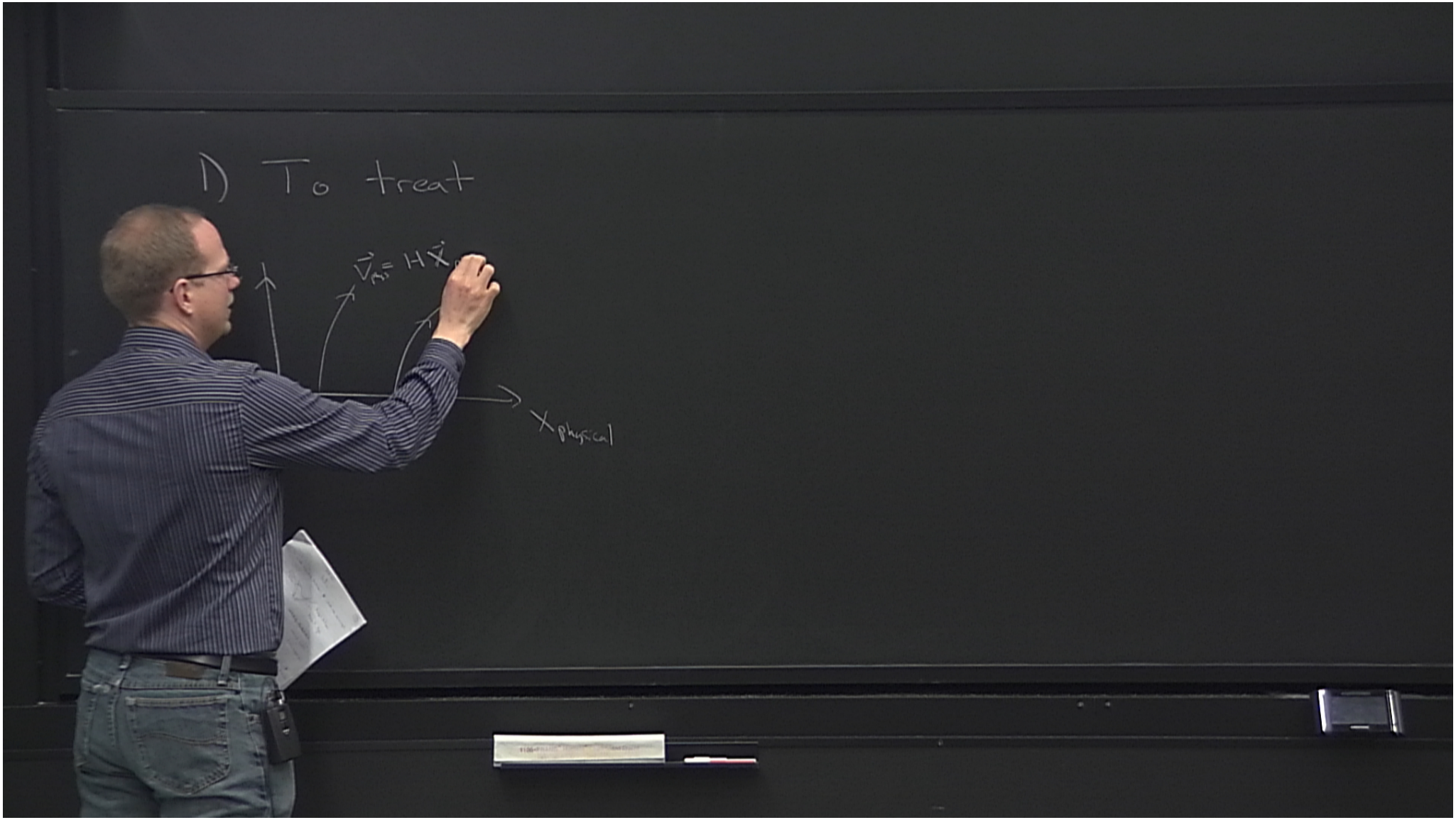
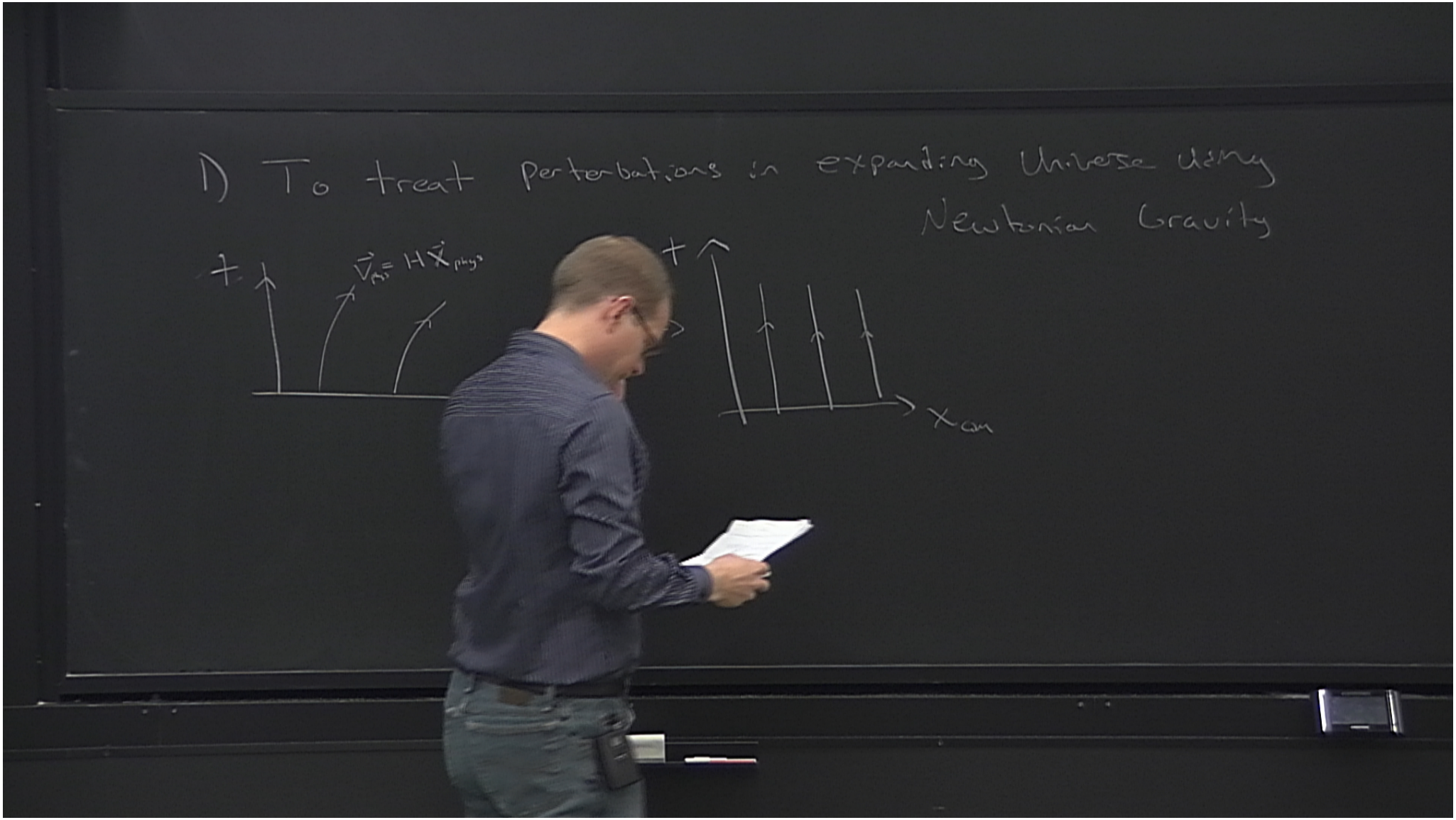
Title: 13/14 PSI - Explorations in Cosmology - Lecture 3

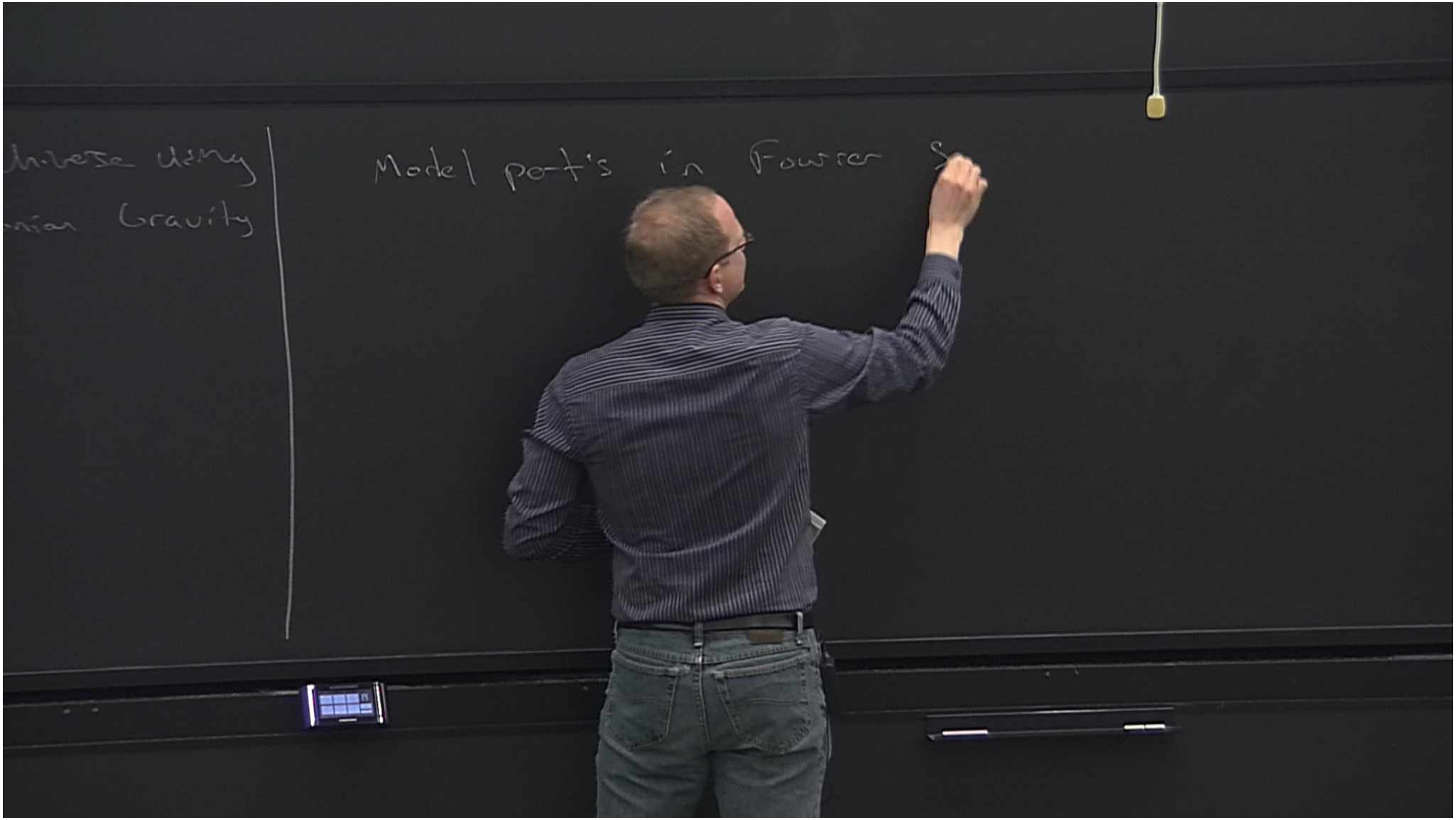
Date: Apr 09, 2014 10:15 AM

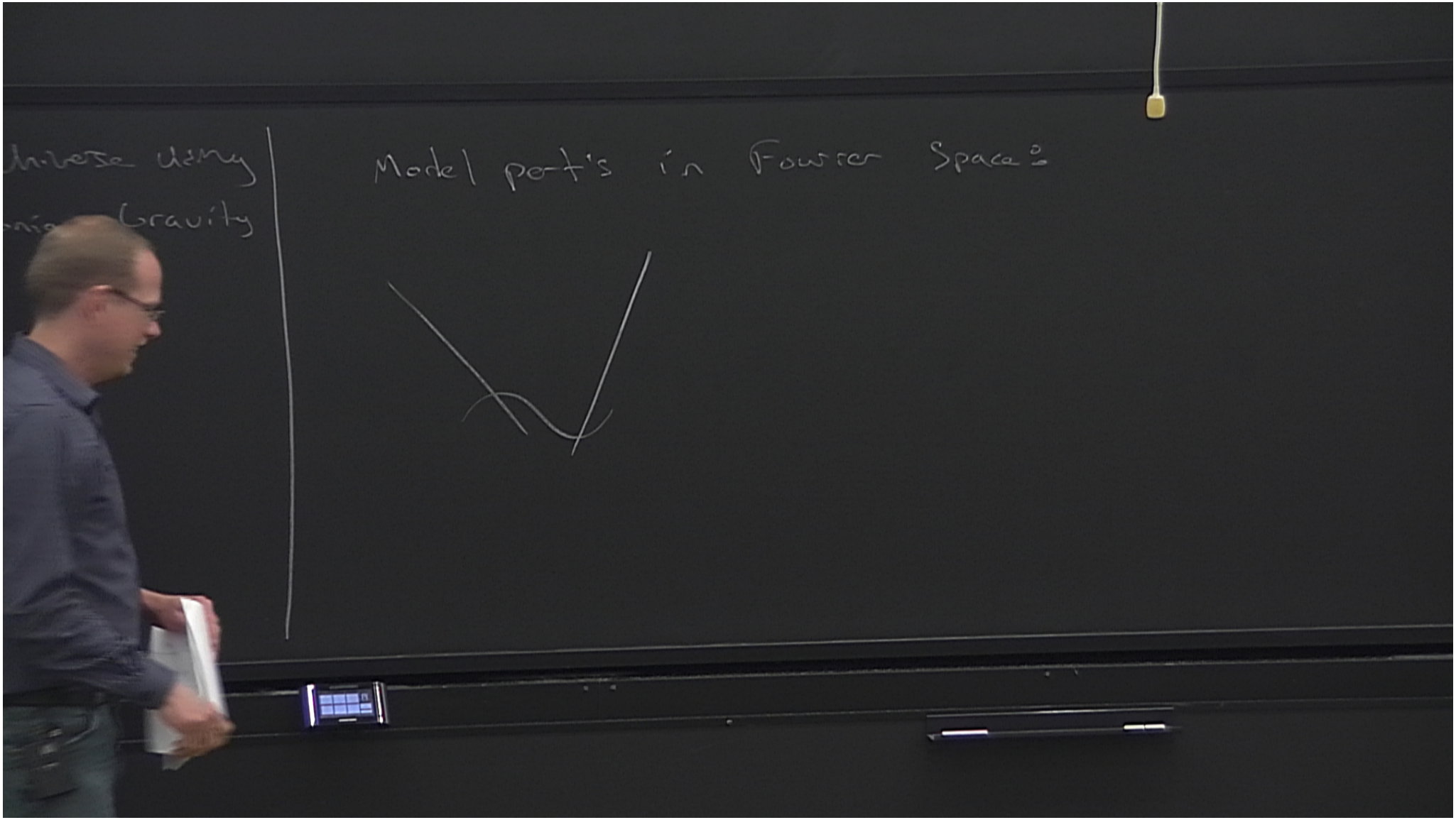
URL: http://pirsa.org/14040043

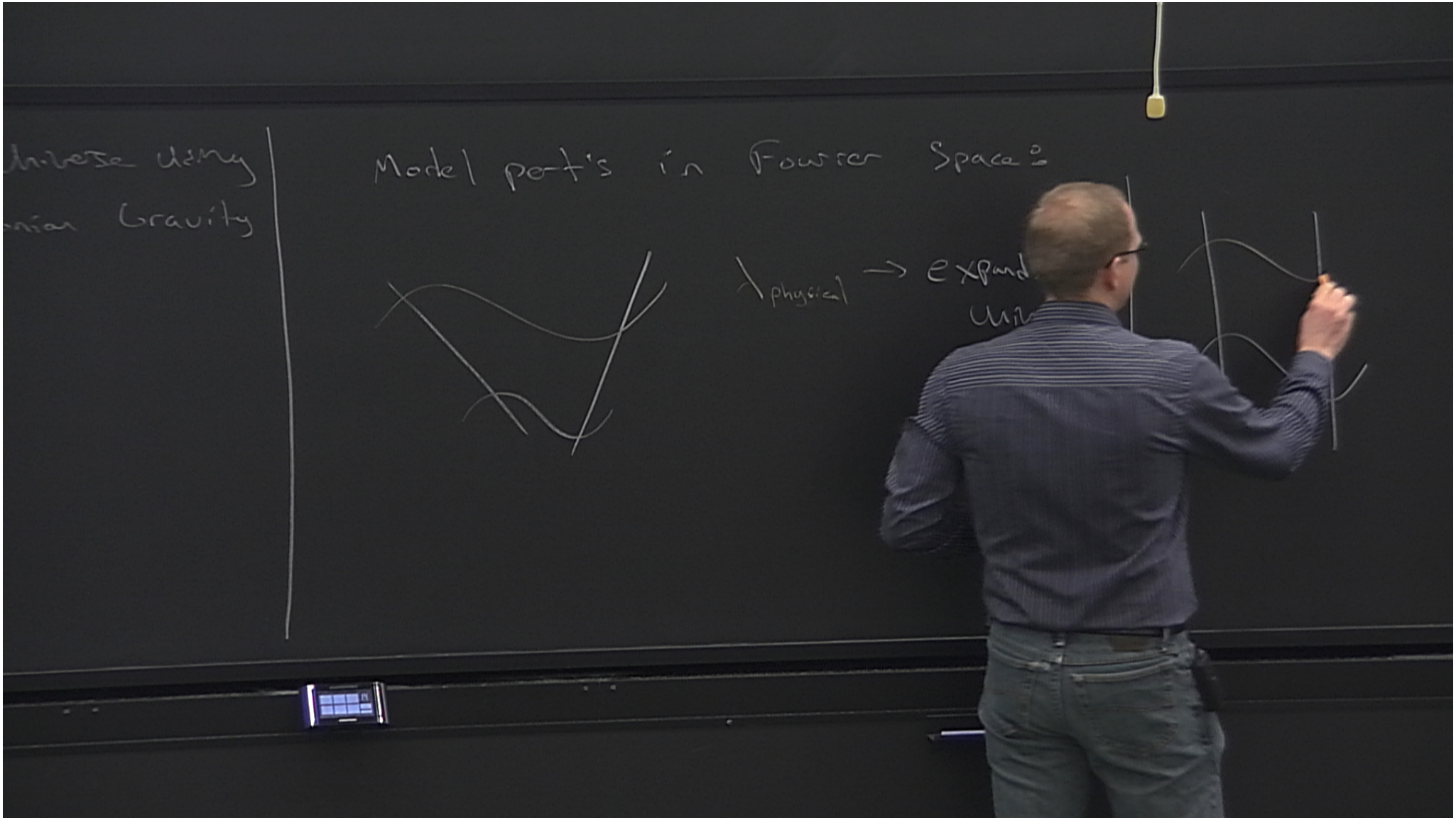
Abstract:

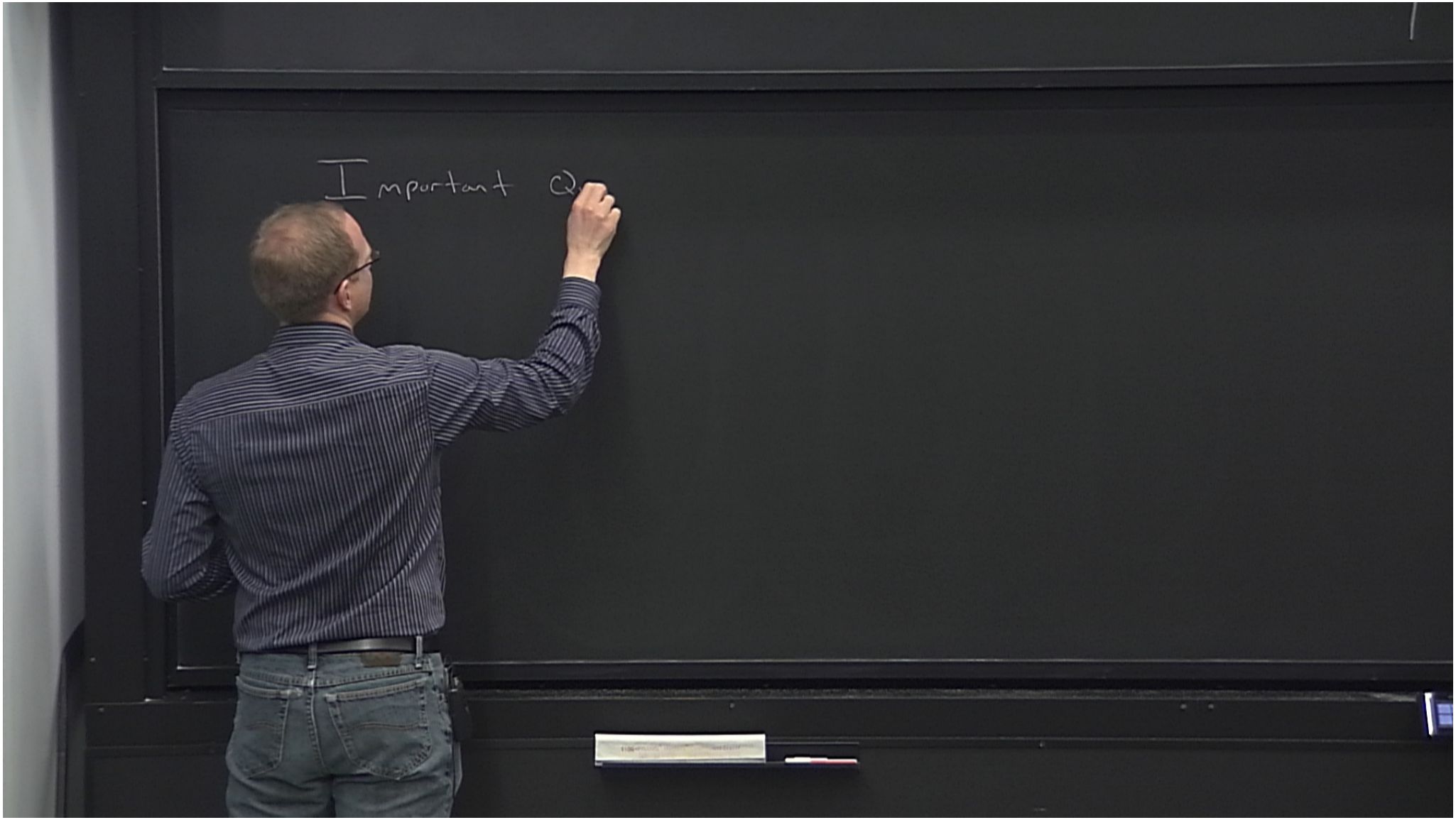

1) To treat
physical

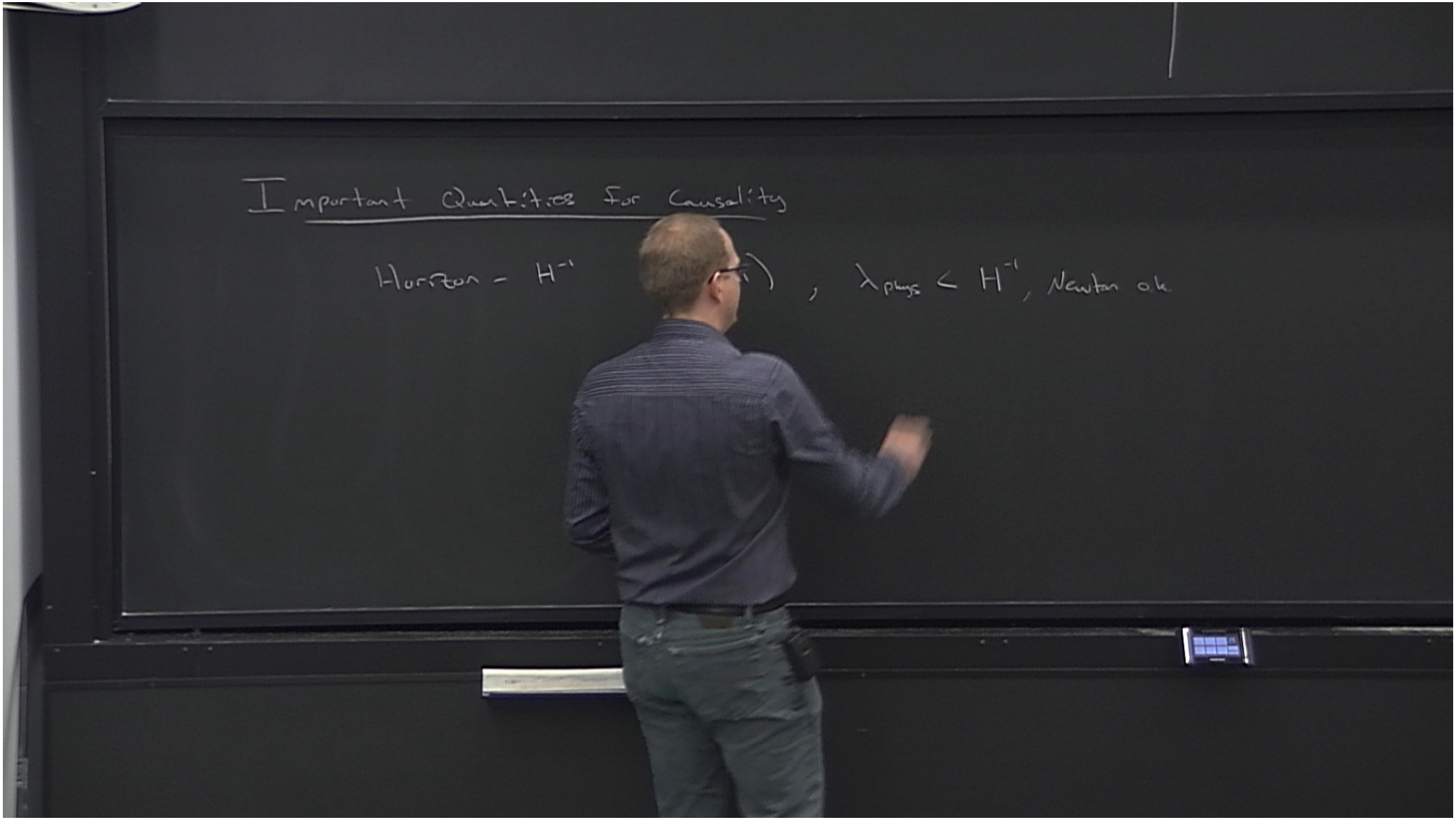

1) To treat perterbations in expanding Universe using
Newtonian Gravity
t
$\vec{V}_{pec} = H\vec{X}_{phys}$
t
x_{com}

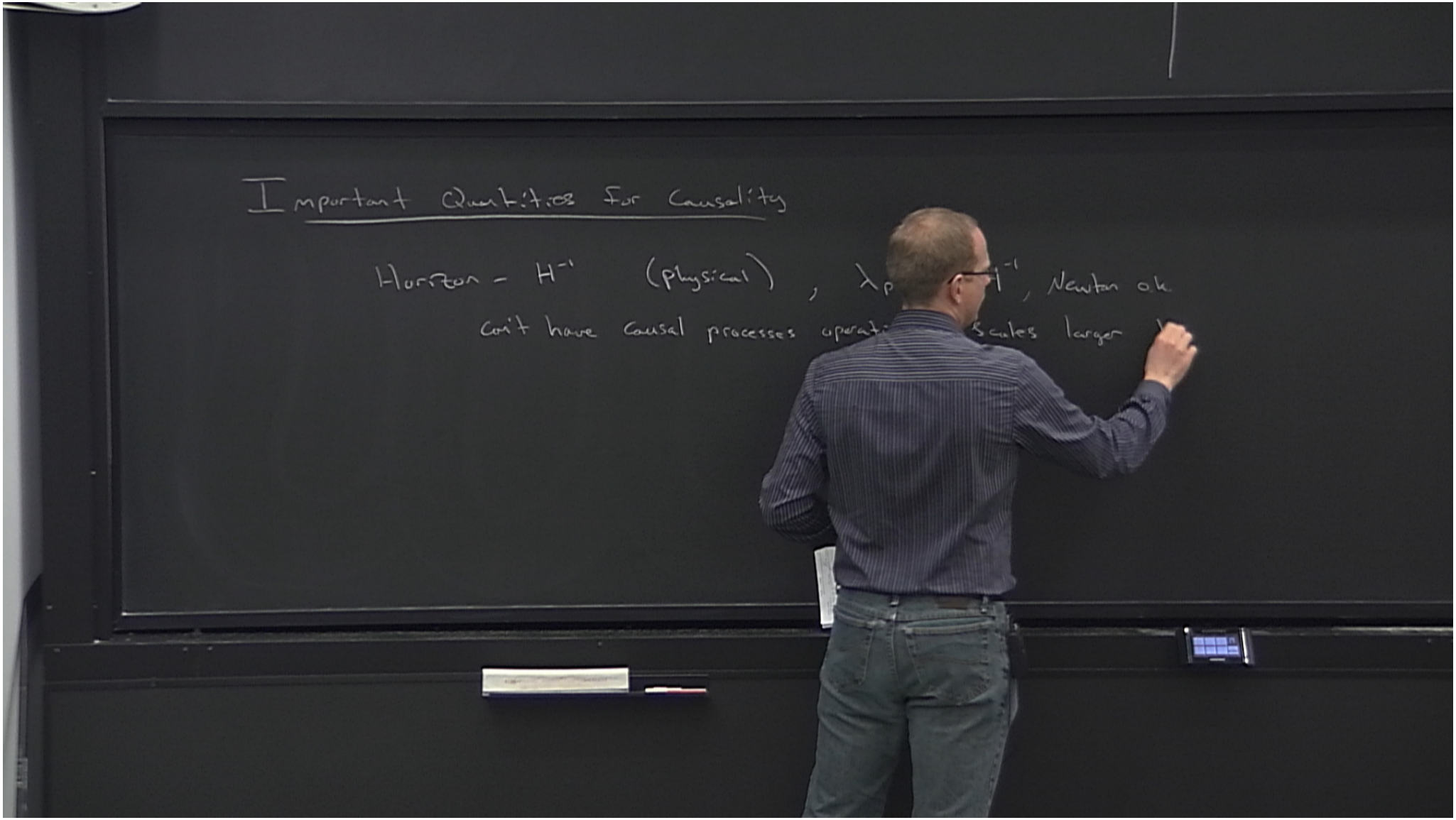

Model pdf's in Fourier

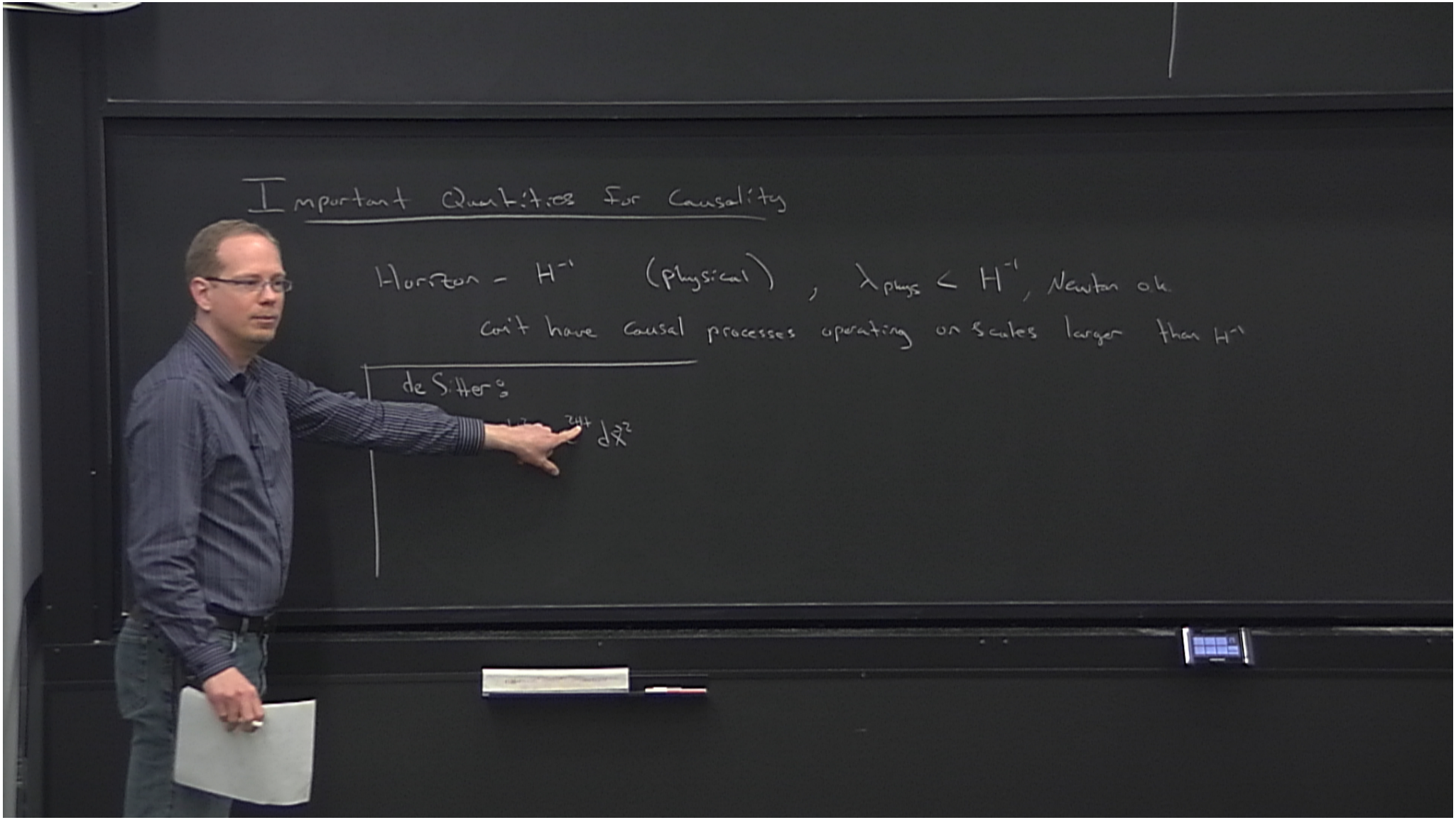

Model pdf's in Fourier Space:

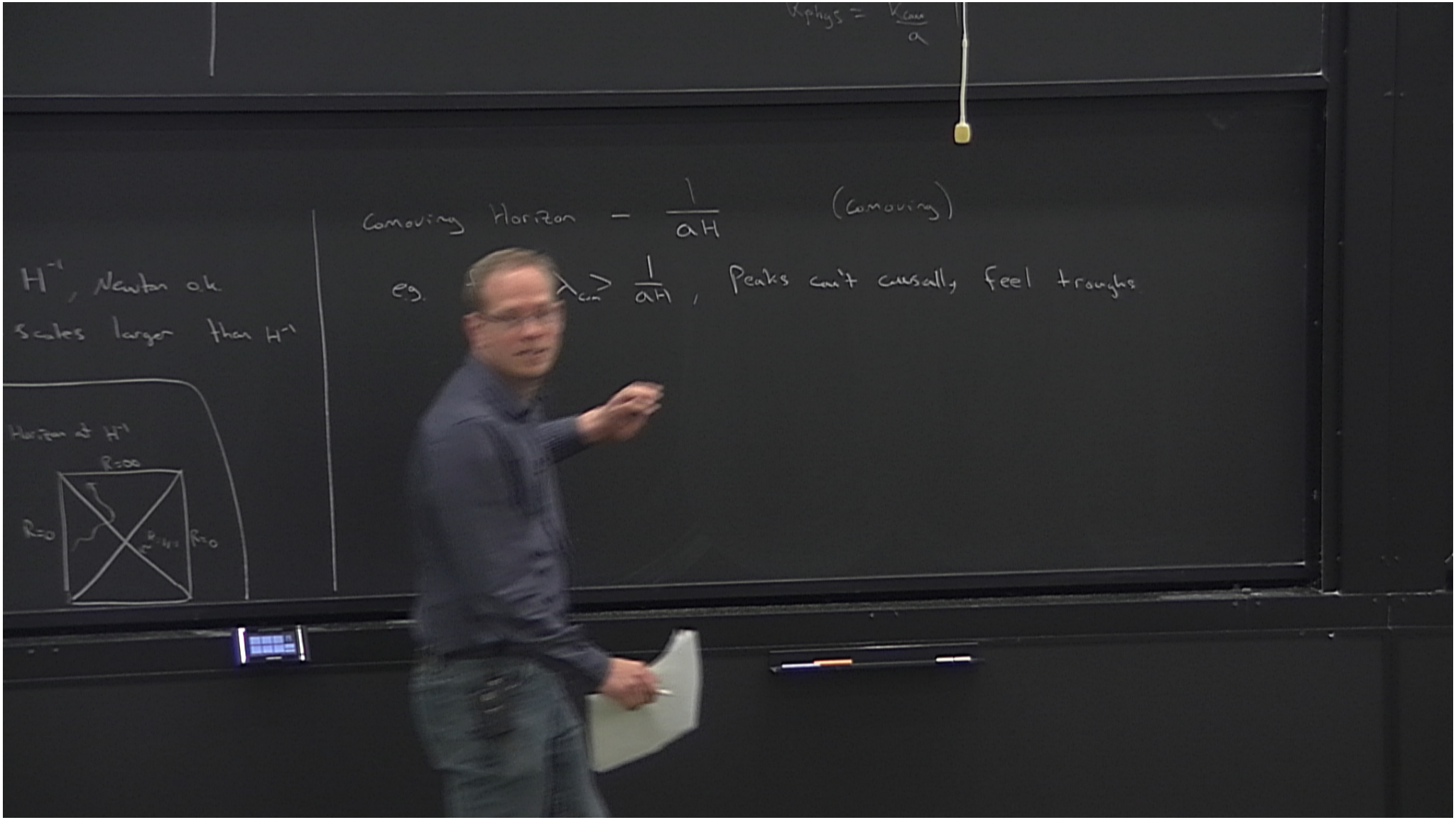

Model pert's in Fourier Space:
physical

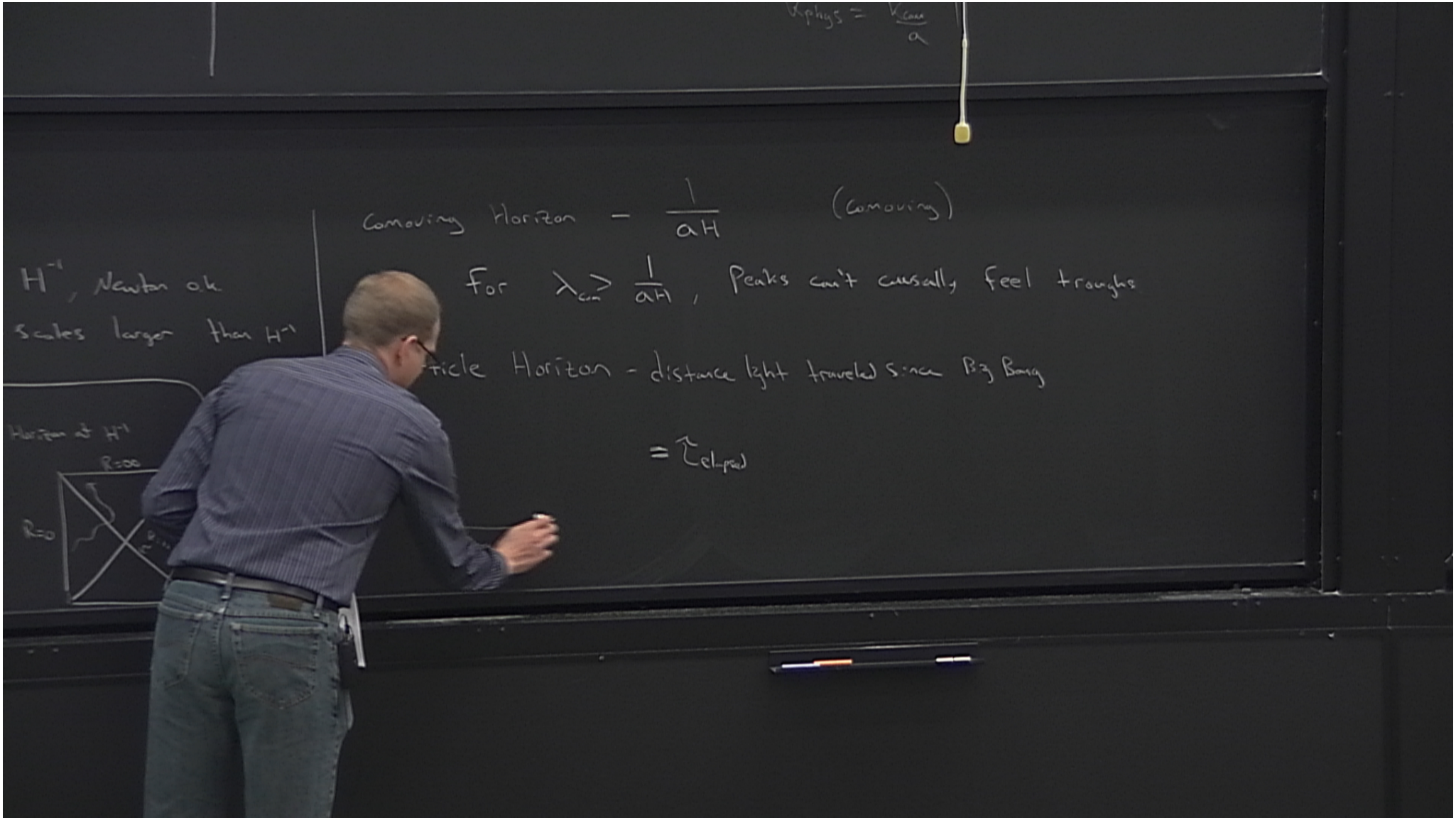

Important Q

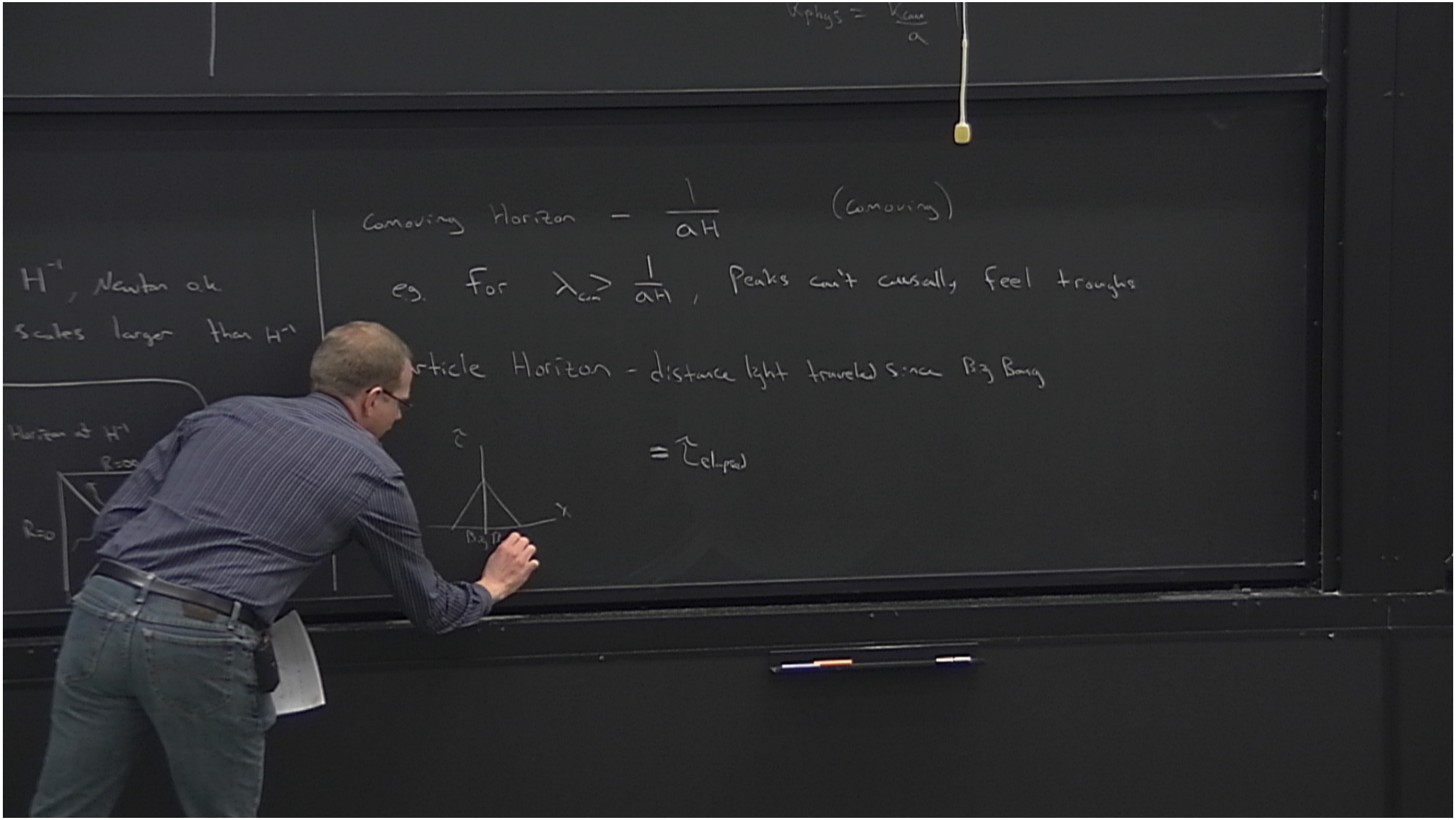

Important Quantities for Causality
Horizon - H^{-1}
$\lambda_{phys} < H^{-1}$, Newton o.k.

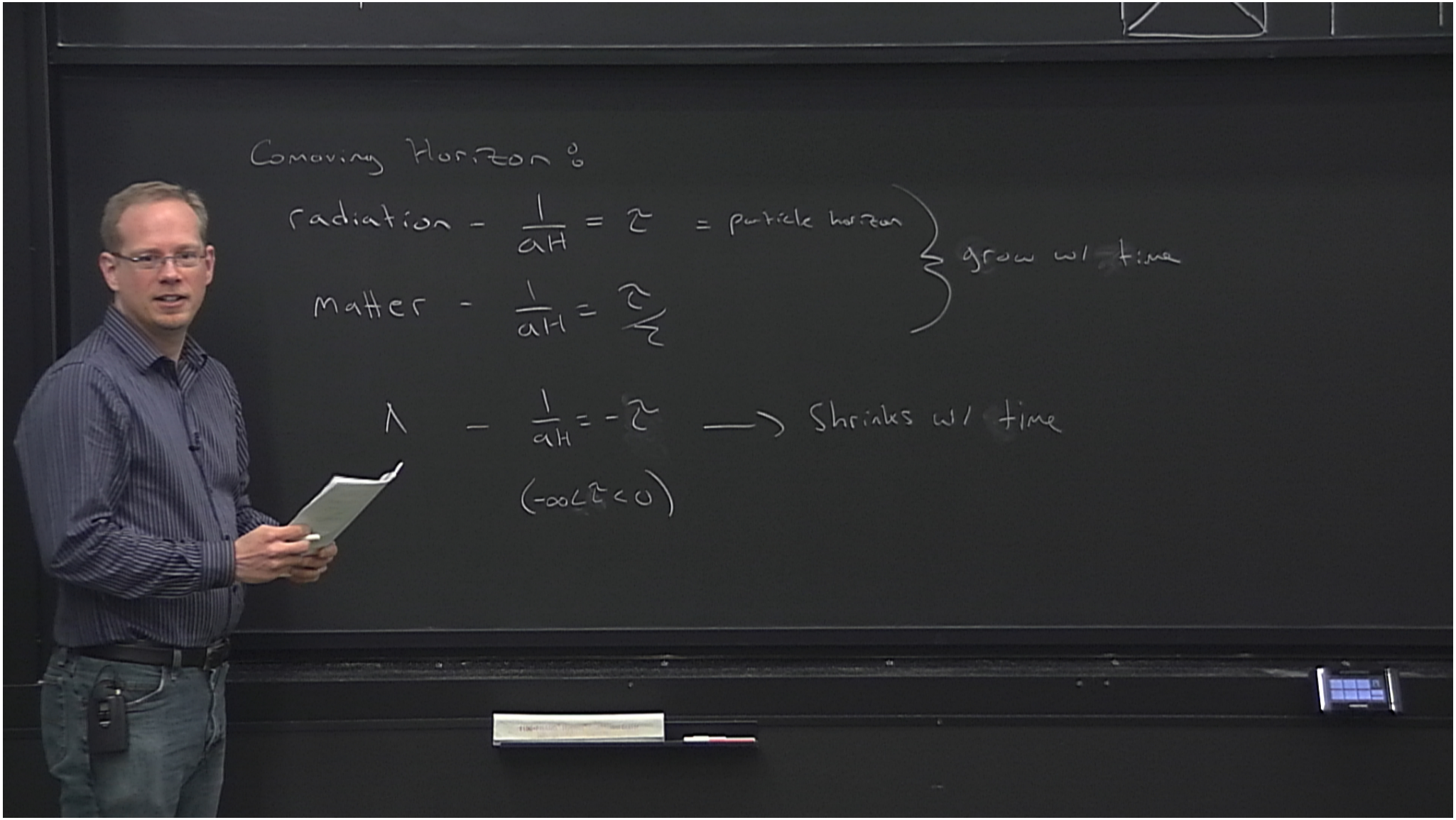

Important Quantities for Causality
Horizon - H^{-1} (physical)
Newton ok

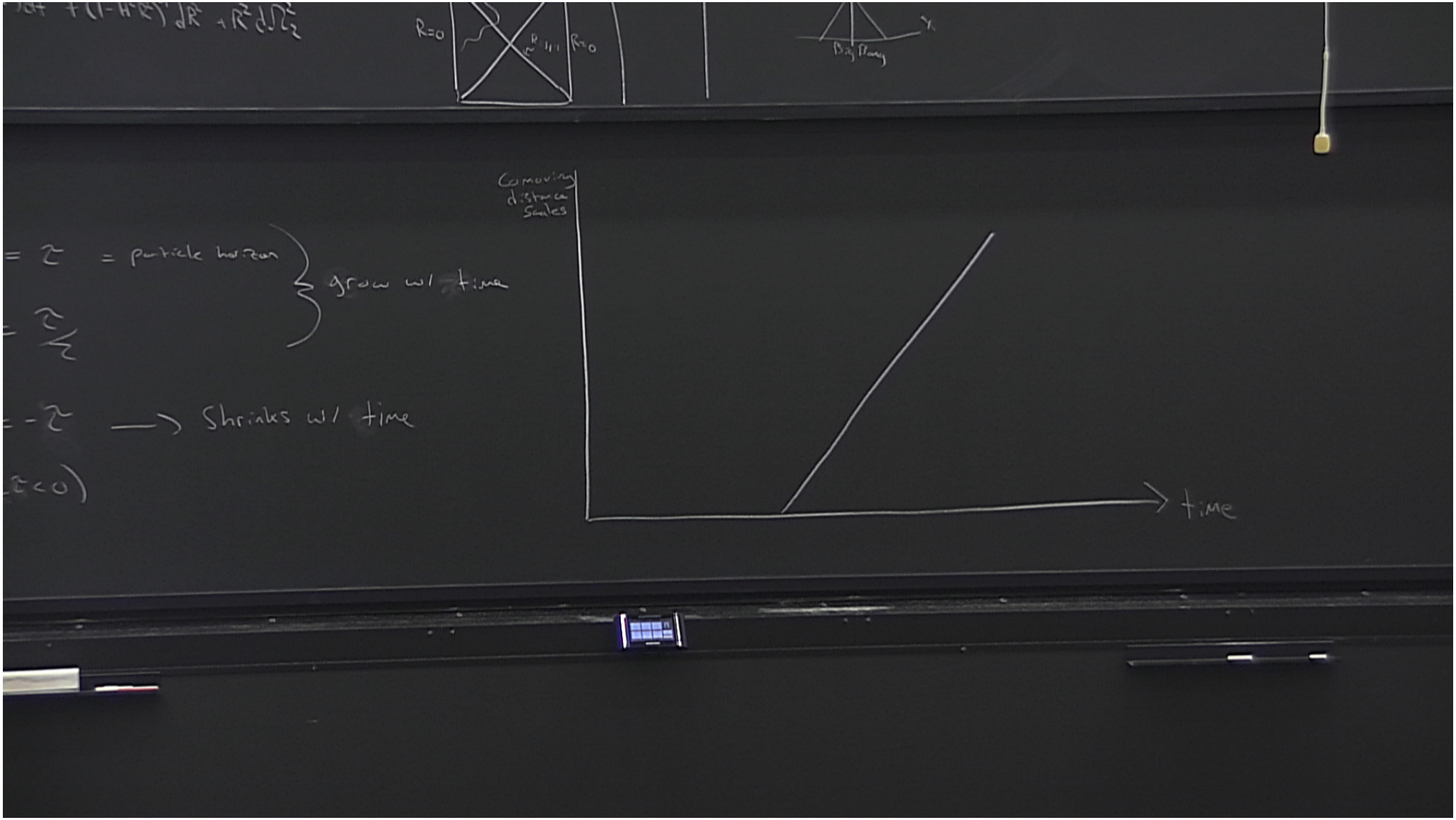

Important Questions for Causality
Horizon - H^{-1} (physical), $\lambda_{phys} < H^{-1}$, Newton ok
can't have causal processes operating on scales larger than H^{-1}
de Sitter's
dx^2

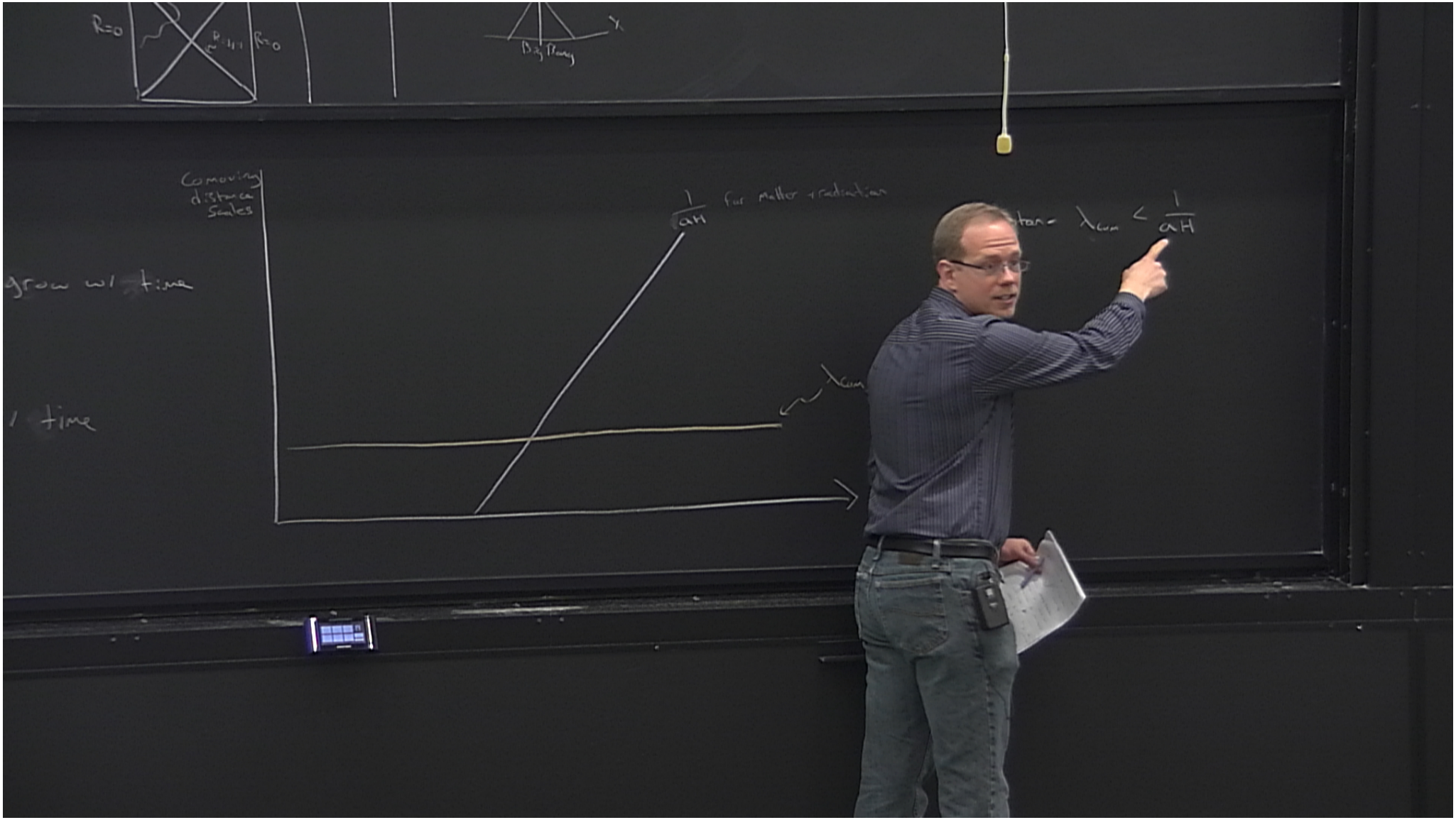

$k_{phys} = \frac{k_{comov}}{a}$
Comoving Horizon $= \frac{1}{aH}$ (comoving)
H^{-1}, Newton o.k.
scales larger than H^{-1}
eg. $\lambda_{com} > \frac{1}{aH}$, Peaks can't causally feel troughs
Horizon at H^{-1}
R=∞
R=0
R=0

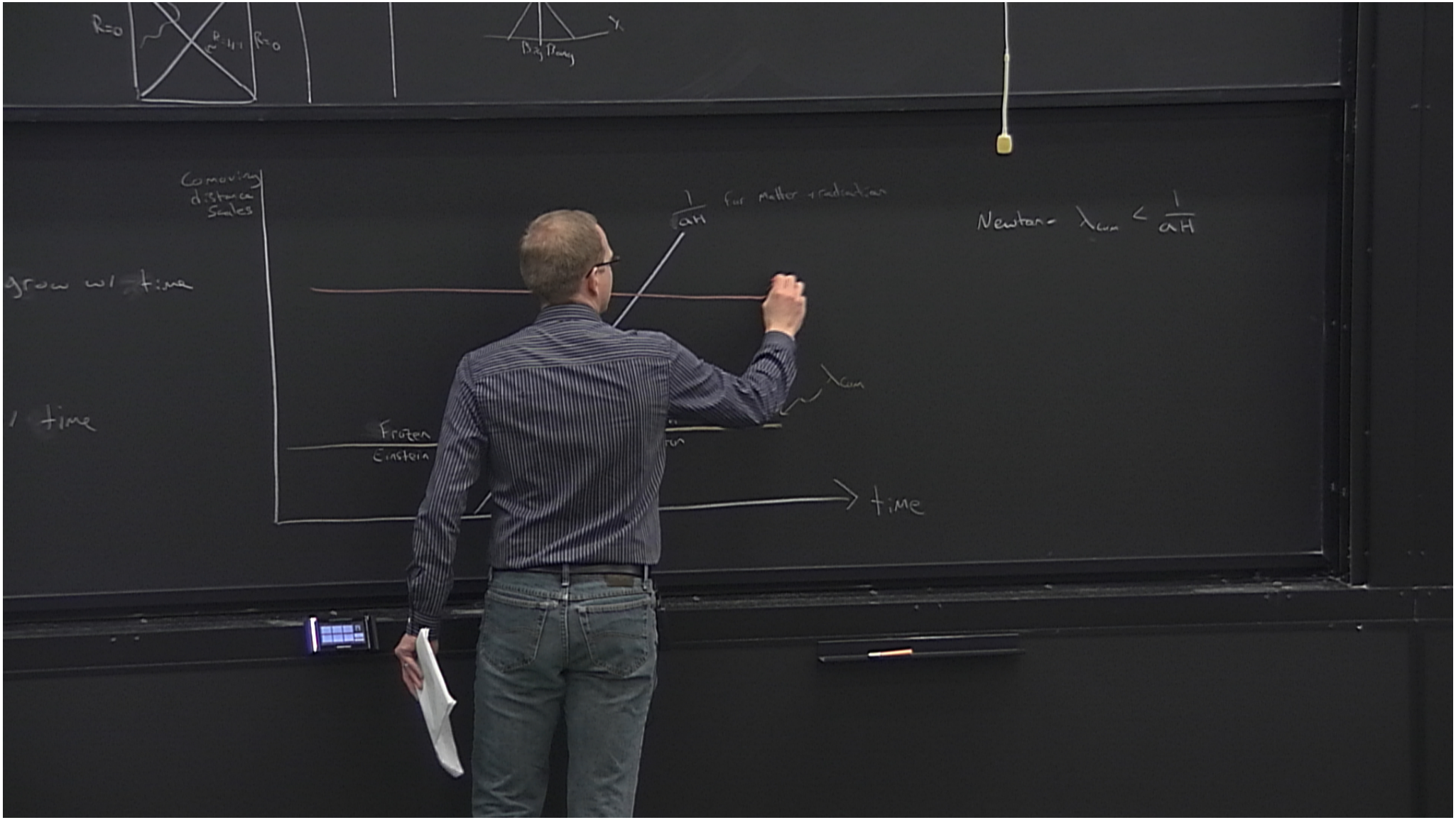

Comoving Horizon $= \frac{1}{aH}$ (Comoving)
for $\lambda_{com} > \frac{1}{aH}$, Peaks can't causally feel troughs
H^{-1}, Newton o.k.
scales larger than H^{-1}
Horizon at H^{-1}
R=∞
R=0
$= \tau_{elapsed}$

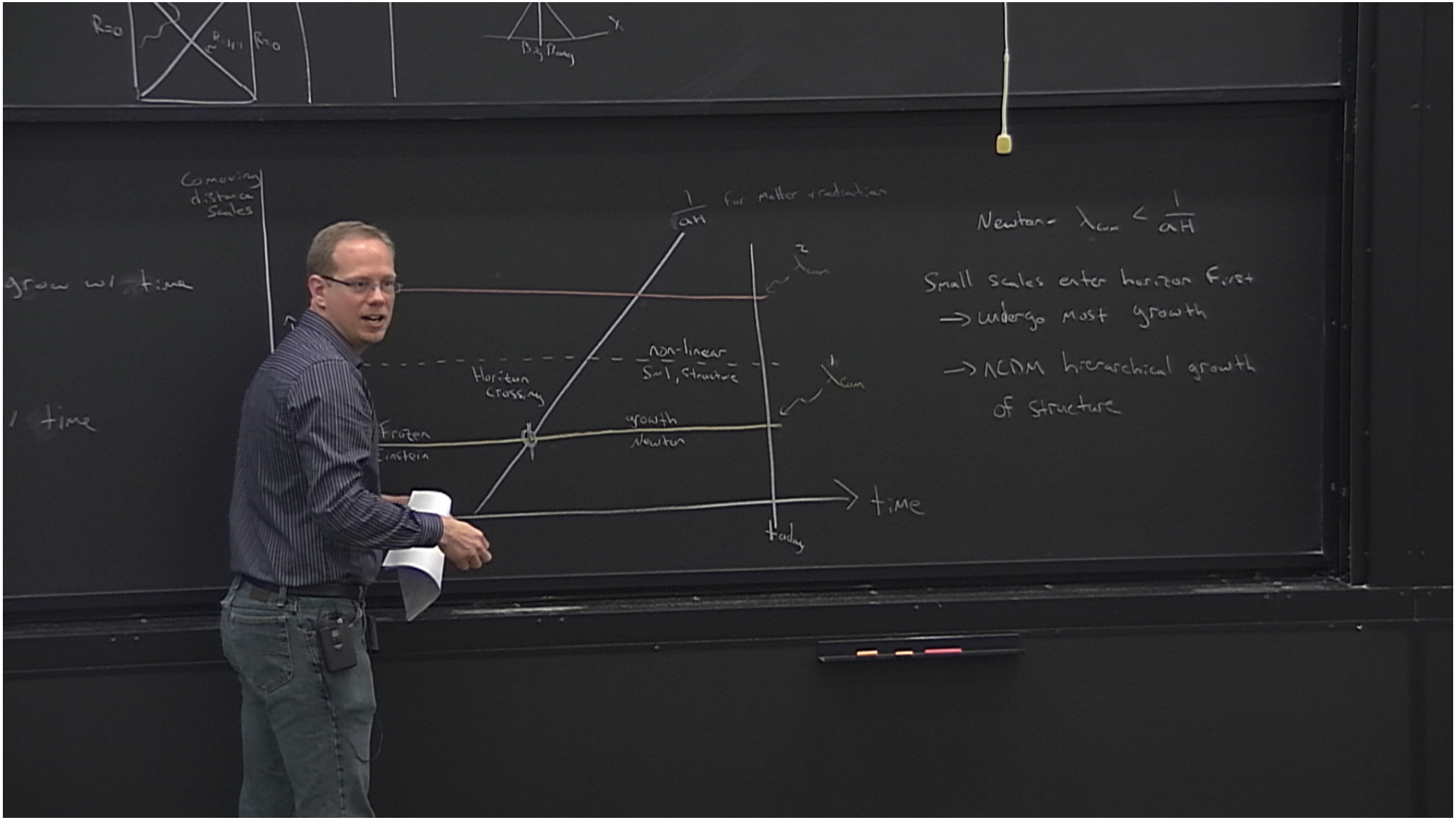

Comoving Horizon $= \frac{1}{aH}$ (Comoving)
H^{-1}, Newton o.k.
scales larger than H^{-1}
eg. for $\lambda_{com} > \frac{1}{aH}$, Peaks can't causally feel troughs
rticle Horizon - distance light traveled since Big Bang
$= \tau_{elapsed}$
Horizon at H^{-1}
R_{EQ}
τ
x

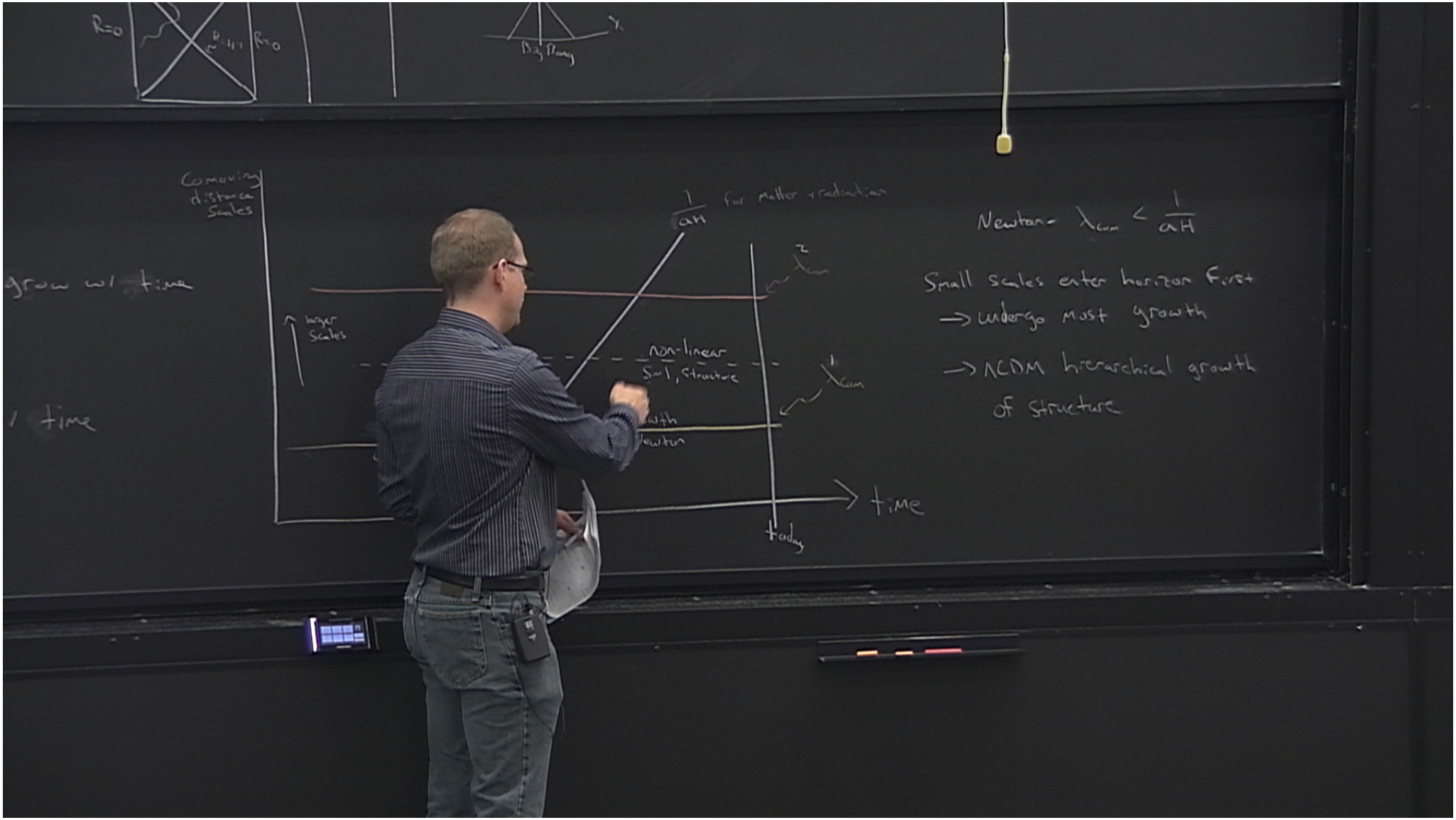

Comoving Horizon:
radiation - $\frac{1}{aH} = \tau$ = particle horizon
matter - $\frac{1}{aH} = \frac{\tau}{2}$
grow w/ time
Λ - $\frac{1}{aH} = -\tau$ ⟶ Shrinks w/ time
$(-\infty < \tau < 0)$

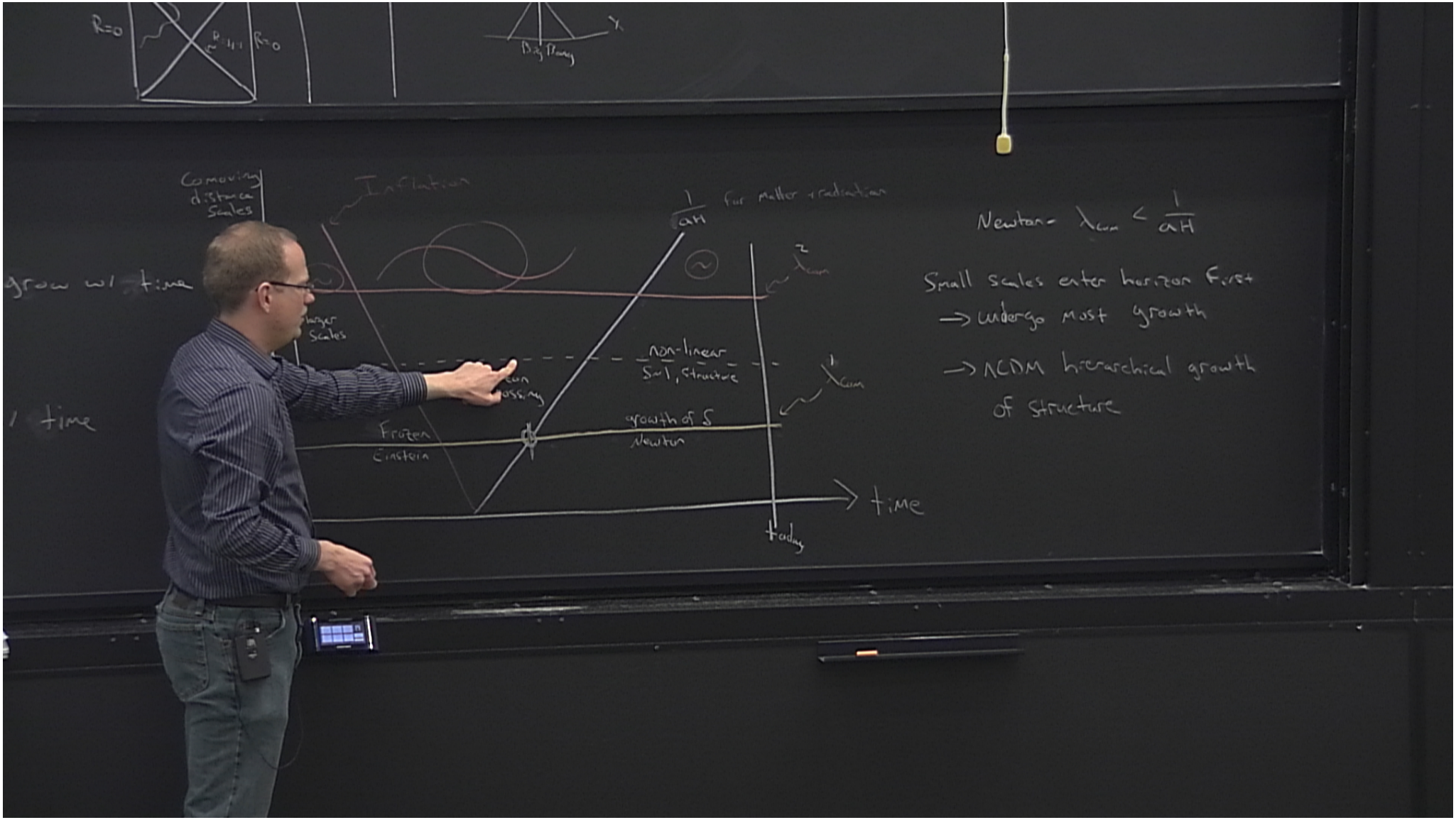

R=0
R=0
Comoving distance scales
= particle horizon
grow w/ time
Shrinks w/ time
time

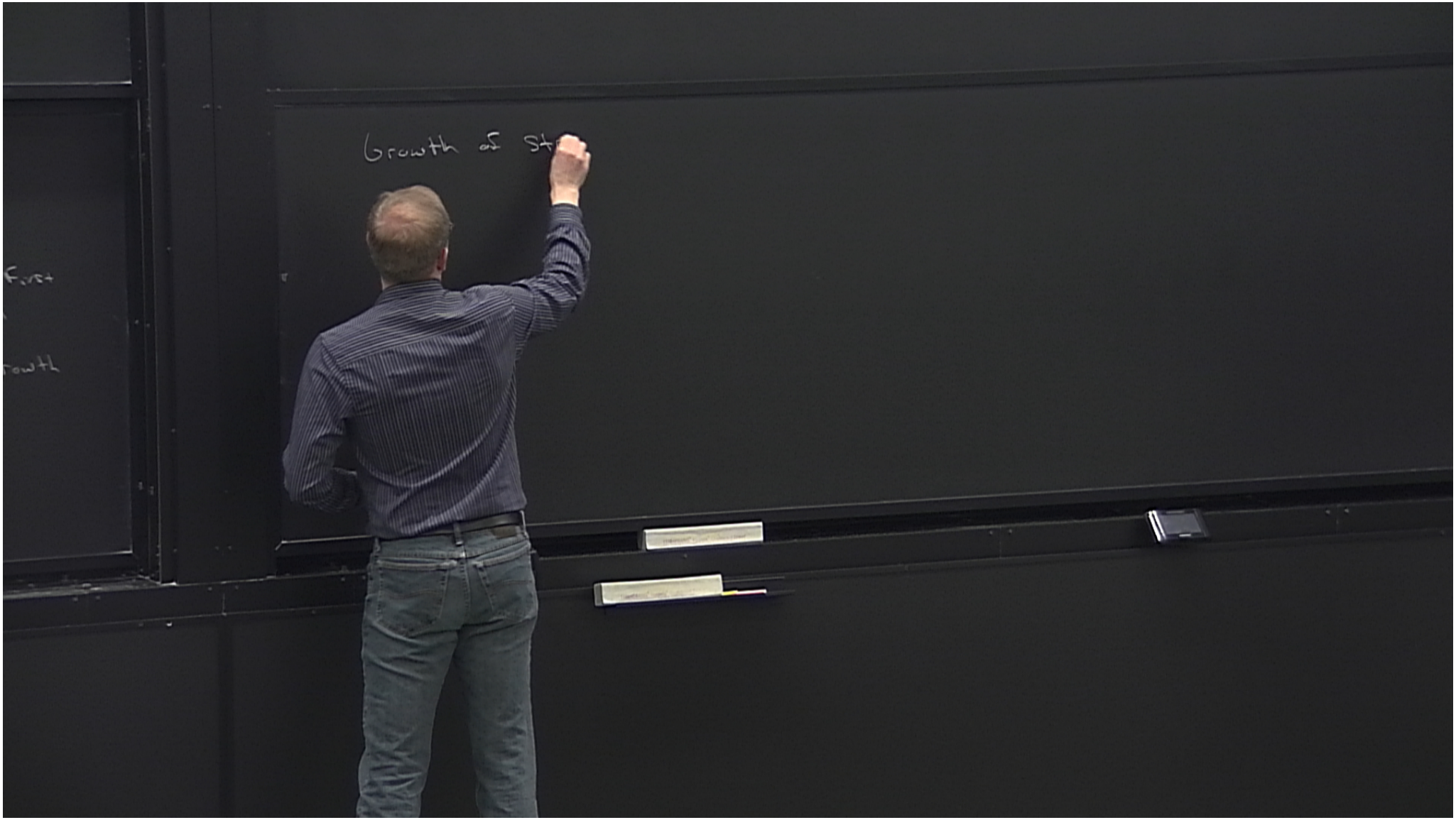

R=0
Big Bang
Comoving distance scales
grow w/ time
/ time
for matter + radiation

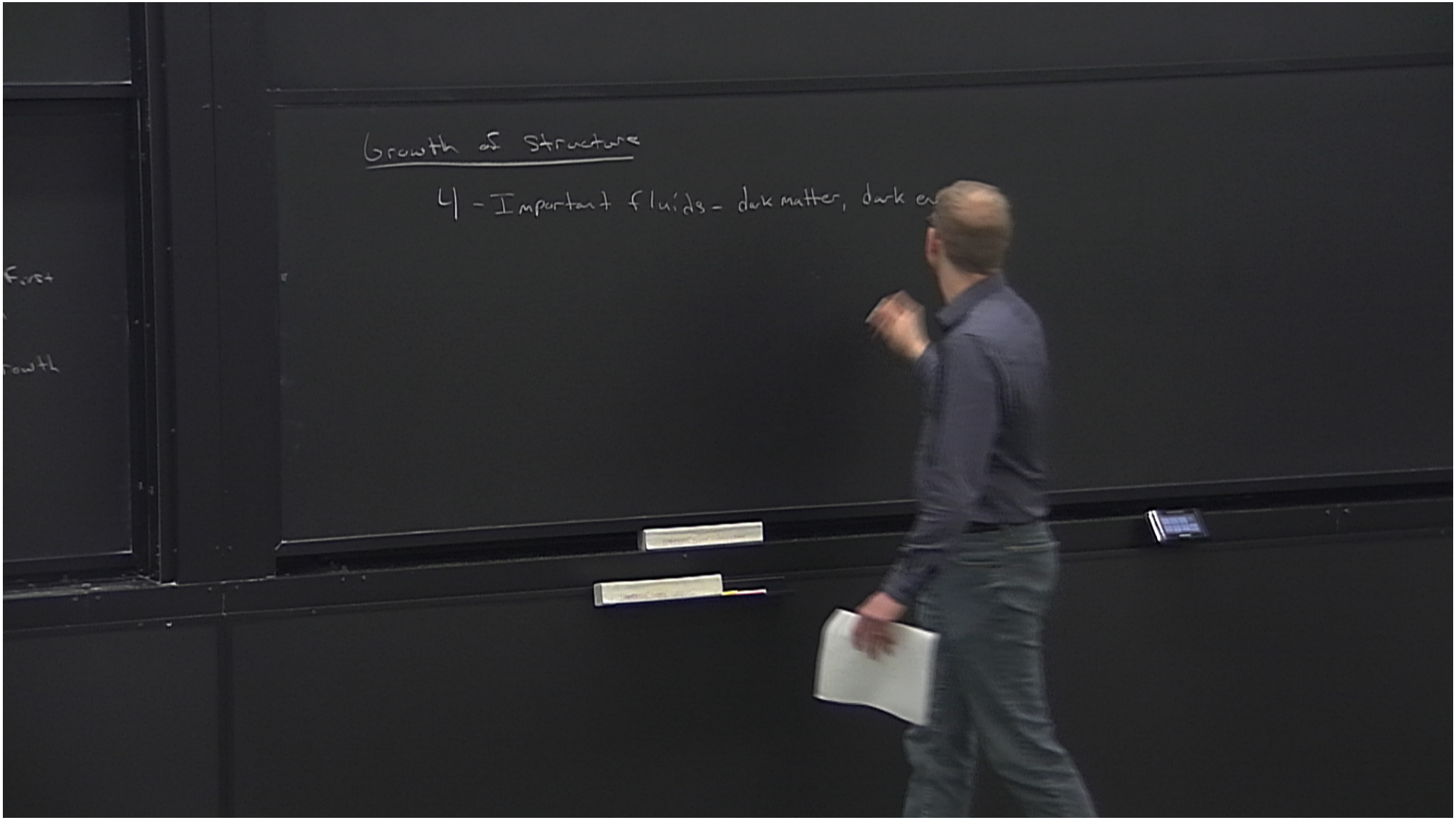

R=0
R=0
Big Bang
x
Comoving distance Scales
grow w/ time
/ time
1/aH for matter + radiation
Newton- λcom < 1/aH
λcom
Frozen
time

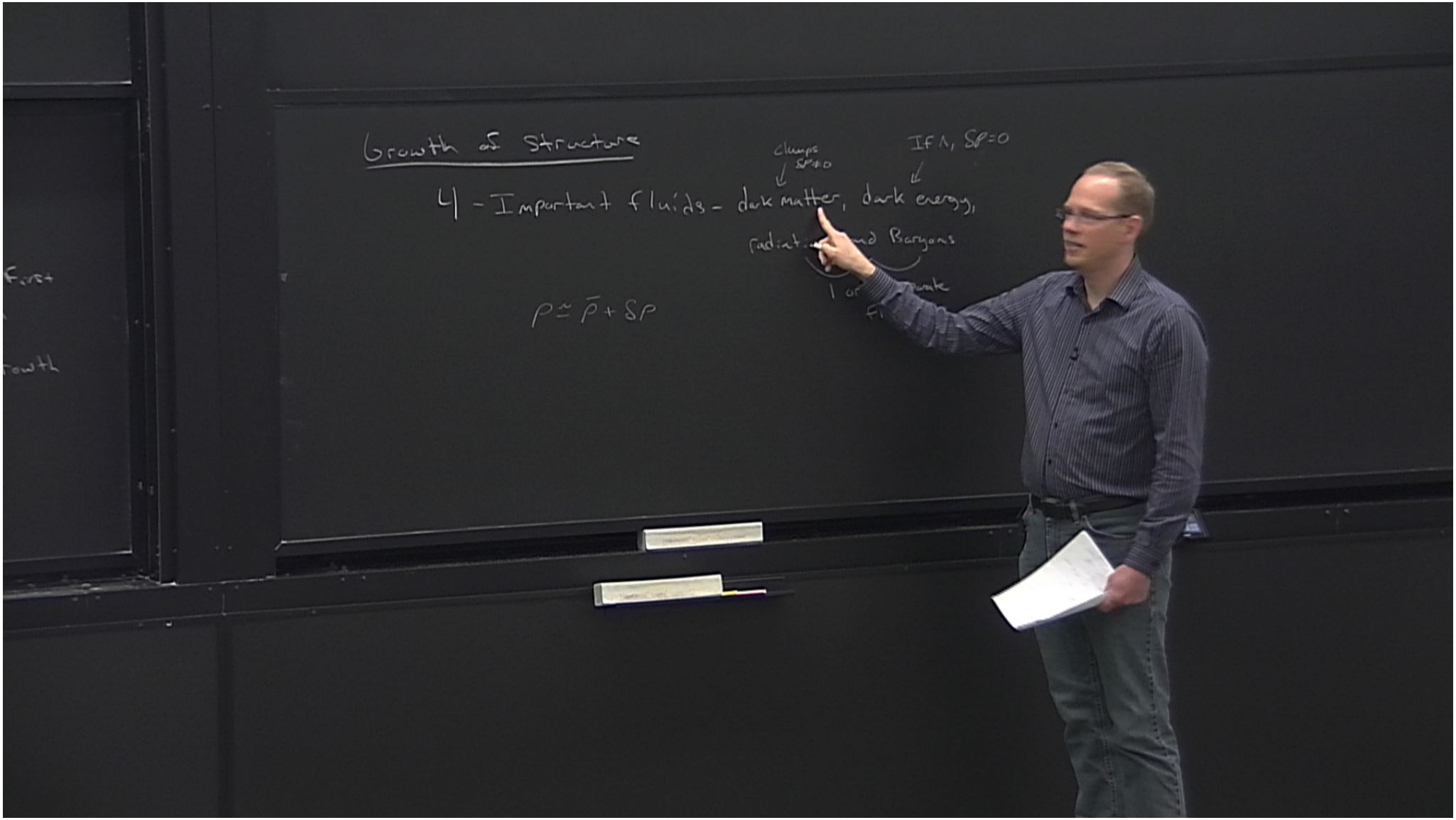

R=0
Big Bang
Comoving distance Scales
grow w/ time
time
1/aH for matter + radiation
Newton- $\lambda_{com} < \frac{1}{aH}$
Small scales enter horizon First
→ undergo most growth
→ ΛCDM hierarchical growth of structure
Horizon crossing
non-linear Str, structure
Frozen
growth
Newton
time
today

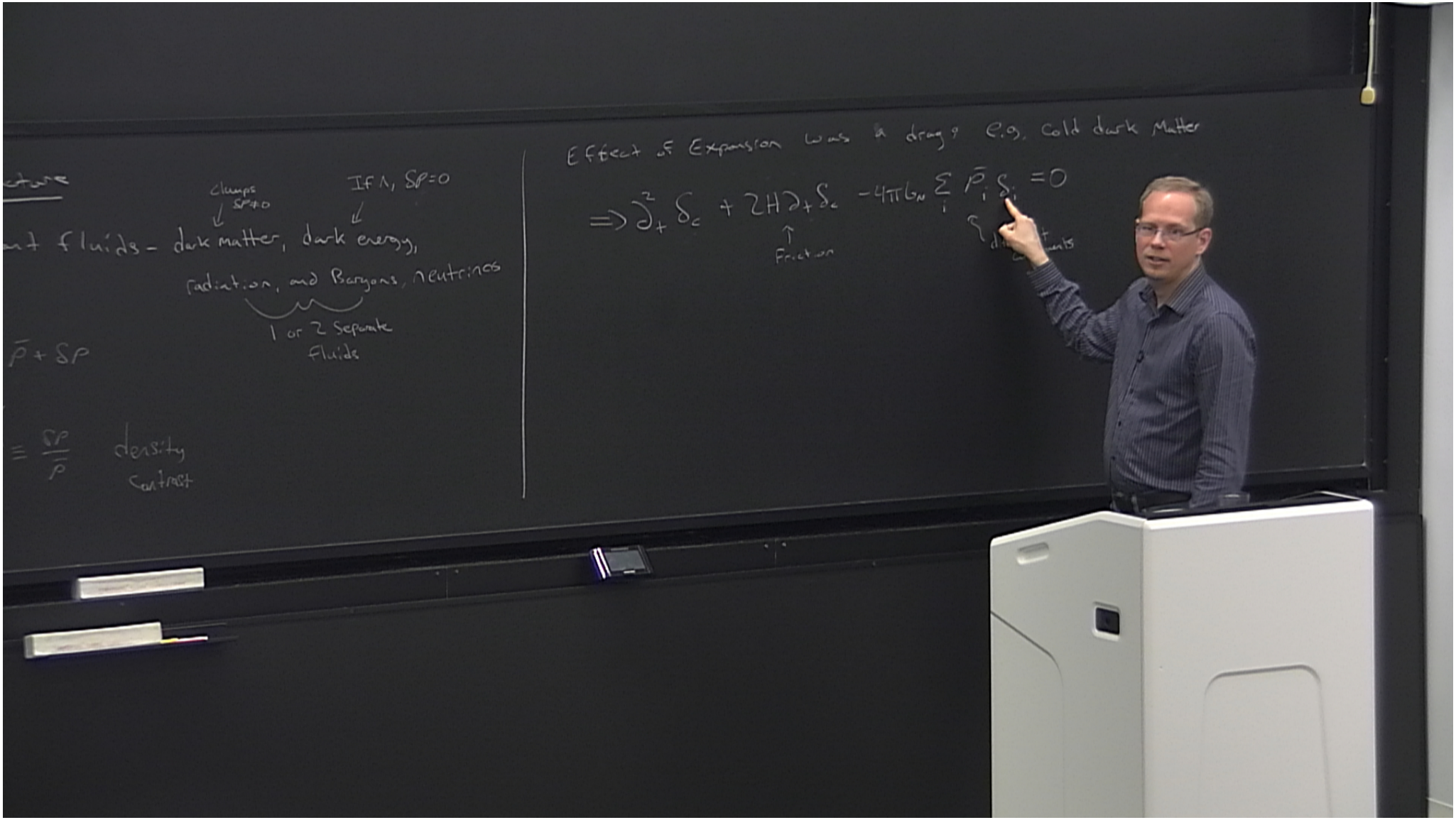

R=0
Big Bang
Comoving distance Scales
grow w/ time
1/ time
1/aH for matter + radiation
Newton- $\lambda_{com} < \frac{1}{aH}$
Small scales enter horizon First
→ undergo most growth
→ ΛCDM hierarchical growth of structure
larger Scales
non-linear
time
today

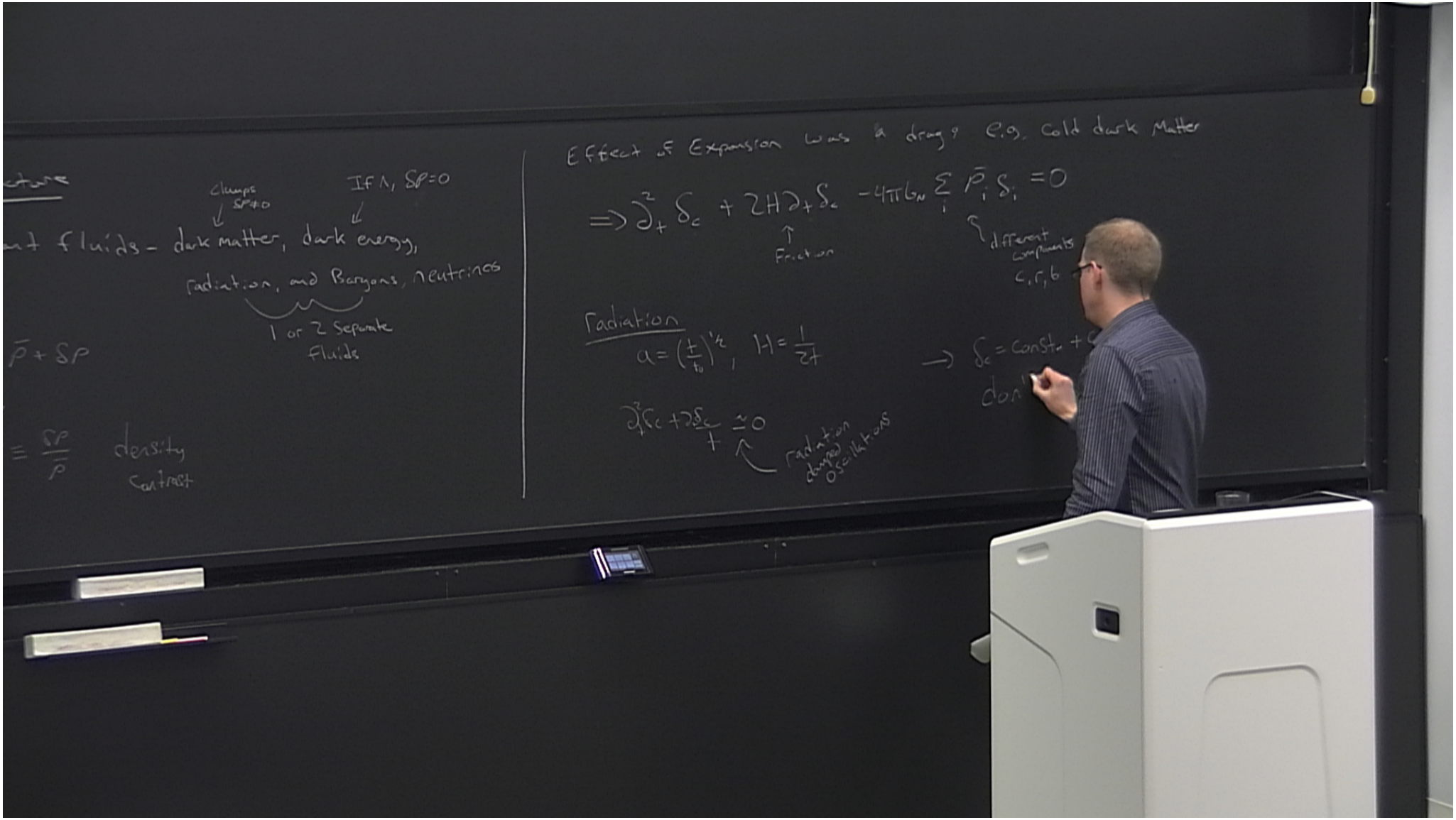

R=0
Big Bang
Comoving distance scales
Inflation
grow w/ time
larger scales
Frozen
Einstein
Non-linear
S+T, structure
growth of S
Newton
time
today
for matter + radiation
Newton- $\lambda_{com} < \frac{1}{aH}$
Small scales enter horizon First
→ undergo most growth
→ ΛCDM hierarchical growth of structure

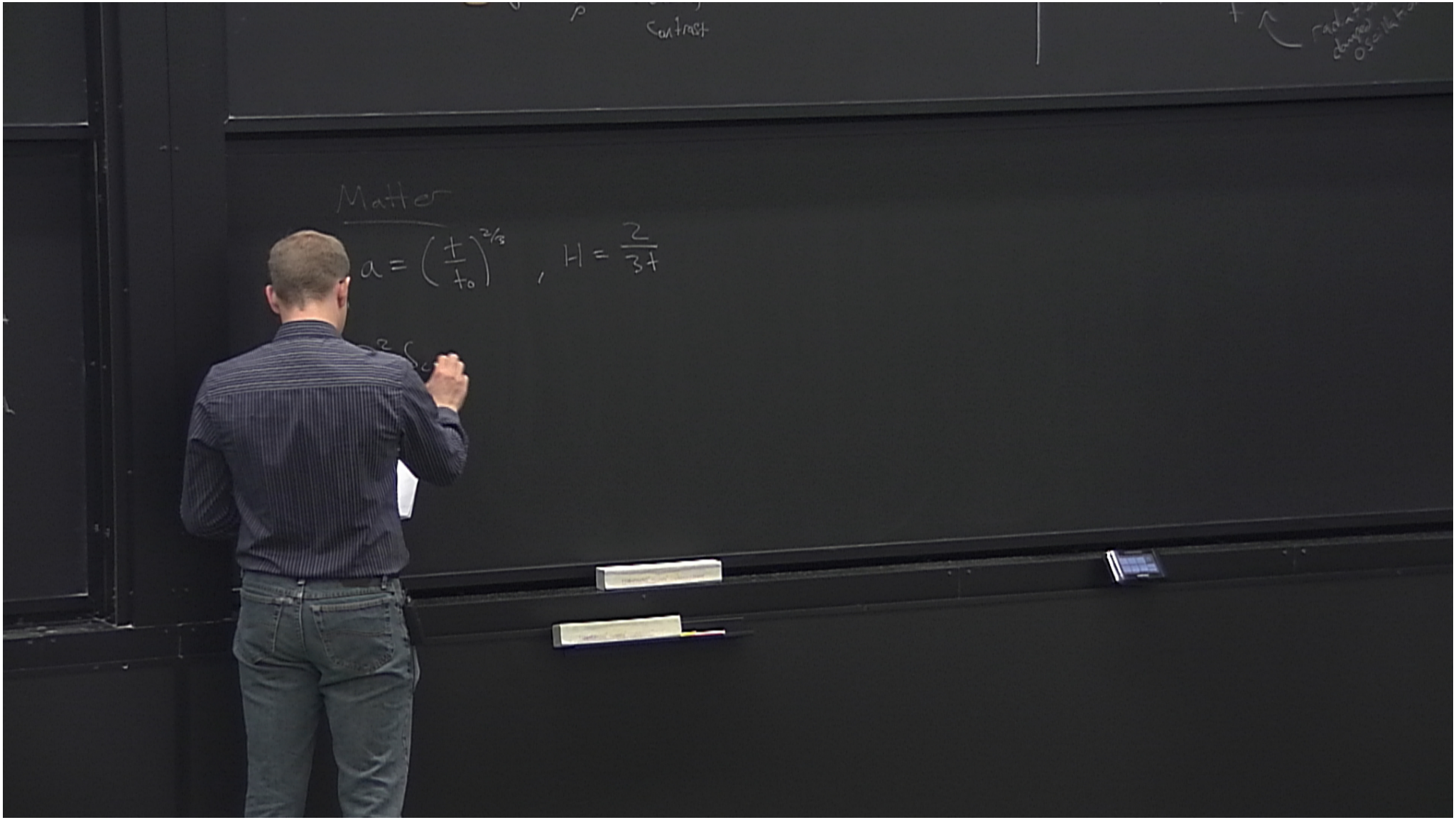

Growth of

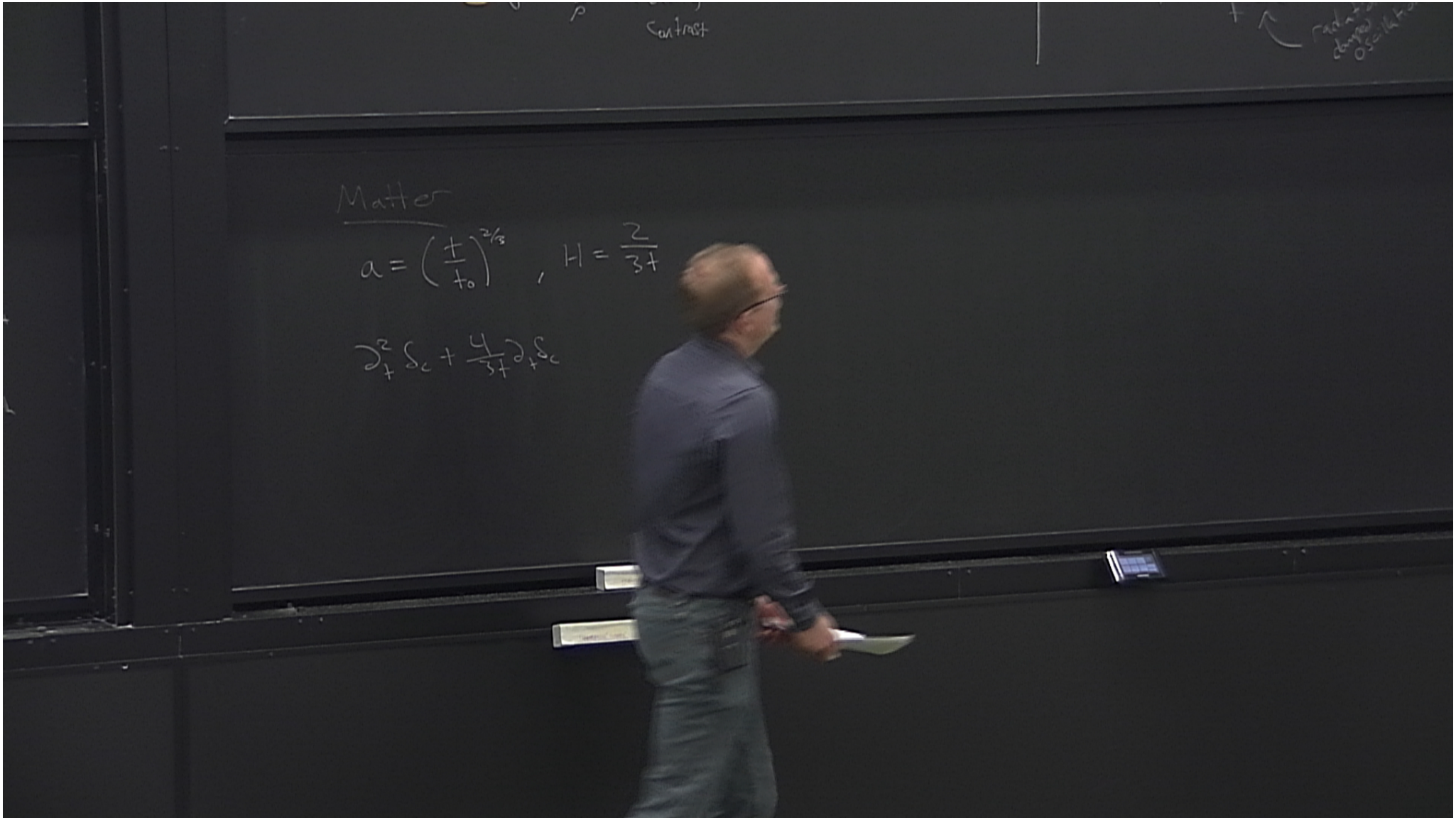

Growth of Structure
4 - Important fluids - dark matter, dark

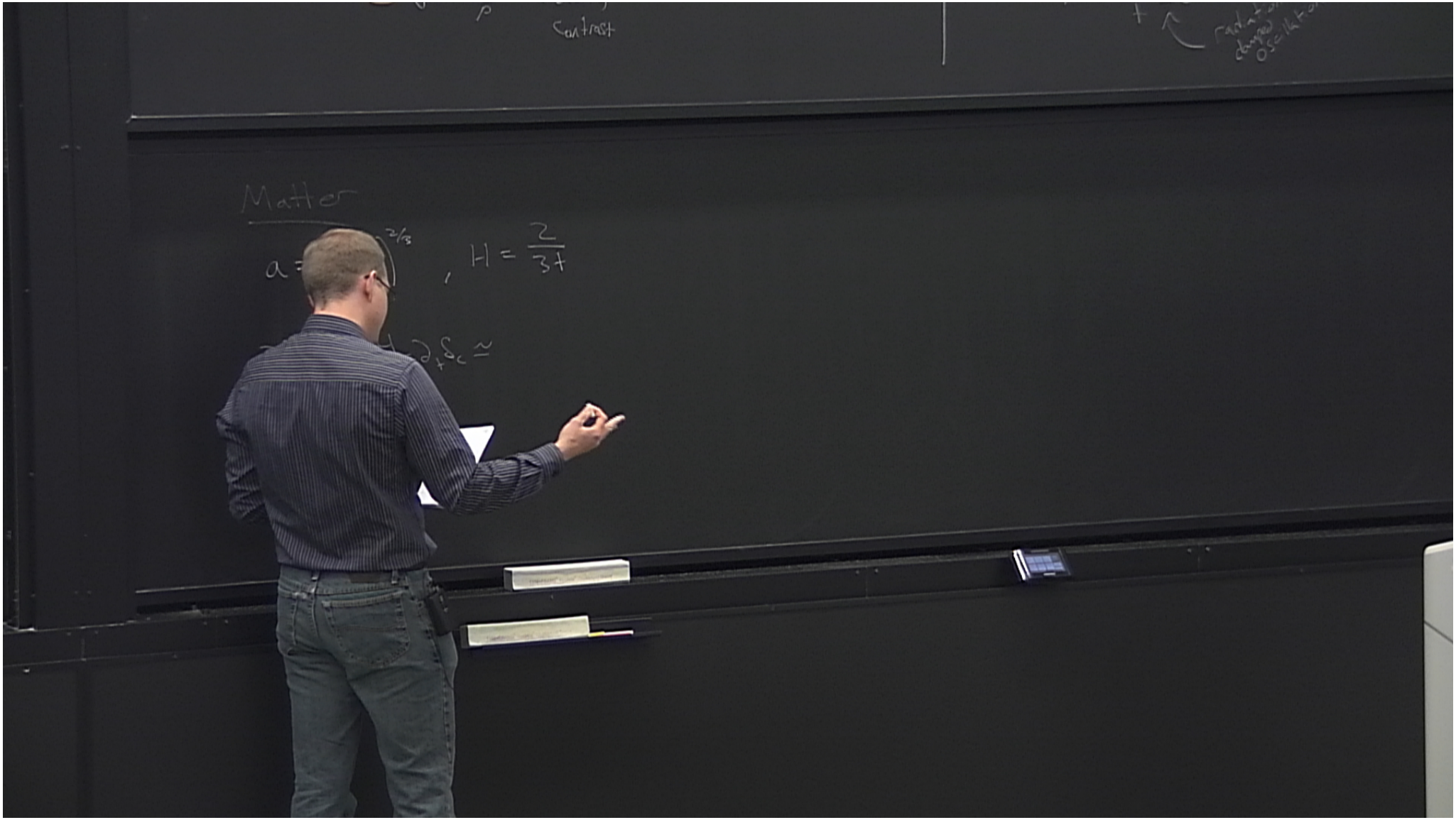

Growth of Structure
clumps δP≠0
If Λ, δP=0
4 - Important fluids - dark matter, dark energy,
ρ ≃ ρ̄ + δP

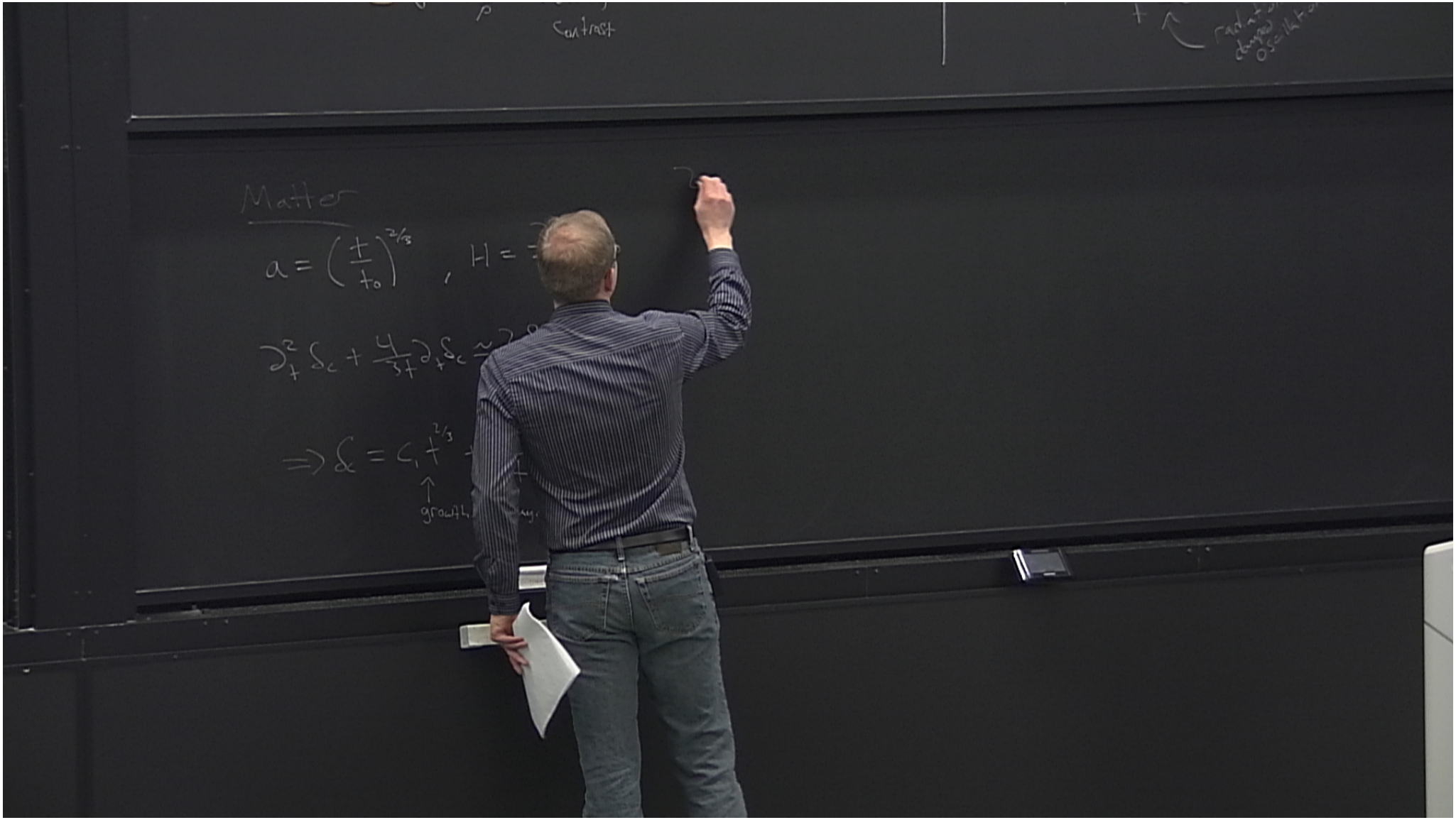

Effect of Expansion Was a drag? e.g. Cold dark Matter
$\Rightarrow \partial_+^2 \delta_c + 2H\partial_+ \delta_c - 4\pi G_N \sum_i \bar{\rho}_i \delta_i = 0$
Friction
clumps $\delta P \neq 0$
If Λ, $\delta P = 0$
fluids - dark matter, dark energy,
radiation, and Baryons, neutrinos
1 or 2 Separate fluids
$\bar{\rho} + \delta P$
$\equiv \frac{\delta P}{\bar{\rho}}$ density contrast

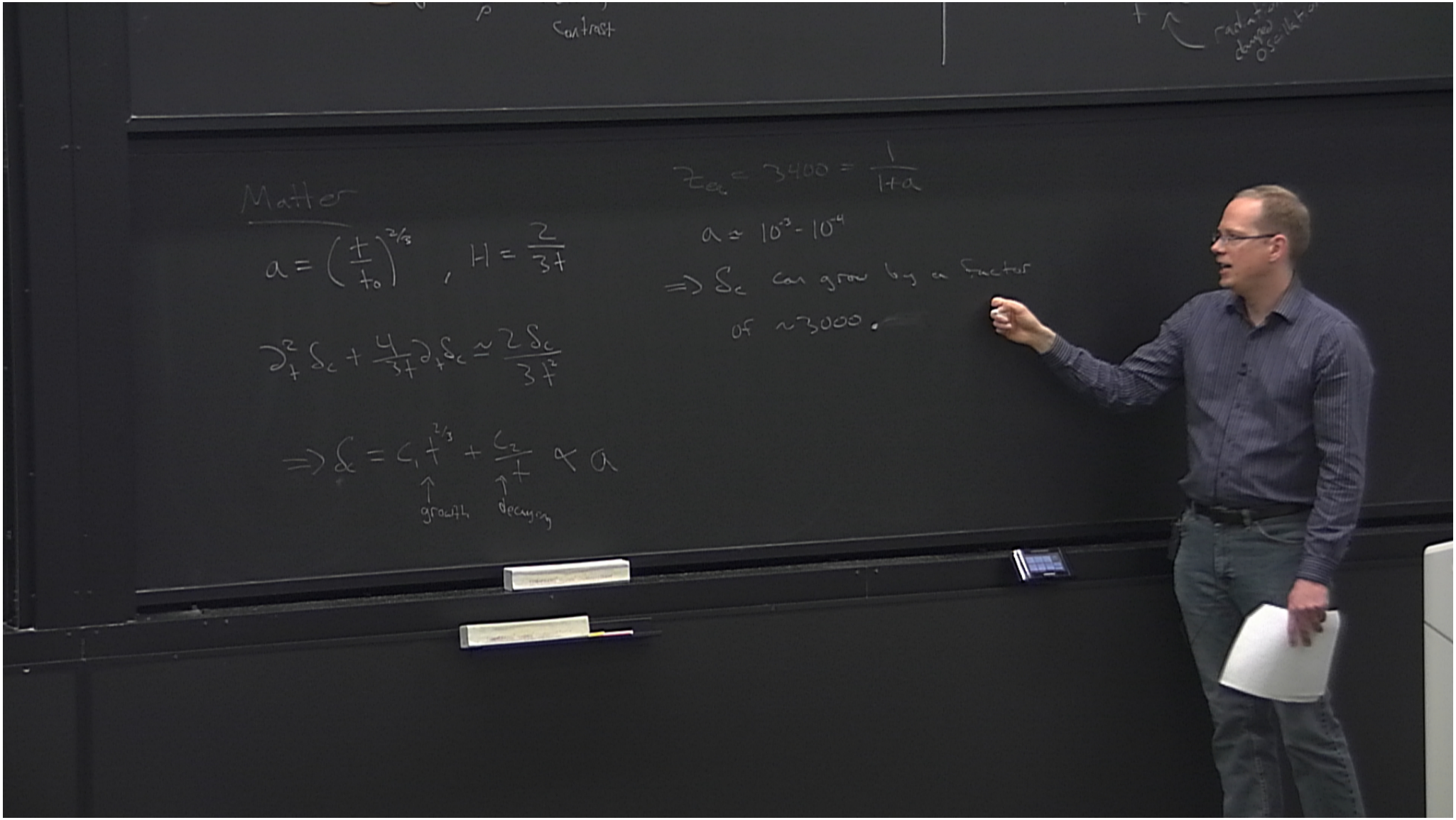

ucture
Clumps δP≠0
If Λ, δP=0
nt fluids - dark matter, dark energy,
radiation, and Baryons, neutrinos
1 or 2 separate fluids
$\bar{\rho} + \delta P$
$\equiv \frac{\delta P}{\bar{\rho}}$ density contrast
Effect of Expansion Looks like a drag, e.g. Cold dark Matter
$\Rightarrow \partial_+^2 \delta_c + 2H\partial_+\delta_c - 4\pi G_N \sum_i \bar{\rho}_i \delta_i = 0$
Friction
different components c, r, b
Radiation
$a = (\frac{t}{t_0})^{1/2}$, $H = \frac{1}{2t}$
$\rightarrow \delta_c = \text{Const}_+ +$
$\partial_+^2 \delta_c + \frac{2}{t}\delta_c \simeq 0$
radiation damped oscillations

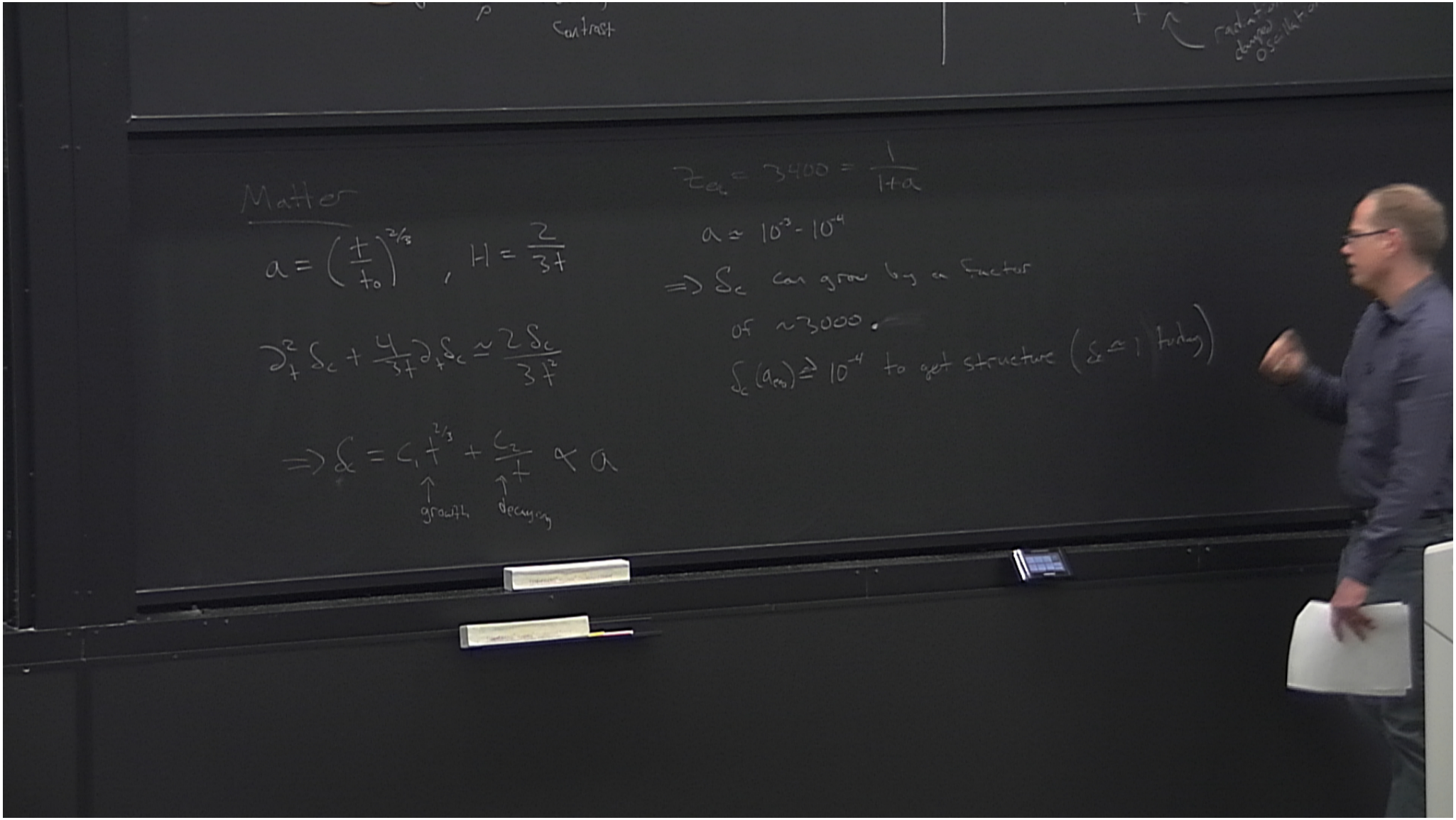

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$, $H = \frac{2}{3t}$

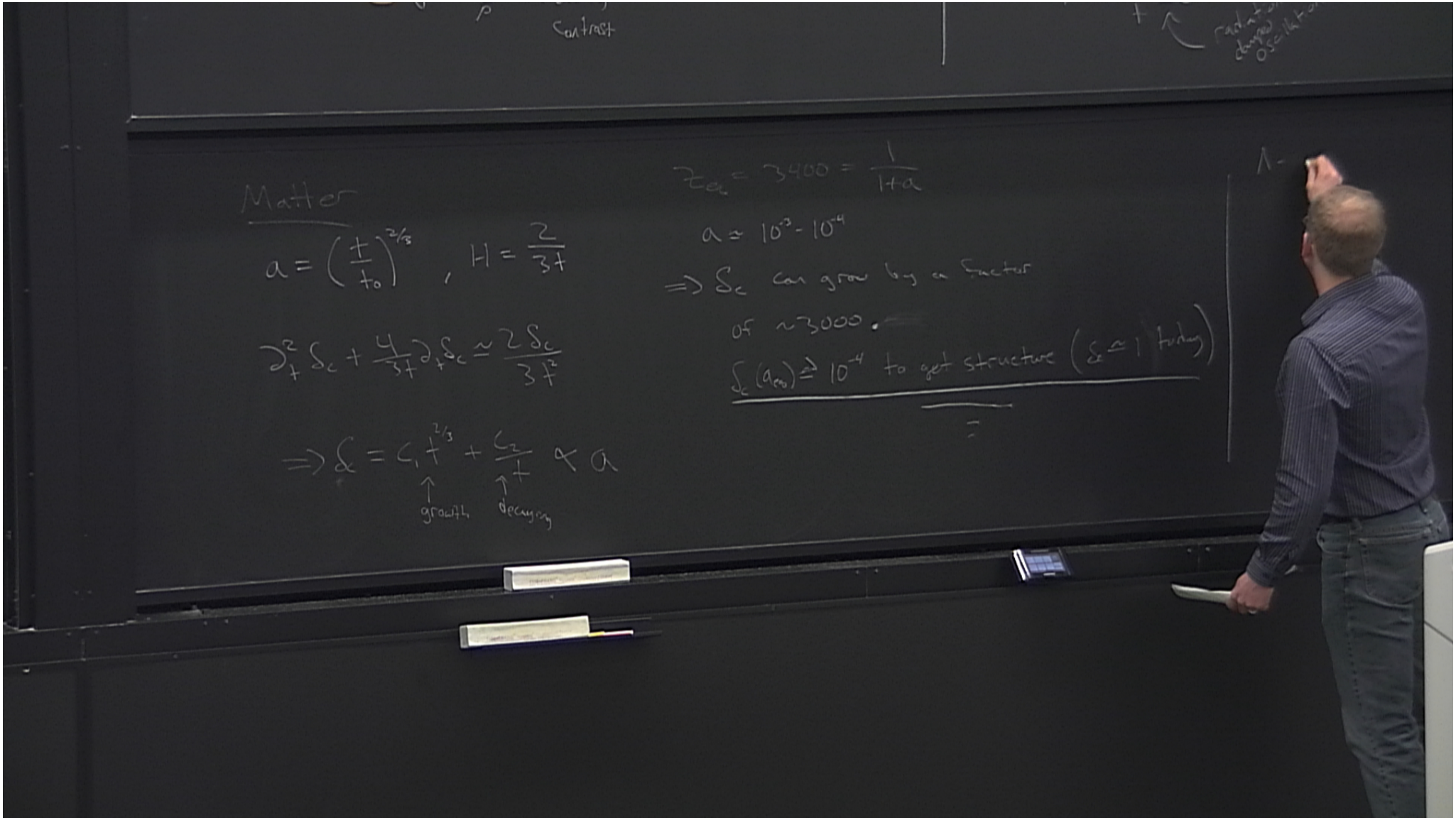

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$, $H = \frac{2}{3t}$
$\partial_t^2 \delta_c + \frac{4}{3t}\partial_t \delta_c$

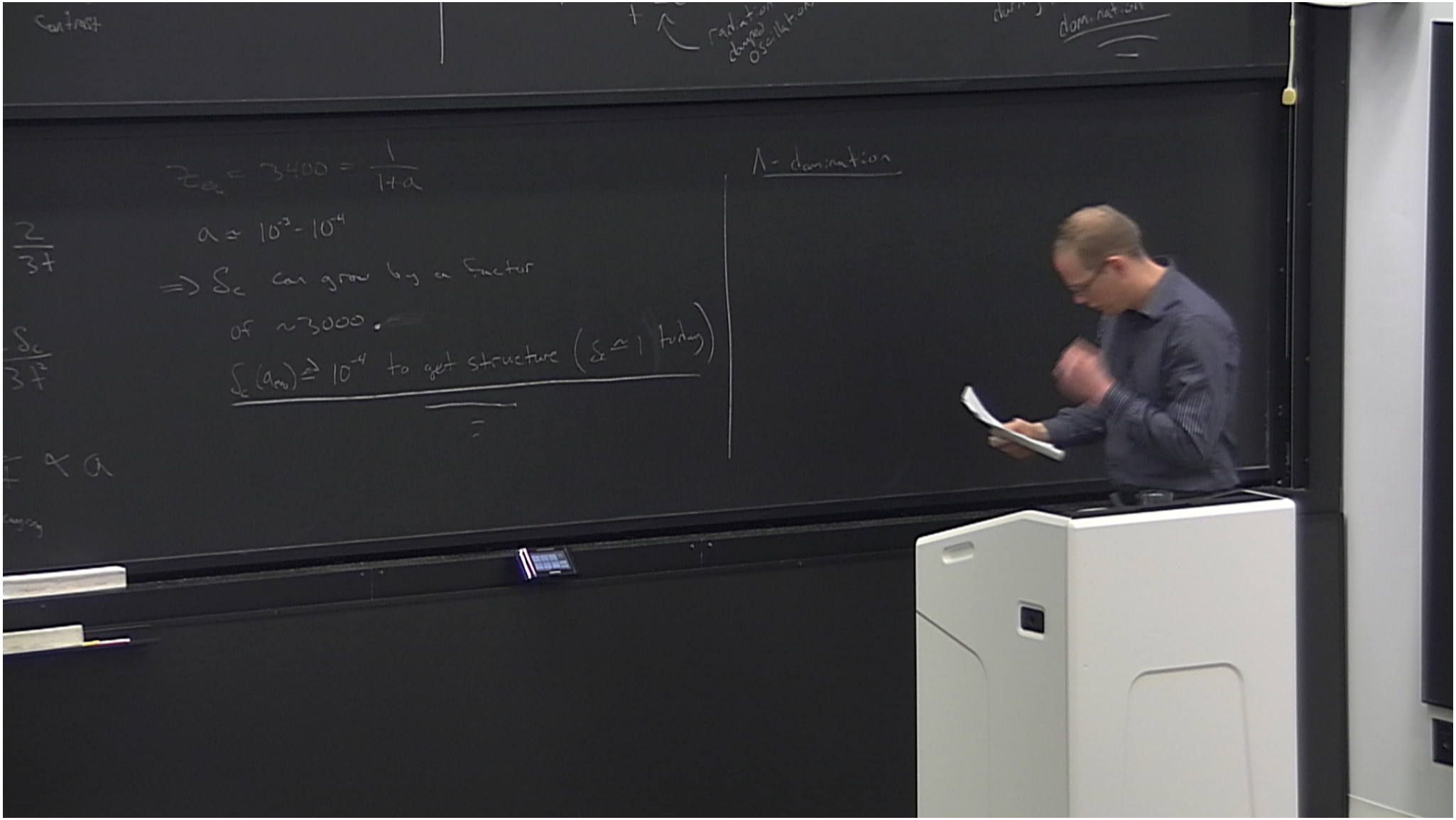

Contrast
Matter
$H = \frac{2}{3t}$

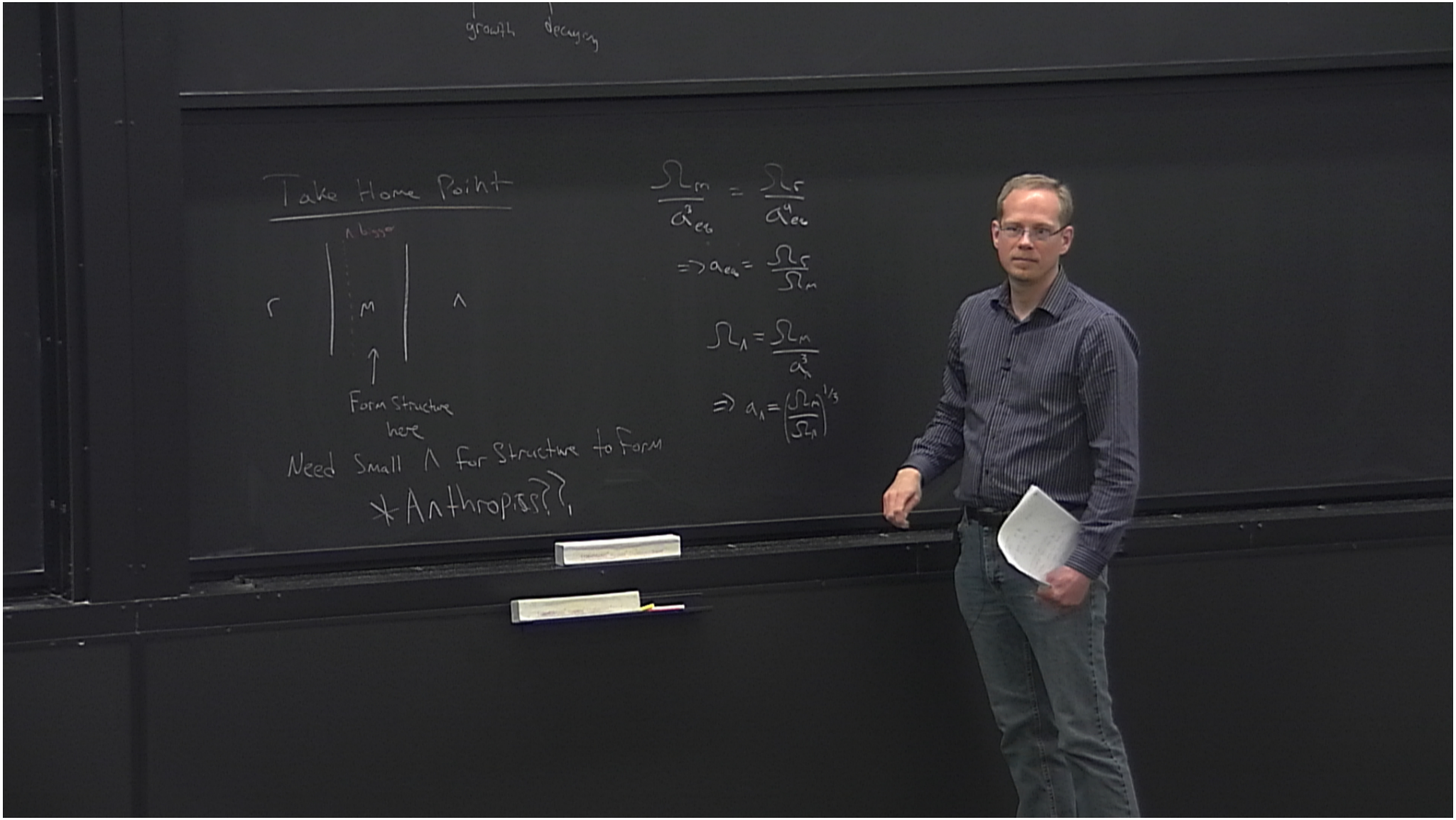

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$
$\partial_t^2 \delta_c + \frac{4}{3t}\partial_t \delta_c \approx$
$\Rightarrow \delta = C_1 t^{2/3}$
growth

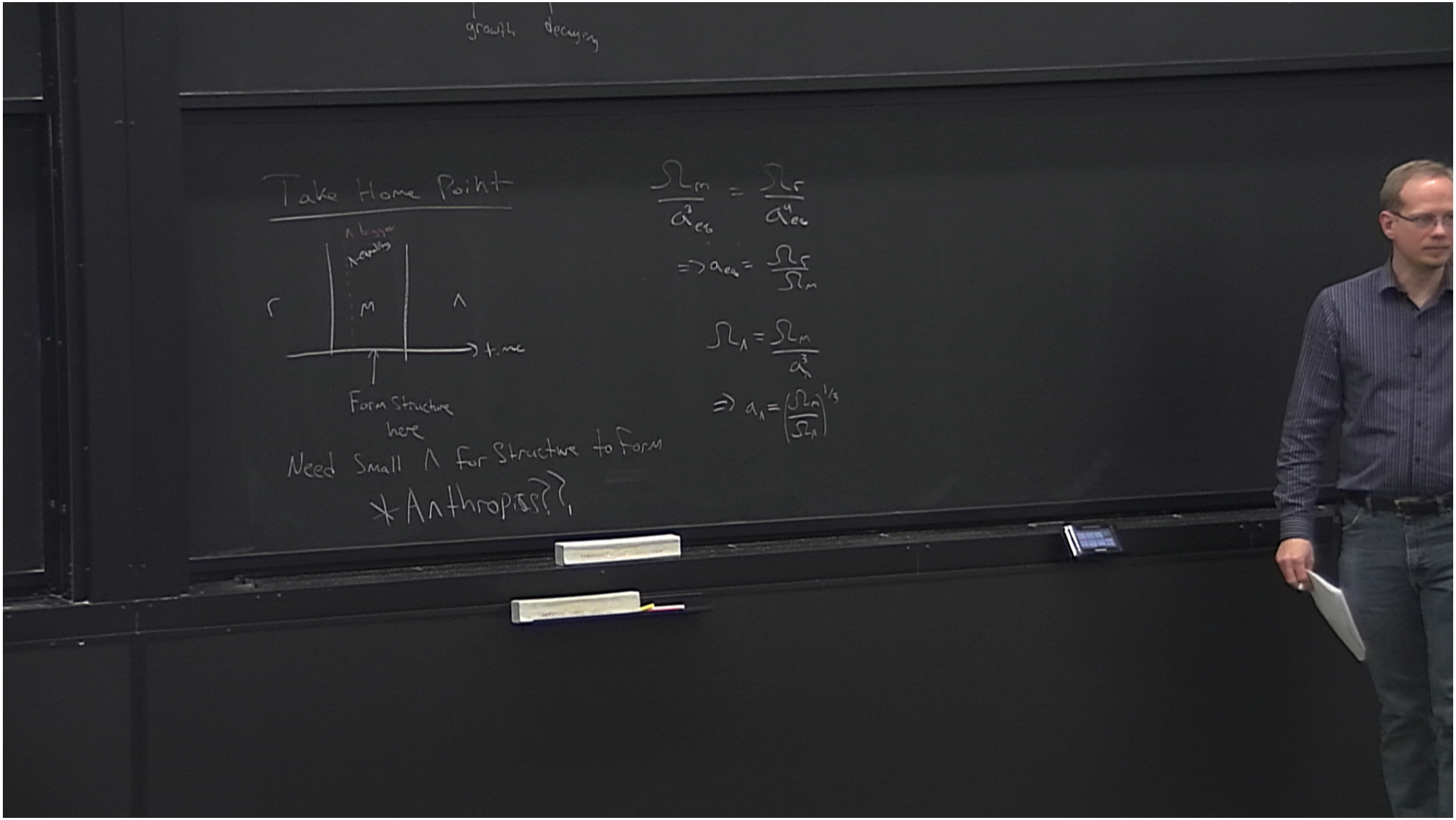

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$, $H = \frac{2}{3t}$
$\partial_t^2 \delta_c + \frac{4}{3t}\partial_t \delta_c \simeq \frac{2\delta_c}{3t^2}$
$\Rightarrow \delta_c = c_1 t^{2/3} + \frac{c_2}{t} \propto a$
growth
decaying
$z_{eq} = 3400 = \frac{1}{1+a}$
$a \simeq 10^{-3} - 10^{-4}$
$\Rightarrow \delta_c$ can grow by a factor
of ~3000.

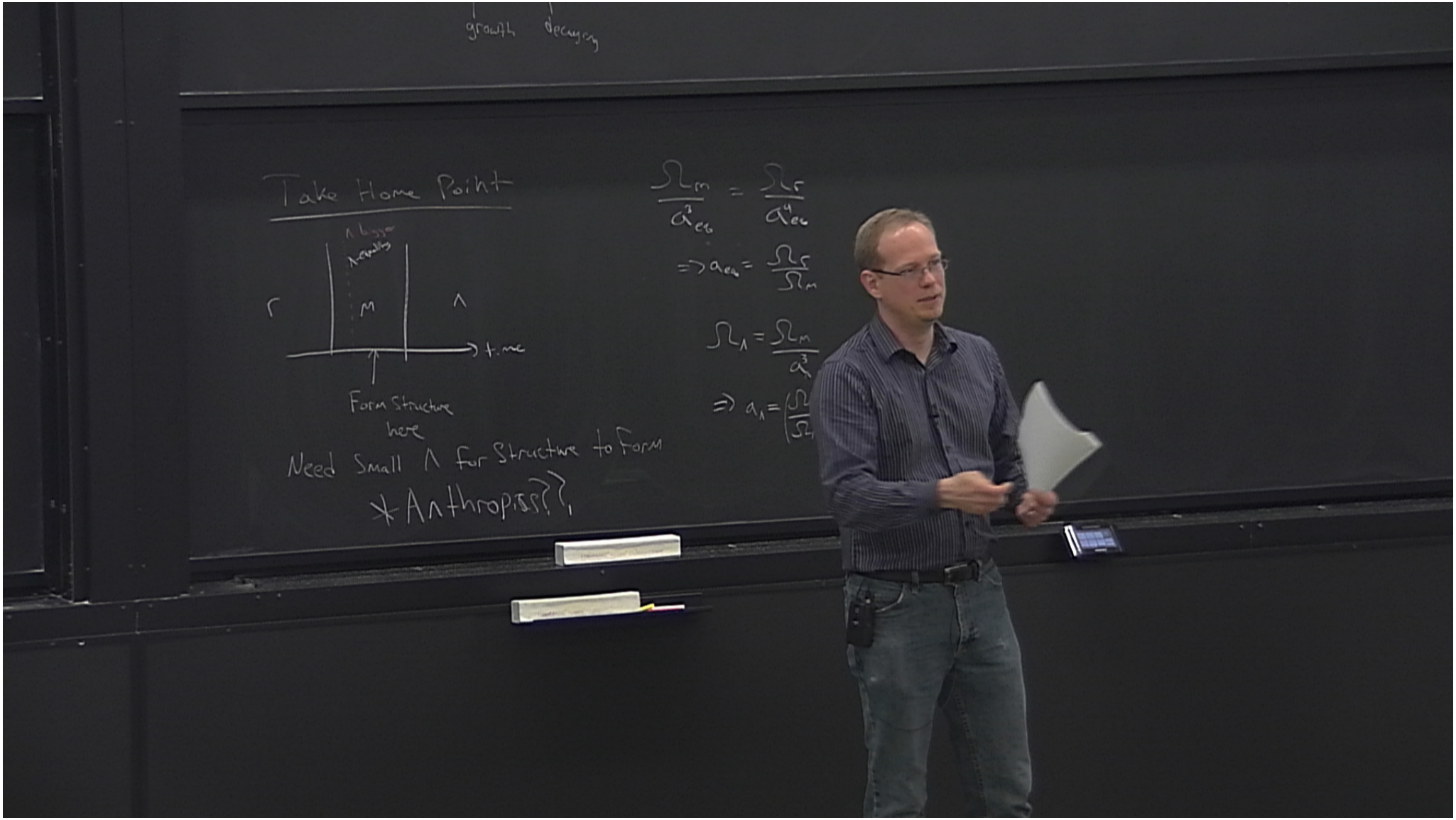

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$, $H = \frac{2}{3t}$
$\partial_t^2 \delta_c + \frac{4}{3t}\partial_t \delta_c \simeq \frac{2\delta_c}{3t^2}$
$\Rightarrow \delta = C_1 t^{2/3} + \frac{C_2}{t} \propto a$
growth
decaying
$z_{eq} = 3400 = \frac{1}{1+a}$
$a \simeq 10^{-3} - 10^{-4}$
$\Rightarrow \delta_c$ can grow by a factor
of ~3000.
$\delta_c(a_{eq}) \geq 10^{-4}$ to get structure ($\delta_c \simeq 1$ today)

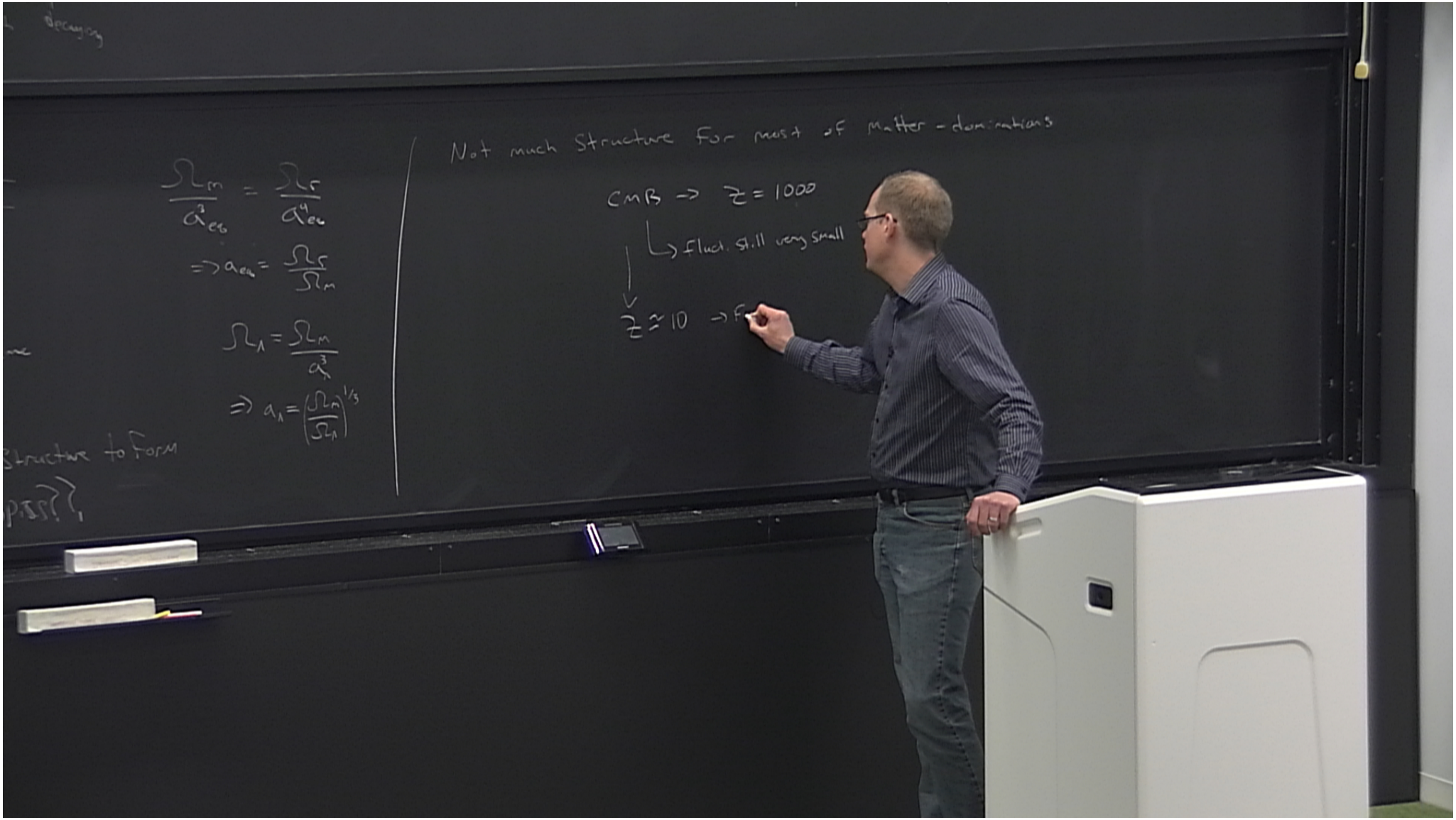

Contrast
Matter
$a = \left(\frac{t}{t_0}\right)^{2/3}$, $H = \frac{2}{3t}$
$\partial_t^2 \delta_c + \frac{4}{3t}\partial_t \delta_c \simeq \frac{2\delta_c}{3t^2}$
$\Rightarrow \delta = C_1 t^{2/3} + \frac{C_2}{t} \propto a$
growth
decaying
$z_{eq} = 3400 = \frac{1}{1+a}$
$a \simeq 10^{-3} - 10^{-4}$
$\Rightarrow \delta_c$ can grow by a factor
of ~3000.
$\delta_c(a_{eq}) \geq 10^{-4}$ to get structure ($\delta \simeq 1$ today)

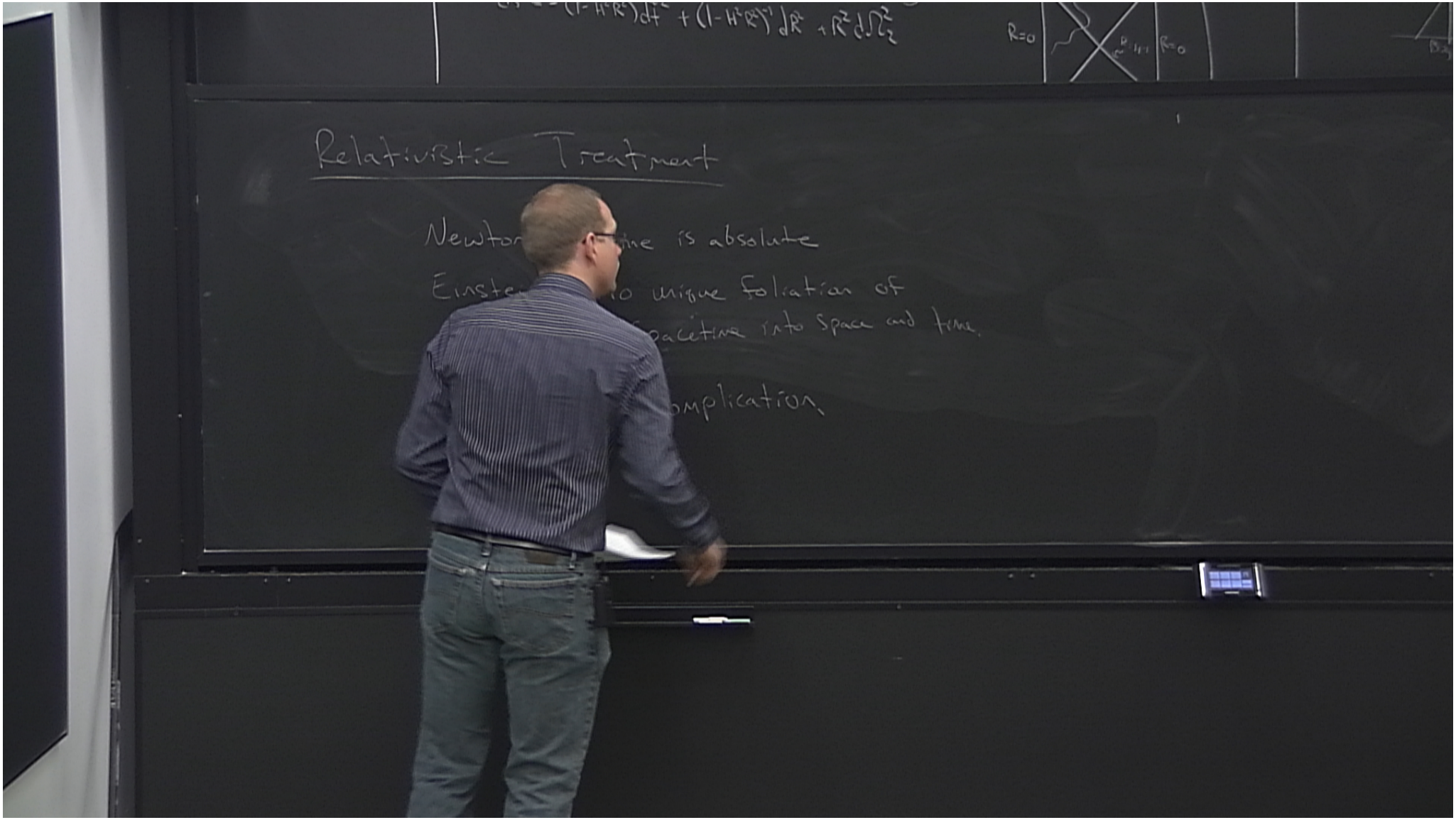

Contrast
$z_{eq} \simeq 3400 = \frac{1}{1+a}$
$a \simeq 10^{-3} - 10^{-4}$
$\Rightarrow \delta_c$ can grow by a factor
of ~ 3000.
$\delta_c(a_{eq}) \geq 10^{-4}$ to get structure ($\delta \simeq 1$ today)
Λ - domination
$\frac{2}{3t}$
$\frac{\delta_c}{3t^2}$
$\propto a$


growth
decaying
Take Home Point
Λ big
r
M
Λ
Form Structure here
Need Small Λ for Structure to Form
*Anthropic??
$\frac{\Omega_m}{a_{eq}^3} = \frac{\Omega_r}{a_{eq}^4}$
$\Rightarrow a_{eq} = \frac{\Omega_r}{\Omega_m}$
$\Omega_\Lambda = \frac{\Omega_m}{a^3}$
$\Rightarrow a_\Lambda = \left(\frac{\Omega_\Lambda}{\Omega_m}\right)^{1/3}$


growth
decaying
Take Home Point
$\frac{\Omega_m}{a_{eq}^3} = \frac{\Omega_r}{a_{eq}^4}$
$\Rightarrow a_{eq} = \frac{\Omega_r}{\Omega_m}$
$\Omega_\Lambda = \frac{\Omega_m}{a^3}$
$\Rightarrow a_\Lambda = \left(\frac{\Omega_\Lambda}{\Omega_\Lambda}\right)^{1/3}$
Λ begins dominating
r
M
Λ
time
Form Structure here
Need Small Λ for Structure to Form
*Anthropics??


growth
decaying
Take Home Point
$\frac{\Omega_m}{a_{eq}^3} = \frac{\Omega_r}{a_{eq}^4}$
$\Rightarrow a_{eq} = \frac{\Omega_r}{\Omega_m}$
$\Omega_\Lambda = \frac{\Omega_m}{a^3}$
$\Rightarrow a_\Lambda = \frac{\Omega_\Lambda}{\Omega_r}$
Λ bigger
Density
r
M
Λ
time
Form Structure
here
Need Small Λ for Structure to Form
*Anthropic??


decaying
$\frac{\Omega_m}{a_{eq}^3} = \frac{\Omega_r}{a_{eq}^4}$
$\Rightarrow a_{eq} = \frac{\Omega_r}{\Omega_m}$
$\Omega_\Lambda = \frac{\Omega_m}{a^3}$
$\Rightarrow a_\Lambda = \left(\frac{\Omega_m}{\Omega_\Lambda}\right)^{1/3}$
structure to form
Not much structure for most of matter-domination
CMB -> z = 1000
fluct. still very small
z ≈ 10


Relativistic Treatment
is absolute
unique foliation of
spacetime into space and time.
complication.
R=0
R=0