Title: Explorations in Cosmology-15

Date: Apr 24, 2015 10:15 AM

URL: http://pirsa.org/15040043

Abstract:

FREE MASSIVE SCALAR FIELD IN FRW

$$S = \int \frac{1}{2}\sqrt{-g}\left(-\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m^2\phi^2\right) + \cdots$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2$$

$$P_\phi = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

$$H^2 = H^2_{\text{OTHER}} + H^2_\phi$$

$$= H^2_{\text{OTHER}} + \frac{1}{3M_{Pl}^2}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2\right)$$

	$H_{\text{other}} \gg H_\phi$	$H_{\text{other}} \ll H_\phi$
$H \gg m$	FROZEN $w \approx -1$	
$H \ll m$		

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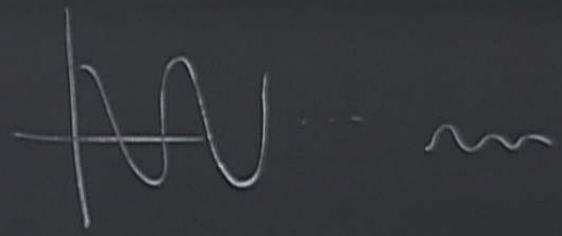
CASE 2: $H_{\text{other}} \gg H_\phi, \quad H \ll m$

$\ddot{\phi} + m^2\phi \approx 0$



HOW FAST DOES OSCILLATION LOSE ENERGY?

$$\frac{d\rho}{dt} = \frac{d}{dt}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2\right) = \dot{\phi}\left(\ddot{\phi} + m^2\phi\right) = \dot{\phi}(-3H\dot{\phi})$$

CASE 2: $H_{\text{other}} \gg H_\phi$, $H \ll m$

$$\ddot{\phi} + m^2\phi \simeq 0$$

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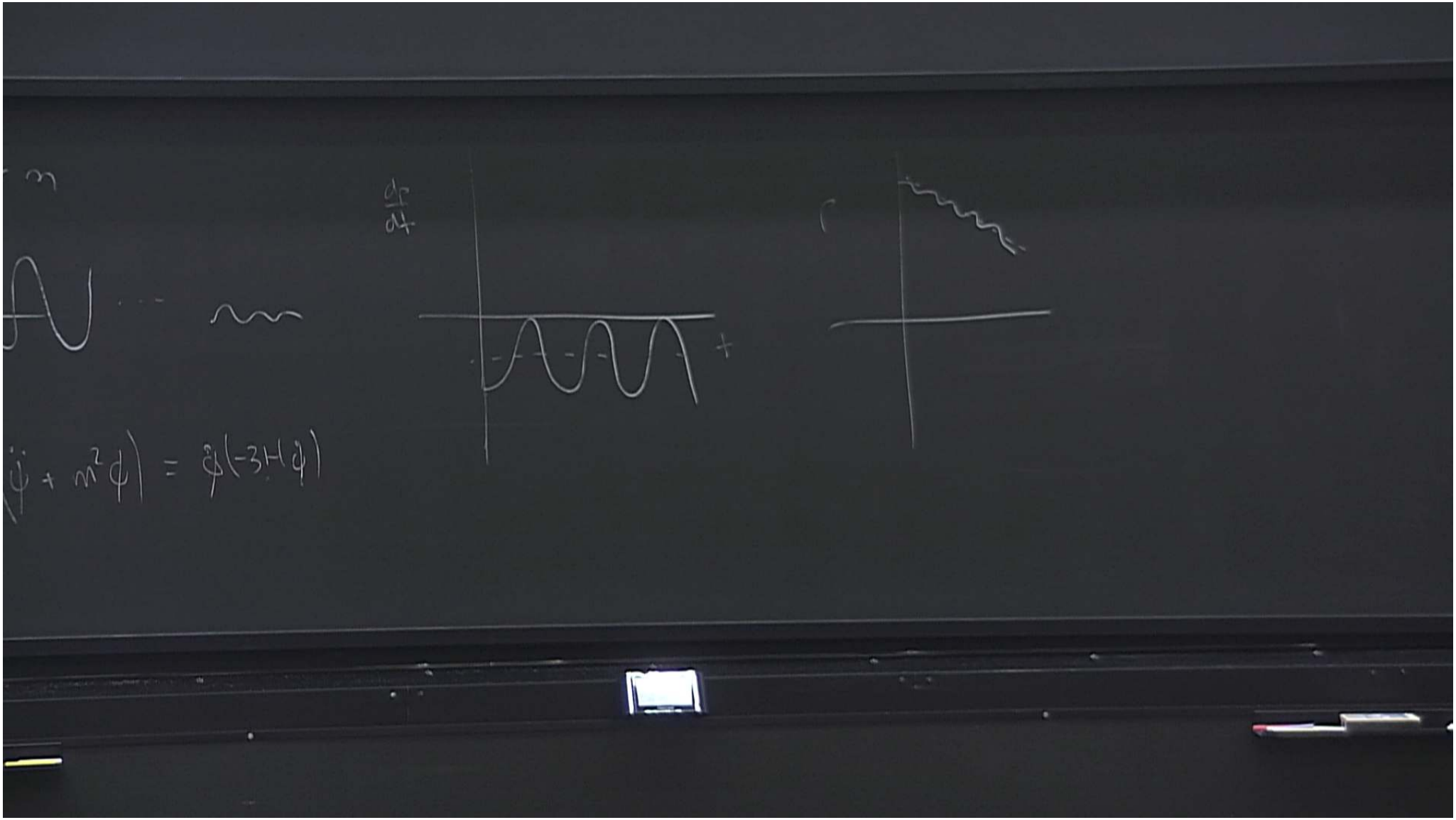
$\frac{d\rho}{dt}$
ρ
t
$(\ddot{\phi} + m^2\phi) = \dot{\phi}(-3H\dot{\phi})$

CASE 2: $H_{other} \gg H_\phi$, $H \ll m$

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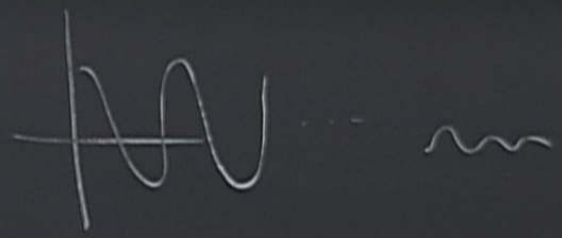

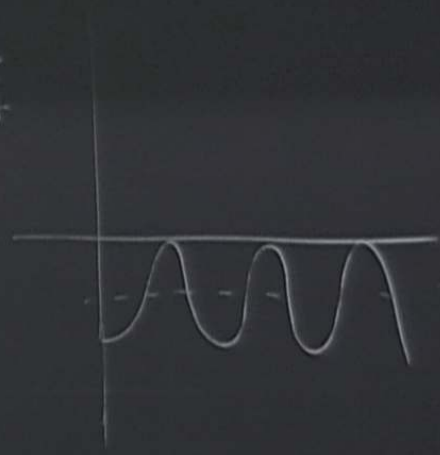

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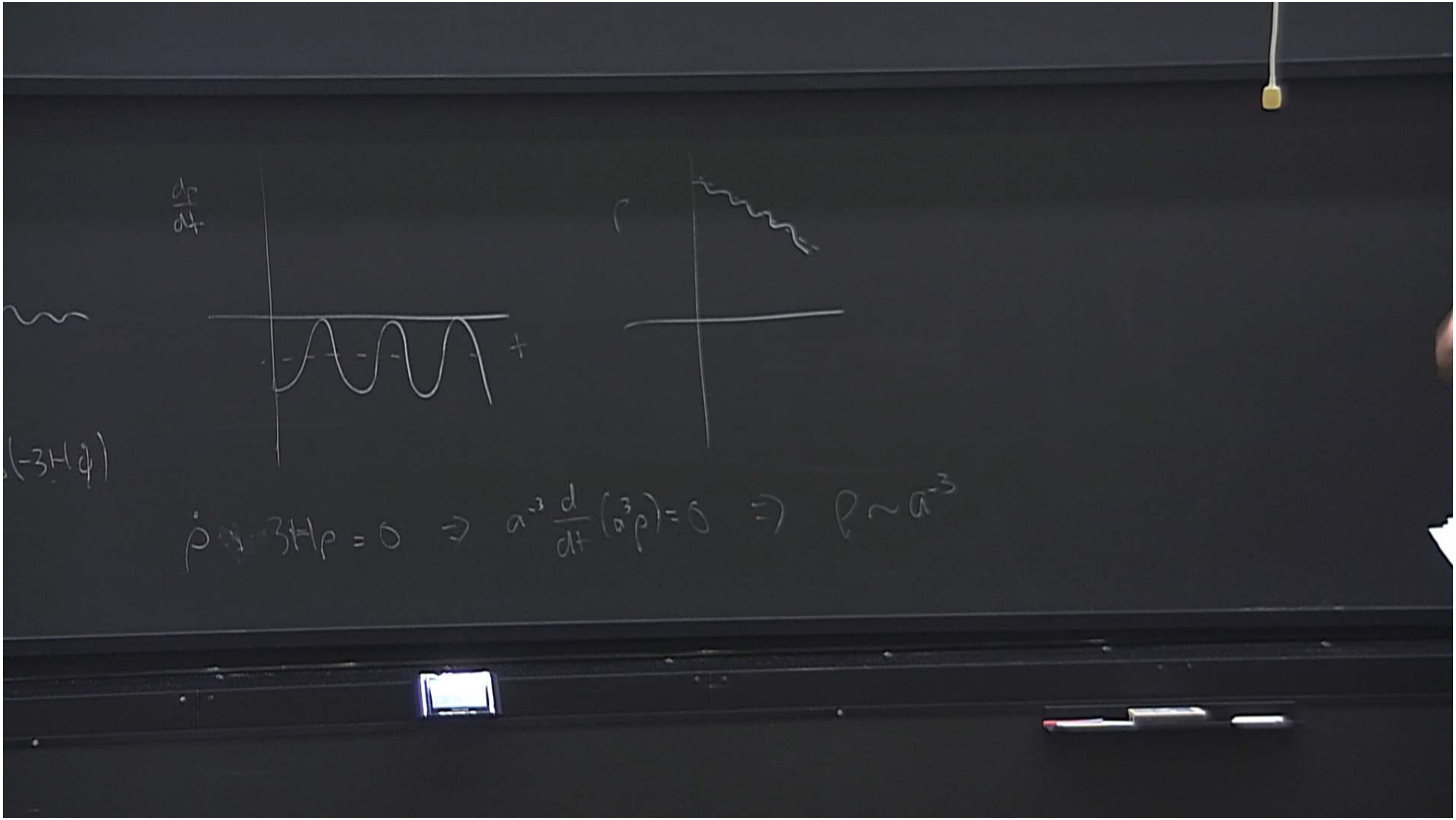
$$\left\langle \frac{d\rho}{dt} \right\rangle = -3H\langle\dot{\phi}^2\rangle = -3H\rho$$


$\frac{d\rho}{dt}$
ρ
$(-3H\phi)$
$\dot{\rho} + 3H\rho = 0 \Rightarrow a^{-3}\frac{d}{dt}(a^3\rho) = 0 \Rightarrow \rho \sim a^{-3}$

$\left\langle \frac{d\dot{\phi}}{dt} \right\rangle = -3H\langle \dot{\phi}^2 \rangle = -3H\rho$

CASE 3 $H_{OTHER} \gg H_\phi$ $H \gg m$

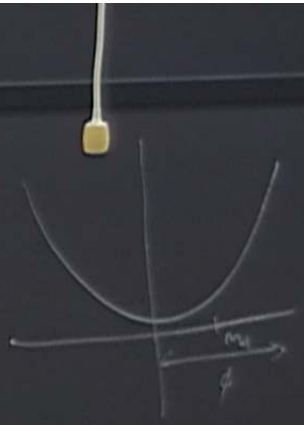
$\Leftrightarrow$ SLOW-ROLL SINGLE FIELD INFLATION

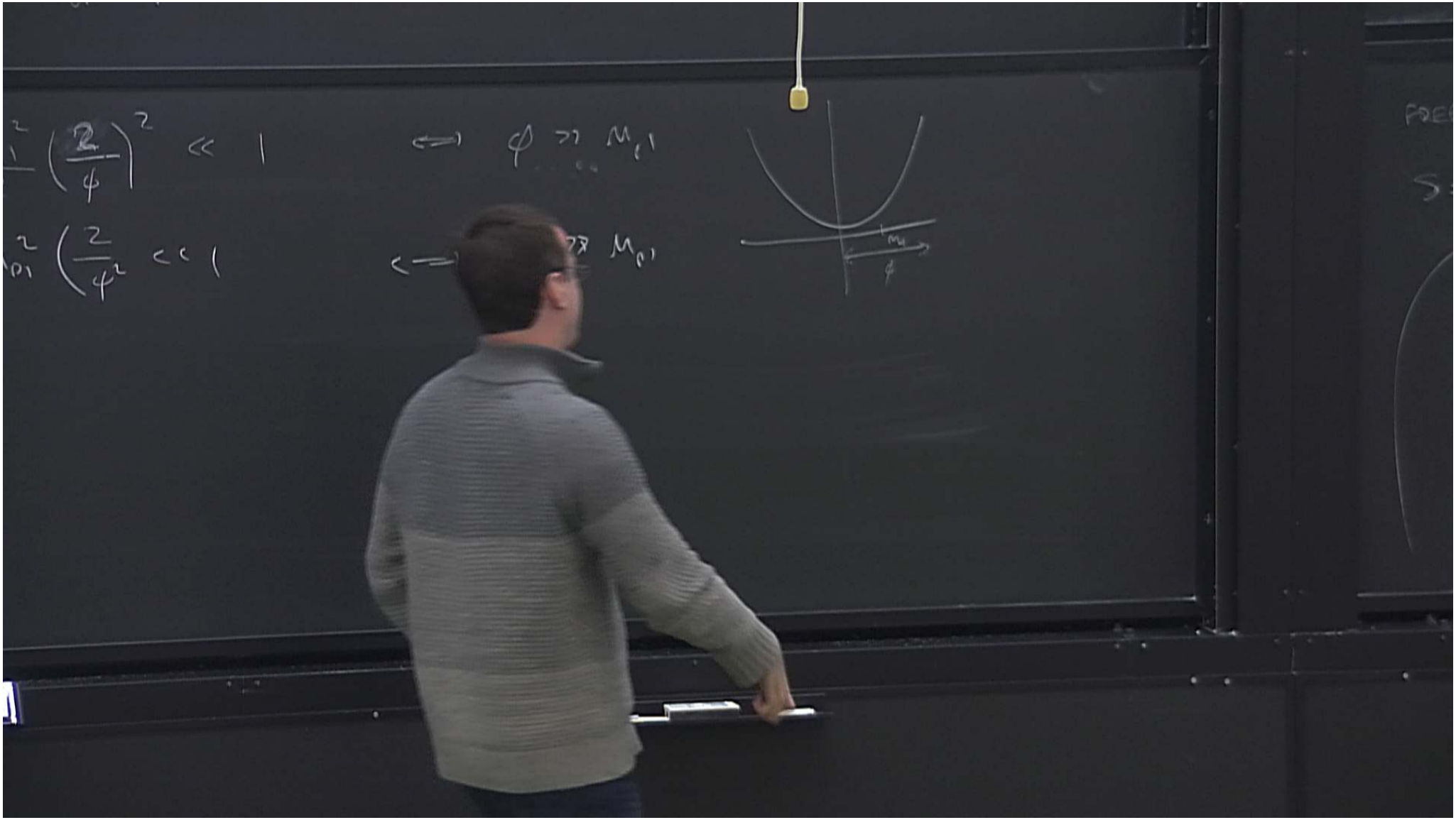
$\varepsilon = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{M_{Pl}^2}{2}\left($

$\eta = M_{Pl}^2\left(\frac{V''}{V}\right)$

$$\varepsilon = \frac{M_{Pl}^2}{2}\left(\frac{v'}{v}\right)^2 = \frac{M_{Pl}^2}{2}\left(\frac{2}{\phi}\right)^2 \ll 1 \quad \Longleftrightarrow \quad \phi \gg M_{Pl}$$

$$\eta = M_{Pl}^2\left(\frac{v''}{v}\right)$$





$\left(\frac{2}{\phi}\right)^2 \ll 1 \iff \phi \gg M_{Pl}$

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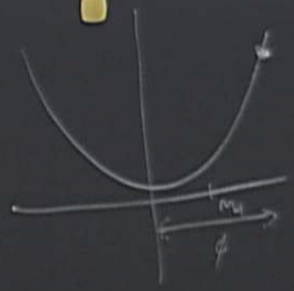
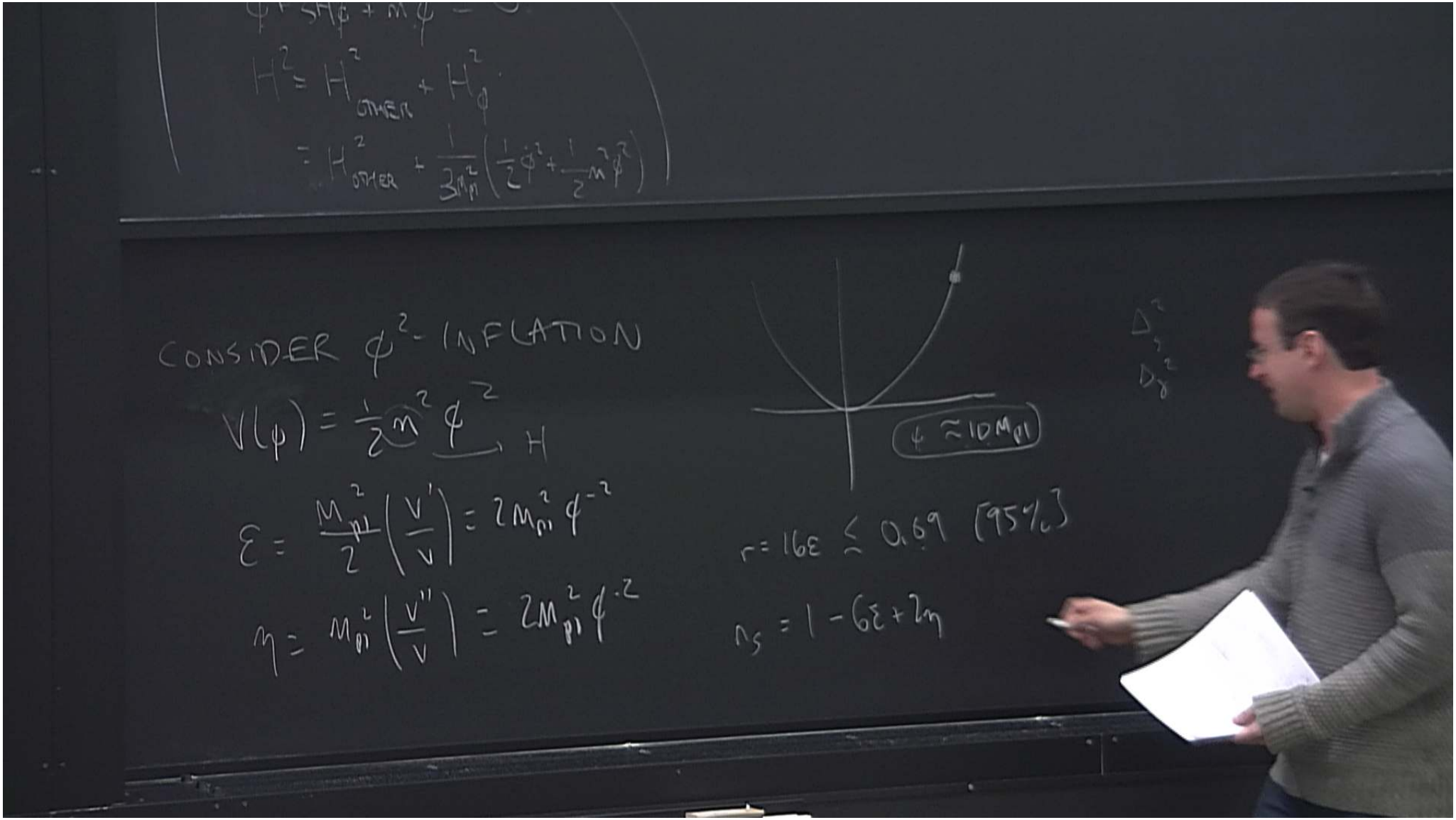
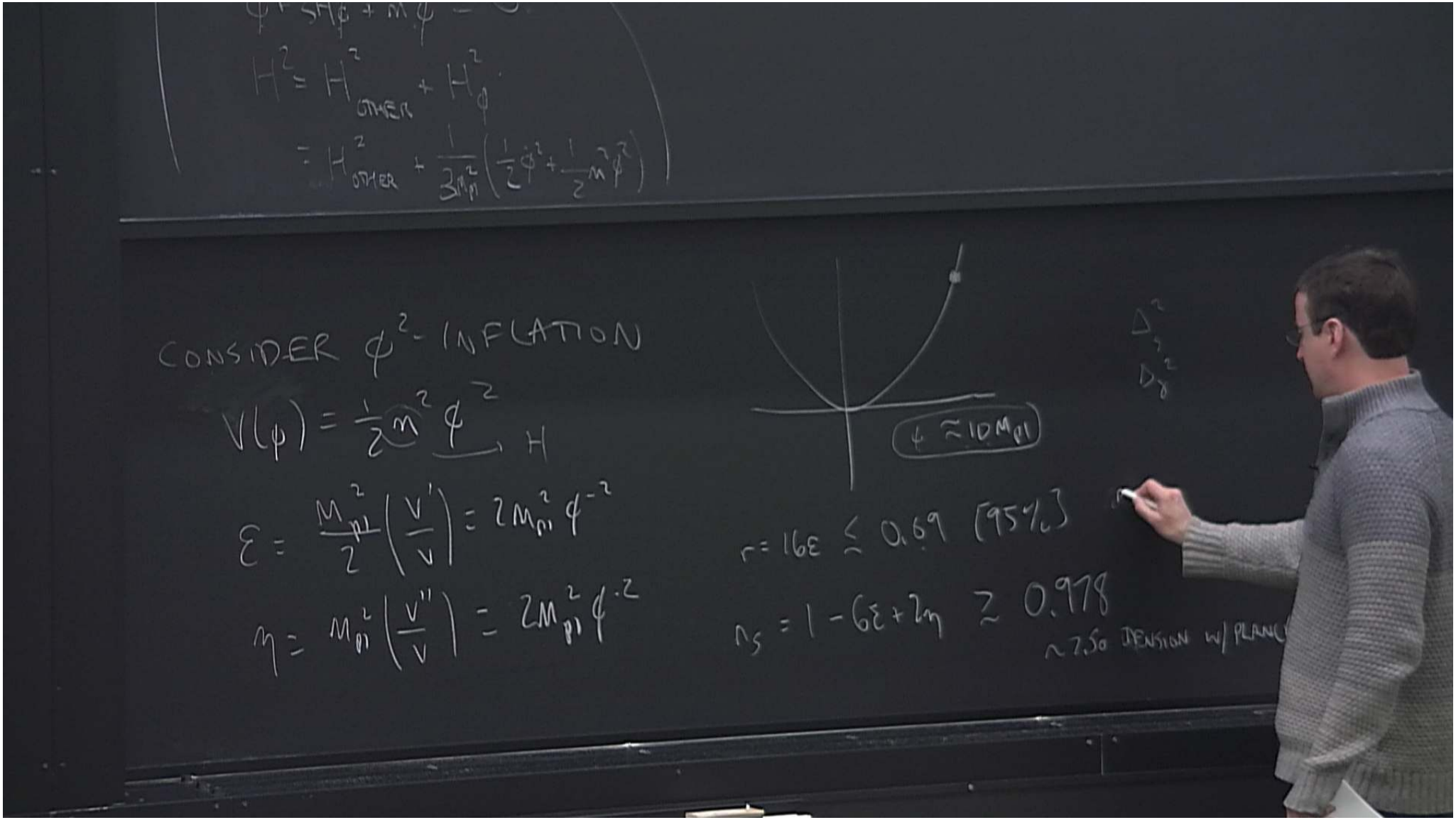
$m \iff \phi \gg M_{Pl}$




$H^2 = H^2_{OTHER} + H^2_\phi$
$= H^2_{OTHER} + \frac{1}{3M_{Pl}^2}\left(\frac{1}{2}\dot\phi^2 + \frac{1}{2}m^2\phi^2\right)$
CONSIDER ϕ^2 - INFLATION
$V(\phi) = \frac{1}{2}m^2\phi^2$
H
$\phi \approx 10 M_{Pl}$
$\varepsilon = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right) = 2M_{Pl}^2\phi^{-2}$
$\eta = M_{Pl}^2\left(\frac{V''}{V}\right) = 2M_{Pl}^2\phi^{-2}$
$r = 16\varepsilon \lesssim 0.69$ [95%]
$n_s = 1 - 6\varepsilon + 2\eta$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$r = 16\varepsilon \lesssim 0.69$ [95%]
$n_s = 1 - 6\varepsilon + 2\eta \gtrsim 0.978$
$\sim 2.5\sigma$ TENSION W/ PLANC

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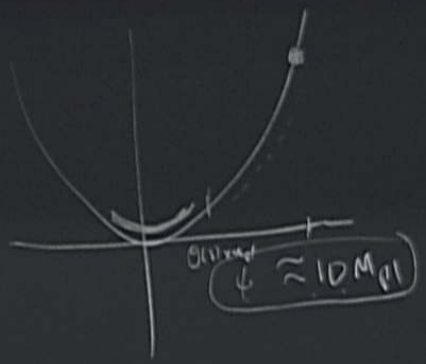
DER ϕ^2 - INFLATION

$\phi) = \frac{1}{2}m^2\phi^2 \rightarrow H$

$= \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right) = 2M_{Pl}^2\phi^{-2}$

$\eta = M_{Pl}^2\left(\frac{V''}{V}\right) = 2M_{Pl}^2\phi^{-2}$



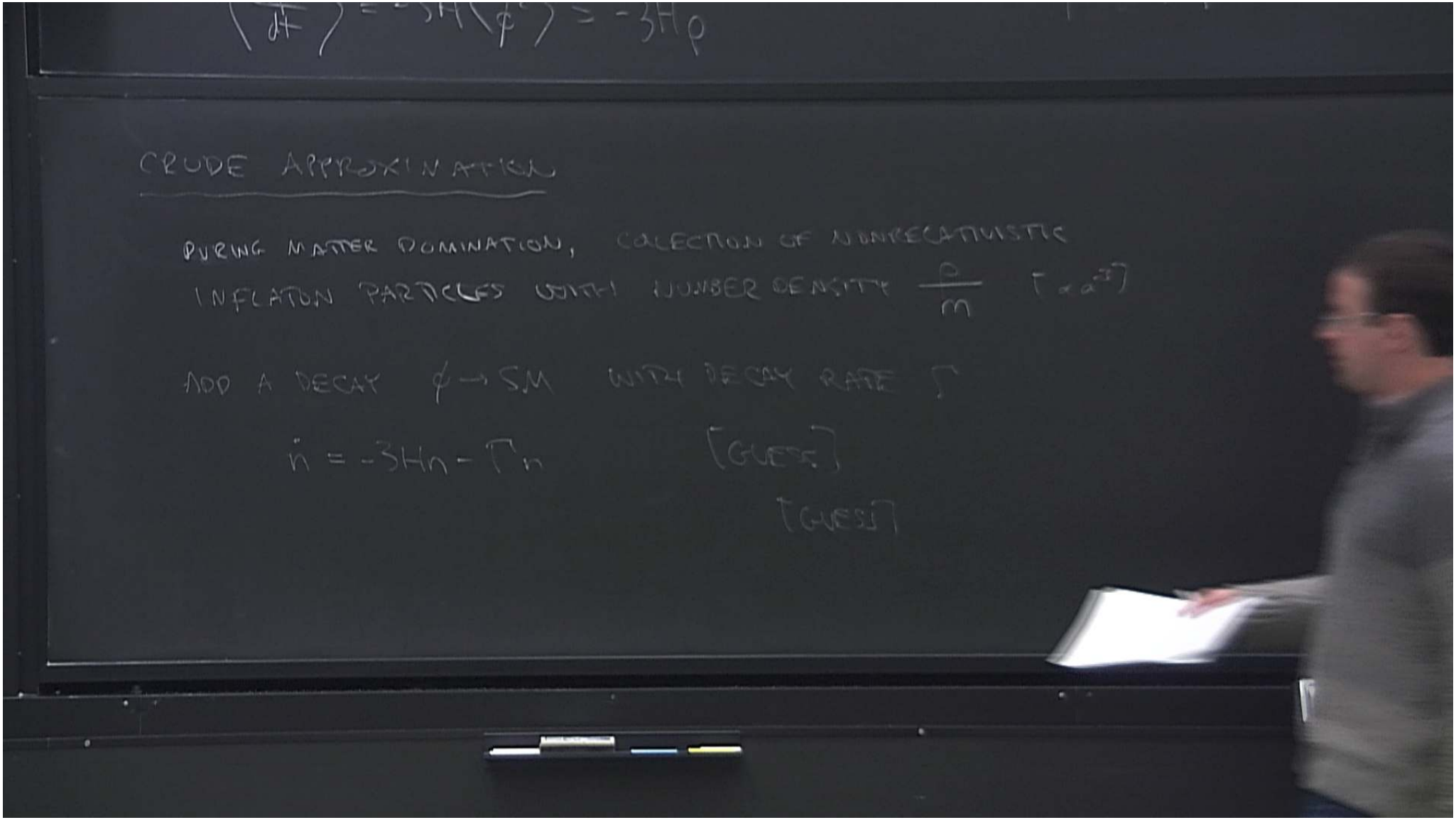
$r = 16\varepsilon \leq 0.69$ (95% CL) PLANCK + BICEP2 + KECK

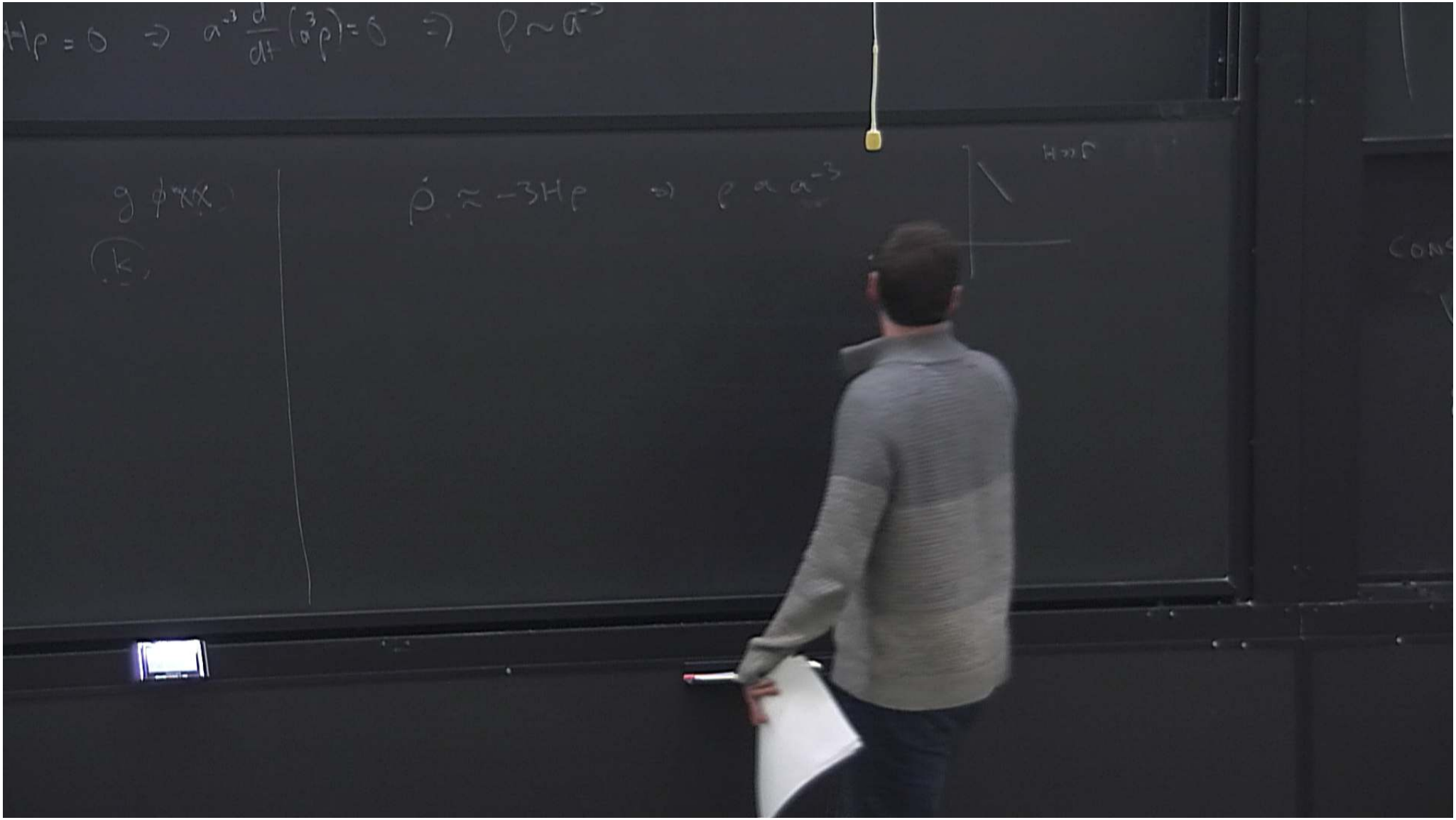
$n_s = 1 - 6\varepsilon + 2\eta \geq 0.978$

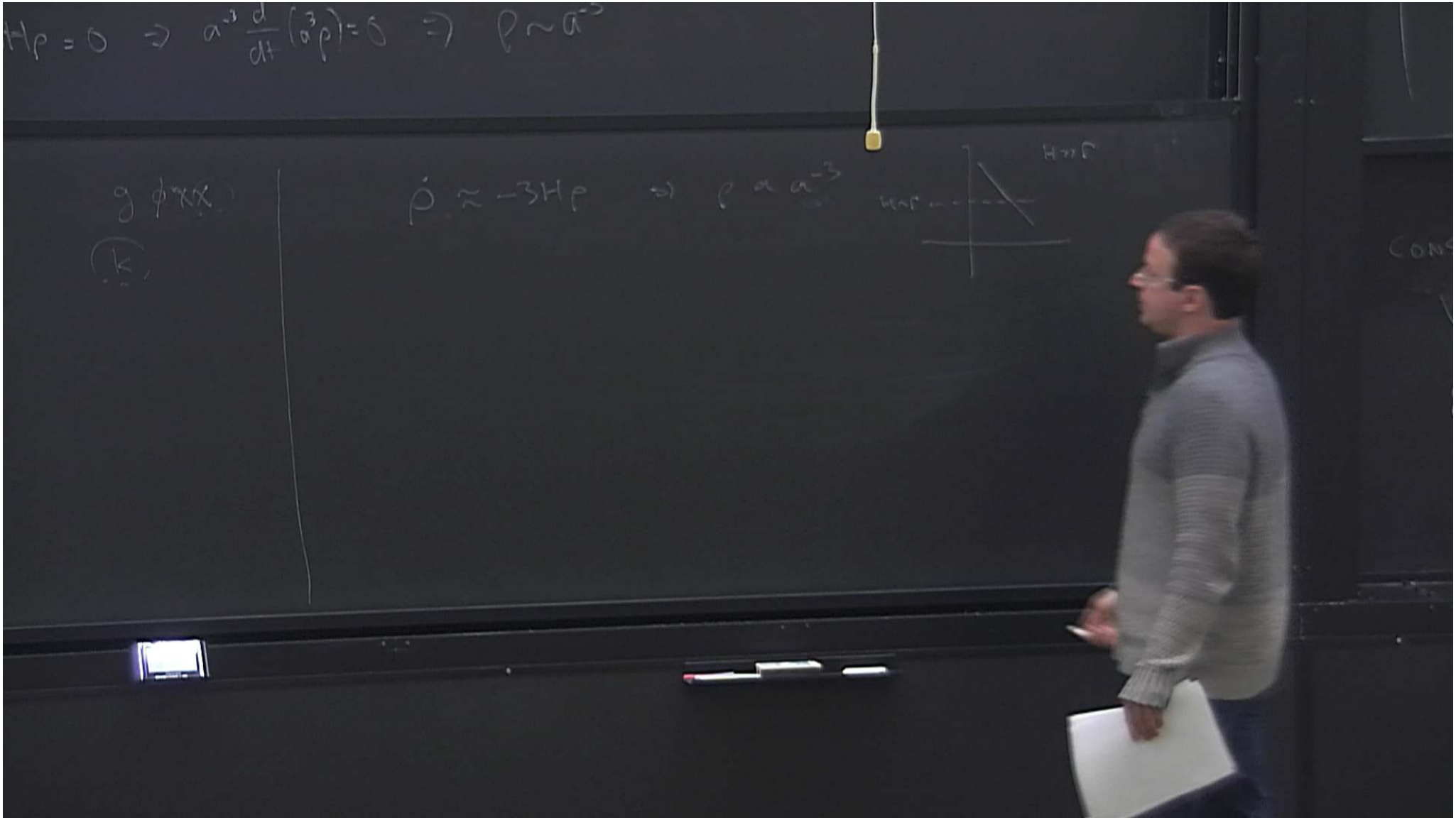
$\sim 2.5\sigma$ TENSION W/ PLANCK + BICEP2 + KECK

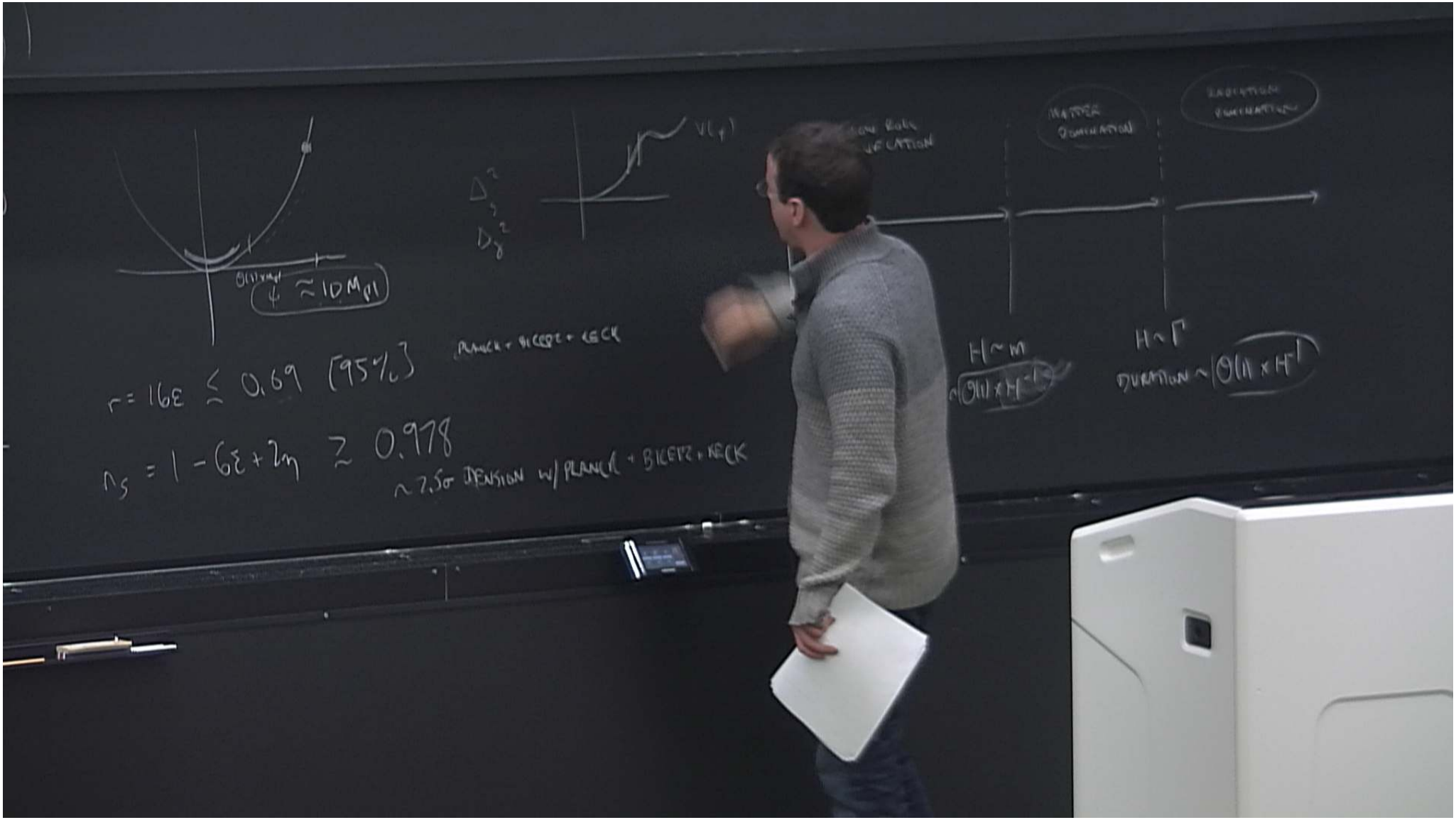
SLOW ROLL INFLATION

SLOW ROLL INFLATION
MATTER DOMINATION
RADIATION DOMINATION
$\simeq 10 M_{Pl}$
PLANCK + BICEP2 + KECK
$\sim 2.5\sigma$ TENSION W/ PLANCK + BICEP2 + KECK

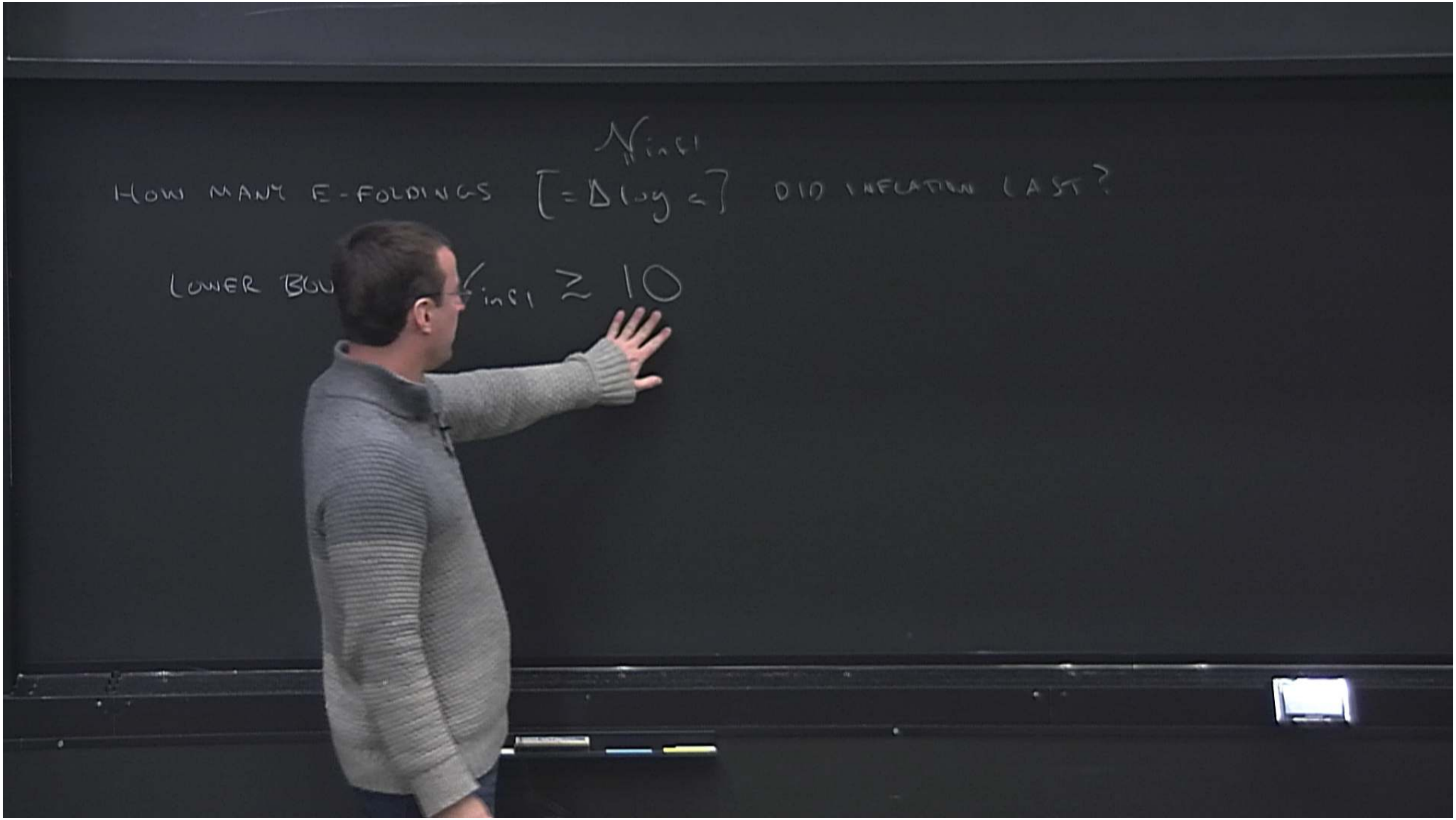

$\left\langle \frac{d\rho}{dt} \right\rangle = -3H\langle \phi' \rangle = -3H\rho$
CRUDE APPROXIMATION
DURING MATTER DOMINATION, COLECTION OF NONRELATIVISTIC
INFLATON PARTICLES WITH NUMBER DENSITY $\frac{\rho}{m}$ $[\propto a^{-3}]$
ADD A DECAY $\phi \to SM$ WITH DECAY RATE Γ
$\dot{n} = -3Hn - \Gamma n$ [GUESS]
[GUESS]

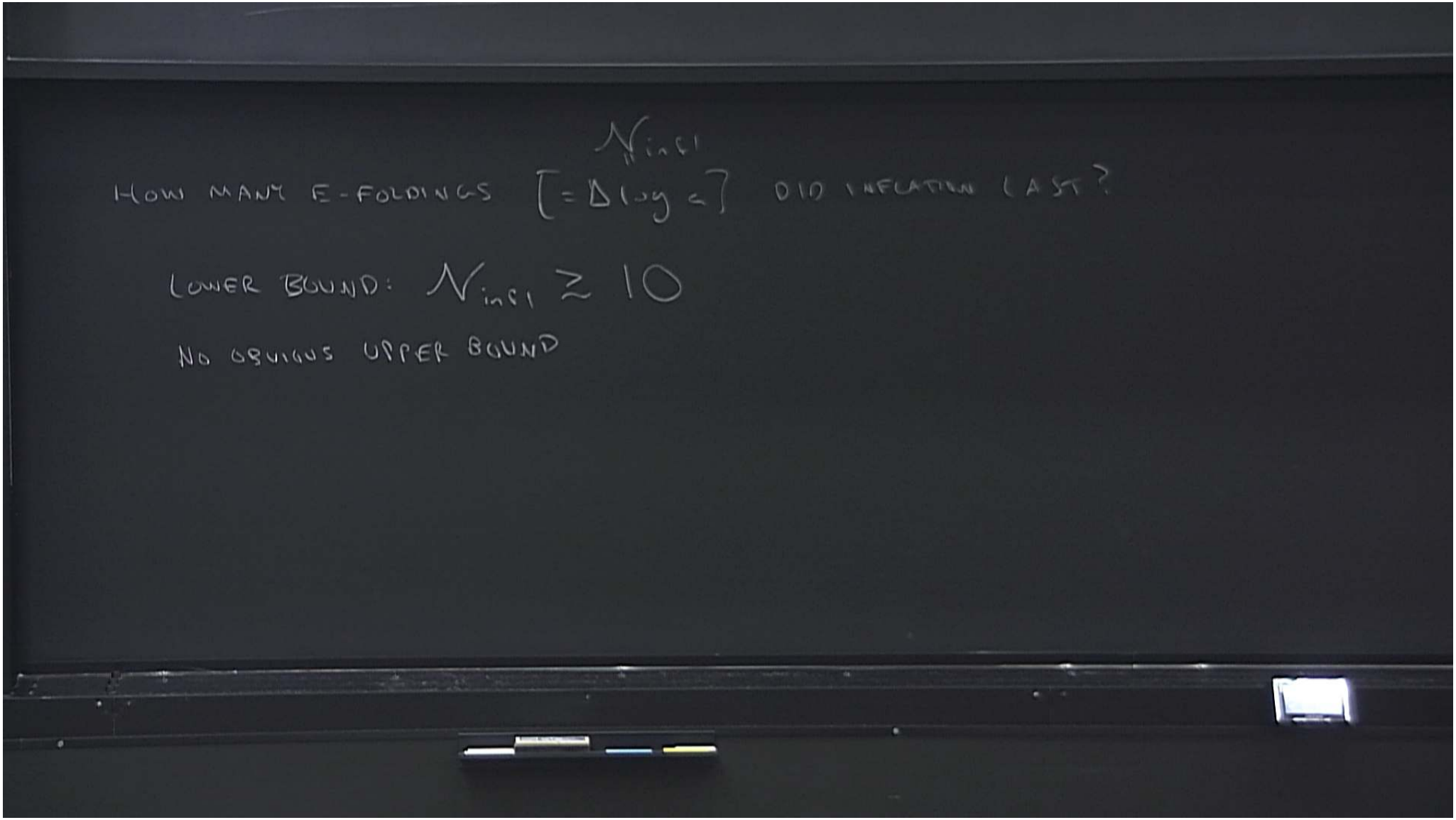

$\dot{\rho} \approx -3H\rho \Rightarrow \rho \propto a^{-3}$
$H \gg \Gamma$

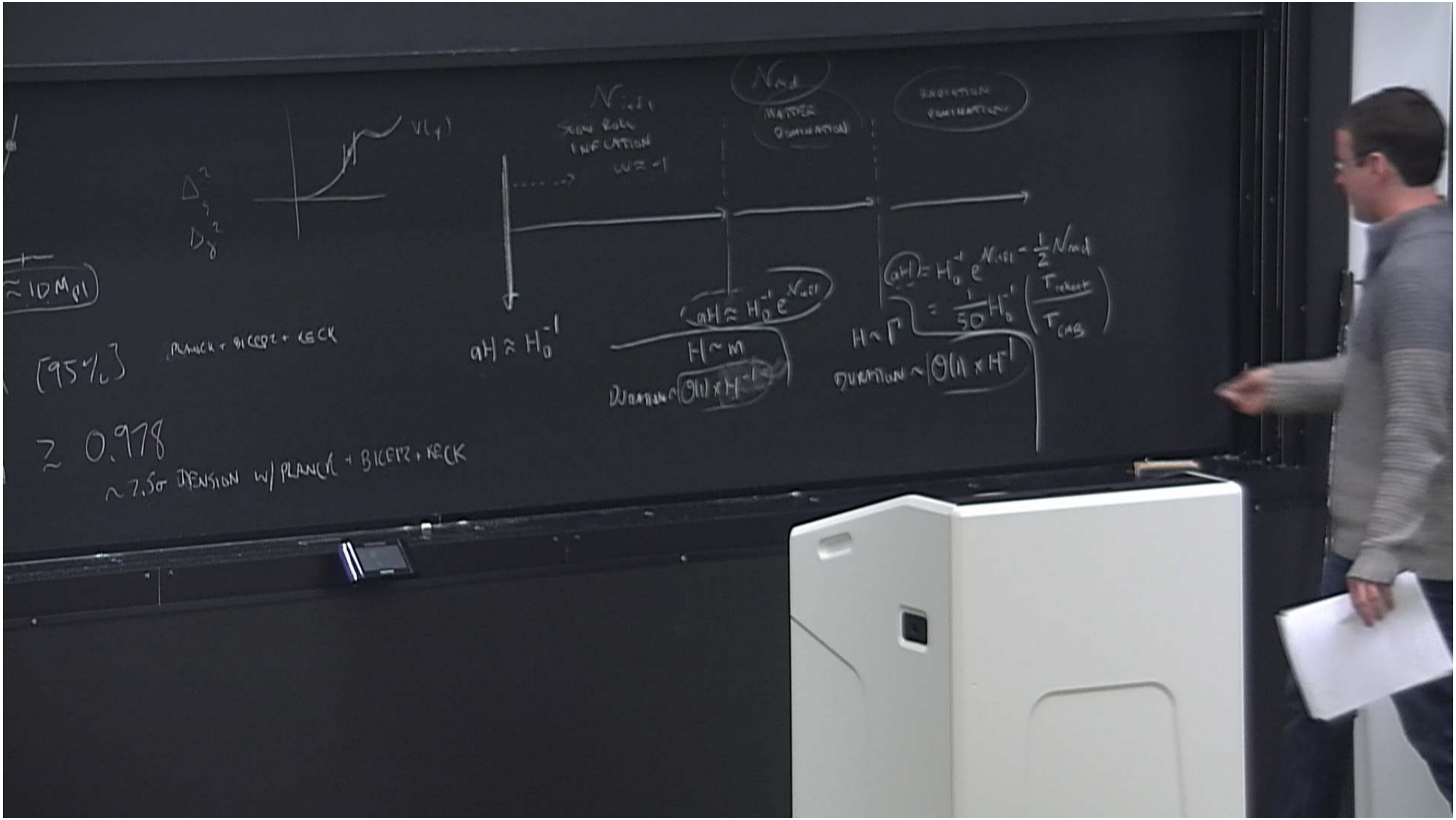

Hρ = 0 ⇒ a^-3 d/dt (a^3 ρ) = 0 ⇒ ρ ~ a^-3
ρ̇ ≈ −3Hρ ⇒ ρ ∝ a^-3
H ≫ Γ
H ≪ Γ

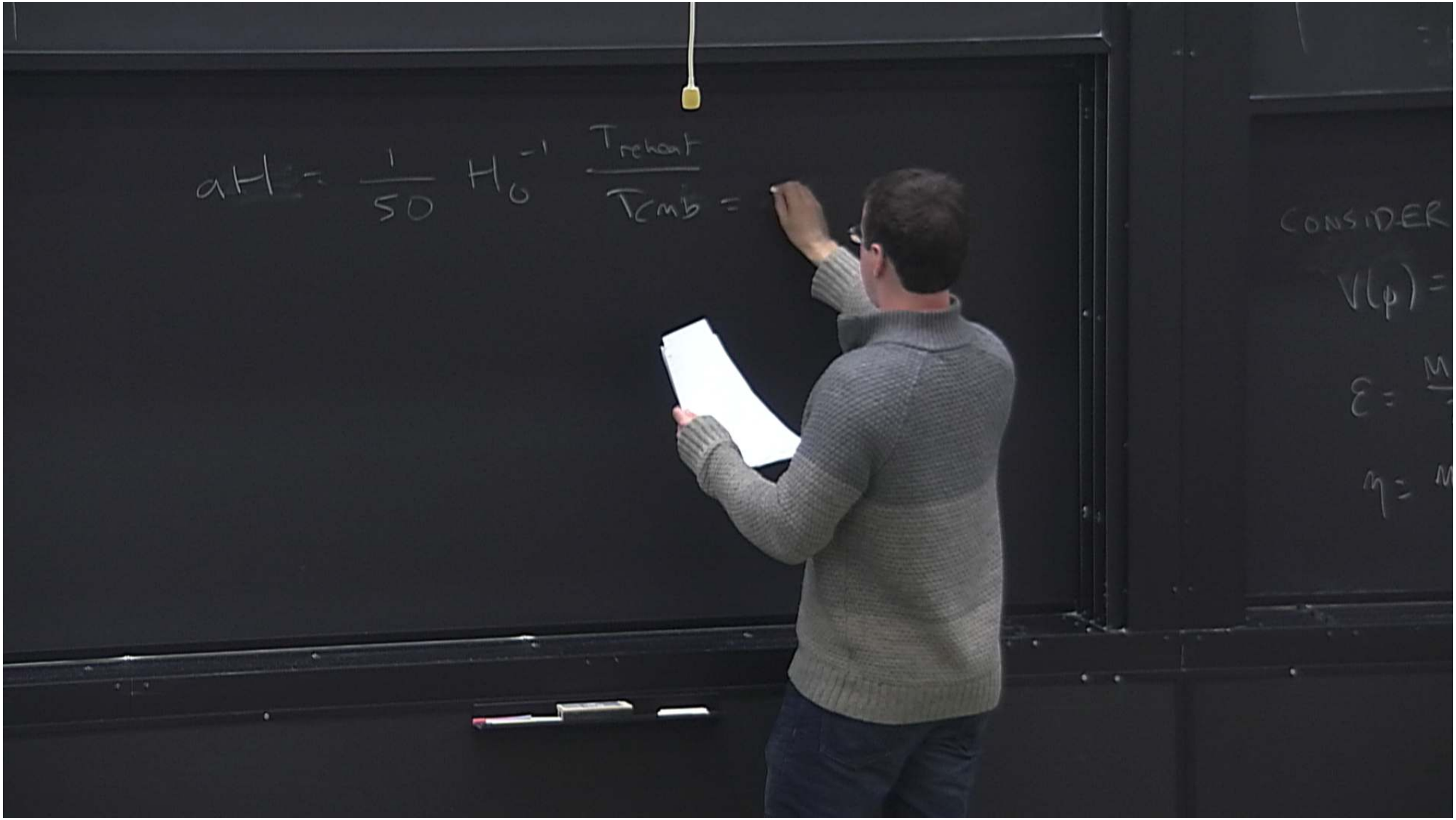


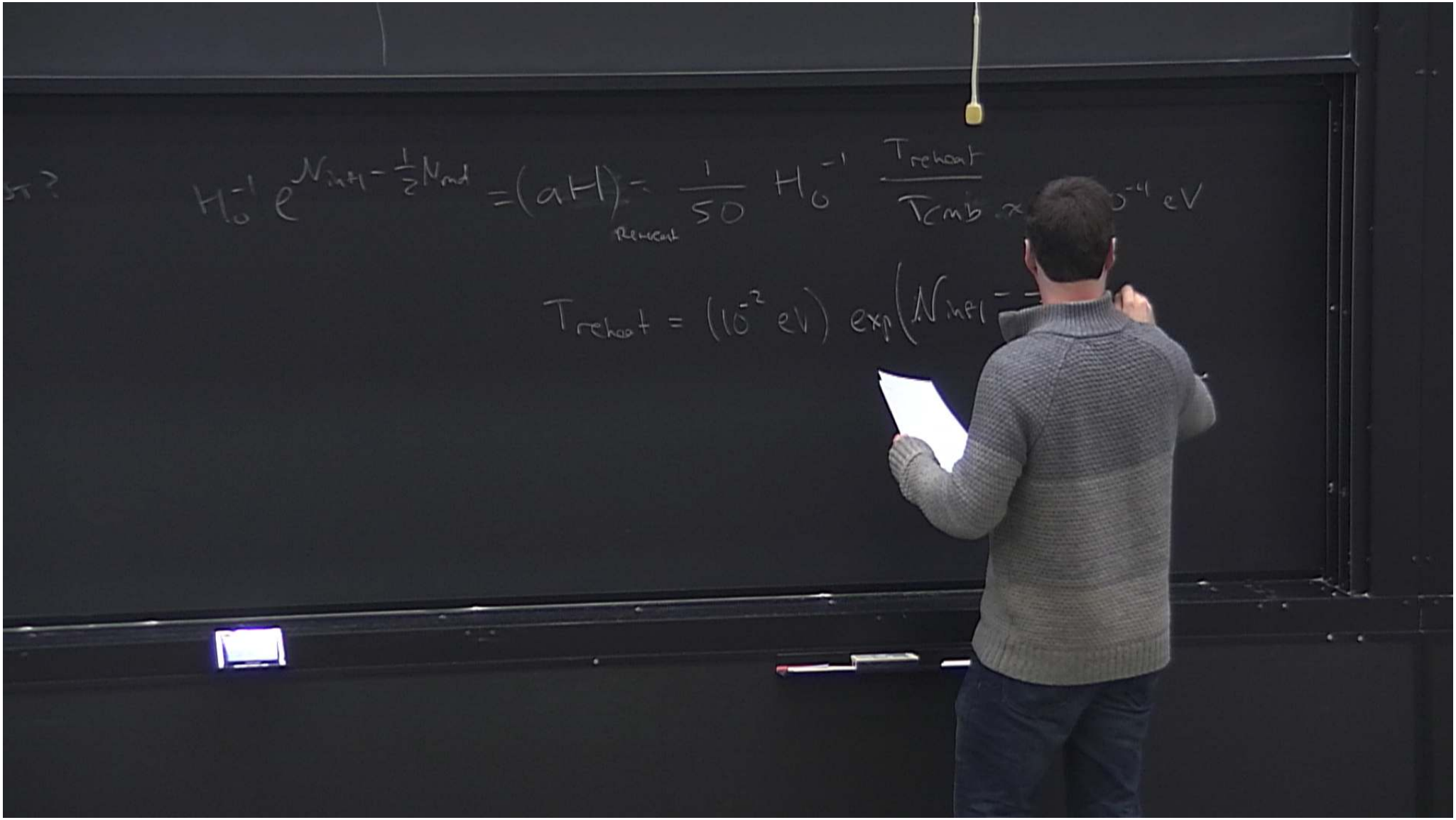
$\psi \approx 10 M_{pl}$
$r = 16\varepsilon \lesssim 0.69$ [95%]
PLANCK + BICEP2 + KECK
$n_s = 1 - 6\varepsilon + 2\eta \gtrsim 0.978$
~2.5σ TENSION W/ PLANCK + BICEP2 + KECK
$H \sim m$
$H \sim \Gamma$
DURATION ~ $\mathcal{O}(1) \times H^{-1}$

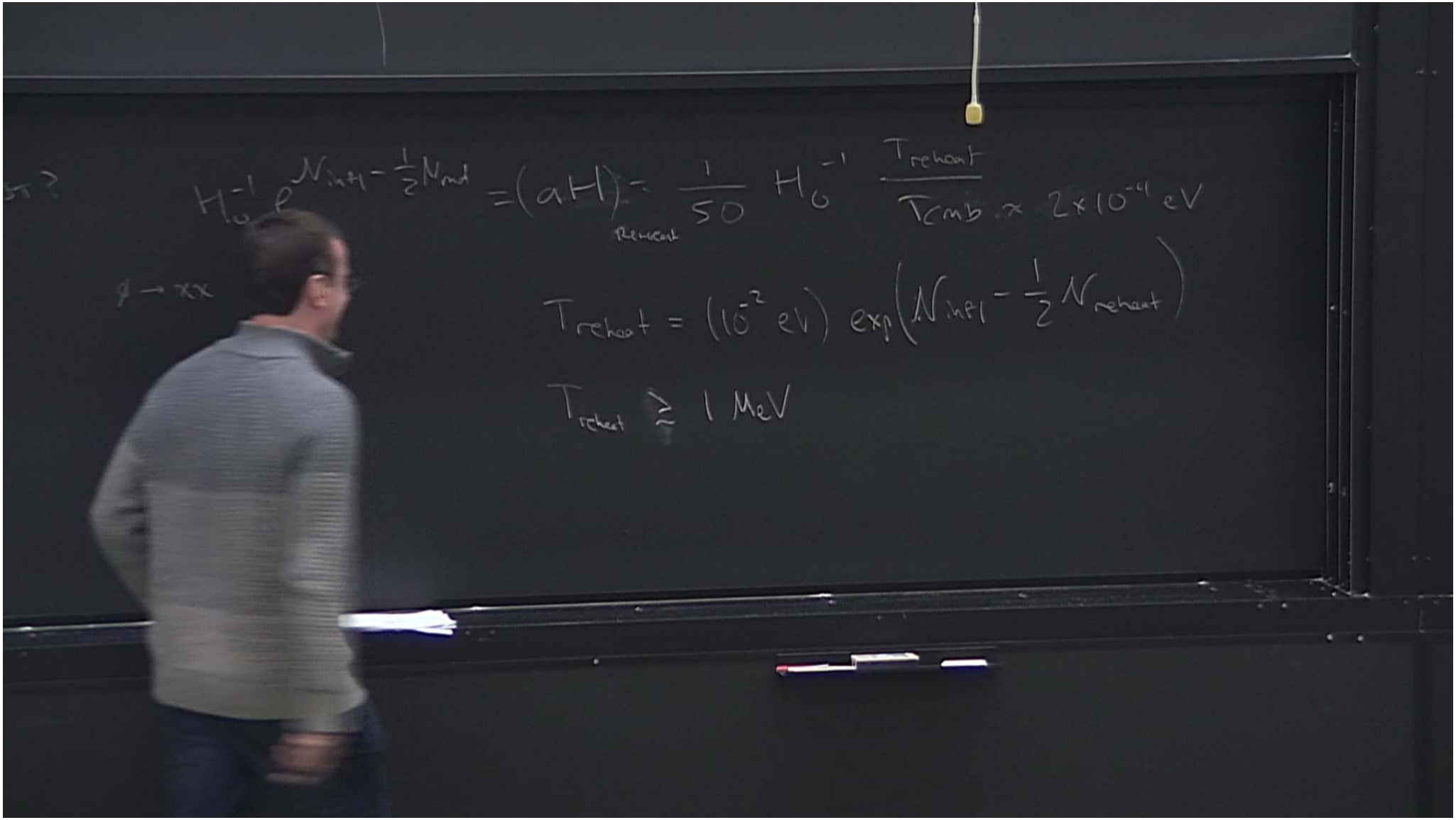

HOW MANY E-FOLDINGS N_{infl} $[= \Delta \log a]$ DID INFLATION LAST?
LOWER BOU $N_{infl} \geq 10$

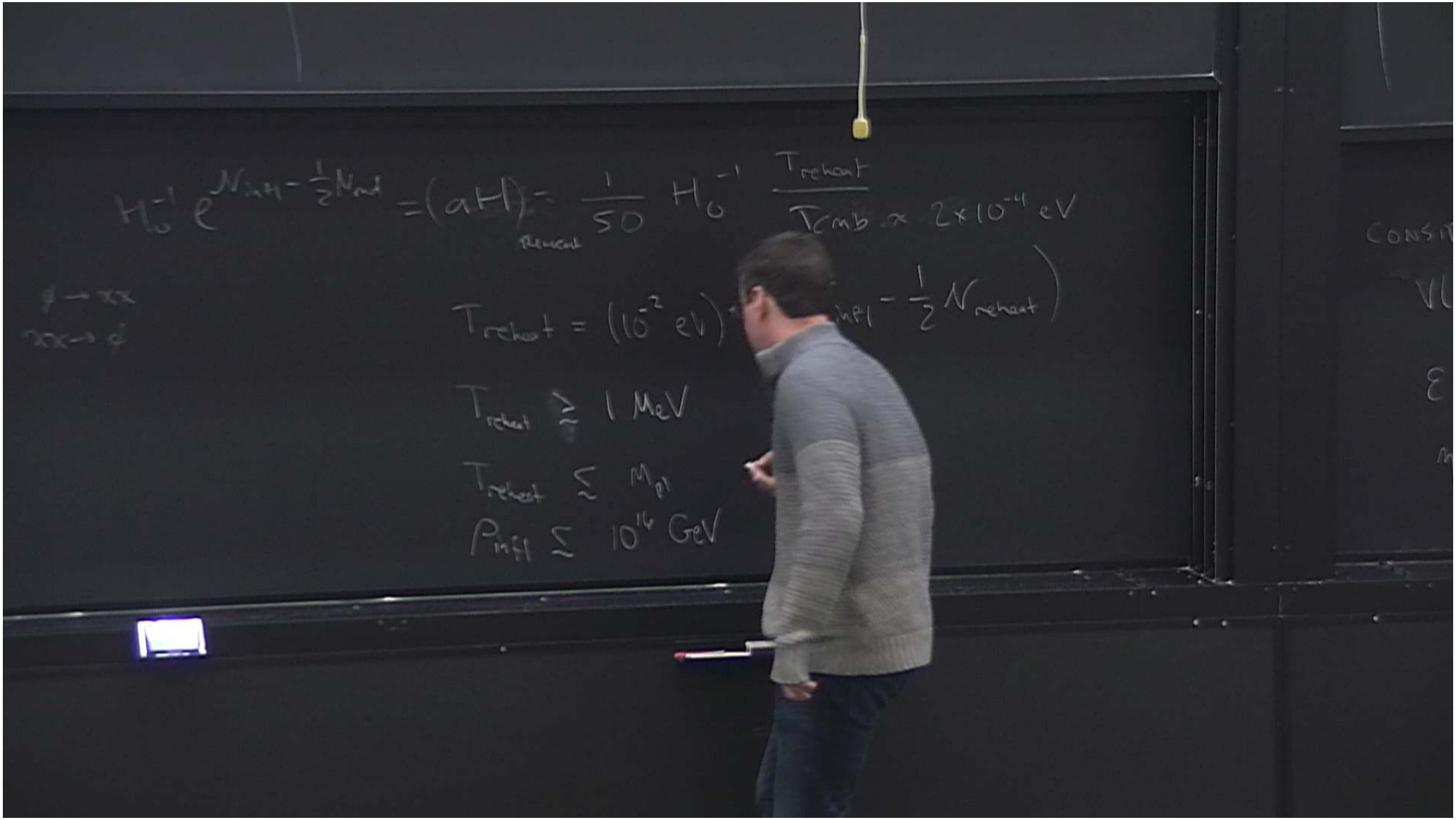

HOW MANY E-FOLDINGS N_{infl} $[= \Delta \log a]$ DID INFLATION LAST?
LOWER BOUND: $N_{infl} \geq 10$
NO OBVIOUS UPPER BOUND


SLOW ROLL INFLATION
MATTER DOMINATION
RADIATION DOMINATION
PLANCK + BICEP2 + KECK
[95%]
≥ 0.978
~2.5σ TENSION W/ PLANCK + BICEP2 + KECK
H ~ m
H ~ Γ


$a_H = \frac{1}{50} H_0^{-1} \frac{T_{reheat}}{T_{cmb}} =$
CONSIDER
$V(\varphi) =$
$\varepsilon =$
$\eta =$


$H_0^{-1} e^{N_{inf} - \frac{1}{2}N_{md}} = (aH)_{reheat} = \frac{1}{50} H_0^{-1} \frac{T_{reheat}}{T_{cmb}}$
$T_{reheat} = (10^{-2}\ eV) \exp($


$H_0^{-1} e^{N_{infl} - \frac{1}{2}N_{rad}} = (aH)_{reheat} = \frac{1}{50} H_0^{-1} \frac{T_{reheat}}{T_{cmb}} \times 2 \times 10^{-4}\ eV$
$T_{reheat} = (10^{-2}\ eV) \exp\left(N_{infl} - \frac{1}{2} N_{reheat}\right)$
$T_{reheat} \gtrsim 1\ MeV$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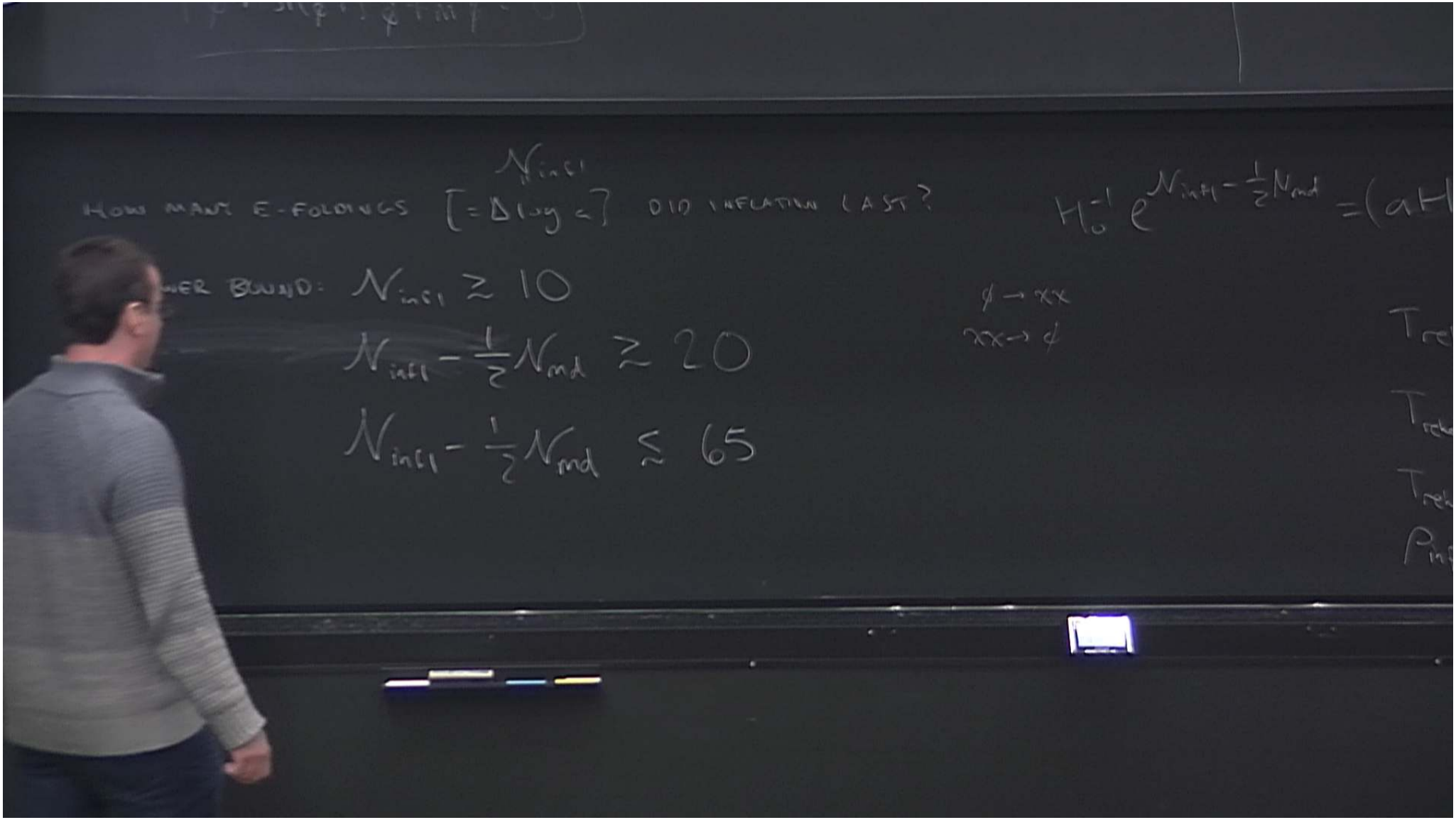
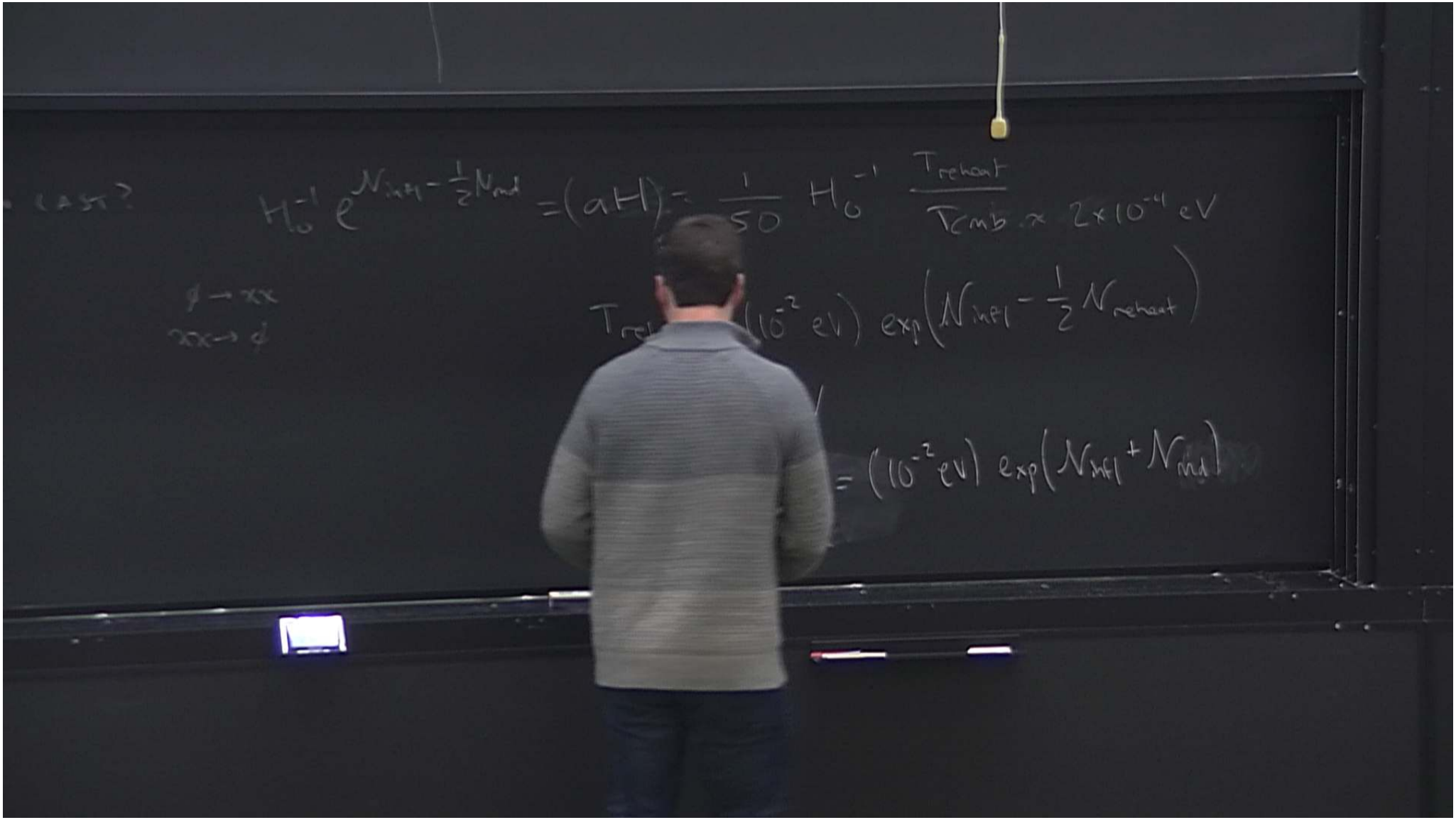
$T_{reheat} = (10^{-2}\ eV)$
$T_{reheat} \gtrsim 1\ MeV$
$T_{reheat} \lesssim M_{pl}$
$\rho_{inf} \lesssim 10^{16}\ GeV$


N_{infl}
HOW MANY E-FOLDINGS $[= \Delta \log a]$ DID INFLATION LAST?
$H_0^{-1} e^{N_{infl} - \frac{1}{2}N_{rad}} = (aH$
ER BOUND: $N_{infl} \gtrsim 10$
$N_{infl} - \frac{1}{2}N_{rad} \gtrsim 20$
$N_{infl} - \frac{1}{2}N_{rad} \lesssim 65$
$\phi \to \chi\chi$
$\chi\chi \to \phi$
T
P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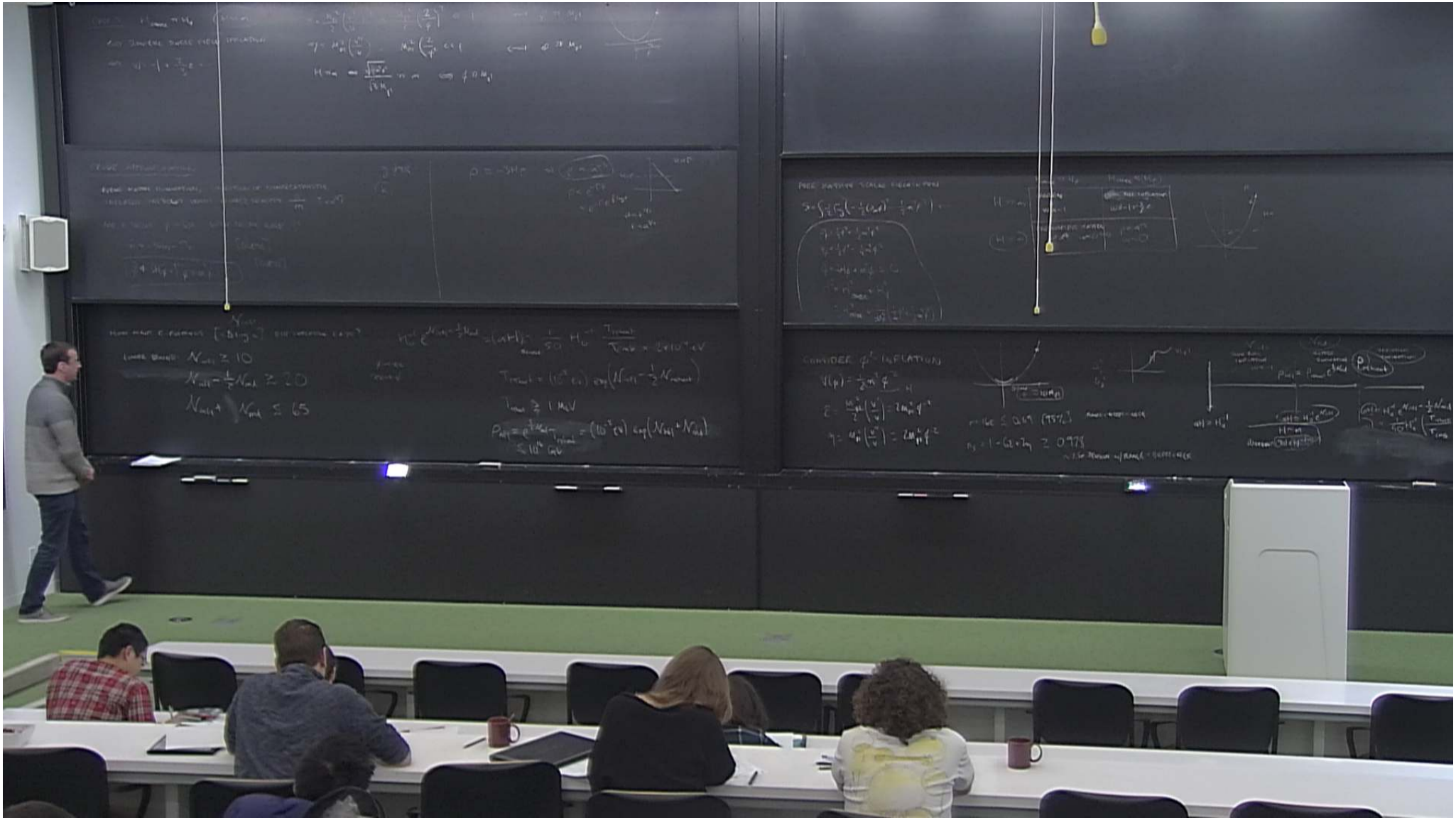
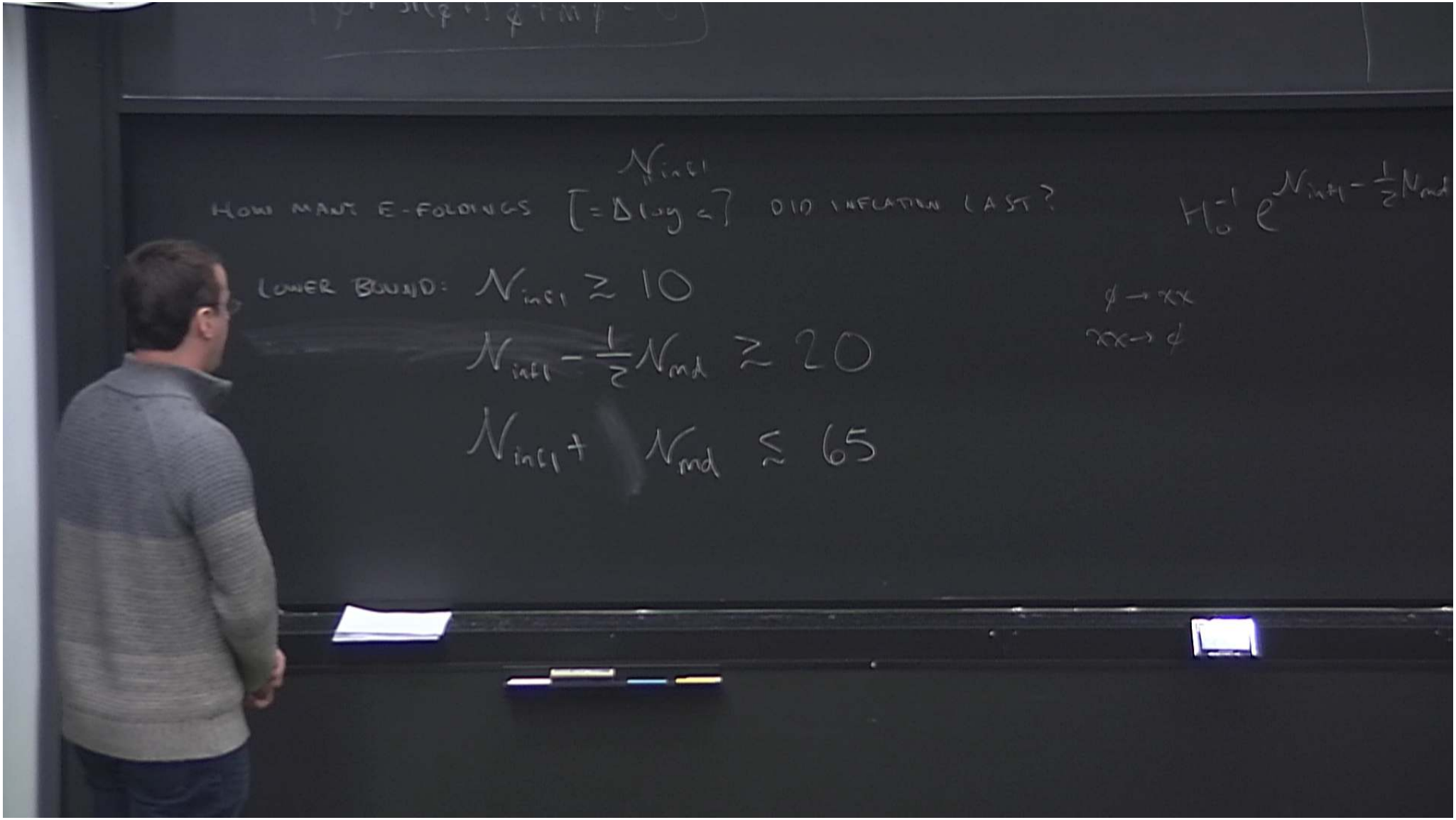
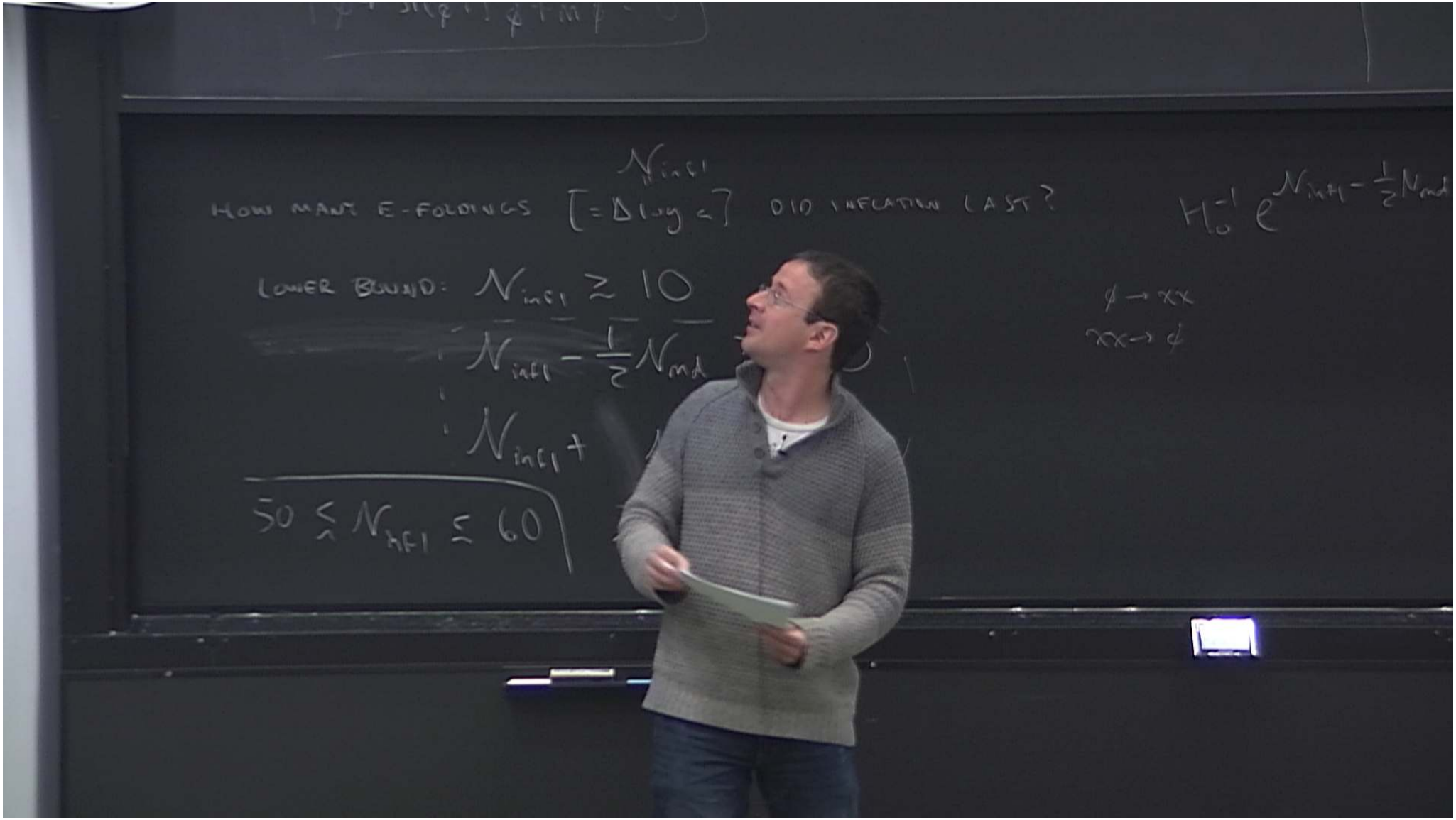
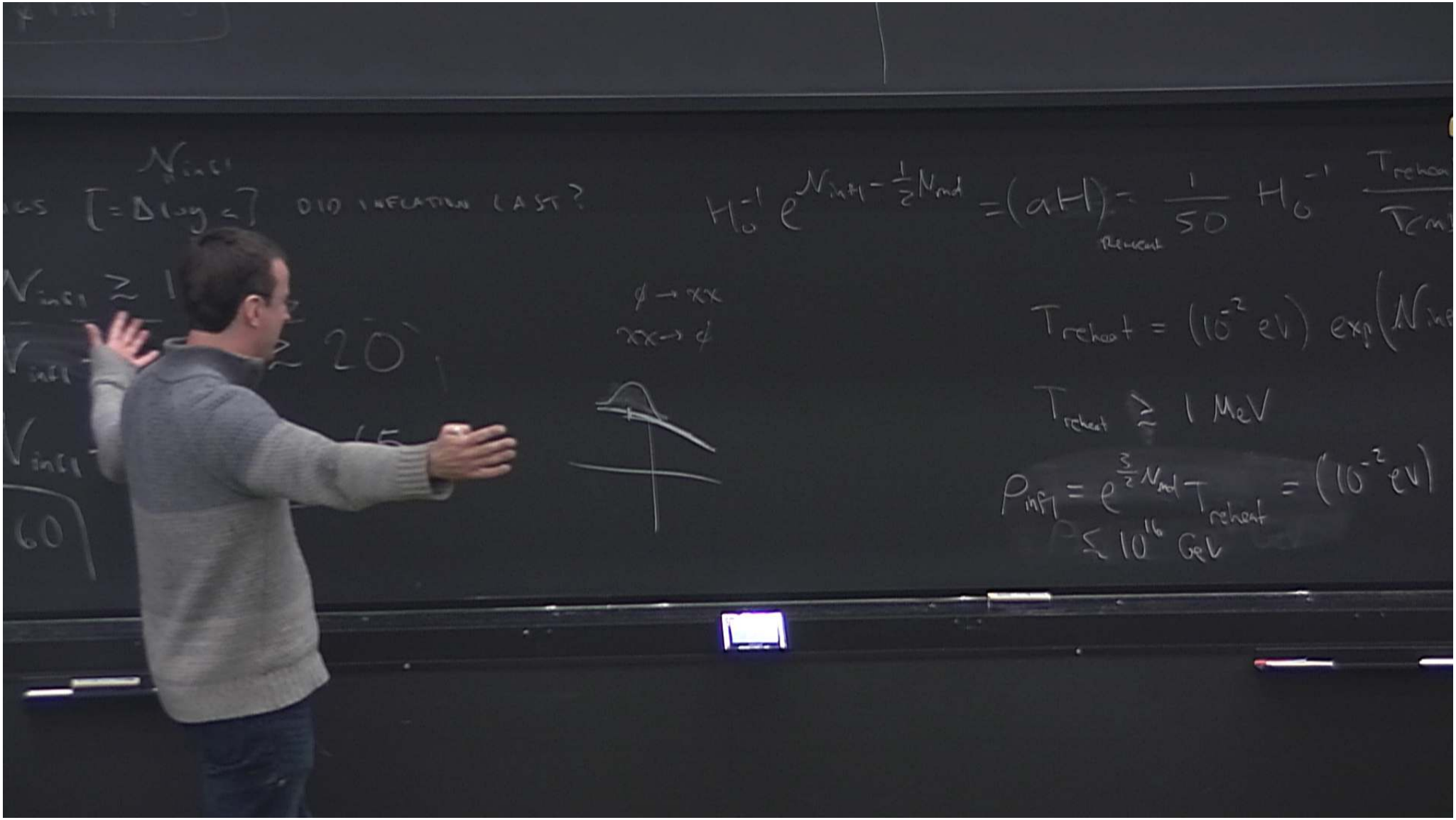
$\phi \to xx$
$xx \to \phi$
$(10^{-2}\,eV)\, exp\left(N_{inf} - \frac{1}{2} N_{reheat}\right)$
$= (10^{-2}\,eV)\, exp\left(N_{inf} + N_{rad}\right)$




HOW MANY E-FOLDINGS N_{infl} [$= \Delta \log a$] DID INFLATION LAST?
$H_0^{-1} e^{N_{infl} - \frac{1}{2}N_{rad}}$
LOWER BOUND: $N_{infl} \gtrsim 10$
$N_{infl} - \frac{1}{2}N_{rad} \gtrsim 20$
$N_{infl} + N_{rad} \lesssim 65$
$\phi \to \chi\chi$
$\chi\chi \to \phi$


HOW MANY E-FOLDINGS [= Δ log a] DID INFLATION LAST?
LOWER BOUND:
50 ≲ N_infl ≲ 60


DID INFLATION LAST?
$\phi \to \chi\chi$
$\chi\chi \to \phi$
$T_{reheat} \gtrsim 1\ MeV$
$\rho_{inf} = e^{\frac{3}{2}N_{end}} T_{reheat} = (10^{-2}\ eV)$
$\lesssim 10^{16}\ GeV$