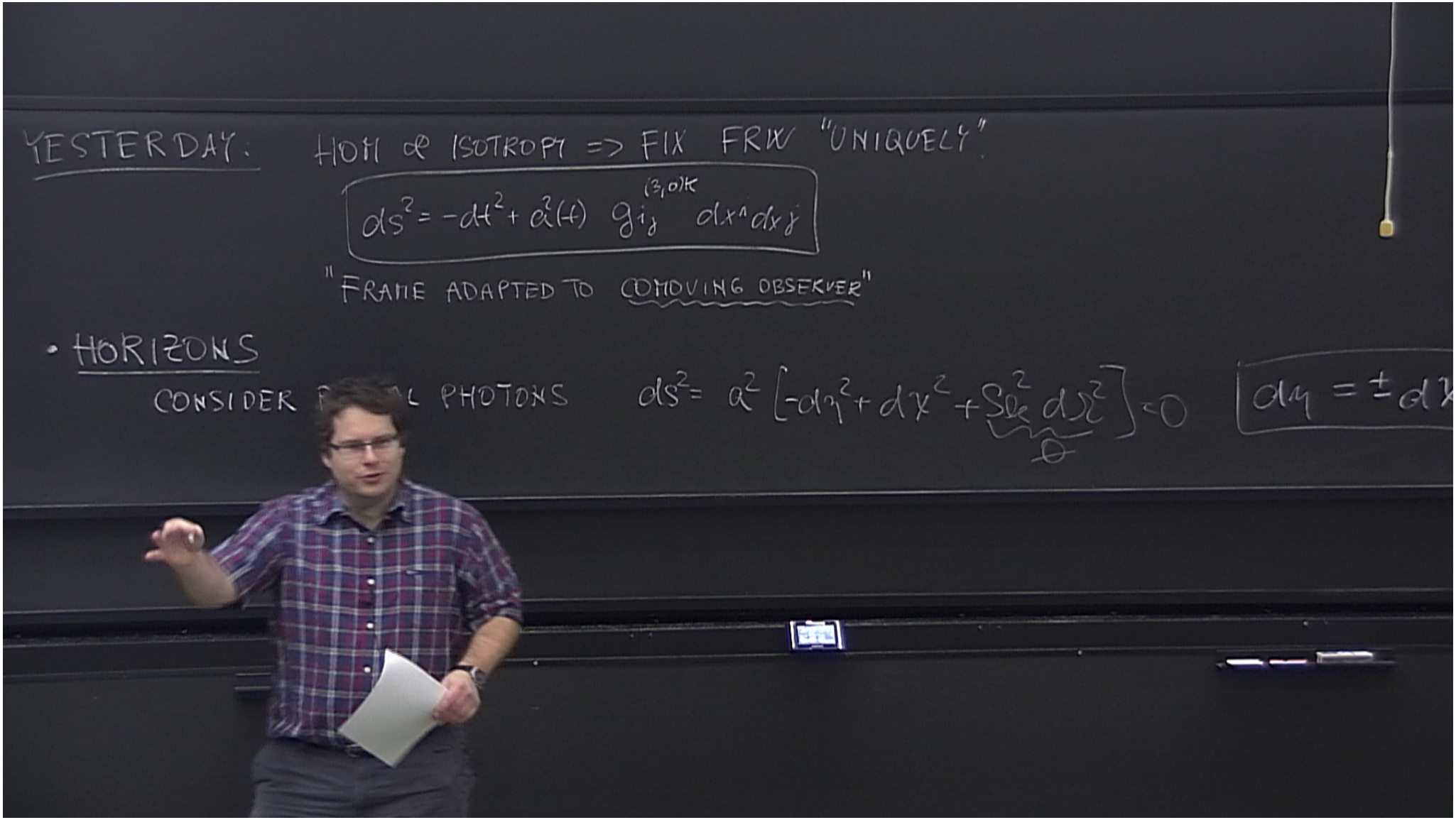
Title: PSI 2015/2016 Cosmology - Lecture 3

Date: Feb 03, 2016 11:30 AM

URL: http://pirsa.org/16020053

Abstract:




YESTERDAY: HOM & ISOTROPY => FIX FRW "UNIQUELY"
$ds^2 = -dt^2 + a^2(t)\, g^{(3,0)k}_{ij}\, dx^i dx^j$
"FRAME ADAPTED TO COMOVING OBSERVER"
• HORIZONS
CONSIDER PHOTONS
$ds^2 = a^2[-d\eta^2 + d\chi^2 + S_k^2 d\Sigma^2] = 0$
$d\eta = \pm d\chi$

- UNIVERSE EXPANDING $\dot{a} > 0$ & $t: 0 \to \infty$.
- FOR SIMPLICITY

$$a = a_0 \left(\frac{t}{t_0}\right)^p \propto t^p \qquad p = \text{CONST} > 0$$

$$\Rightarrow \quad (2)\ \ddot{a} \propto p(p-1)\, t^{p-2}$$

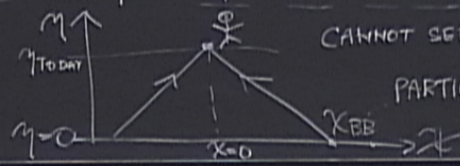
$$(3)\ \eta = \int \frac{dt}{a} \propto \int t^{-p}\, dt \propto t^{1-p}$$

DECELERATING $\ddot{a} < 0$

ACCELERATING $\ddot{a} > 0$

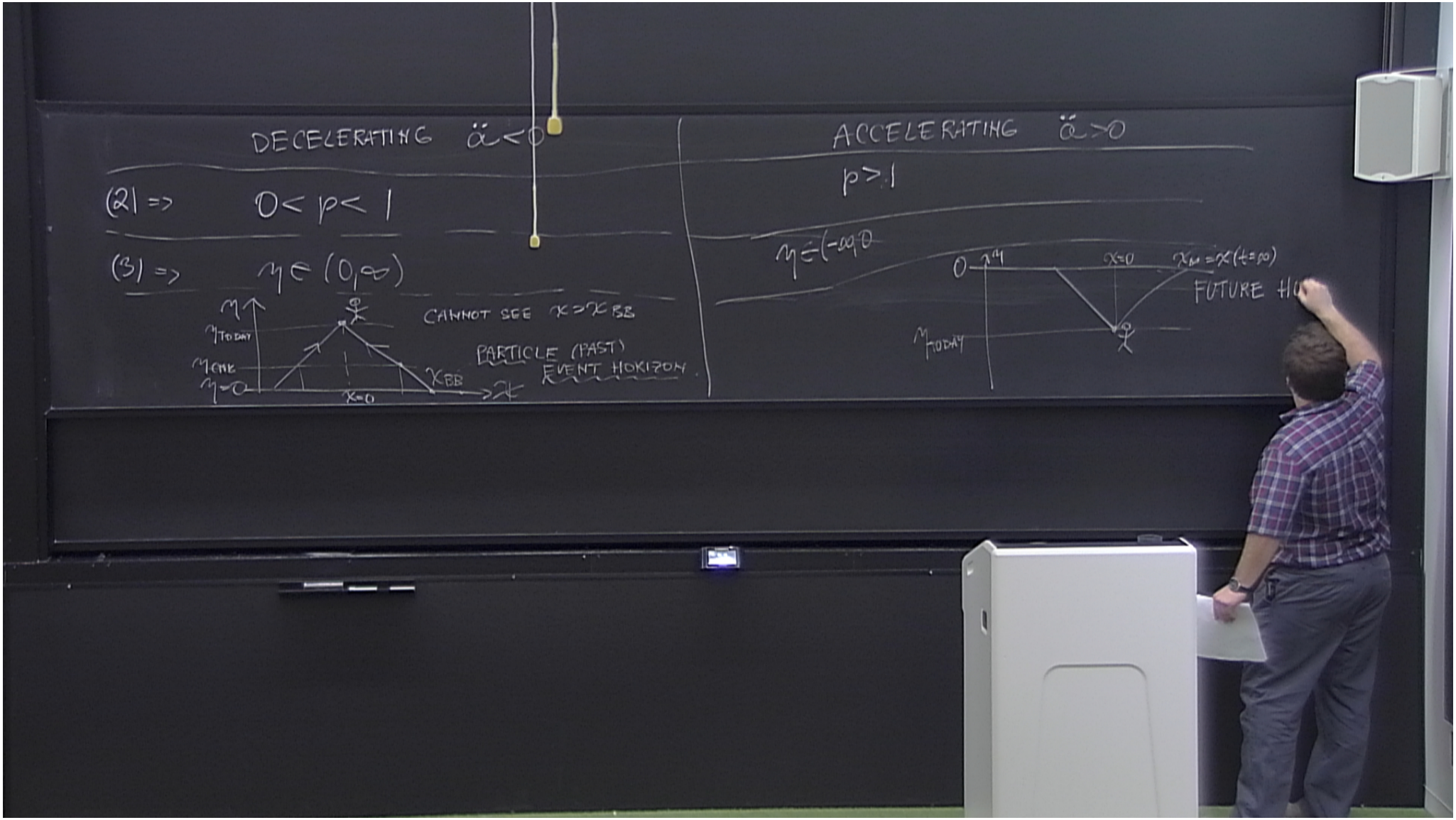
(2) $\Rightarrow$ $0 < p < 1$

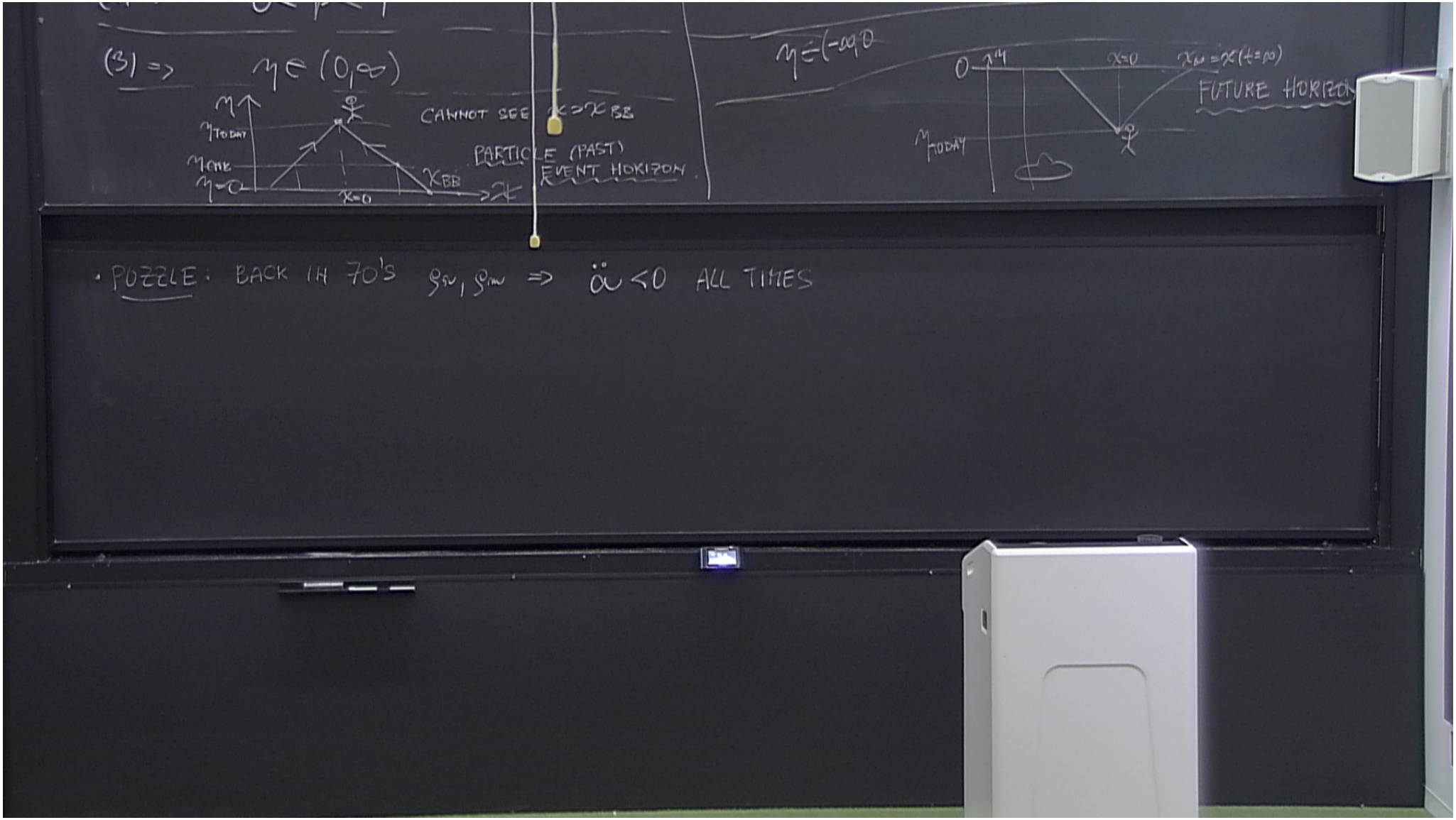
(3) $\Rightarrow$ $\eta \in (0, \infty)$

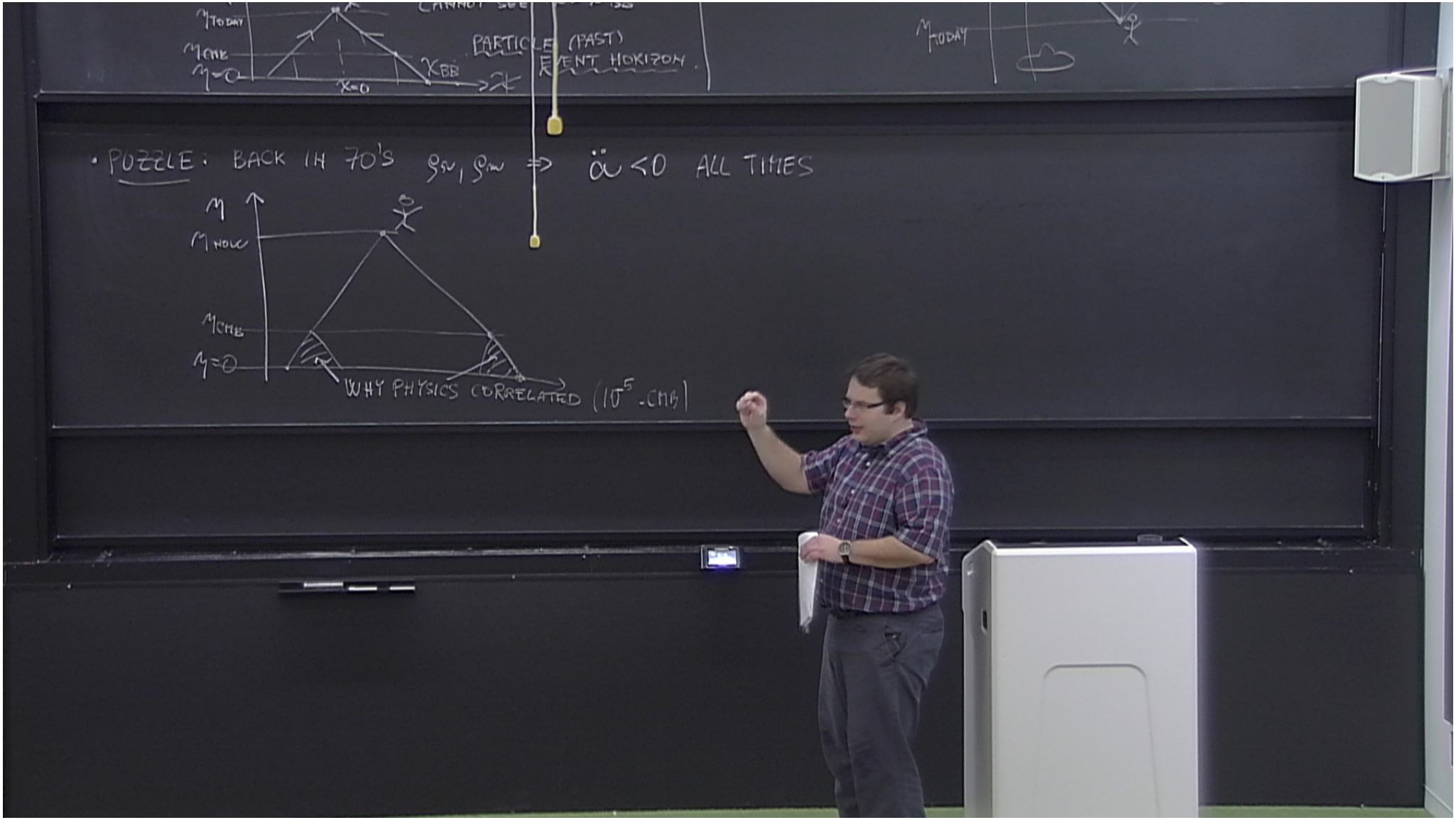


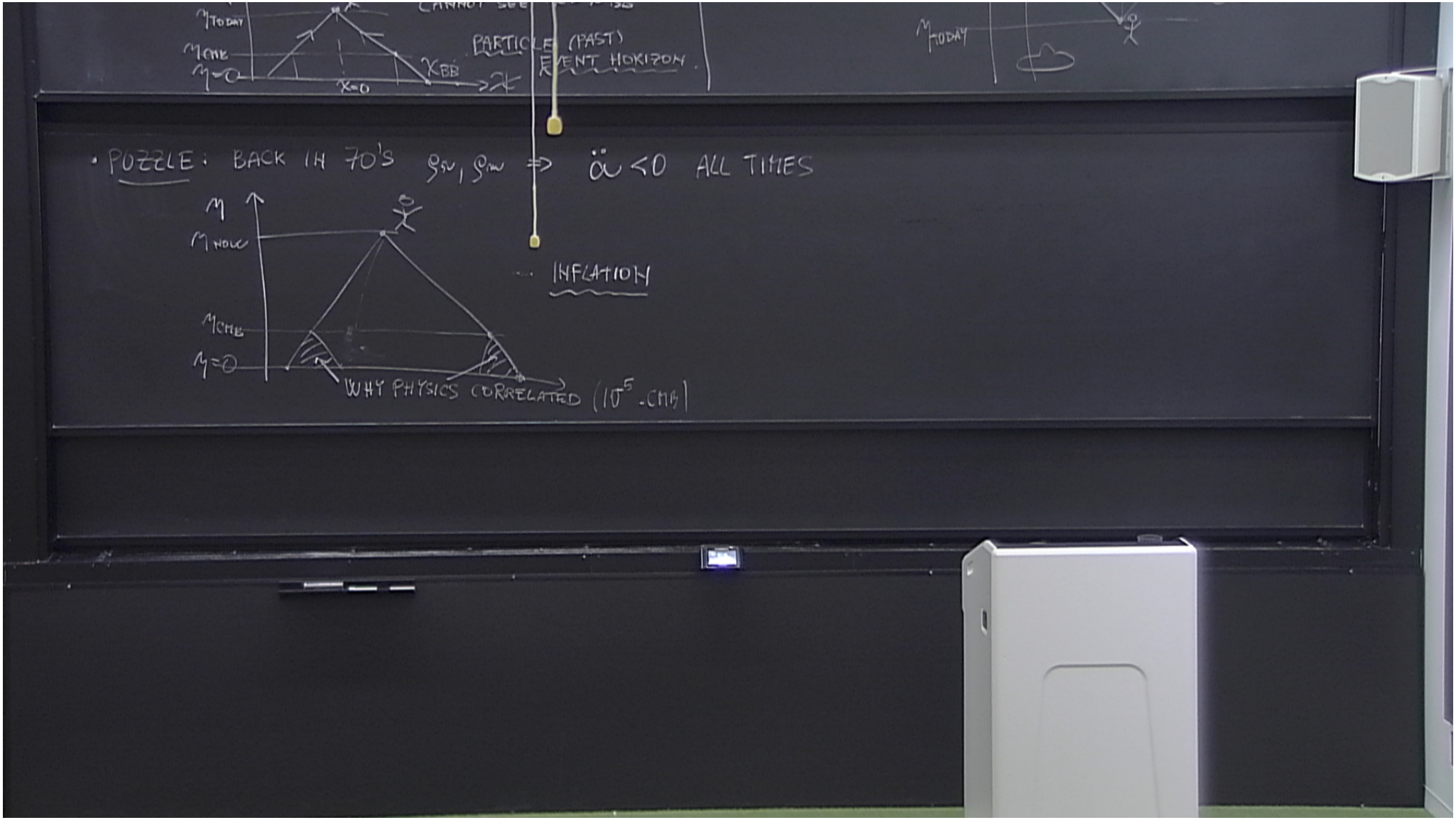
CANNOT SEE $\chi > \chi_{BB}$

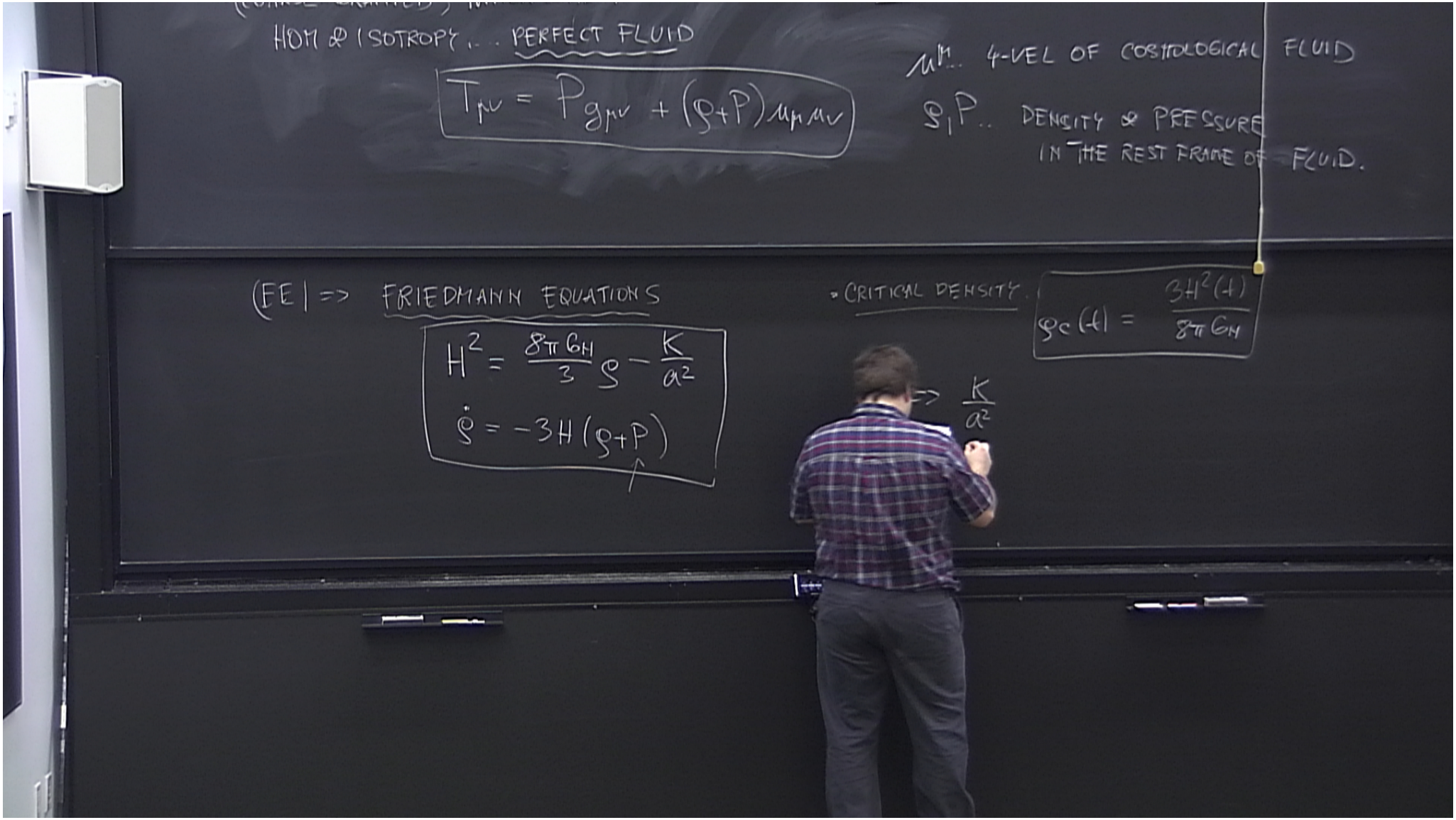
PARTICLE (PAST) EVENT HORIZON

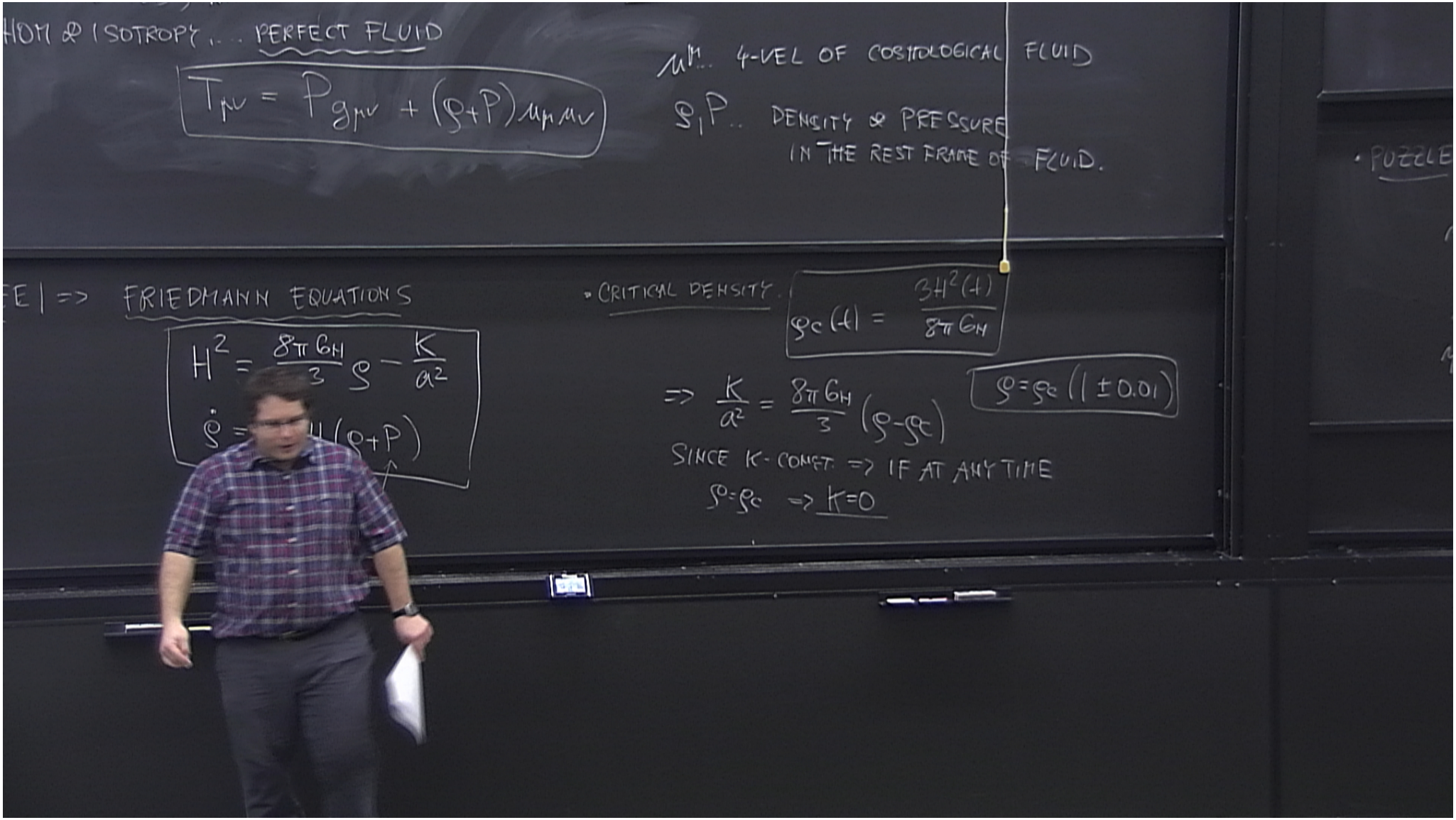

DECELERATING
(2) =>
0 < p < 1
(3) =>
η ∈ (0, ∞)
CANNOT SEE x > x_BB
PARTICLE (PAST)
EVENT HORIZON
ACCELERATING
p > 1
η ∈ (-∞, 0
FUTURE


(3) => η ∈ (0,∞)
η
η TODAY
η BBN
η = 0
x = 0
x BB
x
CANNOT SEE x > x BB
PARTICLE (PAST)
EVENT HORIZON
η ∈ (-∞, 0
0
η
x = 0
x = x(t = ∞)
η TODAY
FUTURE HORIZON
• POZZLE: BACK IN 70's ρ_M, ρ_Λ => ä < 0 ALL TIMES


PARTICLE (PAST)
EVENT HORIZON
• PUZZLE: BACK IN 70's
ALL TIMES
WHY PHYSICS CORRELATED


PARTICLE (PAST)
EVENT HORIZON
• PUZZLE: BACK IN 70's
ALL TIMES
INFLATION
WHY PHYSICS CORRELATED


HOM & ISOTROPY ... PERFECT FLUID
$T_{\mu\nu} = P g_{\mu\nu} + (\rho + P) u_\mu u_\nu$
u^μ .. 4-VEL OF COSMOLOGICAL FLUID
ρ, P .. DENSITY & PRESSURE IN THE REST FRAME OF FLUID.
(EE) => FRIEDMANN EQUATIONS
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2}$
$\dot{\rho} = -3H(\rho + P)$
• CRITICAL DENSITY
$\rho_c(t) = \frac{3H^2(t)}{8\pi G_N}$
=> $\frac{K}{a^2}$


HOM & ISOTROPY ... PERFECT FLUID
$T_{\mu\nu} = P g_{\mu\nu} + (\rho + P) u_\mu u_\nu$
u^μ ... 4-VEL OF COSMOLOGICAL FLUID
ρ, P ... DENSITY & PRESSURE IN THE REST FRAME OF FLUID.
• PUZZLE
FRIEDMANN EQUATIONS
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2}$
$\dot{\rho} = -H(\rho + P)$
• CRITICAL DENSITY
$\rho_c(t) = \frac{3H^2(t)}{8\pi G_N}$
$\Rightarrow \frac{K}{a^2} = \frac{8\pi G_N}{3}(\rho - \rho_c)$
$\rho = \rho_c (1 \pm 0.01)$
SINCE K-CONST. => IF AT ANY TIME
$\rho = \rho_c \Rightarrow K = 0$

HOM & ISOTROPY ... PERFECT FLUID

$$T_{\mu\nu} = P g_{\mu\nu} + (\rho + P) u_\mu u_\nu$$

u^μ .. 4-VEL OF COSMOLOGICAL FLUID

ρ, P .. DENSITY & PRESSURE IN THE REST FRAME OF FLUID.

E | => FRIEDMANN EQUATIONS

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2}$$

$$\dot{\rho} = -3H(\rho + P)$$

• CRITICAL DENSITY

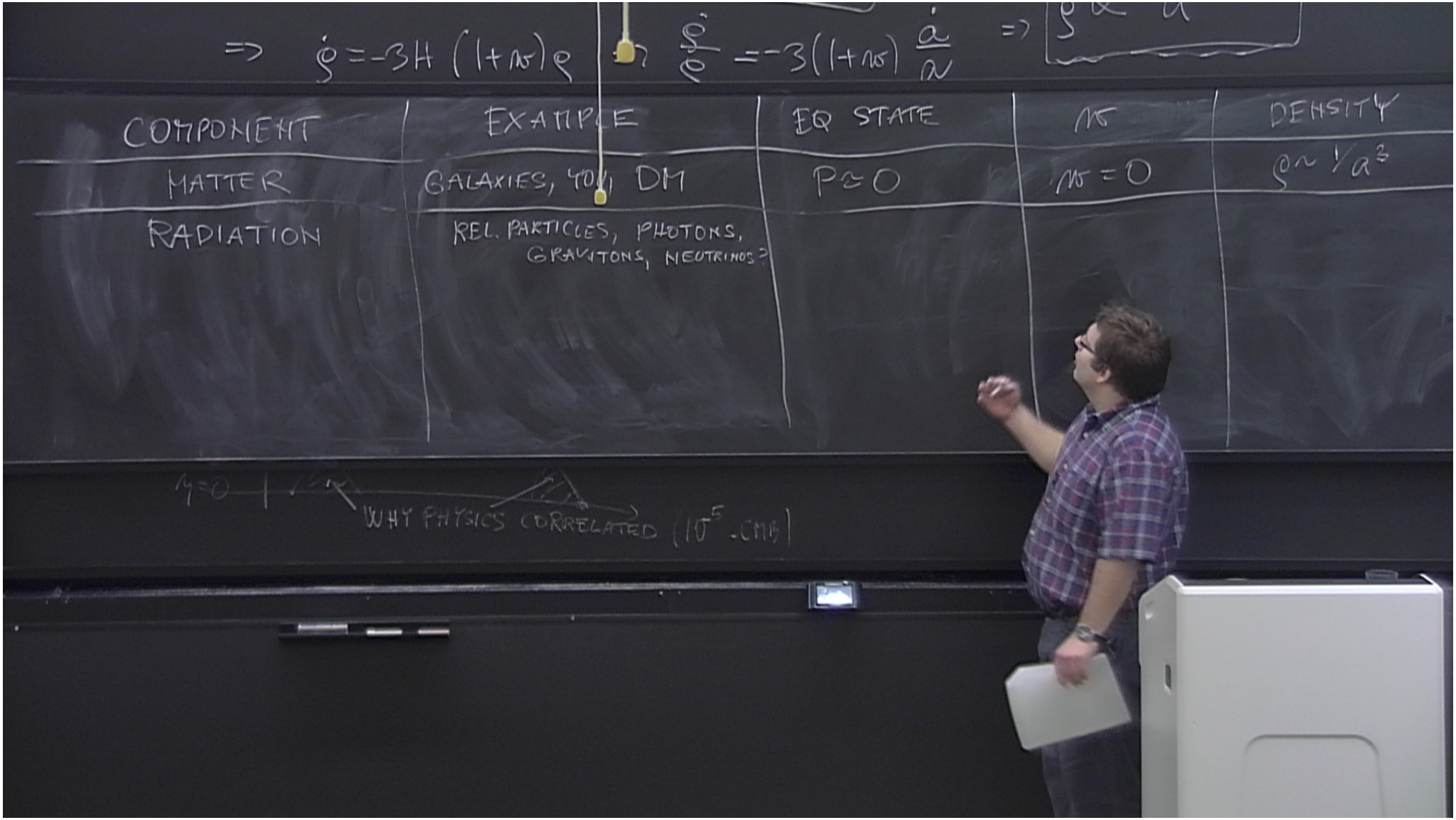
$$\rho_c(t) = \frac{3H^2(t)}{8\pi G_N}$$

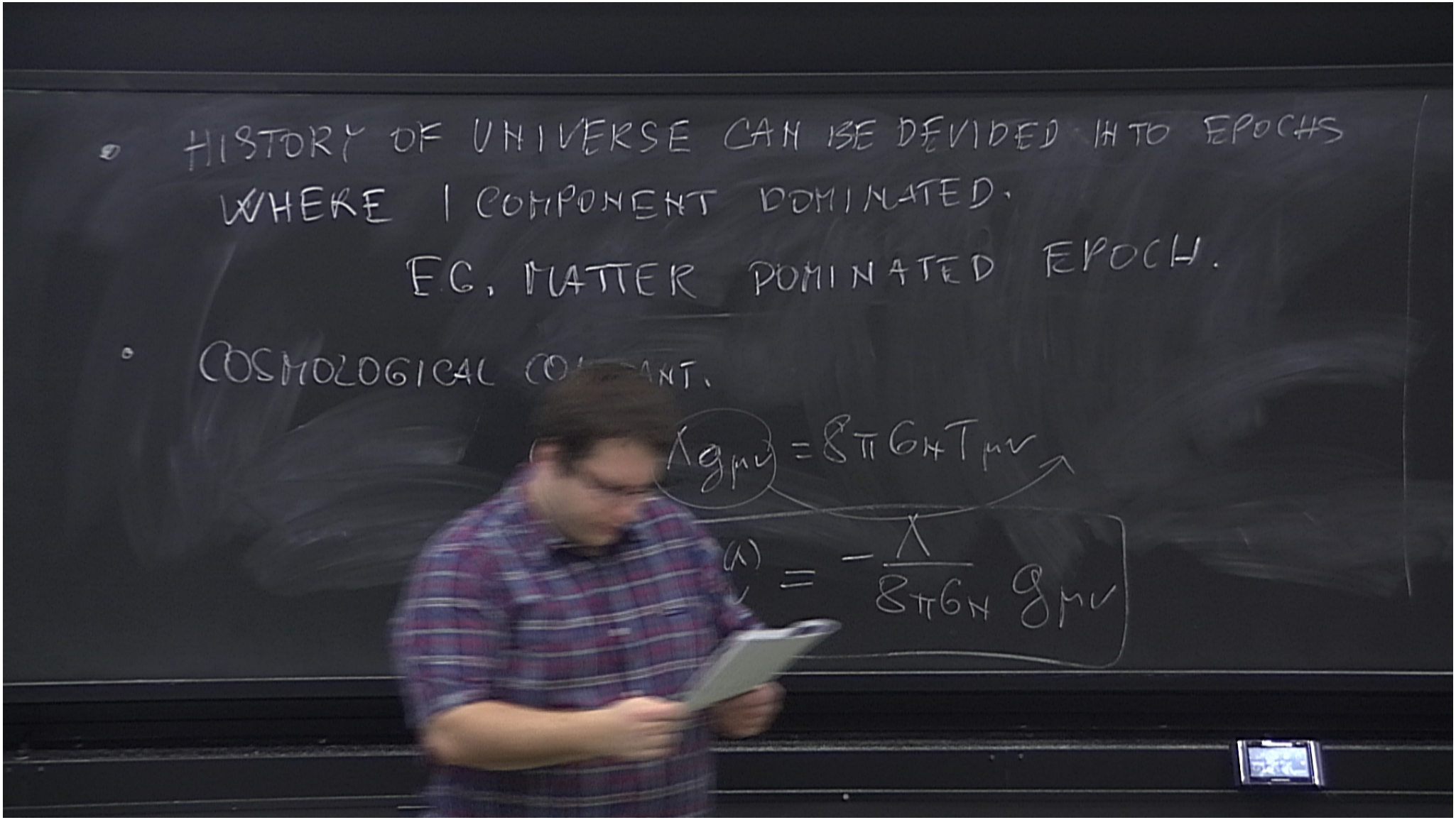
$$\Rightarrow \frac{K}{a^2} = \frac{8\pi G_N}{3}(\rho - \rho_c)$$

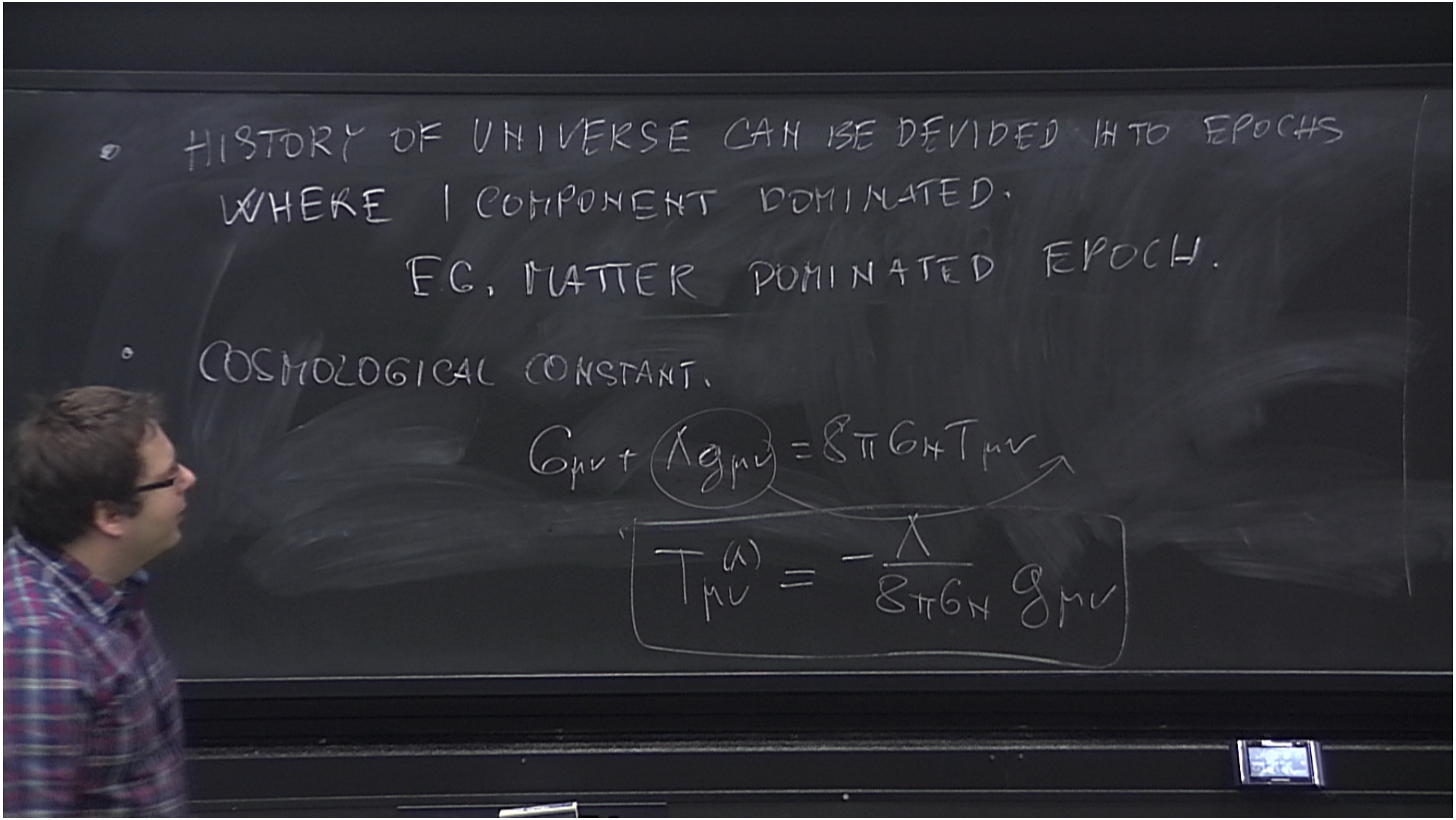
$\rho = \rho_c (1 \pm 0.01)$

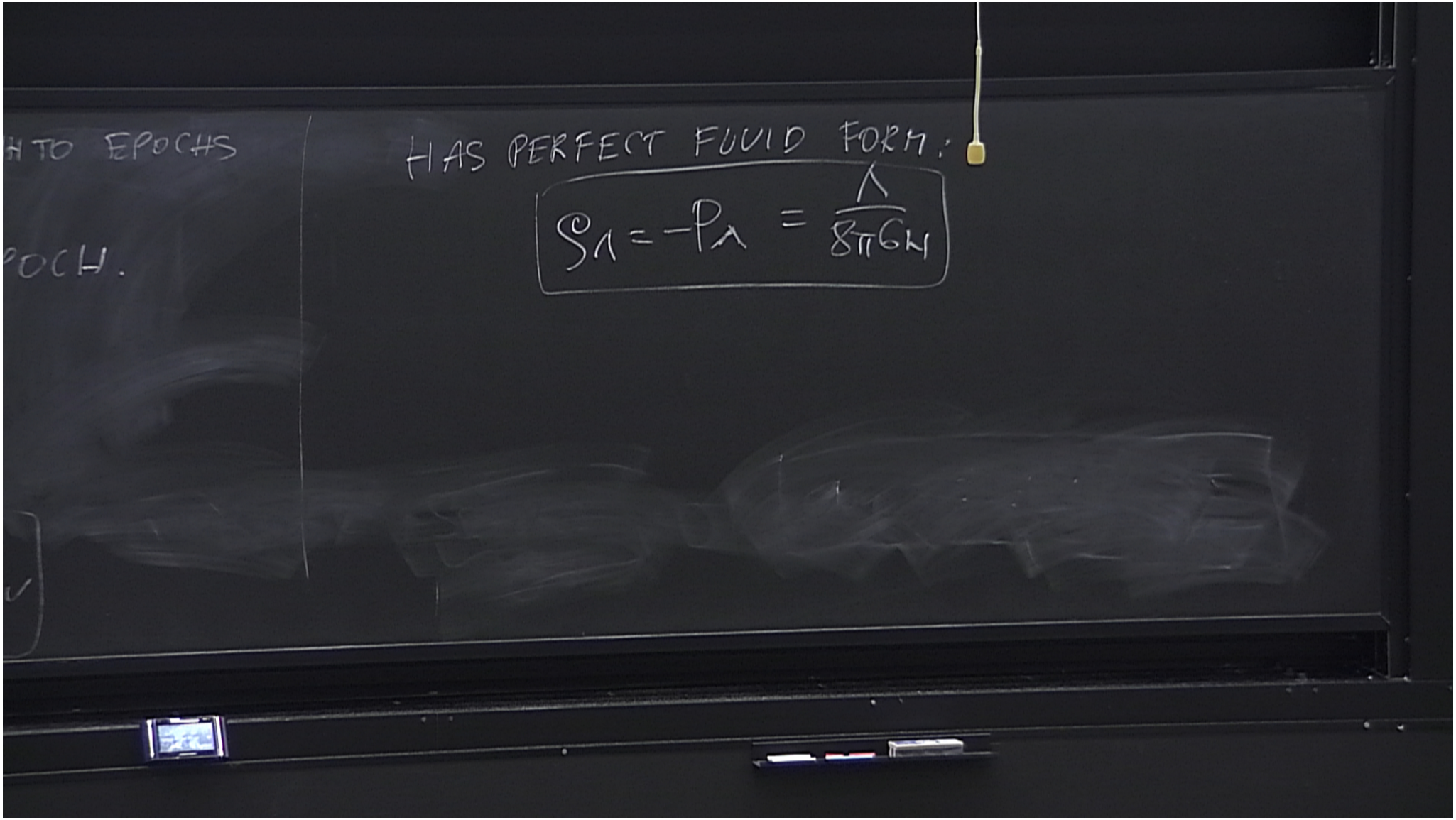
FLATNESS PUZZLE

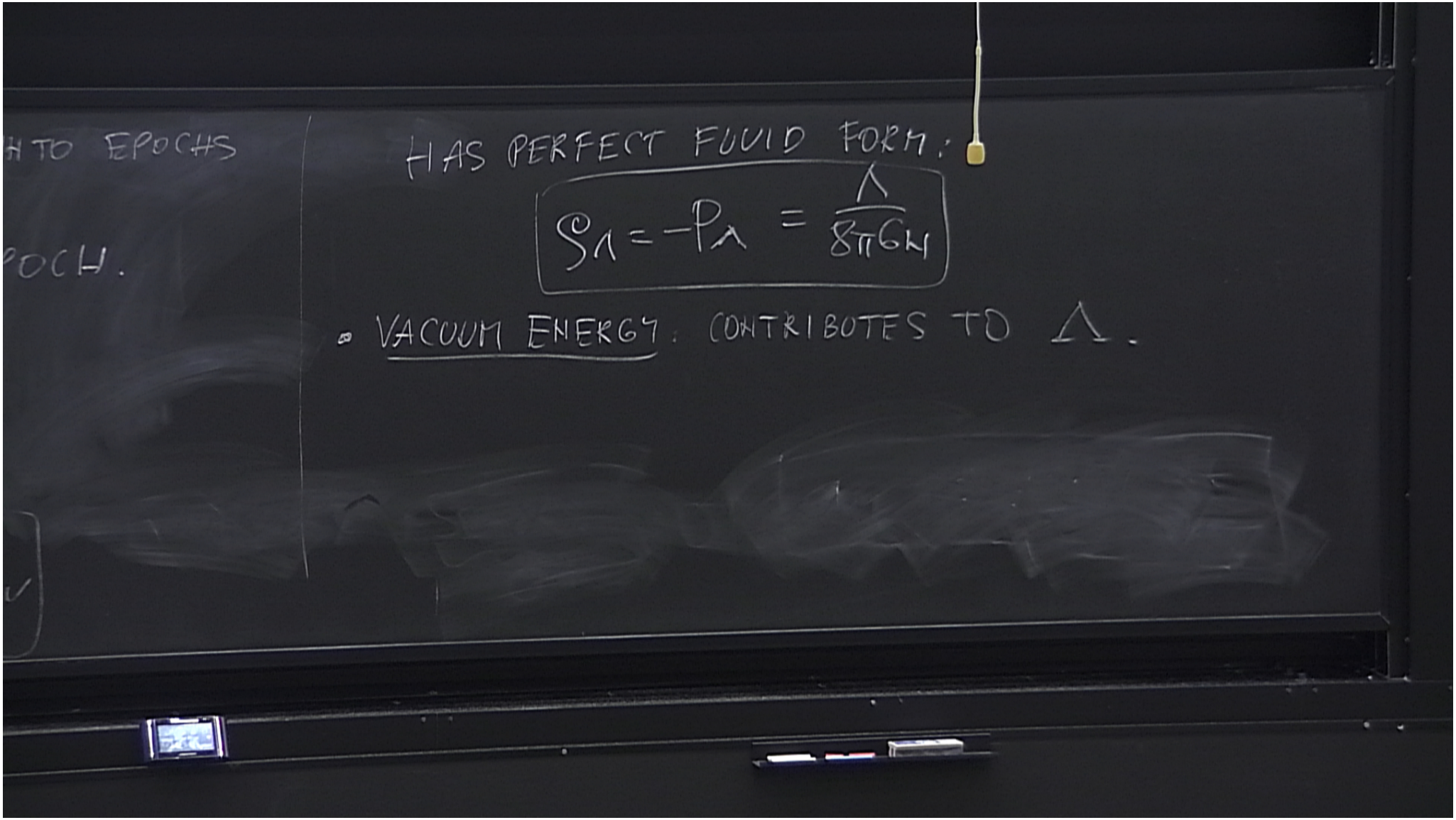
SINCE K-CONST. => IF AT ANY TIME $\rho = \rho_c \Rightarrow K = 0$

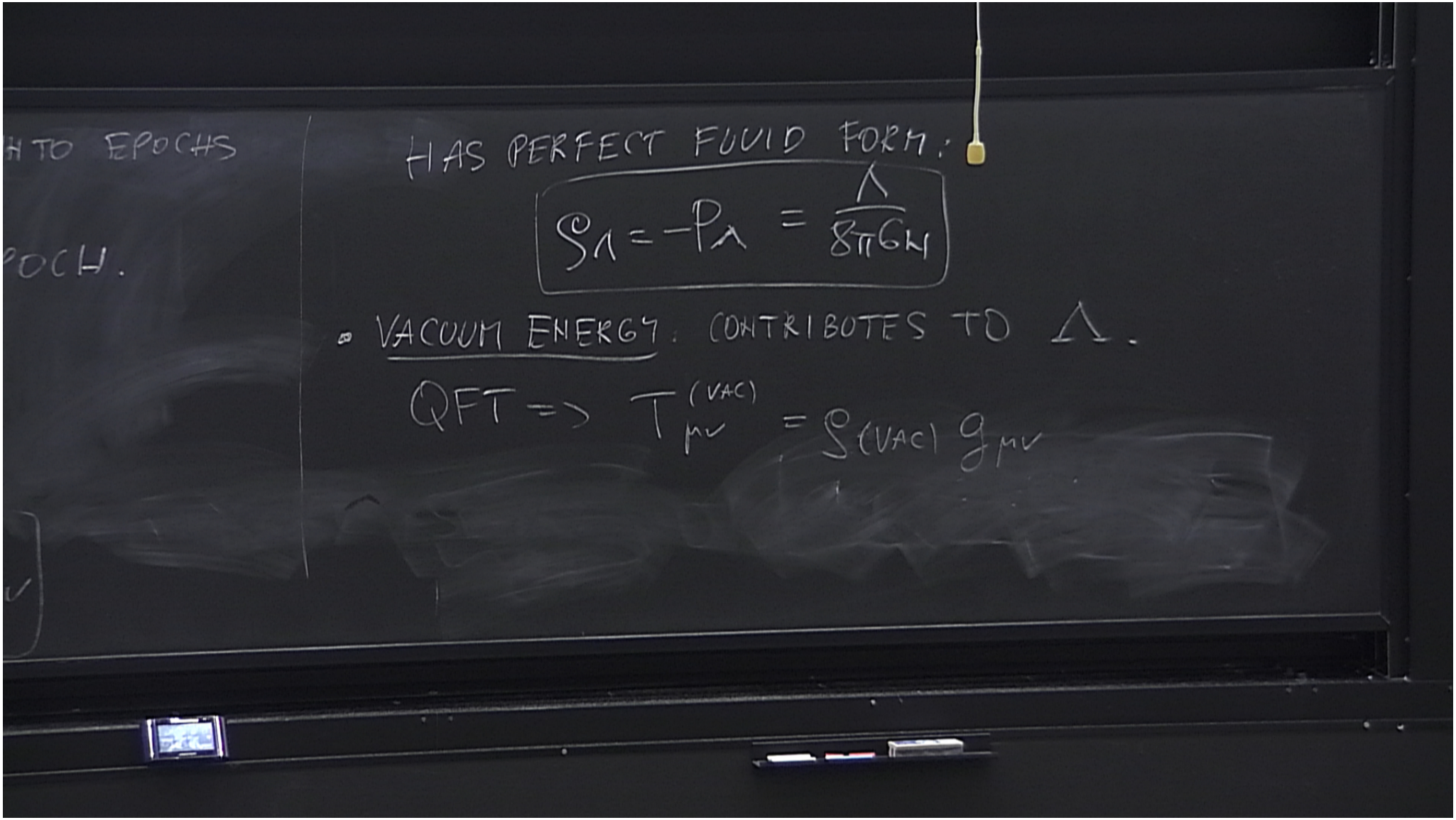

$\Rightarrow \dot{\rho} = -3H(1+w)\rho$
$\Rightarrow \frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a}$
$\Rightarrow \rho \propto a$
COMPONENT
EXAMPLE
EQ STATE
w
DENSITY
MATTER
GALAXIES, YOU, DM
$P \simeq 0$
$w = 0$
$\rho \sim 1/a^3$
RADIATION
REL. PARTICLES, PHOTONS, GRAVITONS, NEUTRINOS?
$t = 0$
WHY PHYSICS CORRELATED (10^5 CMH)

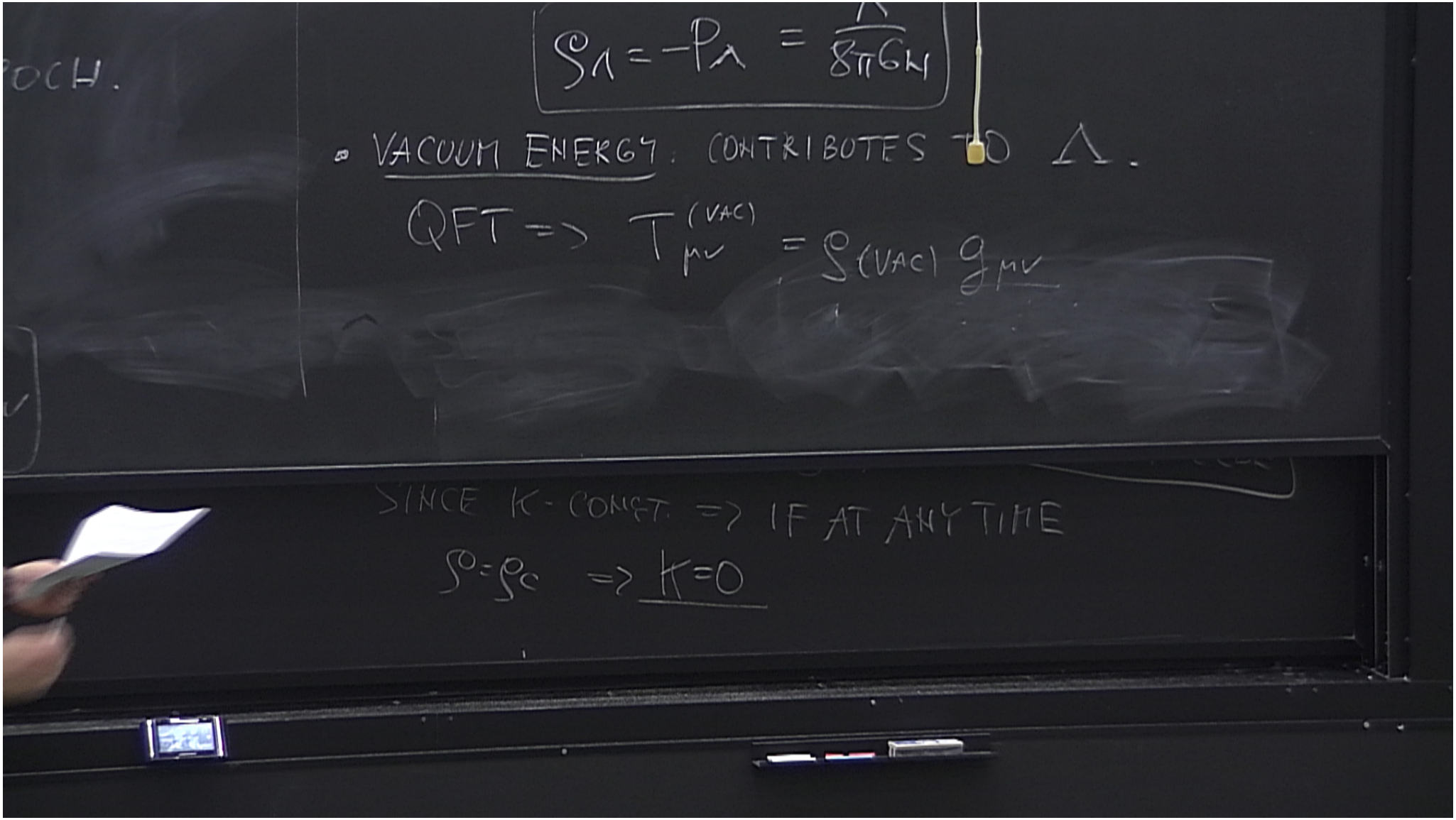

HISTORY OF UNIVERSE CAN BE DEVIDED IN TO EPOCHS
WHERE 1 COMPONENT DOMINATED.
EG. MATTER POMINATED EPOCH.
COSMOLOGICAL CO NT.
$\Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$
$= -\frac{\Lambda}{8\pi G_N} g_{\mu\nu}$

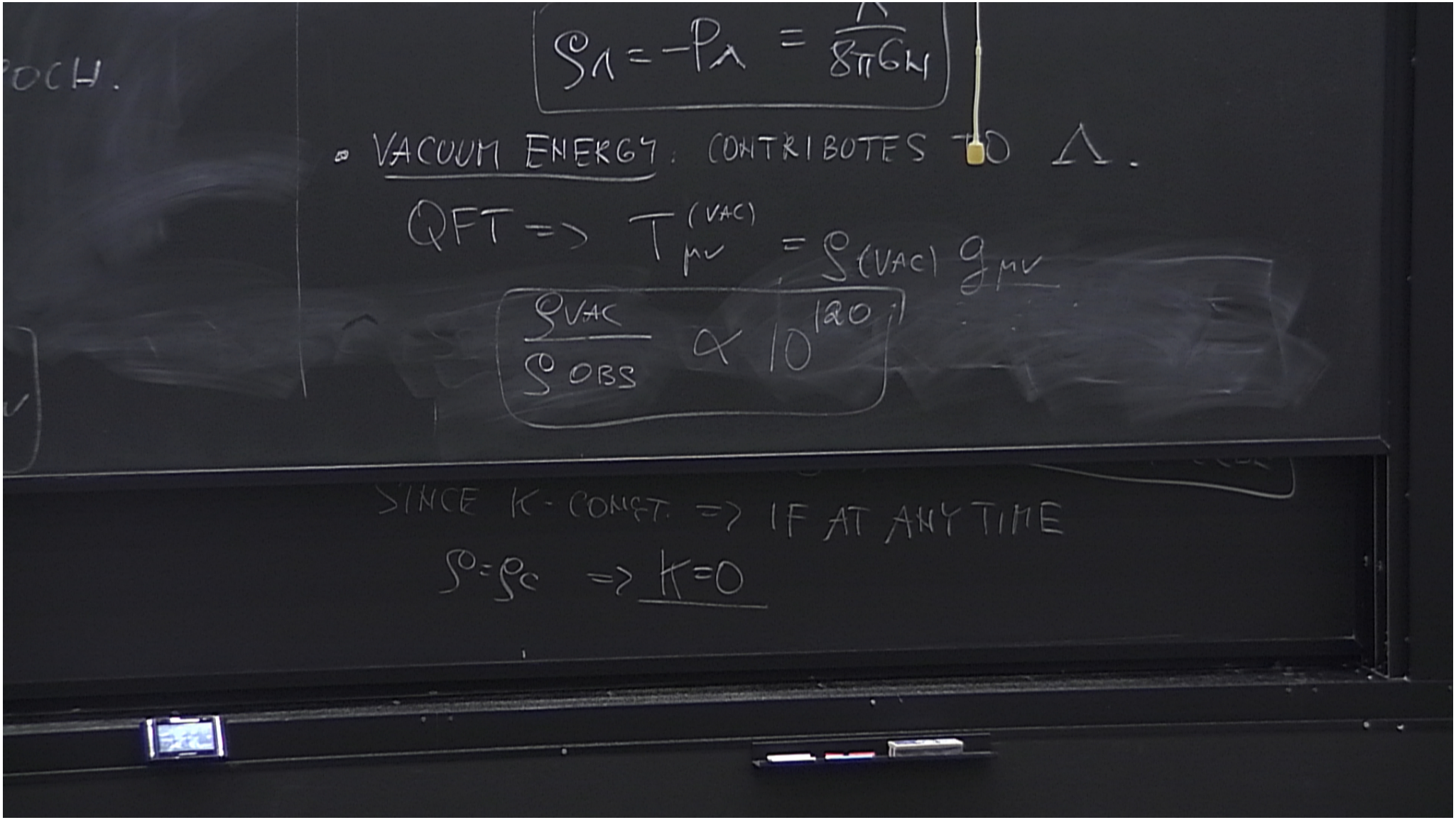

• HISTORY OF UNIVERSE CAN BE DEVIDED IN TO EPOCHS WHERE 1 COMPONENT DOMINATED.
EG. MATTER POMINATED EPOCH.
• COSMOLOGICAL CONSTANT.
$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$
$T^{(\Lambda)}_{\mu\nu} = -\frac{\Lambda}{8\pi G_N} g_{\mu\nu}$

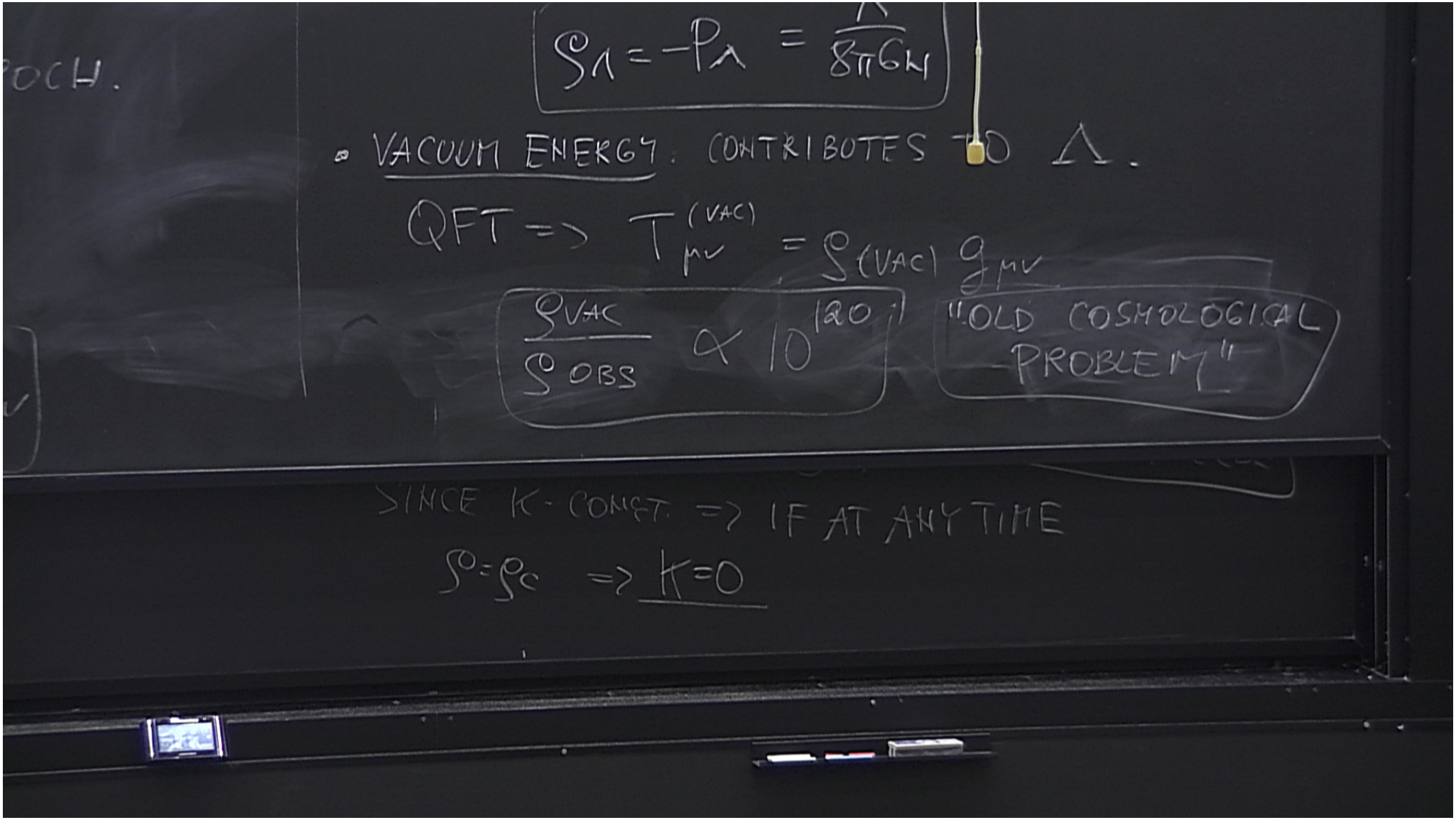

H TO EPOCHS
POCH.
HAS PERFECT FLUID FORM:
$S_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$


H TO EPOCHS
POCH.
HAS PERFECT FLUID FORM:
$\rho_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$
• VACUUM ENERGY: CONTRIBOTES TO Λ.


H TO EPOCHS
POCH.
HAS PERFECT FLUID FORM:
$\rho_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$
• VACUUM ENERGY: CONTRIBUTES TO Λ.
QFT => $T^{(VAC)}_{\mu\nu} = \rho_{(VAC)}\, g_{\mu\nu}$

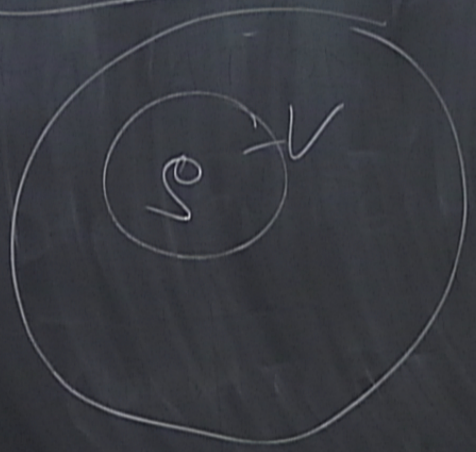

$\rho_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$
VACUUM ENERGY: CONTRIBUTES TO Λ.
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SINCE K-CONST. => IF AT ANY TIME
$\rho = \rho_c$ => $K = 0$

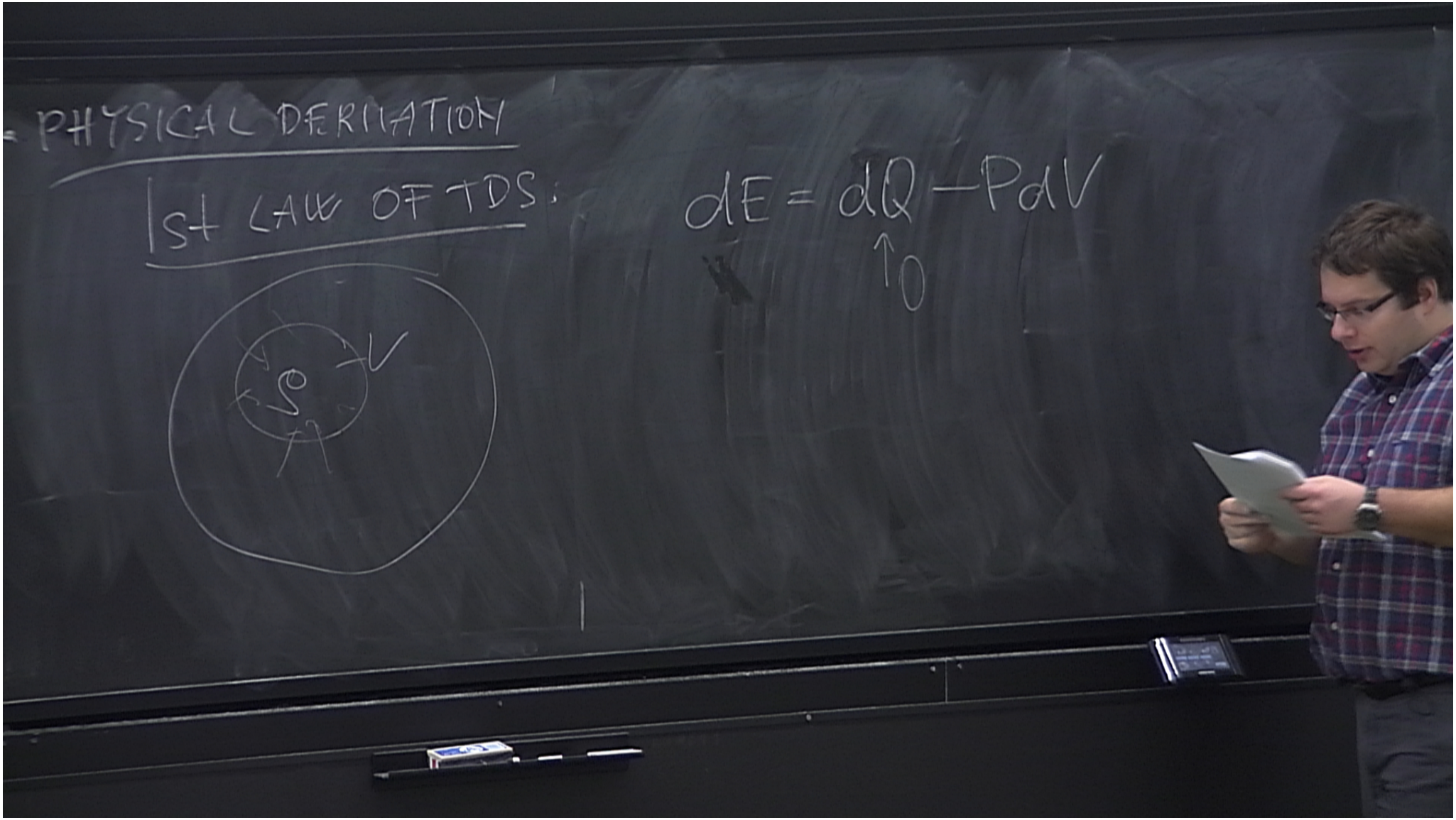

$\rho_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$
VACUUM ENERGY: CONTRIBUTES TO Λ.
QFT => $T^{(VAC)}_{\mu\nu} = \rho_{(VAC)}\, g_{\mu\nu}$
$\frac{\rho_{VAC}}{\rho_{OBS}} \propto 10^{120}$
SINCE K-CONST. => IF AT ANY TIME
$\rho = \rho_c$ => $K = 0$

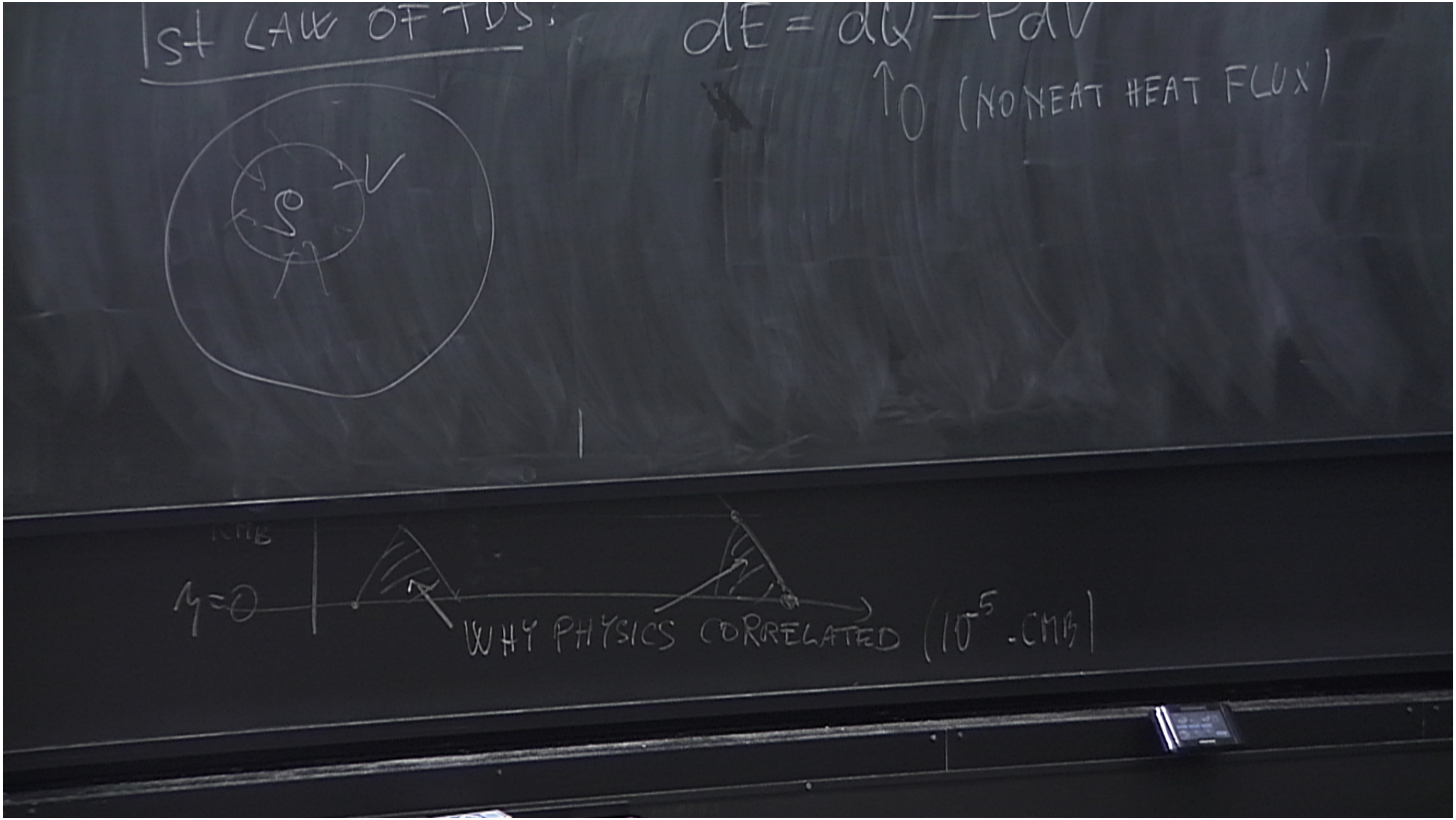

$\rho_\Lambda = -P_\Lambda = \frac{\Lambda}{8\pi G_N}$
• VACUUM ENERGY: CONTRIBUTES TO Λ.
QFT => $T^{(VAC)}_{\mu\nu} = \rho_{(VAC)}\, g_{\mu\nu}$
$\frac{\rho_{VAC}}{\rho_{OBS}} \propto 10^{120}$
"OLD COSMOLOGICAL PROBLEM"
SINCE K-CONST. => IF AT ANY TIME
$\rho = \rho_c$ => $K = 0$

PHYSICAL DERIVATION

1st LAW OF TDS:




PHYSICAL DERIVATION
1st LAW OF TDS:
dE = dQ − PdV
↑0
V
S

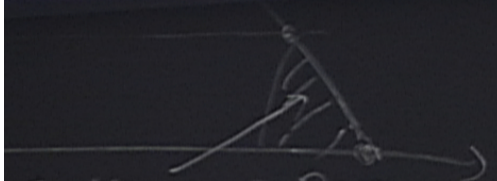

1st LAW OF TDS:
dE = dQ − PdV
↑0 (NO NET HEAT FLUX)
S
V
CMB
WHY PHYSICS CORRELATED (10^-5 . CMB)

$dE = dQ - PdV$

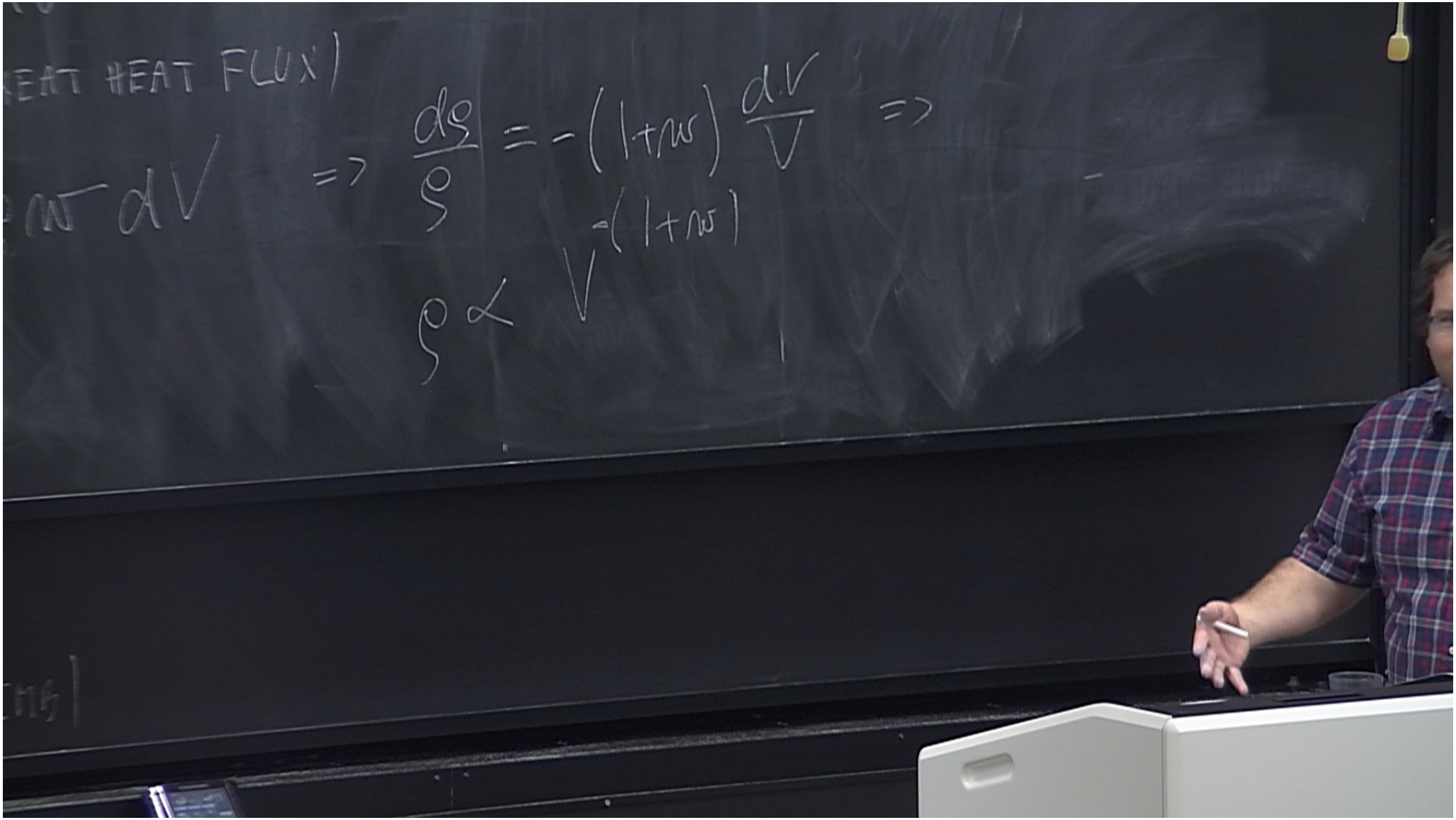
$\uparrow 0$ (NO NET HEAT FLUX)

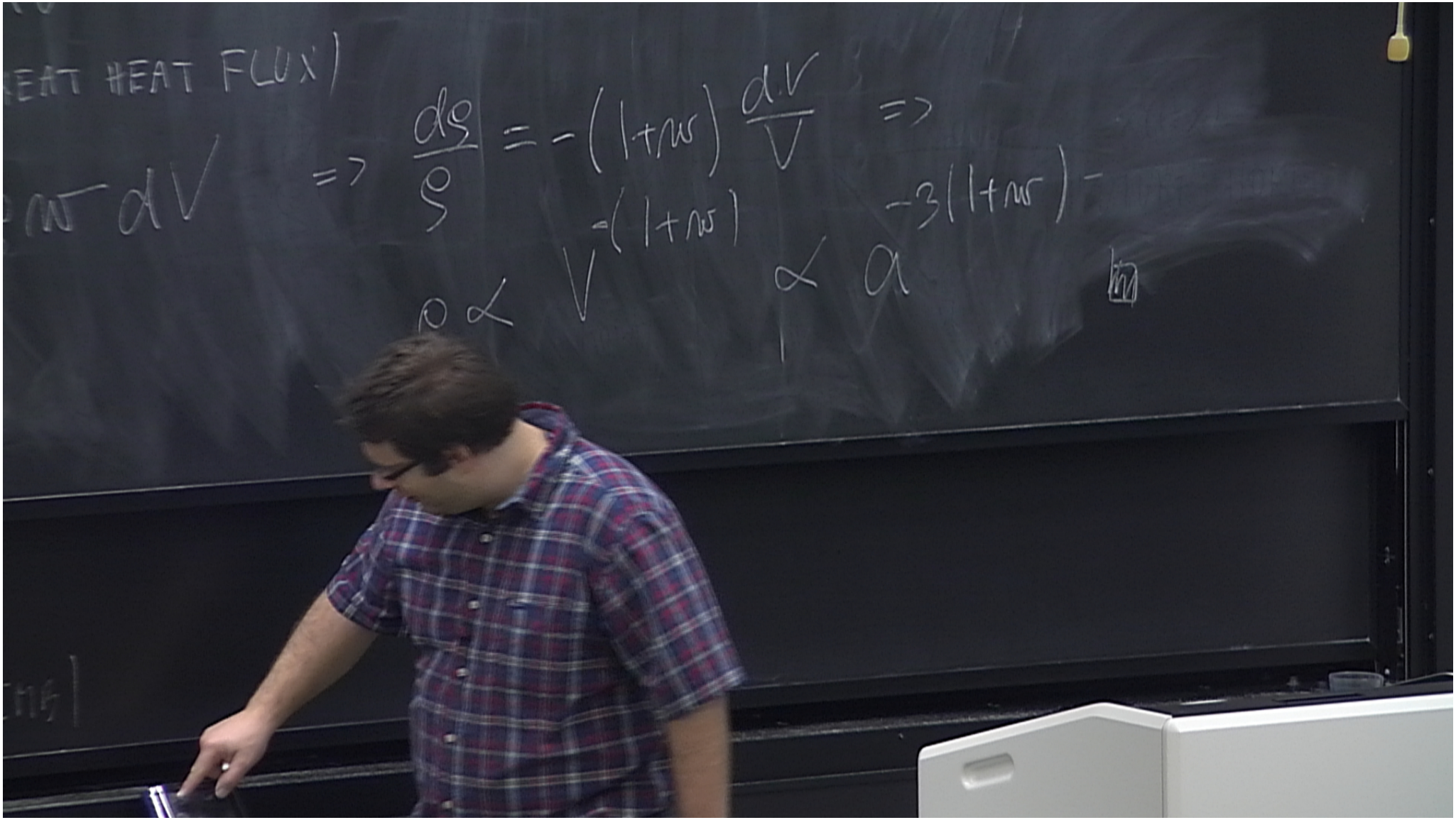
$d(\rho V) = 0 = \rho w\, dV \quad \Rightarrow \quad \frac{d\rho}{\rho} = -(1+w)\frac{dV}{V}$

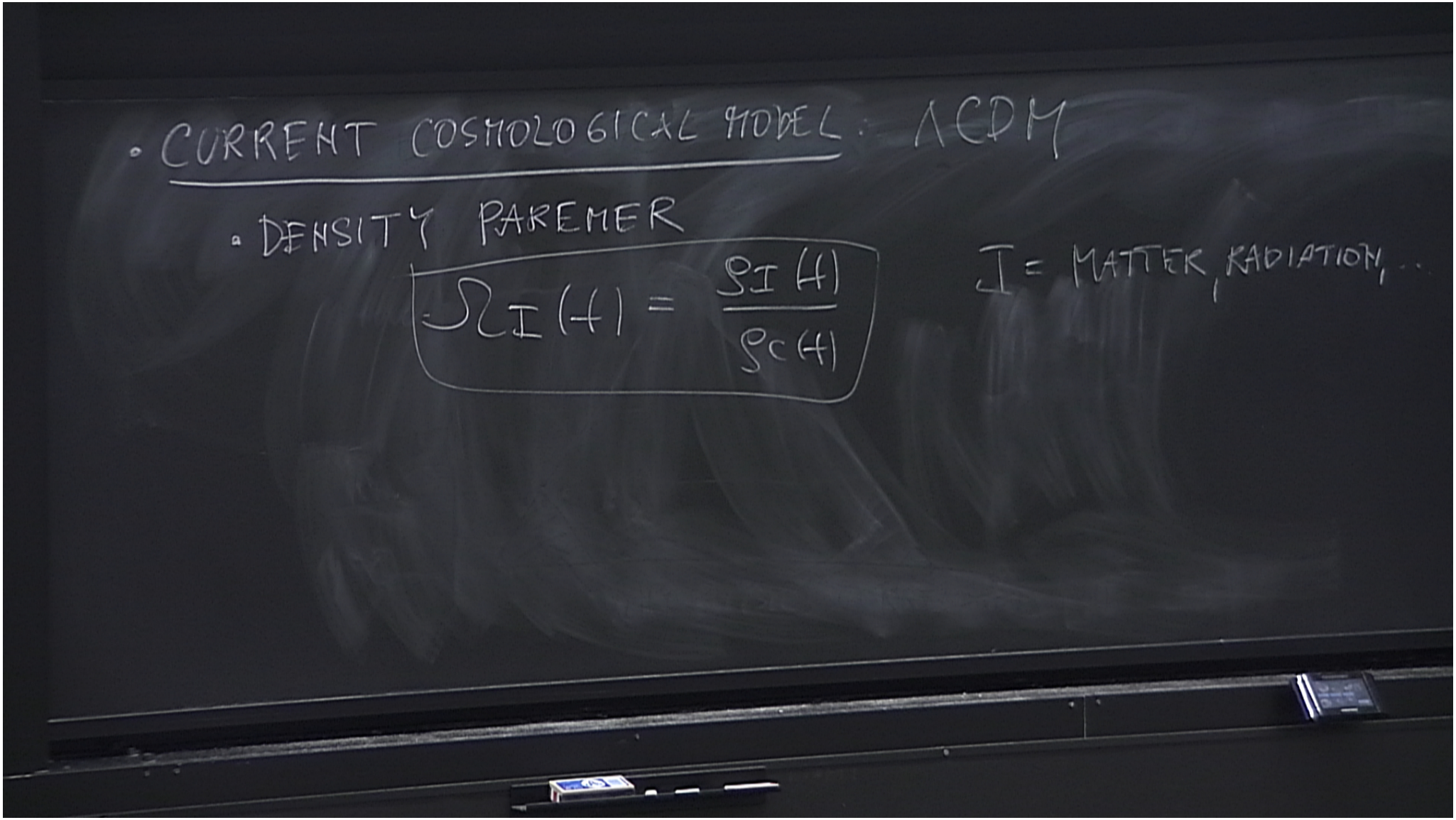
$\| \quad d\rho V + \rho dV$

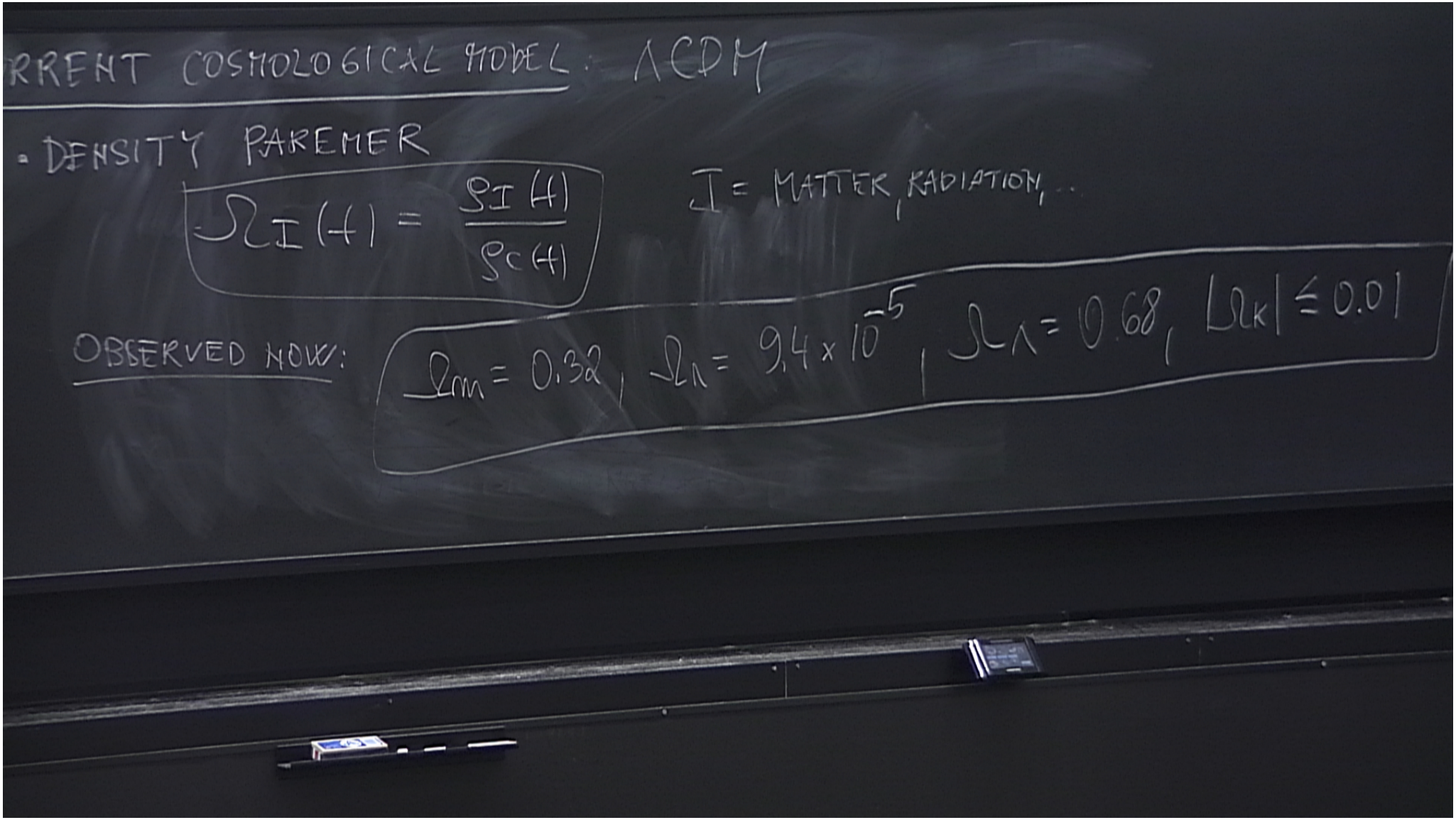


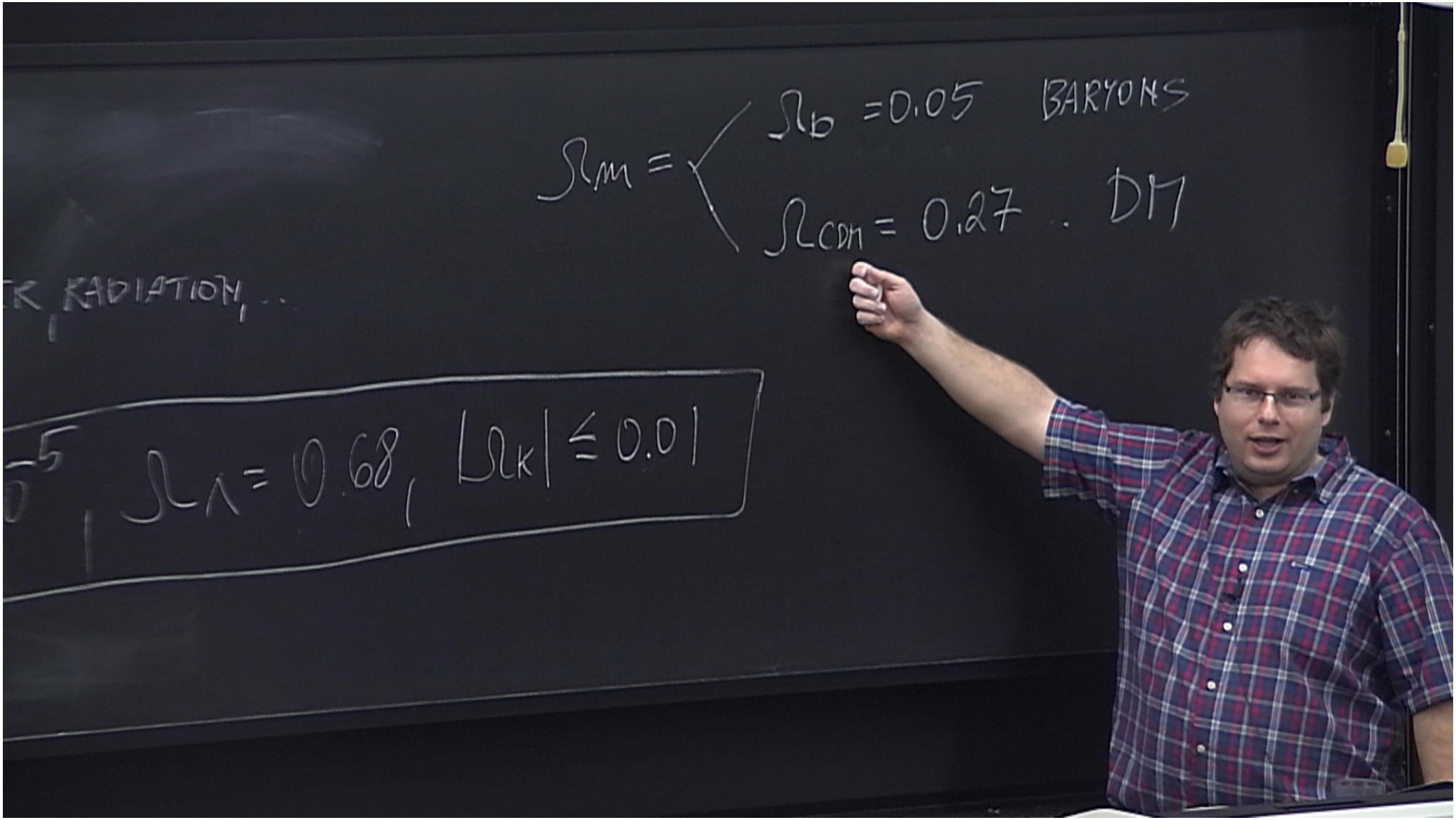
PHYSICS CORRELATED $(10^{-5}$ - CMB)

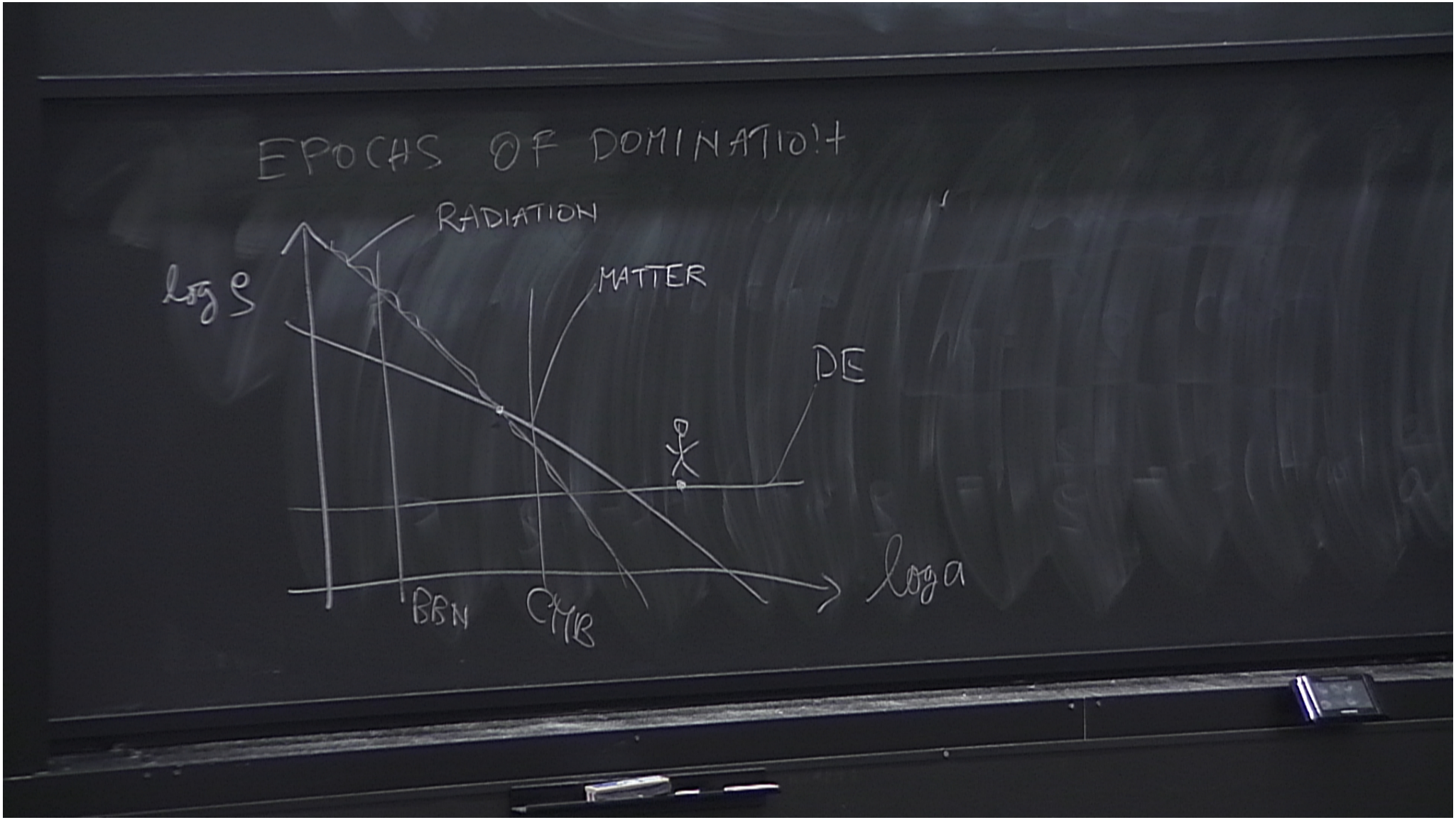

HEAT HEAT FLUX)
$\frac{d\rho}{\rho} = -(1+n)\frac{dV}{V}$ =>
$\rho \propto V^{-(1+n)}$

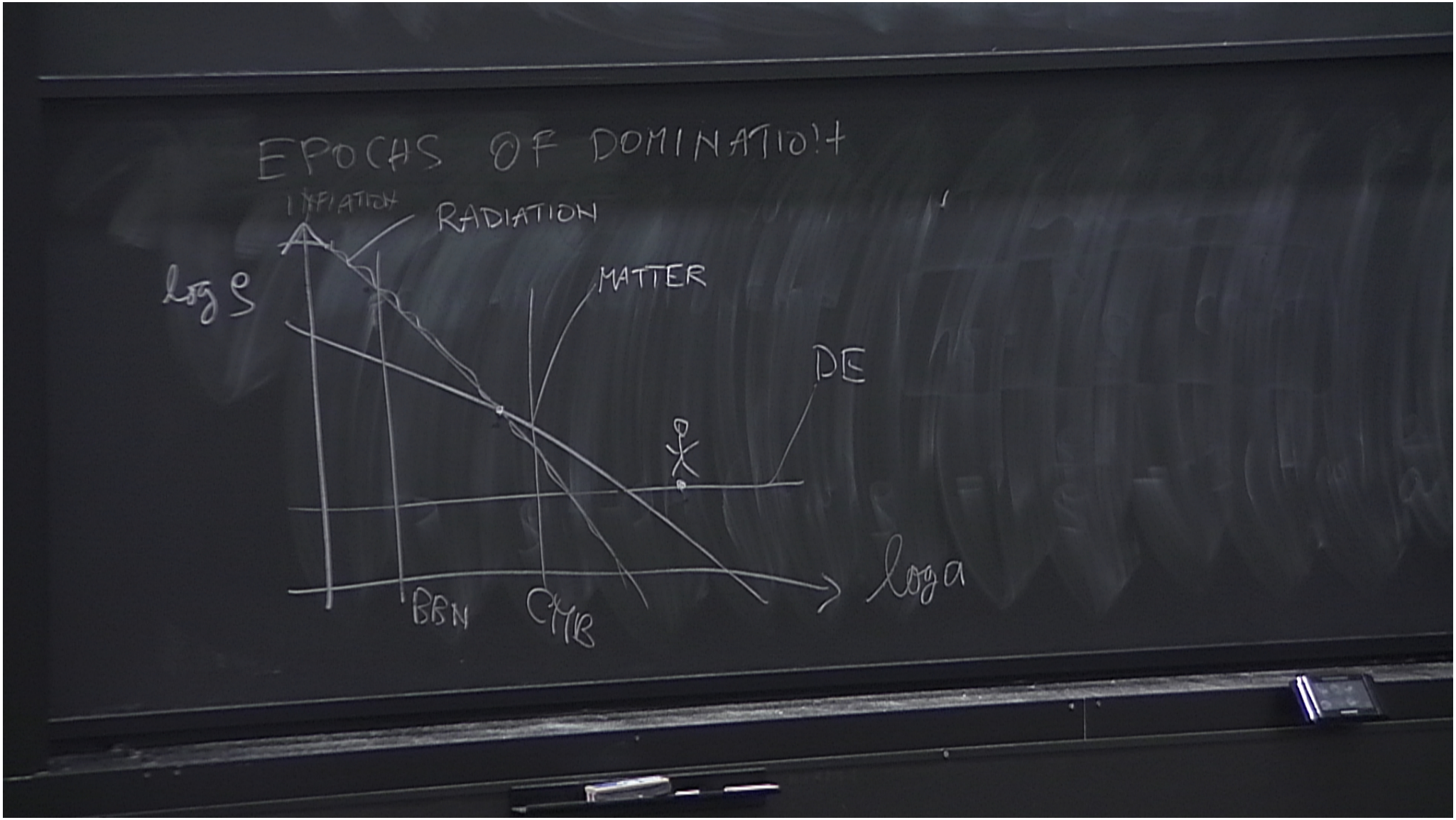

EAT HEAT FLUX)
$\frac{dQ}{Q} = -(1+w)\frac{dV}{V}$ =>
$\rho \propto V^{-(1+w)}$
$\propto a^{-3(1+w)}$


• CURRENT COSMOLOGICAL MODEL: ΛCDM
• DENSITY PAREMER
$\Omega_I(t) = \frac{\rho_I(t)}{\rho_c(t)}$
I = MATTER, RADIATION, ..


RRENT COSMOLOGICAL MODEL: ΛCDM
• DENSITY PARAMER
$\Omega_I(t) = \frac{\rho_I(t)}{\rho_c(t)}$
I = MATTER, RADIATION, ..
OBSERVED NOW:
$\Omega_m = 0.32$, $\Omega_\Lambda = 9.4 \times 10^{-5}$, $\Omega_\Lambda = 0.68$, $|\Omega_k| \leq 0.01$


$\Omega_m = \begin{cases} \Omega_b = 0.05 & \text{BARYONS} \\ \Omega_{CDM} = 0.27 & \text{DM} \end{cases}$
RADIATION
$\Omega_\Lambda = 0.68$, $|\Omega_k| \leq 0.01$


EPOCHS OF DOMINATION
RADIATION
MATTER
DE
log ρ
log a
BBN
CMB


EPOCHS OF DOMINATION
INFLATION
RADIATION
MATTER
DE
log ρ
log a
BBN
CMB