto a(t)$

→ Galaxy require $\frac{\delta\rho}{\rho} \gtrsim 1$

→ $\frac{\delta\rho}{\rho} \simeq 10^{-5}$ at recombination

In order for $\frac{\delta\rho}{\rho}$ to grow require:

1) matter dominated universe

2) mode label $k = \frac{2\pi}{\lambda}$ must satisfy $k/a < H$

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$\rho_b \propto \frac{1}{a^3}$

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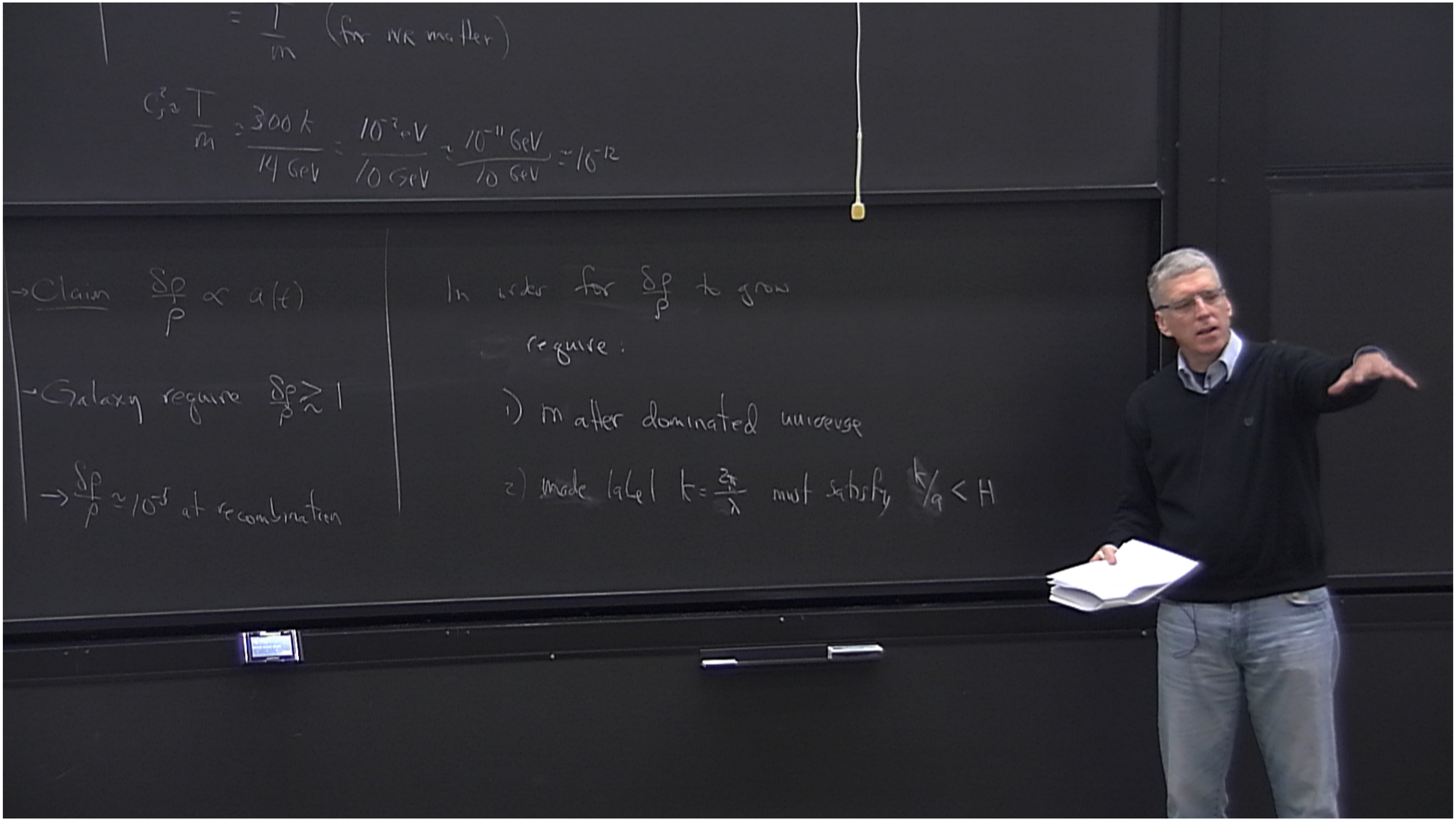
= T/m (for NR matter)
c_s^2 ≃ T/m ≃ 300 K / 10 GeV ≃ 10^-2 eV / 10 GeV ≃ 10^-11 GeV / 10 GeV ≃ 10^-12
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In order for δρ/ρ to grow
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1) matter dominated universe
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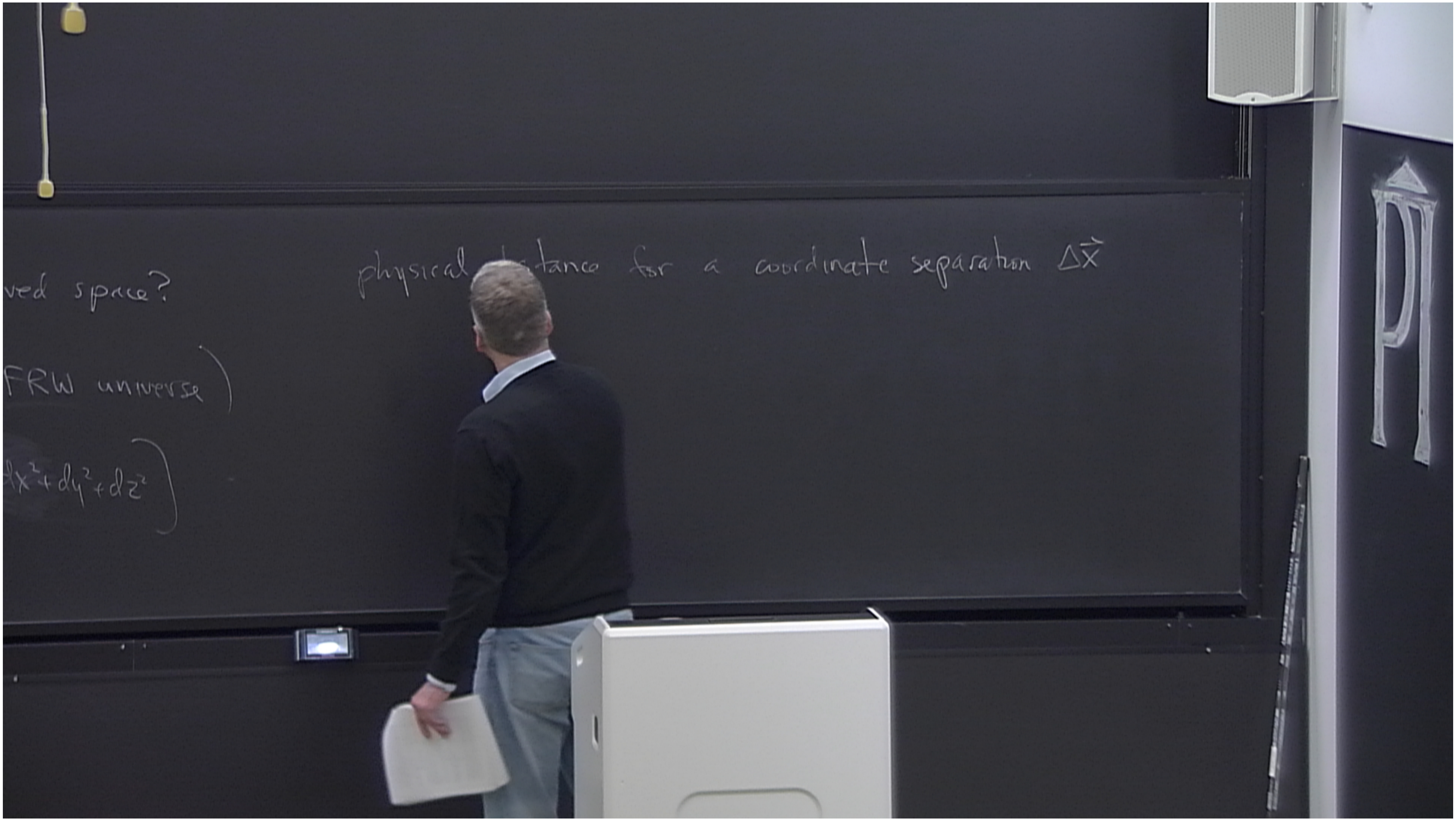
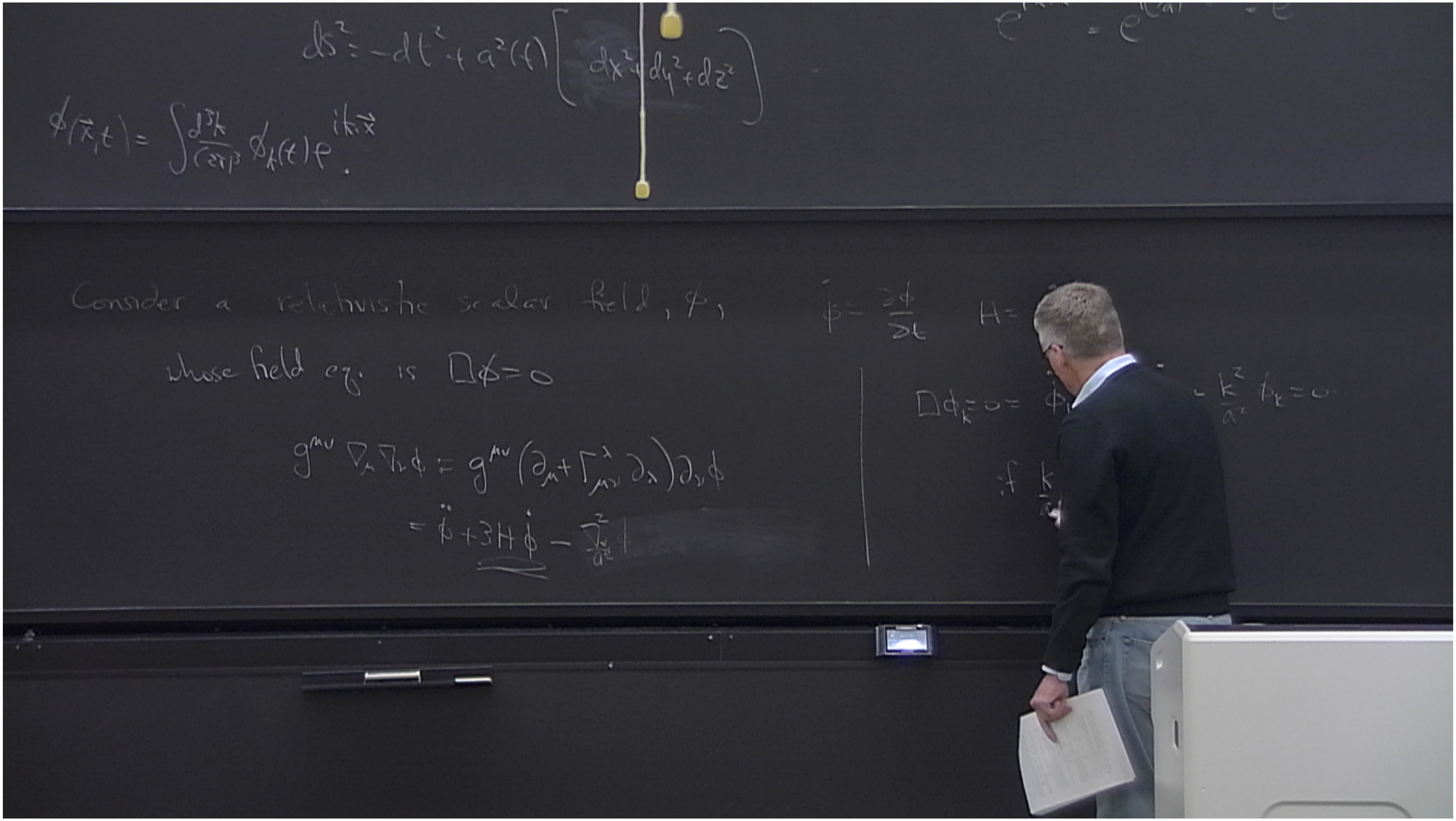
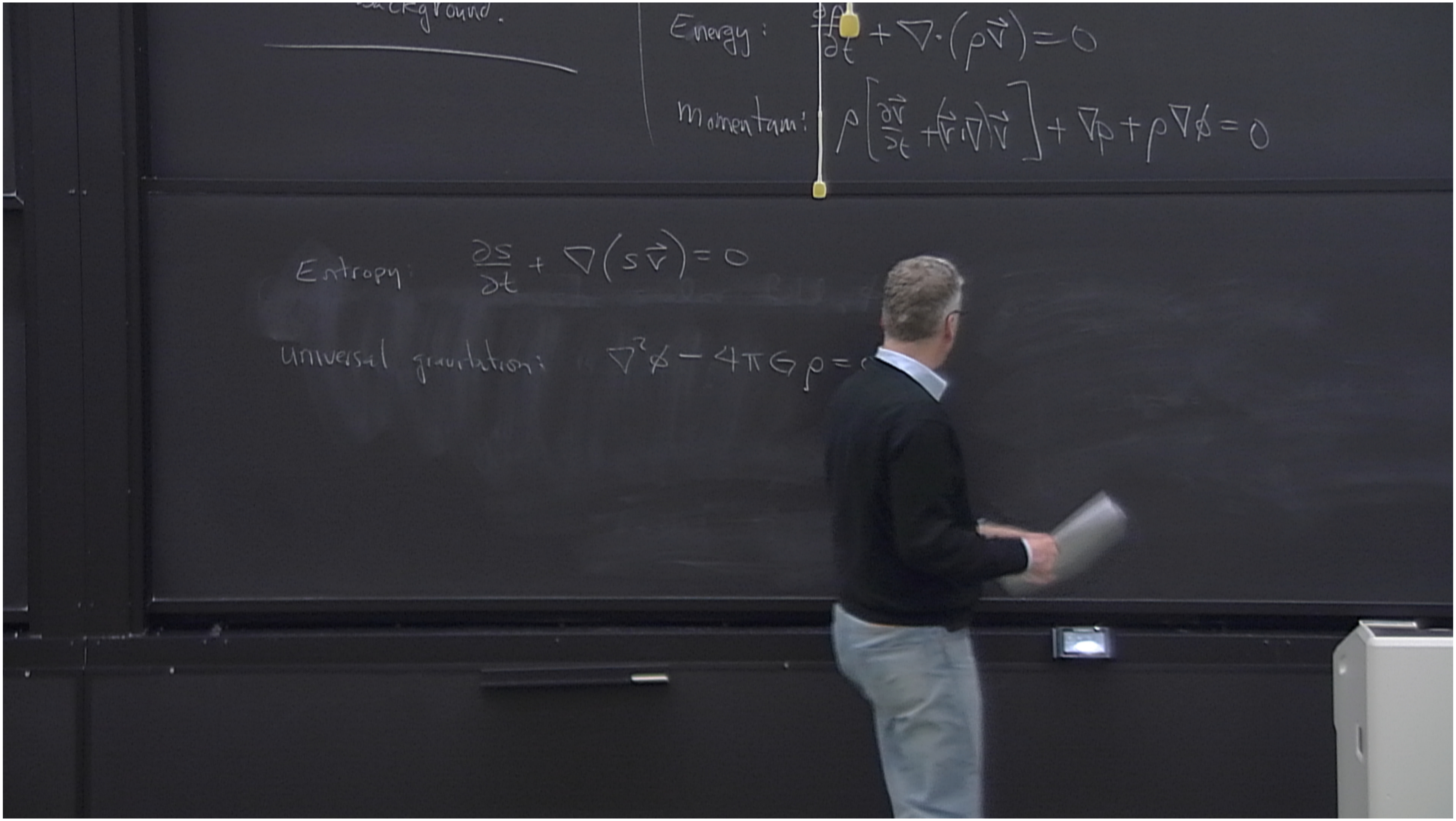
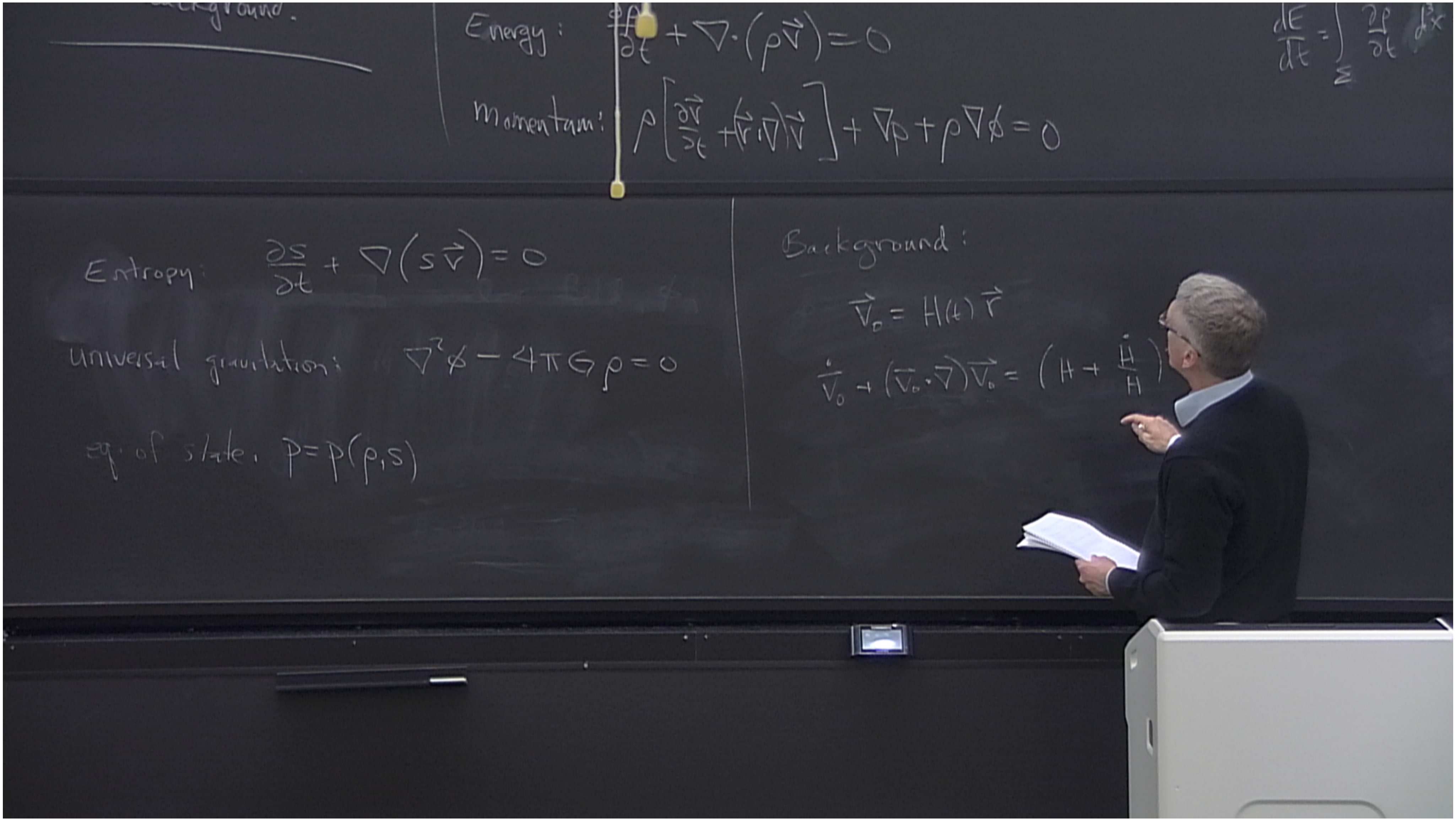
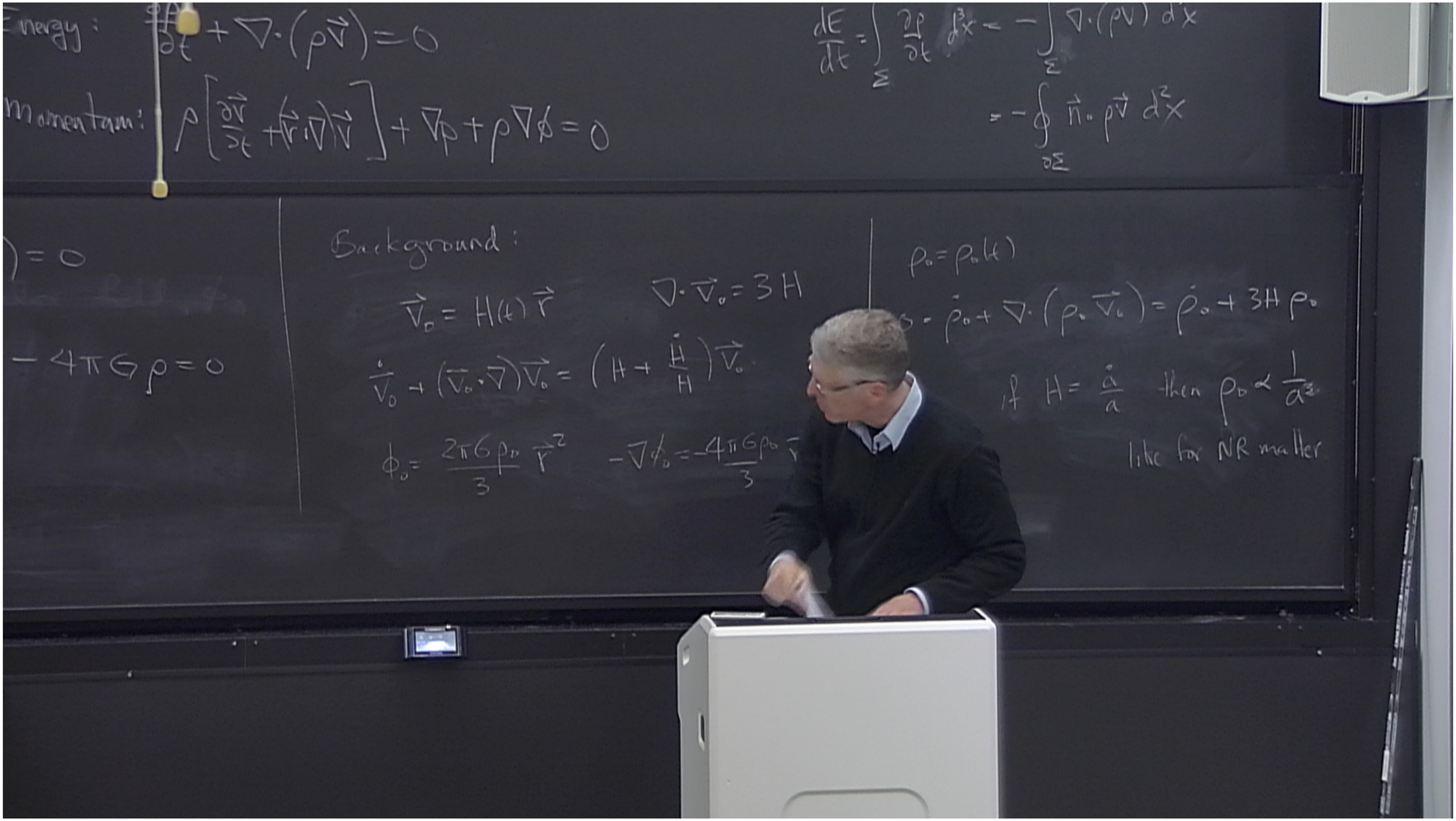

physical
tance for a coordinate separation $\Delta\vec{x}$
ved space?
FRW universe)
$x^2+dy^2+dz^2$)

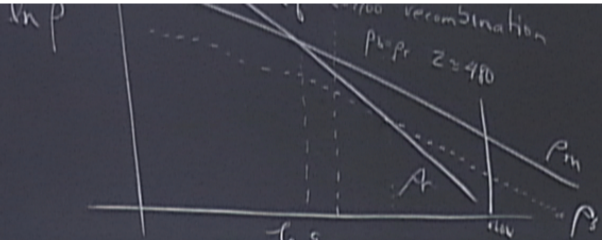

$ds^2 = -dt^2 + a^2(t)\left[dx^2 + dy^2 + dz^2\right]$
$\phi(\vec{x},t) = \int \frac{d^3k}{(2\pi)^3} \phi_k(t) e^{i\vec{k}\cdot\vec{x}}$
Consider a relativistic scalar field, ϕ,
whose field eq. is $\Box\phi = 0$
$g^{\mu\nu}\nabla_\mu\nabla_\nu\phi = g^{\mu\nu}(\partial_\mu + \Gamma^\lambda_{\mu\nu}\partial_\lambda)\partial_\nu\phi$
$= \ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2}{a^2}\phi$
$\dot{\phi} = \frac{\partial\phi}{\partial t}$
$H =$
$\Box\phi_k = 0 =$
$\frac{k^2}{a^2}\phi_k = 0$



Energy: $\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0$
momentum: $\rho\left[\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right] + \nabla p + \rho\nabla\phi = 0$
Entropy: $\frac{\partial s}{\partial t} + \nabla(s\vec{v}) = 0$
universal gravitation: $\nabla^2\phi - 4\pi G\rho =$


Energy: ∂ρ/∂t + ∇·(ρv⃗) = 0
momentum: ρ[∂v⃗/∂t + (v⃗·∇)v⃗] + ∇p + ρ∇φ = 0
dE/dt = ∫ ∂ρ/∂t d³x
Entropy: ∂s/∂t + ∇(sv⃗) = 0
universal gravitation: ∇²φ − 4πGρ = 0
eq. of state: p = p(ρ, s)
Background:
V⃗₀ = H(t) r⃗
V̇₀ + (V⃗₀·∇)V⃗₀ = (H + Ḣ/H)


Energy: $\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0$
Momentum: $\rho\left[\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right] + \nabla p + \rho\nabla\phi = 0$
$\frac{dE}{dt} = \int_\Sigma \frac{\partial \rho}{\partial t}\, d^3x = -\int_\Sigma \nabla\cdot(\rho\vec{v})\, d^3x$
$= -\oint_{\partial\Sigma} \vec{n}\cdot\rho\vec{v}\, d^2x$
$) = 0$
$- 4\pi G\rho = 0$
Background:
$\vec{v}_0 = H(t)\,\vec{r}$
$\nabla\cdot\vec{v}_0 = 3H$
$\dot{\vec{v}}_0 + (\vec{v}_0\cdot\nabla)\vec{v}_0 = \left(H + \frac{\dot{H}}{H}\right)\vec{v}_0$
$\phi_0 = \frac{2\pi G\rho_0}{3}\vec{r}^2$
$-\nabla\phi_0 = -\frac{4\pi G\rho_0}{3}\vec{r}$
$\rho_0 = \rho_0(t)$
$\dot{\rho}_0 + \nabla\cdot(\rho_0\vec{v}_0) = \dot{\rho}_0 + 3H\rho_0$
if $H = \frac{\dot{a}}{a}$ then $\rho_0 \propto \frac{1}{a^3}$
like for NR matter



$\rho_m \propto \frac{1}{a^3}$

$\rho_b \propto \frac{1}{a^3}$

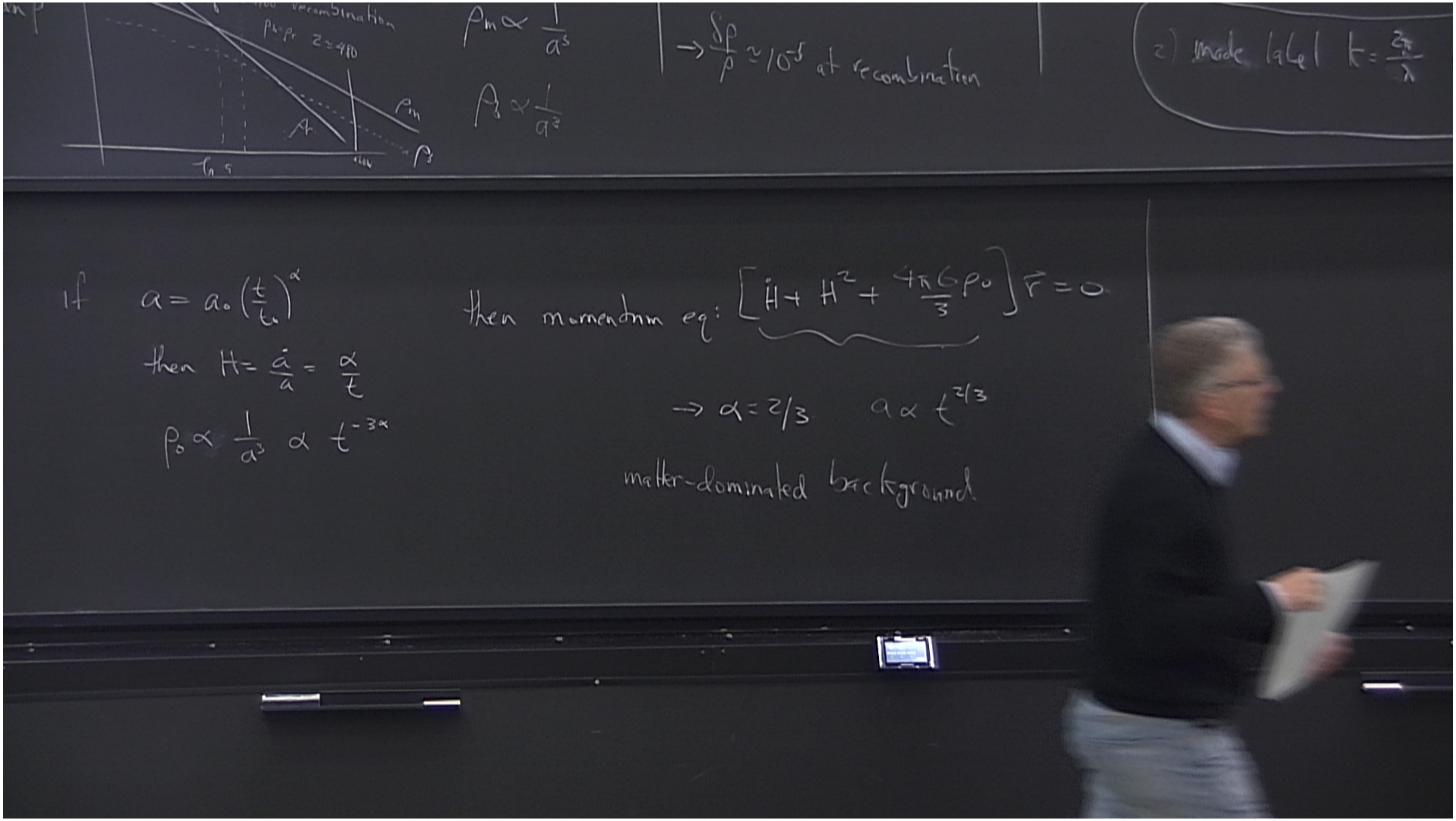
$\rightarrow \frac{\delta\rho}{\rho} \simeq 10^{-5}$ at recombination

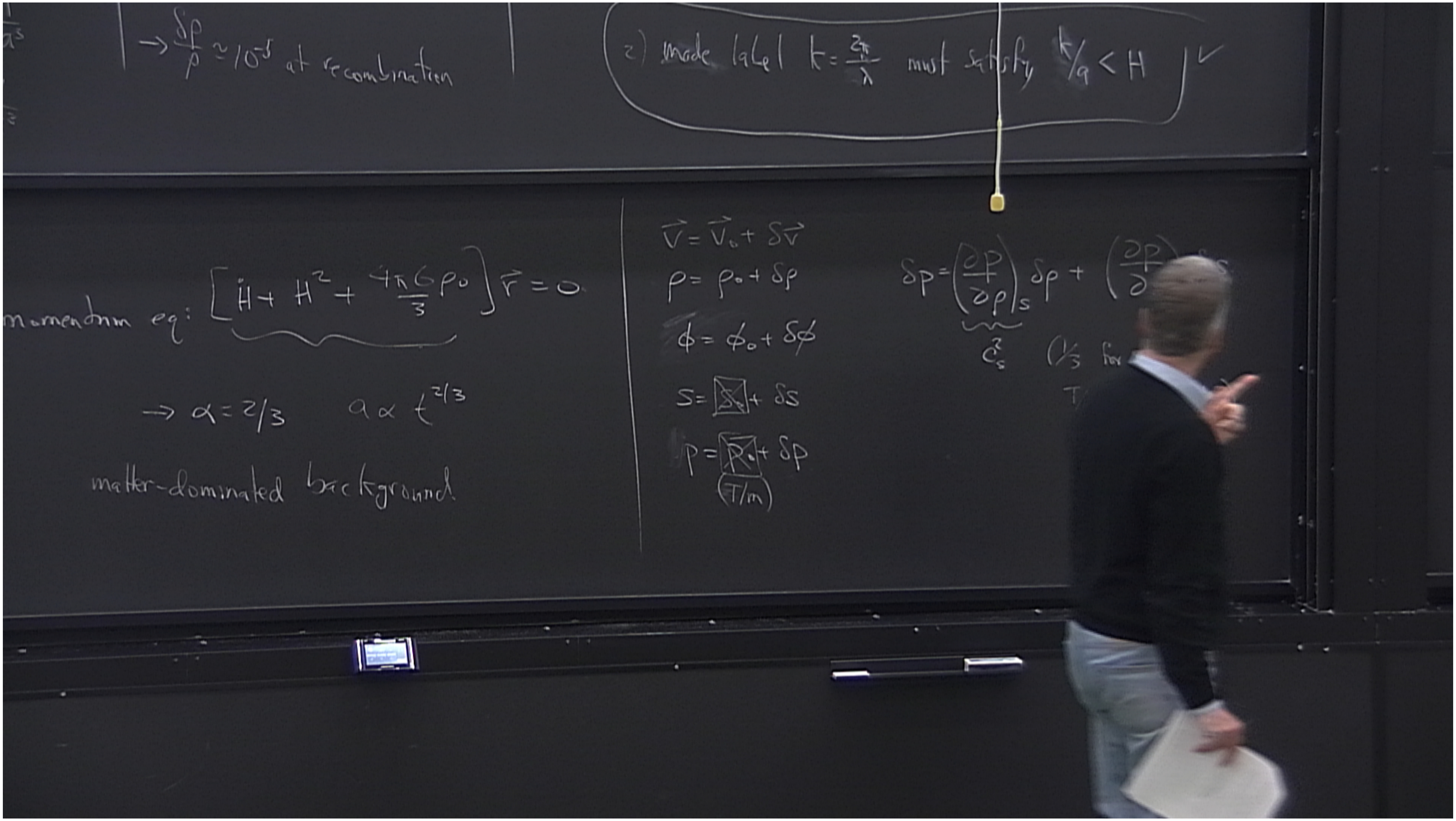
2) made la

if $a = a_0 \left(\frac{t}{t_0}\right)^\alpha$

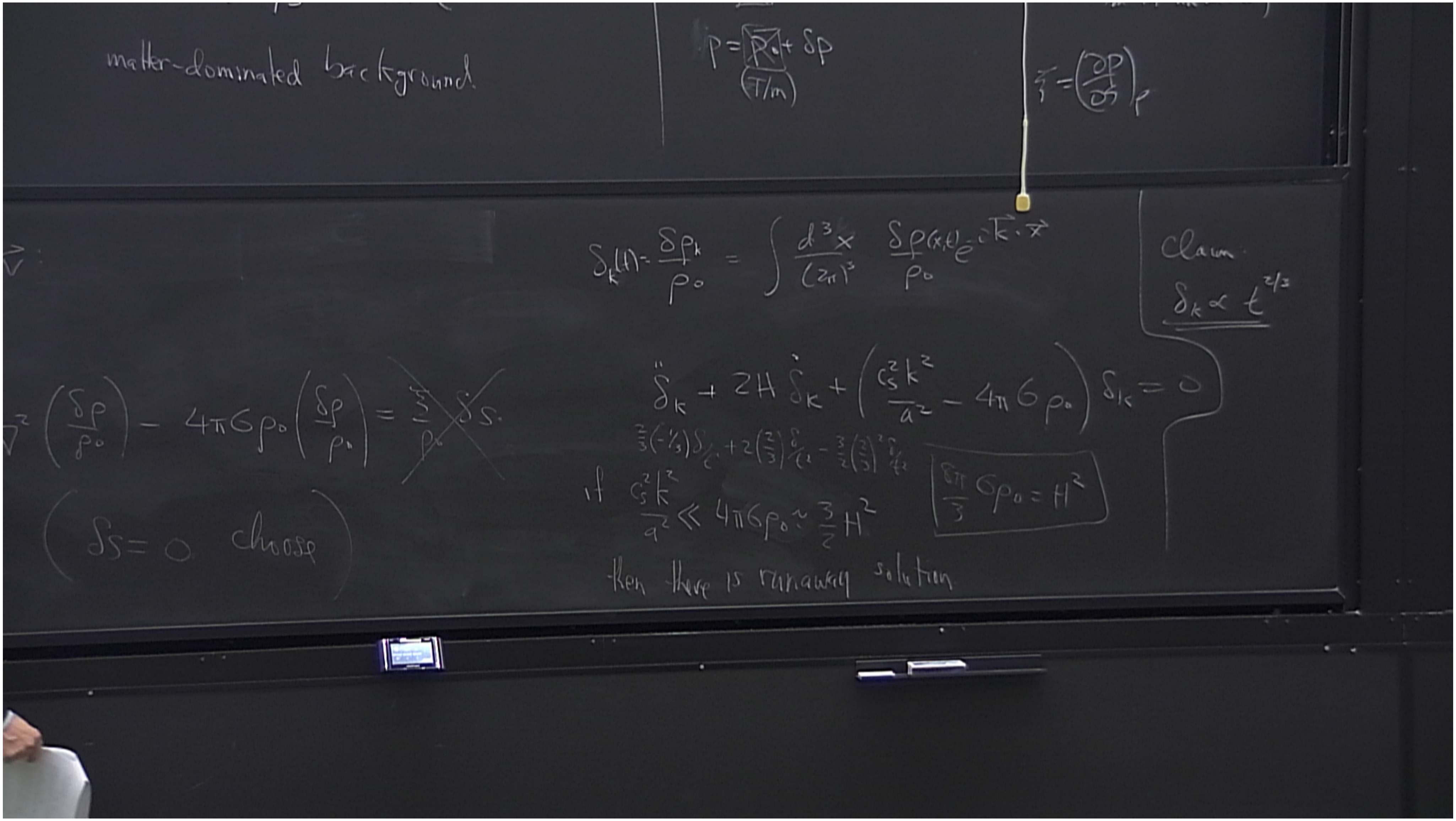
then $H = \frac{\dot{a}}{a} = \frac{\alpha}{t}$

$\rho_0 \propto \frac{1}{a^3} \propto t^{-3\alpha}$


recombination
$\rho_m \propto \frac{1}{a^3}$
$\rho_\gamma \propto \frac{1}{a^3}$
$\rightarrow \frac{\delta\rho}{\rho} \simeq 10^{-5}$ at recombination
2) mode label $k = \frac{2\pi}{\lambda}$
if $a = a_0 \left(\frac{t}{t_0}\right)^\alpha$
then $H = \frac{\dot a}{a} = \frac{\alpha}{t}$
$\rho_0 \propto \frac{1}{a^3} \propto t^{-3\alpha}$
then momentum eq: $\left[\dot H + H^2 + \frac{4\pi G\rho_0}{3}\right]\vec r = 0$
$\rightarrow \alpha = 2/3 \quad a \propto t^{2/3}$
matter-dominated background



→ δρ/ρ ≈ 10^-5 at recombination
2) mode label k = 2π/λ must satisfy k/a < H
momentum eq: [Ḣ + H² + 4πGρ₀/3] r = 0
→ α = 2/3   a ∝ t^2/3
matter-dominated background
V = V₀ + δV
ρ = ρ₀ + δρ
φ = φ₀ + δφ
S = S₀ + δS
p = p₀ + δp
(T/m)
δp = (∂p/∂ρ)_s δρ + (∂p/∂
c_s²


matter-dominated background
p = p₀ + δp
(T/m)
ξ = (∂p/∂s)_ρ
δ_k(t) = δρ_k/ρ₀ = ∫ d³x/(2π)³ δρ(x,t)/ρ₀ e^{-ik·x}
Claim
δ_k ∝ t^{2/3}
δ̈_k + 2H δ̇_k + (c_s² k²/a² − 4πG ρ₀) δ_k = 0
∇² (δρ/ρ₀) − 4πG ρ₀ (δρ/ρ₀) = ξ/ρ₀ δs
8π/3 G ρ₀ = H²
if c_s² k²/a² ≪ 4πG ρ₀ ≈ 3/2 H²
(δs = 0 choose)
then there is runaway solution