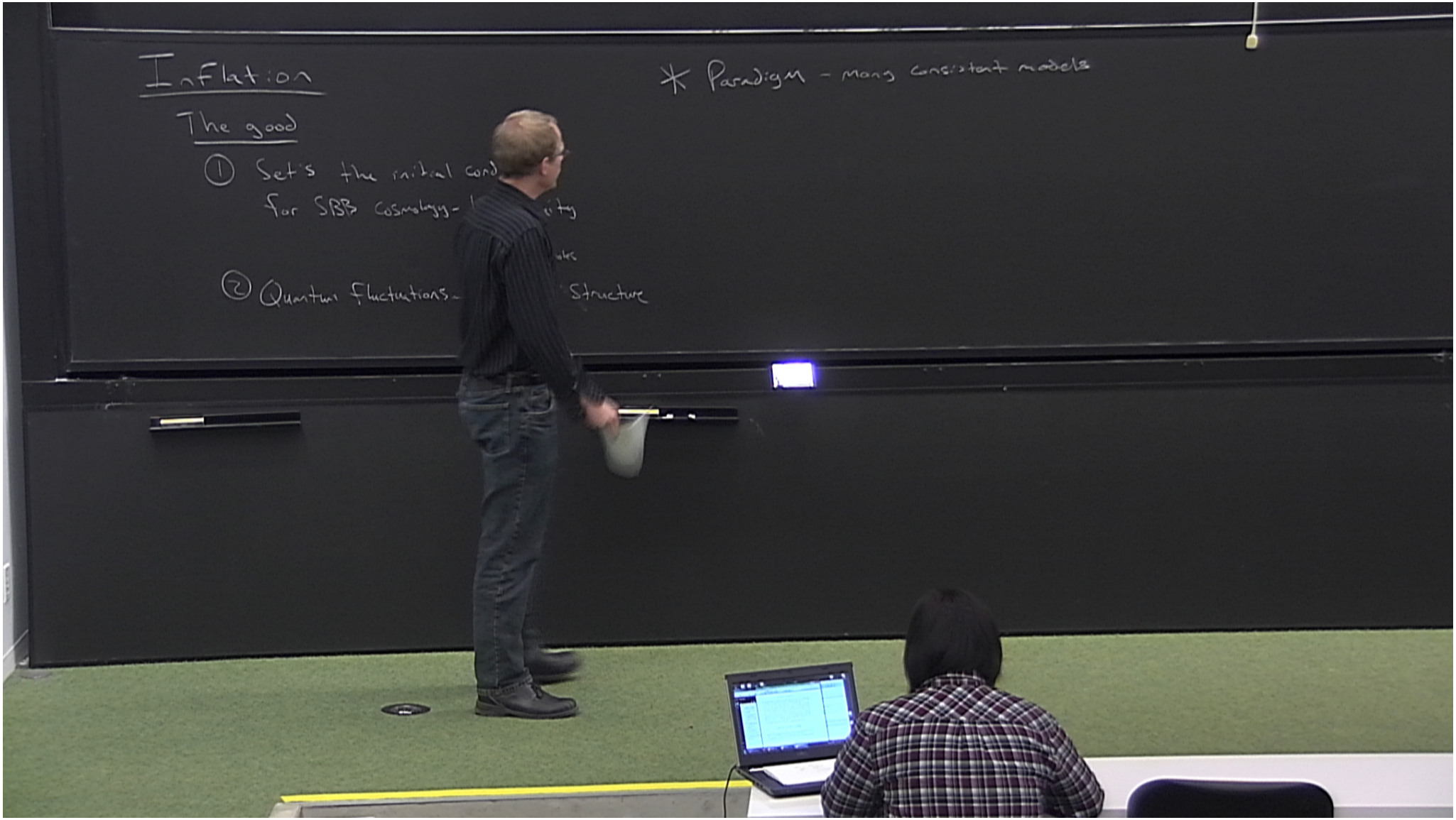
Title: Explorations in Cosmology - Lecture 15

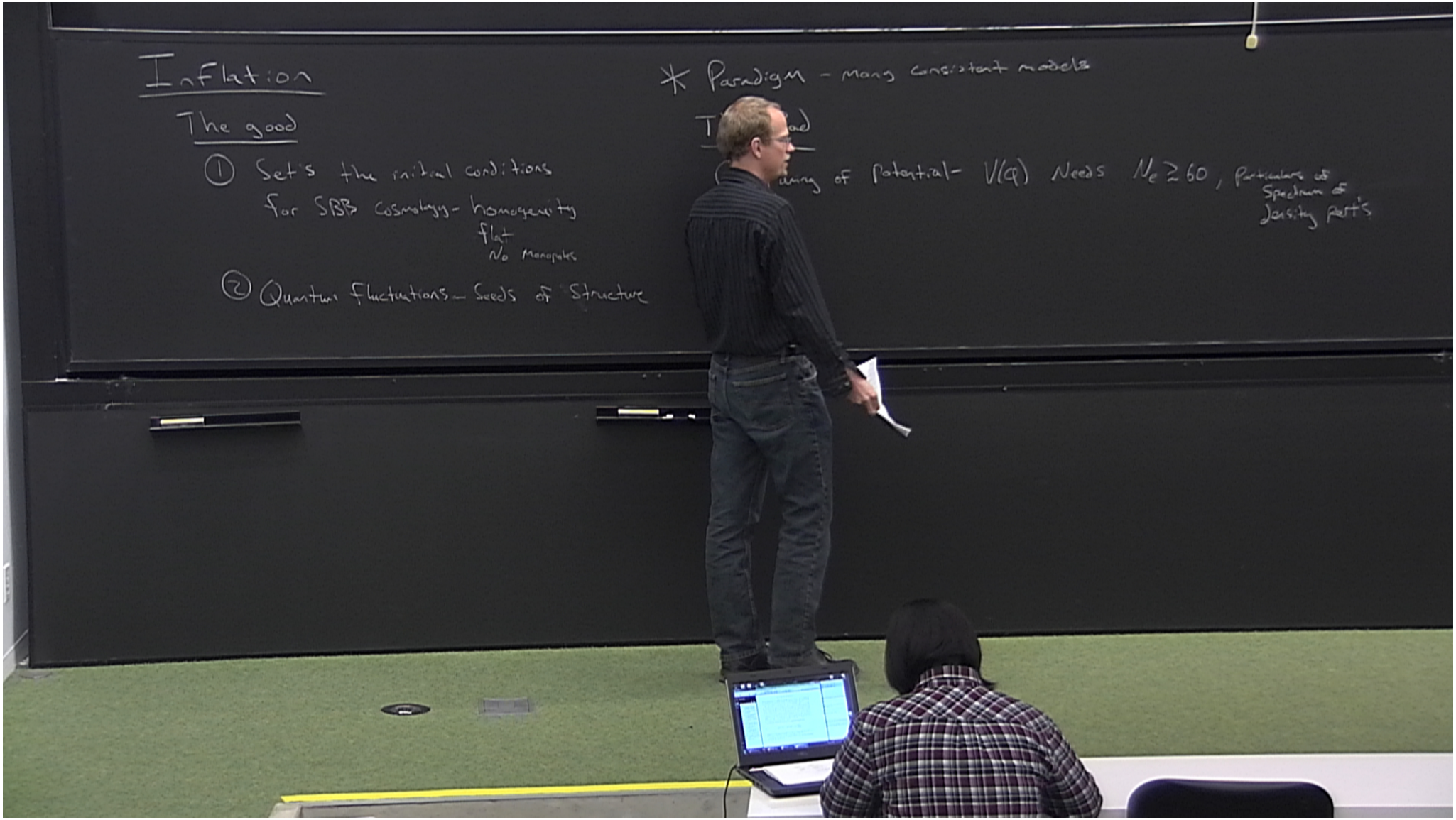
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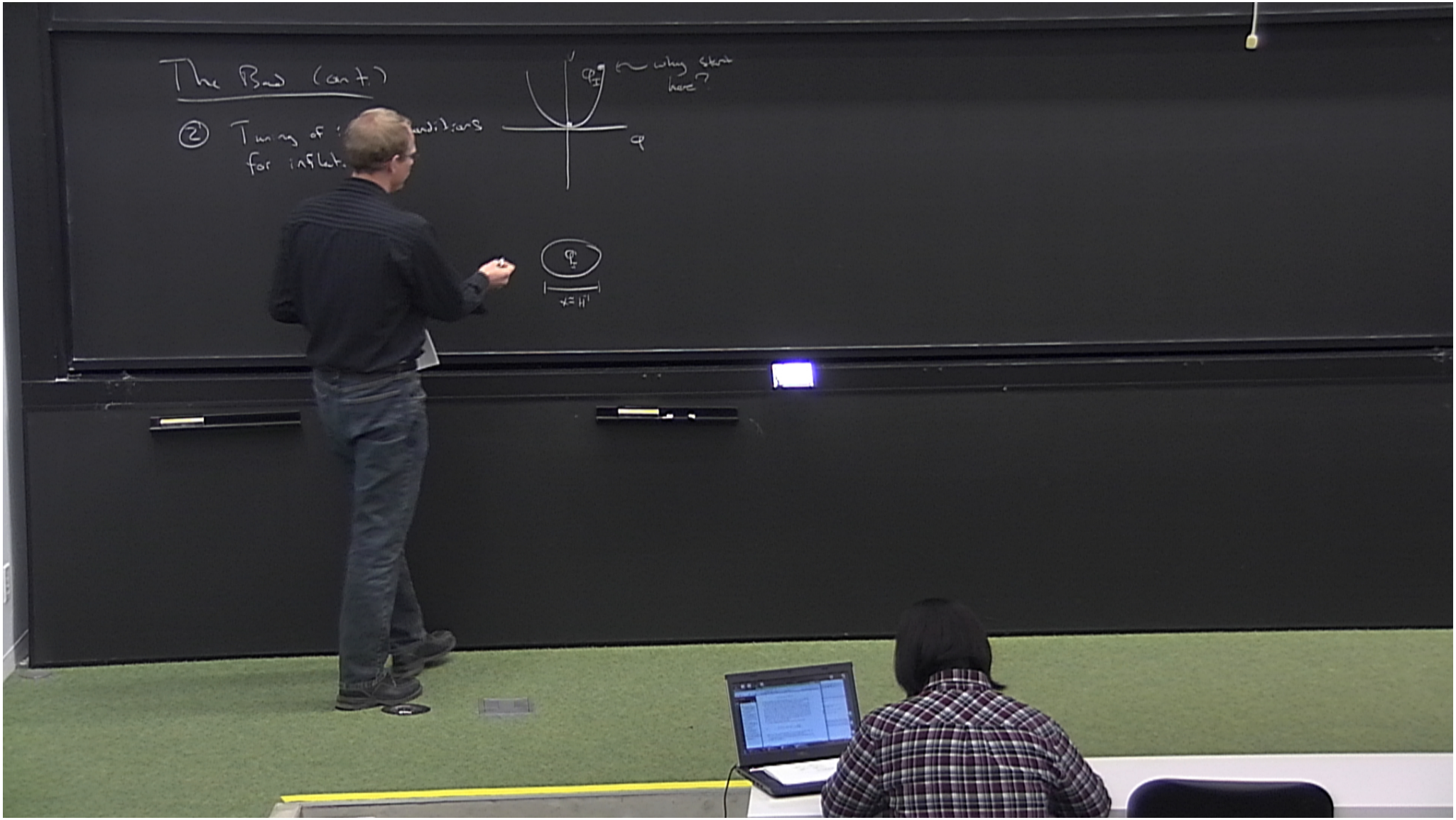
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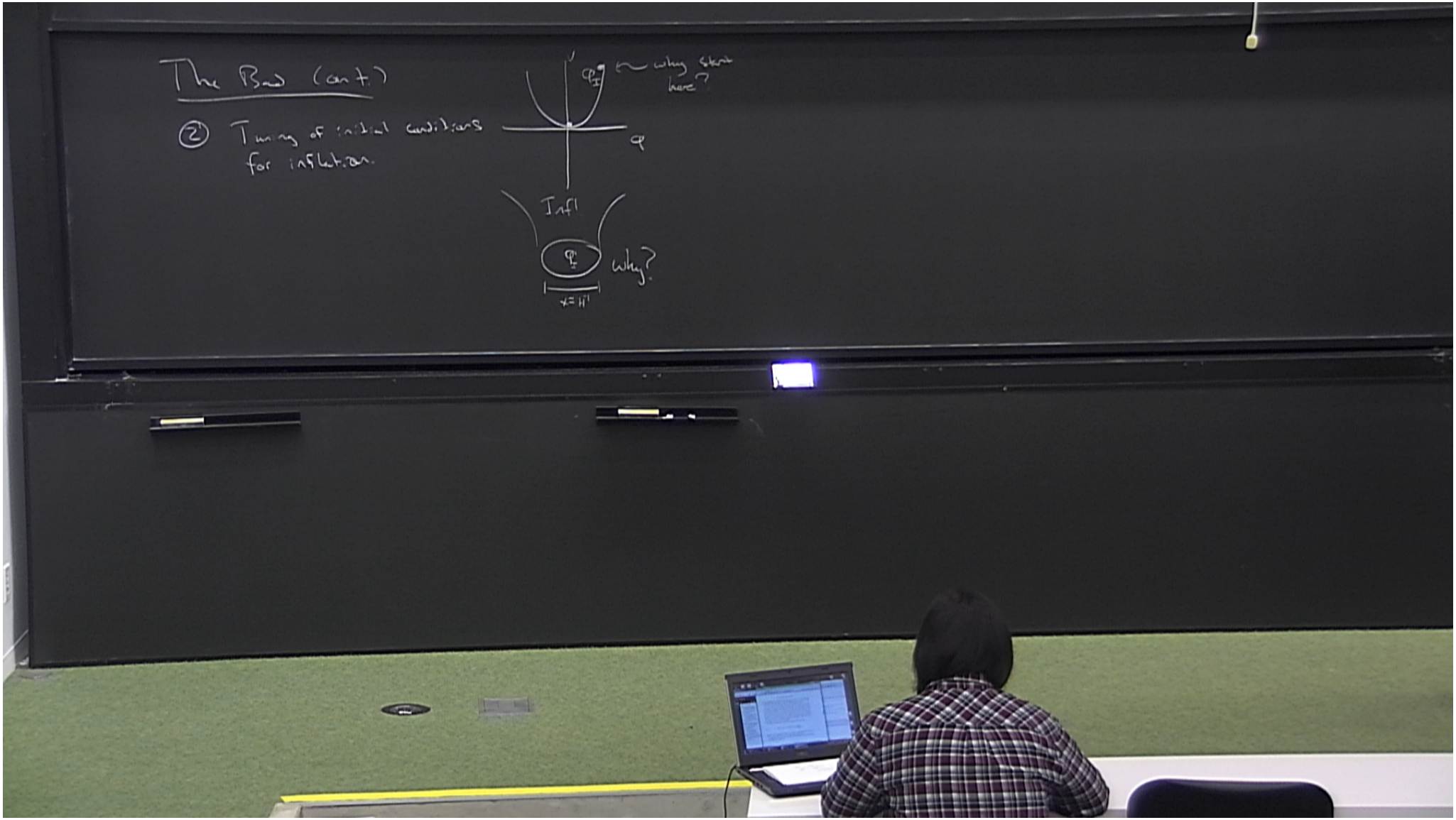

Inflation

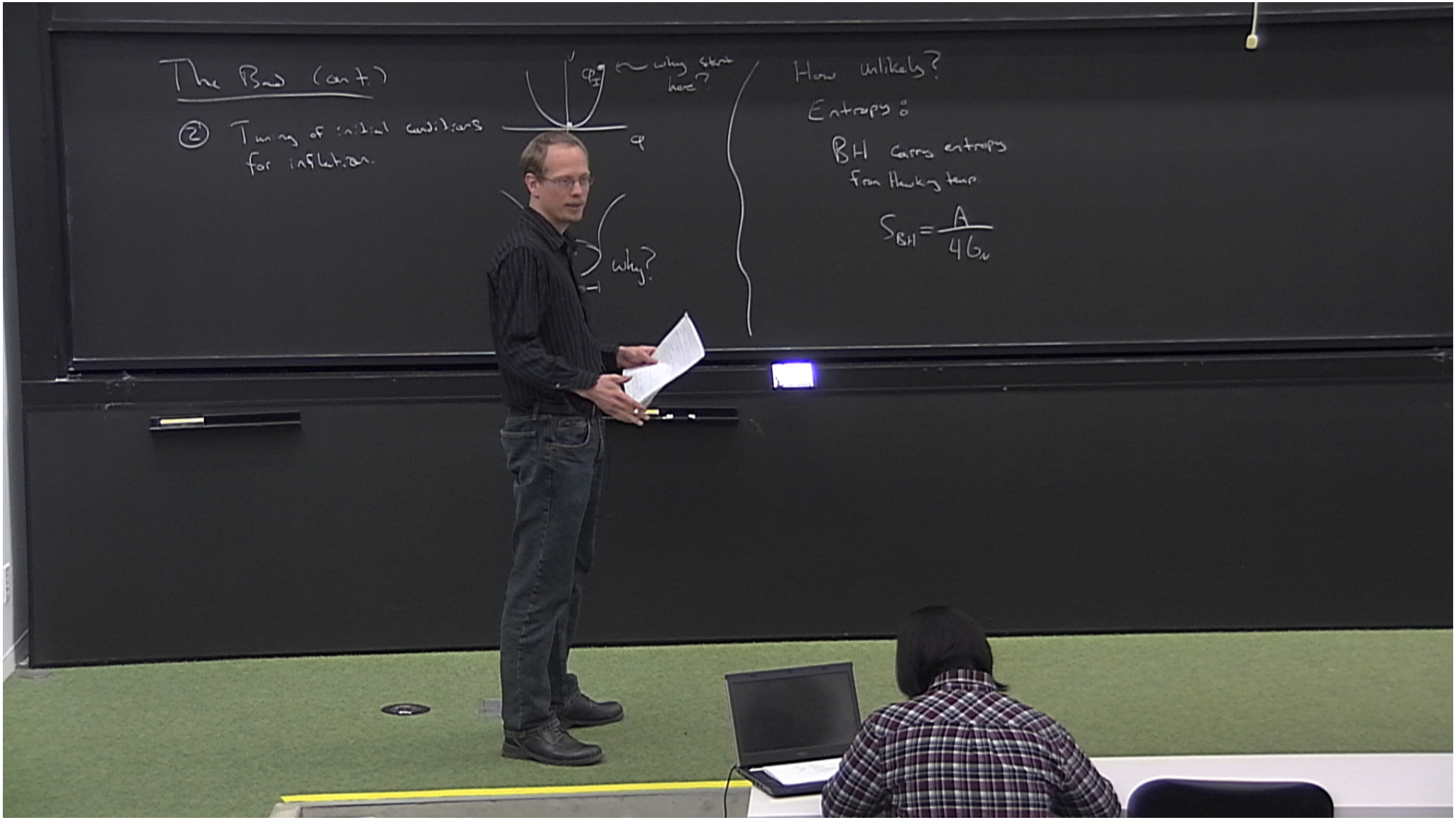

Inflation
The good
* Paradigm - many consistent models
Structure

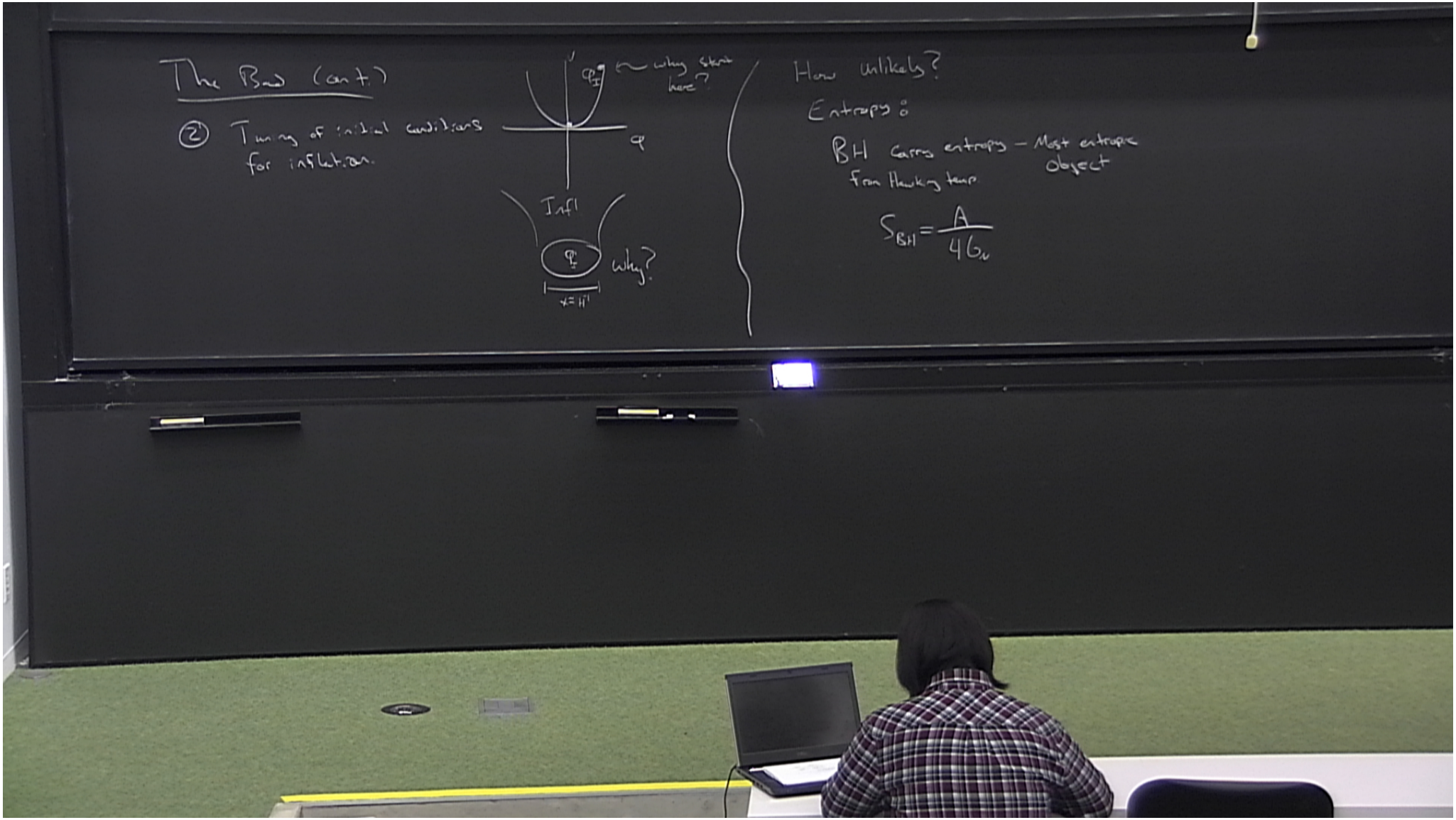

Inflation
The good
① Sets the initial conditions for SBB cosmology - homogeneity flat No Monopoles
② Quantum fluctuations - Seeds of Structure
* Paradigm - Many consistent models
Needs $N_e \geq 60$,
Particulars of Spectrum of Density Pert's

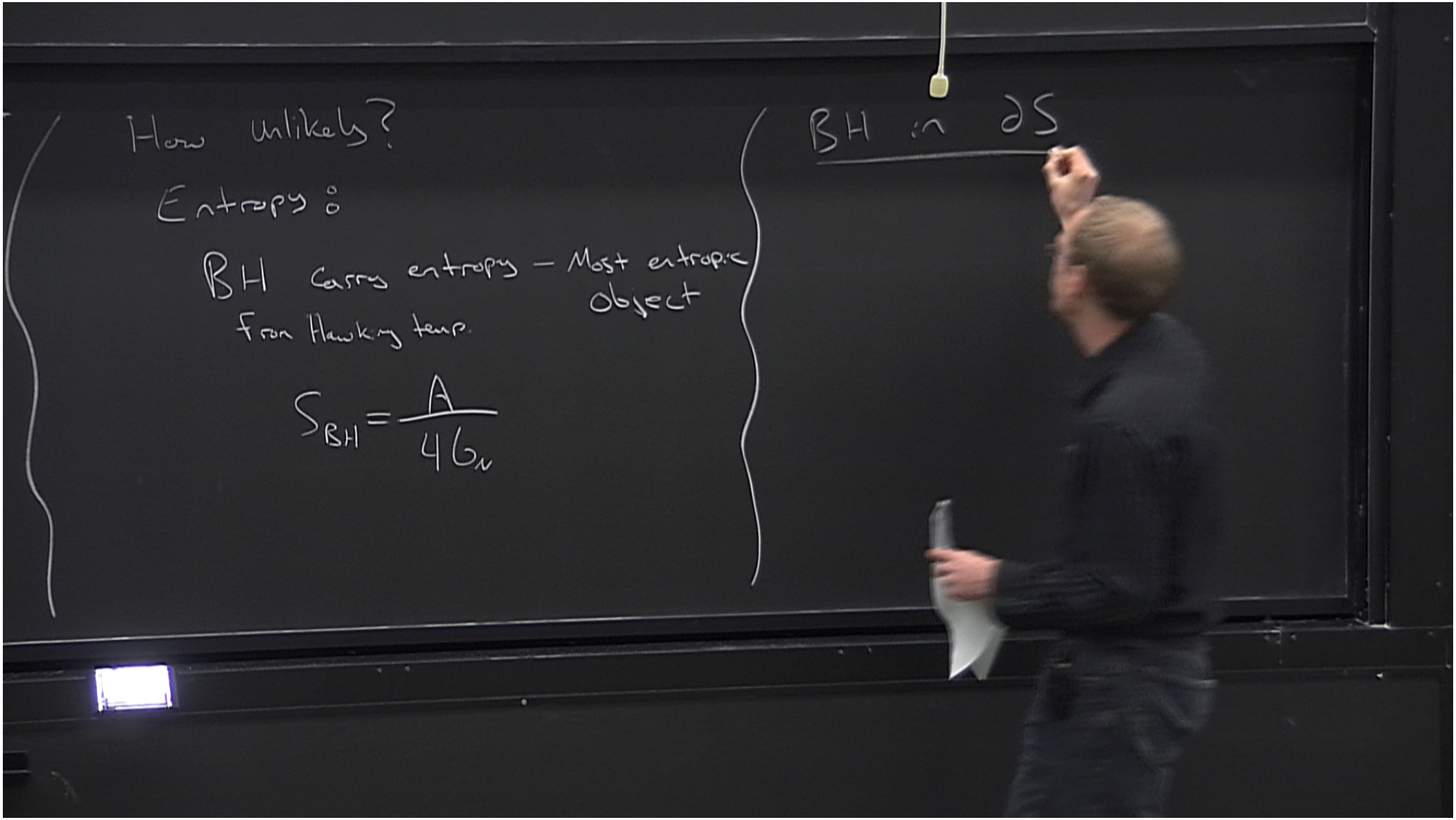

The Bird (cont.)

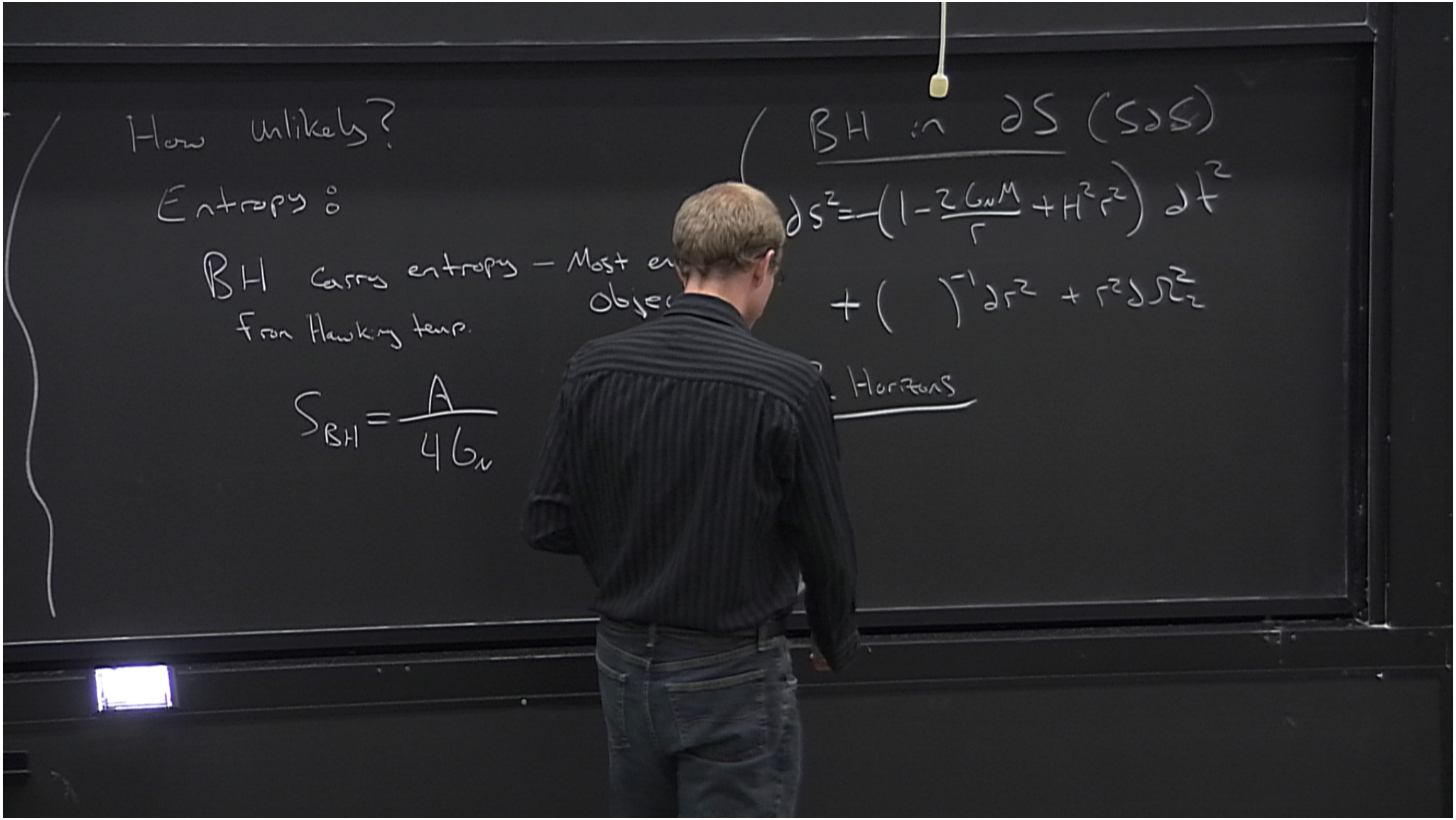

The Bad (cont.)
(2)
for inflat.
V
φ
φ_f
~ why start here?
φ_i
r = 1/T

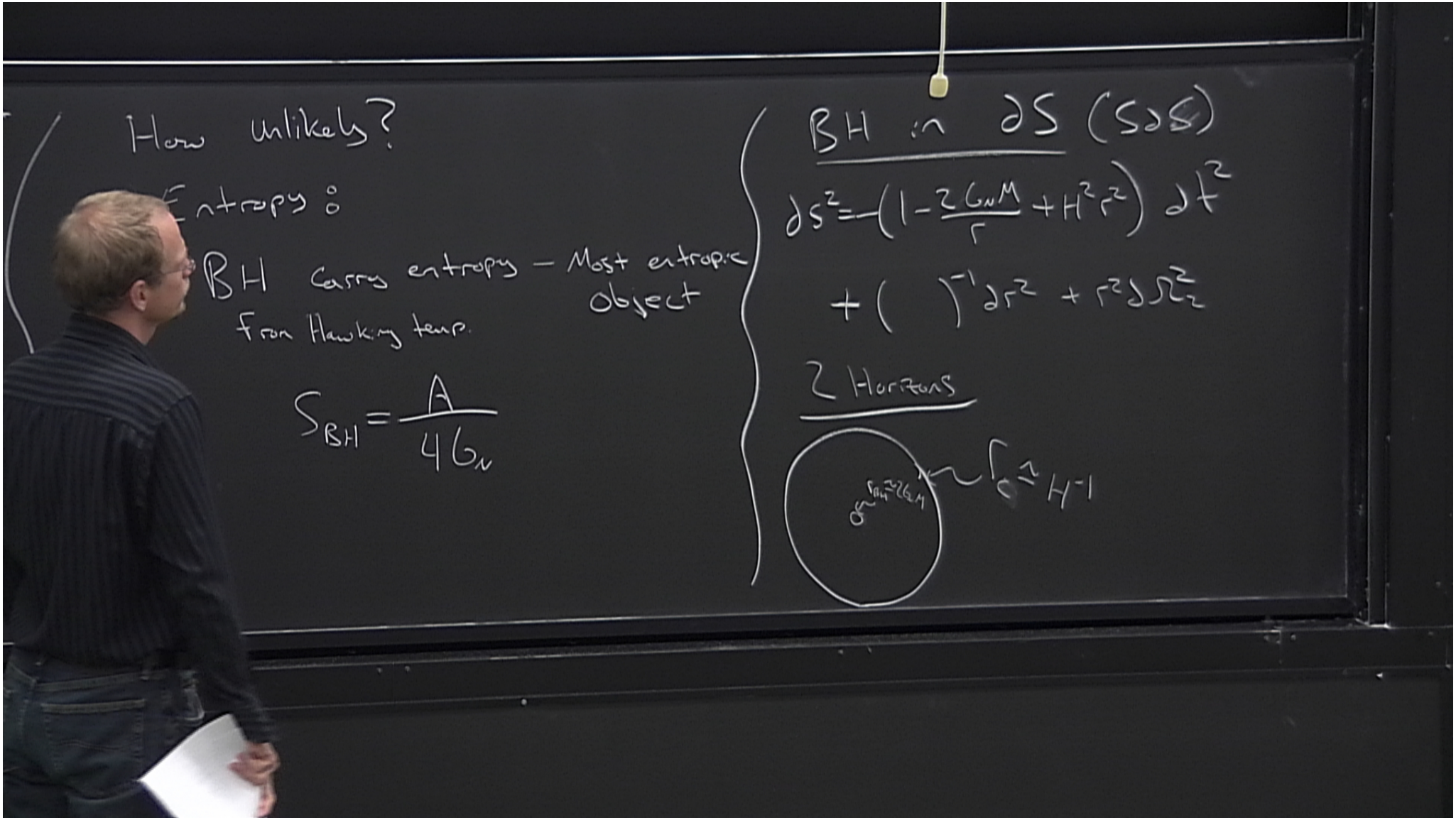

The Bad (cont.)
② Tuning of initial conditions for inflation.
V
φ
Infl
why?
why start here?

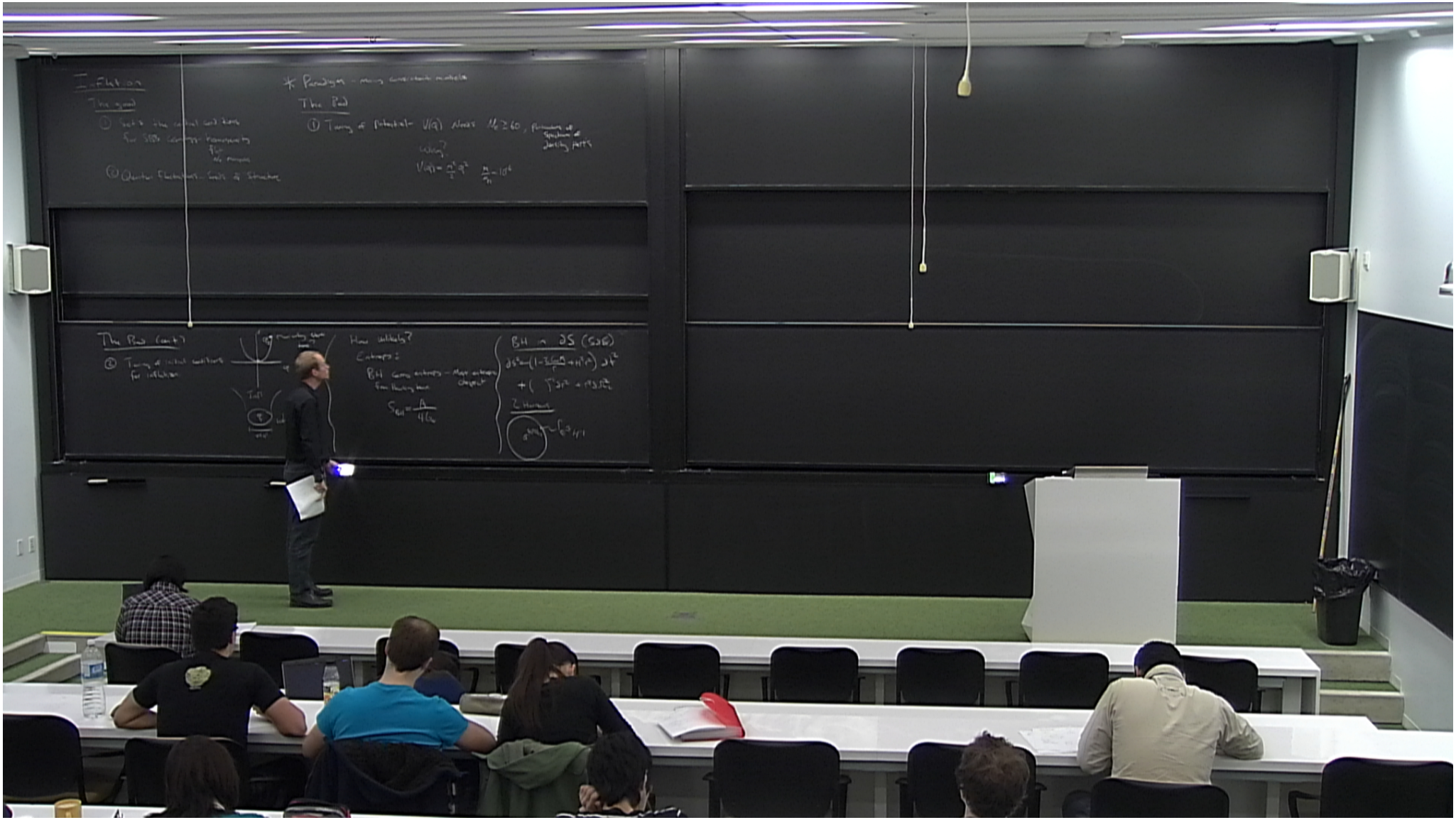

The Bad (cont.)
② Tuning of initial conditions for inflation.
why start here?
why?
How unlikely?
Entropy:
BH carries entropy from Hawking temp
$S_{BH} = \frac{A}{4G_N}$

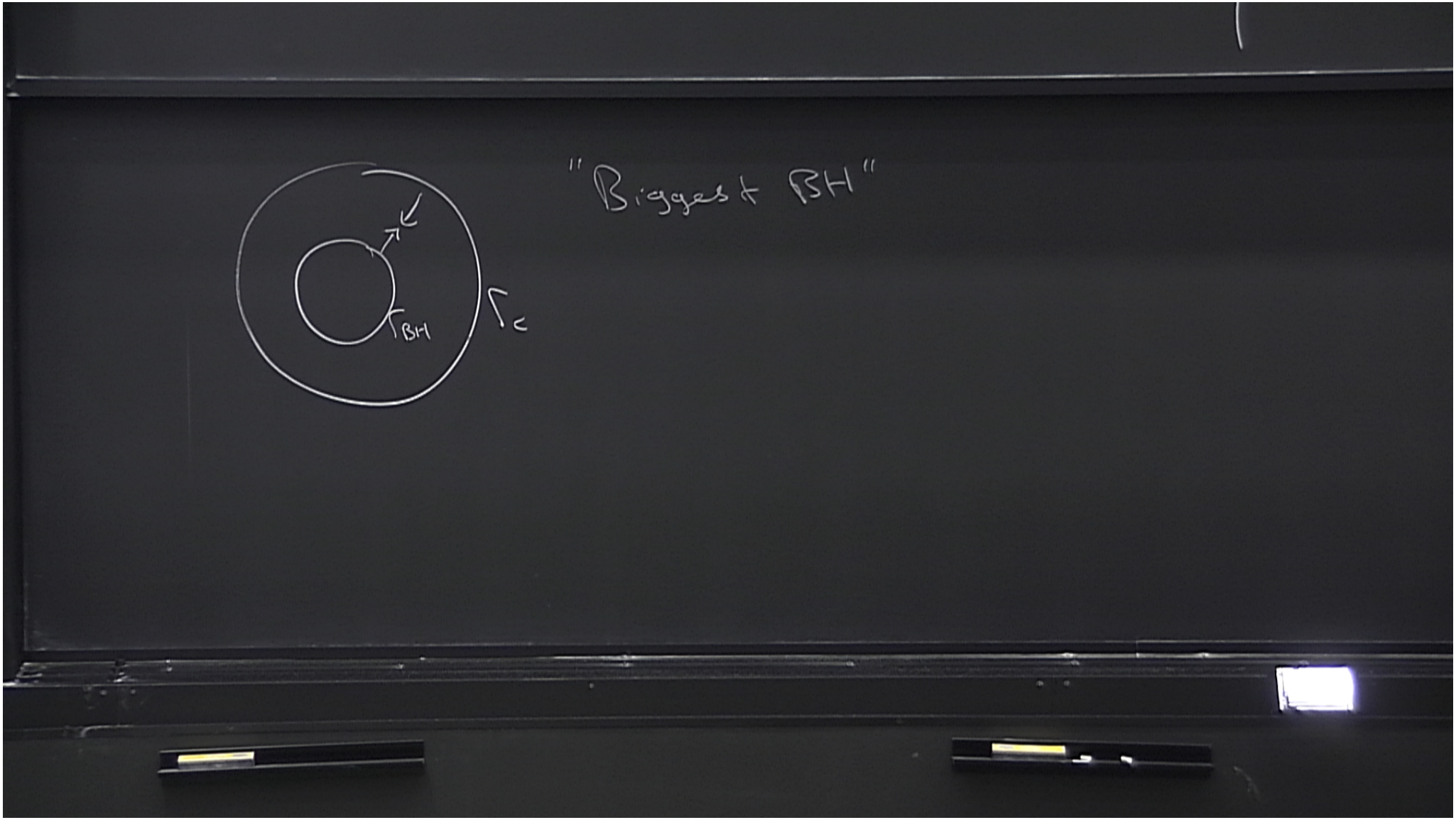

The Bad (cont.)
② Tuning of initial conditions for inflation.
V
φ
Infl
why?
x = H⁻¹
why start here?
How unlikely?
Entropy:
BH carries entropy – Most entropic object
from Hawking temp
$S_{BH} = \frac{A}{4G_N}$

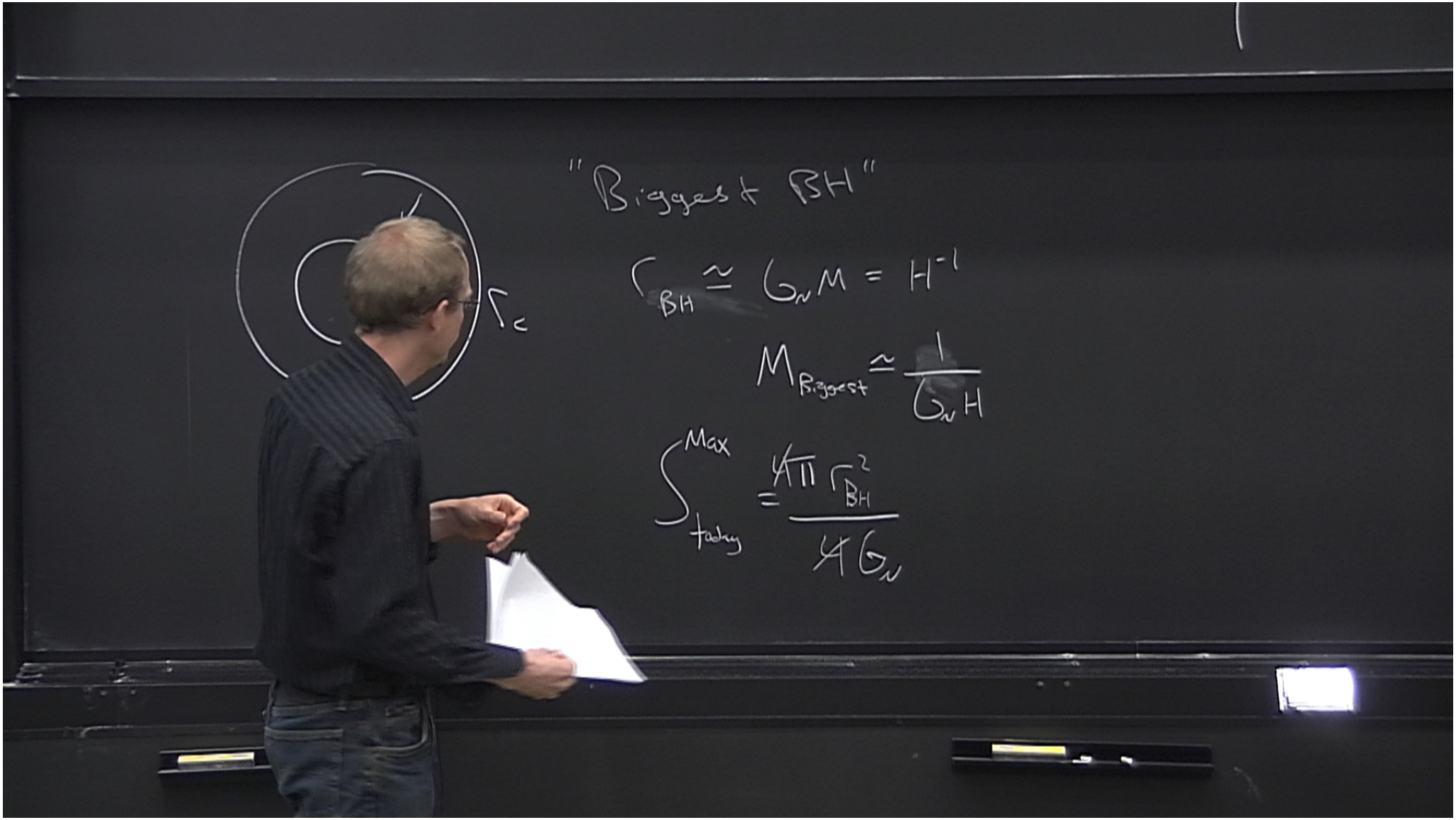

How unlikely?
Entropy:
BH carry entropy – Most entropic object
from Hawking temp.
$S_{BH} = \frac{A}{4G_N}$
BH in dS

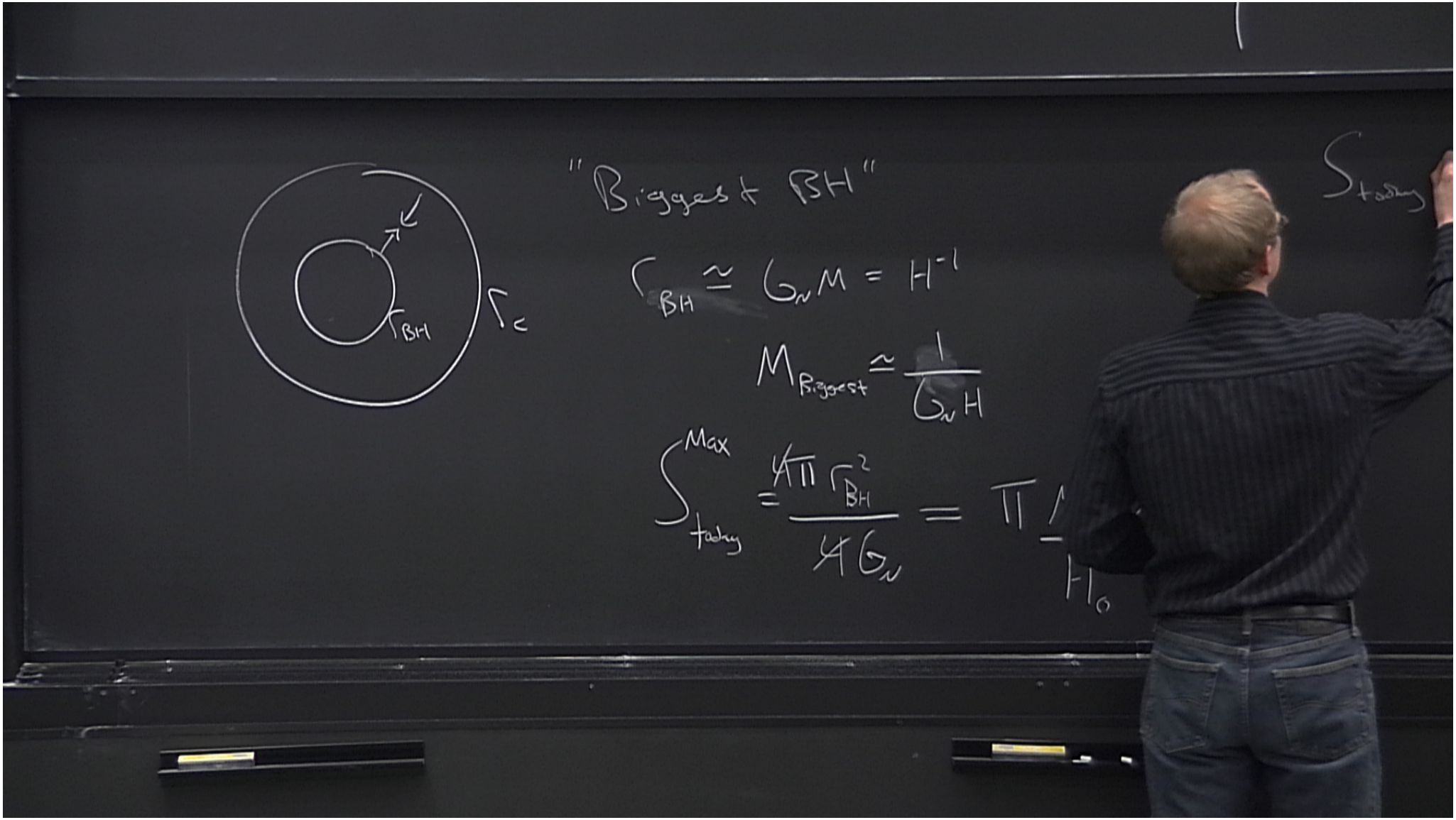

How unlikely?
Entropy:
BH carry entropy – Most
from Hawking temp.
$S_{BH} = \frac{A}{4G_N}$
BH in dS (SdS)
$ds^2 = -\left(1 - \frac{2G_N M}{r} + H^2 r^2\right) dt^2$
$+ (\quad)^{-1} dr^2 + r^2 d\Omega_2^2$
Horizons

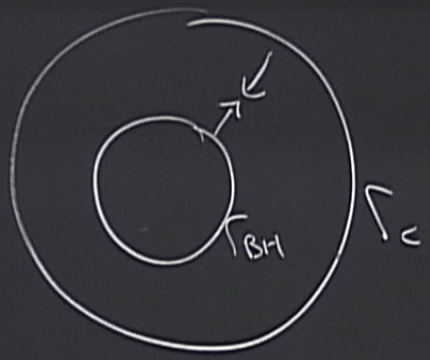

How unlikely?
Entropy:
BH carry entropy – Most entropic object
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$S_{BH} = \frac{A}{4G_N}$
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$+ (\quad)^{-1} dr^2 + r^2 d\Omega_2^2$
2 Horizons
$r_H \simeq 2G_N M$
$r_C \simeq H^{-1}$


Inflation
The good
The Bad
The Bad (cont.)
How unlikely?
Caveats:
BH → DS (SdS)


"Biggest BH"
r_{BH}
r_c


"Biggest BH"
$r_{BH} \simeq G_N M = H^{-1}$
$M_{Biggest} \simeq \frac{1}{G_N H}$
$\int_{today}^{Max} = \frac{4\pi r_{BH}^2}{4 G_N}$
r_c


"Biggest BH"
$r_{BH} \simeq G_N M = H^{-1}$
$M_{Biggest} \simeq \frac{1}{G_N H}$
$S_{today}^{Max} = \frac{4\pi r_{BH}^2}{4 G_N} = \pi$
r_{BH}
r_c



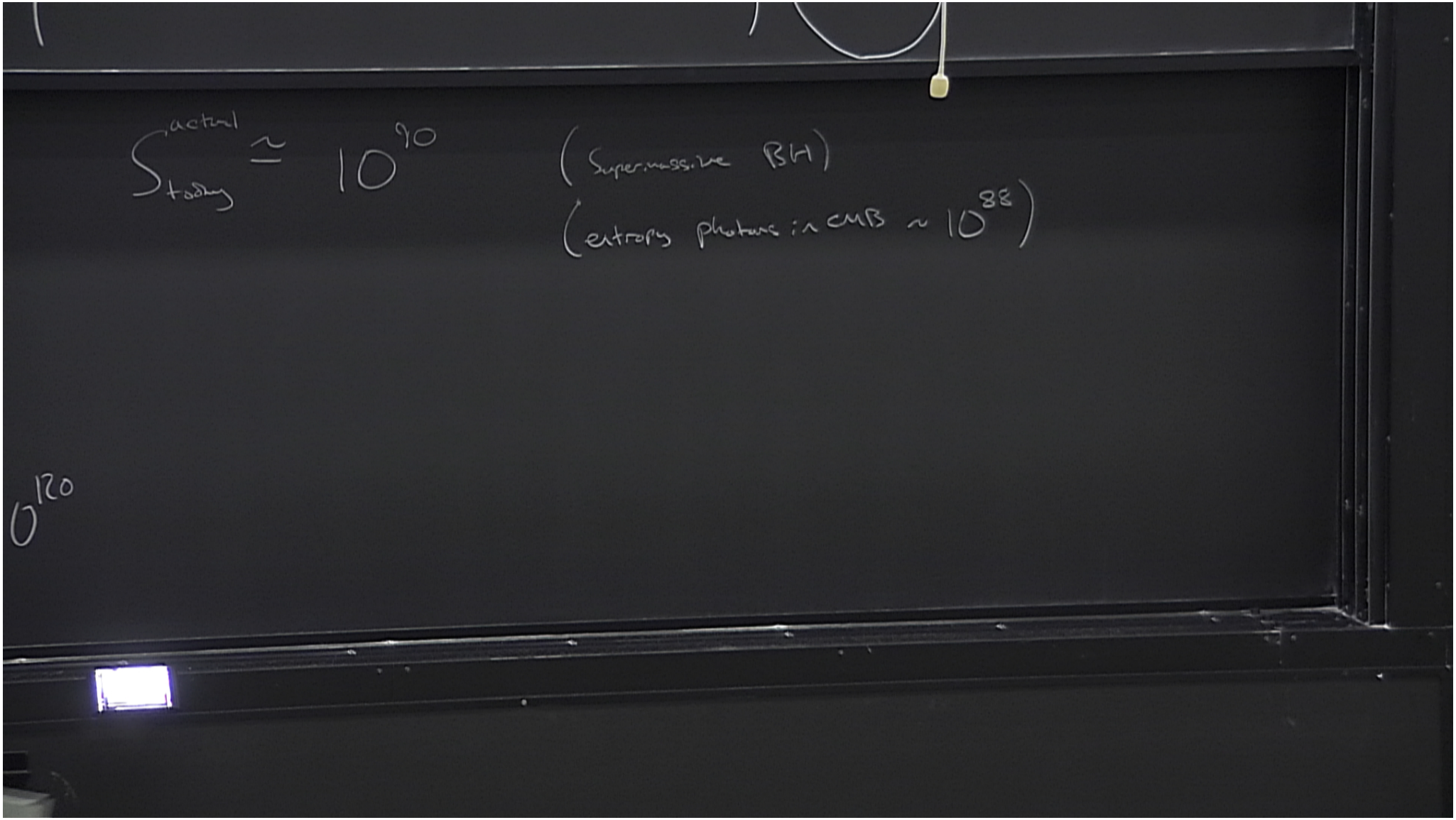
"Biggest BH"

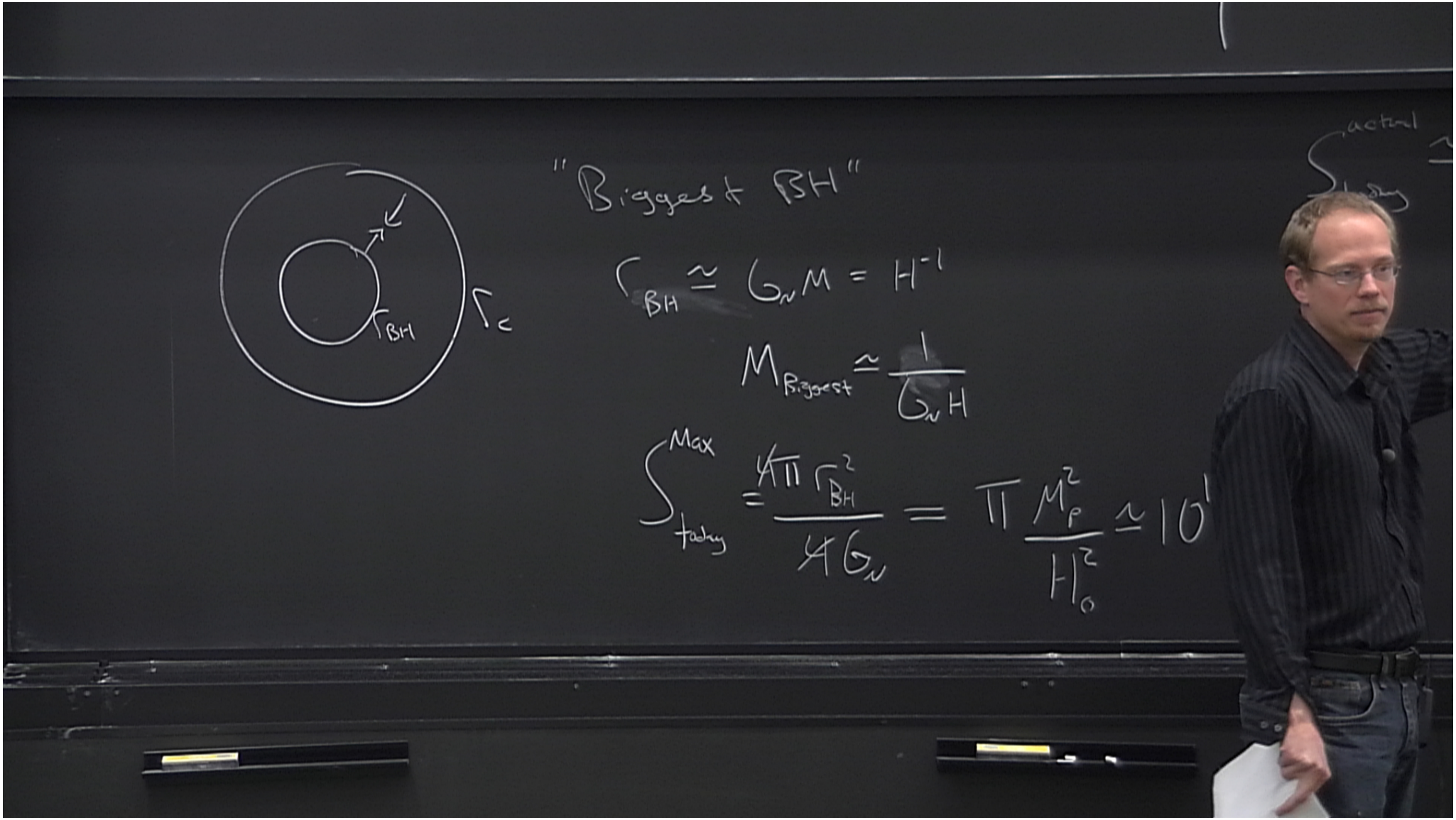
$$r_{BH} \simeq G_N M = H^{-1}$$

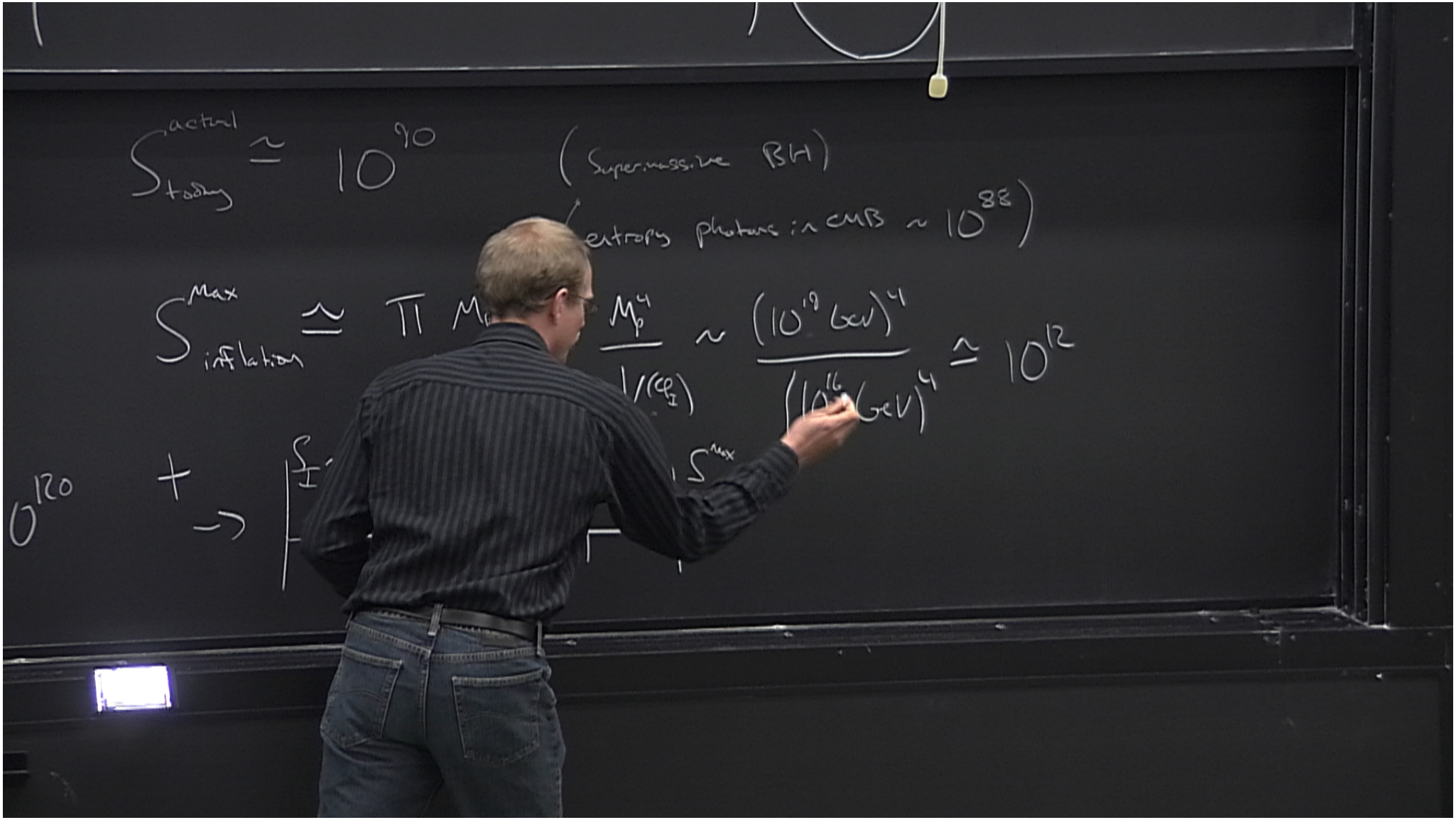
$$M_{Biggest} \simeq \frac{1}{G_N H}$$

$$S^{Max}_{today} = \frac{4\pi r_{BH}^2}{4 G_N} = \pi \frac{M_P^2}{H_0^2} \simeq 10^{120}$$

S^{actual}_{today}


$S_{today}^{actual} \simeq 10^{90}$
(Supermassive BH)
(entropy photons in CMB $\sim 10^{88}$)
10^{120}

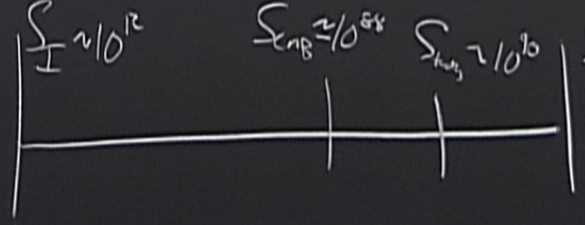

"Biggest BH"
$r_{BH} \simeq G_N M = H^{-1}$
$M_{Biggest} \simeq \frac{1}{G_N H}$
$\int_{today}^{Max} = \frac{4\pi r_{BH}^2}{4 G_N} = \pi \frac{M_P^2}{H_0^2} \simeq 10^1$
r_{BH}
r_c
actual

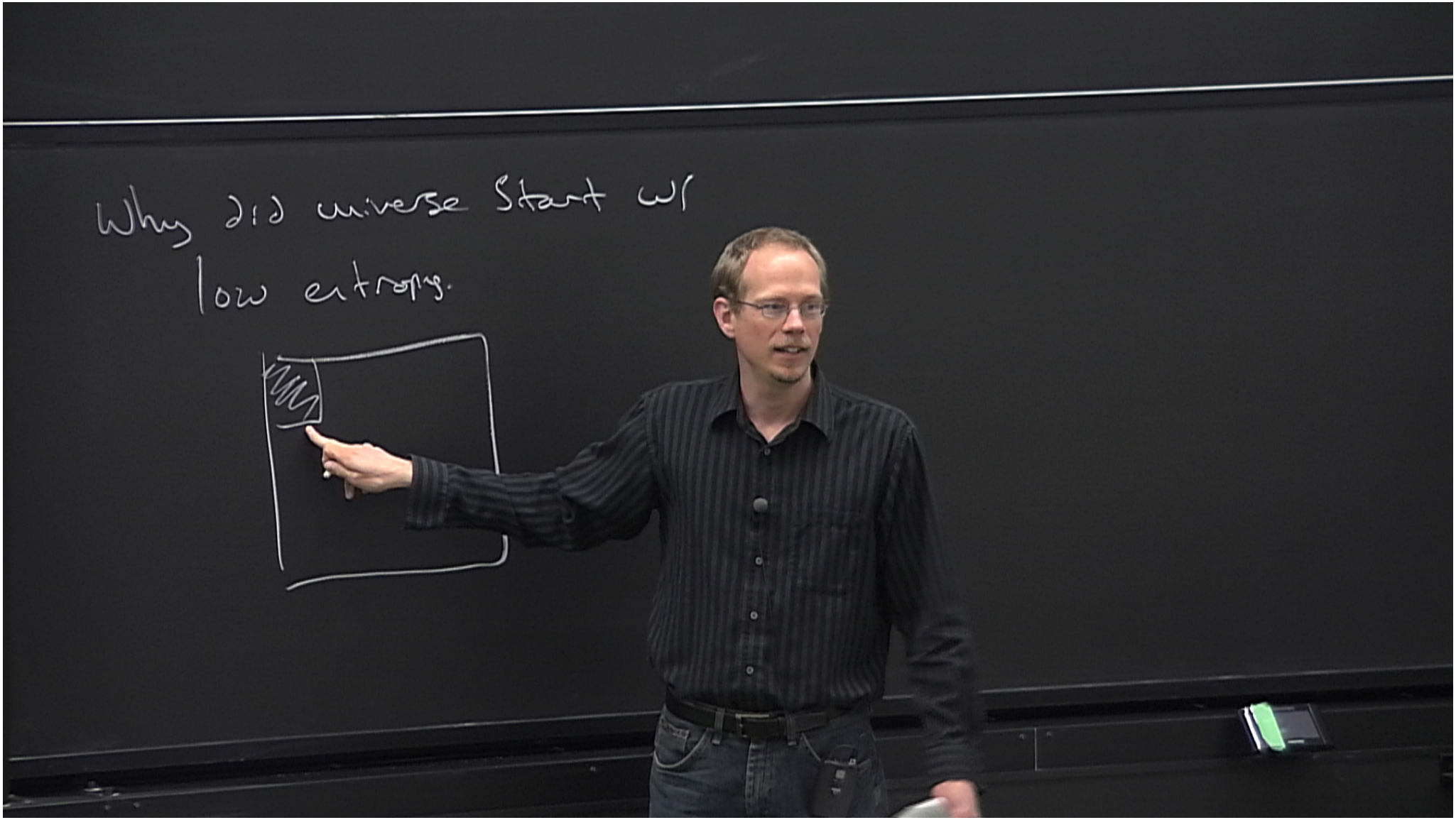

$S^{actual}_{today} \simeq 10^{90}$
(Supermassive BH)
(entropy photons in CMB $\sim 10^{88}$)
$S^{Max}_{inflation} \simeq \pi M_I \frac{M_p^4}{V(\phi_I)} \sim \frac{(10^{19}\,GeV)^4}{(10^{16}\,GeV)^4} \simeq 10^{12}$
10^{120}
+
S^{Max}

$S_{today}^{actual} \simeq 10^{90}$ (Supermassive BH)

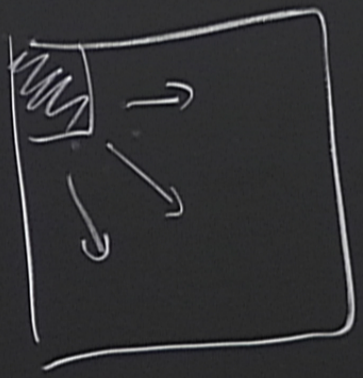
(entropy photons in CMB $\sim 10^{88}$)

$S_{inflation}^{Max} \simeq \pi \frac{M_p^2}{H_I^2} \sim \frac{M_p^4}{V(\phi_I)} \sim \frac{(10^{19}\,GeV)^4}{(10^{16}\,GeV)^4} \simeq 10^{12}$

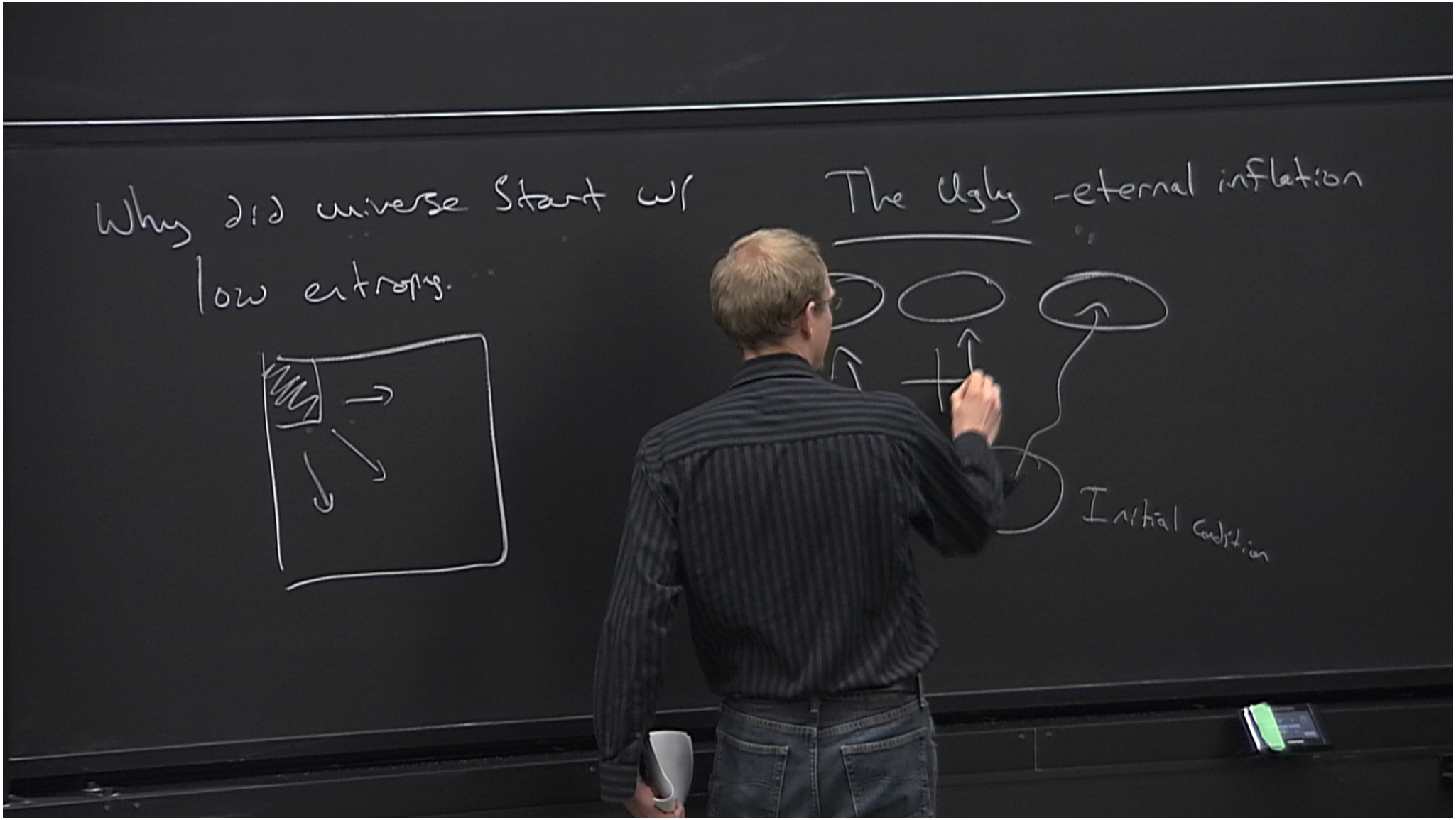
$10^{120} + \ldots \rightarrow$ 

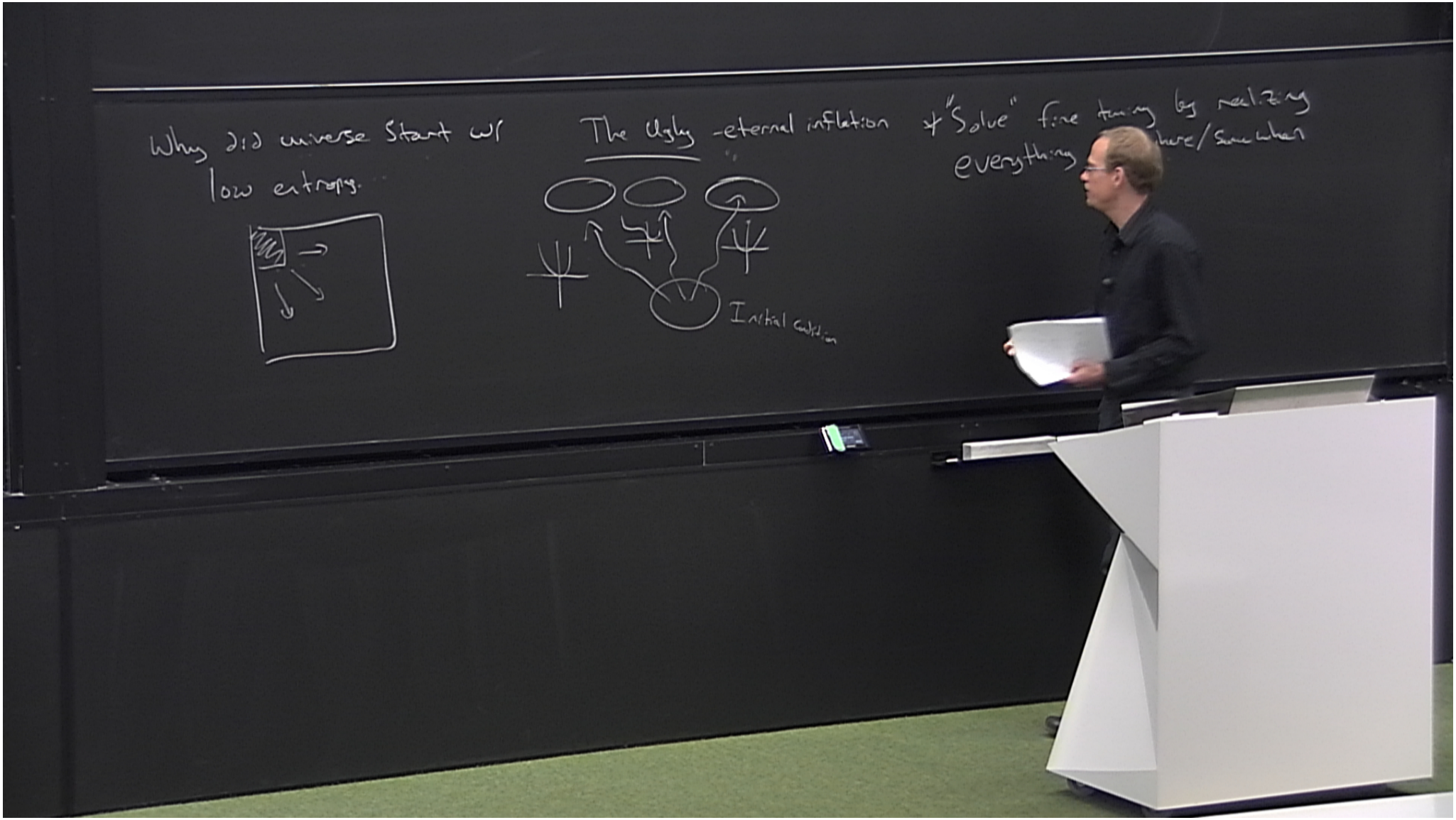

Why did universe start w/
low entropy.

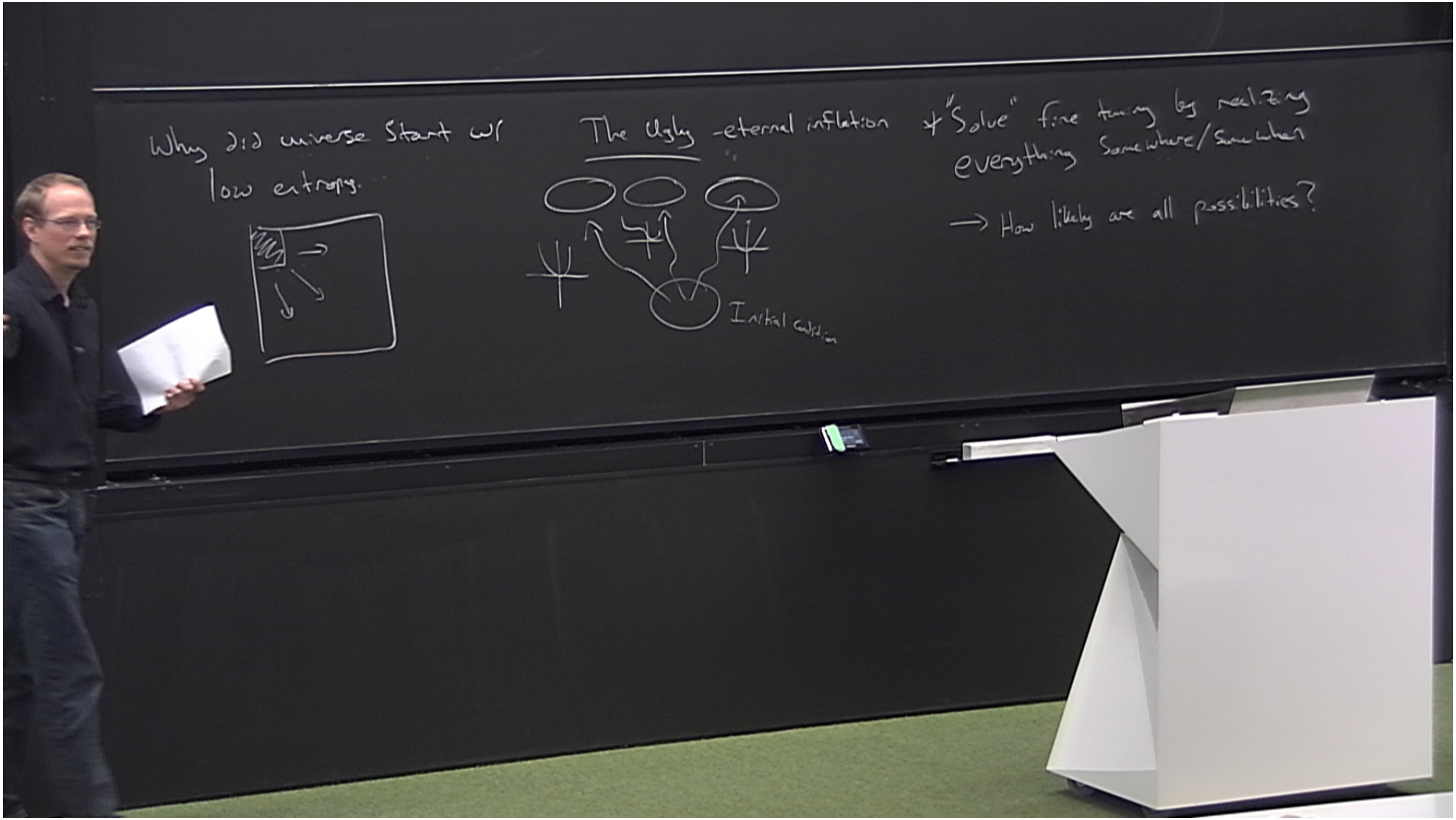
Why did universe start w/ low entropy.

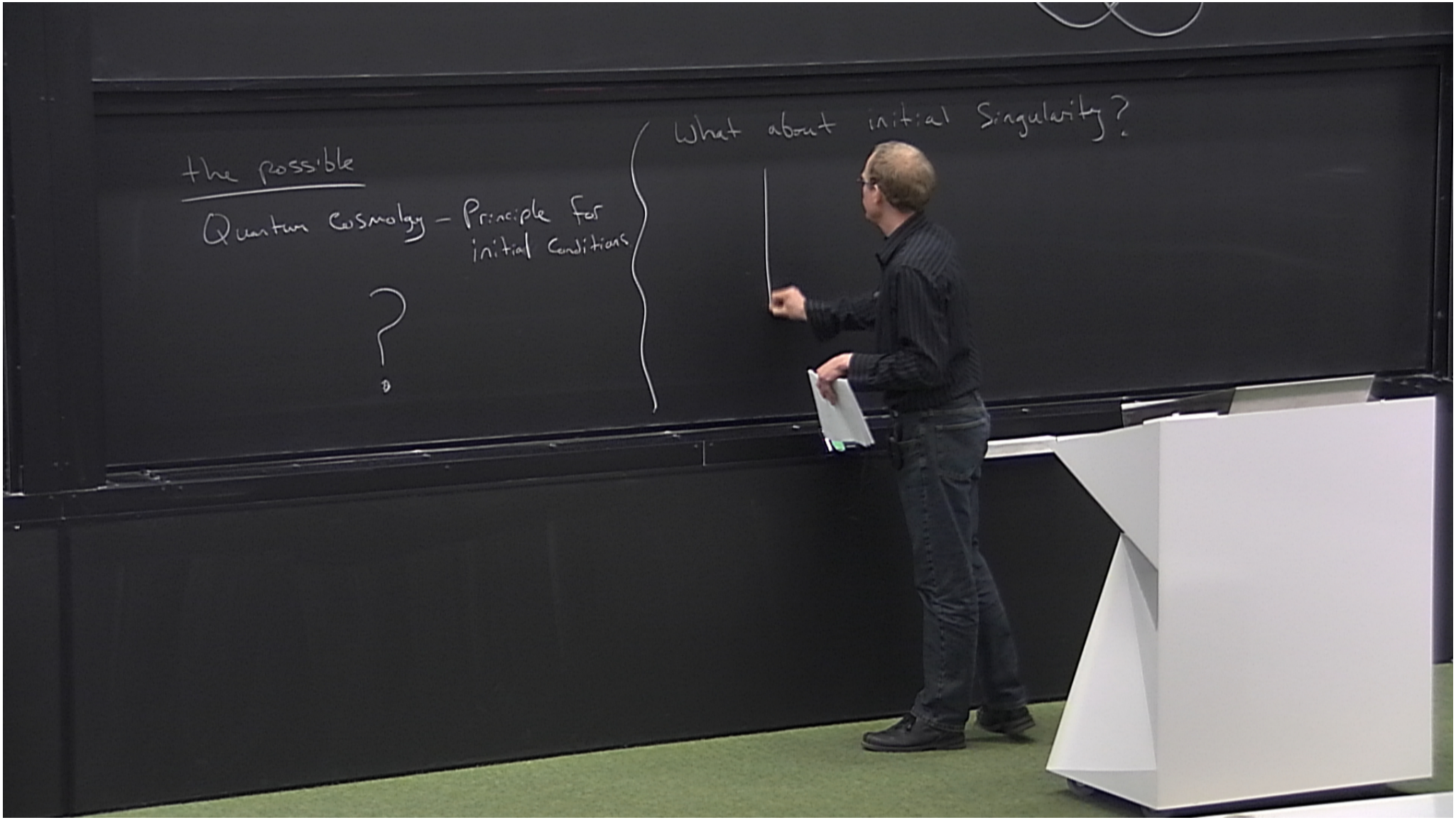


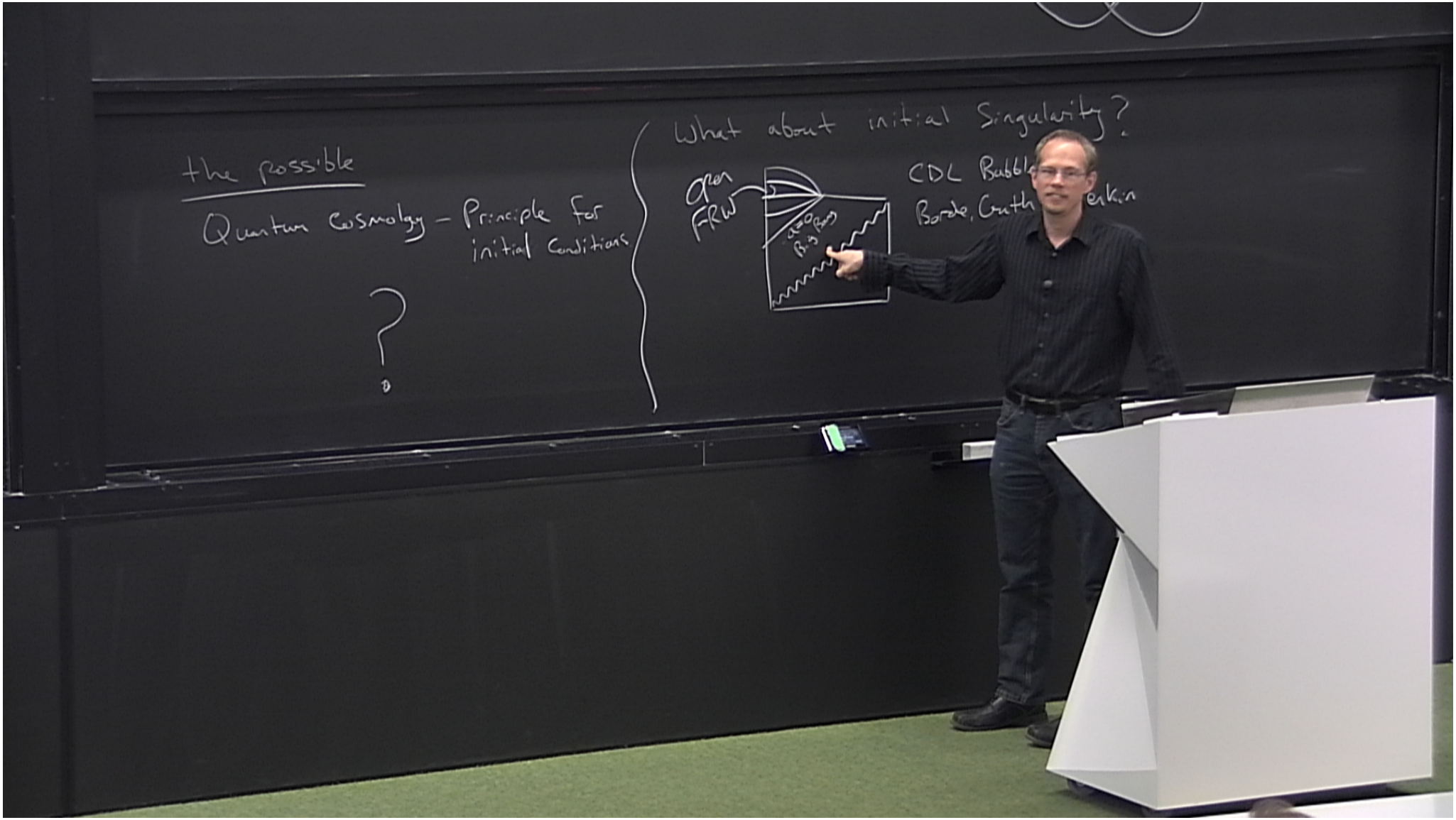
The Ugly - eternal inflation

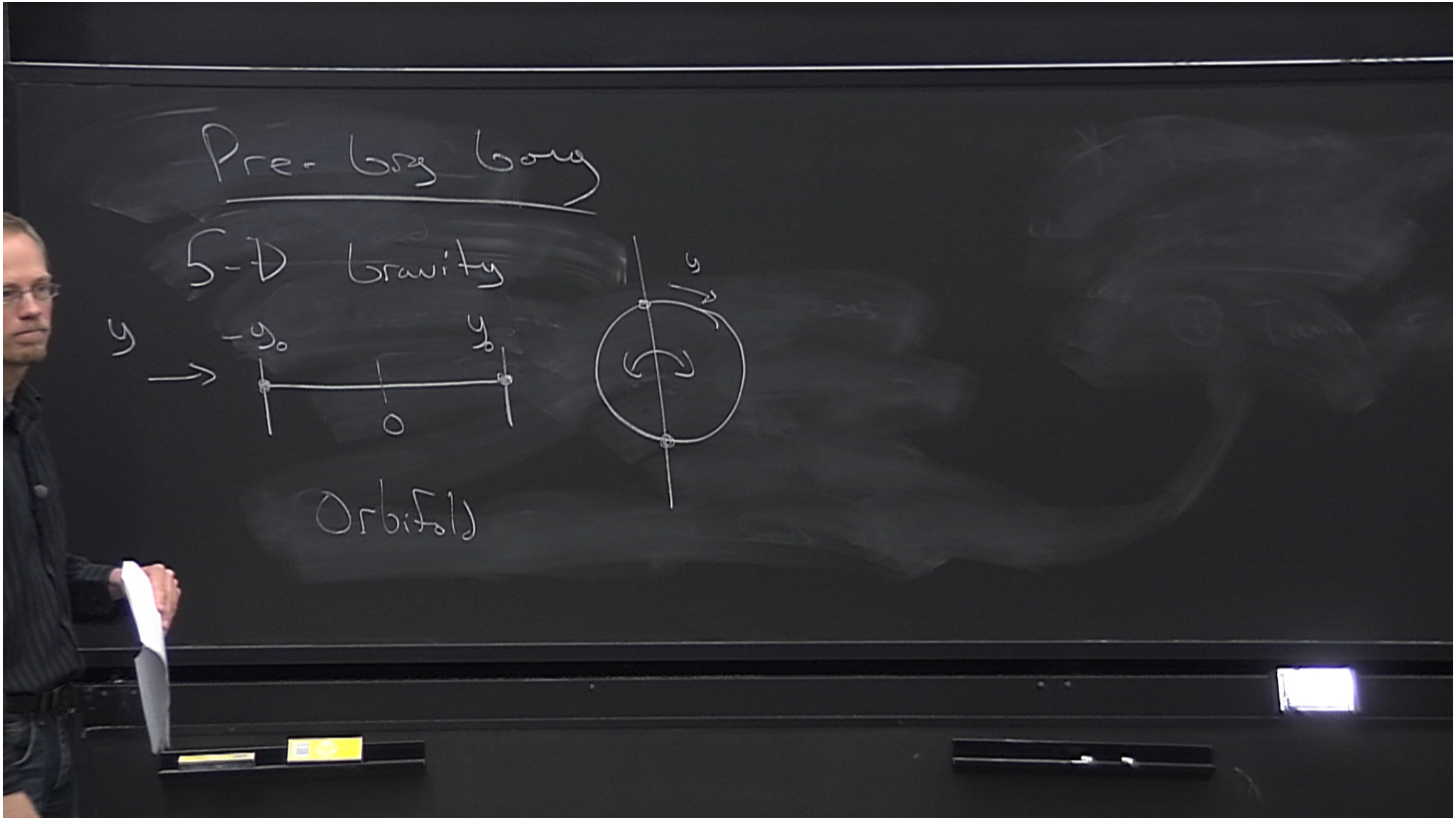

Why did universe start w/ low entropy.
The Ugly -eternal inflation
Initial condition

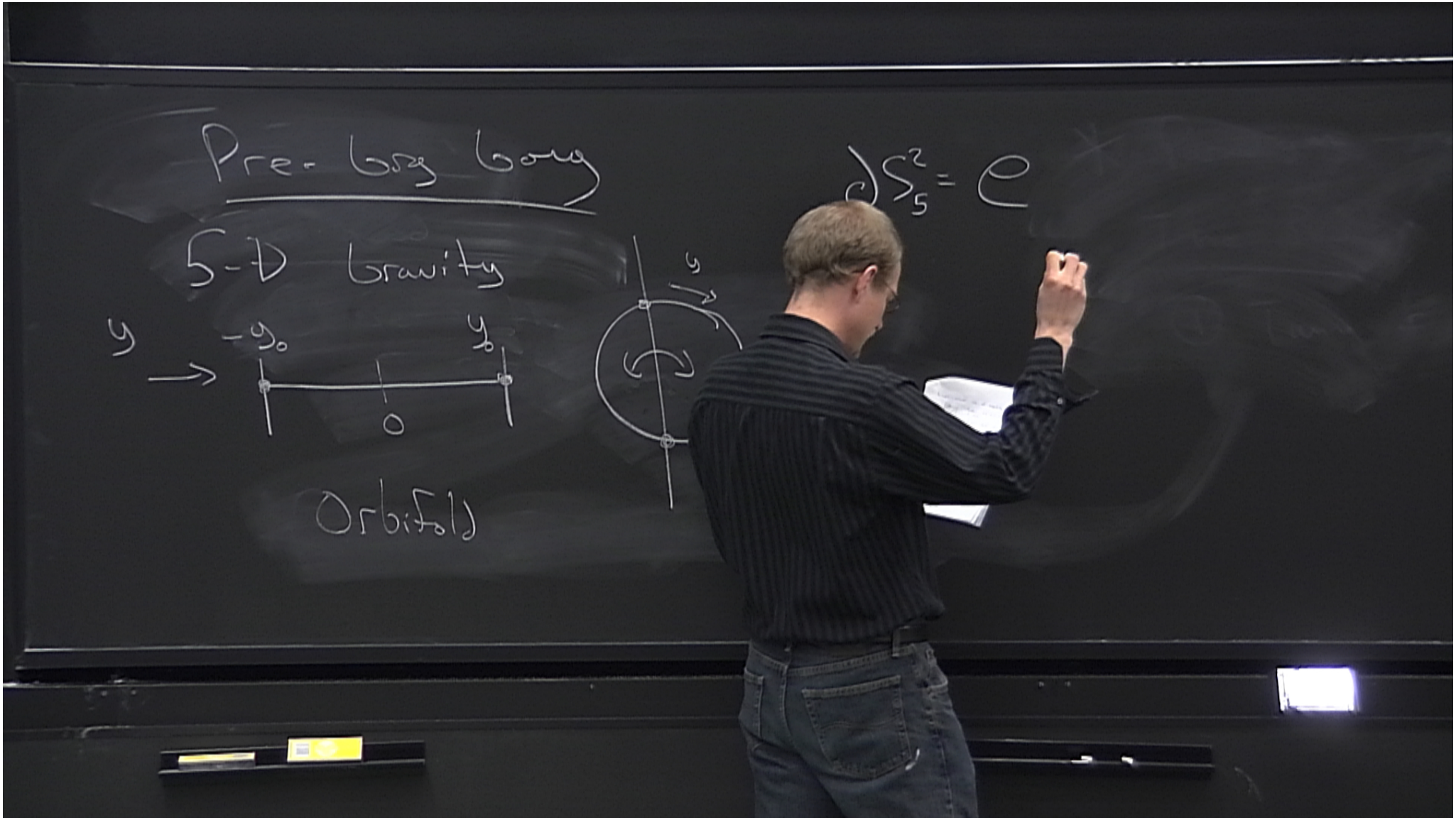

Why did universe start w/ low entropy.
The Ugly -eternal inflation
Initial condition

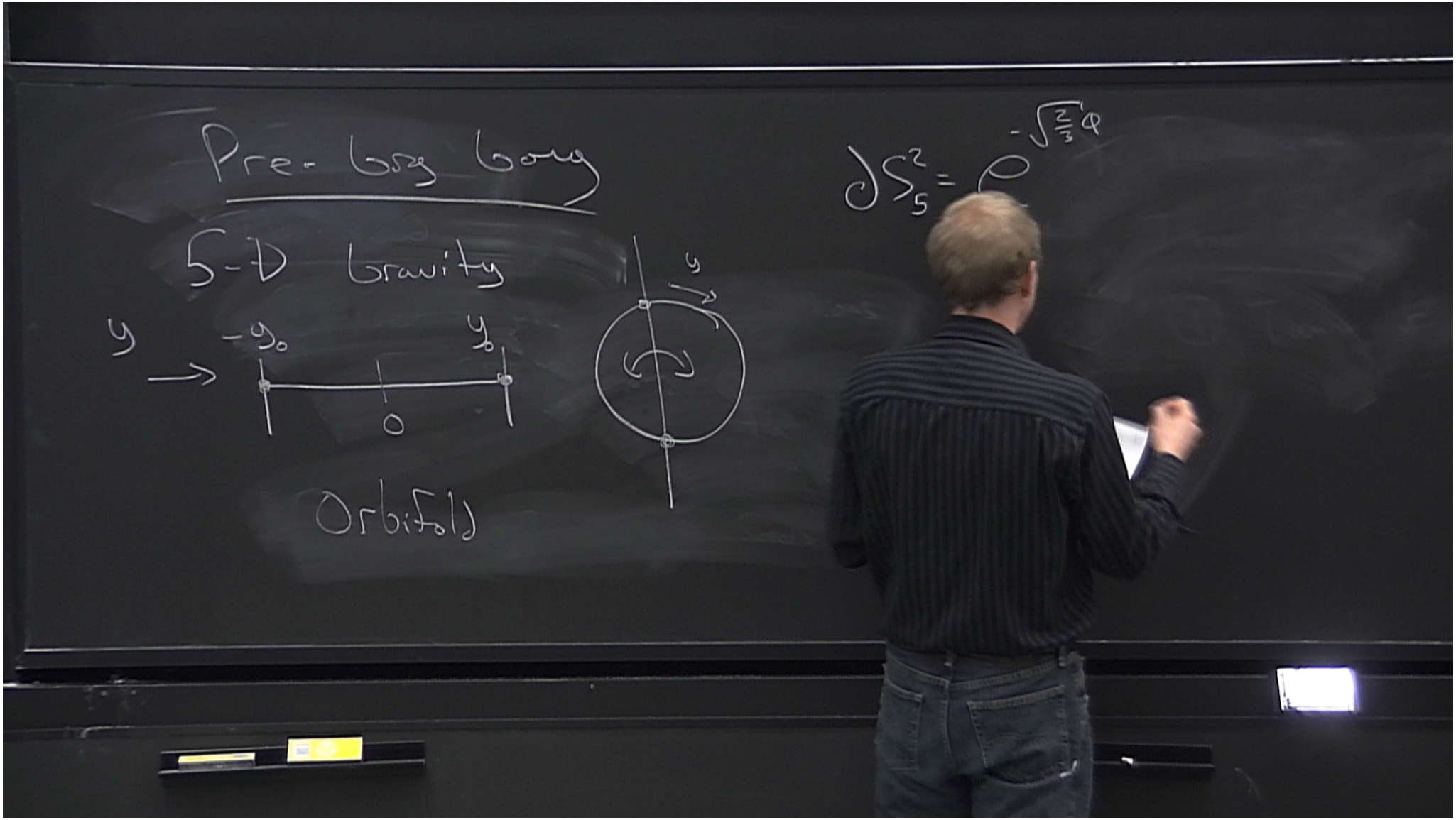

Why did universe start w/ low entropy.
The Ugly -eternal inflation
* "Solve" fine tuning by realizing everything somewhere/somewhen
→ How likely are all possibilities?
Initial condition

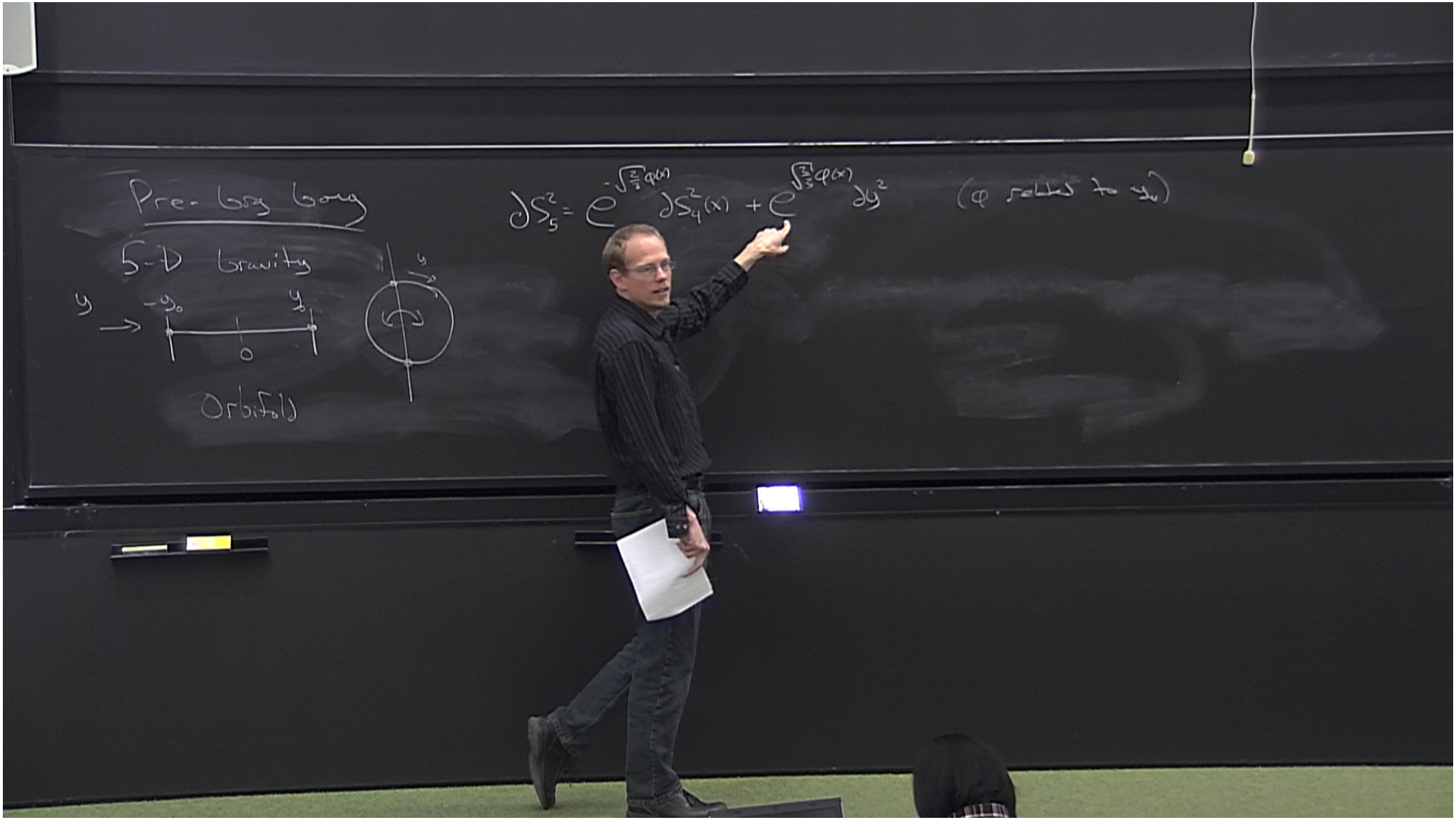

the possible
Quantum Cosmology – Principle for initial Conditions
?
What about initial Singularity?


the possible
Quantum Cosmology – Principle for initial Conditions
?
What about initial Singularity?
open FRW
Big Bang
CDL Bubble
Borde, Guth


Pre-big bang
5-D gravity
y
$-y_0$
y_0
0
y
Orbifold

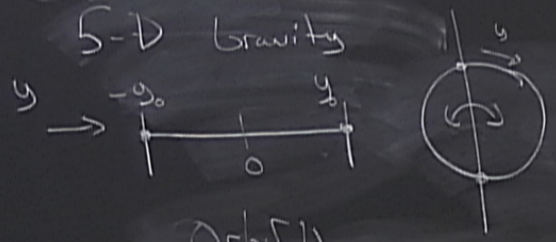

Pre-big bang
5-D gravity
y
$-y_0$
y_0
0
Orbifold
y
$S_5^2 = e$


Pre-big bang
5-D gravity
y
$-y_0$
y_0
0
Orbifold
$ds_5^2 = e^{-\sqrt{\frac{2}{3}}\phi}$


Pre-big bang
5-D gravity
$ds_5^2 = e^{-\sqrt{\frac{2}{3}}\varphi(x)} ds_4^2(x) + e^{\sqrt{\frac{2}{3}}\varphi(x)} dy^2$
(φ rolls to y_0)
y
$-y_0$
y_0
0
Orbifold

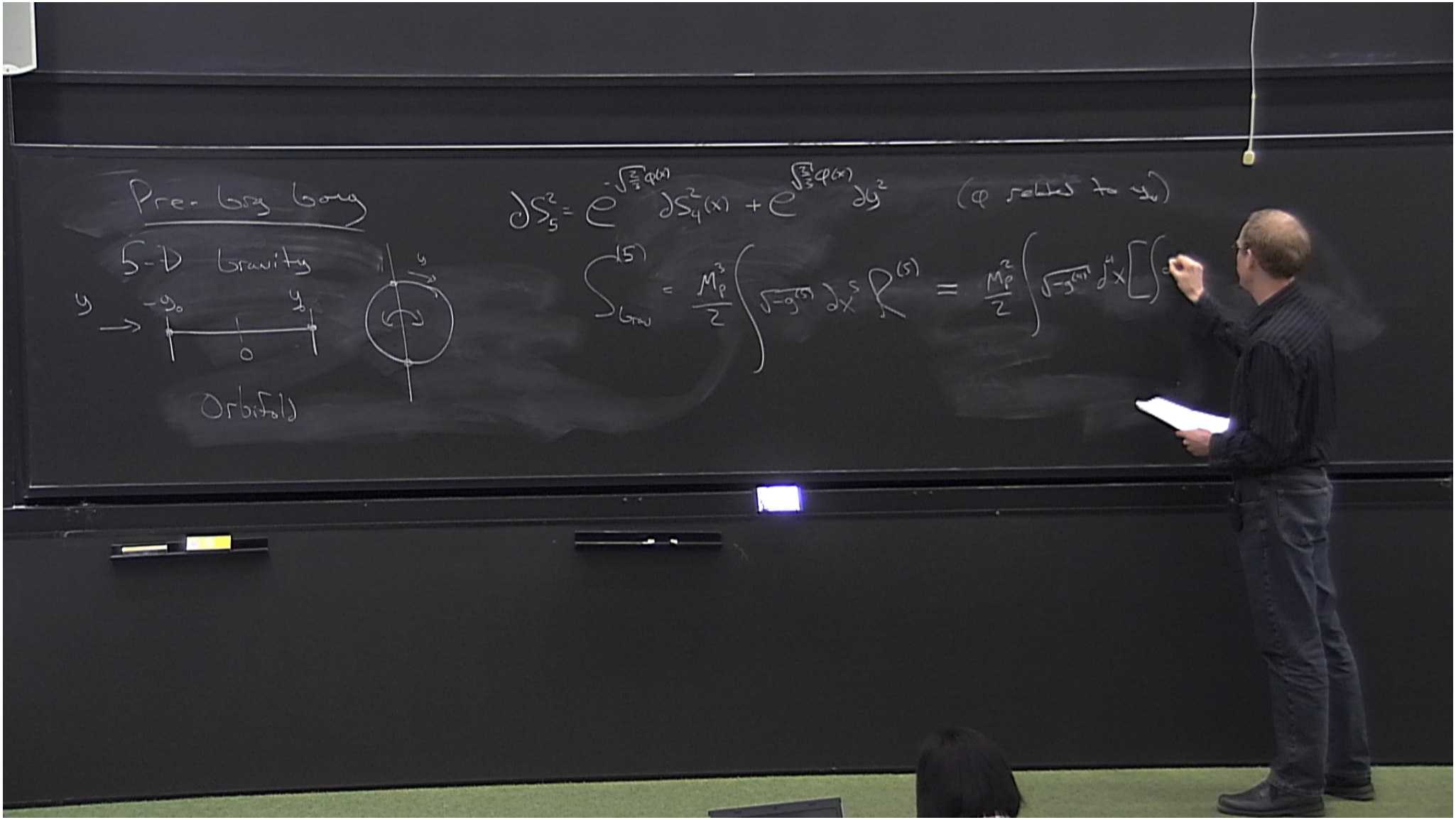
Pre-big bang

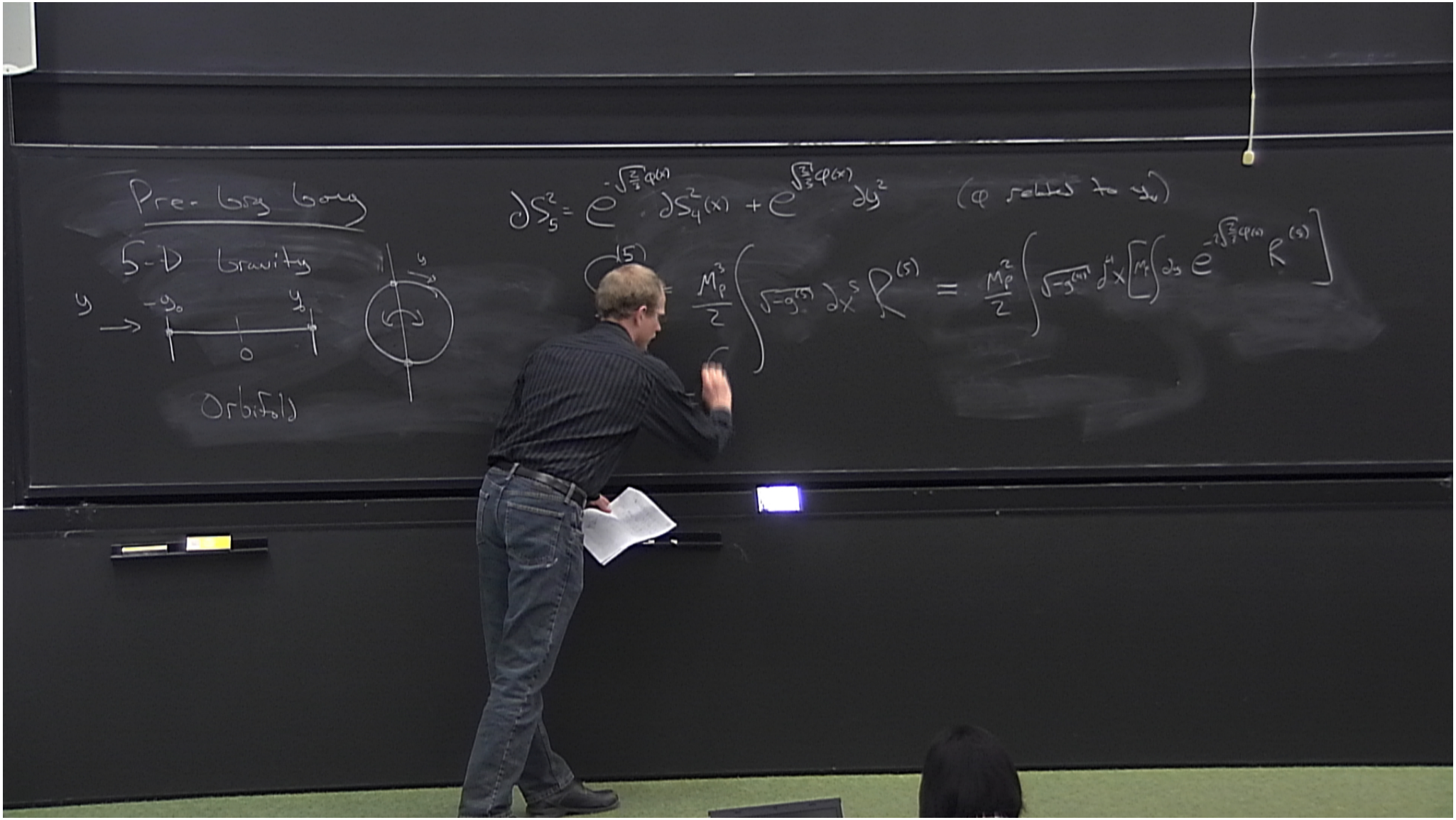
5-D gravity

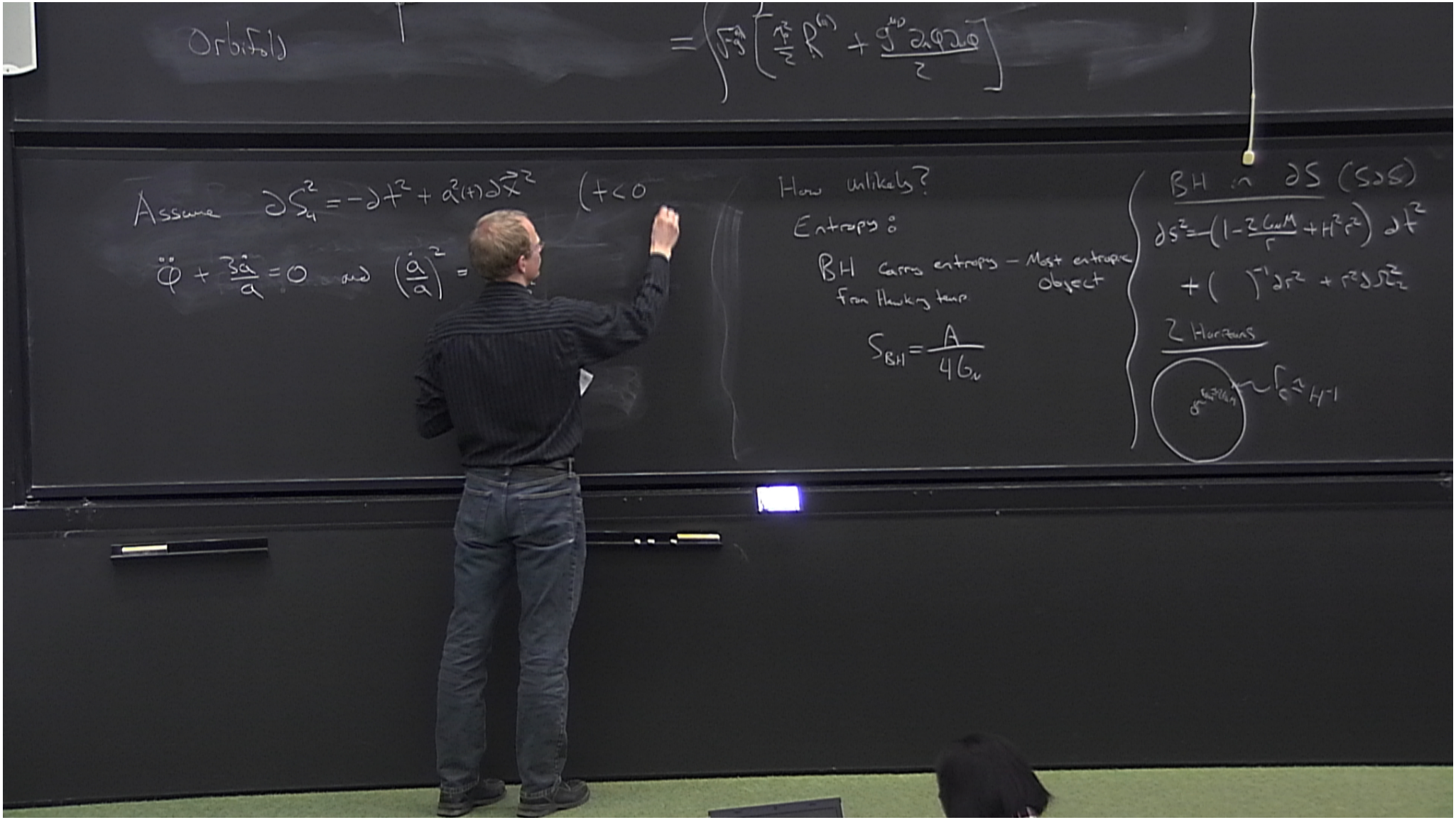


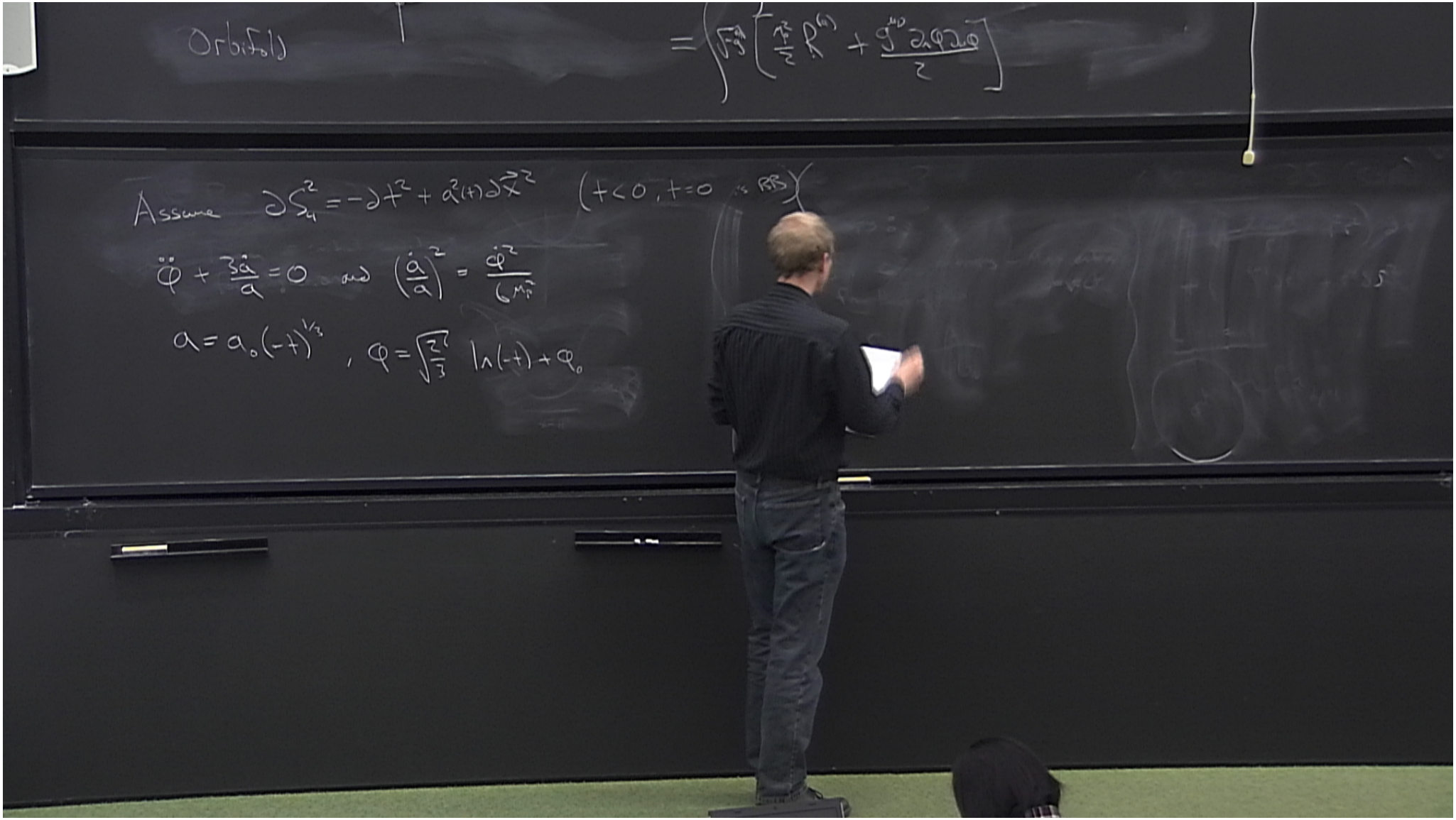
$$ds_5^2 = e^{-\sqrt{\frac{3}{2}}\varphi(x)} ds_4^2(x) + e^{\sqrt{\frac{3}{2}}\varphi(x)} dy^2 \qquad (\varphi \text{ rolls to } y_0)$$

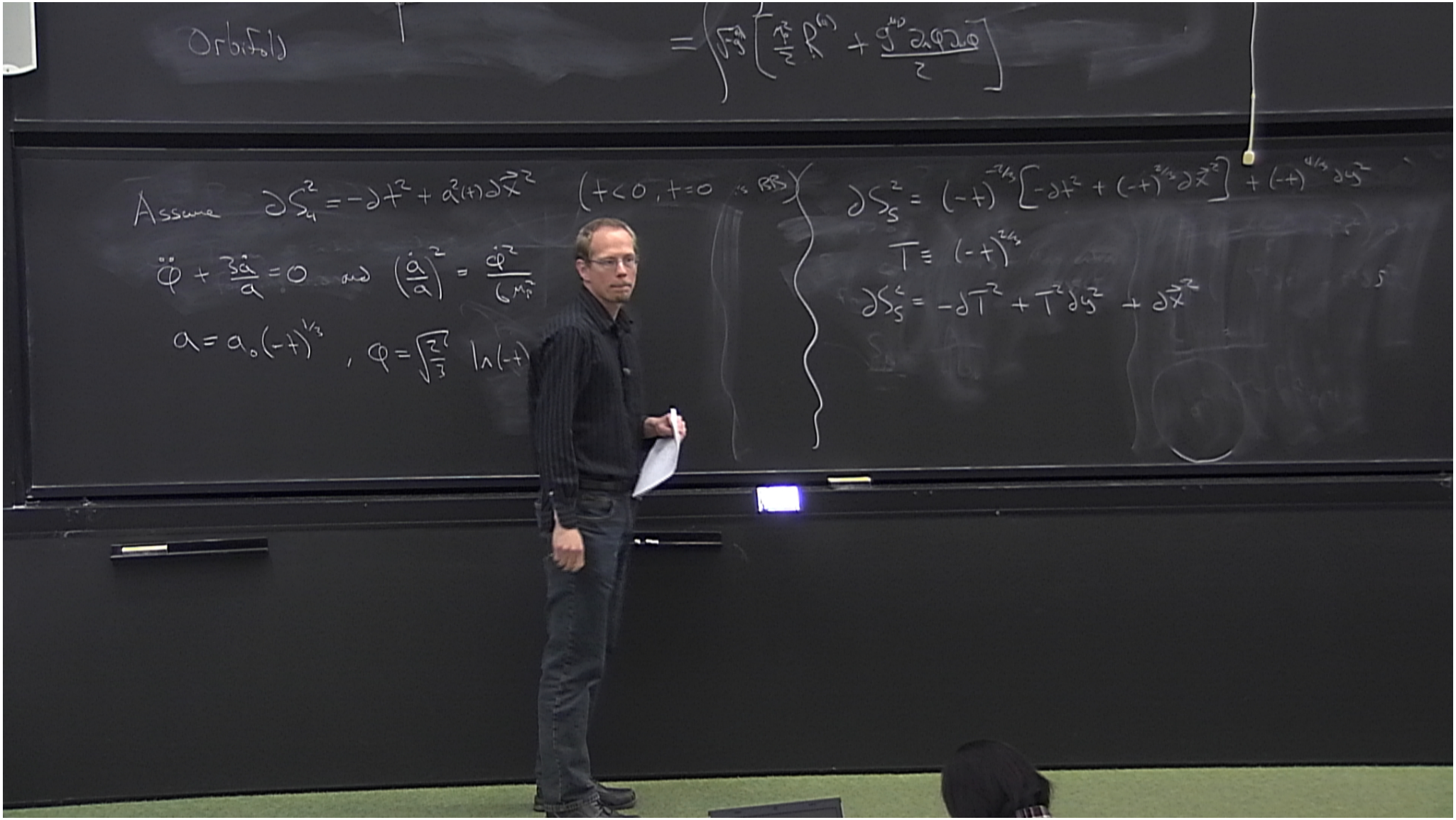
$$S_{GRAV}^{(5)} = \frac{M_P^3}{2} \int \sqrt{-g^{(5)}}\, d^5x\, R^{(5)}$$

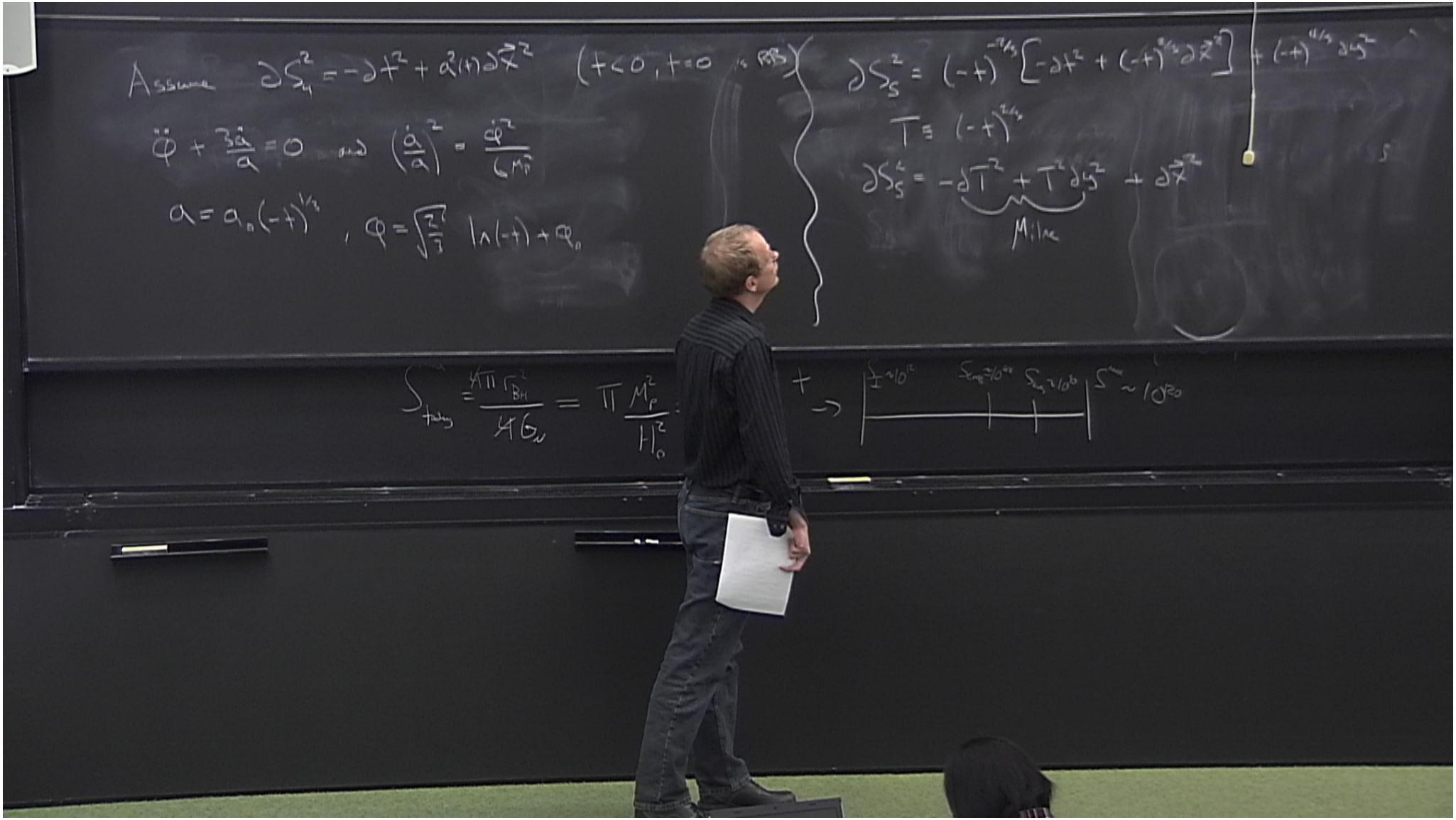

Pre-big bang
5-D gravity
y
$-y_0$
y_1
0
Orbifold
$ds_5^2 = e^{-\sqrt{\frac{2}{3}}\varphi(x)} ds_4^2(x) + e^{\sqrt{\frac{2}{3}}\varphi(x)} dy^2$
(φ rolls to y_1)
$S_{GRAV}^{(5)} = \frac{M_p^3}{2}\int \sqrt{-g^{(5)}}\, d^5x\, R^{(5)} = \frac{M_p^2}{2}\int \sqrt{-g^{(4)}}\, d^4x$

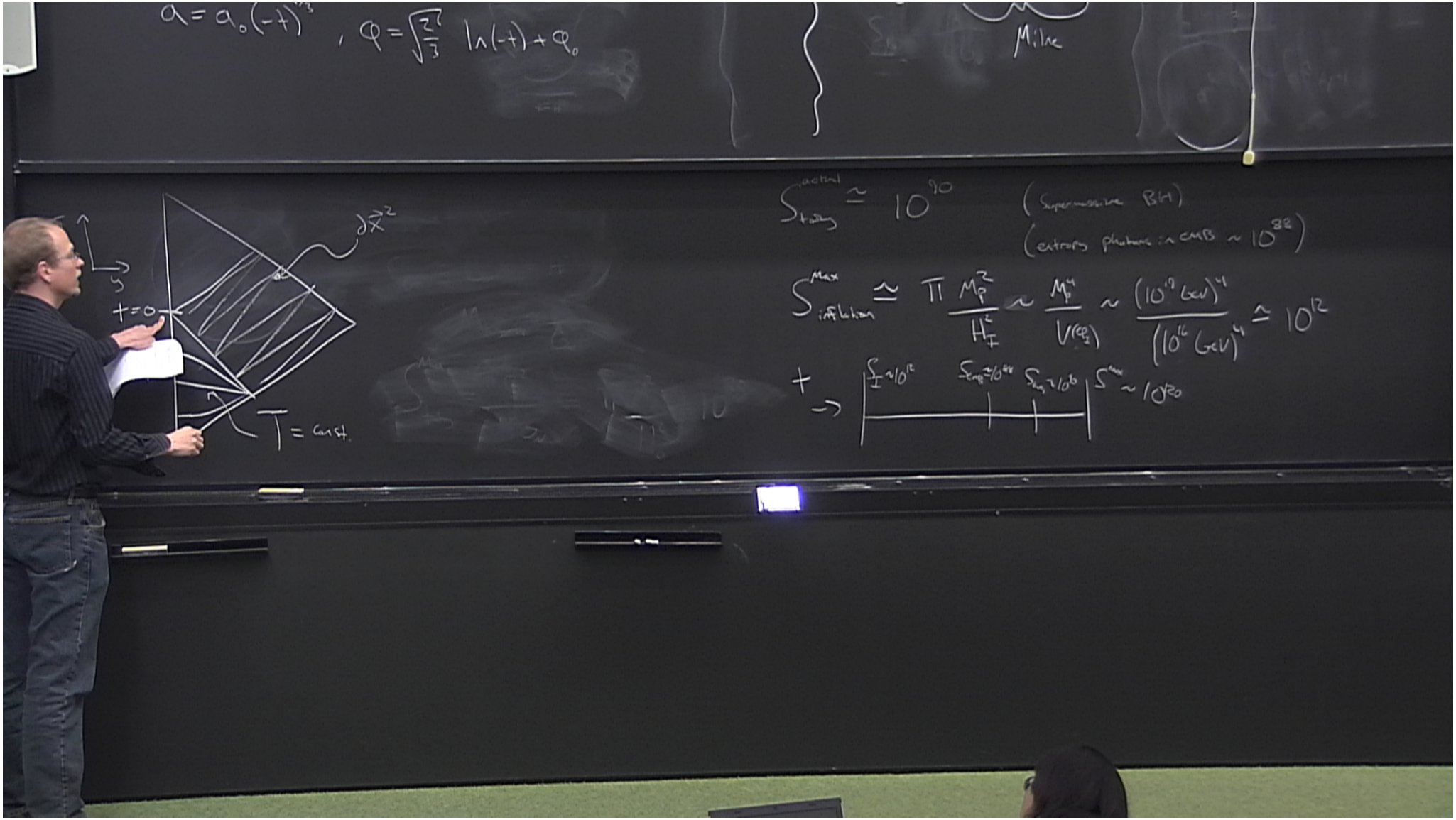

Pre-big bang
5-D gravity
$ds_5^2 = e^{-\sqrt{\frac{3}{2}}\varphi(x)} ds_4^2(x) + e^{\sqrt{\frac{3}{2}}\varphi(x)} dy^2$
(φ relates to y_0)
$-y_0$
y_1
0
Orbifold
$\frac{M_p^3}{2}\int \sqrt{-g^{(5)}}\, d^5x\, R^{(5)} = \frac{M_p^2}{2}\int \sqrt{-g^{(4)}}\, d^4x \left[M_p \int dy\, e^{-\sqrt{\frac{3}{2}}\varphi(x)} R^{(5)}\right]$

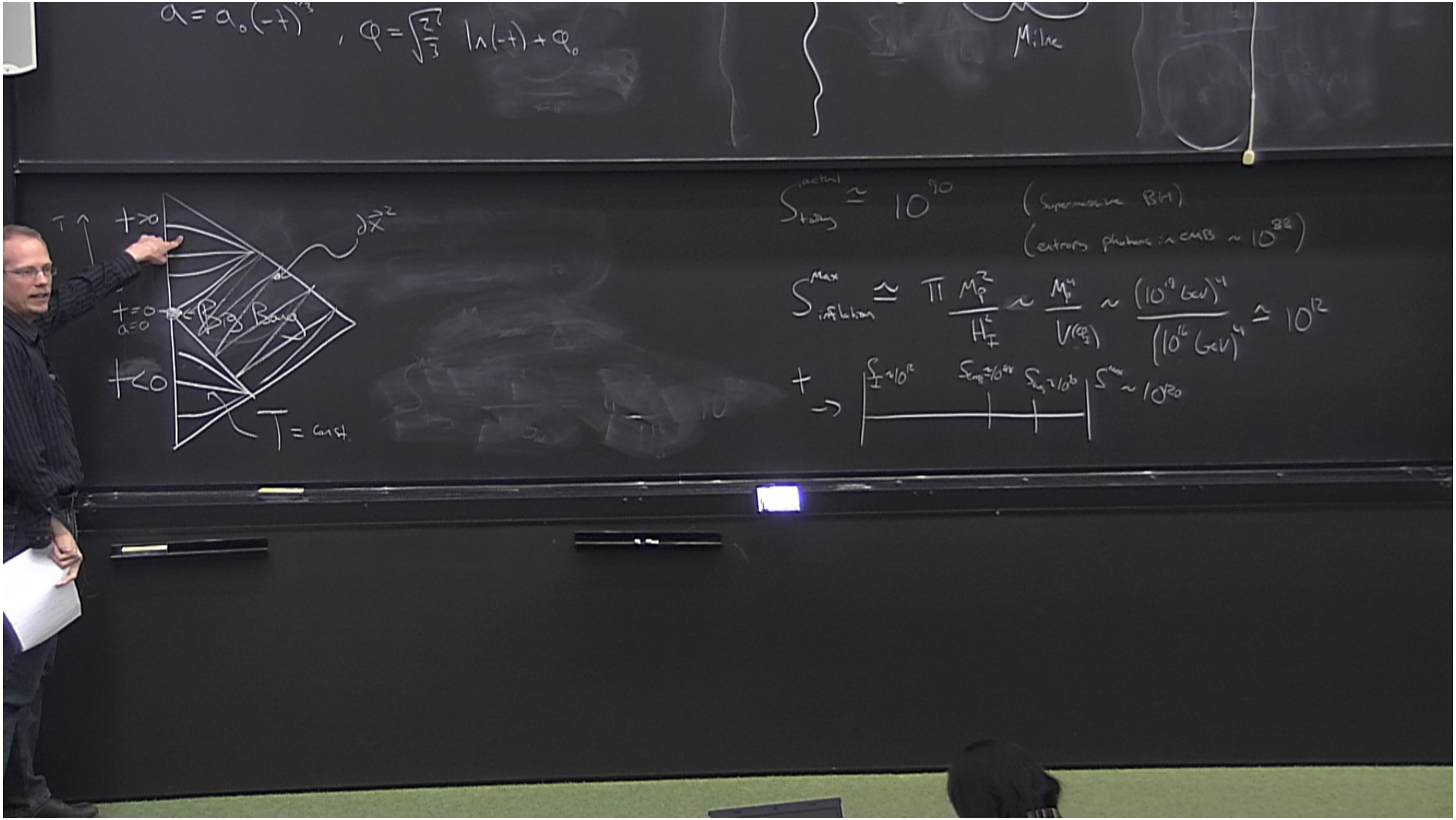

Orbifold
Assume
How unlikely?
Entropy :
BH carries entropy – Most entropic object
from Hawking temp
BH in dS (S>>S)
2 Horizons

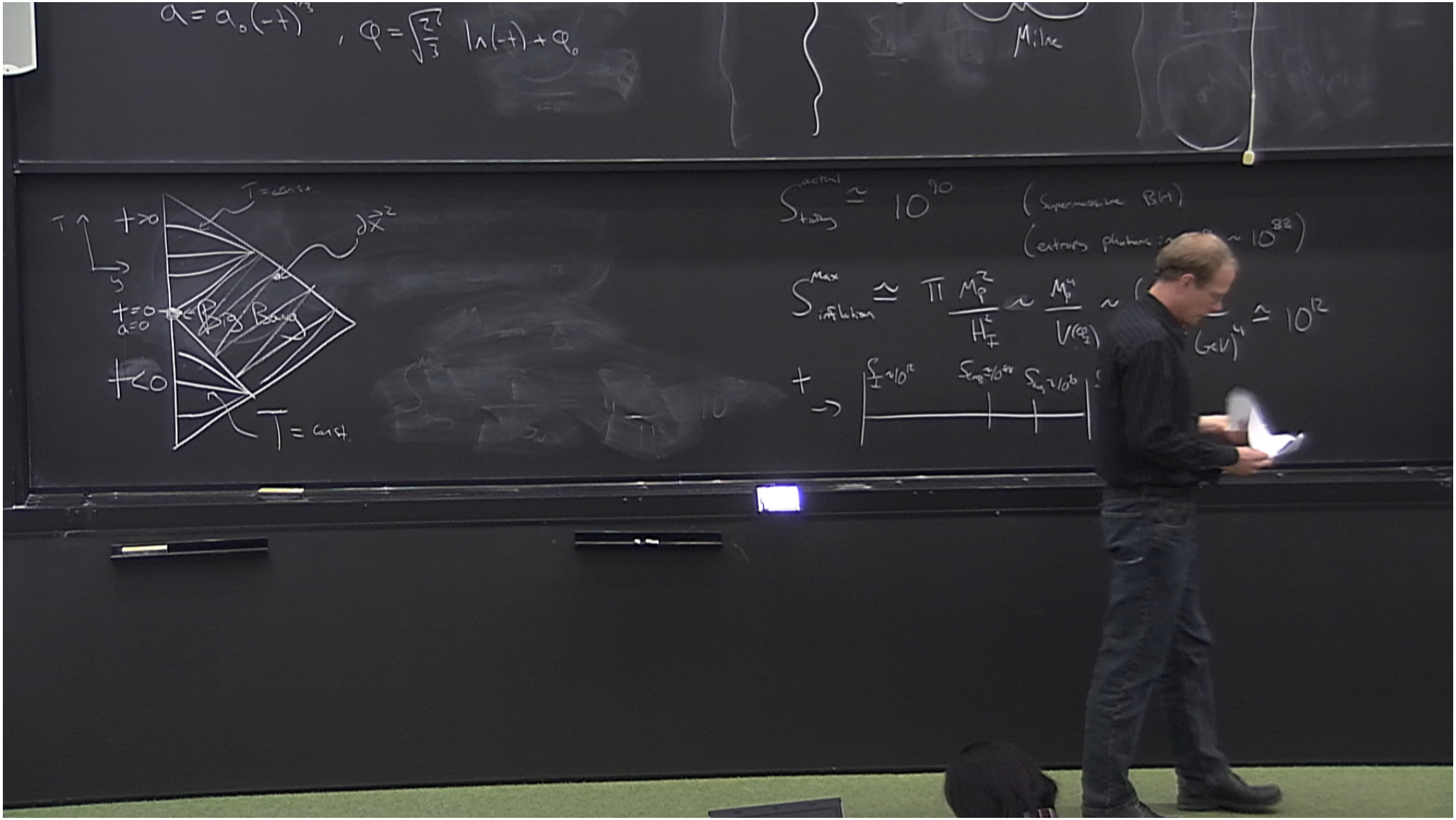

Orbifold
Assume
(t<0, t=0 : BB)

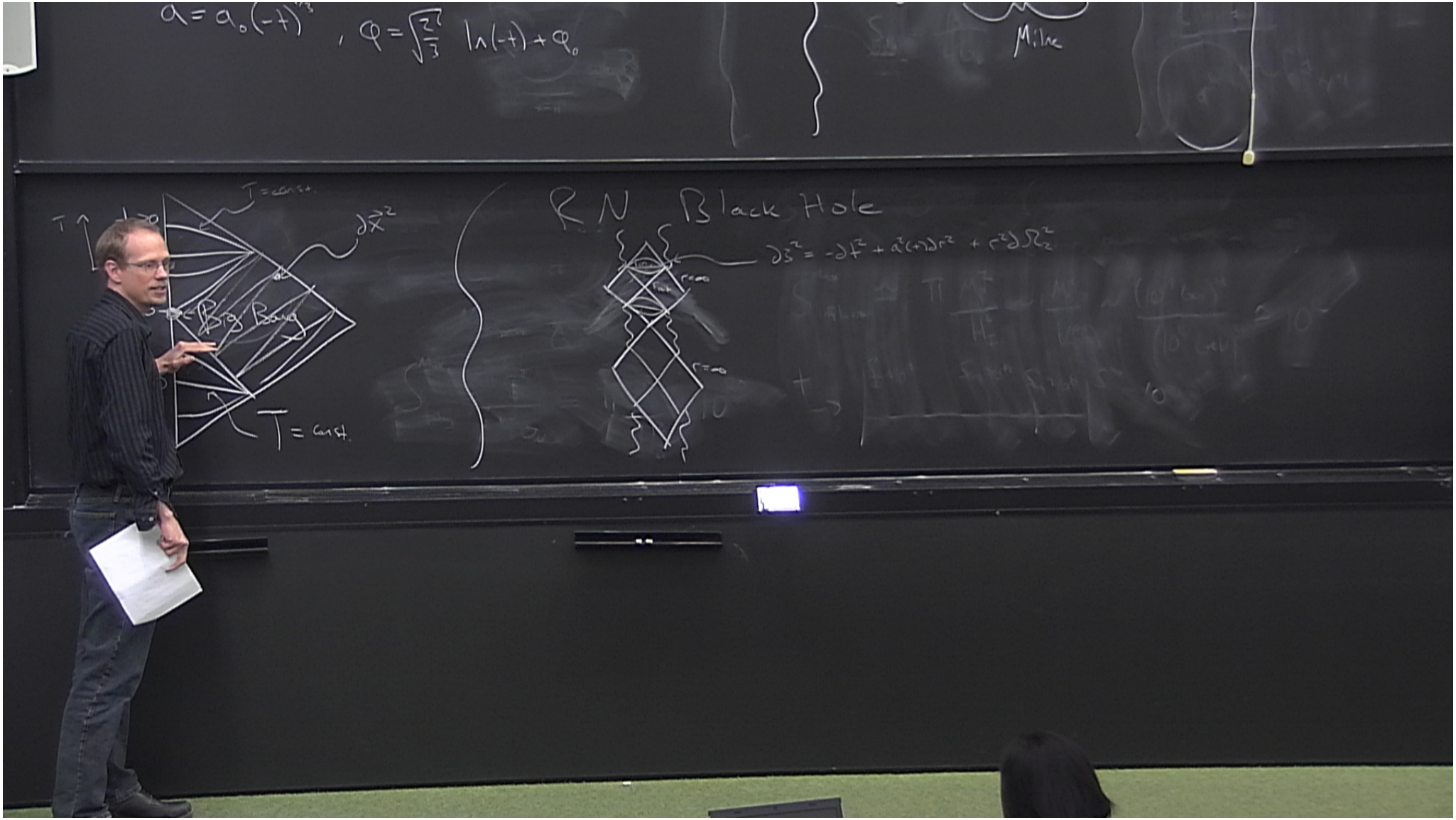

Orbifold
Assume
(t<0, t=0 ⋮ BB)
T ≡ (-t)^{2/3}

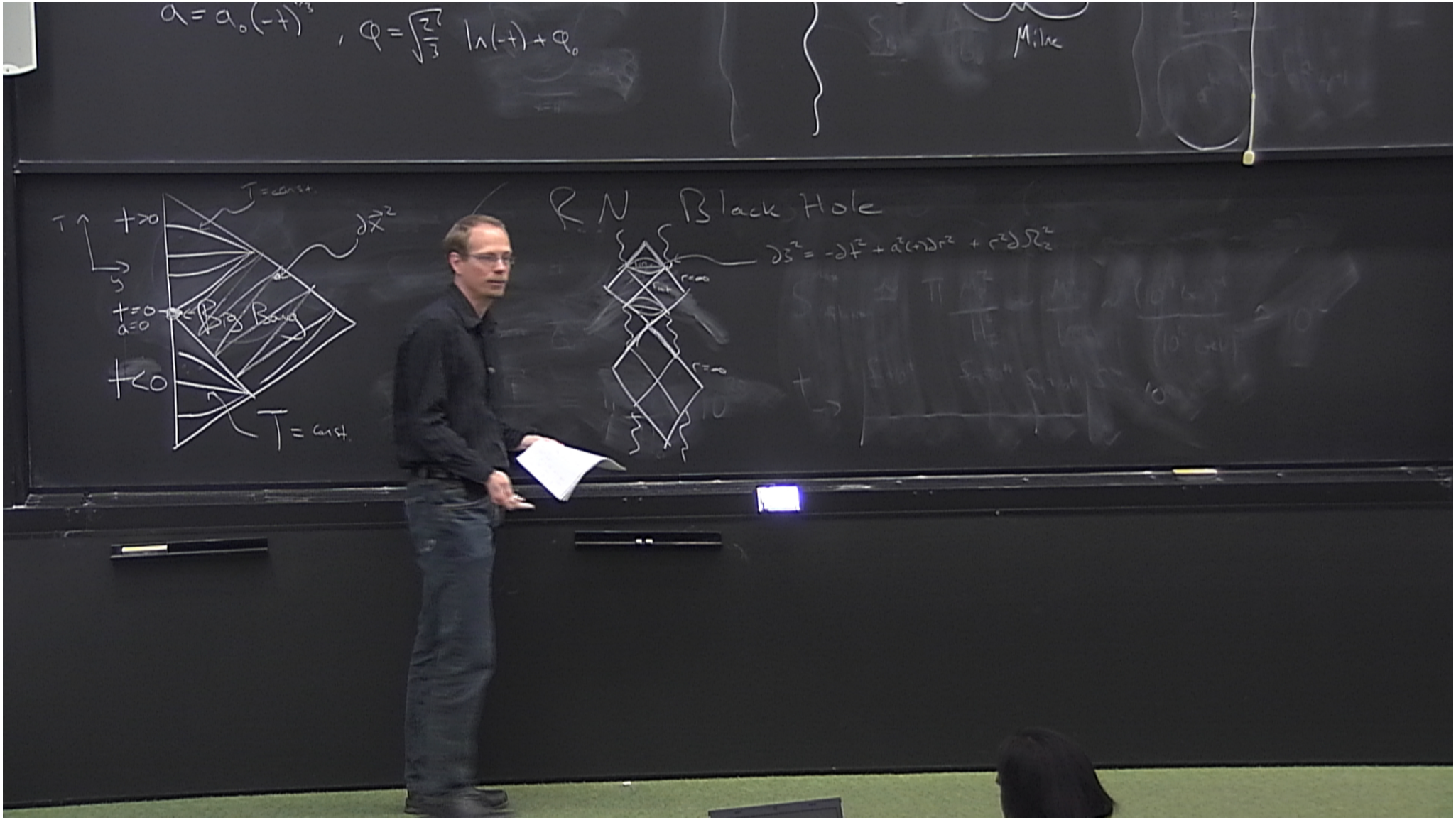

Assume
$\ddot{\varphi} + \frac{3\dot{a}}{a} = 0$ and $\left(\frac{\dot{a}}{a}\right)^2 = \frac{\dot{\varphi}^2}{6M_P^2}$
$a = a_0(-t)^{1/3}$, $\varphi = \sqrt{\frac{2}{3}}\ln(-t) + \varphi_0$
$T \equiv (-t)^{2/3}$
Milne
$S_{today} = \frac{4\pi r_{BH}^2}{4G_N} = \pi \frac{M_P^2}{H_0^2}$
$S^{max} \sim 10^{120}$

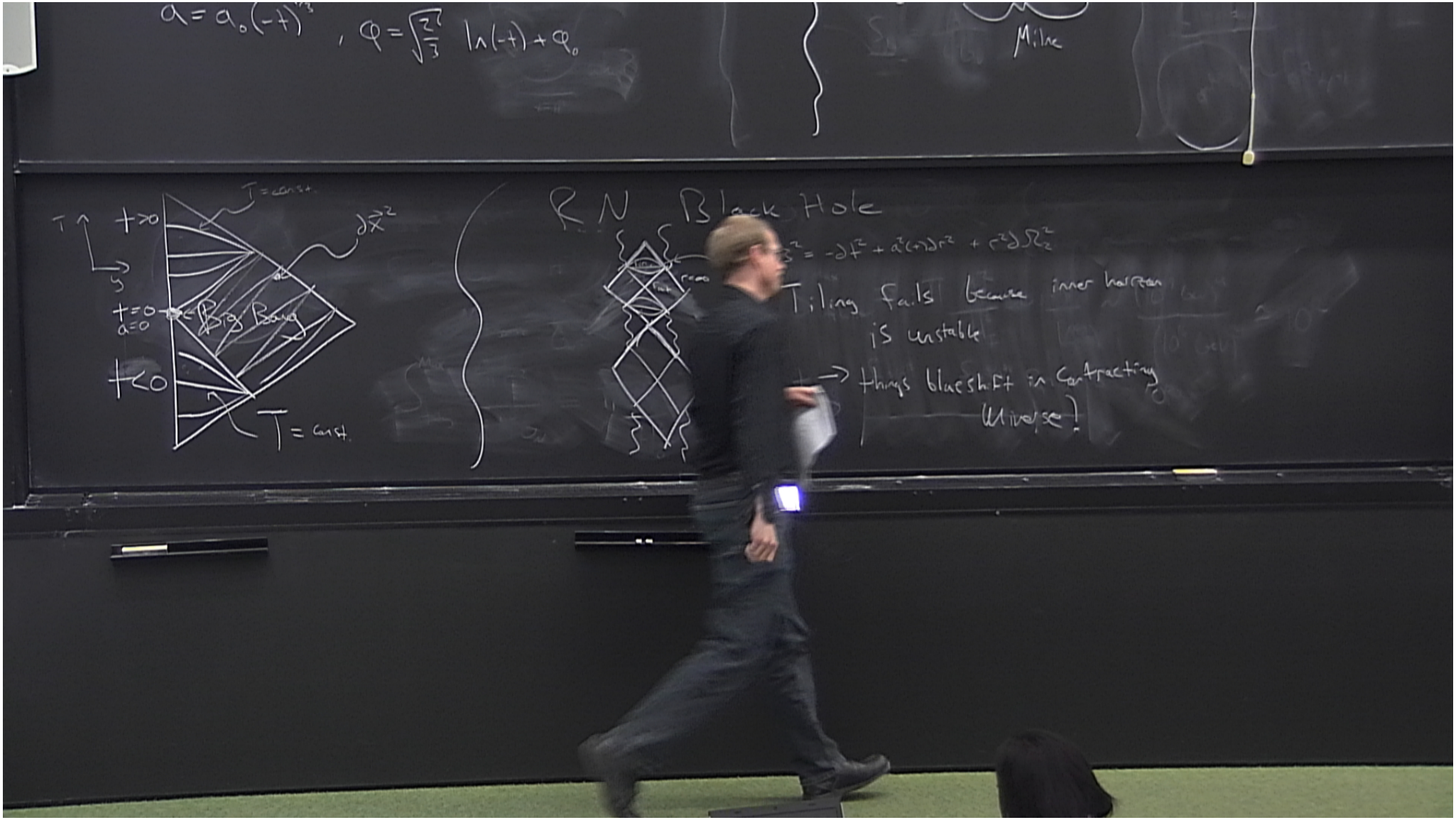

$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}}\ln(-t) + \varphi_0$
Milne
dx^2
$t=0$
$T = \text{const}$
$S_{today}^{actual} \simeq 10^{90}$ (Supermassive BH)
(entropy photons in CMB $\sim 10^{88}$)
$S_{inflation}^{Max} \simeq \pi \frac{M_p^2}{H_I^2} \sim \frac{M_p^4}{V(\varphi_I)} \sim \frac{(10^{19}\,\text{GeV})^4}{(10^{16}\,\text{GeV})^4} \simeq 10^{12}$
$S_I \sim 10^{12}$
$S_{end} \sim 10^{88}$
$S_{today} \sim 10^{90}$
$S^{max} \sim 10^{120}$


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$t \to$ $S_I \sim 10^{12}$ $S_{end\ inf} \sim 10^{88}$ $S_{today} \sim 10^{90}$ $S^{max} \sim 10^{120}$
T
$t = +\infty$
$t = 0$
$a = 0$
Big Bang
$t < 0$
dx^2
$T = Const.$


$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}}\ln(-t) + \varphi_0$
Milne
T
t>0
t=0
a=0
Big Bang
t<0
T = Const.
T = Const.
dx^2
$S_{today}^{actual} \simeq 10^{90}$
(Supermassive BH)
$S_{inflation}^{Max} \simeq \pi \frac{M_p^2}{H_I^2} \sim \frac{M_p^4}{V(\varphi_I)} \sim$
$\simeq 10^{12}$
t
$S_I \sim 10^{12}$
$S_{end} \sim 10^{88}$
$S_{today} \sim 10^{90}$

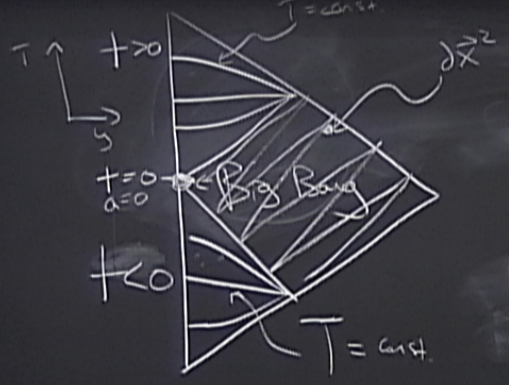

RN Black Hole
Big Bang
T = const.
T = const.
r=0
r=∞
Milne


RN Black Hole
Big Bang
T = const.
T = const.
t>0
t<0
t=0
a=0
Milne

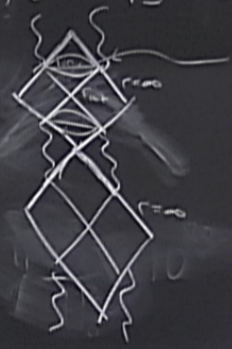

$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}} \ln(-t) + \varphi_0$
Milne
T
t>0
t=0
a=0
Big Bang
t<0
T = const.
dx^2
RN Black Hole
$ds^2 = -dt^2 + a^2(t)dx^2 + r^2 d\Omega_2^2$
Tiling fails because inner horizon is unstable
→ things blueshift in contracting Universe!

$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}}\ln(-t) + \varphi_0$

Milne



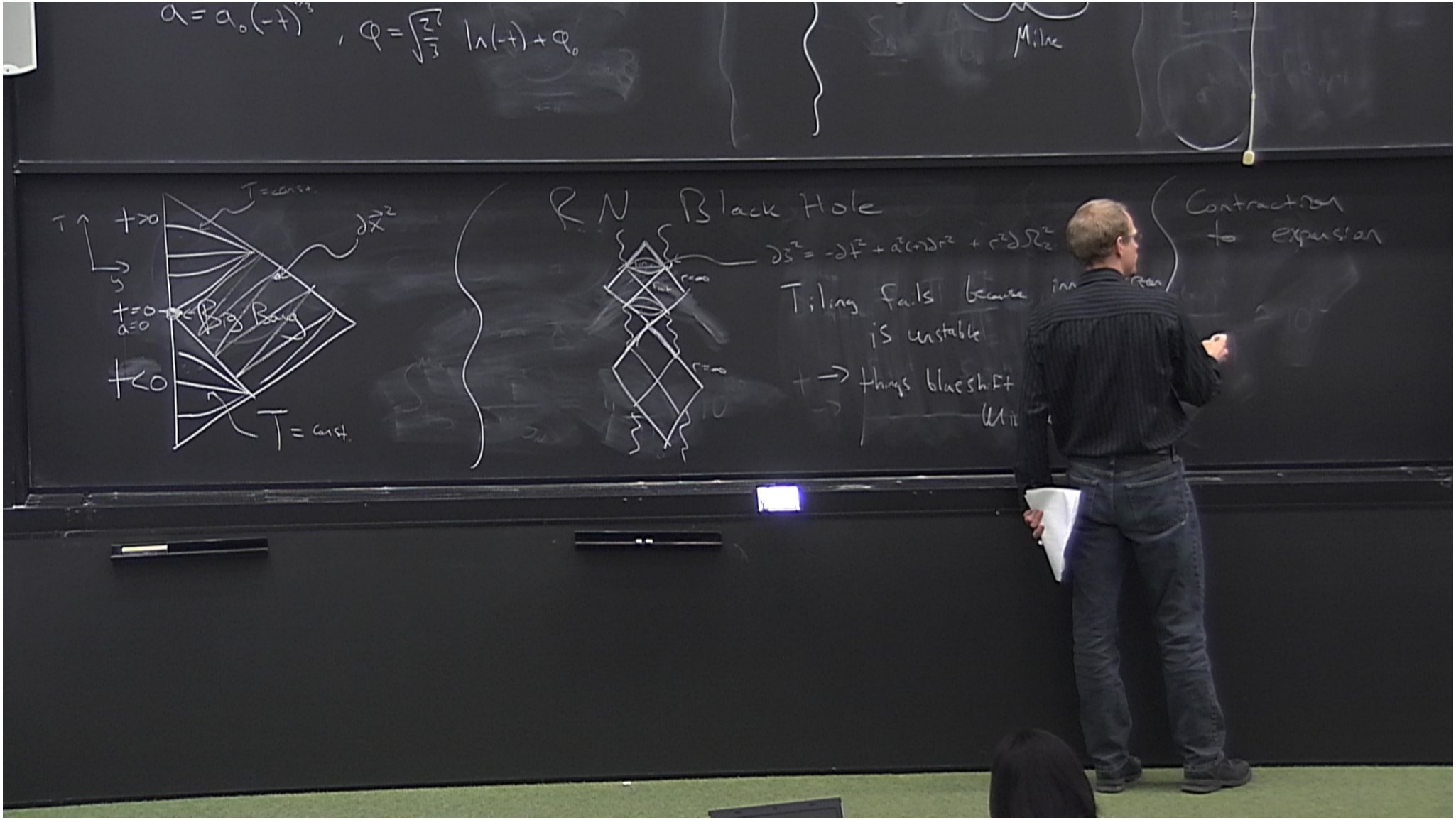
RN Black Hole



$ds^2 = -dt^2 + a^2(t)dr^2 + r^2 d\Omega_2^2$

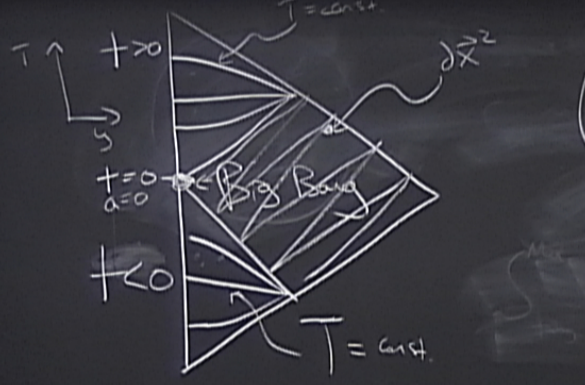
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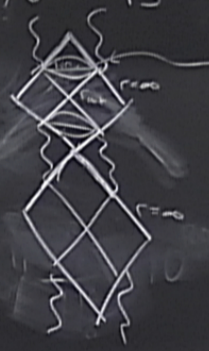

$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}} \ln(-t) + \varphi_0$
Milne
T
t>0
T = const
dx^2
t=0
a=0
Big Bang
t<0
T = const
RN Black Hole
$ds^2 = -dt^2 + a^2(r)dr^2 + r^2 d\Omega_2^2$
r=∞
r=0
r=∞
Tiling fails because
is unstable
t → things blueshift
Contraction
to expansion

$a = a_0(-t)^{\frac{1}{3}}$, $\varphi = \sqrt{\frac{2}{3}}\ln(-t) + \varphi_0$

Milne



RN Black Hole



$ds^2 = -dt^2 + a^2(t)dr^2 + r^2 d\Omega_2^2$

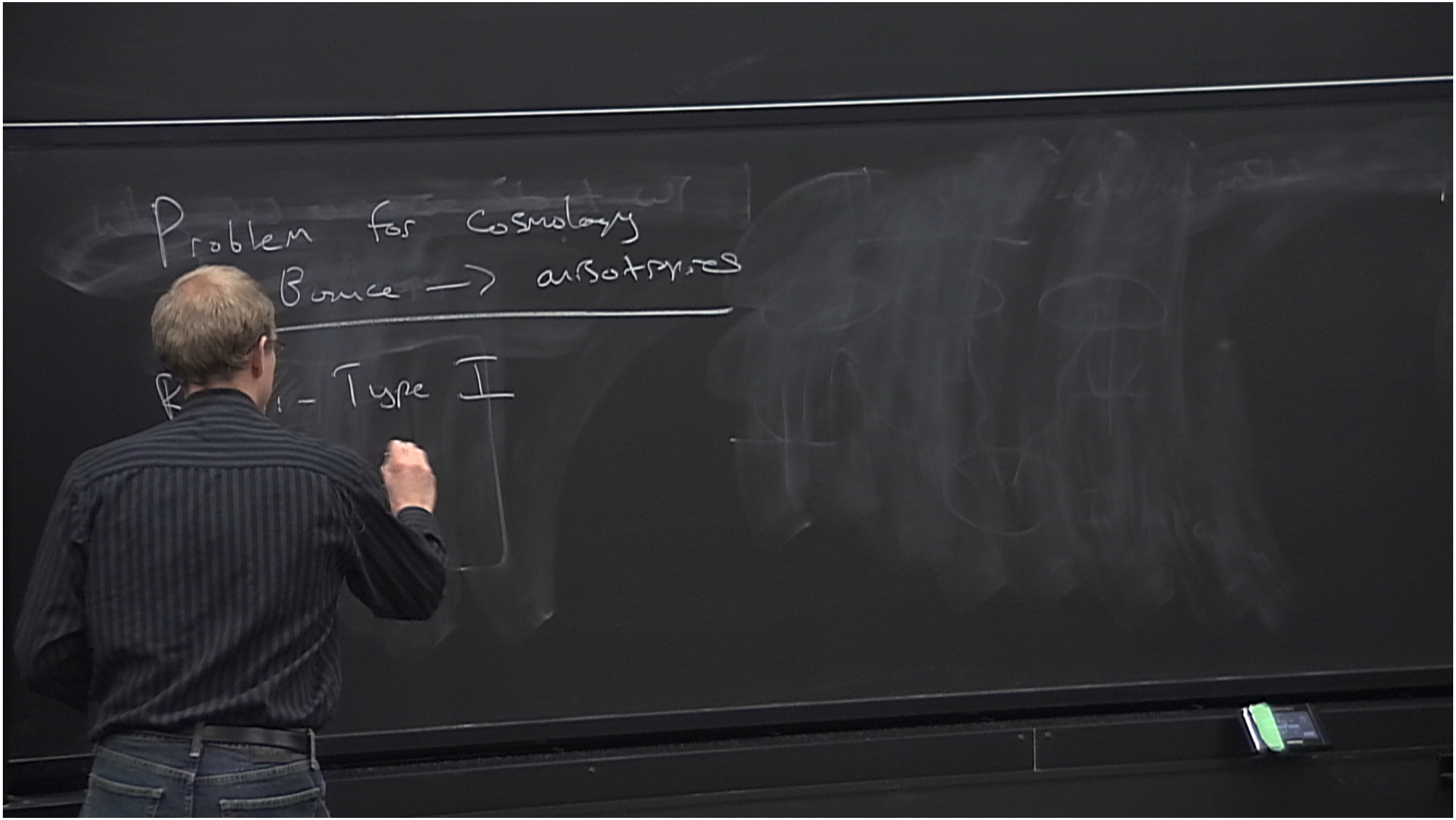
Tiling fails because inner horizon is unstable

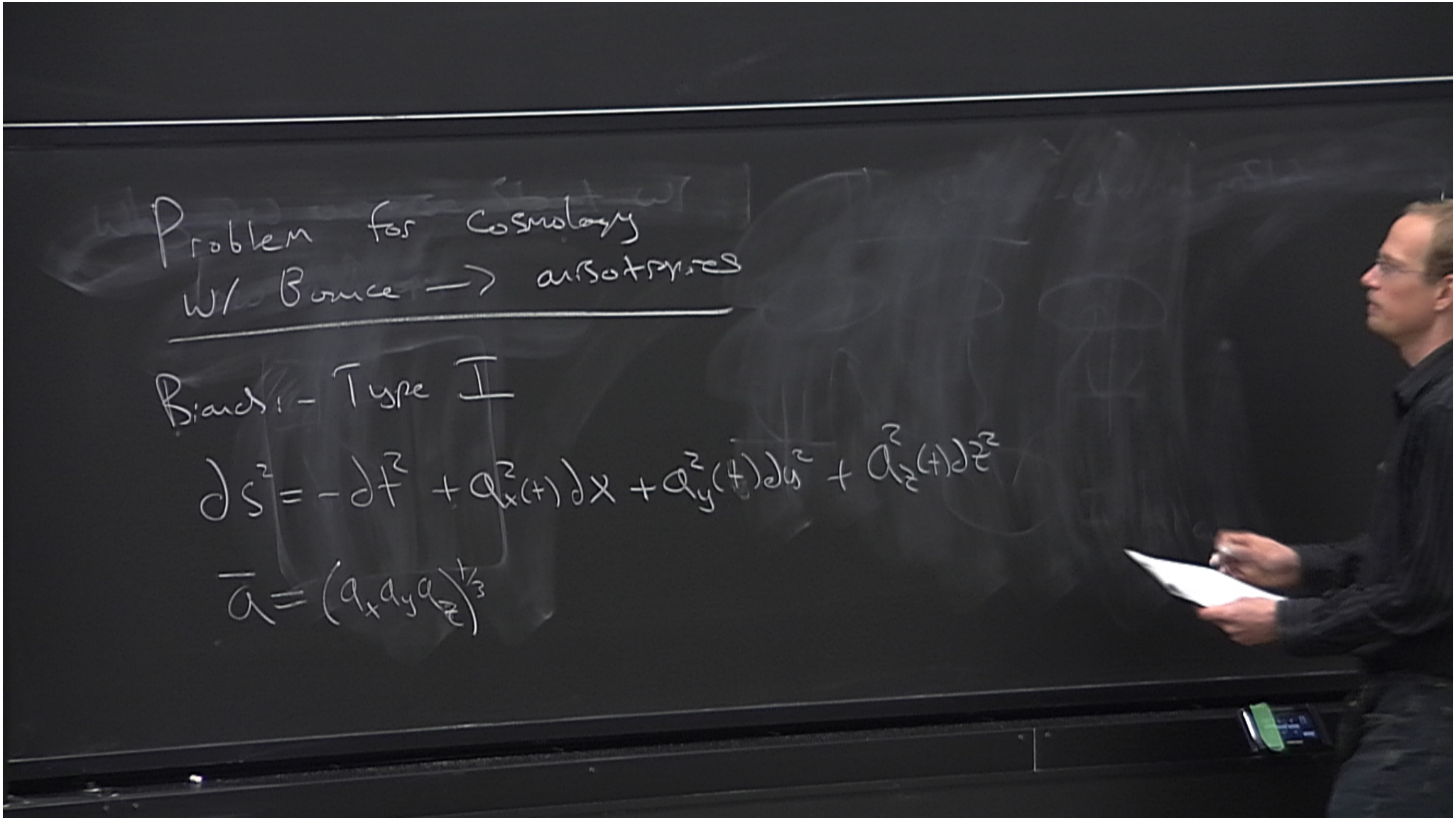
→ things blueshift in Contracting Universe!

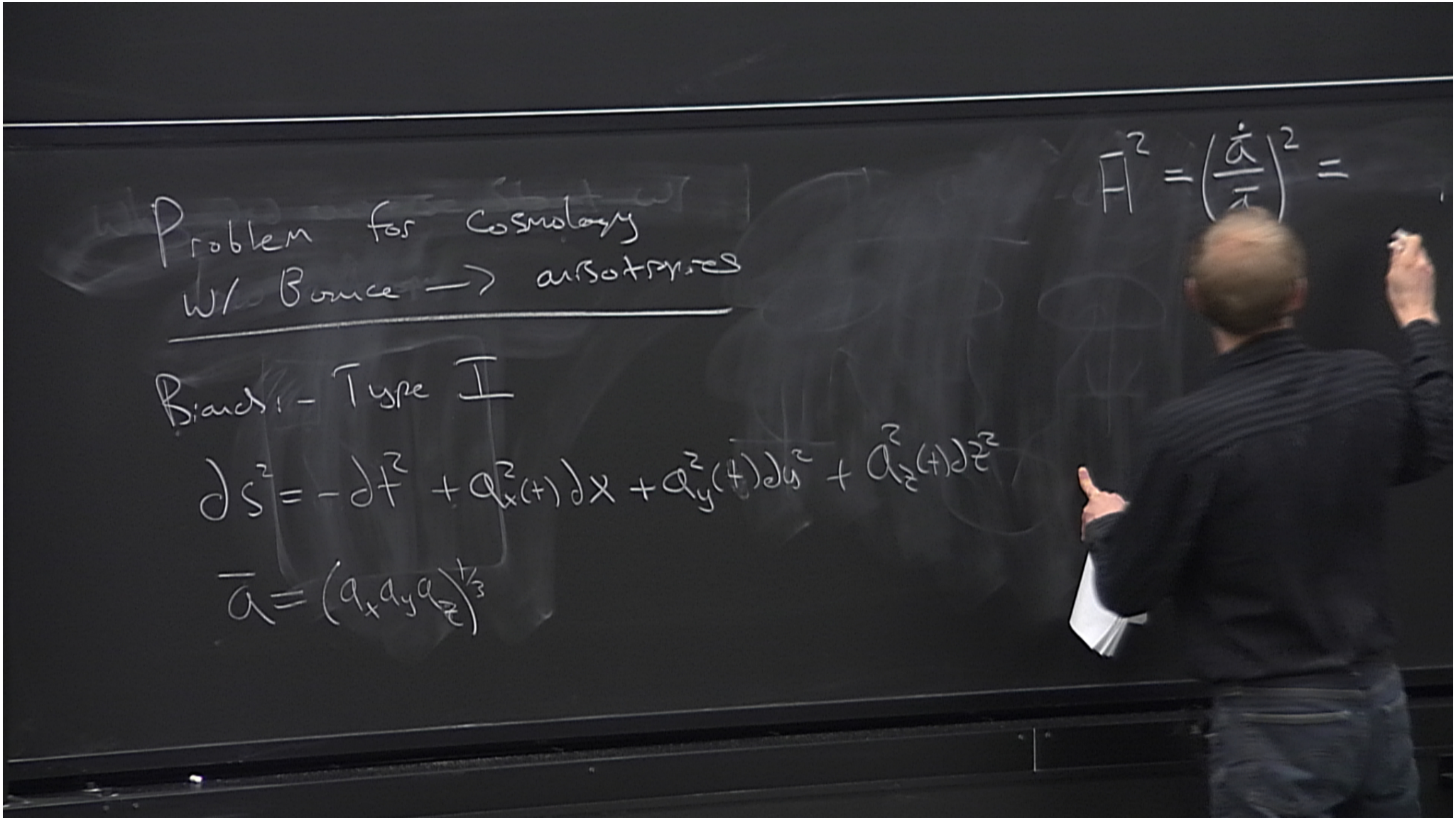
Contraction to expansion

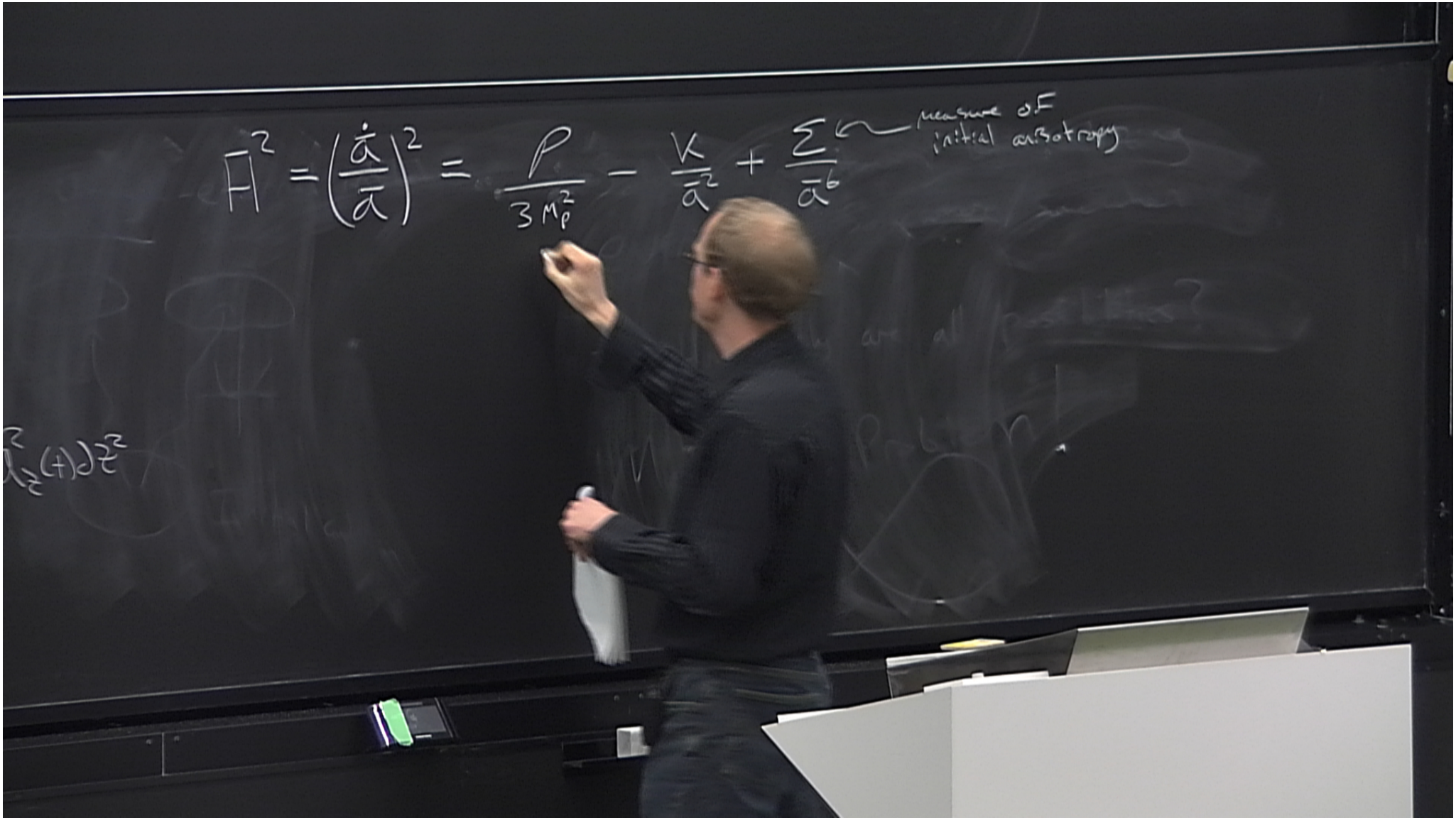
"Bounce"

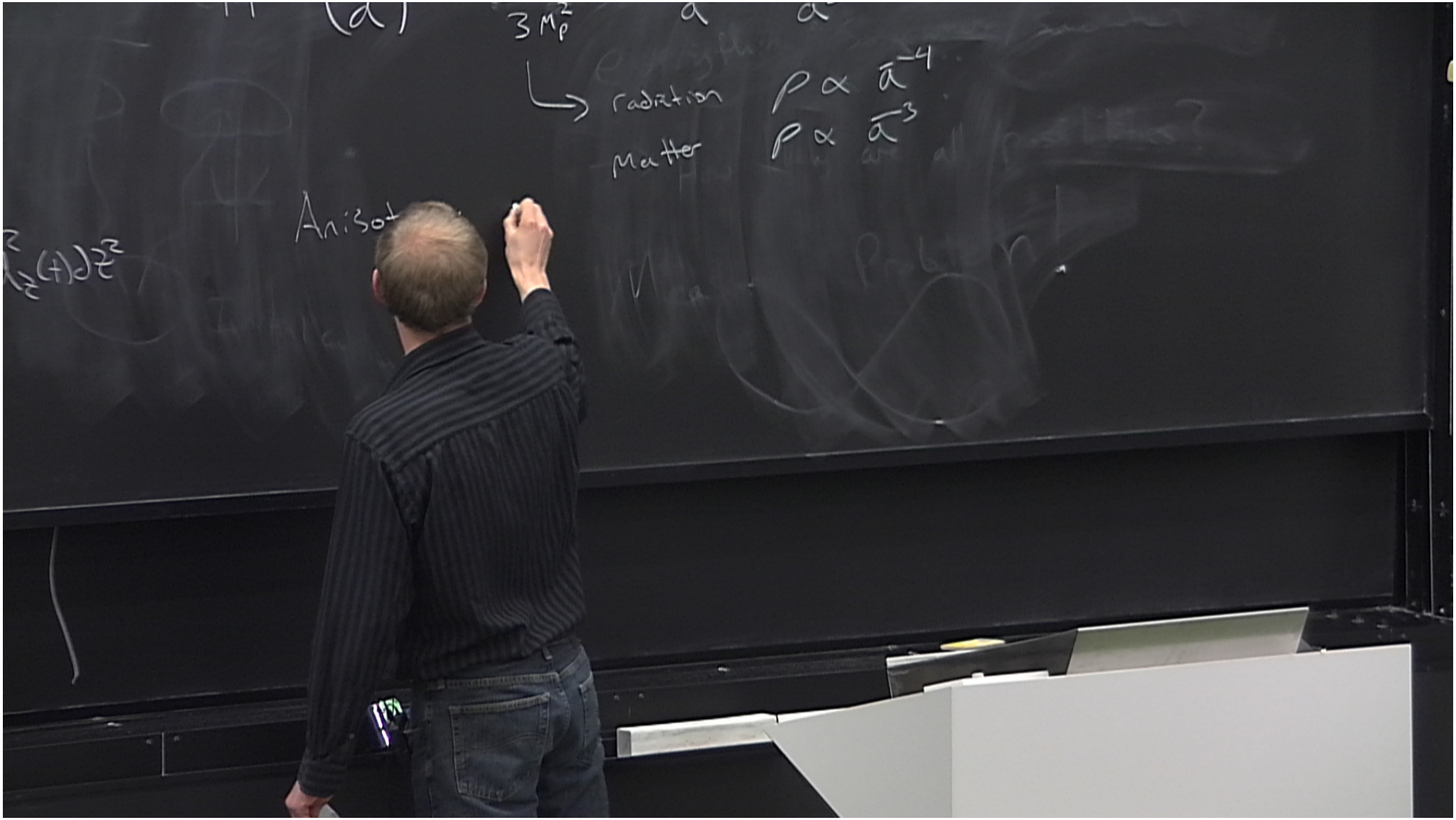
Not instanton

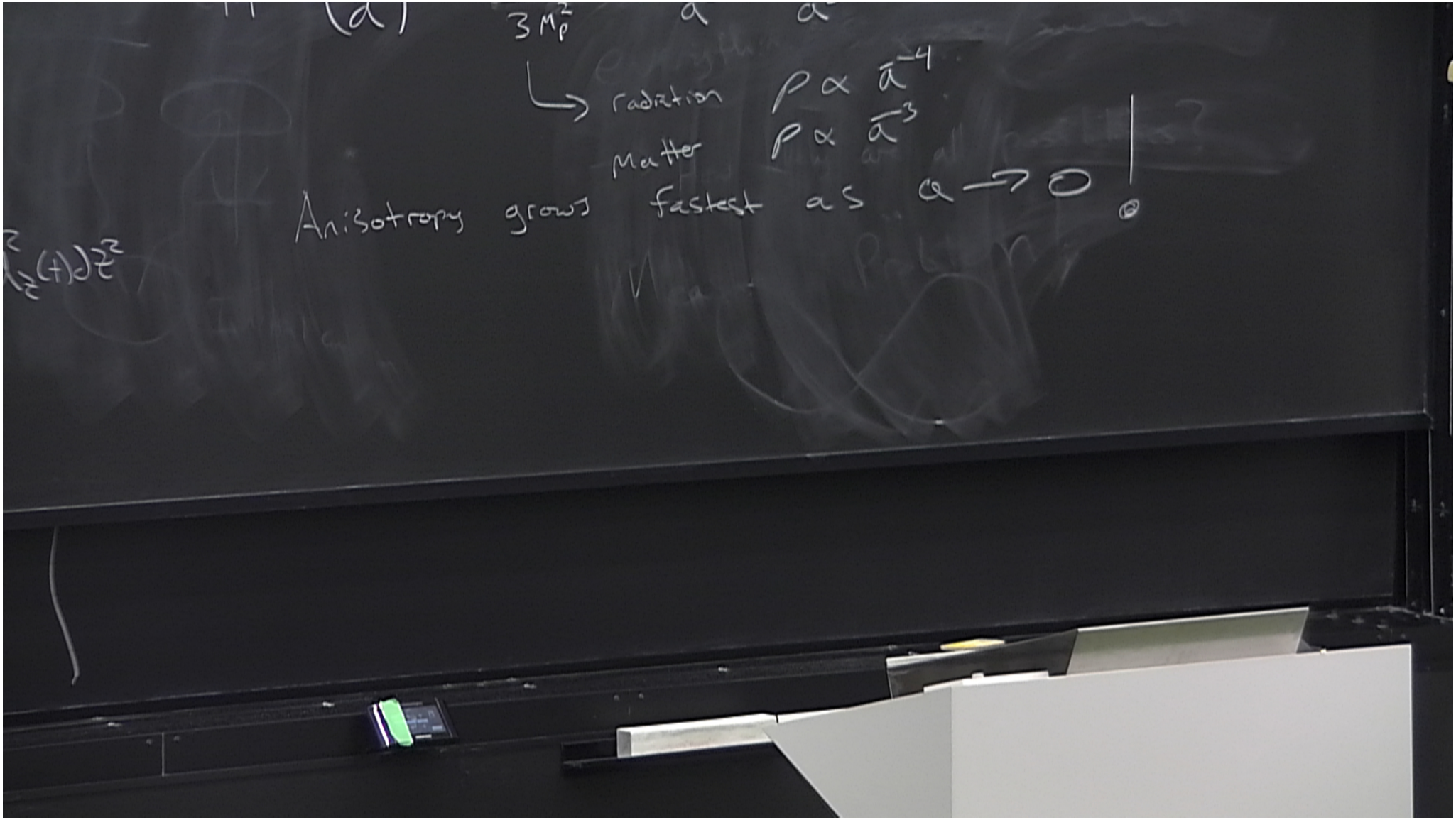

Problem for Cosmology
Bounce → anisotropies
- Type I

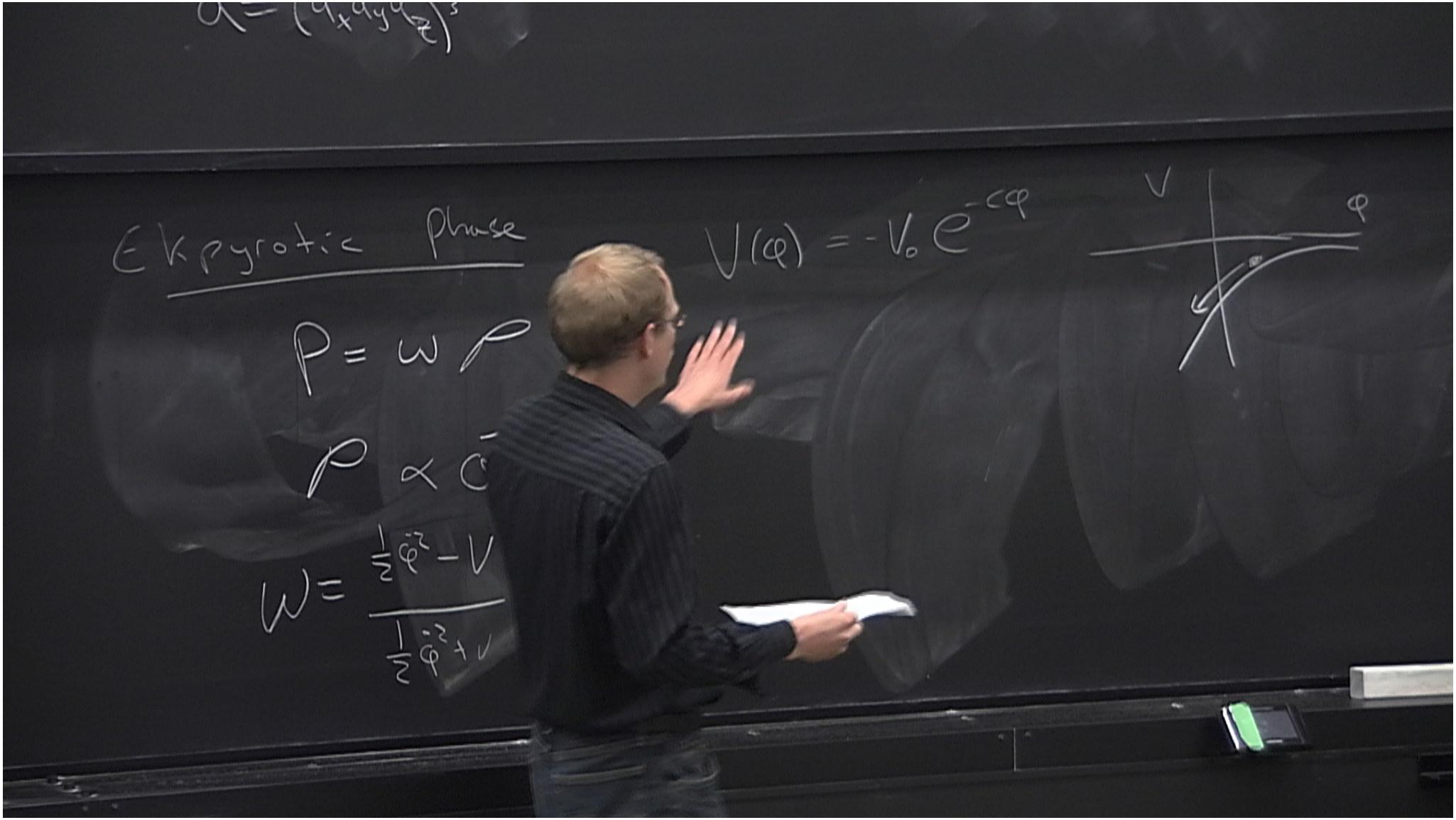

Problem for Cosmology
W/ Bounce → anisotropies
Bianchi - Type I
$ds^2 = -dt^2 + a_x^2(t)dx + a_y^2(t)dy^2 + a_z^2(t)dz^2$
$\bar{a} = (a_x a_y a_z)^{1/3}$

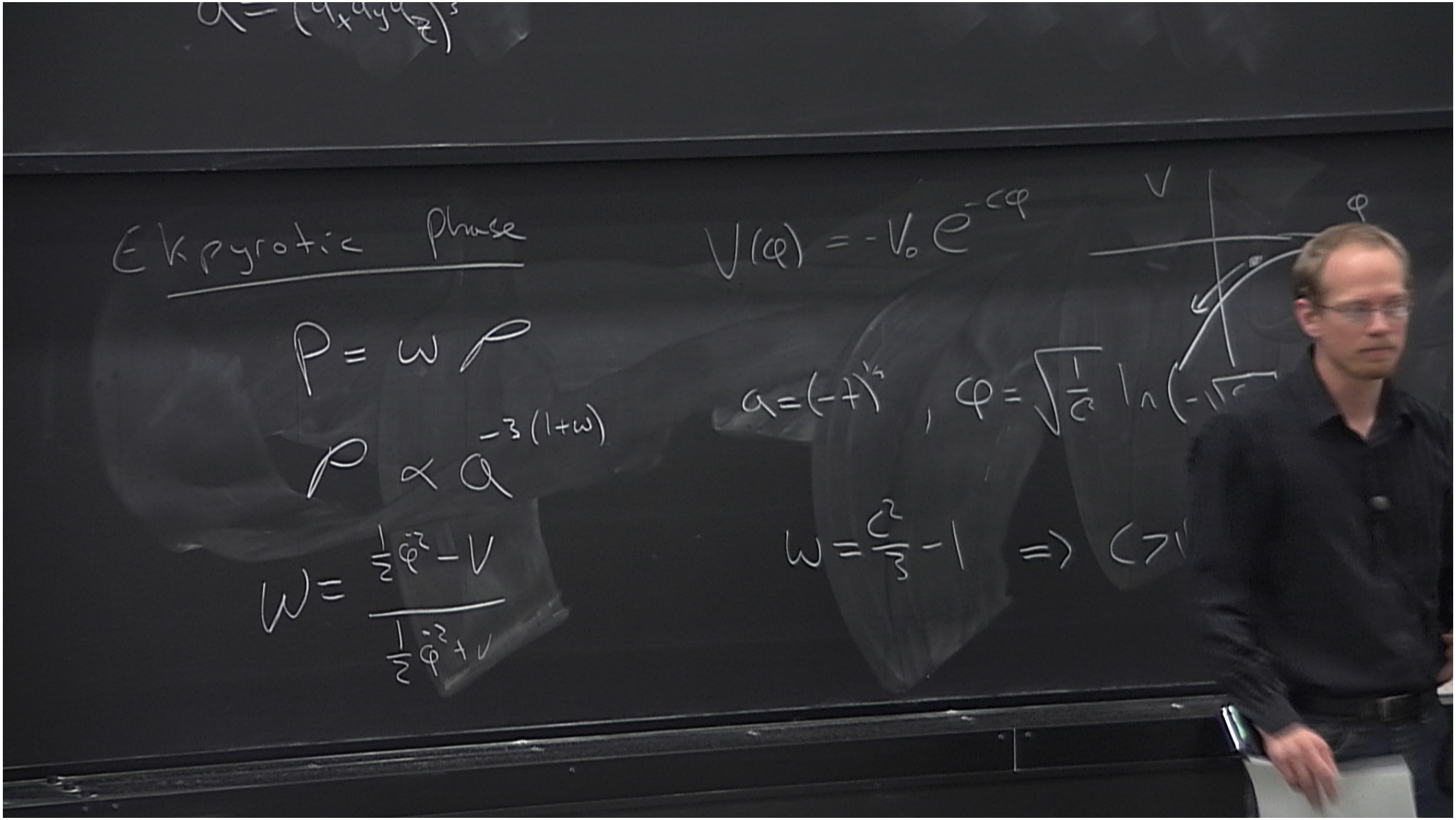

Problem for Cosmology
W/ Bounce → anisotropies
Bianchi - Type I
$ds^2 = -dt^2 + a_x^2(t)dx + a_y^2(t)dy^2 + a_z^2(t)dz^2$
$\bar{a} = (a_x a_y a_z)^{1/3}$
$H^2 = \left(\frac{\dot{a}}{a}\right)^2 =$

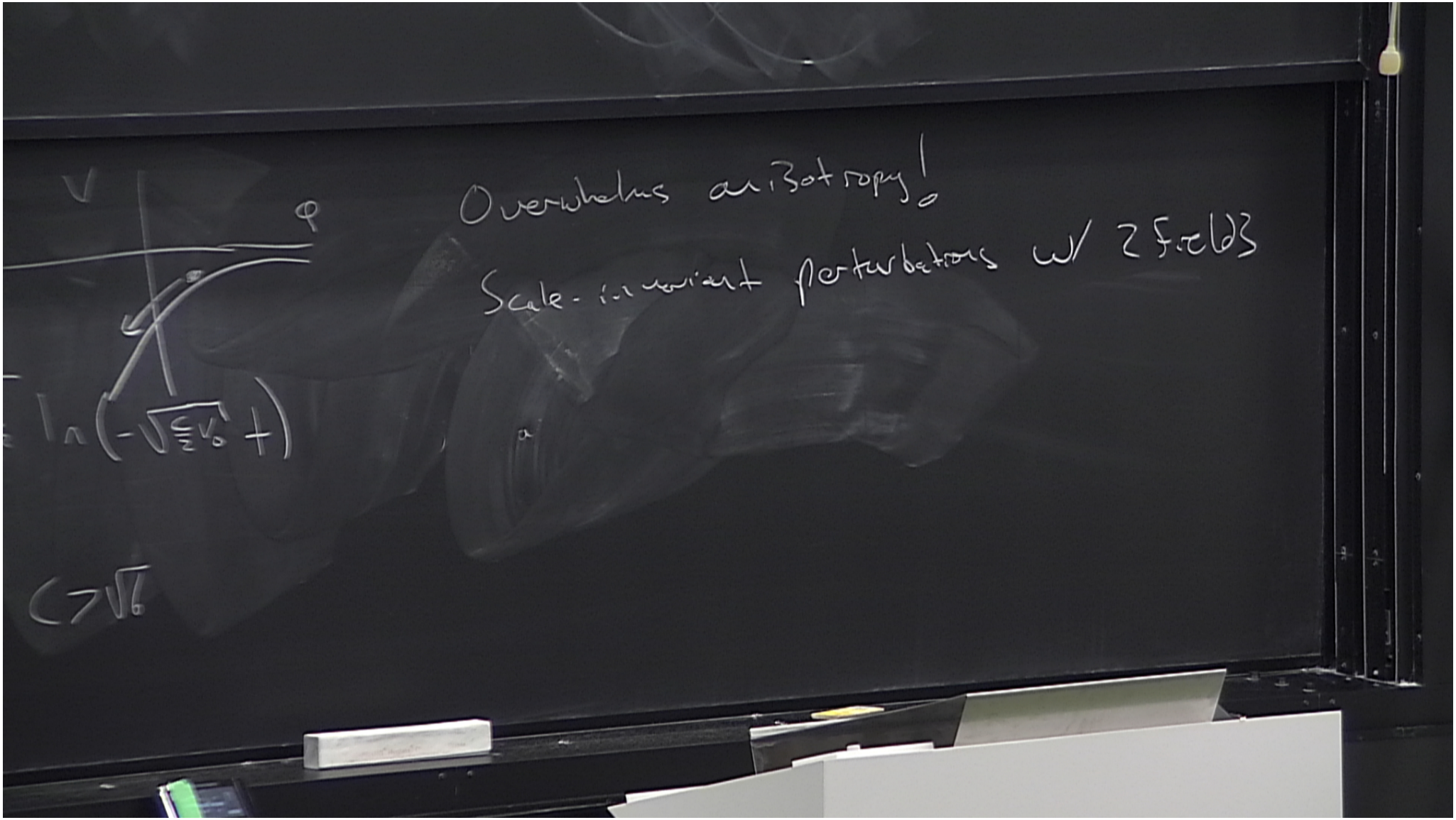

$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2} - \frac{K}{a^2} + \frac{\Sigma}{a^6}$
measure of initial anisotropy


$3M_p^2$
radiation $\rho \propto a^{-4}$
Matter $\rho \propto a^{-3}$
Anisot


$3M_p^2$
radiation $\rho \propto a^{-4}$
Matter $\rho \propto a^{-3}$
Anisotropy grows fastest as $a \to 0$!


Ekpyrotic phase
$V(\varphi) = -V_0 e^{-c\varphi}$
$p = w\rho$
$\rho \propto a^{-}$
$w = \frac{\frac{1}{2}\dot{\varphi}^2 - V}{\frac{1}{2}\dot{\varphi}^2 + V}$
V
φ


Ekpyrotic phase
$V(\varphi) = -V_0 e^{-c\varphi}$
$p = w\rho$
$\rho \propto a^{-3(1+w)}$
$w = \frac{\frac{1}{2}\dot{\varphi}^2 - V}{\frac{1}{2}\dot{\varphi}^2 + V}$
$a = (-t)^{1/3}$, $\varphi = \sqrt{\frac{1}{c}} \ln(-1$
$w = \frac{c^2}{3} - 1 \Rightarrow$
V
φ


Overwhelms anisotropy!
Scale-invariant perturbations w/ 2 fields