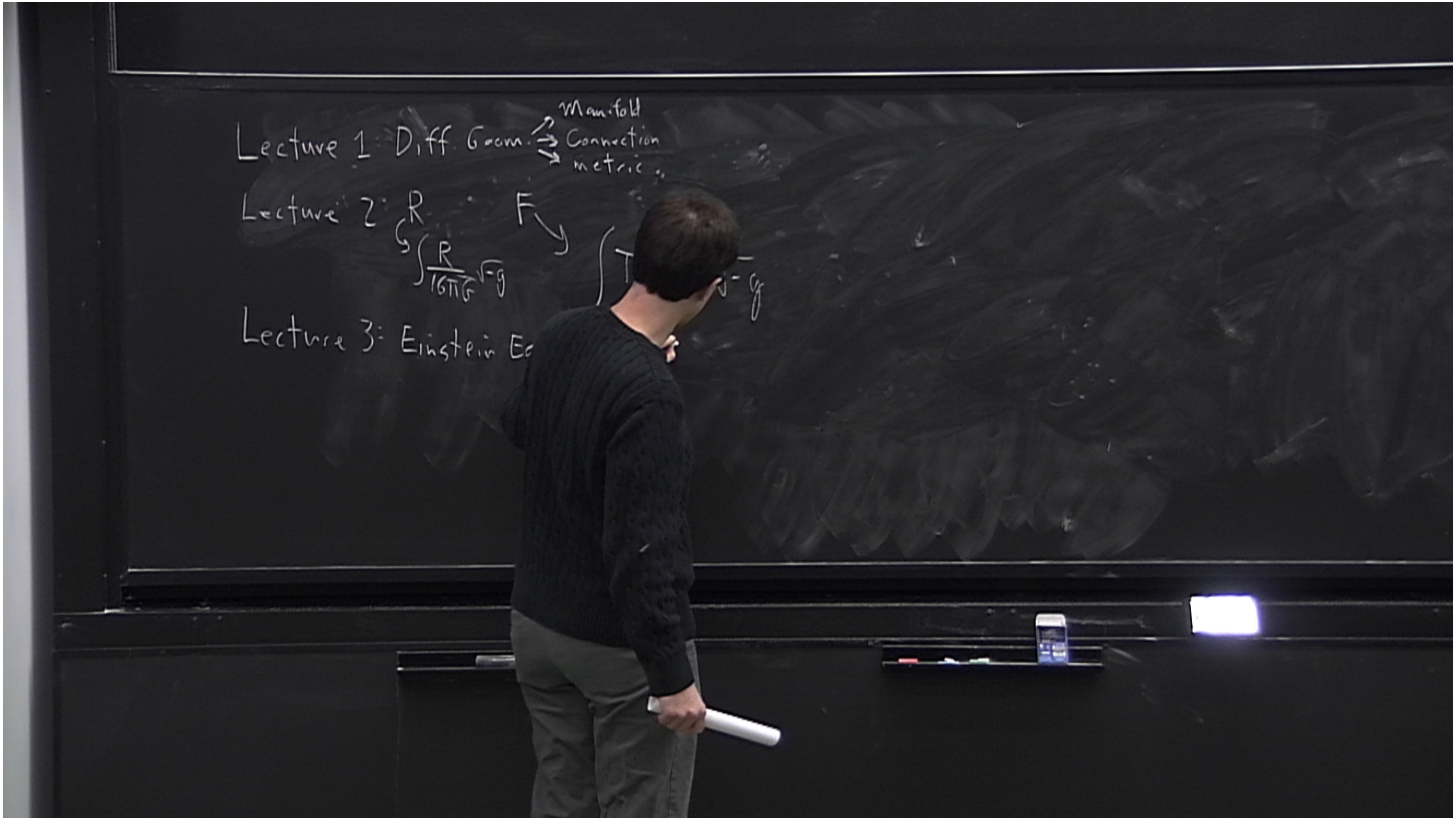
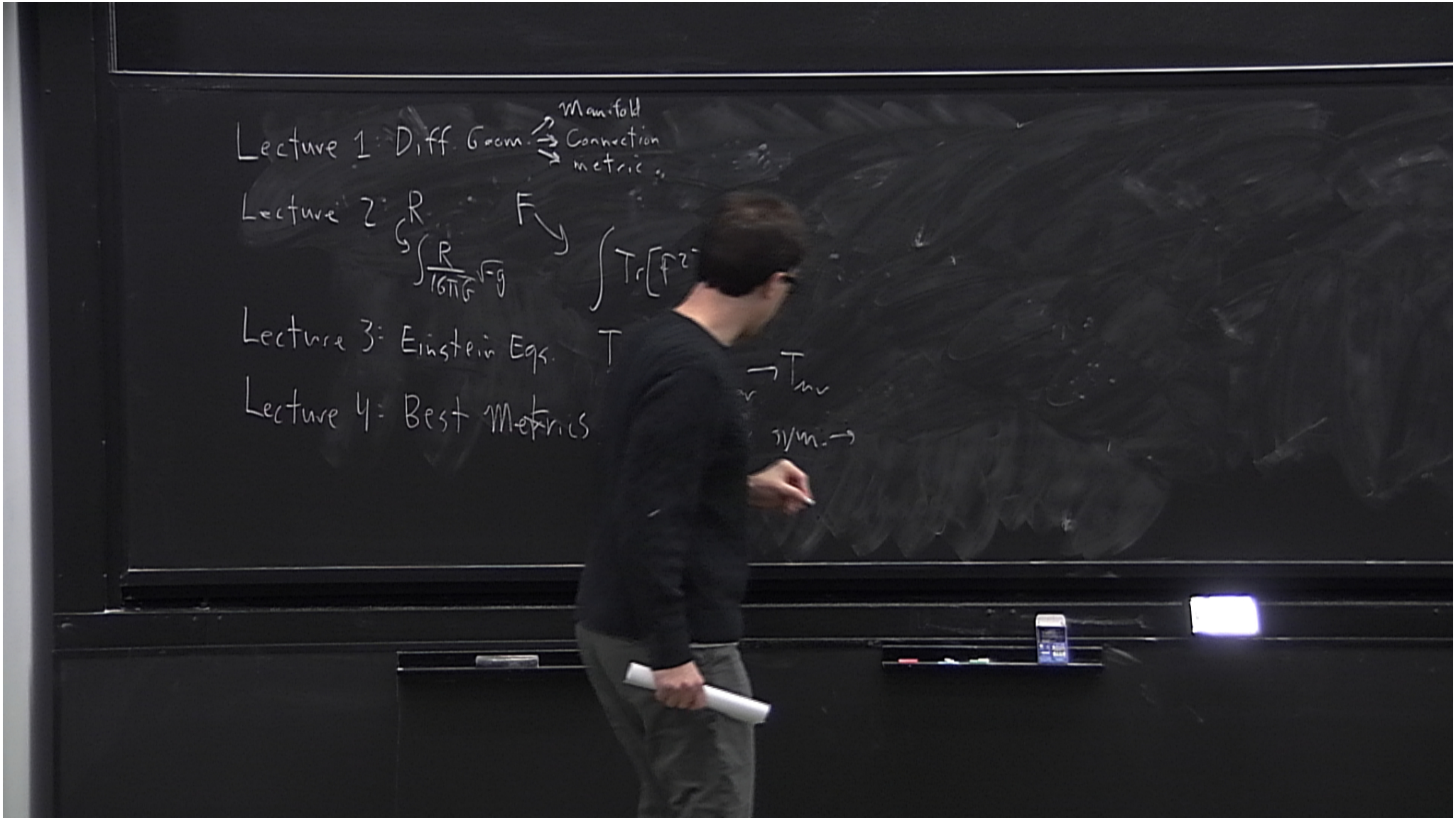
Title: Cosmology (Review) - Lecture 10

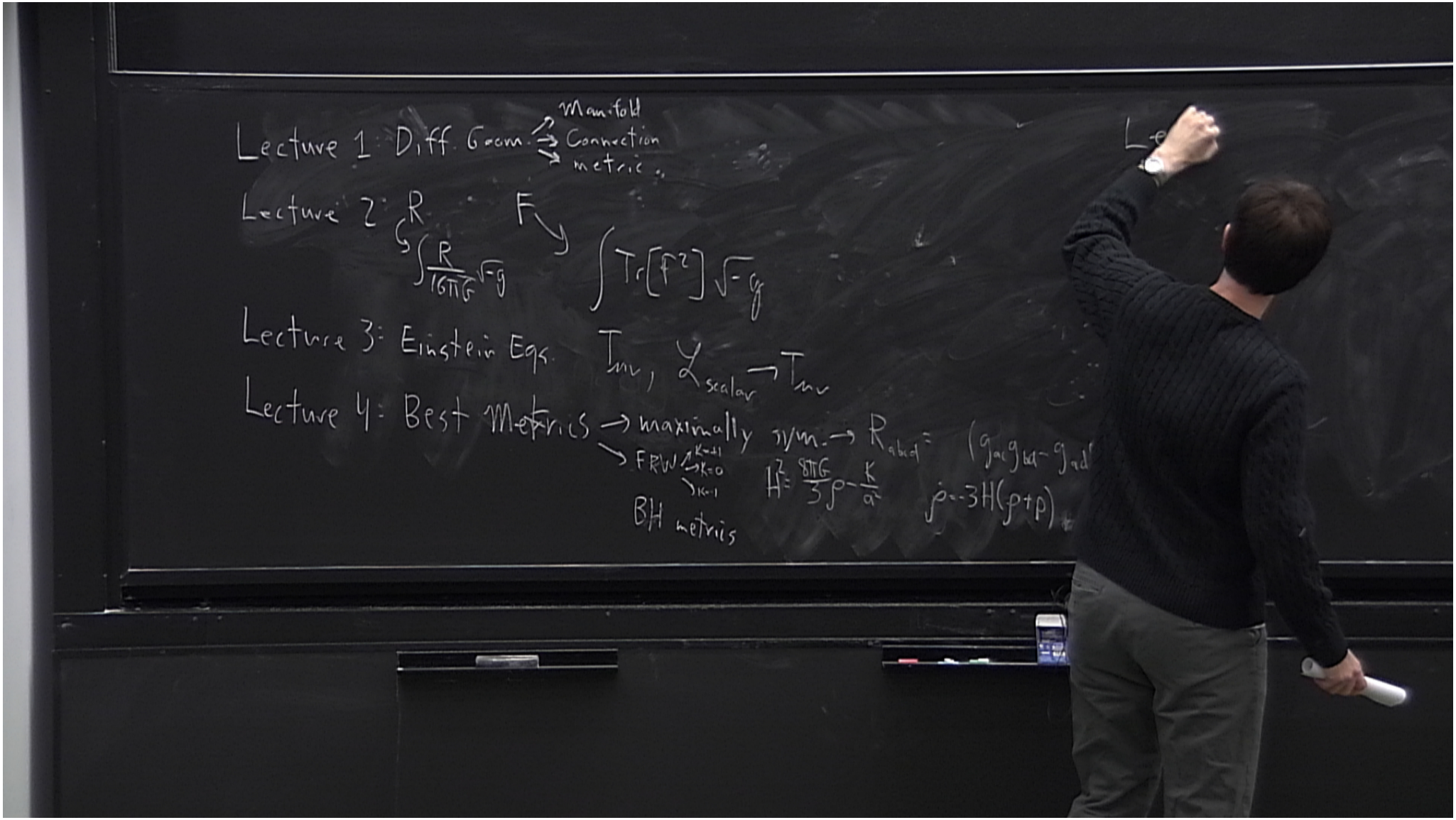
Date: Feb 06, 2012 11:30 AM

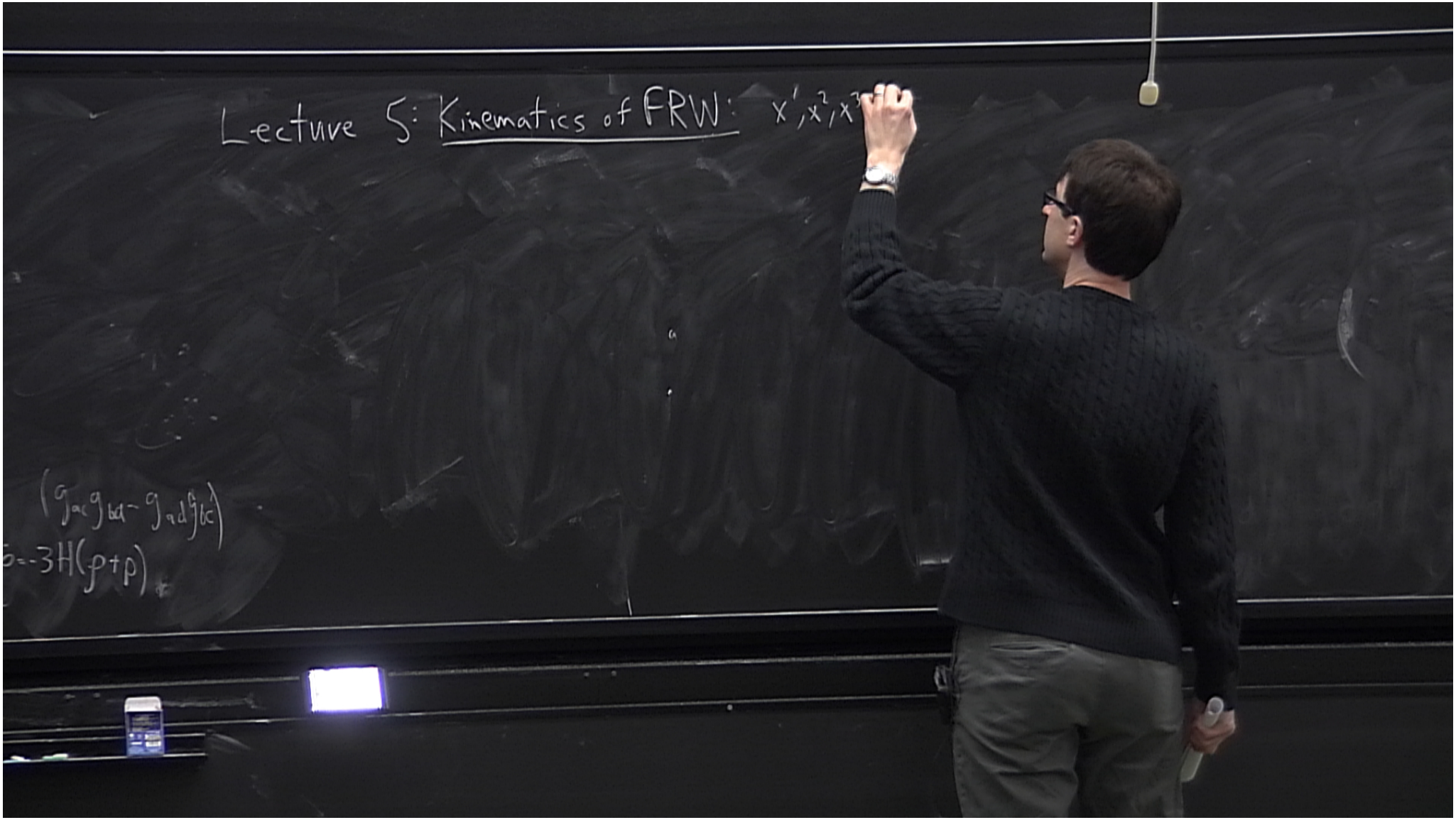
URL: http://pirsa.org/12020025

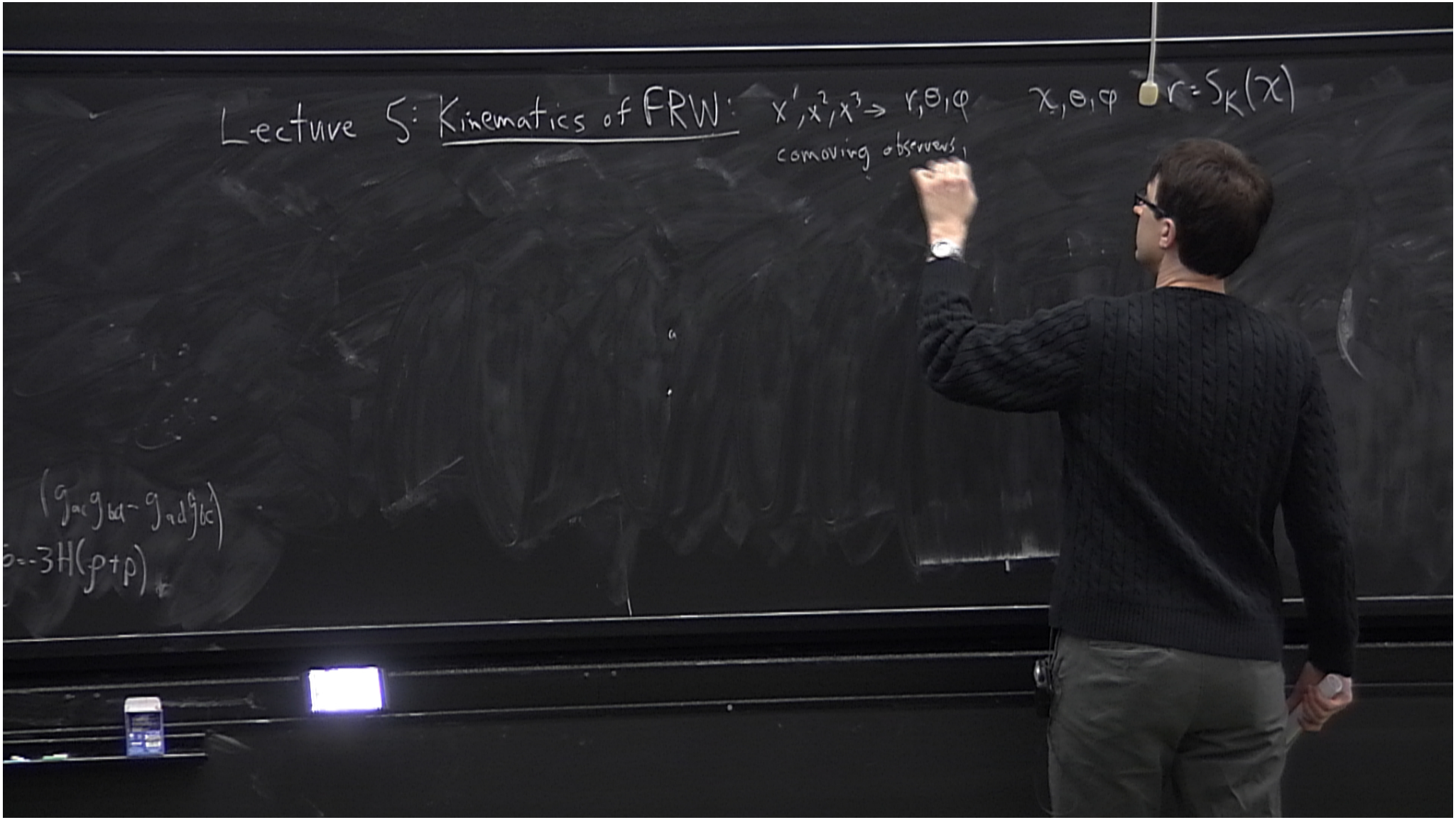
Abstract:

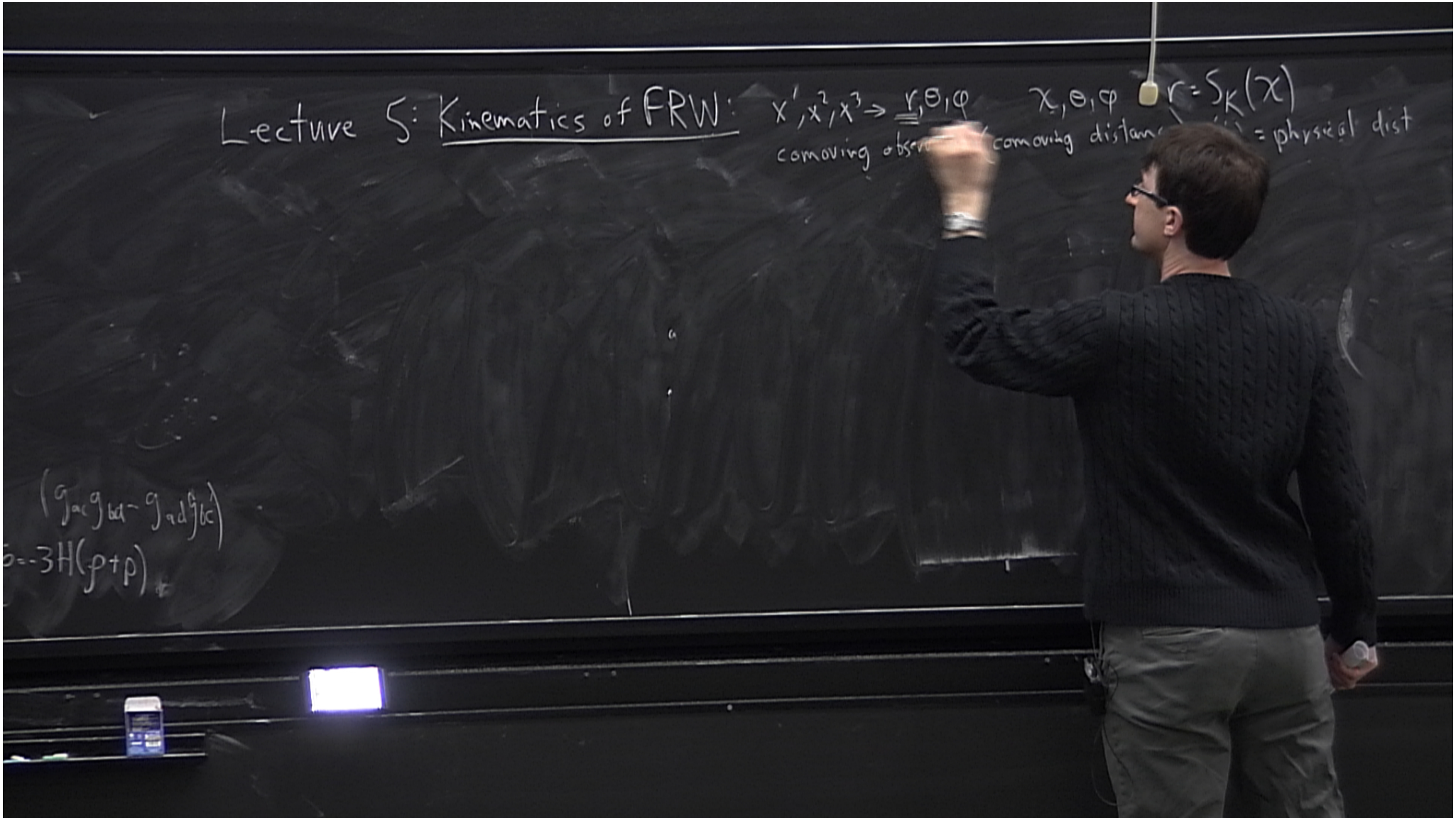

Lecture 1: Diff. Geom.
Manifold
Connection
metric
Lecture 2: R
F
Lecture 3: Einstein Eq


Lecture 1: Diff. Geom. → Manifold, Connection, metric
Lecture 2: R, F
$\int \frac{R}{16\pi G}\sqrt{-g}$
$\int \mathrm{Tr}[F^2$
Lecture 3: Einstein Eqs. T
$\rightarrow T_{\mu\nu}$
Lecture 4: Best Metrics
$\mathfrak{su}/\mathfrak{m} \rightarrow$


Lecture 1: Diff. Geom. → Manifold, Connection, metric
Lecture 2: R → $\int \frac{R}{16\pi G}\sqrt{-g}$
F → $\int \mathrm{Tr}[F^2]\sqrt{-g}$
Lecture 3: Einstein Eqs. $T_{\mu\nu}$, $\mathcal{L}_{scalar} \to T_{\mu\nu}$
Lecture 4: Best Metrics → maximally
→ FRW (K=+1, K=0, K=-1)
BH metrics
sym. → $R_{abcd} = (g_{ac}g_{bd} - g_{ad}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
$\dot{\rho} = -3H(\rho + p)$


Lecture 5: Kinematics of FRW: x^1, x^2, x^3
$(g_{ac}g_{bd} - g_{ad}g_{bc})$
$\dot{\rho} = -3H(\rho + p)$


Lecture 5: Kinematics of FRW: $x^1, x^2, x^3 \to r, \theta, \varphi$ χ, θ, φ $r = S_K(\chi)$
comoving observers
$\dot{\rho} = -3H(\rho + p)$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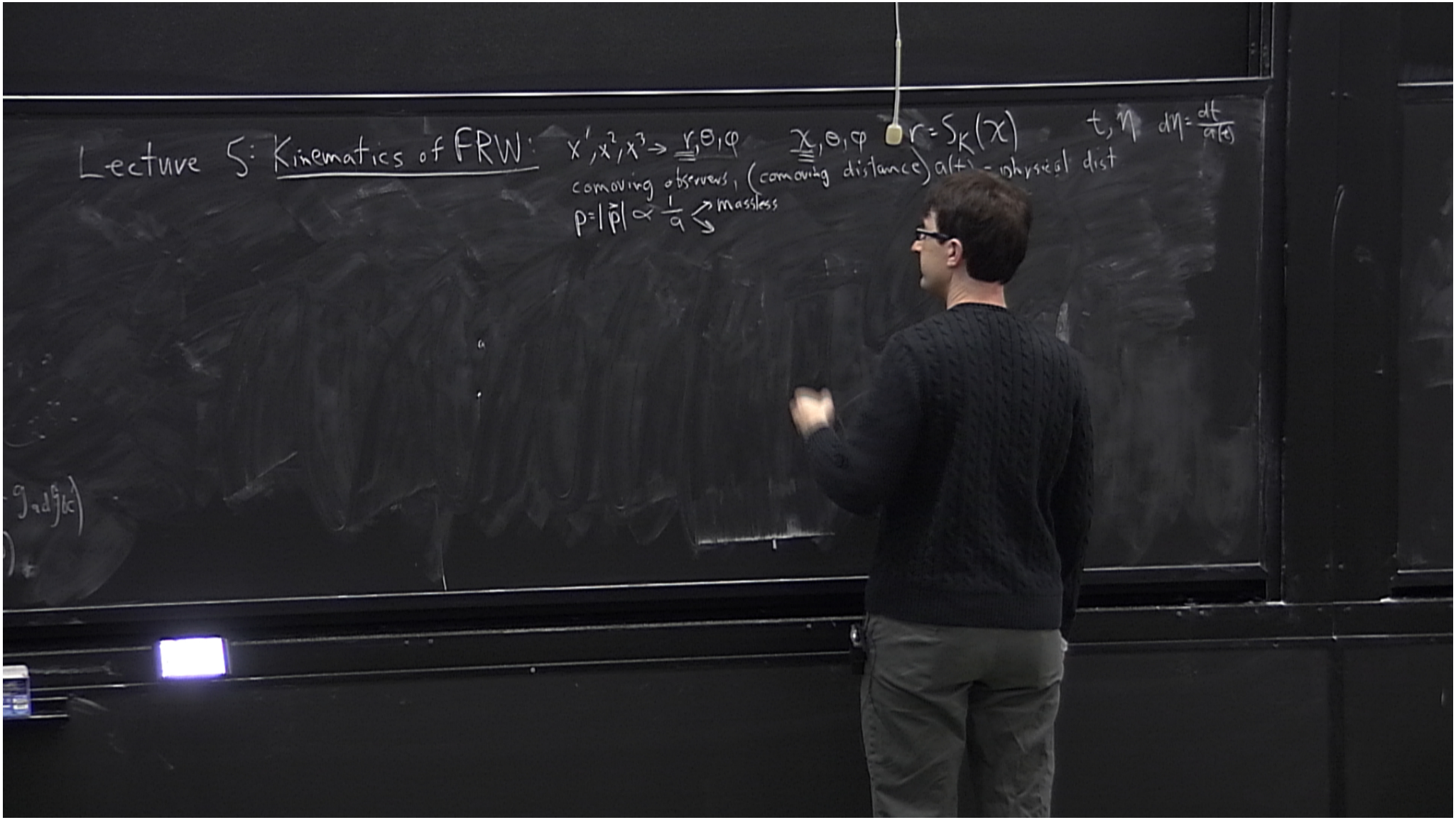
comoving
comoving distance
= physical dist
$\dot{\rho} = -3H(\rho + p)$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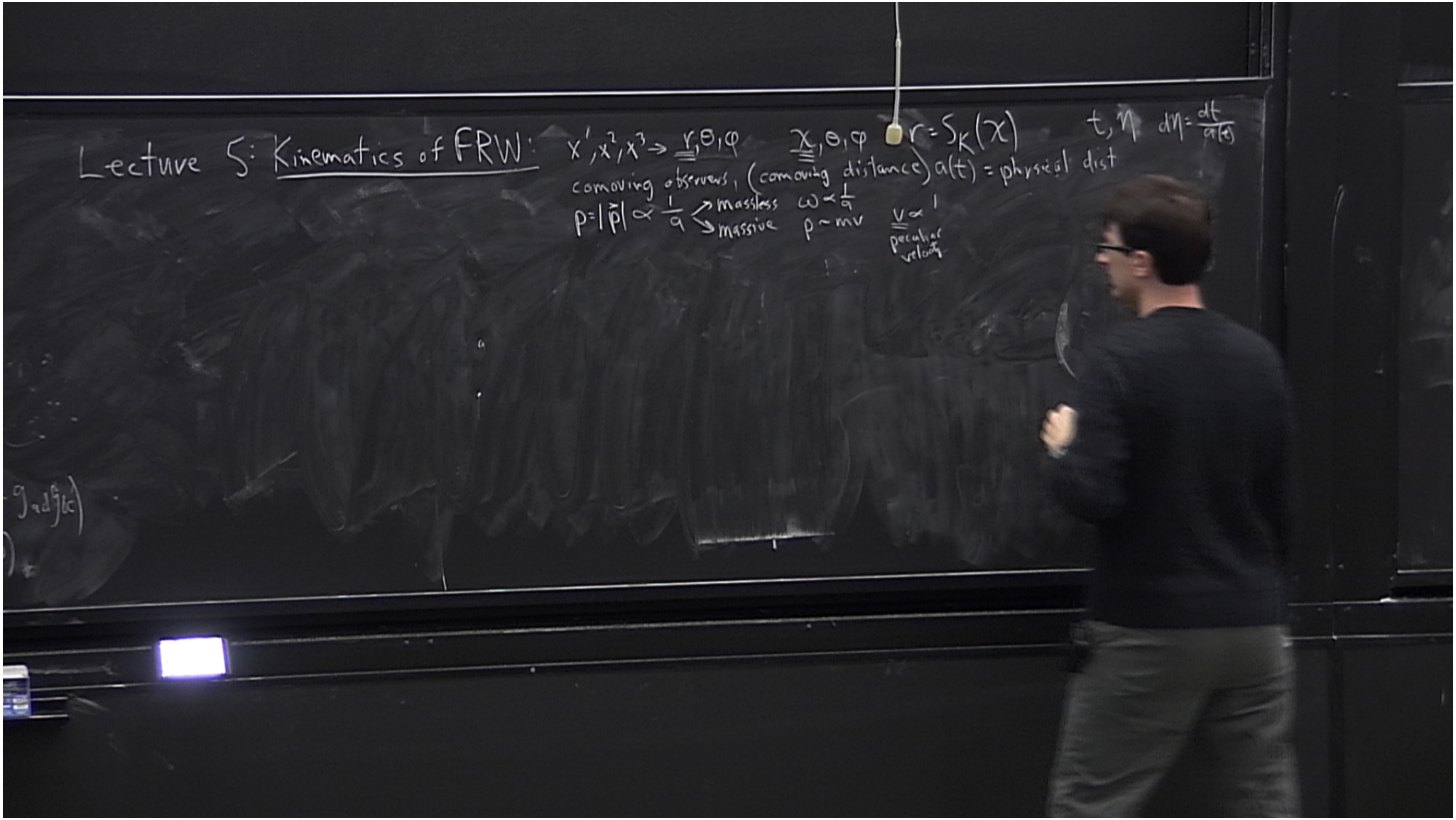
$x^1, x^2, x^3 \to r, \theta, \varphi$
χ, θ, φ
$r = S_K(\chi)$
t, η
$d\eta = \frac{dt}{a(t)}$
comoving observers, (comoving distance) $a(t)$ - physical dist
$p = |\vec{p}| \propto \frac{1}{a}$
massless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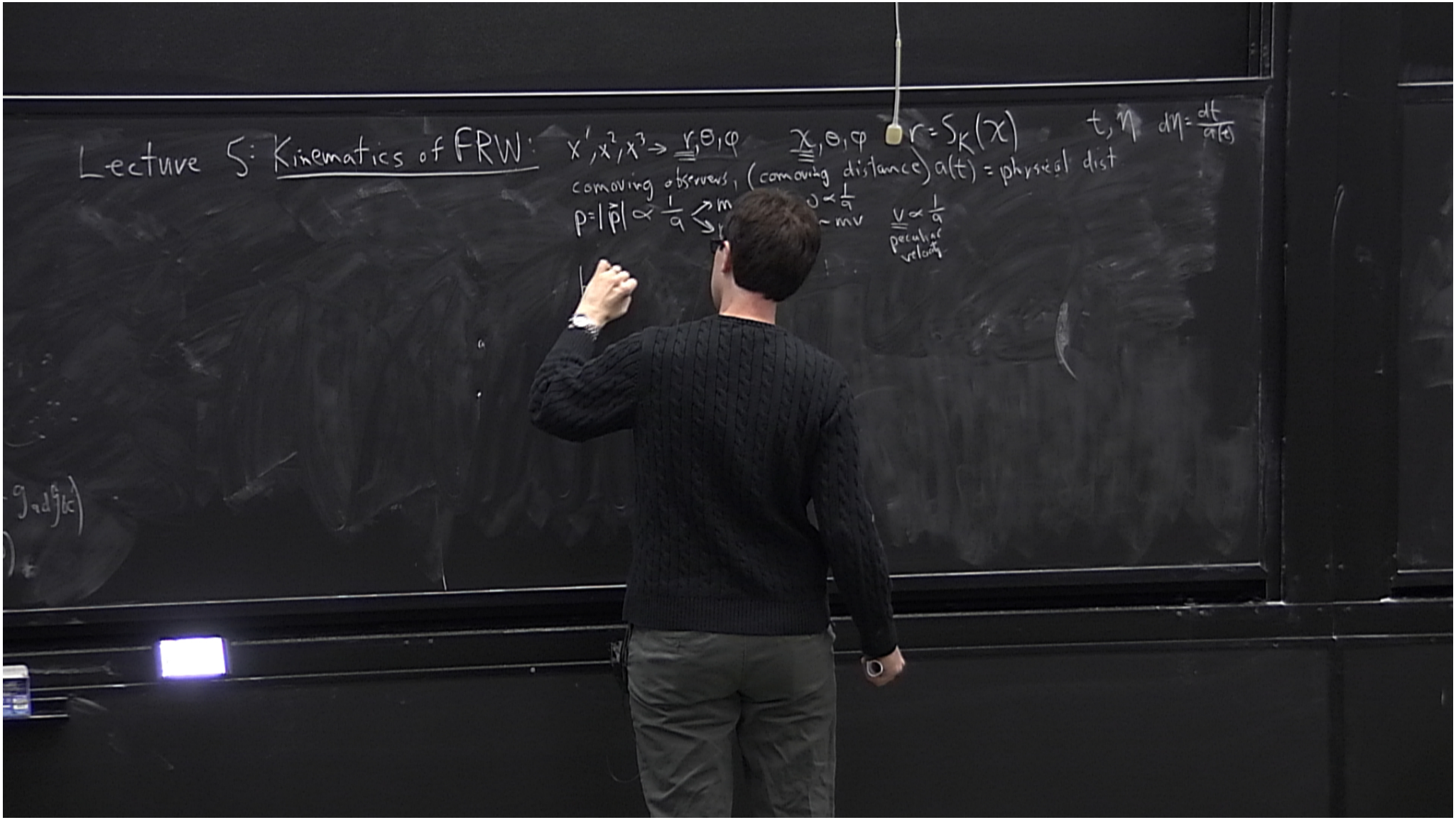
comoving observers, (comoving distance) $a(t)$ = physical dist
$p = |\vec{p}| \propto \frac{1}{a}$
massless $\omega \propto \frac{1}{a}$
massive $p \sim mv$
$v \propto \frac{1}{a}$
peculiar velocity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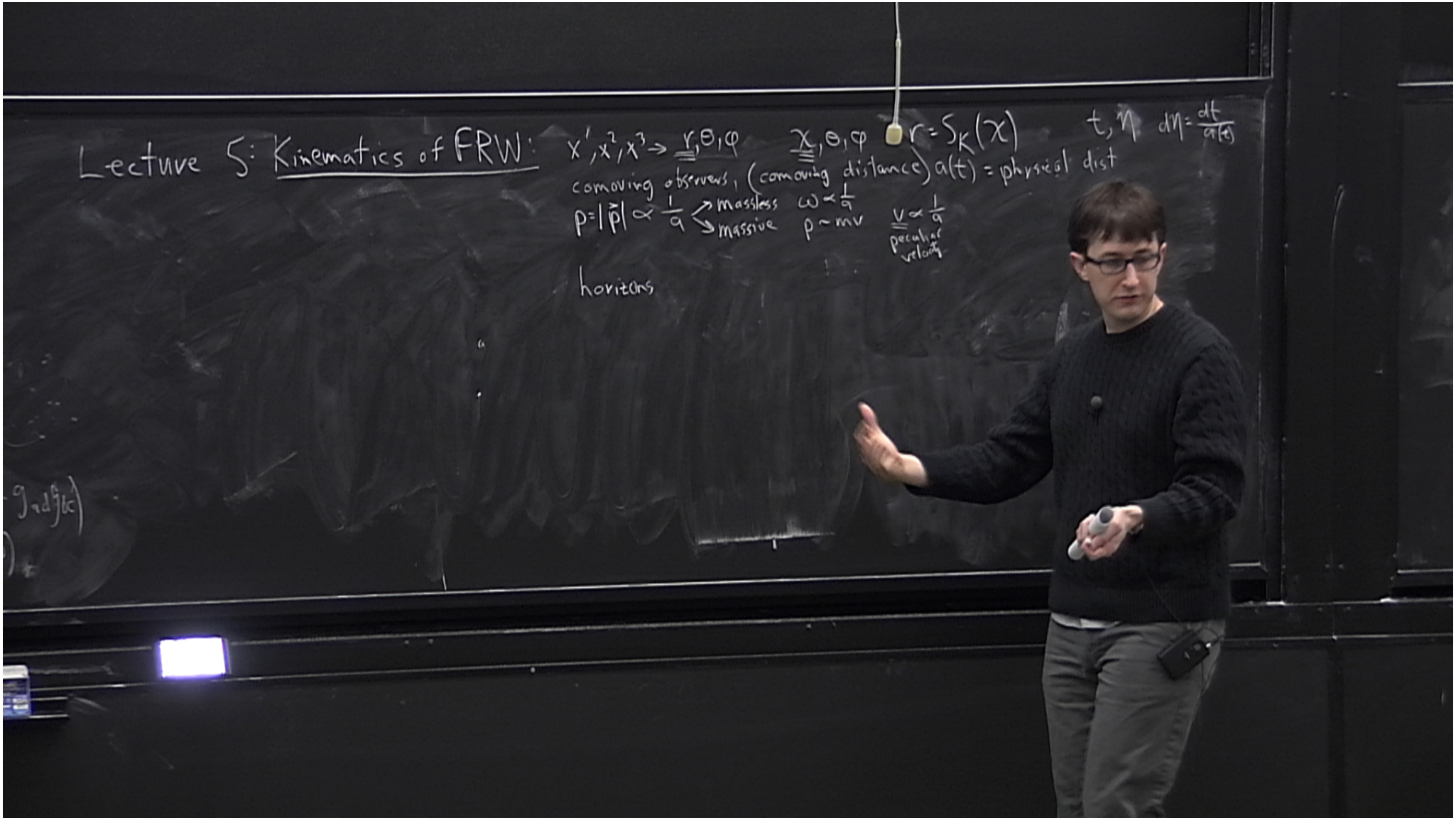
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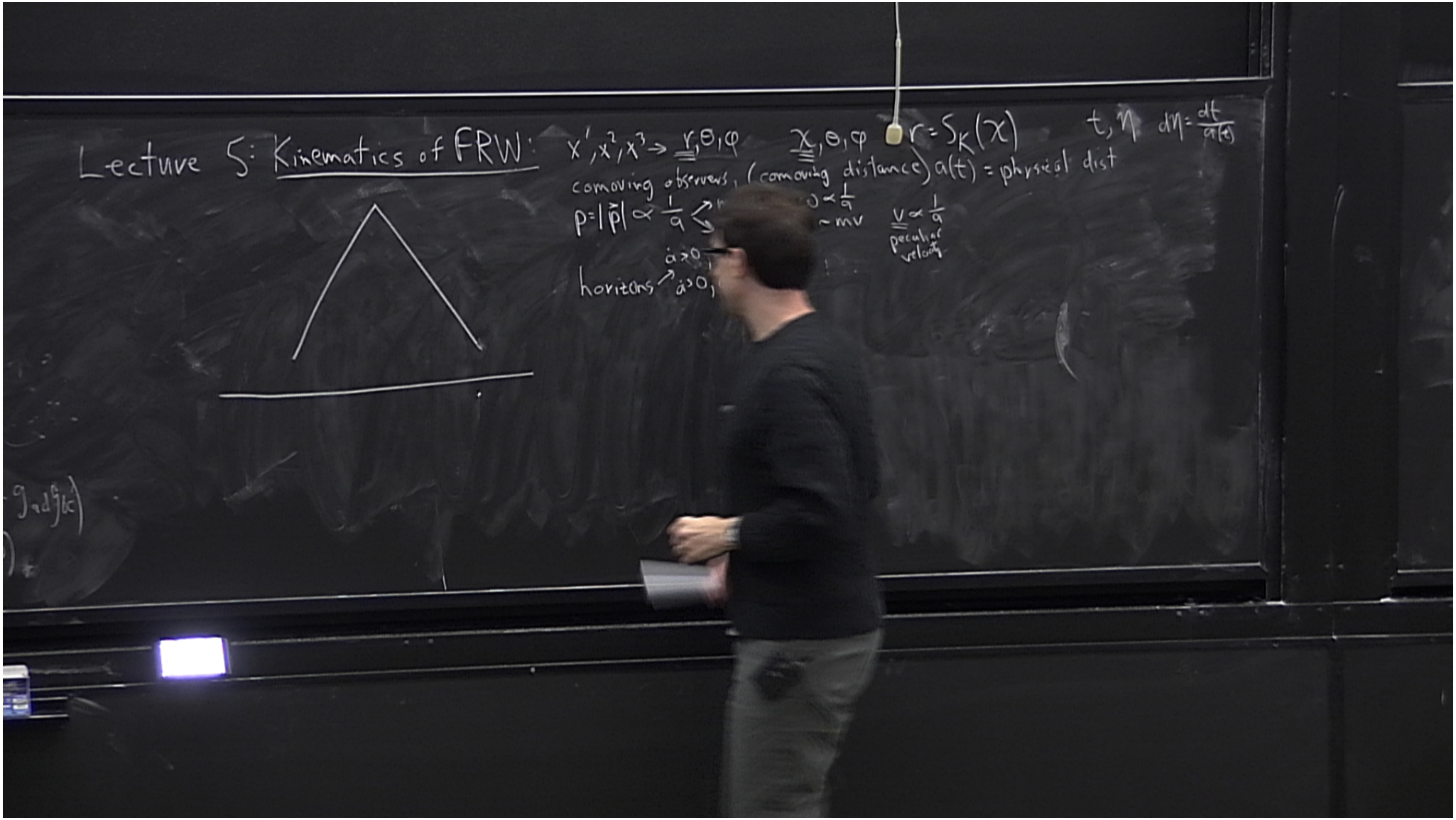
peculiar velocity
horizons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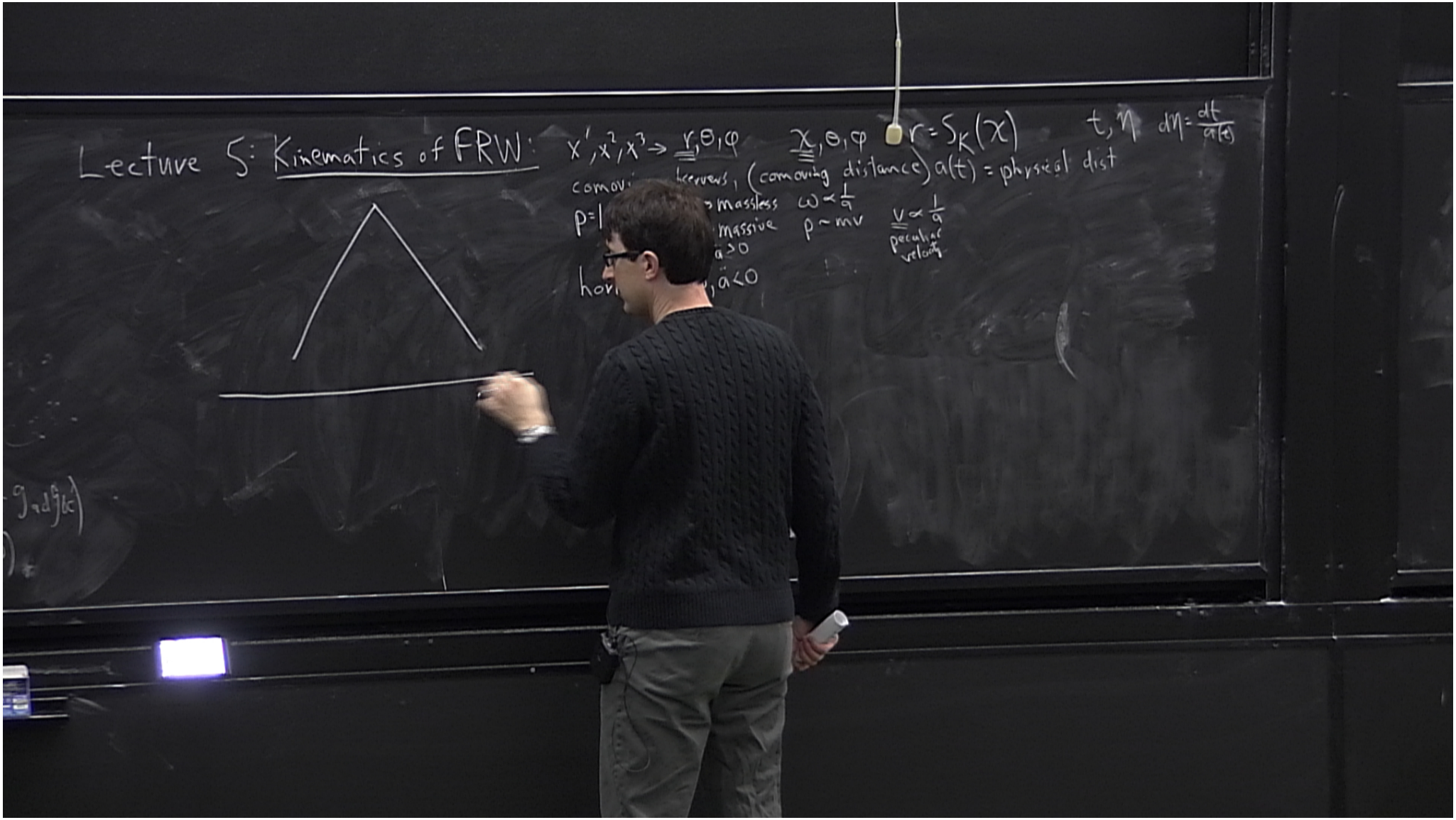
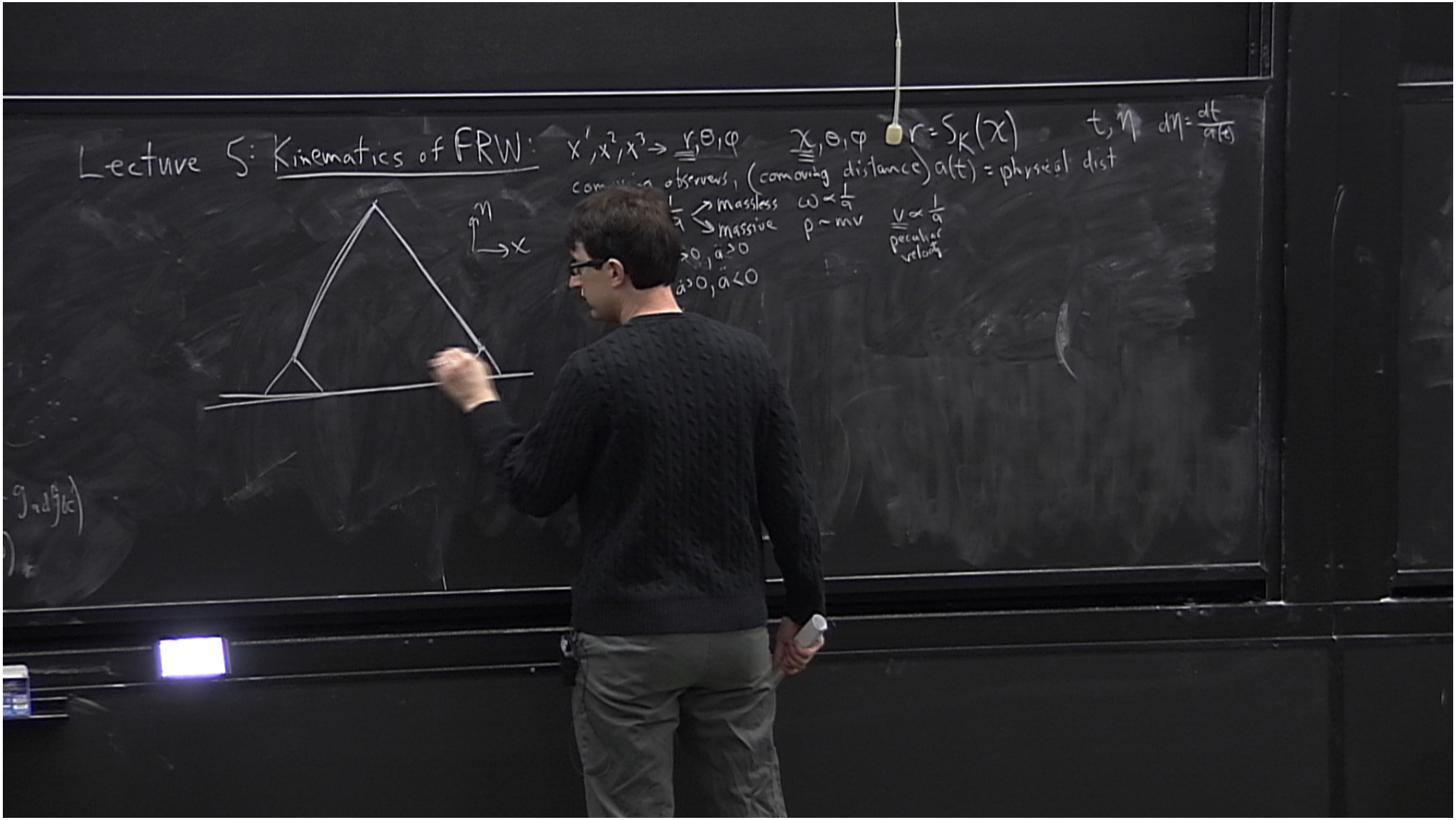
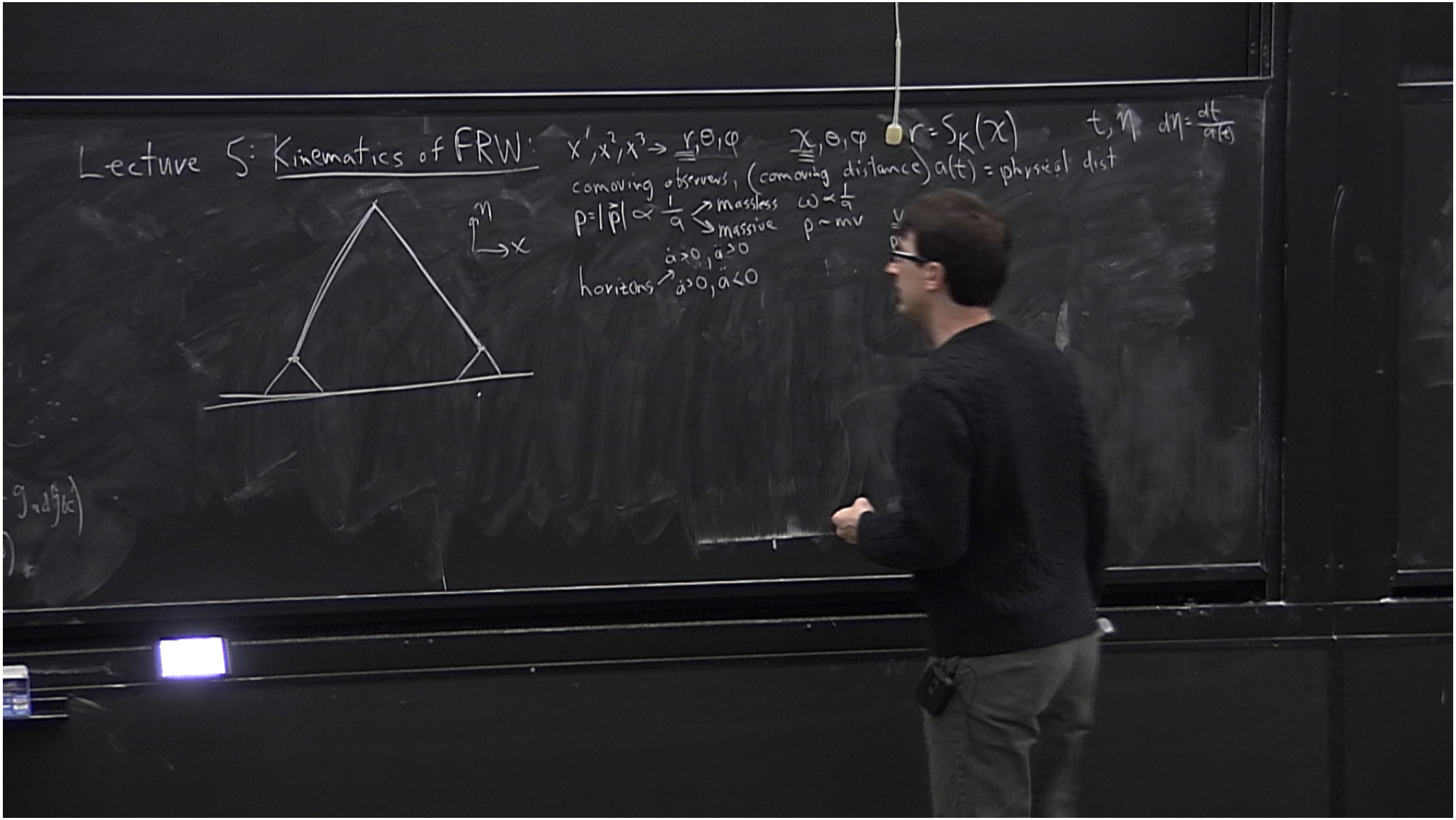
$v \propto \frac{1}{a}$
peculiar velocity
$\sim mv$
horizons
$\dot{a} > 0$,
$\ddot{a} > 0$,


Lecture 5: Kinematics of FRW
massless
massive
p ~ mv
peculiar velocity


Lecture 5: Kinematics of FRW:
x¹, x², x³ → r, θ, φ
χ, θ, φ
r = S_K(χ)
t, η
dη = dt/a(t)
(comoving distance)
a(t) = physical dist
massless
massive
ω ∝ 1/a
p ~ mv
v ∝ 1/a
peculiar velocity
ä > 0, ä > 0
ä > 0, ä < 0
η
x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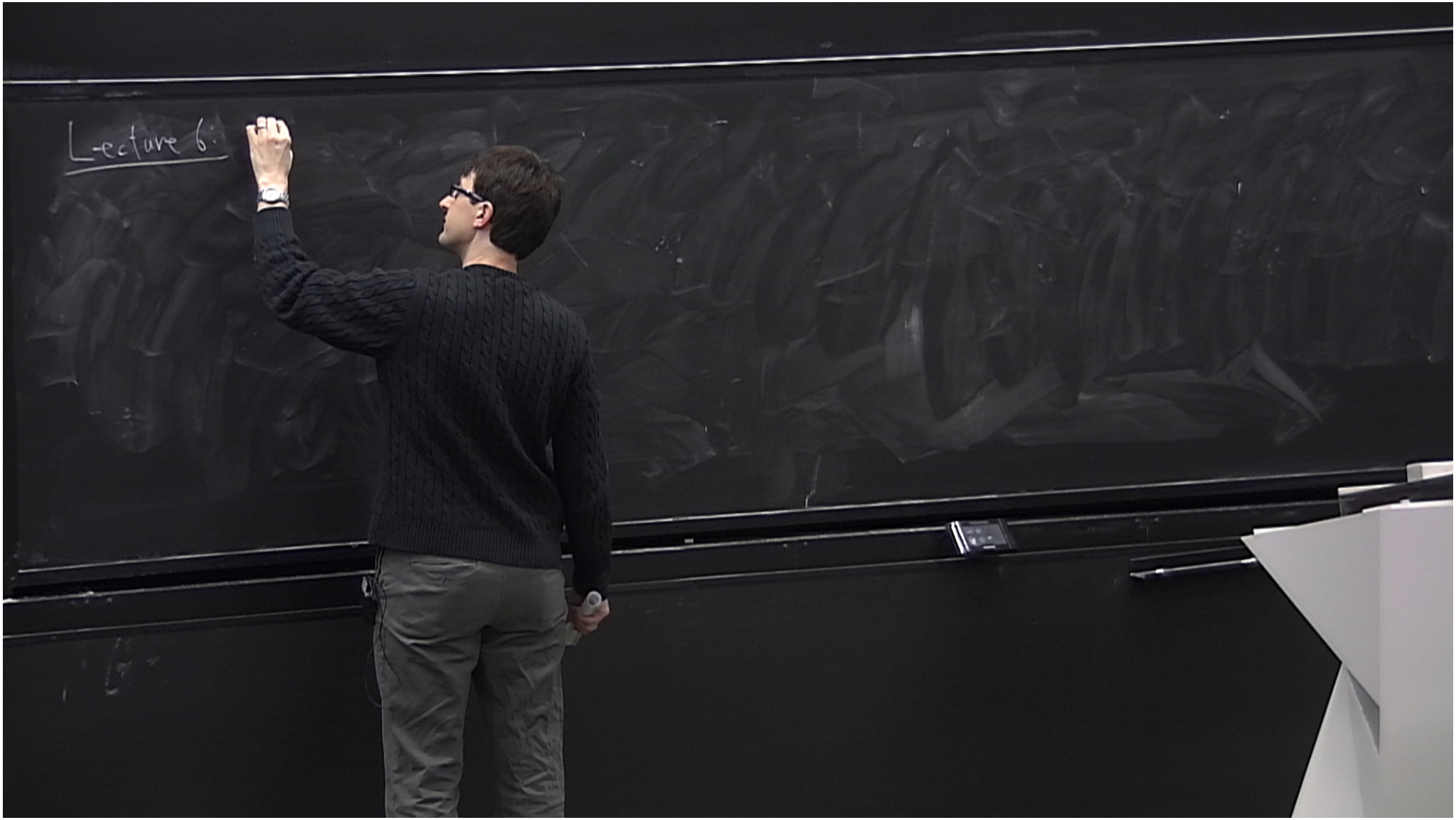
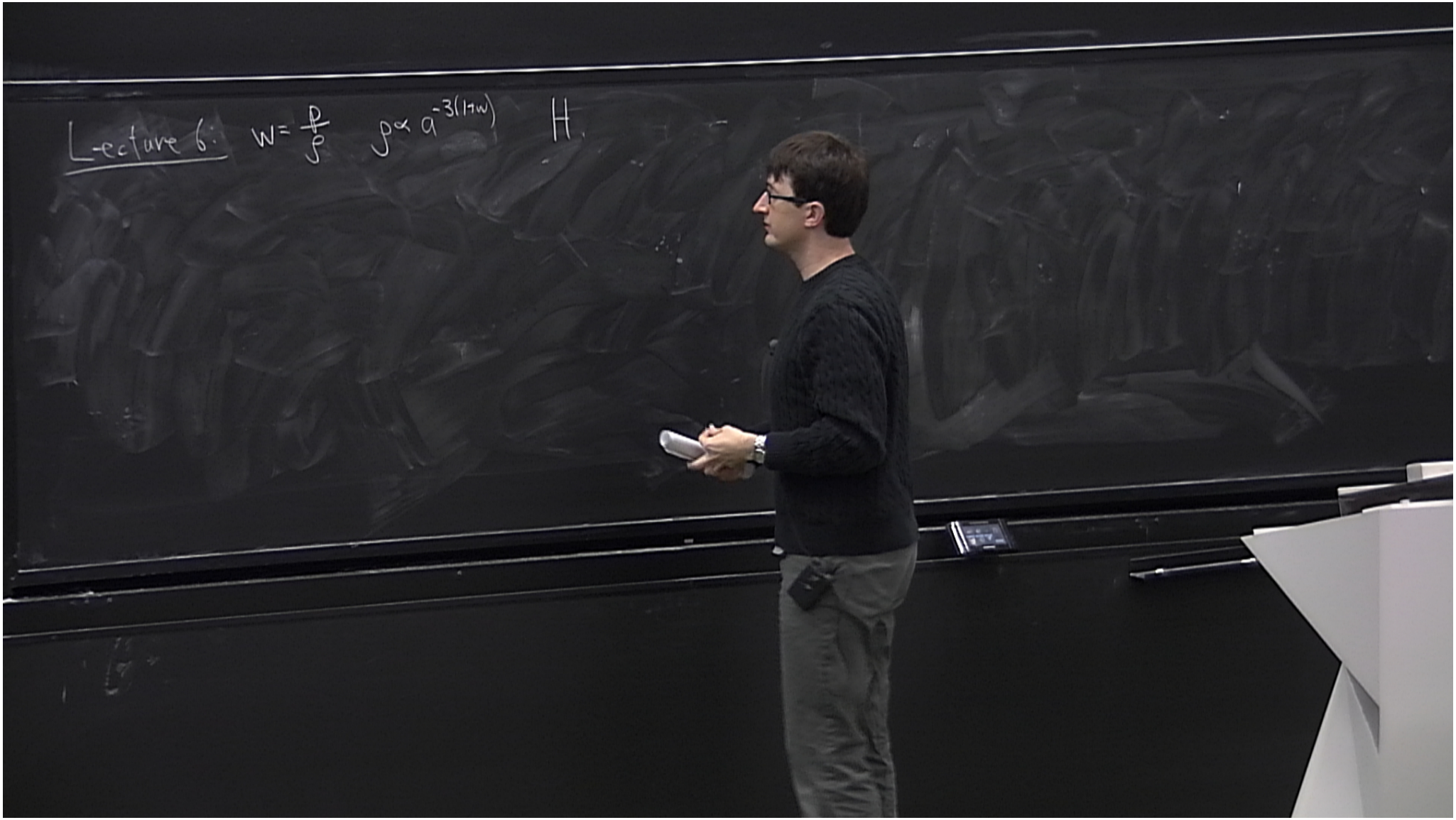
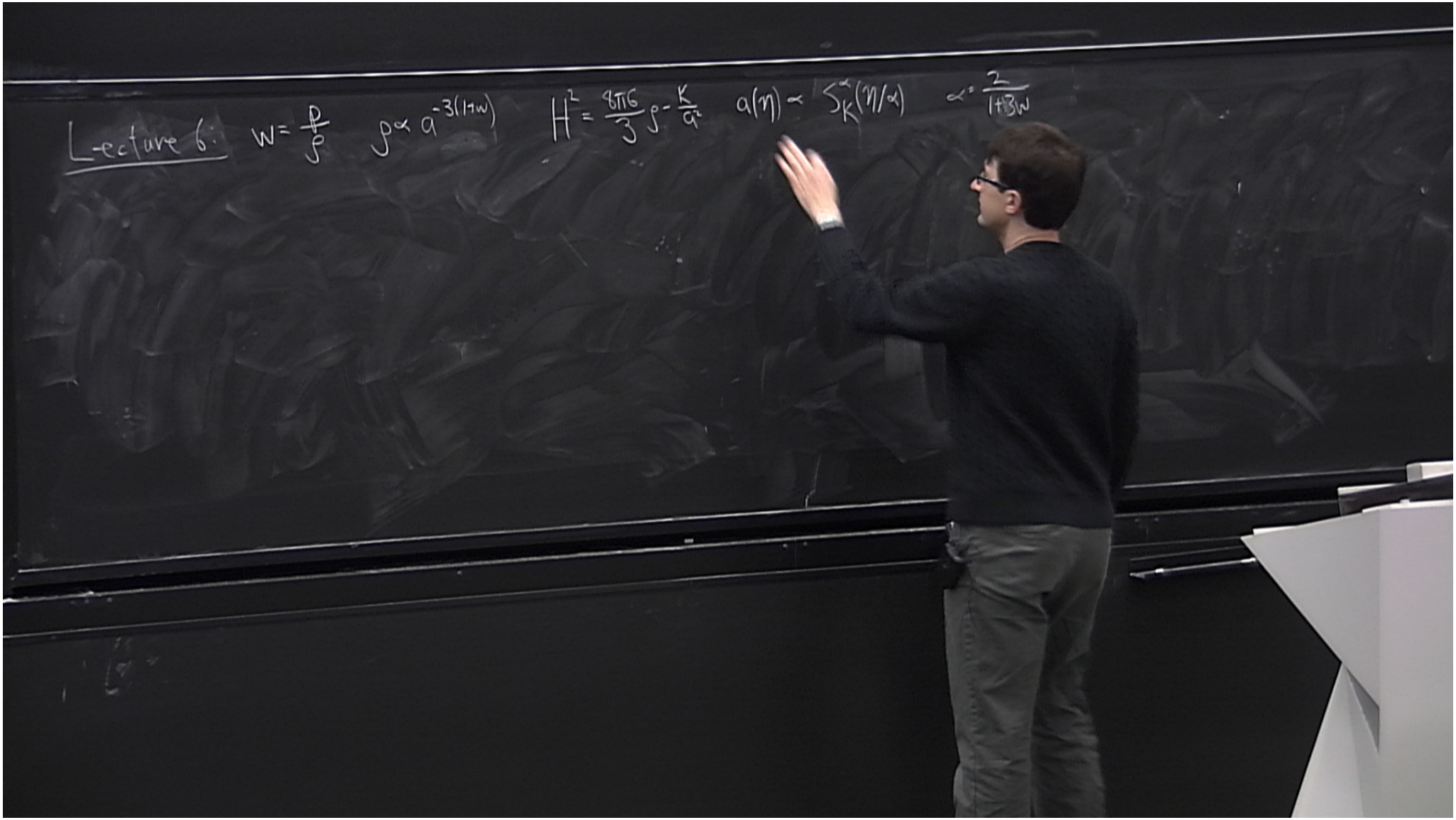
massive $p \sim mv$
$\frac{v}{p}$
horizons
$\dot{a} > 0, \ddot{a} > 0$
$\dot{a} > 0, \ddot{a} < 0$
$\hat{n}$
x


Lecture 6:


Lecture 6: $w = \frac{p}{\rho}$ $\rho \propto a^{-3(1+w)}$ H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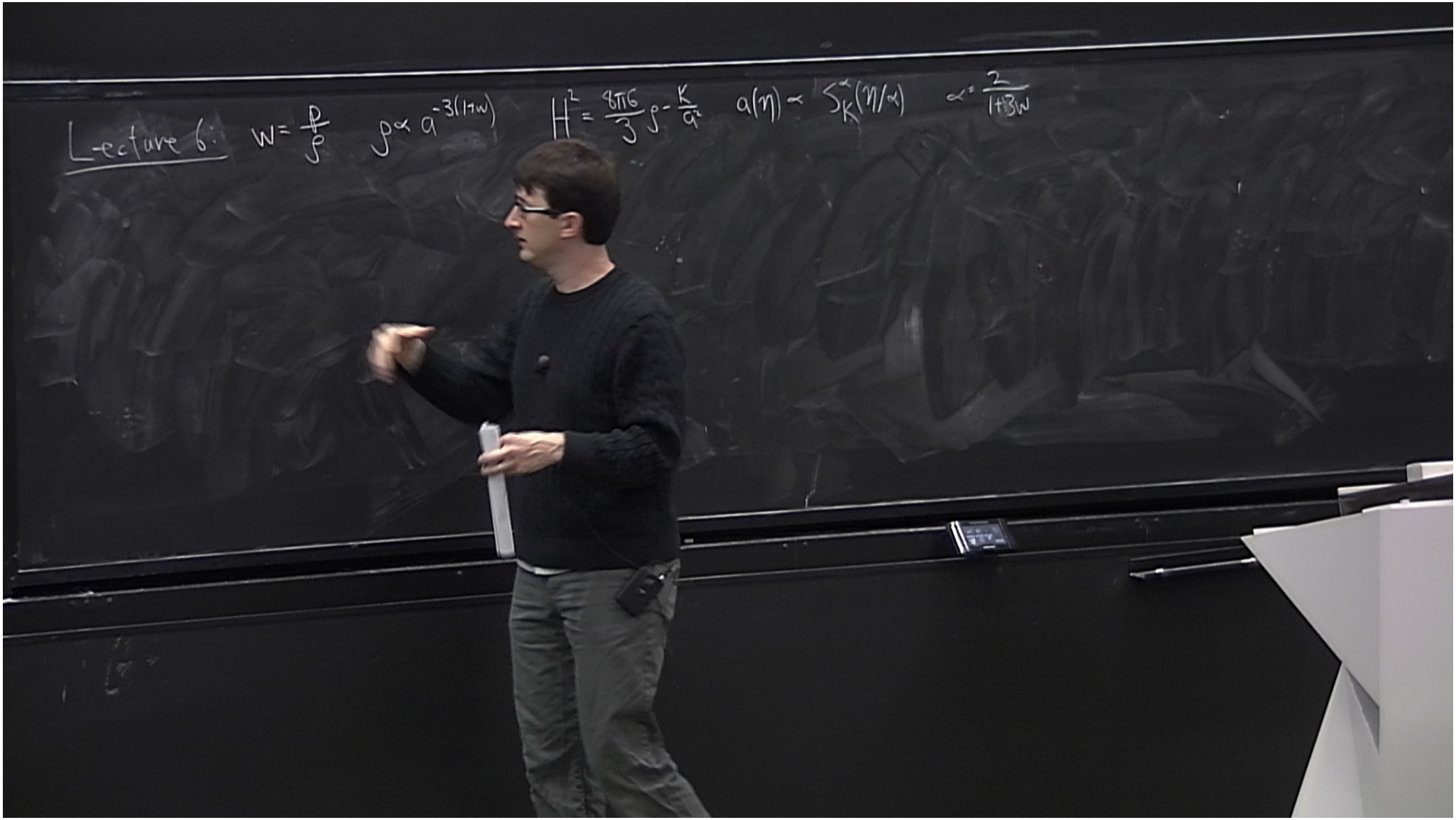
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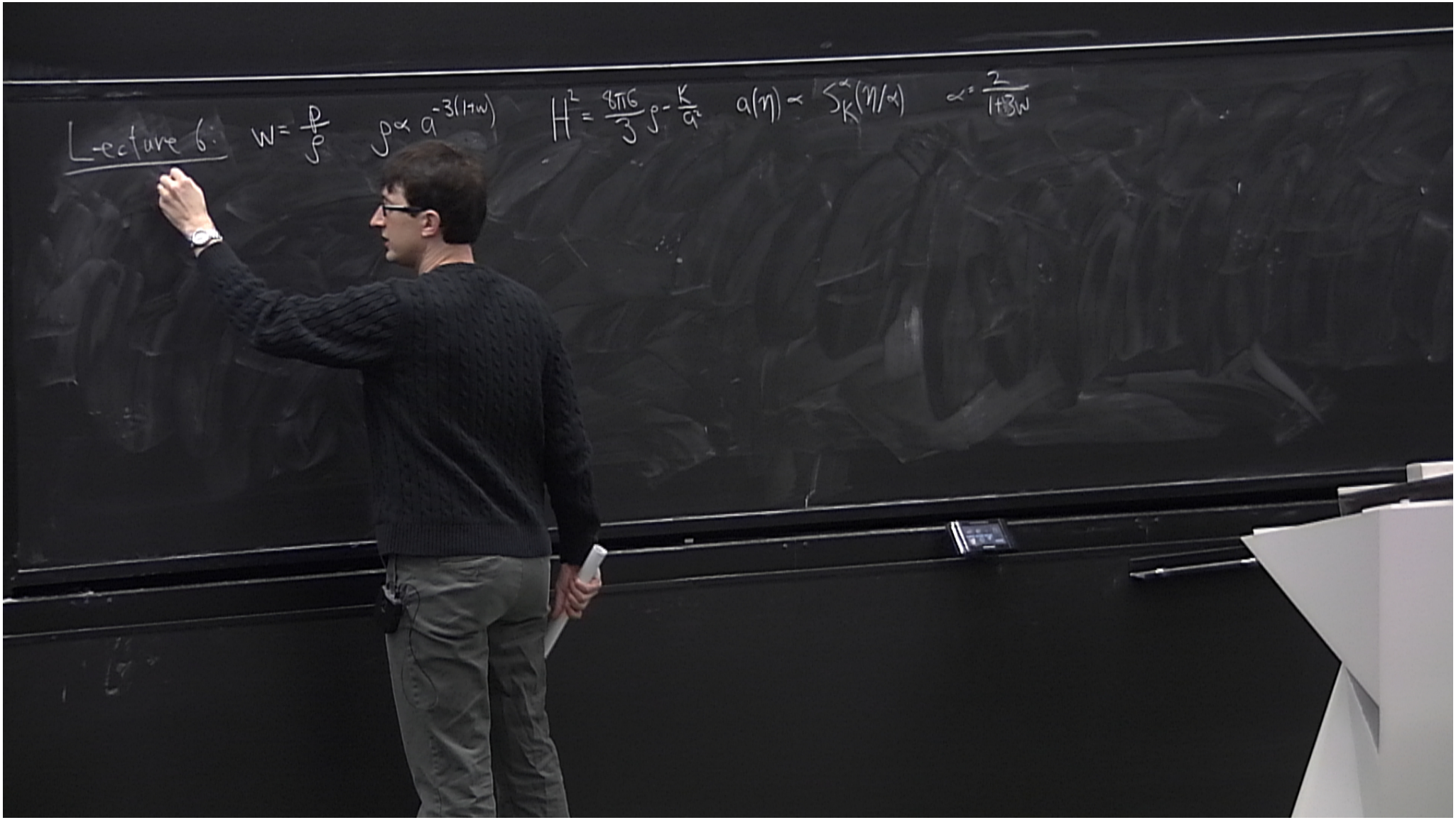
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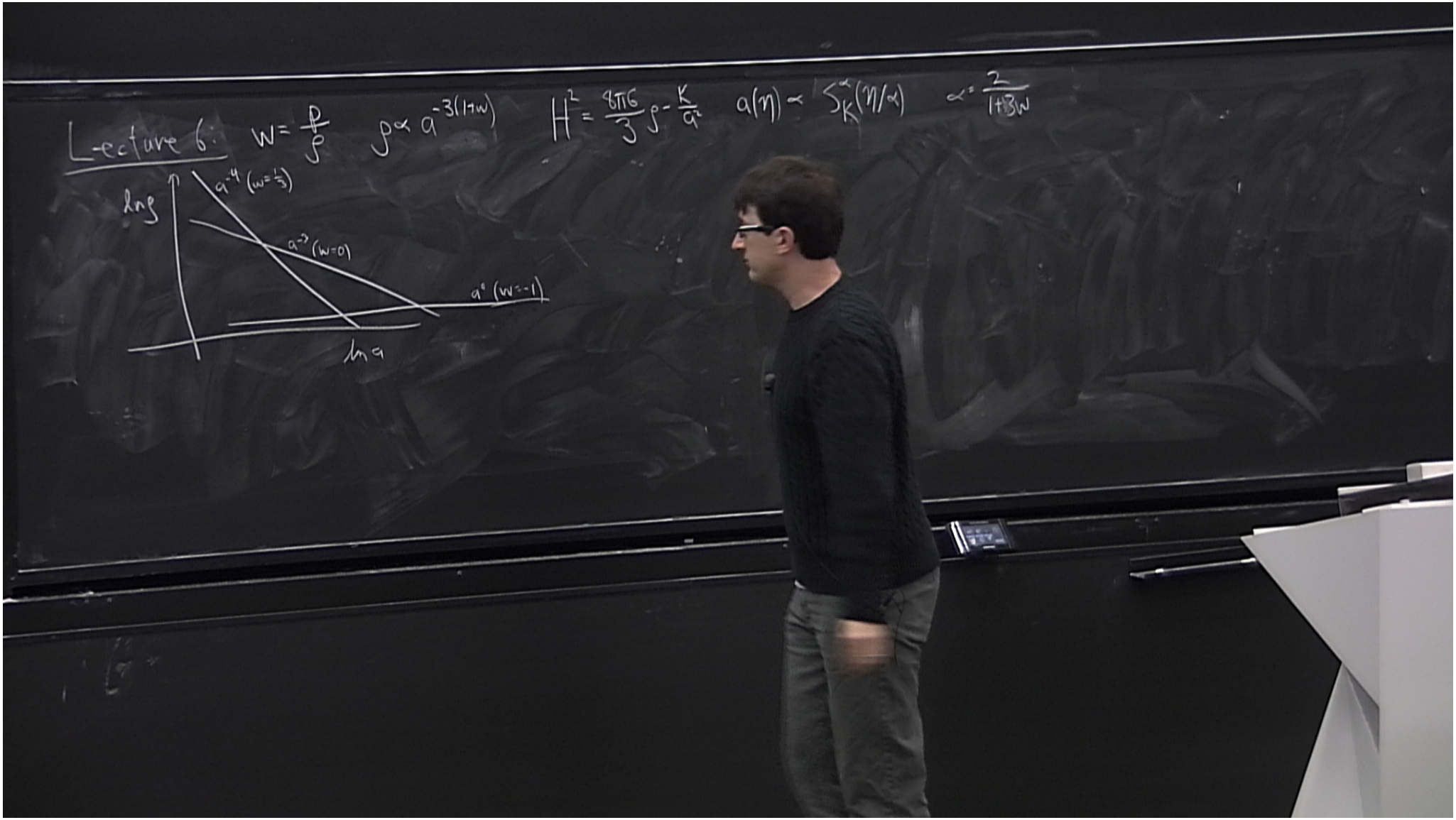
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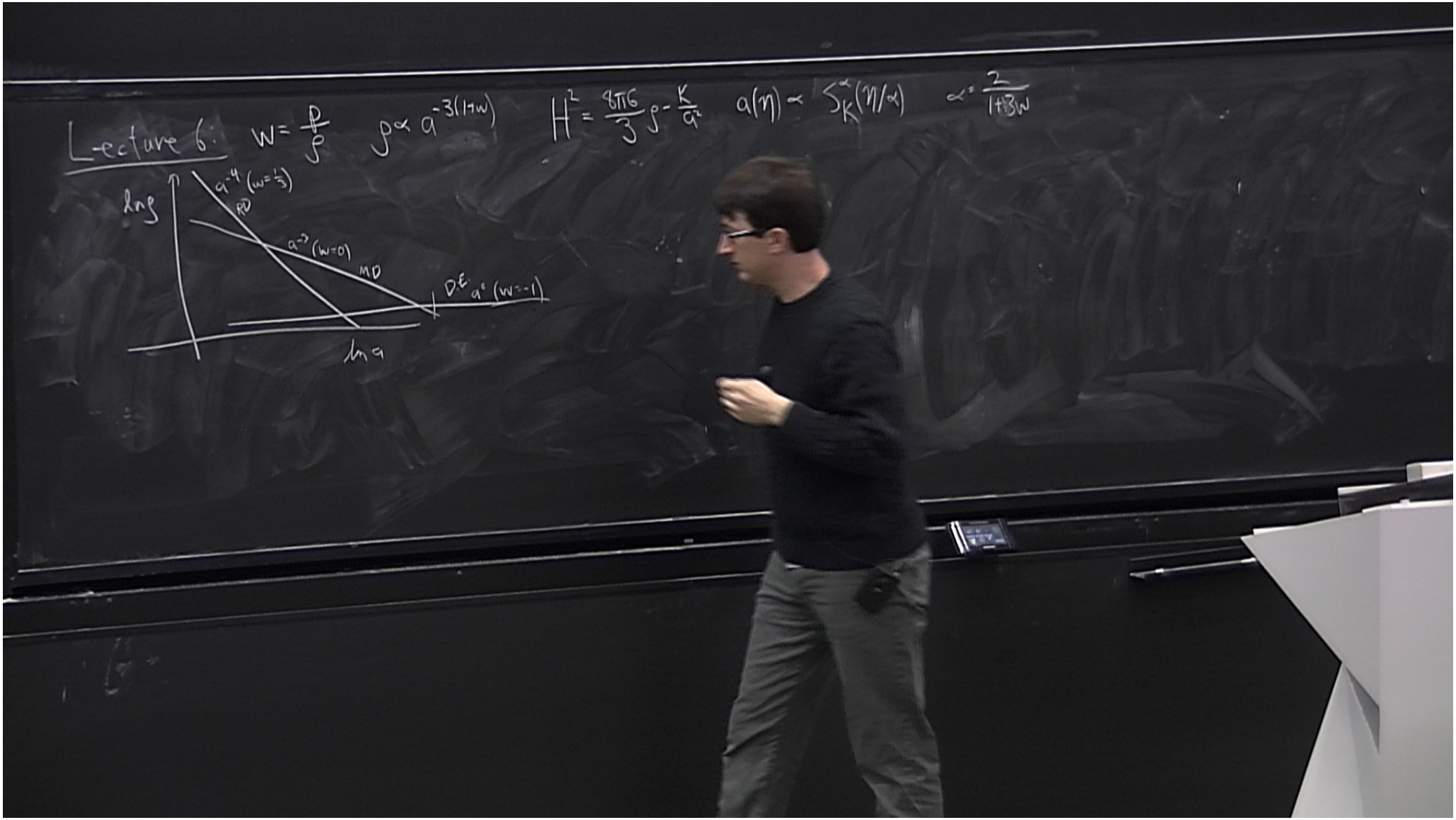
ln ρ
a^{-4} $(w=\frac{1}{3})$
a^{-3} $(w=0)$
a^{0} $(w=-1)$
ln a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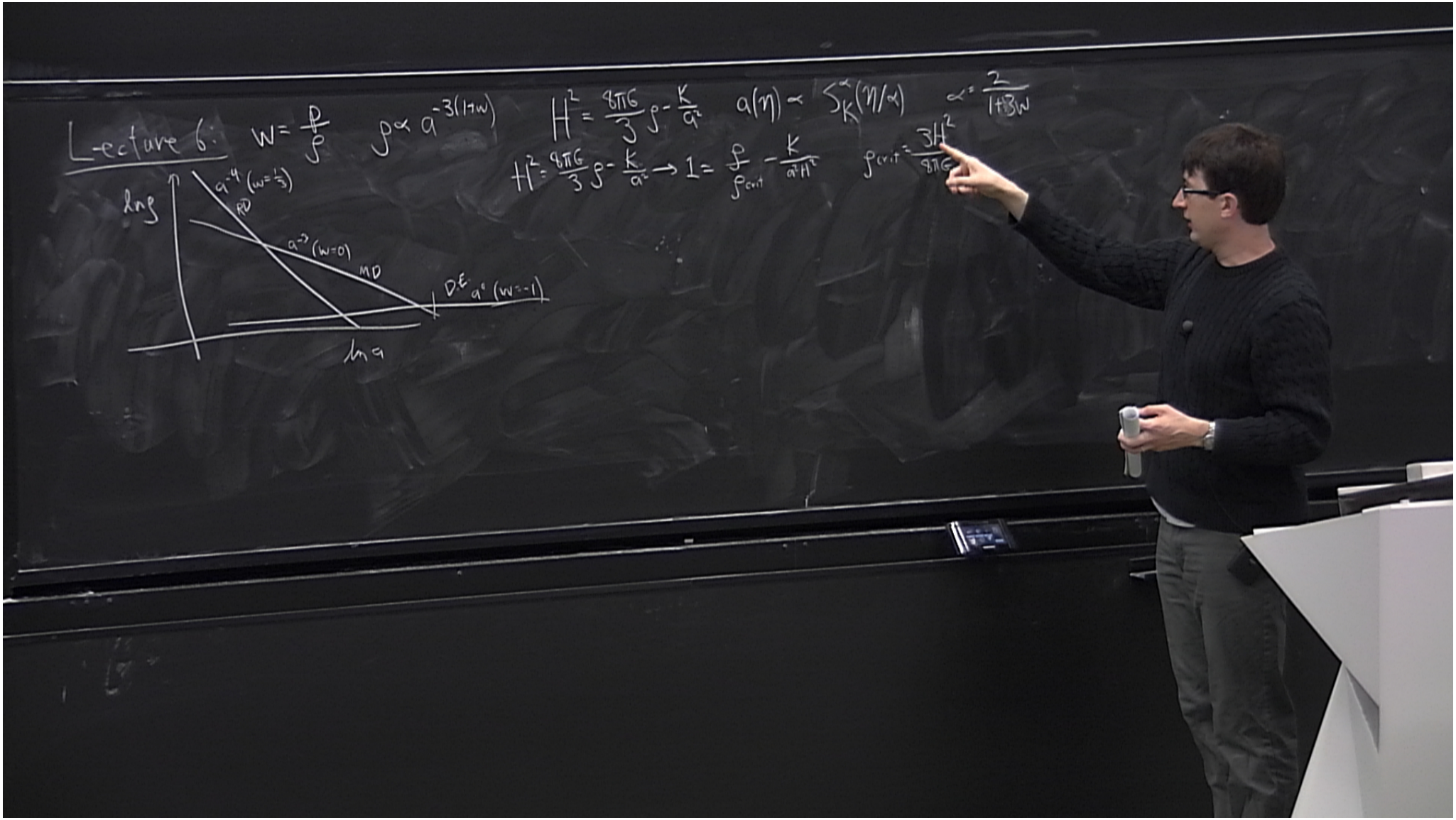
$\alpha = \frac{2}{1+3w}$
ln ρ
a^{-4} $(w=\frac{1}{3})$
RD
a^{-3} $(w=0)$
MD
DE
a^0 $(w=-1)$
ln a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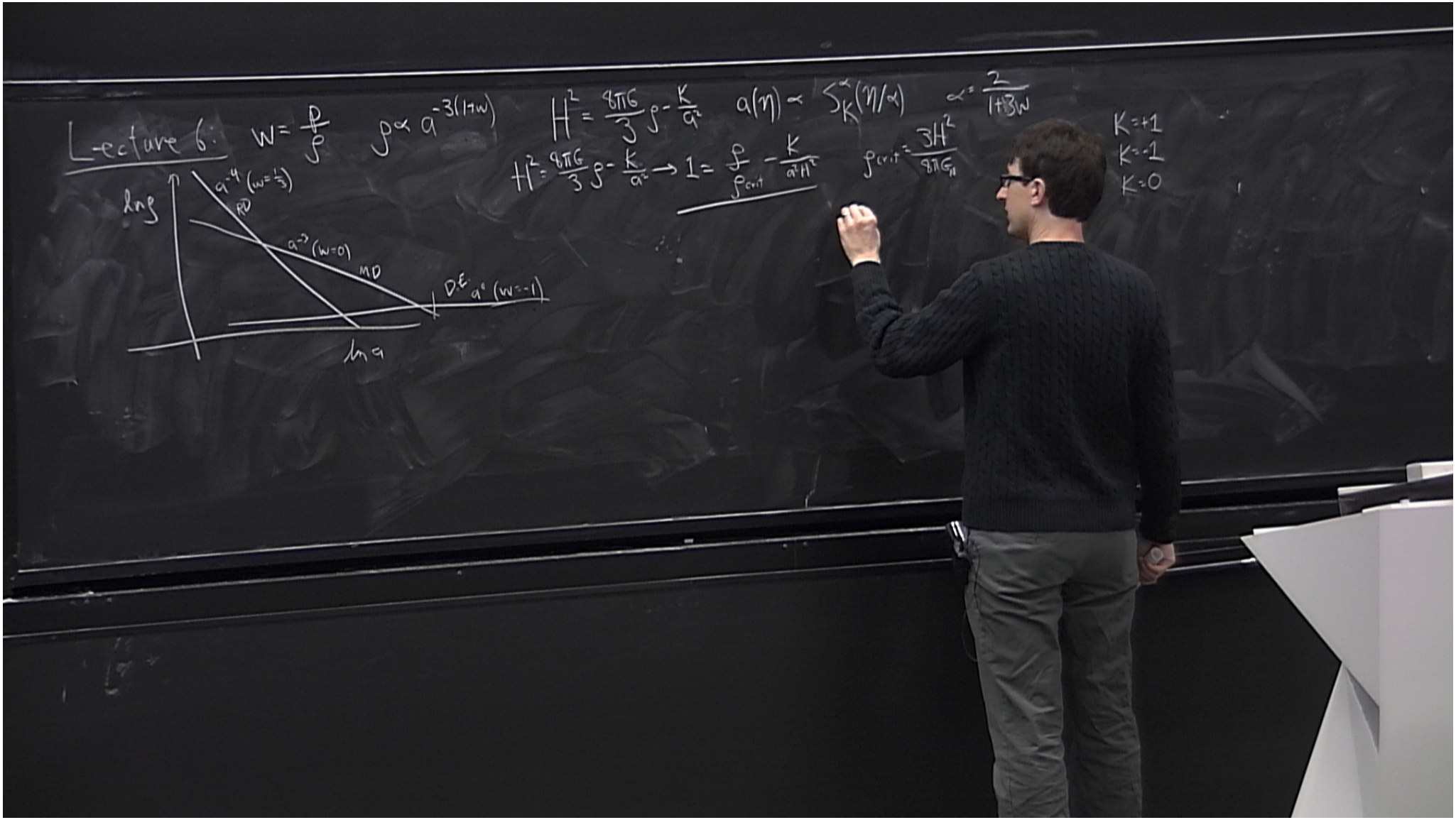
$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G}$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a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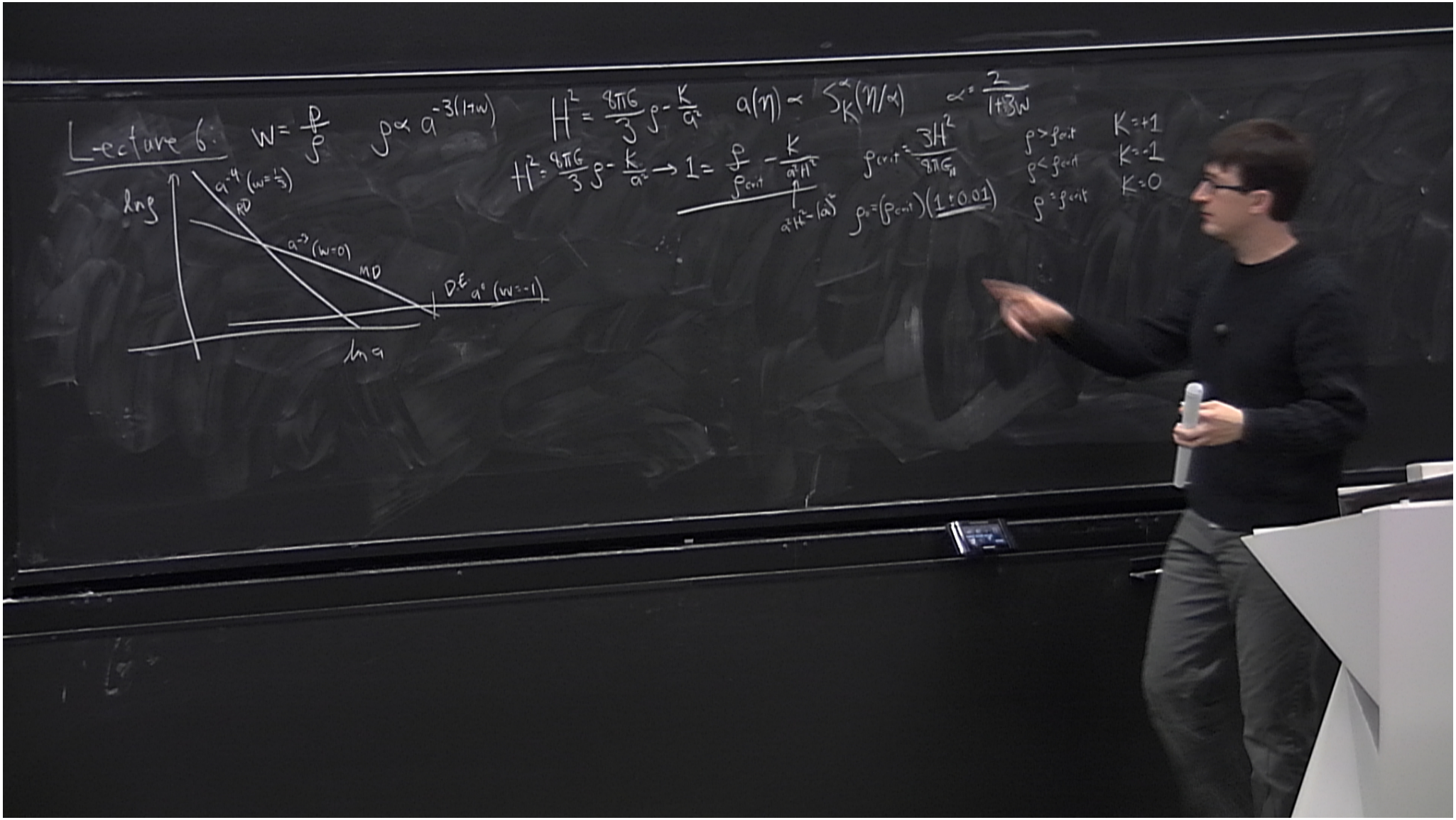
$a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$
$\alpha = \frac{2}{1+3w}$
$1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
K=+1
K=-1
K=0
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
DE a^0 (w=-1)
ln a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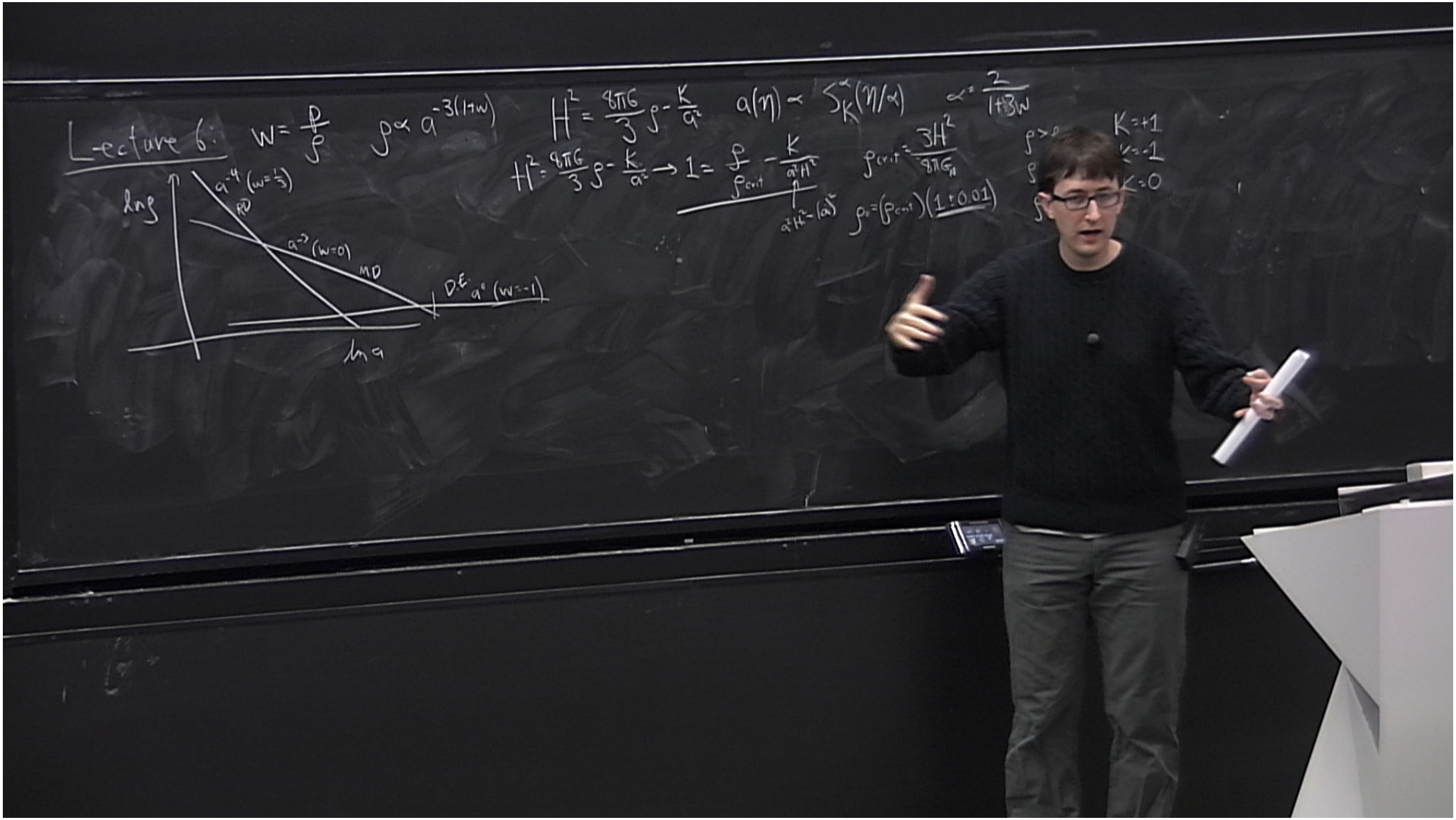
$1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
a^0 (w=-1) DE
ln a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$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$a^2H^2 = |a|^2$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > 0$
$K = +1$
$K = -1$
$K = 0$
ln ρ
a^{-4} (w = 1/3) RD
a^{-3} (w = 0) MD
a^0 (w = -1) DE
ln a

Lecture 6: $w = \frac{p}{\rho}$ $\rho \propto a^{-3(1+w)}$ $H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$ $a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$ $\alpha = \frac{2}{1+3w}$

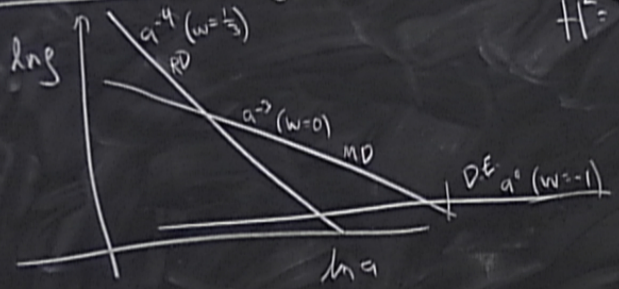
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$ $\rho_{crit} = \frac{3H^2}{8\pi G_N}$ $a^2H^2 = (\dot{a})^2$

$\rho_0 = (\rho_{crit})(1 \pm 0.01)$

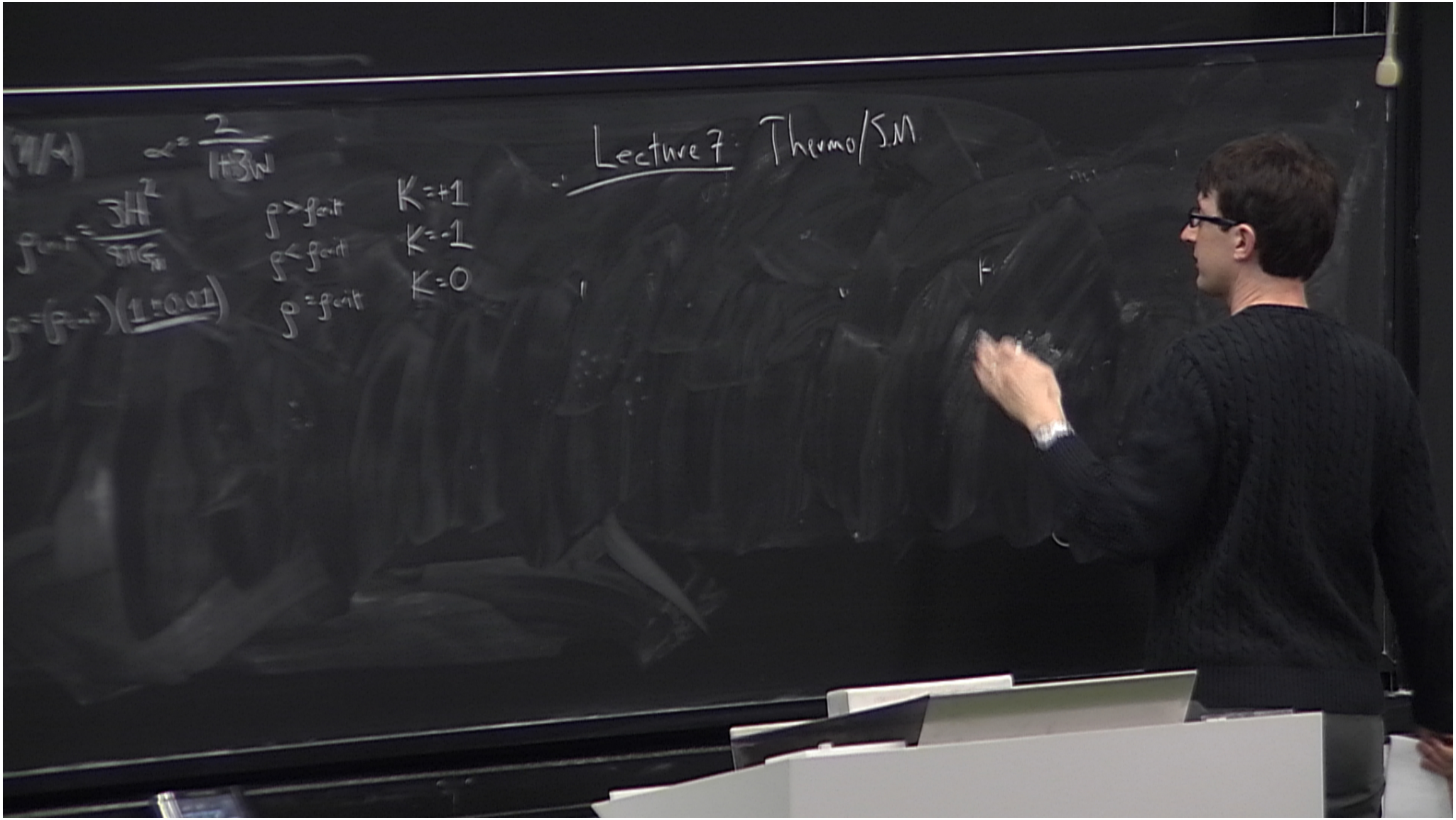
$\rho > \rho_{crit}$ $K = +1$

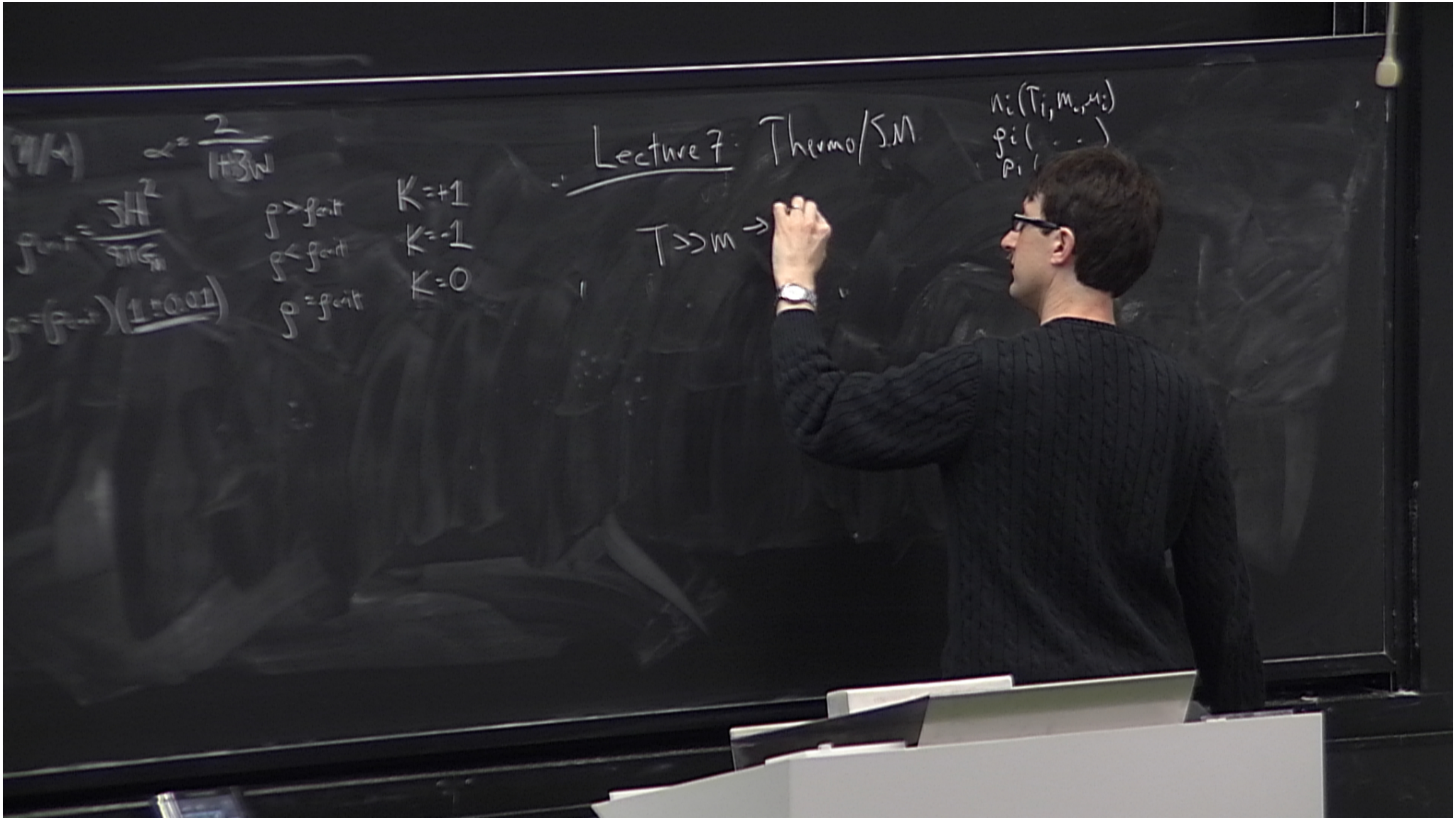
$\rho < \rho_{crit}$ $K = -1$

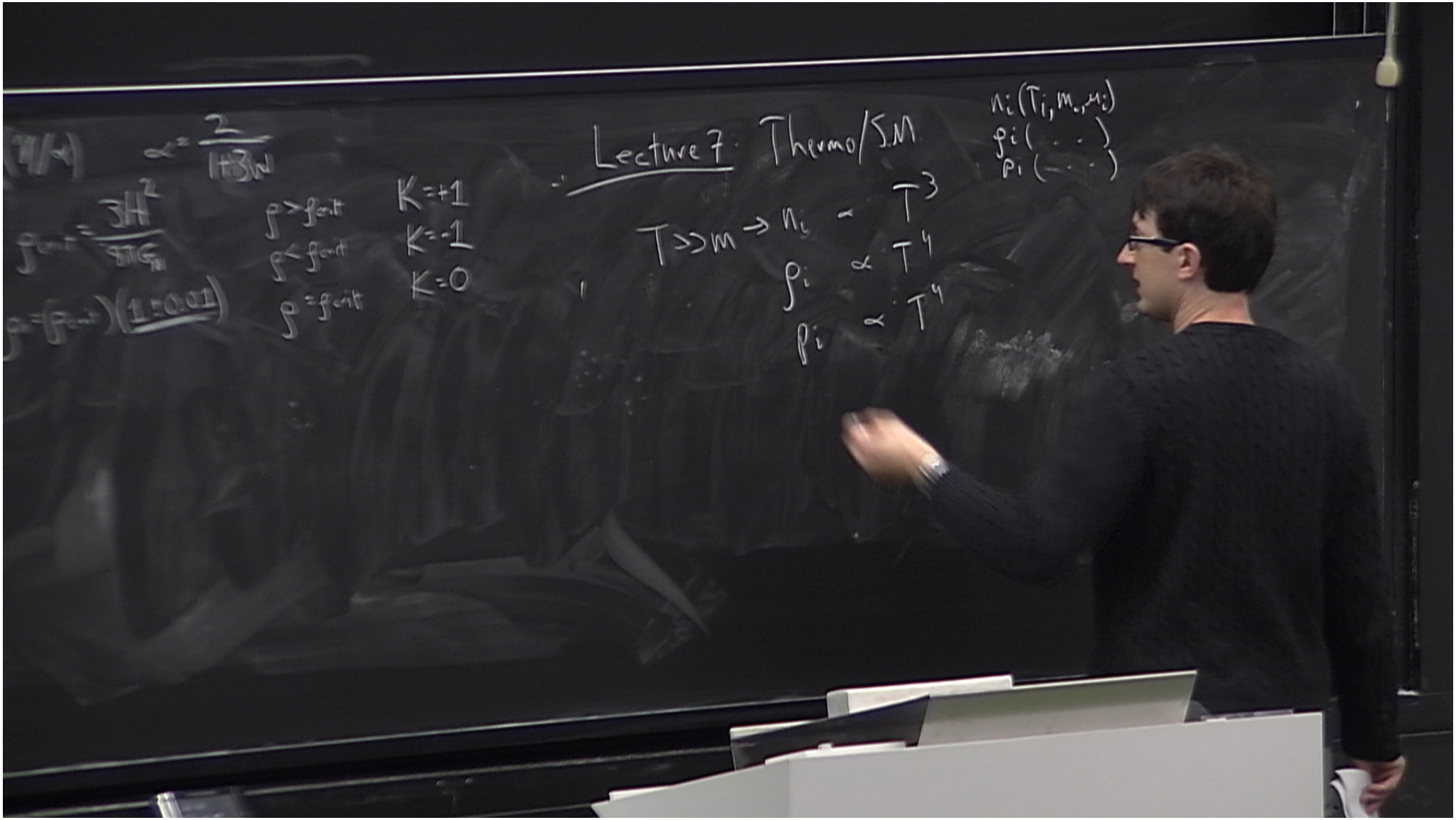
$\rho = \rho_{crit}$ $K = 0$

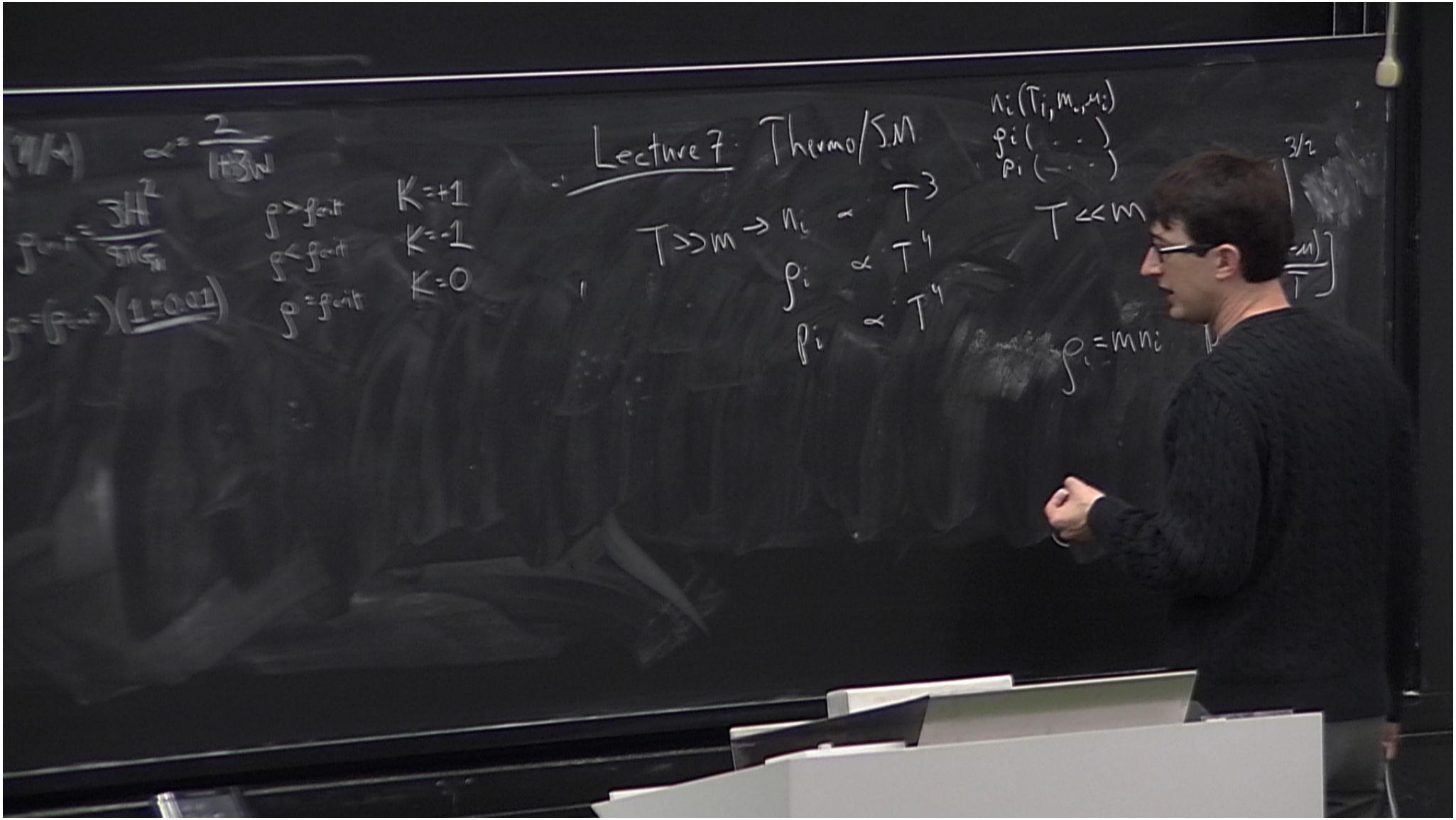


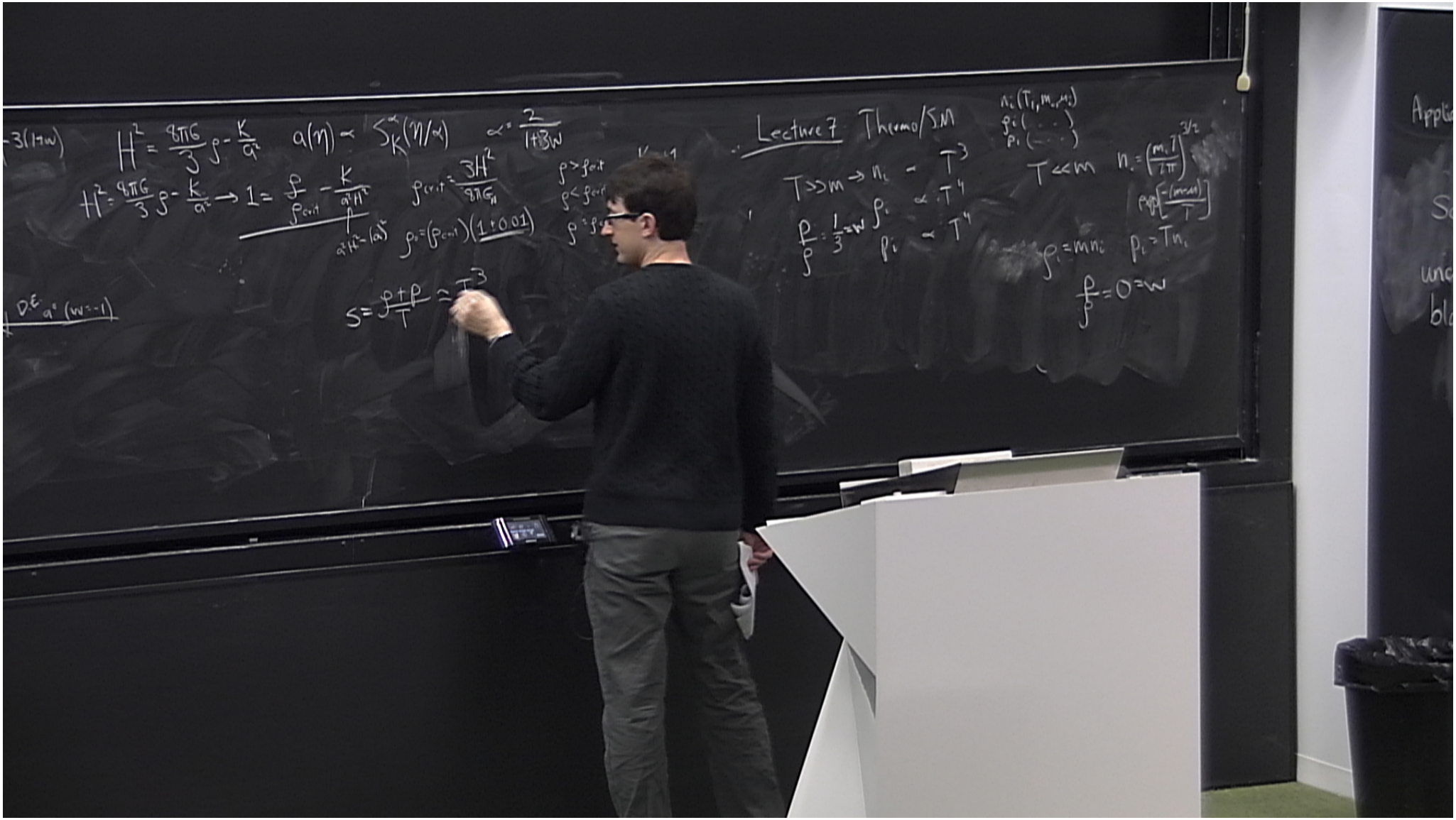
Lecture 7

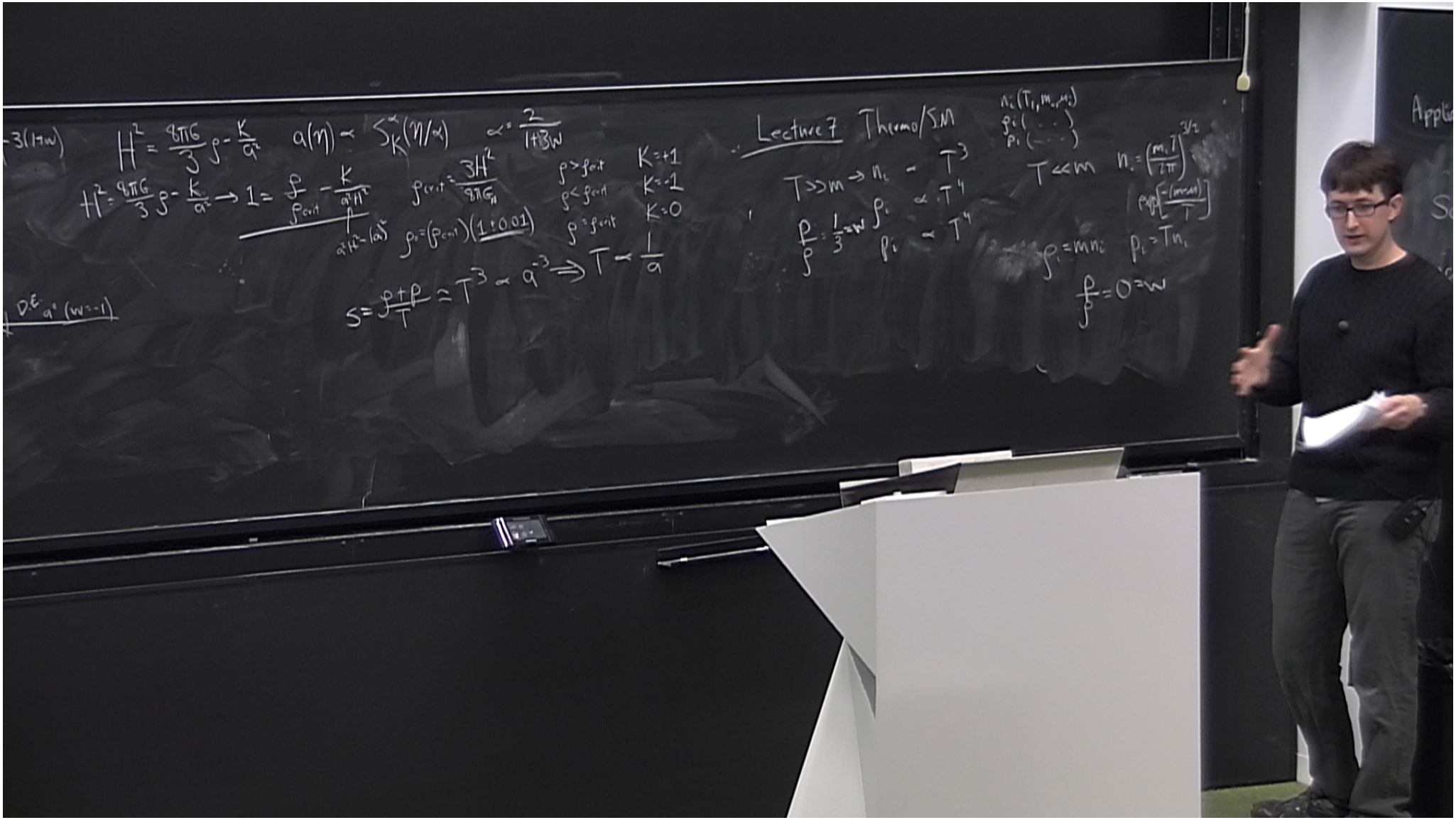

Lecture 7: Thermo/SM
ρ>ρcrit K=+1
ρ<ρcrit K=-1
ρ=ρcrit K=0

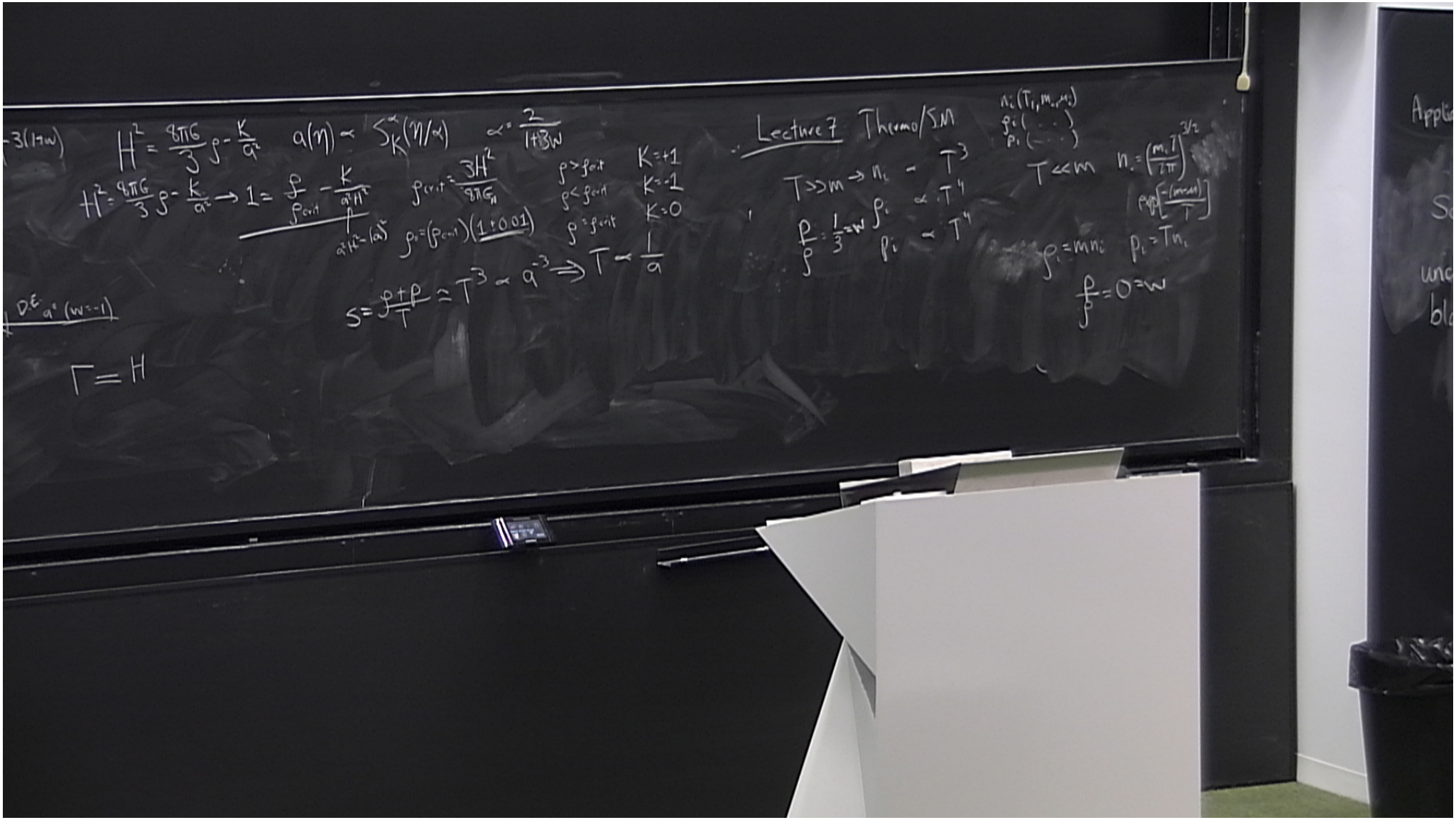

Lecture 7: Thermo/SM
T>>m →
K=+1
K=-1
K=0

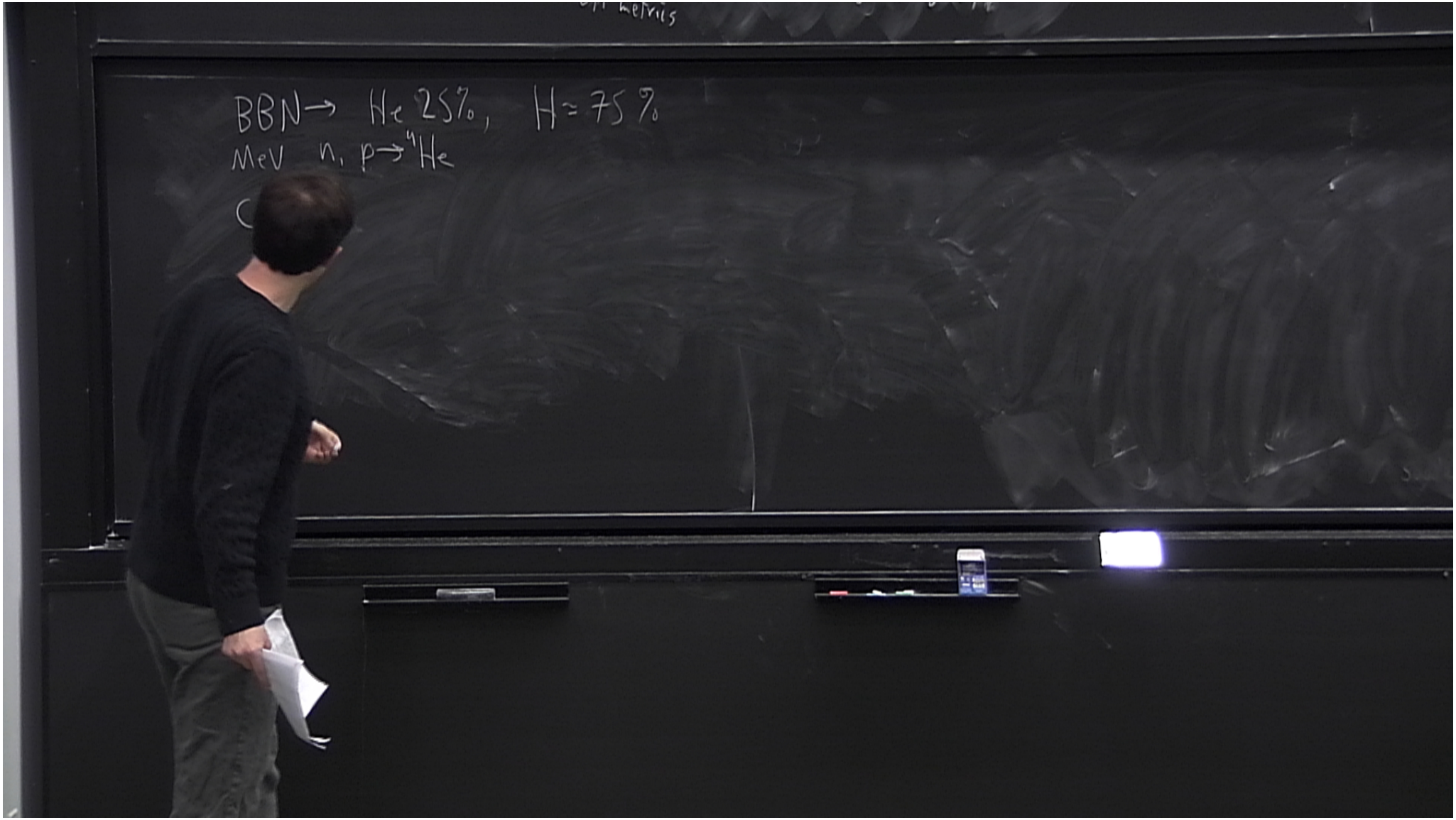

Lecture 7: Thermo/SM
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \gg m \Rightarrow n_i \sim T^3$
$\rho_i \propto T^4$
$p_i \propto T^4$
$n_i(T_i, m_i, \mu_i)$
$\rho_i(\ldots)$
$p_i(\ldots)$

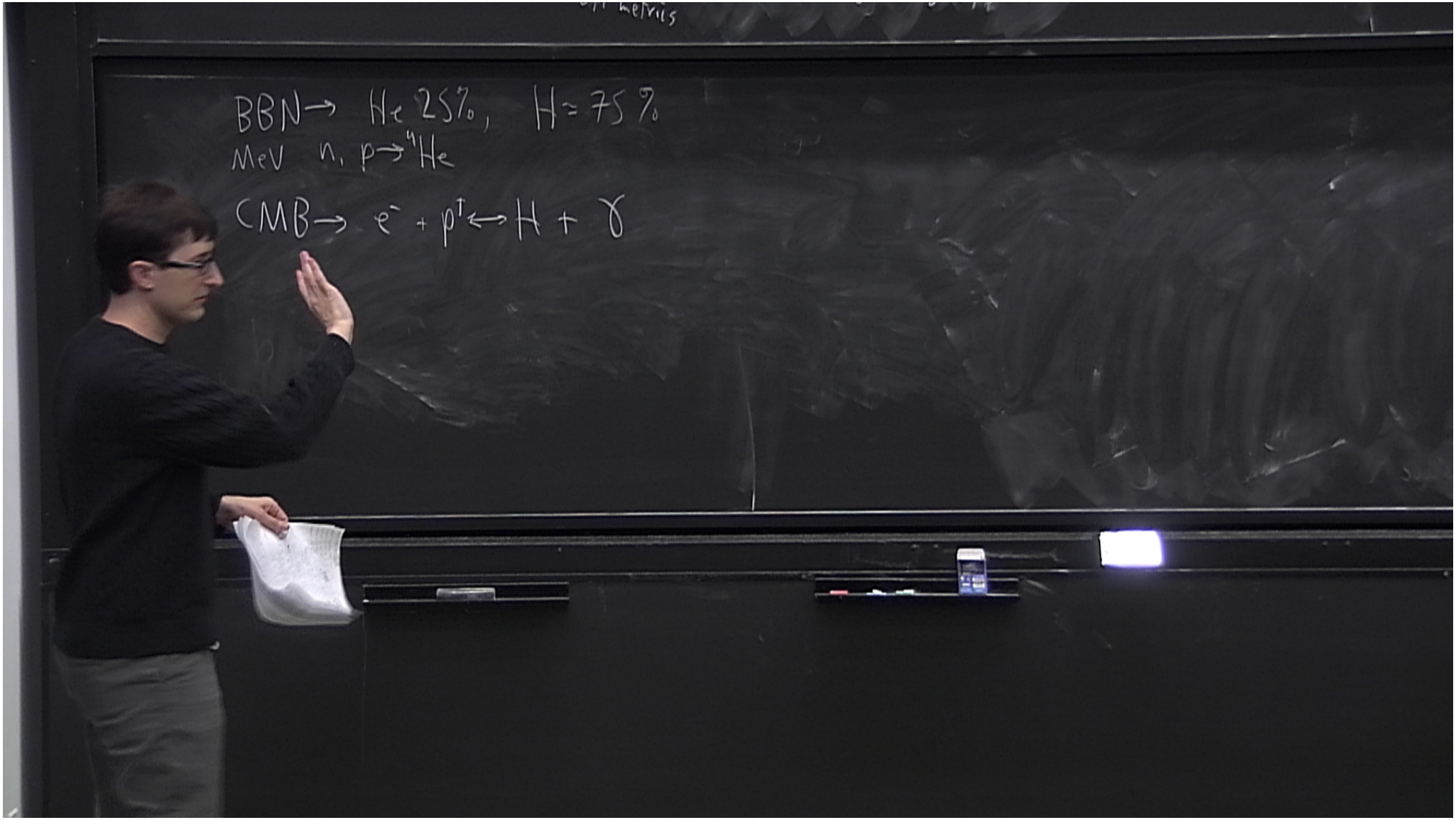

Lecture 7: Thermo/SM
T>>m → n_i ~ T^3
ρ_i ∝ T^4
p_i ∝ T^4
T<<m
ρ_i = m n_i
K=+1
K=-1
K=0

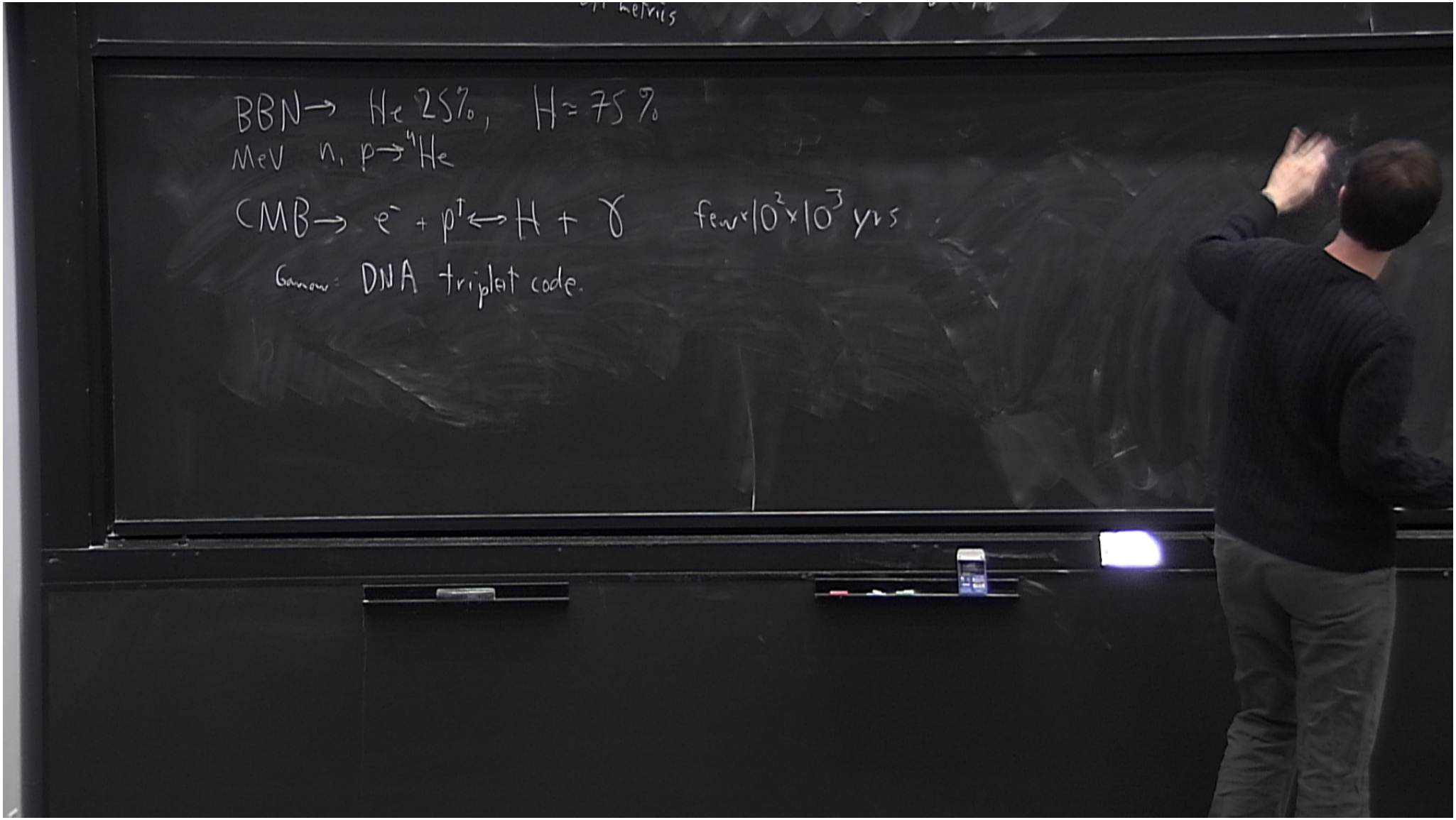

Lecture 7 Thermo/SM
T≫m → n_i ∝ T^3
ρ/p = 1/3 = w
ρ_i ∝ T^4
p_i ∝ T^4
T≪m
ρ_i = m n_i
p_i = T n_i
p/ρ = 0 = w
S = (ρ+p)/T ∝ T^3
H^2 = 8πG/3 ρ − K/a^2
q(η) ∝ S_K^α(η/χ)
α = 2/(1+3w)
ρ_crit = 3H^2/8πG
ρ_0 = (ρ_crit)(1+0.01)
DE q^0 (w=-1)

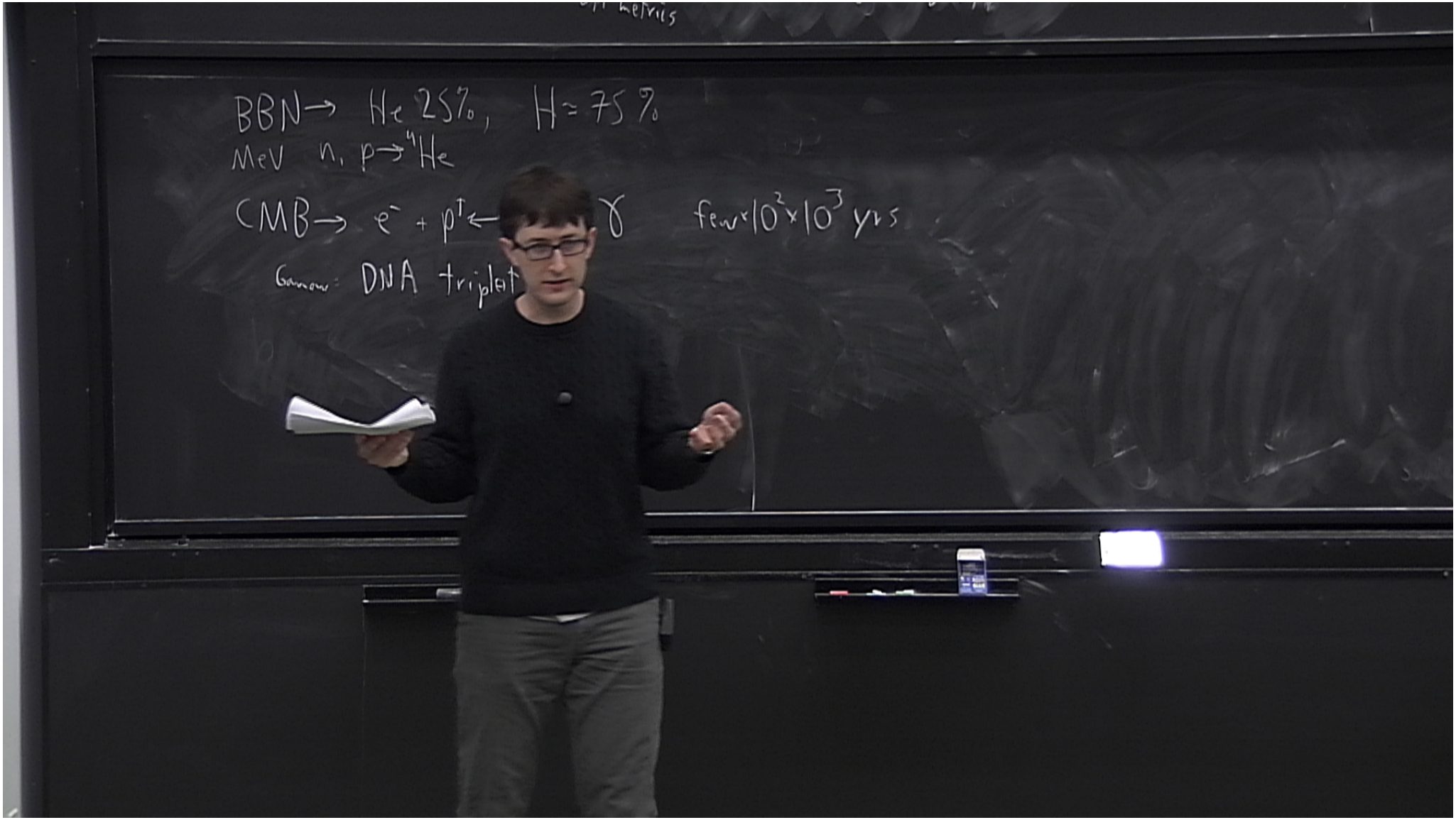

Lecture 7 Thermo/SM
DE
Applic

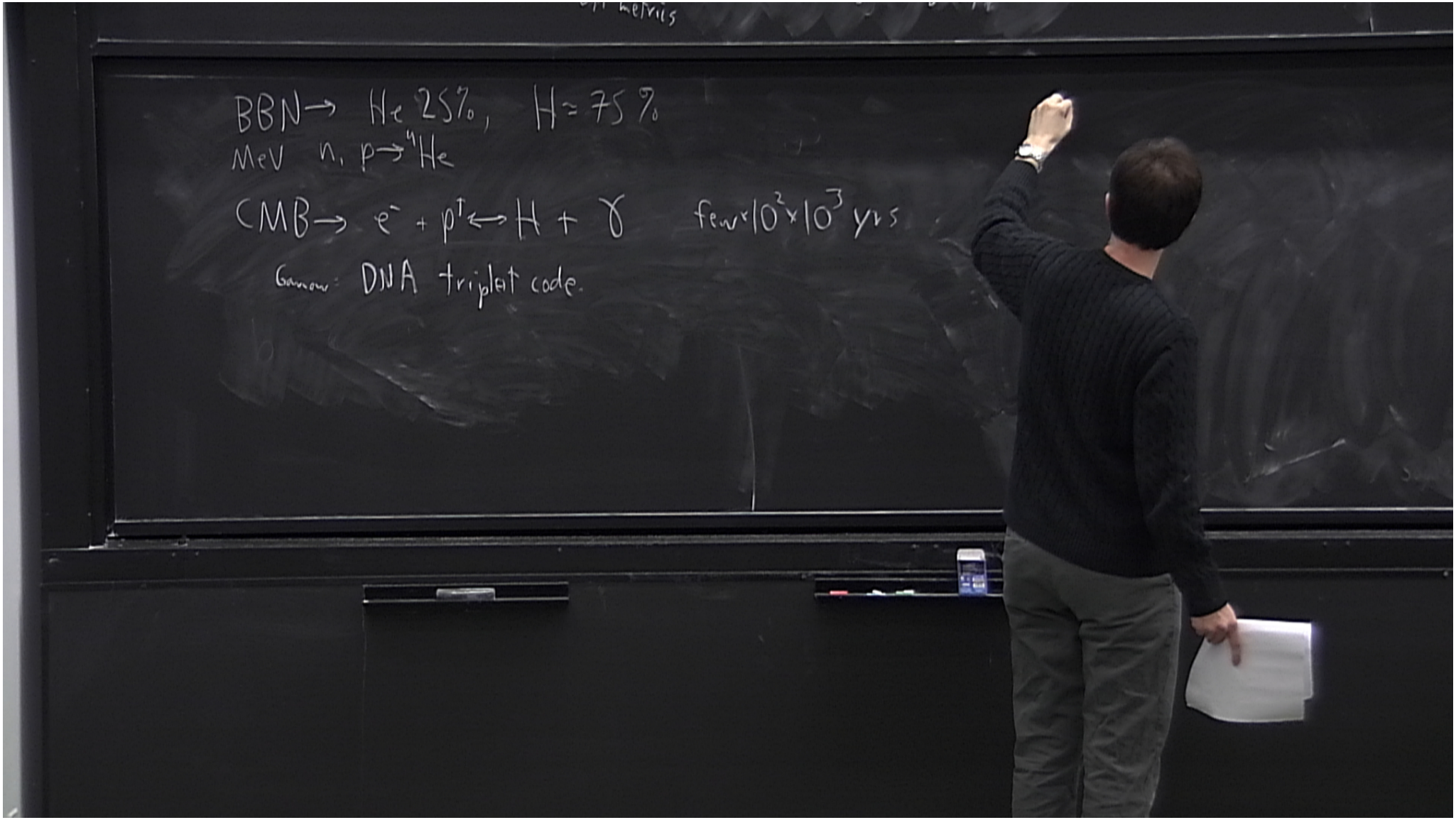

Lecture 7 Thermo/SM
Γ = H

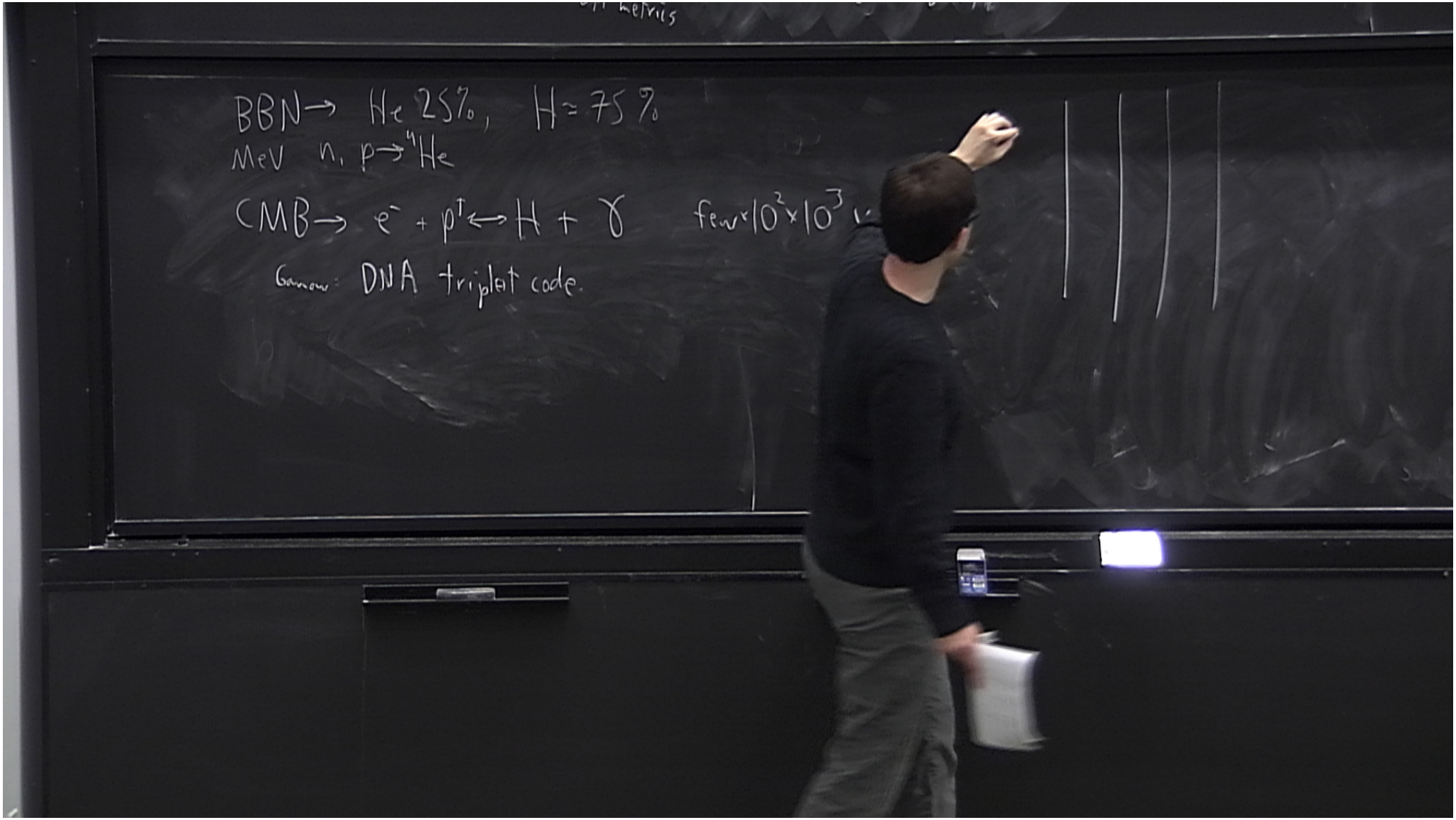

BBN → He 25%, H = 75 %
MeV n, p → ⁴He


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.


BBN → He 25%, H ≈ 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ← γ
few × 10² × 10³ yrs
Gamow: DNA triplet


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.


BBN → He 25%, H = 75 %
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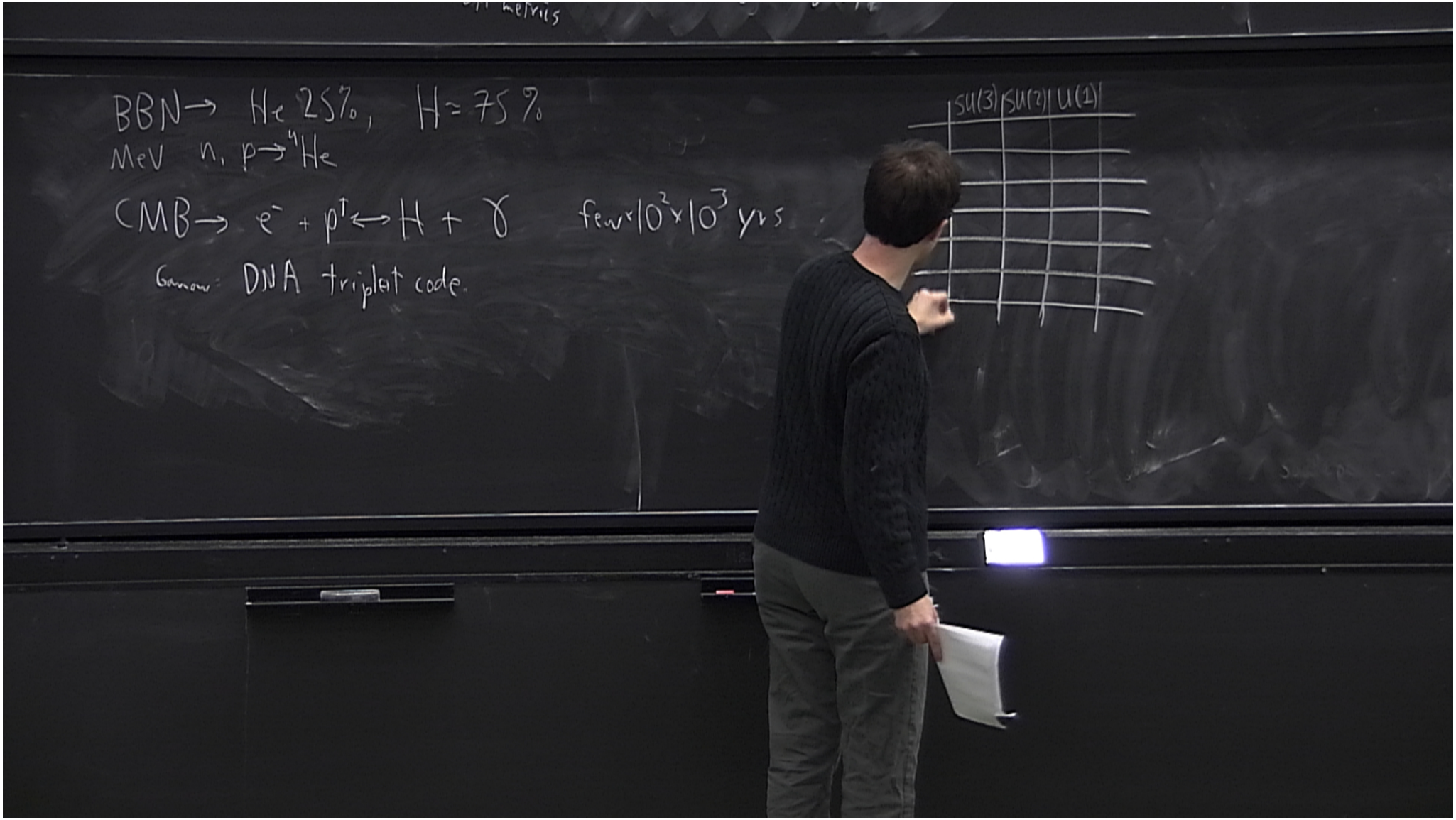
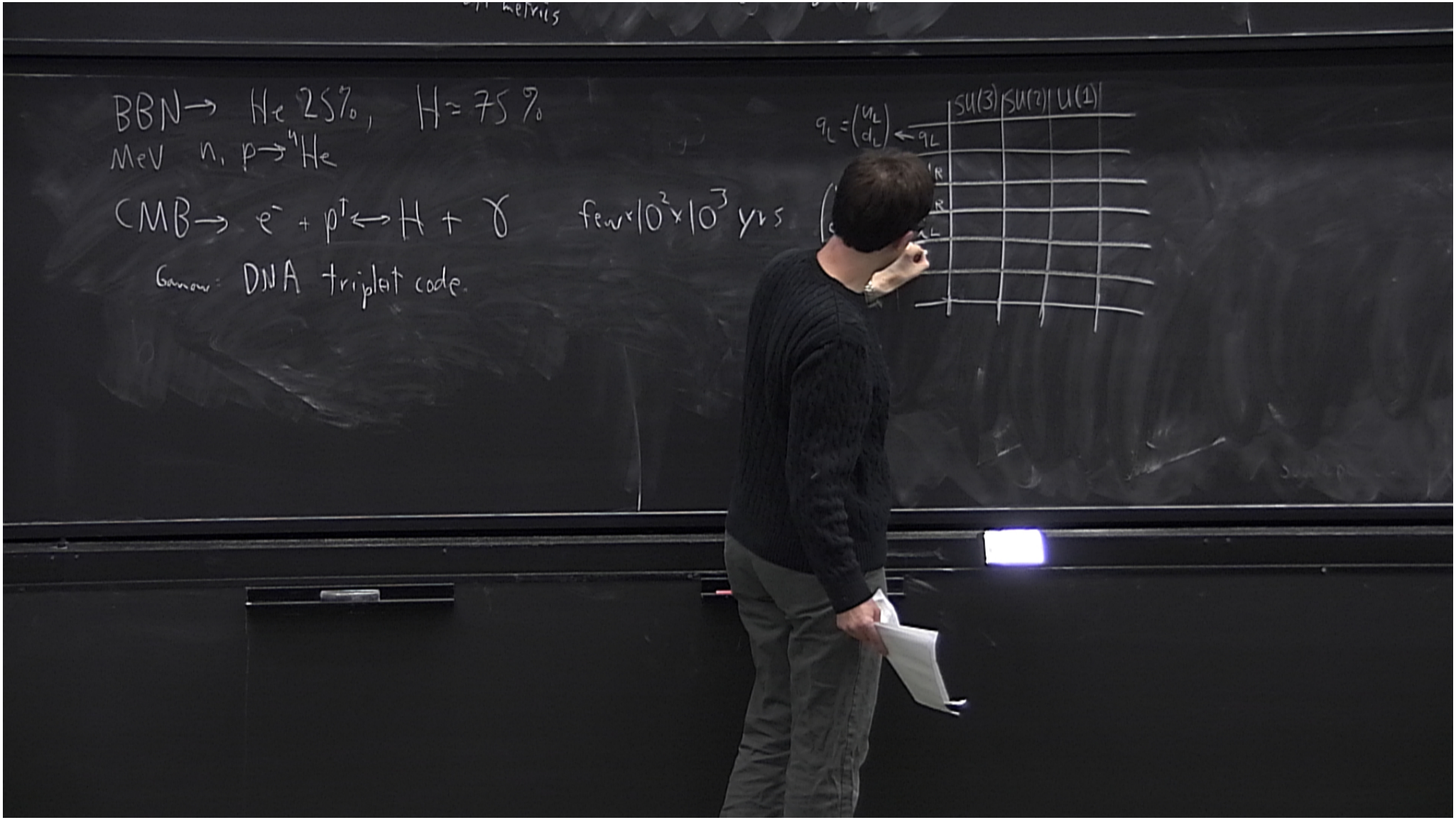
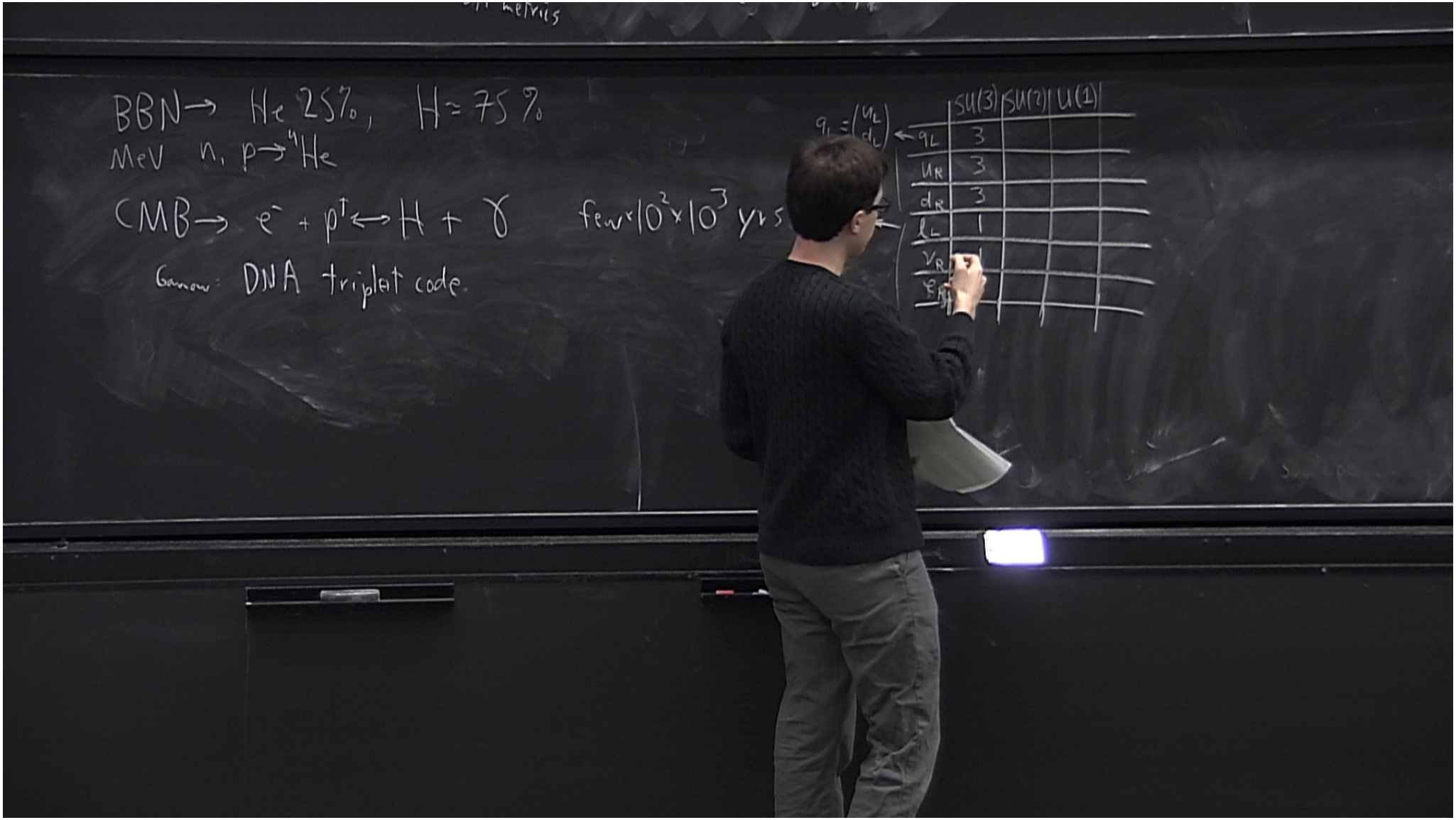
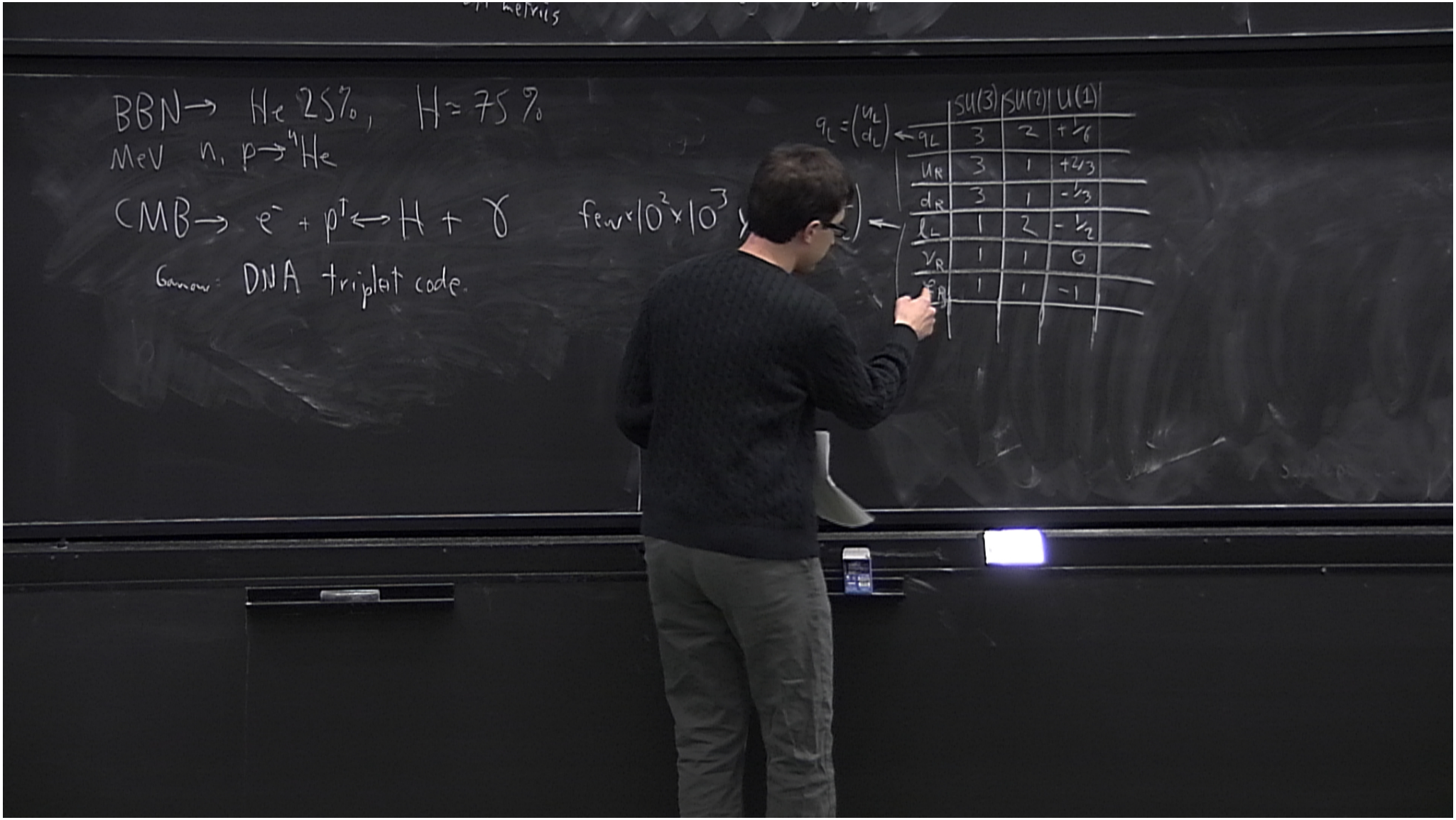
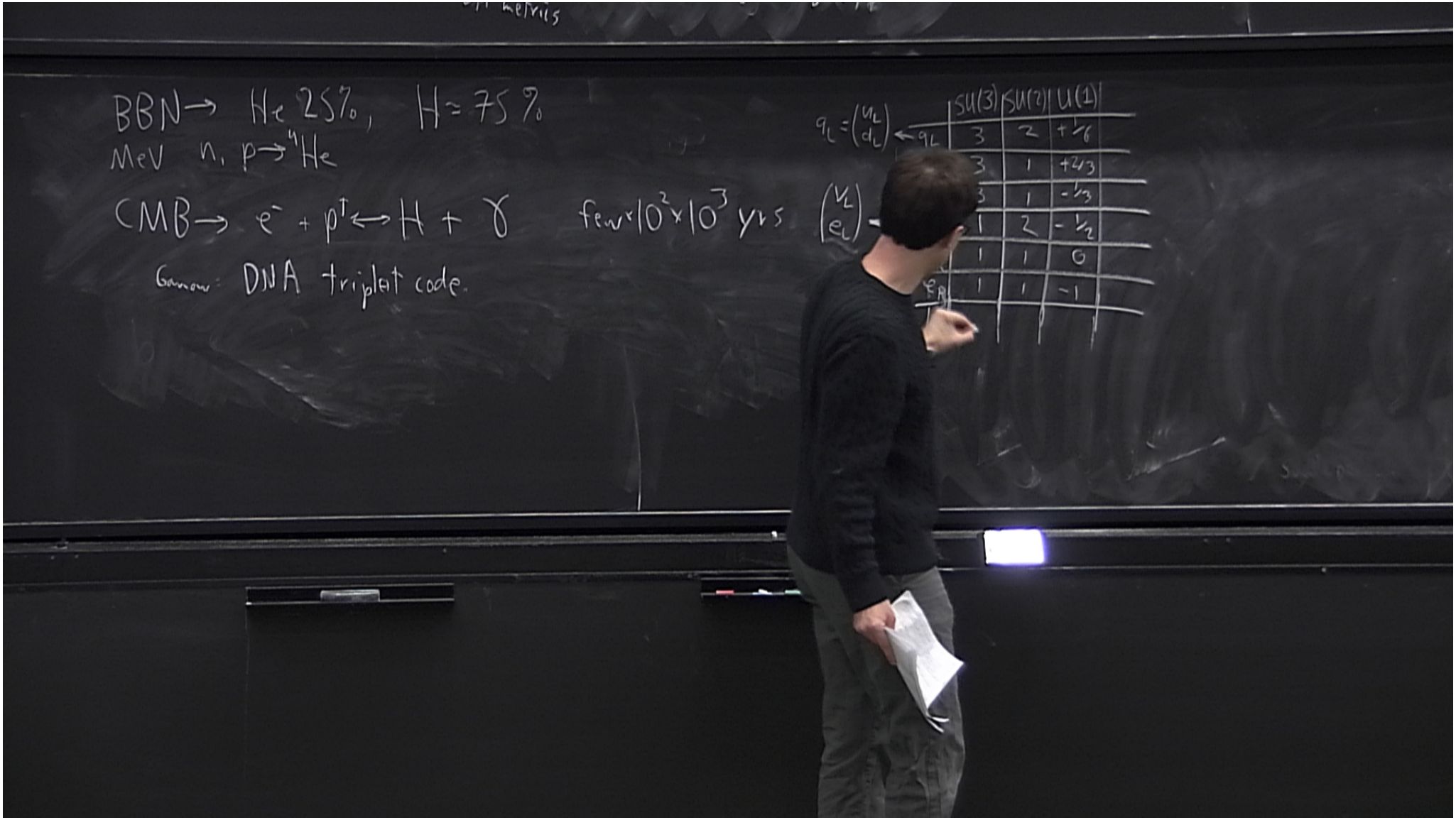
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³
Gamow: DNA triplet code.

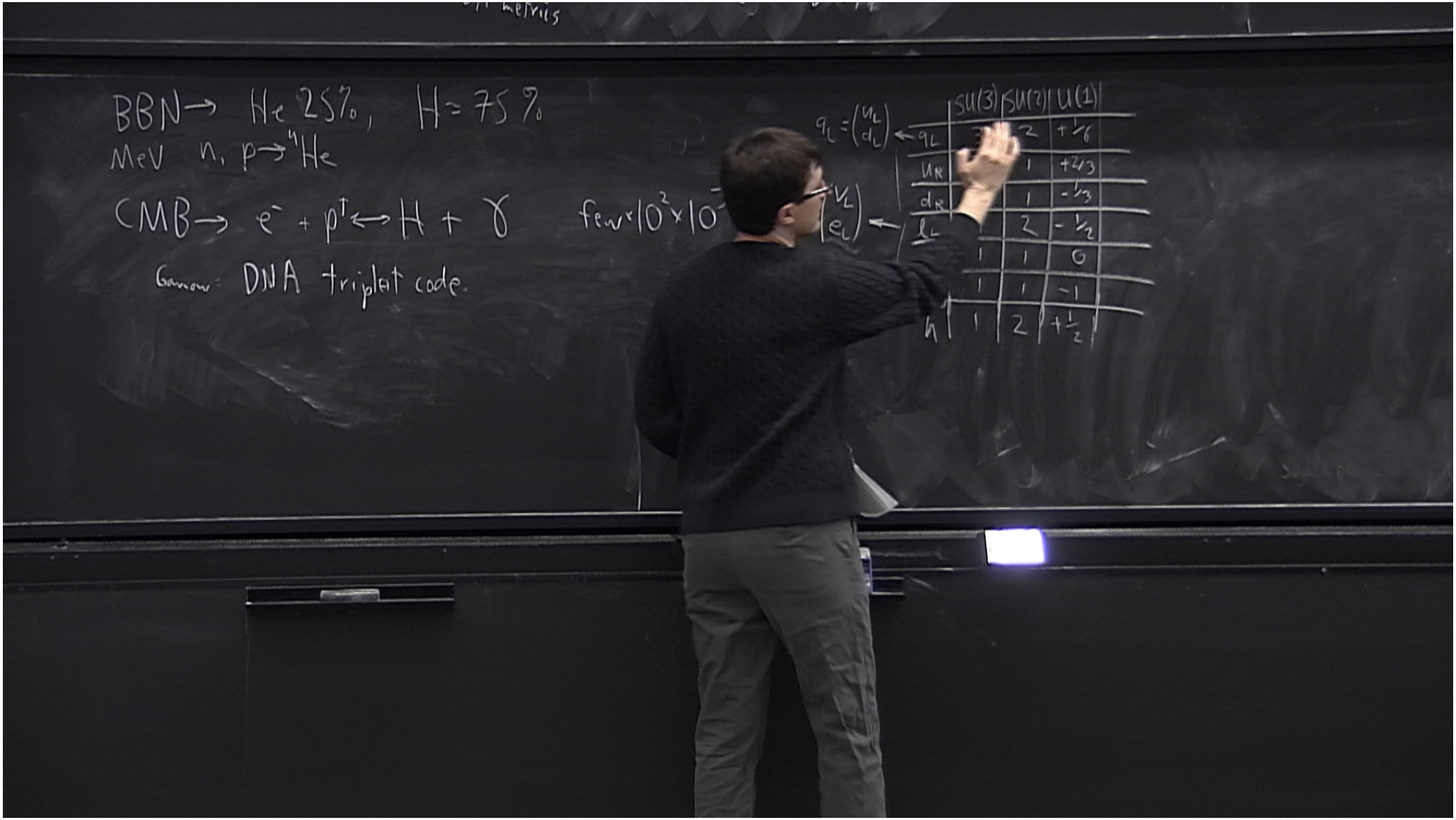

metrics
BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.
SU(3) SU(2) U(1)

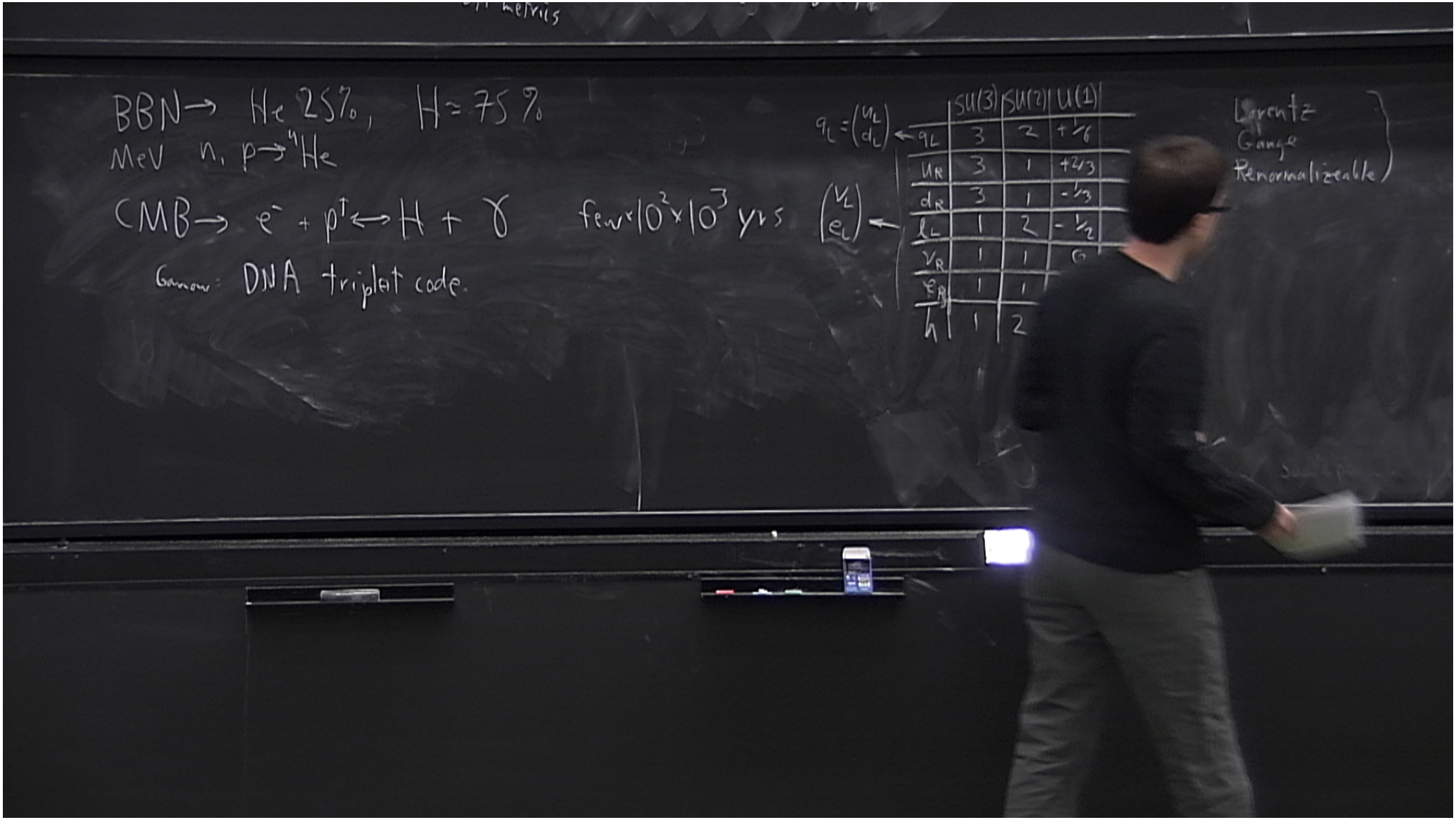

BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.
SU(3) SU(2) U(1)


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.
SU(3) SU(2) U(1)
q_L 3
u_R 3
d_R 3
l_L 1
ν_R 1


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ y
Gamow: DNA triplet code.
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
SU(3) SU(2) U(1)
q_L 3 2 +1/6
u_R 3 1 +2/3
d_R 3 1 -1/3
ℓ_L 1 2 -1/2
ν_R 1 1 0
e_R 1 1 -1


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.
SU(3) SU(2) U(1)
q_L 3 2 +1/6
3 1 +2/3
3 1 -1/3
1 2 -1/2
1 1 0
1 1 -1


BBN → He 25%, H = 75 %
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
Gamow: DNA triplet code.
SU(3) SU(2) U(1)
qL
uR
dR
lL
h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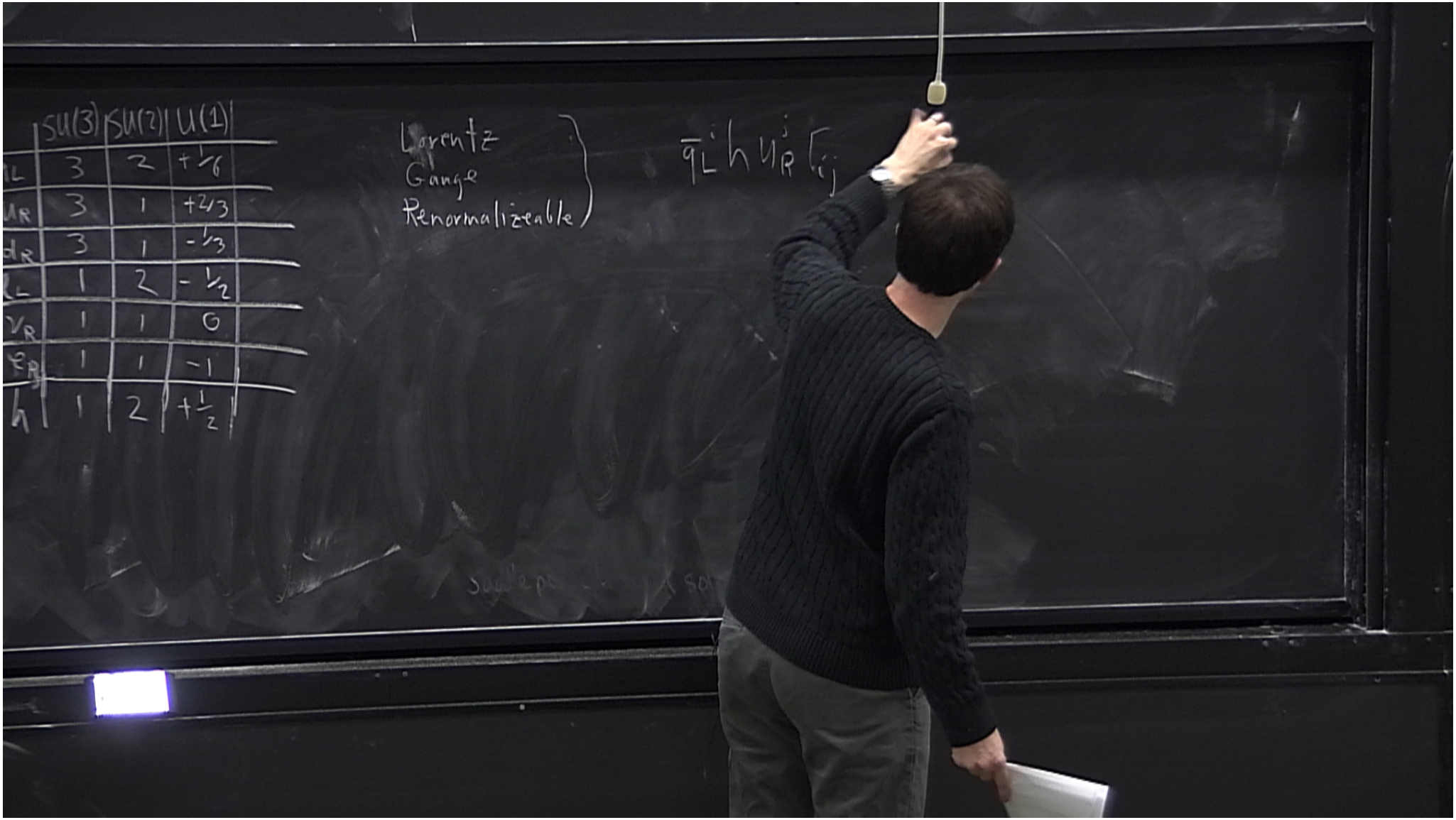
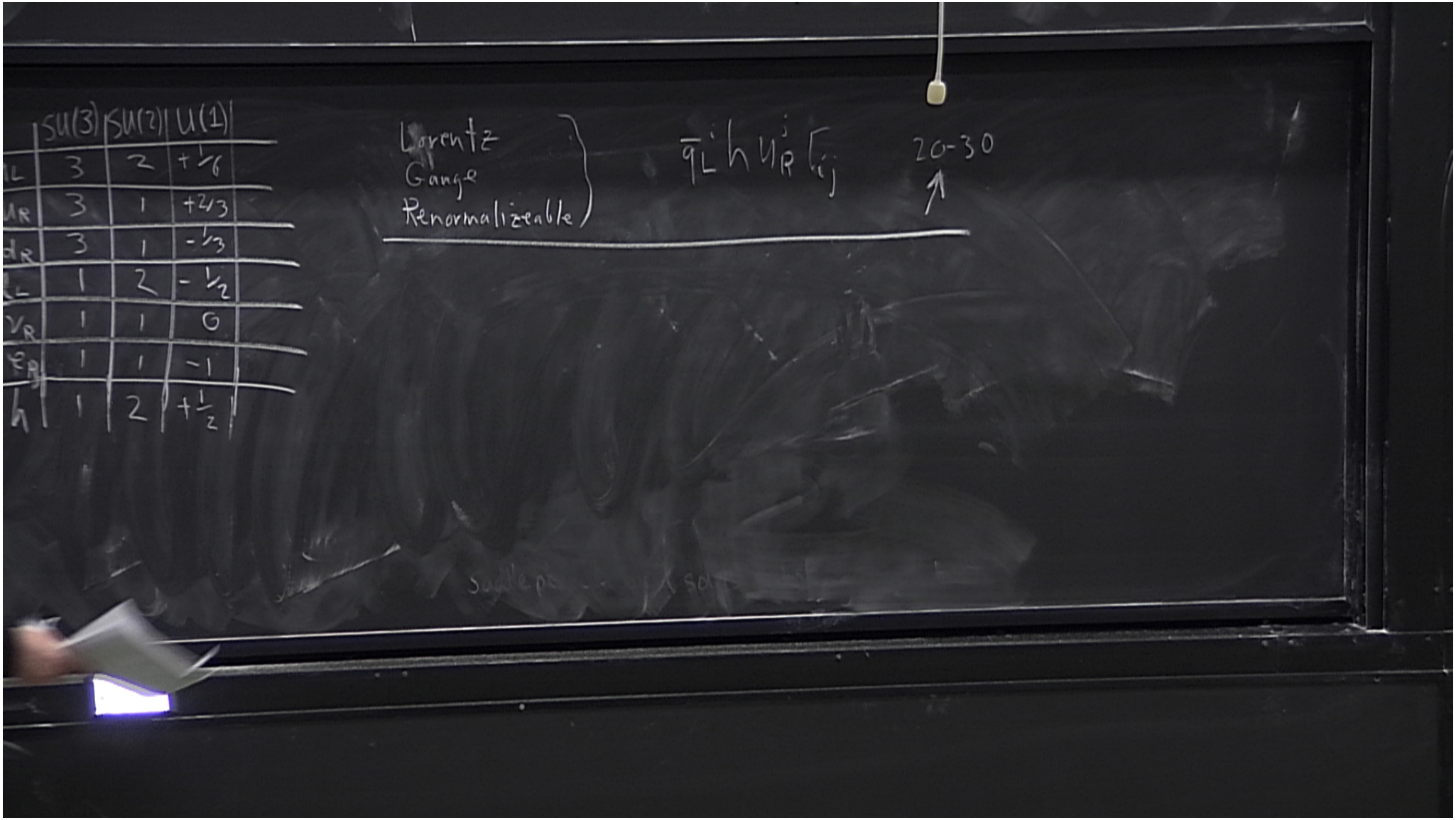
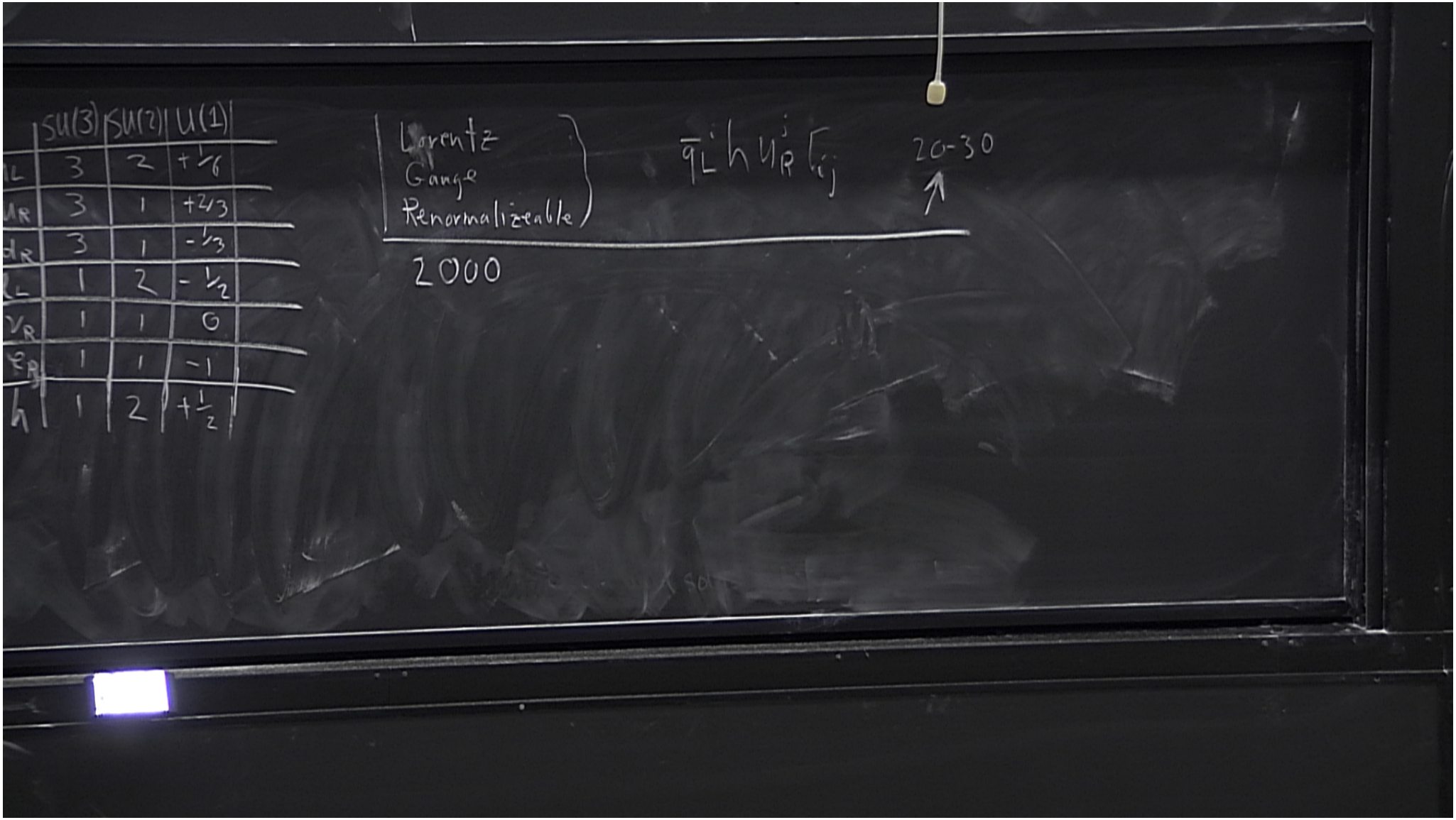
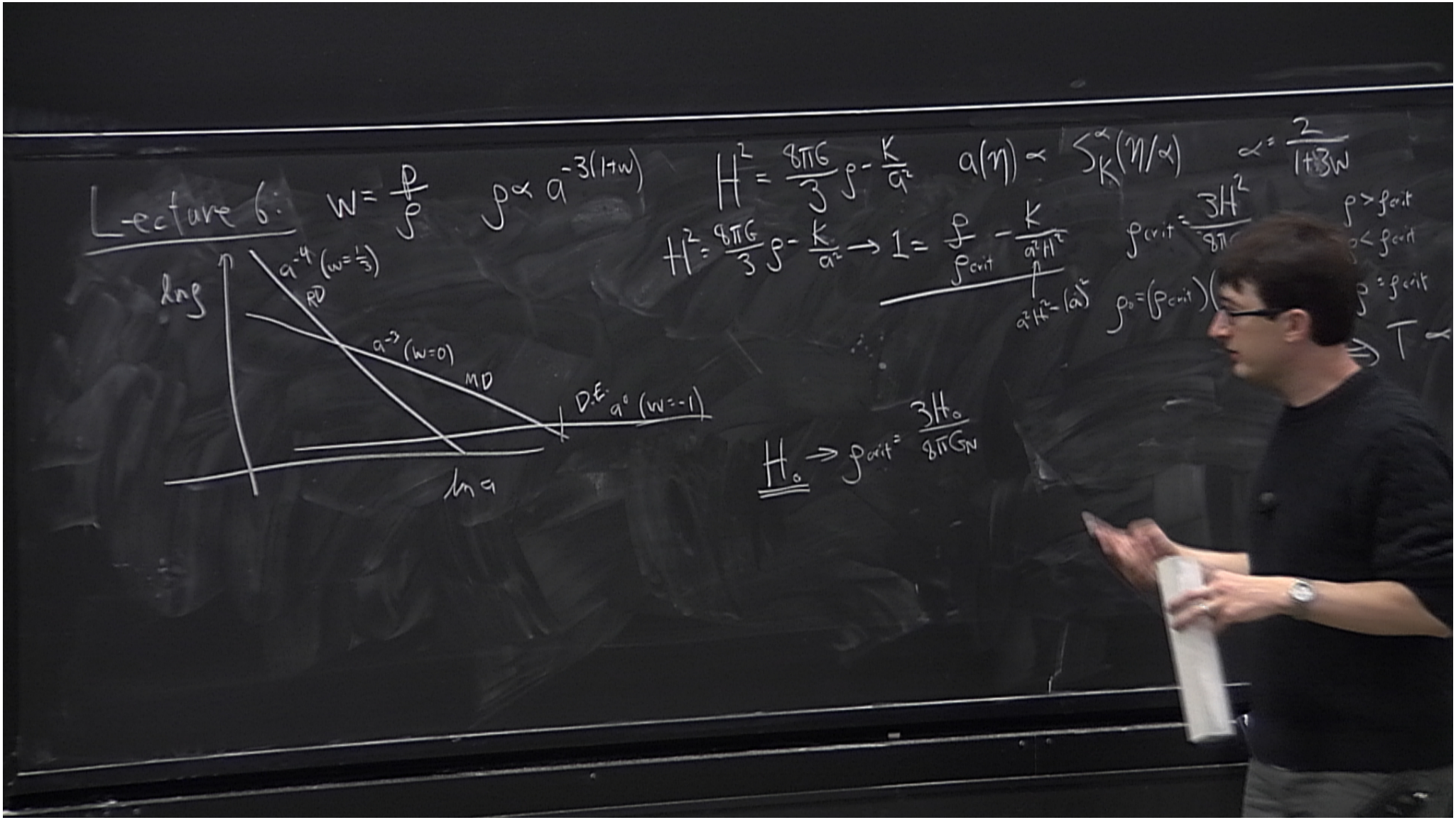
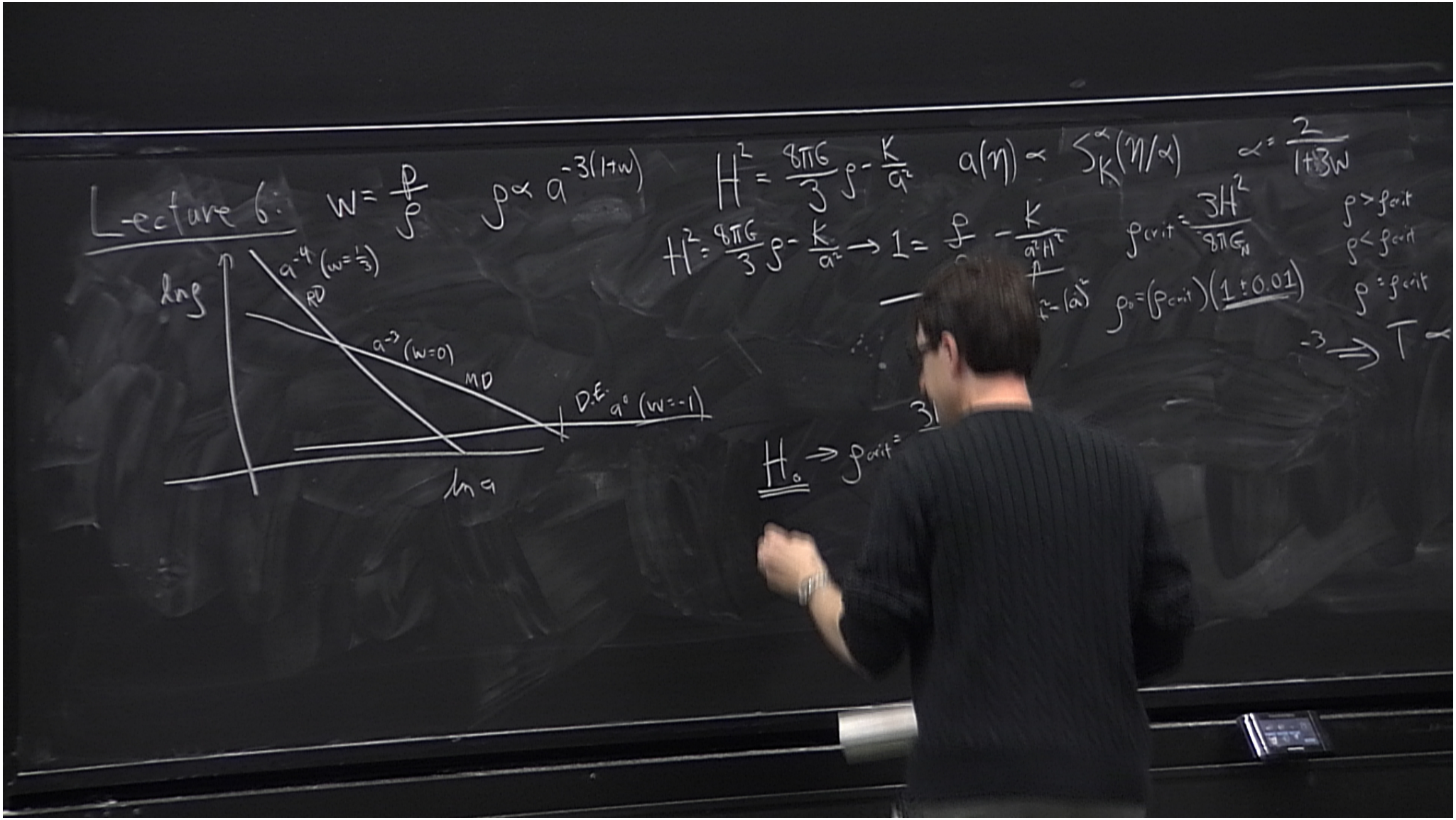
MeV n, p → ⁴He
CMB → e⁻ + p⁺ ⟷ H + γ
few × 10² × 10³ yrs
Gamow: DNA triplet code.
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
SU(3) SU(2) U(1)
q_L 3 2 +1/6
u_R 3 1 +2/3
d_R 3 1 -1/3
l_L 1 2 -1/2
ν_R 1 1 0
e_R 1 1
h 1 2
Lorentz
Gauge
Renormalizeable


SU(3) SU(2) U(1)
3 2 +1/6
3 1 +2/3
3 1 -1/3
1 2 -1/2
1 1 0
1 1 -1
1 2 +1/2
Lorentz
Gauge
Renormalizeable
$\bar{q}_L^i h u_R^j \epsilon_{ij}$


SU(3) SU(2) U(1)
3 2 +1/6
3 1 +2/3
3 1 -1/3
1 2 -1/2
1 1 0
1 1 -1
1 2 +1/2
Lorentz
Gauge
Renormalizeable
$\bar{q}_L h u_R^j \epsilon_{ij}$
20-30


SU(3) SU(2) U(1)
3 2 +1/6
3 1 +2/3
3 1 -1/3
1 2 -1/2
1 1 0
1 1 -1
1 2 +1/2
Lorentz
Gauge
Renormalizeable
2000
$\bar{q}_L h u_R^j \epsilon_{ij}$
20-30


Lecture 6:
$w = \frac{p}{\rho}$
$\rho \propto a^{-3(1+w)}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
$a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$
$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$\rho_{crit} = \frac{3H^2}{8\pi}$
$\rho_0 = (\rho_{crit})($
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$\Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$


Lecture 6:
$w = \frac{p}{\rho}$
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$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
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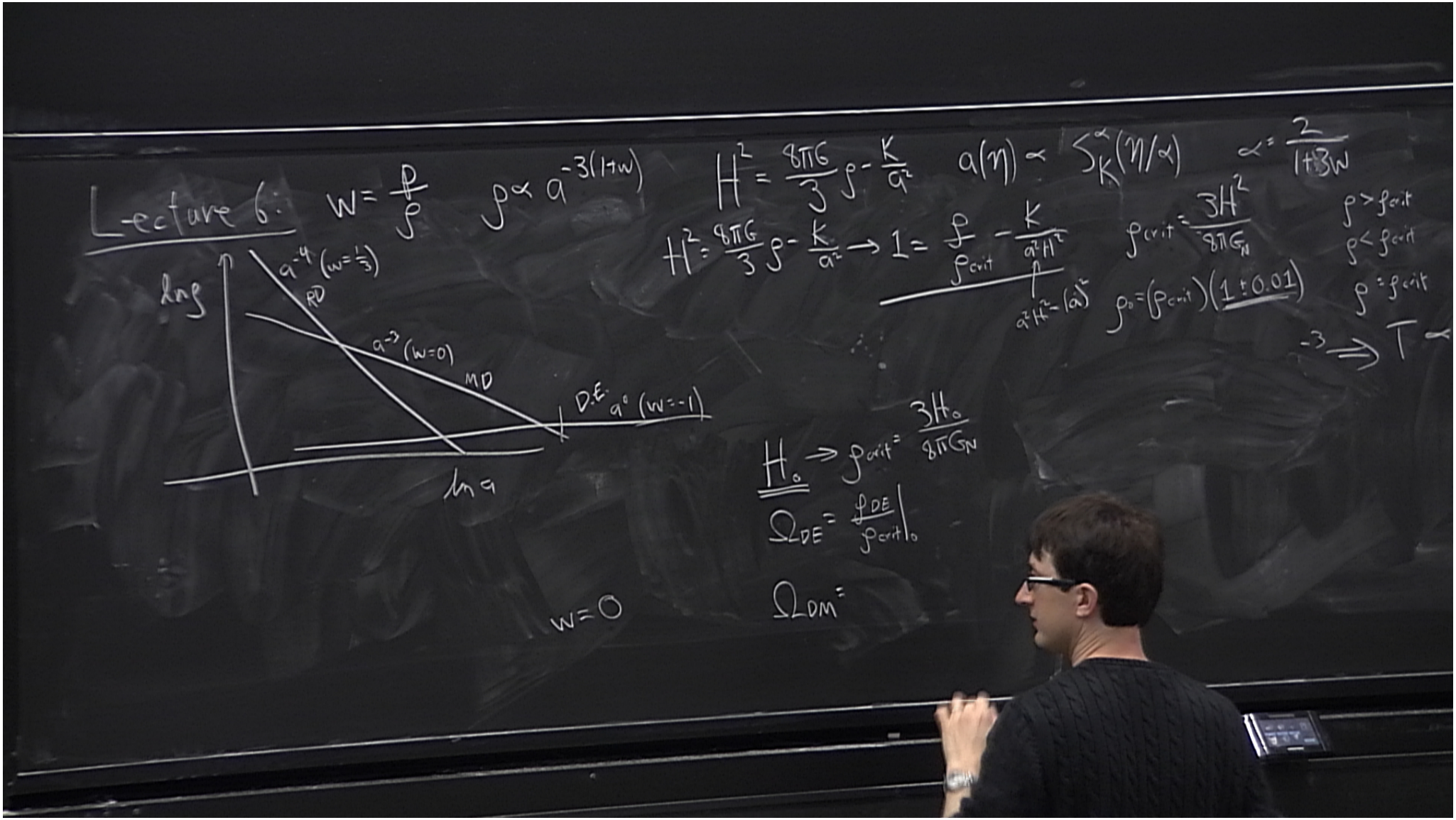
$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_c} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = 3$


Lecture 6:
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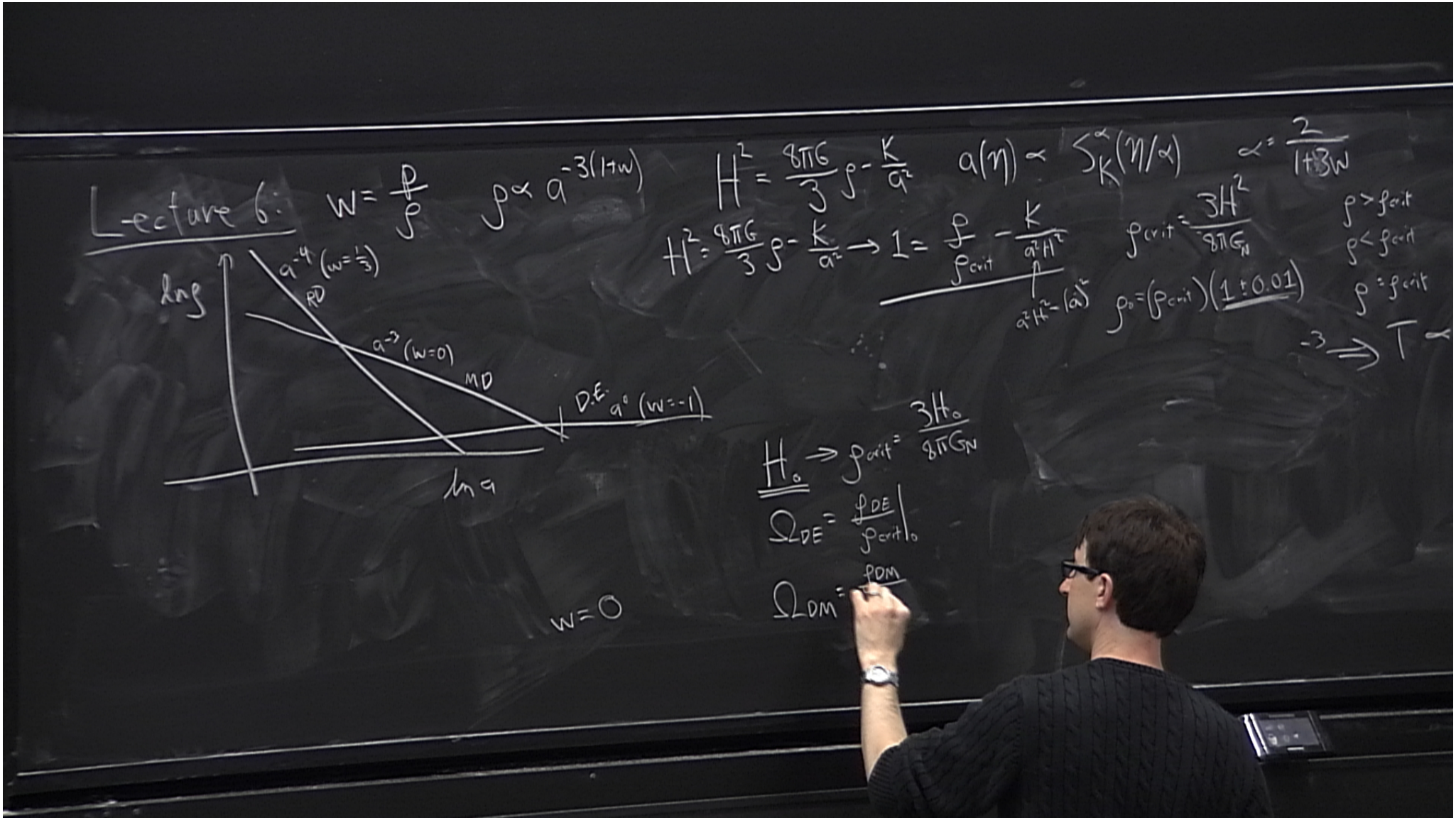
$a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$
$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$a^2H^2 = (\dot{a})^2$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$-3 \Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
w=0
Ω_{DM} =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$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
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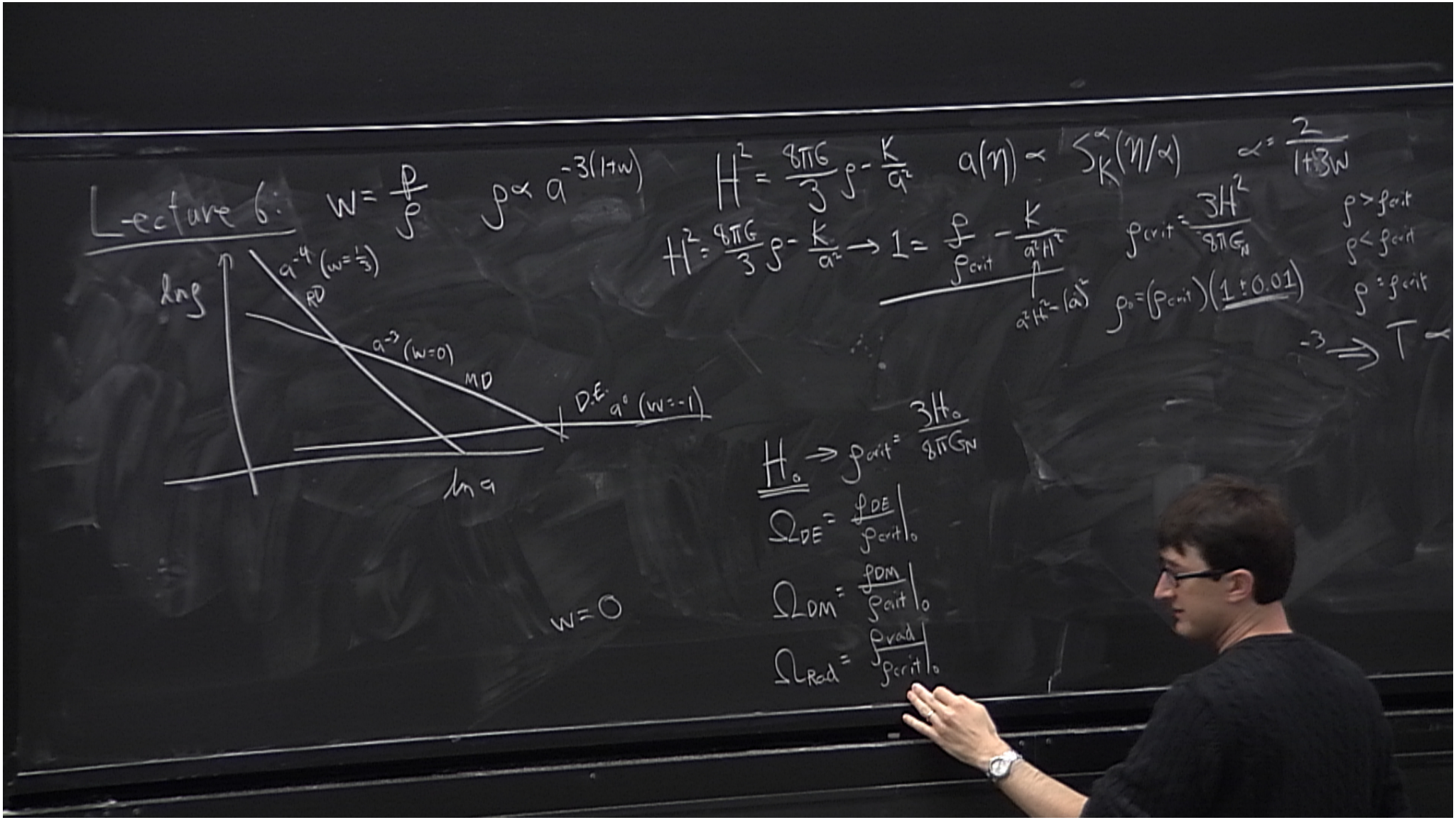
$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$-3 \Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{}$
w=0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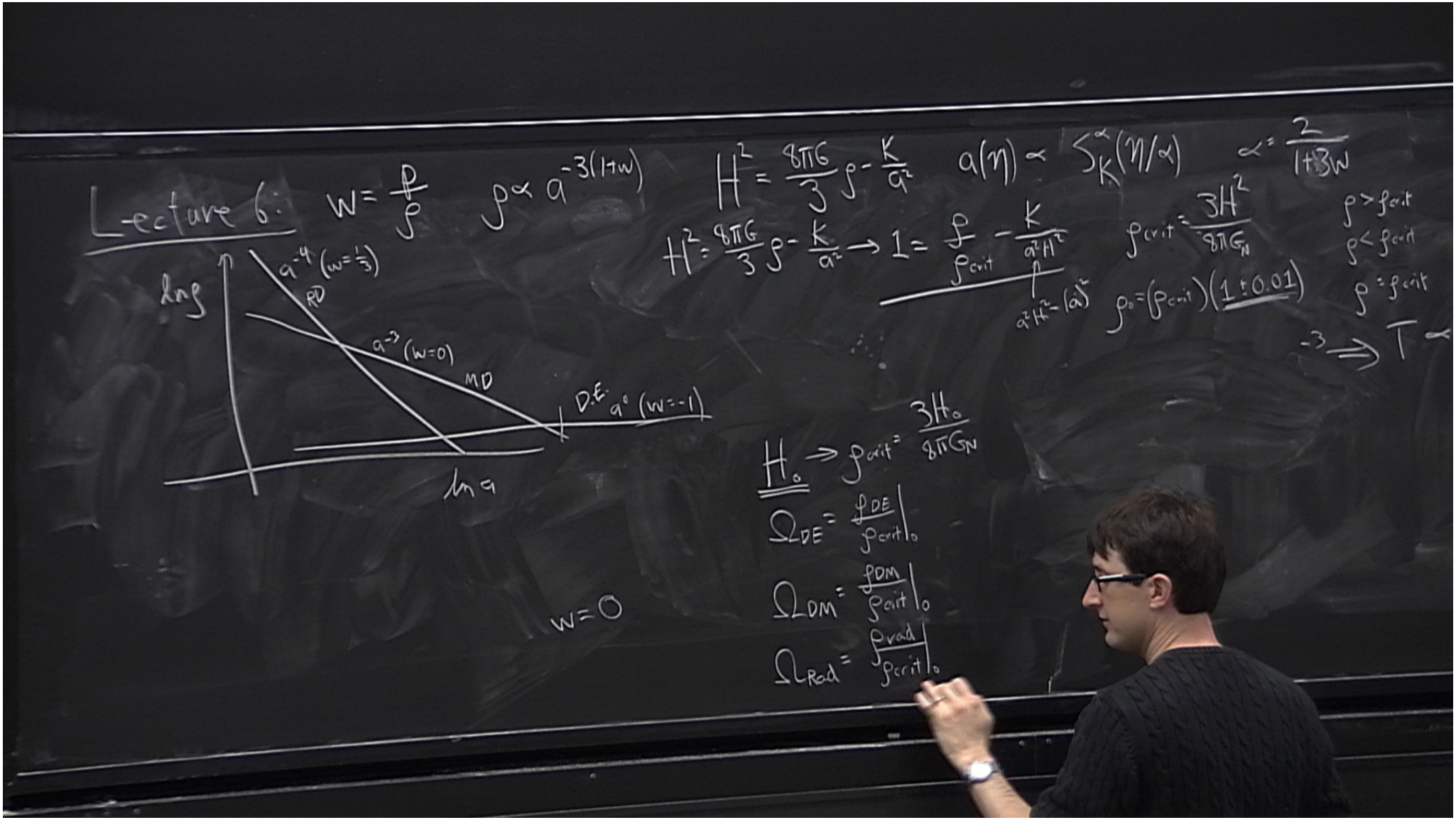
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$-3 \Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$
w=0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$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
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$\alpha = \frac{2}{1+3w}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$-3 \Rightarrow T \propto$
ln ρ
a^{-4} (w=1/3) RD
a^{-3} (w=0) MD
D.E. a^0 (w=-1)
ln a
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$
w=0

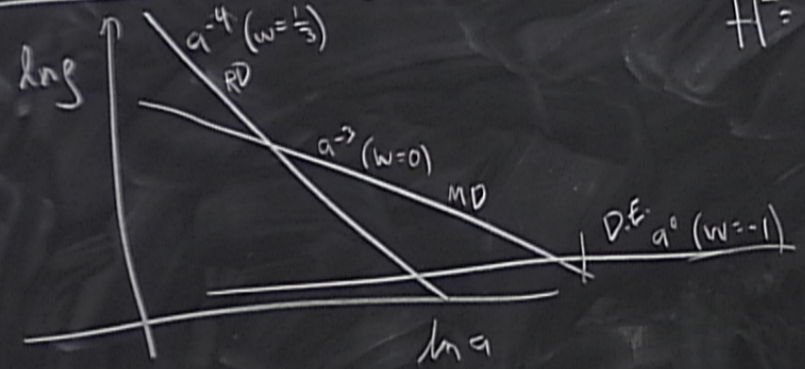
Lecture 6:

$w = \frac{p}{\rho}$ $\quad \rho \propto a^{-3(1+w)}$ $\quad H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$ $\quad a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$ $\quad \alpha = \frac{2}{1+3w}$

$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$ $\quad a^2H^2 = (\dot{a})^2$

$\rho_{crit} = \frac{3H^2}{8\pi G_N}$ $\quad \rho > \rho_{crit}$

$\rho_0 = (\rho_{crit})(1 \pm 0.01)$



$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$

$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$

$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$ $\quad \Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0$

$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$

w = 0

Lecture 6:

$w = \frac{p}{\rho}$ $\quad \rho \propto a^{-3(1+w)}$ $\quad H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$ $\quad a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$ $\quad \alpha = \frac{2}{1+3w}$

$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$ $\quad a^2H^2 = (\dot{a})^2$

$\rho_{crit} = \frac{3H^2}{8\pi G_N}$

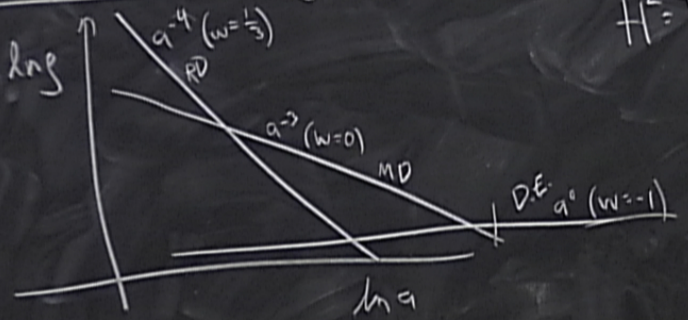
$\rho > \rho_{crit}$ $\quad K = +1$

$\rho < \rho_{crit}$ $\quad K = -1$

$\rho = \rho_{crit}$ $\quad K = 0$

$\rho_0 = (\rho_{crit})(1 \pm 0.01)$

$-3 \Rightarrow T \propto \frac{1}{a}$



$w = 0$

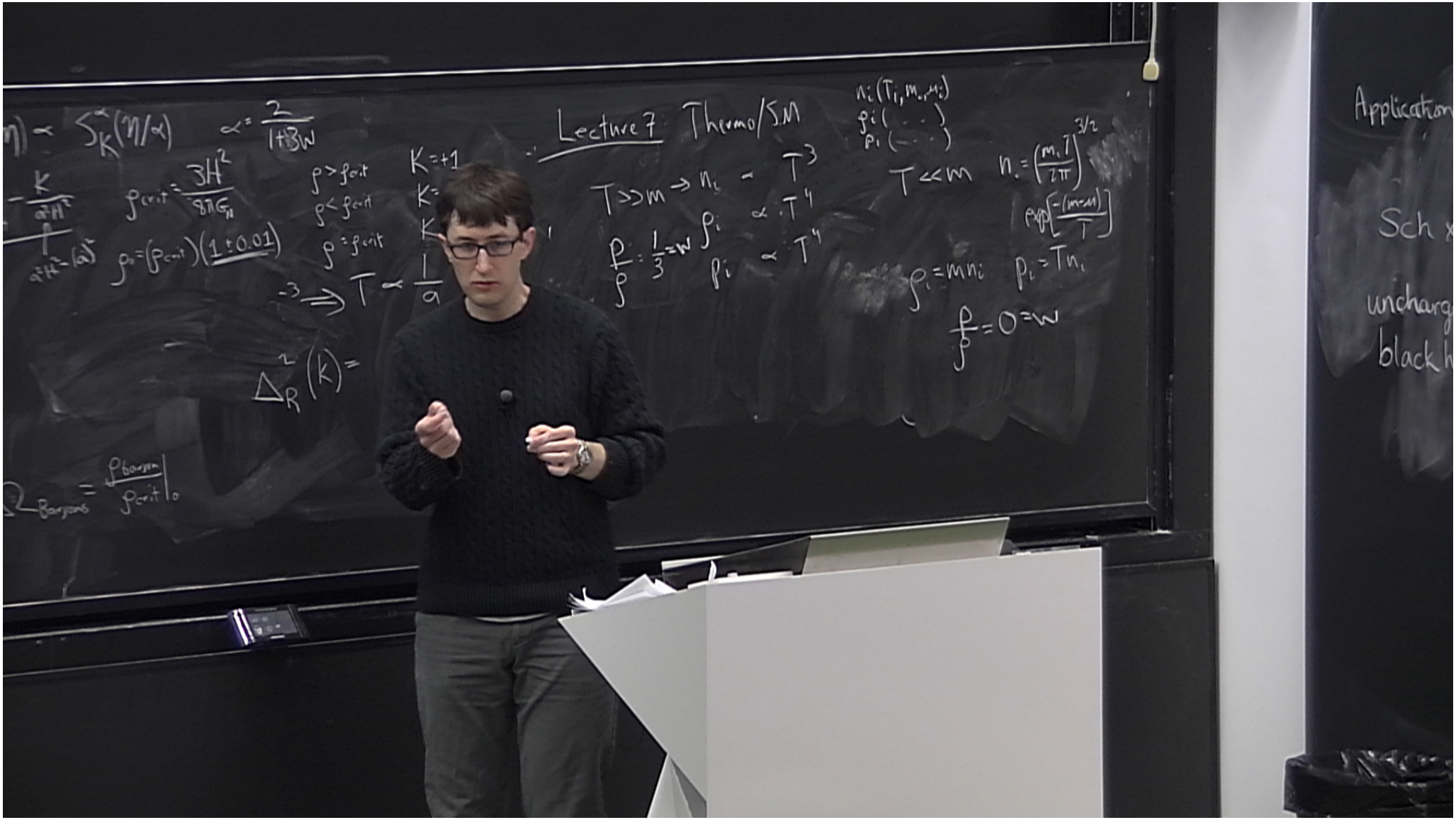
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$

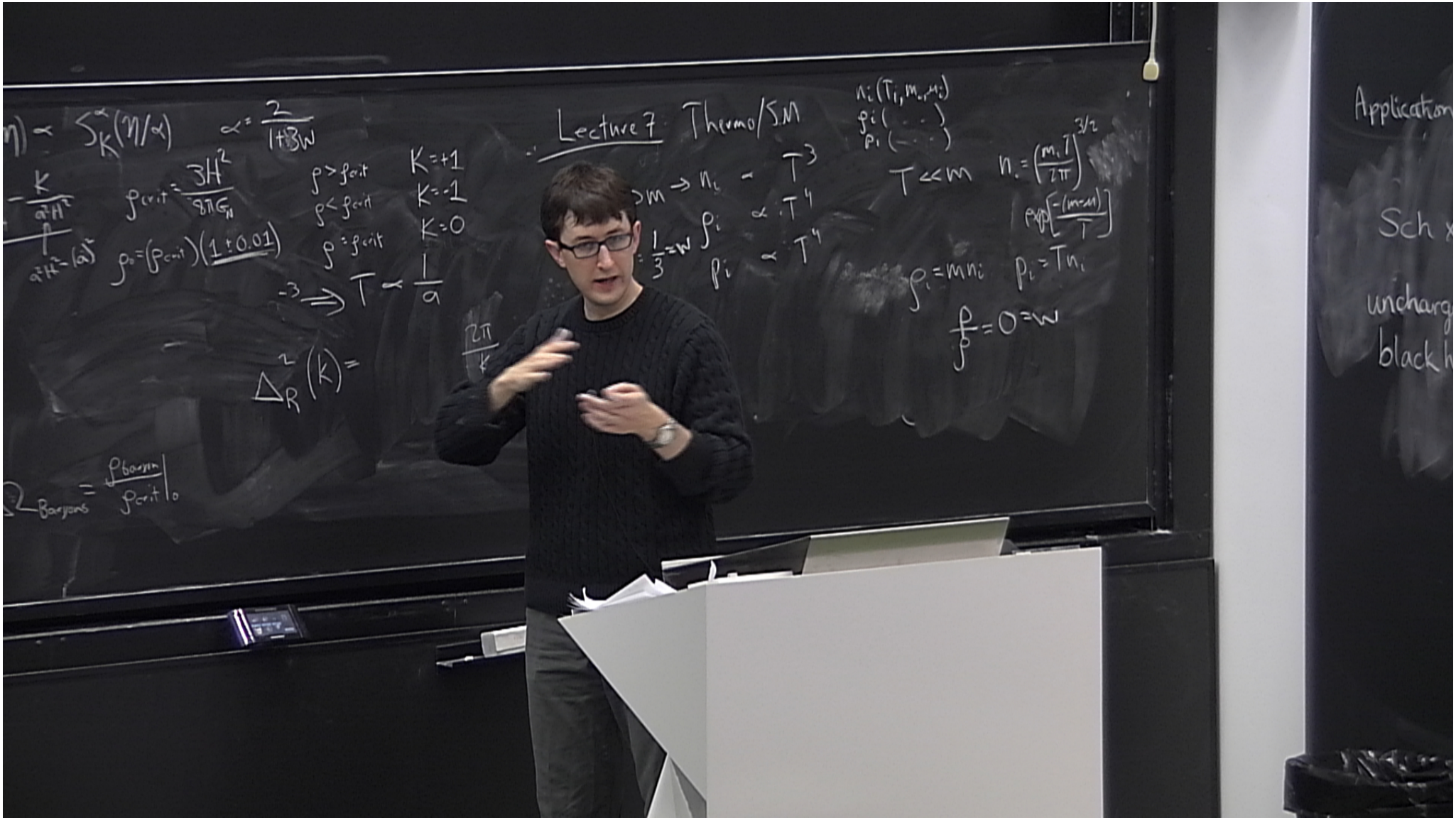
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$

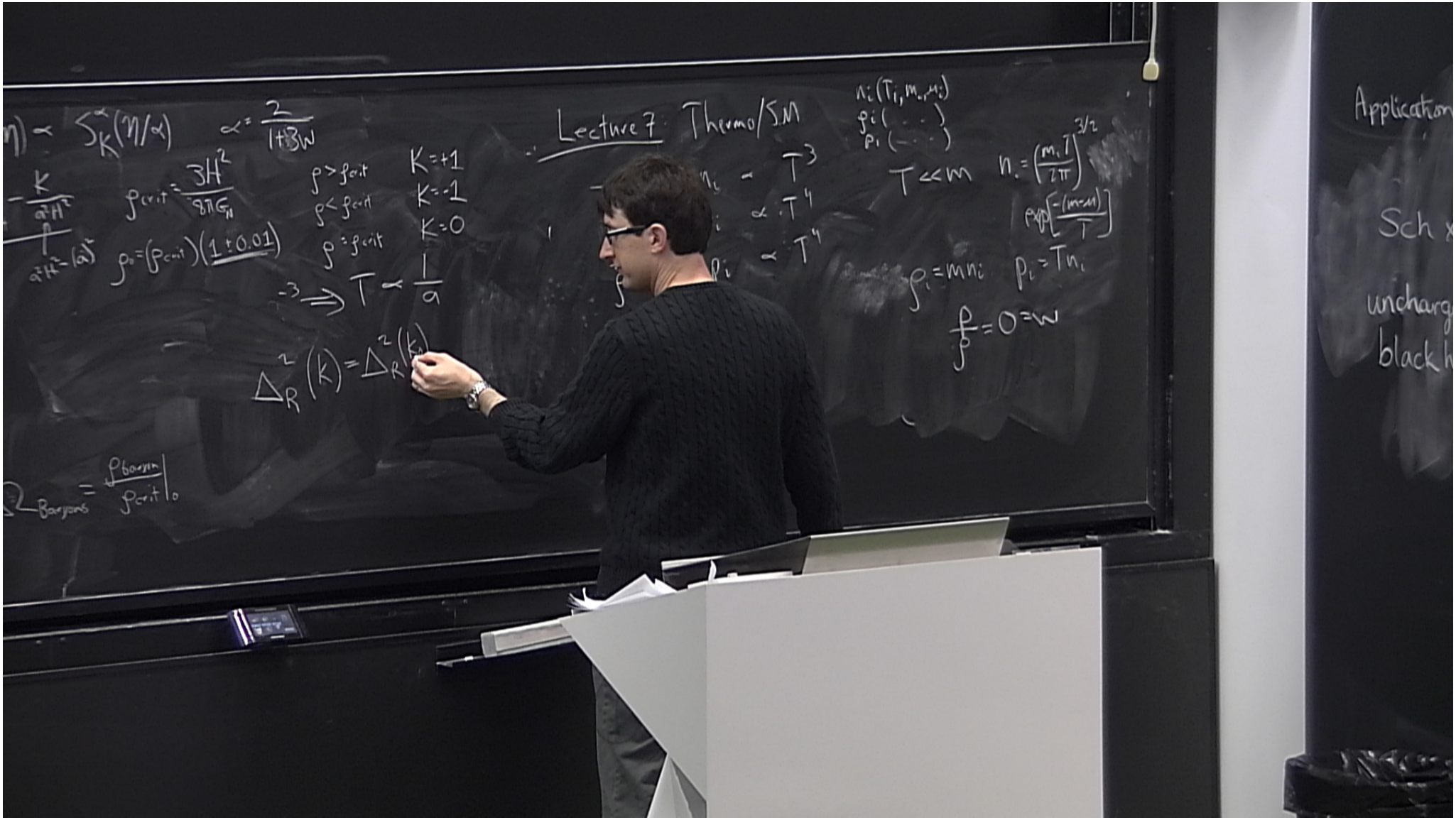
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$ $\quad \Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0$

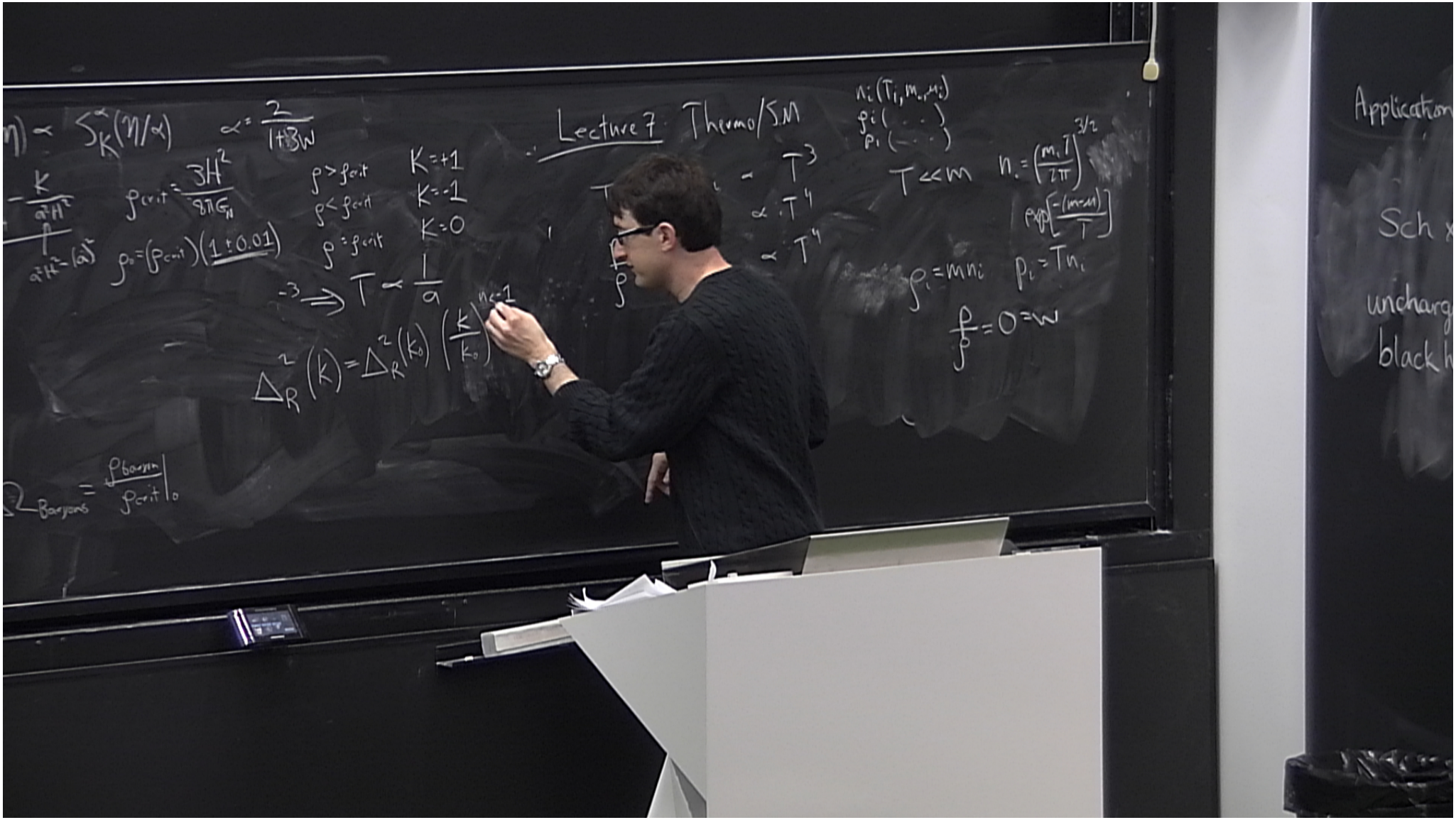
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$

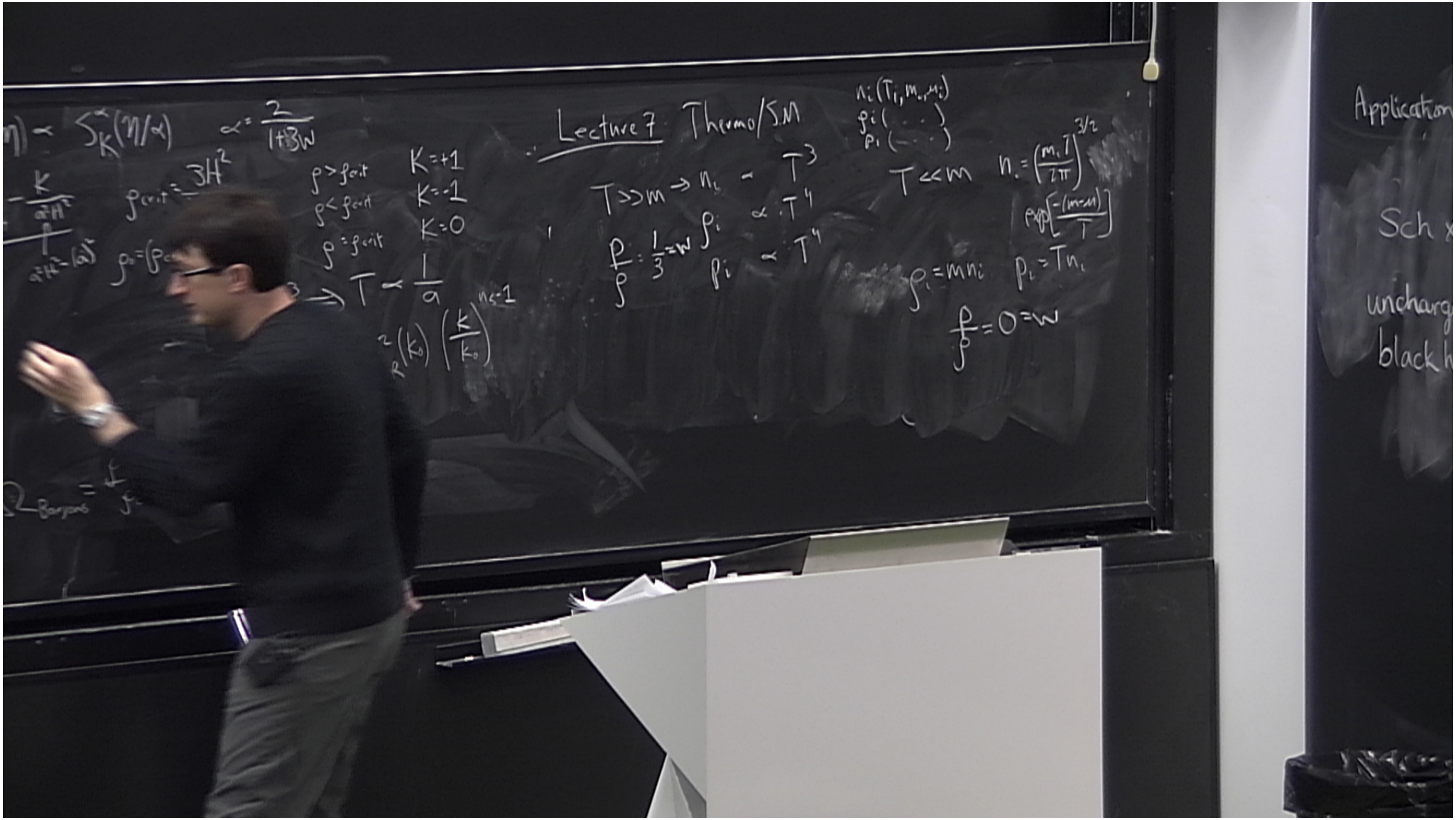
$\Delta_R^2(k) =$

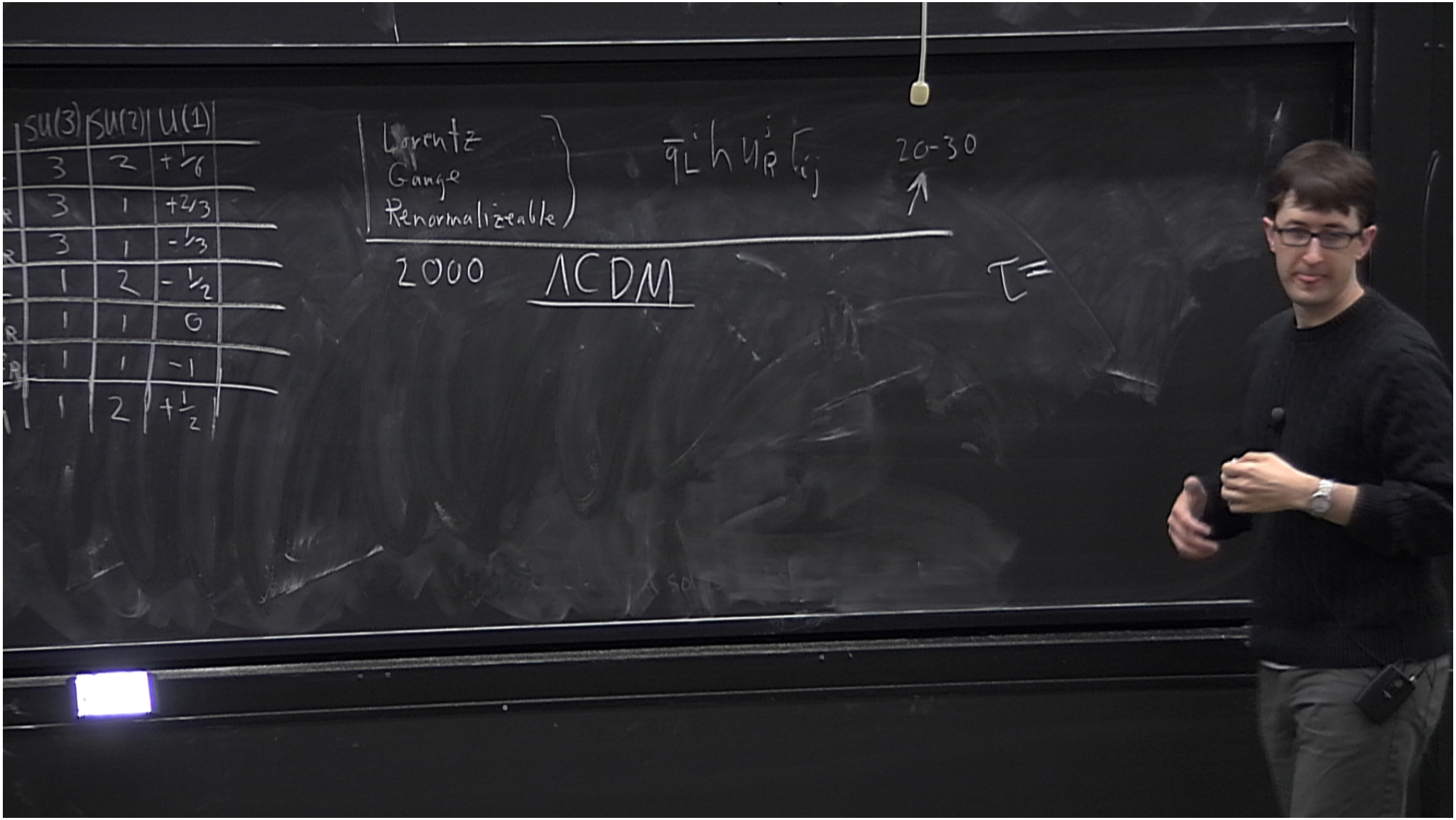

Lecture 7 Thermo/SM
Application
Sch
uncharg
black h

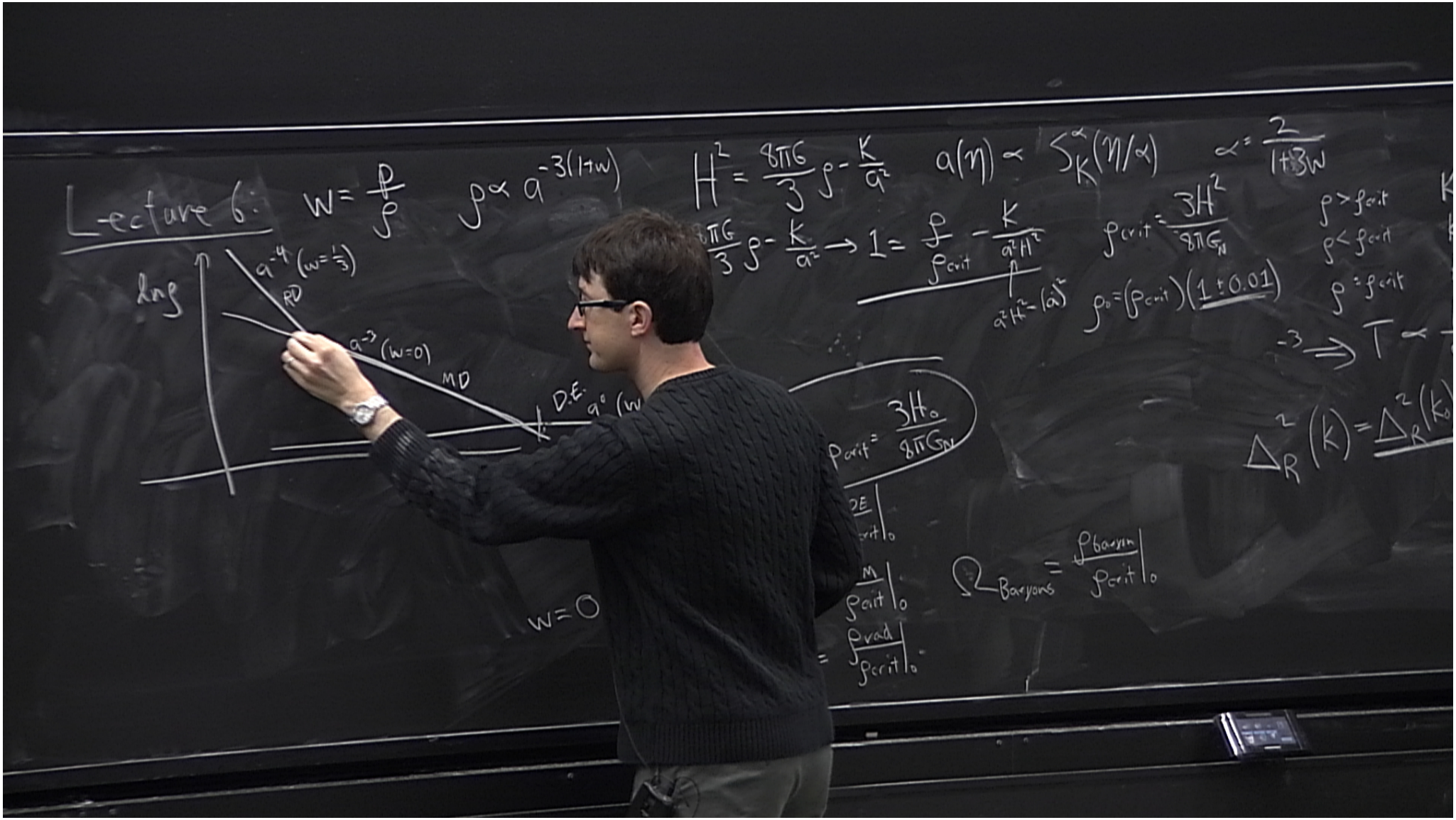

Lecture 7 Thermo/SM
Application
Sch
uncharg
black h


Lecture 7: Thermo/SM
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_*)$
$T \ll m$
$\rho_i = m n_i$ $p_i = T n_i$
$f = 0 = w$
Application
Sch
uncharg
black h


Lecture 7 Thermo/SM
Application
Sch
uncharg
black h


Lecture 7 Thermo/SM
Application
Sch
uncharg
black h


SU(3) SU(2) U(1)
3 2 +1/6
3 1 +2/3
3 1 -1/3
1 2 -1/2
1 1 0
1 1 -1
1 2 +1/2
Lorentz
Gauge
Renormalizeable
$\bar{q}_L h u_R^j$
20-30
2000 ΛCDM
$\tau =$


Lecture 6:
$w = \frac{p}{\rho}$
$\rho \propto a^{-3(1+w)}$
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
$a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$
$\alpha = \frac{2}{1+3w}$
$\frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$
$\Rightarrow T \propto$
$\Delta_R^2(k) = \Delta_R^2(k_0)$
ln ρ
a^{-4} (w=1/3)
RD
a^{-3} (w=0)
MD
D.E.
a^0 (w
$\rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0$
w=0

Lecture 6:

$w = \frac{p}{\rho}$ $\quad \rho \propto a^{-3(1+w)}$ $\quad H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$ $\quad a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$ $\quad \alpha = \frac{2}{1+3w}$

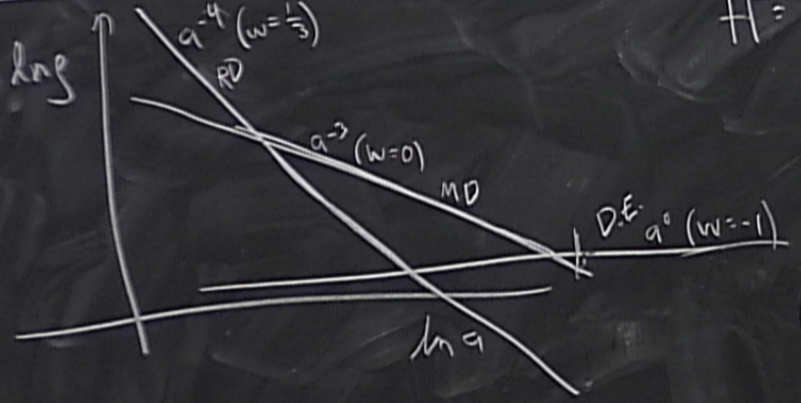
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$ $\quad \rho_{crit} = \frac{3H^2}{8\pi G_N}$

$a^2H^2 = (\dot{a})^2$

$\rho_0 = (\rho_{crit})(1 \pm 0.01)$

$\rho > \rho_{crit}$
$\rho < \rho_{crit}$
$\rho = \rho_{crit}$

$\Rightarrow T \propto$



$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$

$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$

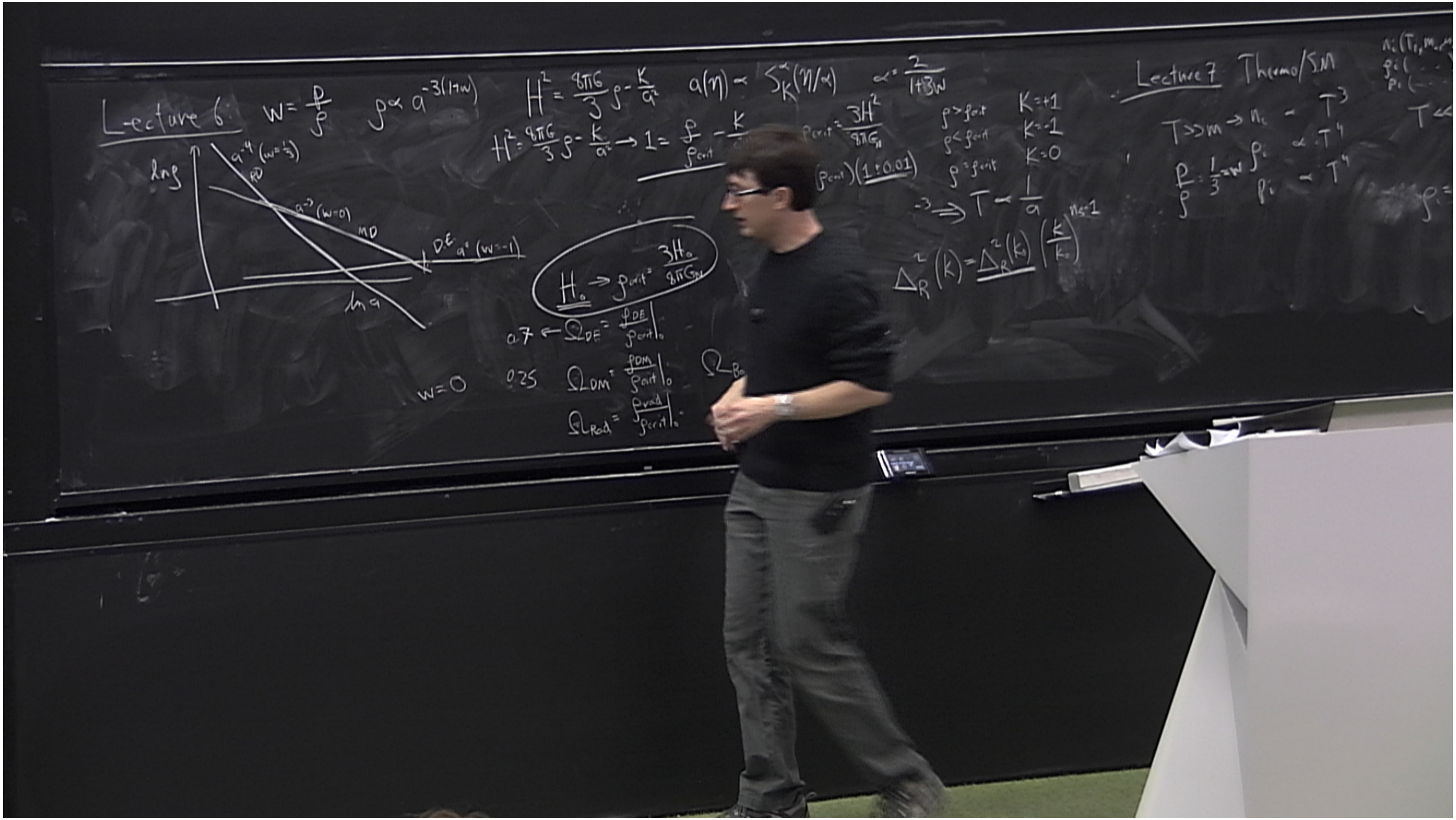
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$

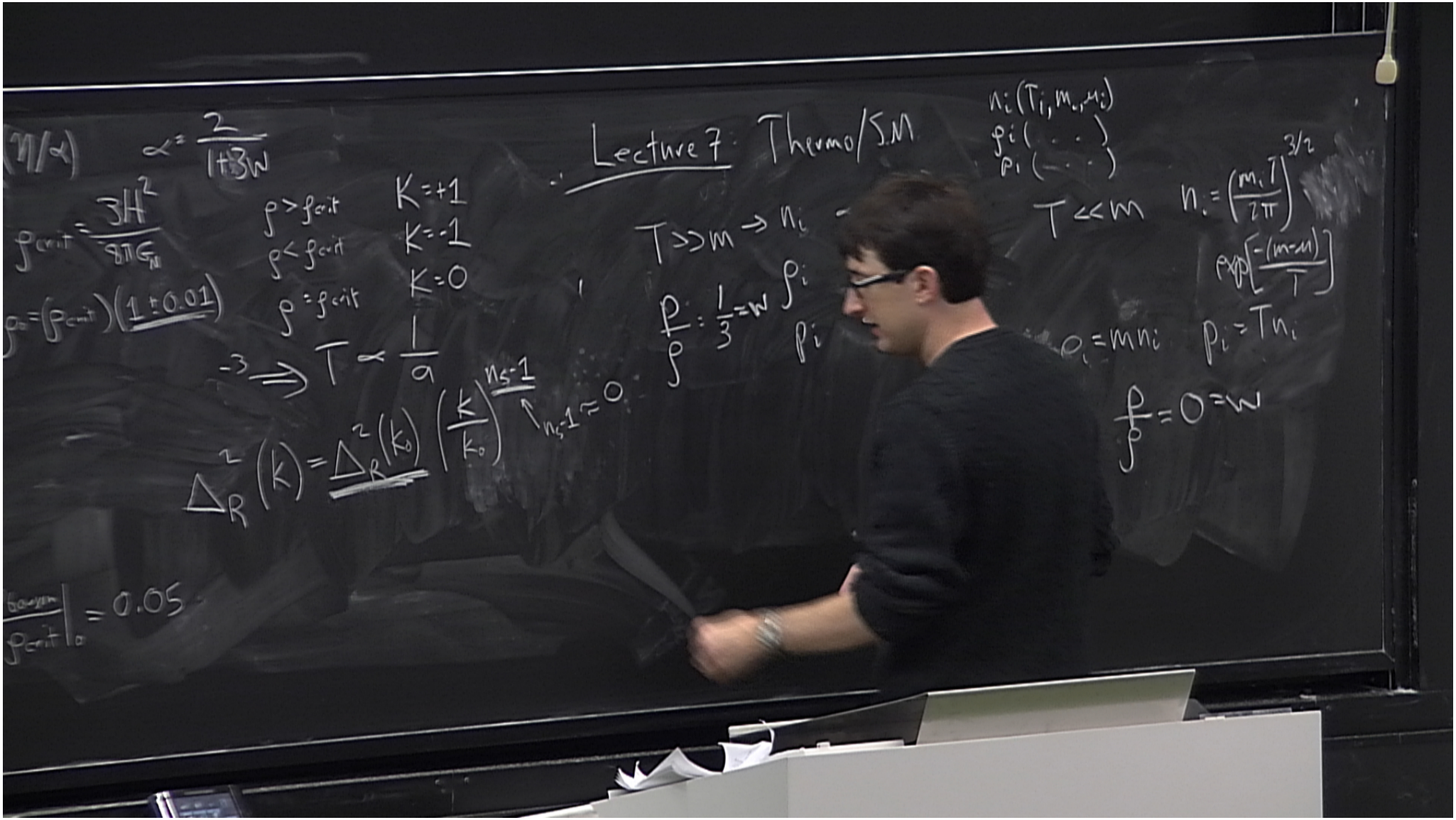
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$

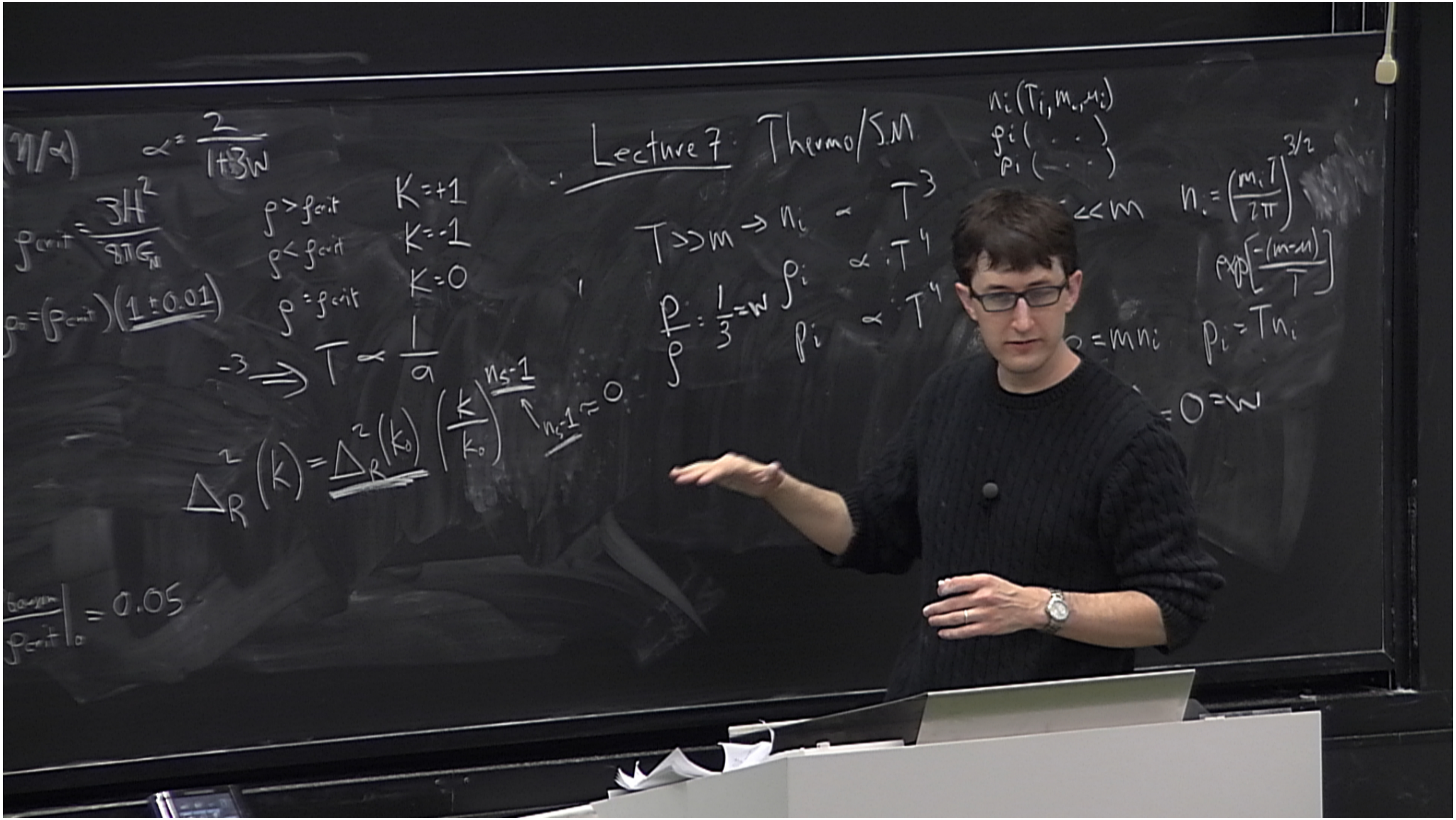
$\Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0$

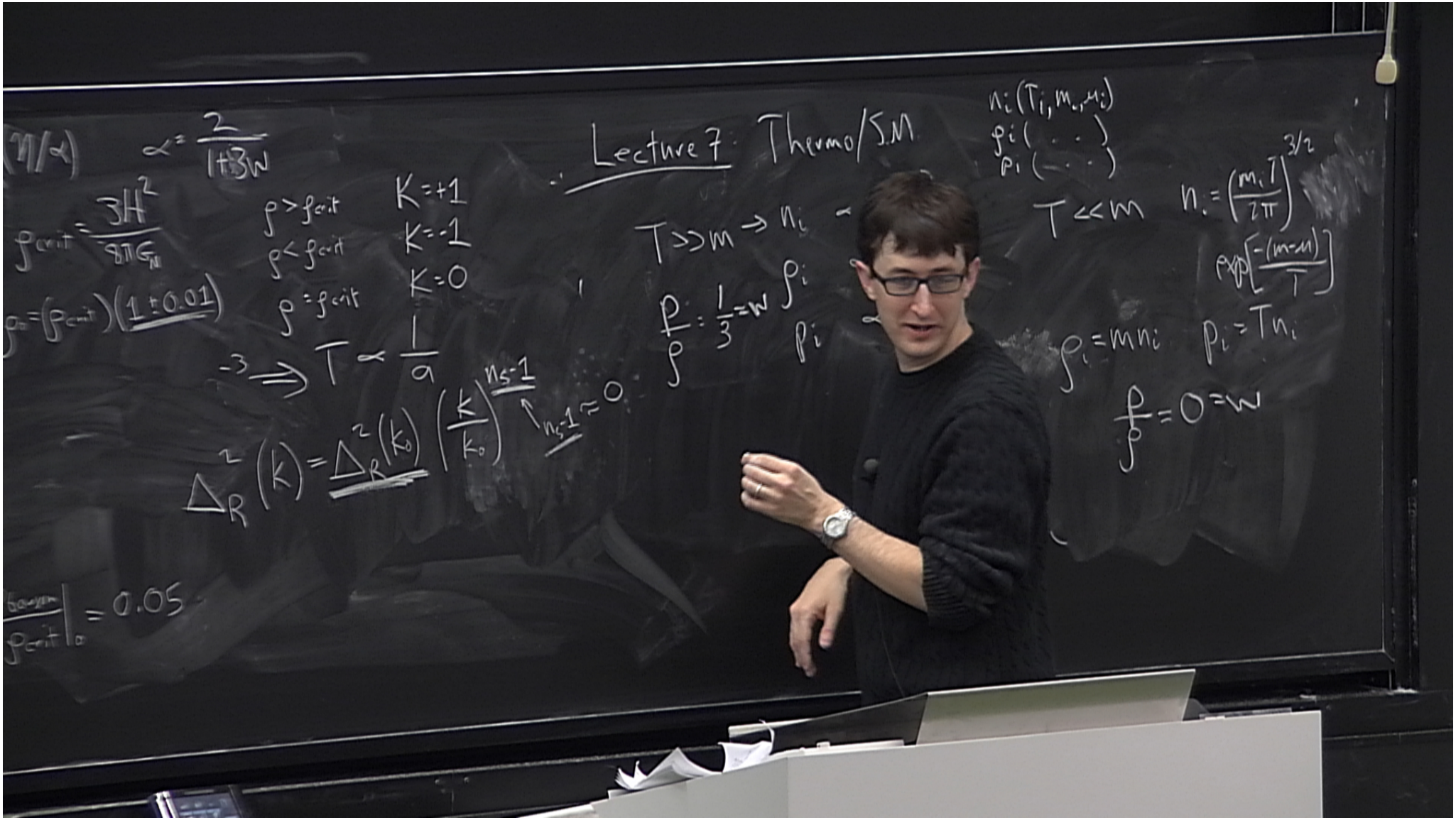
$w = 0$

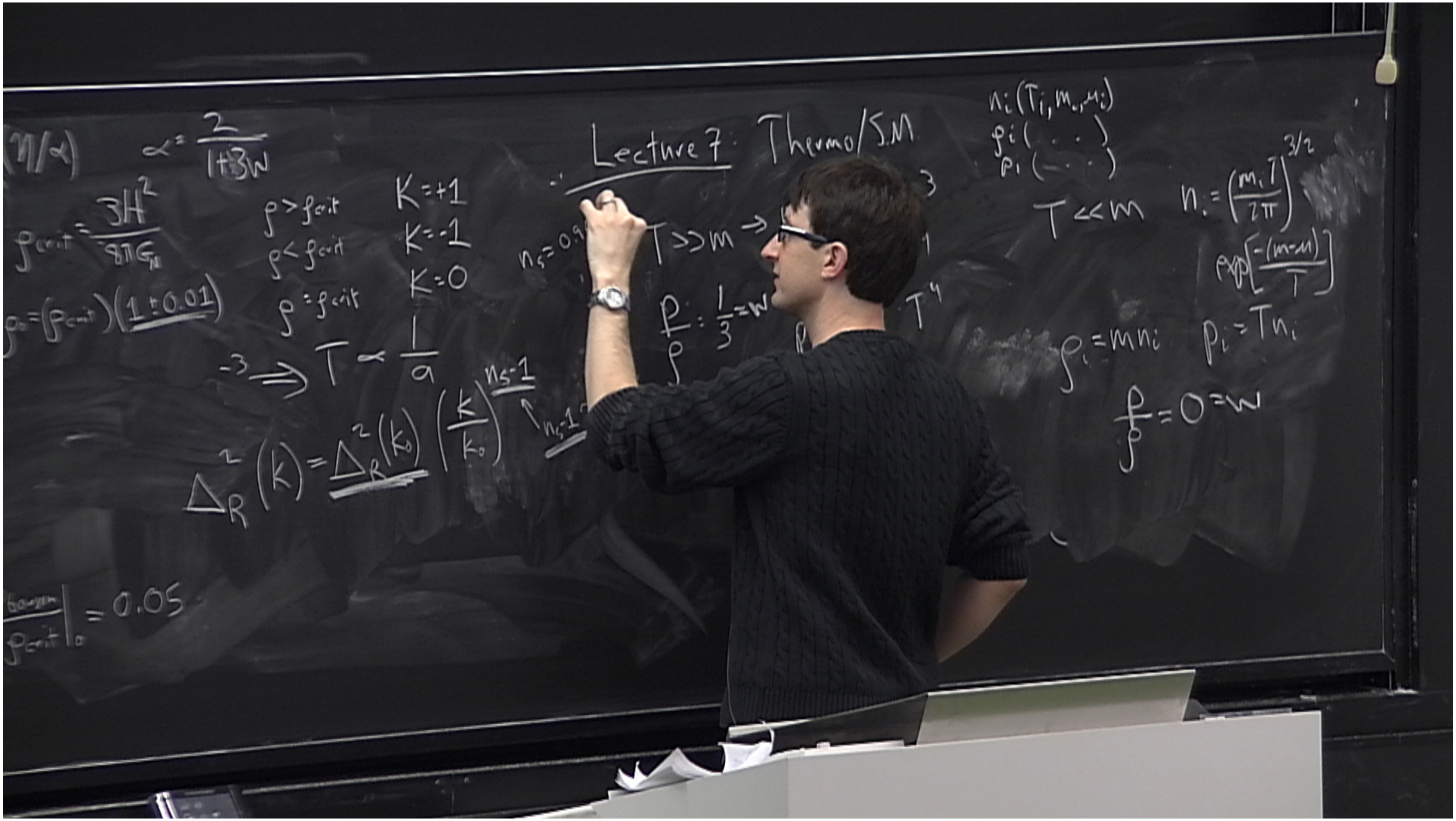
$\Delta_R^2(k) = \Delta_R^2(k_0)$

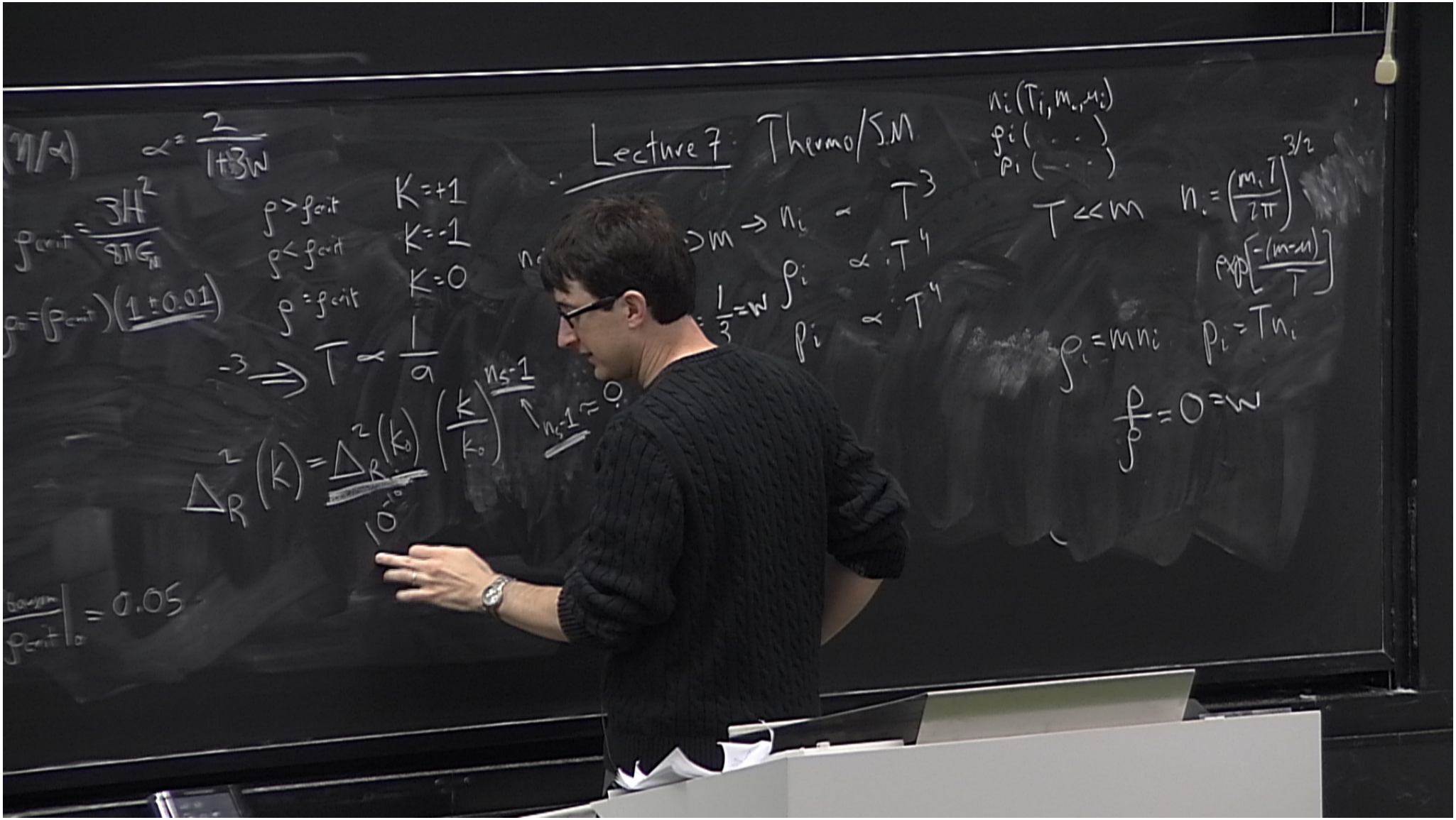

Lecture 6
Lecture 7 Thermo/SM
MD
DE
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$

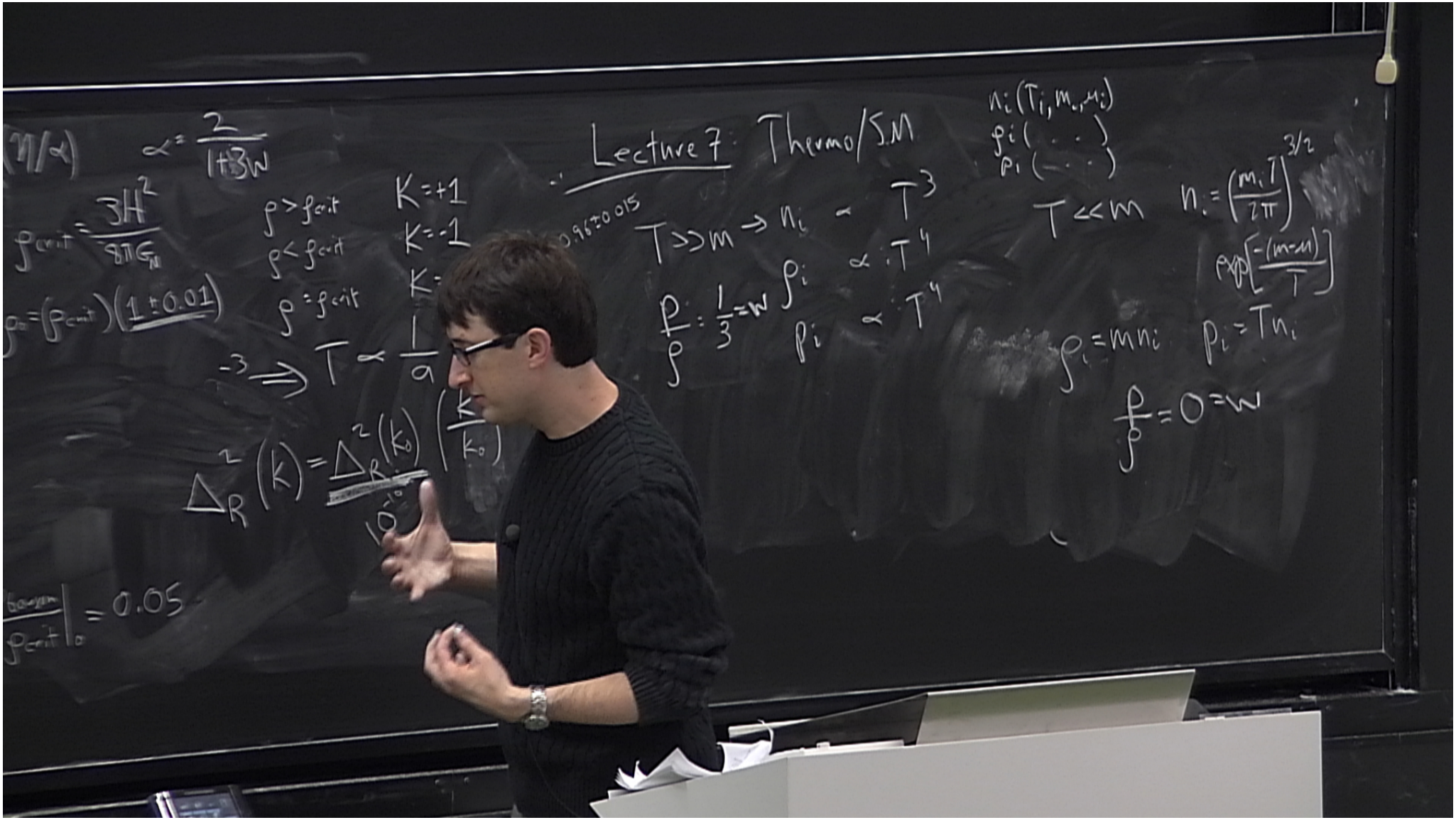

Lecture 7: Thermo/SM
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$
$n_s - 1 \approx 0$
$T \gg m \Rightarrow n_i$
$\frac{p}{\rho} = \frac{1}{3} = w$
$T \ll m$
$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m-\mu)}{T}\right]$
$\rho_i = m n_i$
$p_i = T n_i$
$\frac{p}{\rho} = 0 = w$
$= 0.05$

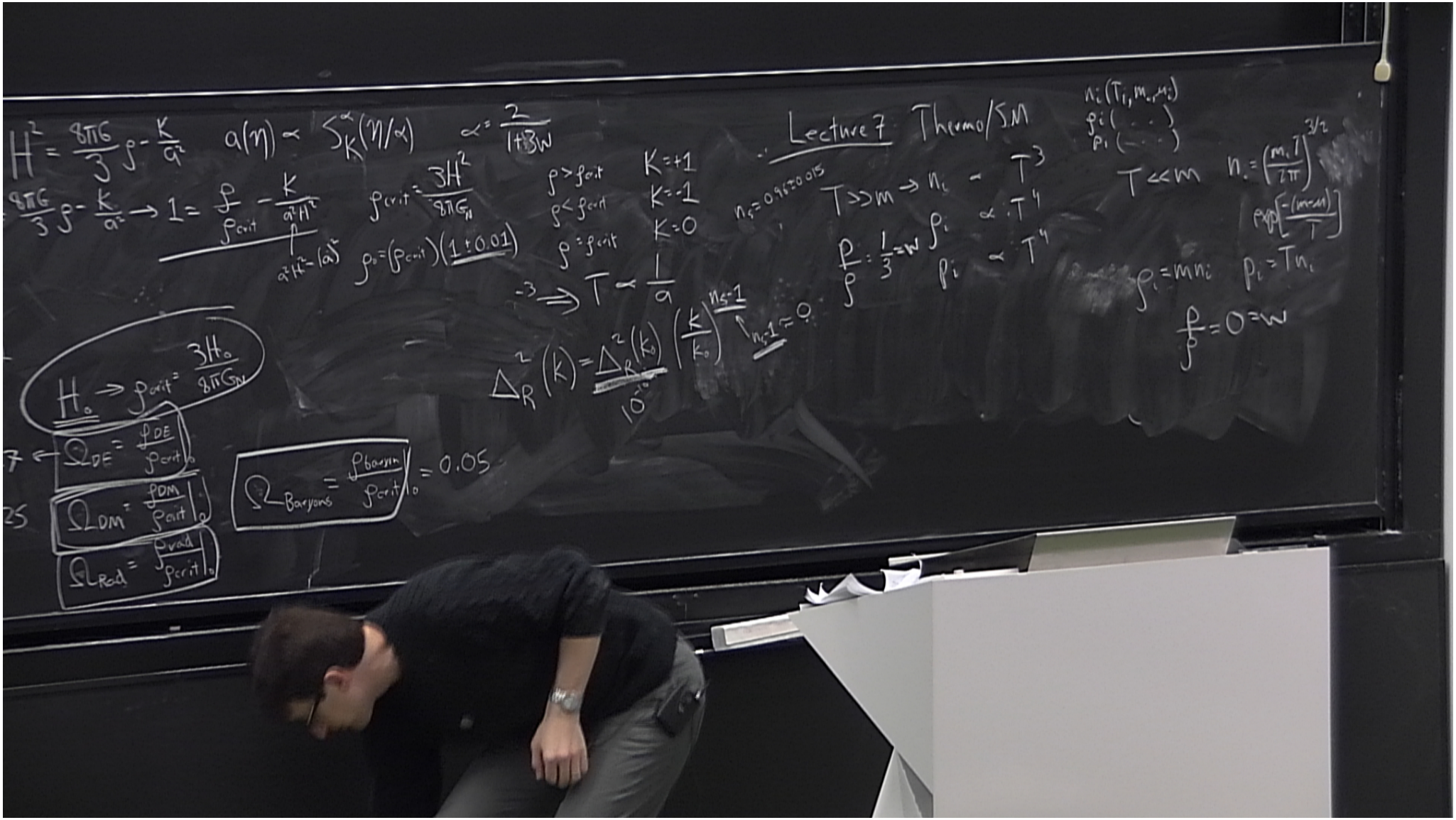

Lecture 7 Thermo/SM
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$
$n_s - 1 \approx 0$
$T \gg m \Rightarrow n_i \propto T^3$
$\frac{p}{\rho} = \frac{1}{3} = w$
$\rho_i \propto T^4$
$p_i \propto T^4$
$n_i(T_i, m_i, \mu_i)$
$\rho_i(\ldots)$
$p_i(\ldots)$
$m \gg T$
$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m-\mu)}{T}\right]$
$\rho = m n_i$
$p_i = T n_i$
$= 0 = w$
$\left.\frac{\rho_{baryon}}{\rho_{crit}}\right|_0 = 0.05$

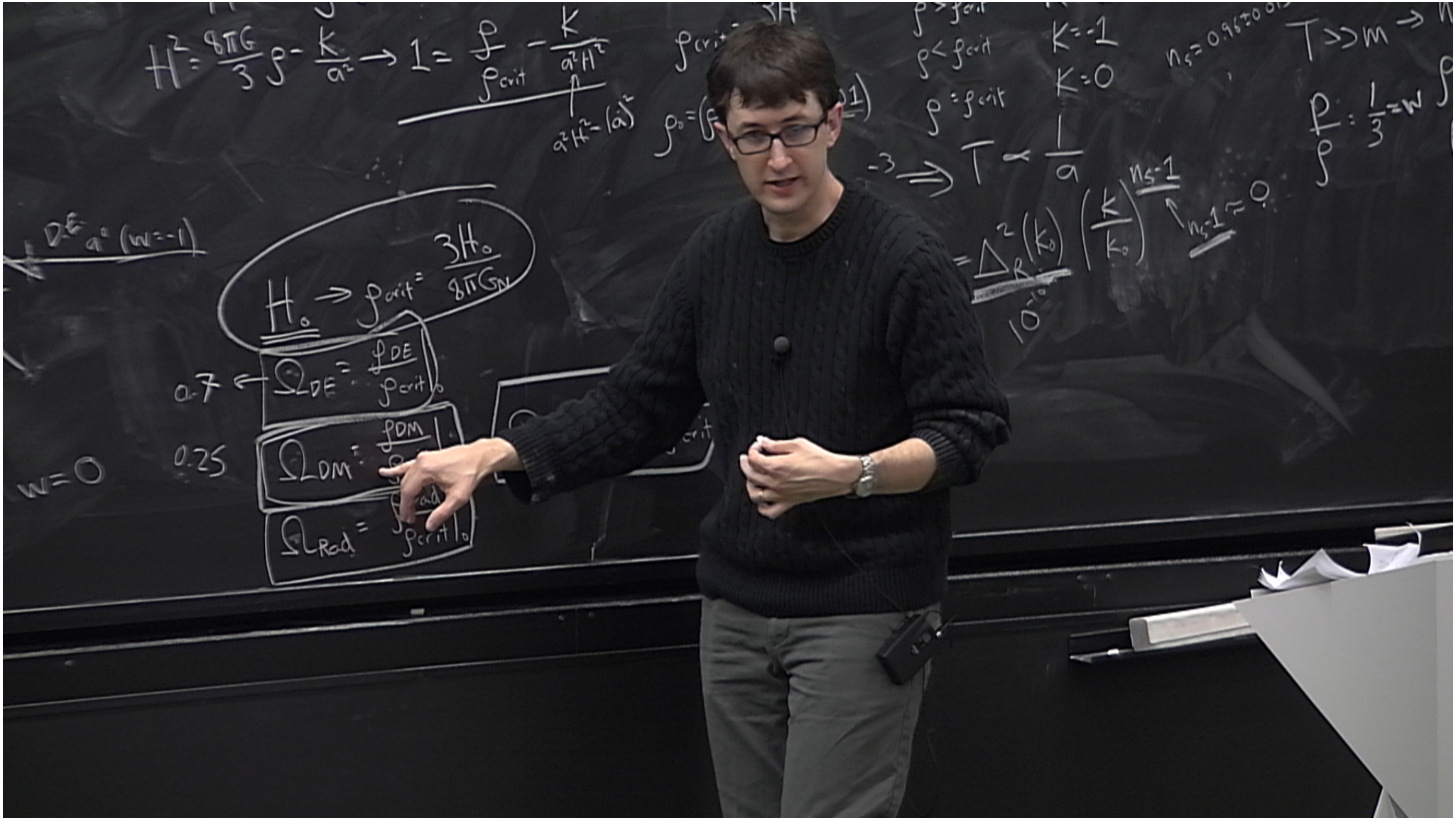

Lecture 7 Thermo/S.M
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$
$n_s - 1 \approx 0$
$T \gg m \Rightarrow n_i \sim$
$\frac{p}{\rho} = \frac{1}{3} = w$
$T \ll m$ $n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m-\mu)}{T}\right]$
$\rho_i = m n_i$ $p_i = T n_i$
$\frac{p}{\rho} = 0 = w$
$= 0.05$

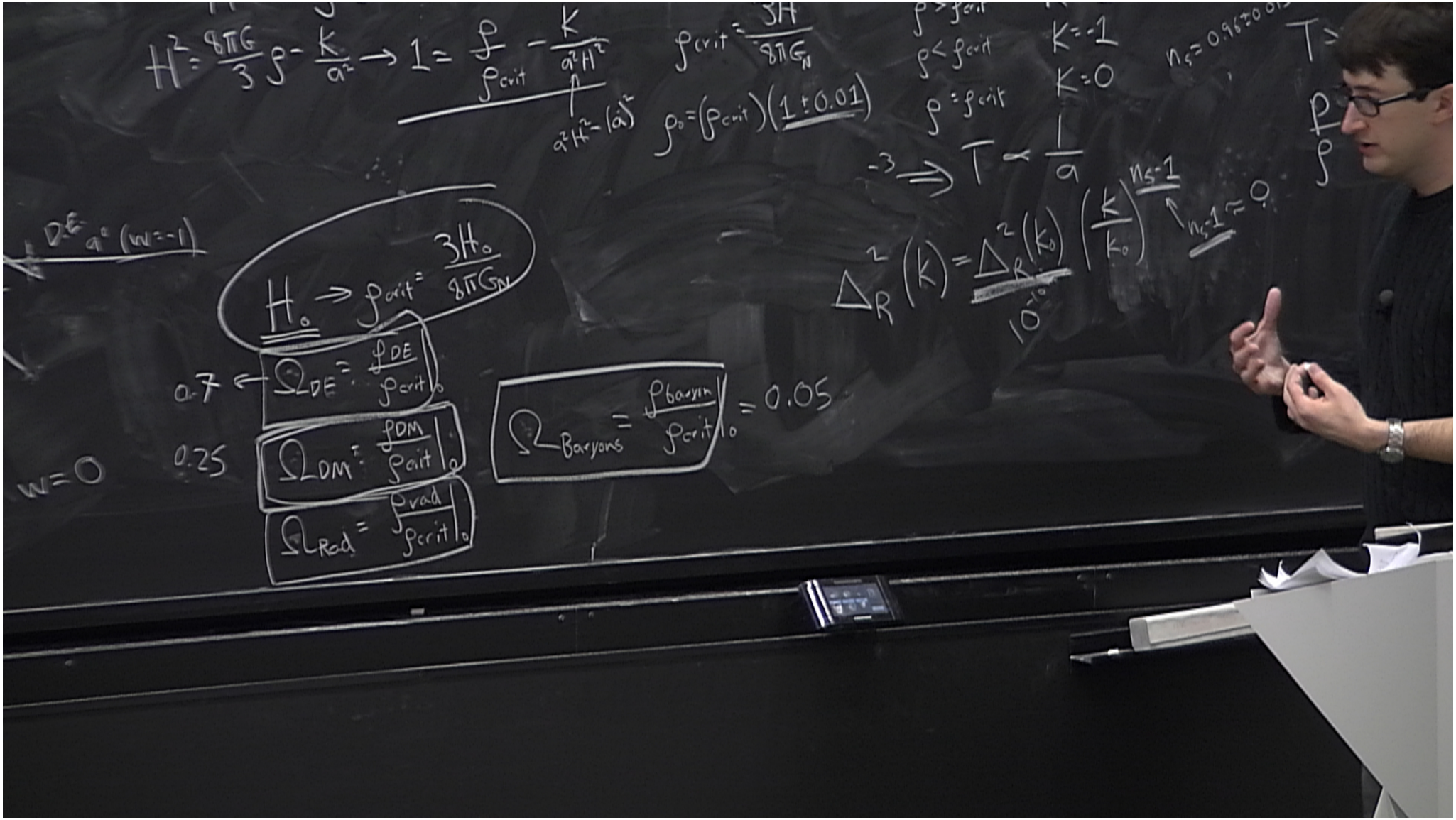

Lecture 7: Thermo/S.M
K=+1
K=-1
K=0
T>>m
T<<m
= 0.05

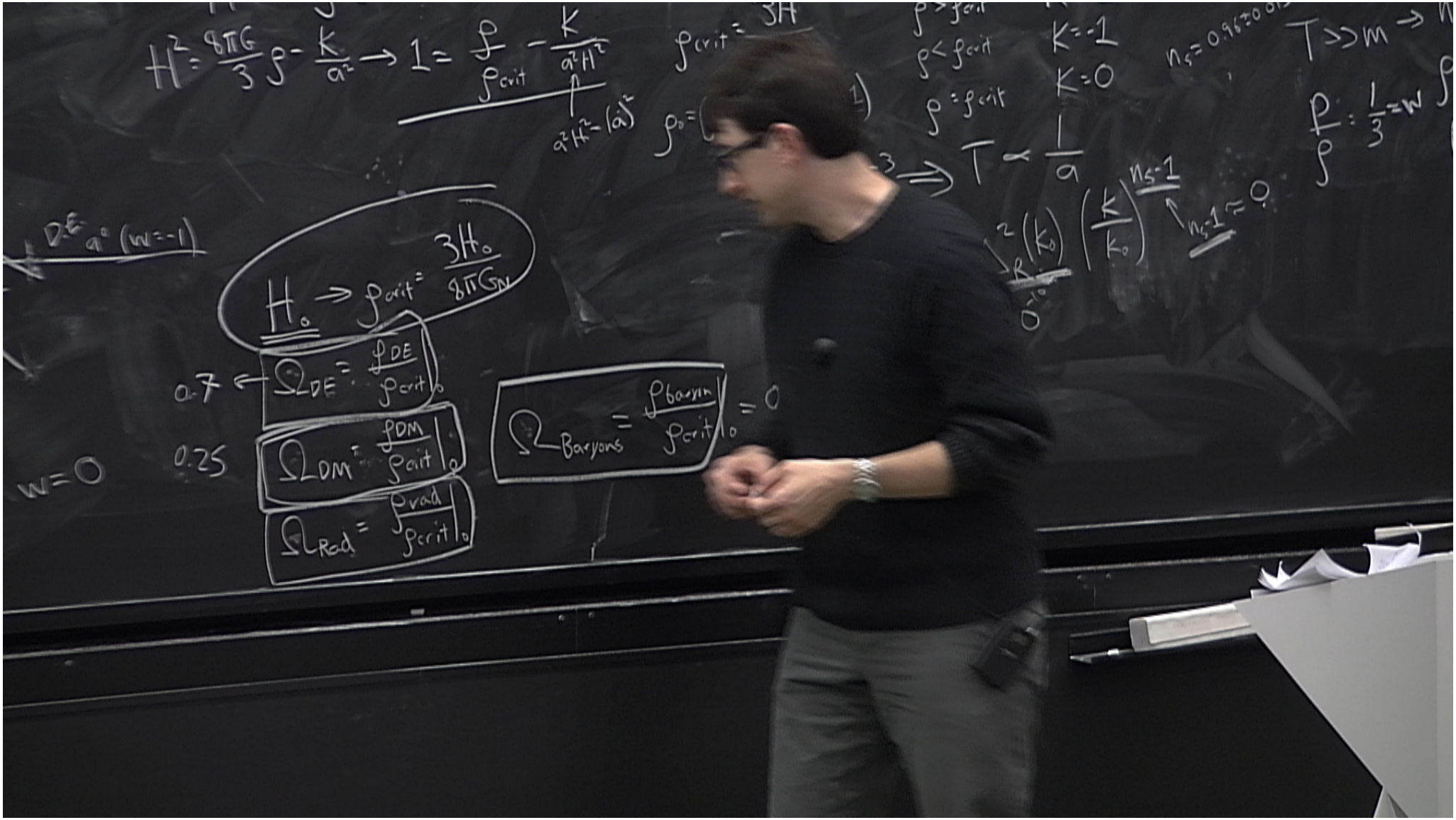

Lecture 7 Thermo/SM
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$
$n_s - 1 \simeq 0$
$w = \frac{1}{3}$
$\rho_i \propto T^4$
$T \ll m$
$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m-\mu)}{T}\right]$
$\rho_i = m n_i$ $p_i = T n_i$
$w = 0$

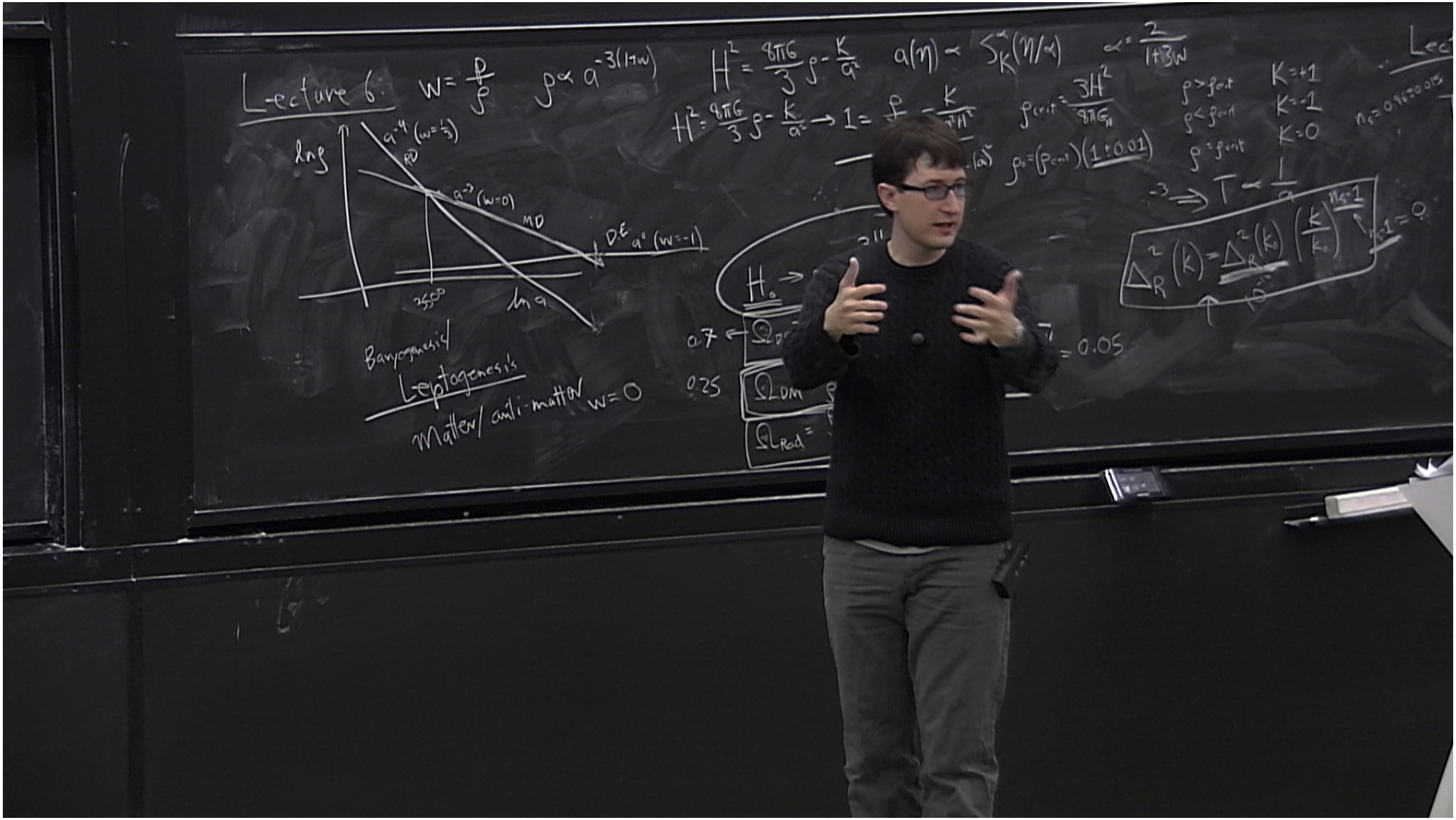

Lecture 7 Thermo/SM
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$ $K = +1$
$\rho < \rho_{crit}$ $K = -1$
$\rho = \rho_{crit}$
$\Rightarrow T \propto \frac{1}{a}$
$\Delta_R^2(k) = \frac{\Delta_R^2(k_0)}{10^{-10}} \left(\frac{k}{k_0}\right)$
$T \gg m \Rightarrow n_i \sim T^3$
$\frac{p}{\rho} = \frac{1}{3} = w$ $\rho_i \propto T^4$
$p_i \propto T^4$
$n_i(T_i, m_i, \mu_i)$
$\rho_i(\ldots)$
$p_i(\ldots)$
$T \ll m$ $n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m-\mu)}{T}\right]$
$\rho_i = m n_i$ $p_i = T n_i$
$\frac{p}{\rho} = 0 = w$
$= 0.05$


Lecture 7 Thermo/SM
$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$
$a(\eta) \propto S_K^{\alpha}(\eta/\alpha)$
$\alpha = \frac{2}{1+3w}$
$\rho_{crit} = \frac{3H^2}{8\pi G_N}$
$\rho > \rho_{crit}$ $K=+1$
$\rho < \rho_{crit}$ $K=-1$
$\rho = \rho_{crit}$ $K=0$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$a^3 \Rightarrow T \propto \frac{1}{a}$
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}|_0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}|_0$
$\Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}|_0 = 0.05$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-10}
$n_s = 0.96 \pm 0.015$
$n_s - 1 \simeq 0$
$T \gg m \rightarrow n_i \propto T^3$
$\frac{p}{\rho} = \frac{1}{3} = w$ $\rho_i \propto T^4$
$p_i \propto T^4$
$n_i(T_i, m_i, \mu_i)$
$\rho_i(\quad\quad)$
$p_i(\quad\quad)$
$T \ll m$ $n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{-(m_i - \mu_i)}{T}\right]$
$\rho_i = m n_i$ $p_i = T n_i$
$\frac{p}{\rho} = 0 = w$


$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$a^2H^2 = (\dot{a})^2$
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}$
0.7
0.25
w=0
DE a^0 (w=-1)
$\rho > \rho_{crit}$ K=-1
$\rho < \rho_{crit}$ K=0
$\rho = \rho_{crit}$
$T \propto \frac{1}{a}$
$n_s = 0.96 \pm 0.01$
$n_s - 1 \simeq 0$
$T \gg m \Rightarrow \frac{\rho}{\rho} = \frac{1}{3} = w$


$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H}{8\pi G_N}$
$a^2H^2 = (\dot{a})^2$
$\rho_0 = (\rho_{crit})(1 \pm 0.01)$
$\rho > \rho_{crit}$ $K = +1$
$\rho < \rho_{crit}$ $K = -1$
$\rho = \rho_{crit}$ $K = 0$
$n_s = 0.96 \pm 0.01$
$T =$
ρ
$-3 \Rightarrow T \propto \frac{1}{a}$
$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-10}
$n_s - 1 \simeq 0$
DE a^0 $(w = -1)$
$H_0 \rightarrow \rho_{crit} = \frac{3H_0}{8\pi G_N}$
0.7 $\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
0.25 $\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$
$w = 0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$
$\Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0 = 0.05$


$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} \rightarrow 1 = \frac{\rho}{\rho_{crit}} - \frac{K}{a^2H^2}$
$\rho_{crit} = \frac{3H^2}{8\pi G}$
$a^2H^2 = (\dot{a})^2$
$\rho > \rho_{crit}$ $K = +1$
$\rho < \rho_{crit}$ $K = -1$
$\rho = \rho_{crit}$ $K = 0$
$T \propto \frac{1}{a}$
$T \gg m \Rightarrow$
$\frac{p}{\rho} = \frac{1}{3} = w$
$n_s = 0.96 \pm 0.01$
$n_s - 1 \neq 0$
$H_0 \rightarrow \rho_{crit} = \frac{3H_0^2}{8\pi G_N}$
$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}\Big|_0$
$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}}\Big|_0$
$\Omega_{Rad} = \frac{\rho_{rad}}{\rho_{crit}}\Big|_0$
$\Omega_{Baryons} = \frac{\rho_{baryon}}{\rho_{crit}}\Big|_0 = 0$
0.7
0.25
$w = 0$
DE a^0 $(w = -1)$


Lecture 6.
ln ρ
ln a
MD
DE
Baryogenesis/
Leptogenesis
Matter/anti-matter
0.7
0.25
0.05
K=+1
K=-1
K=0