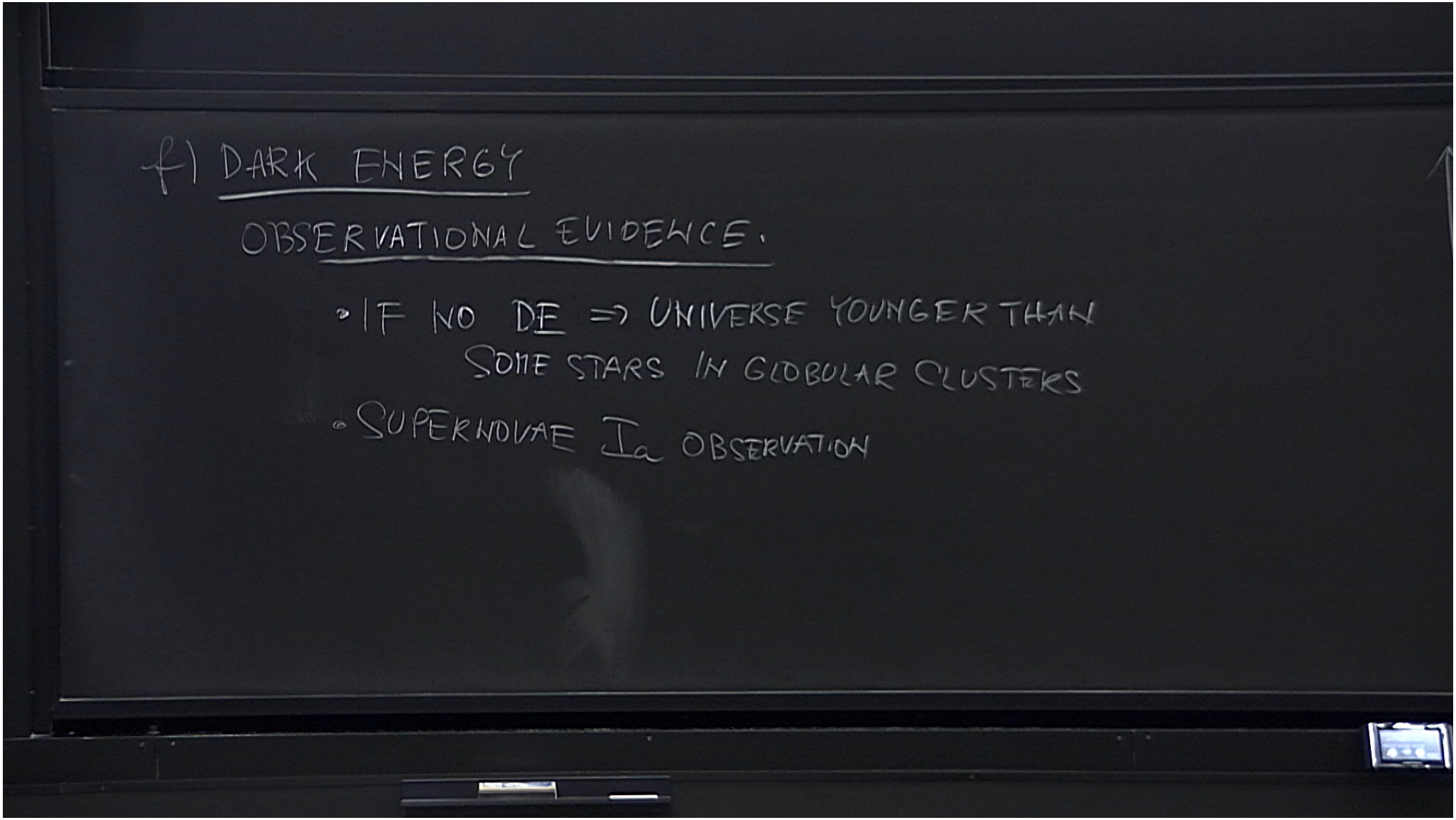
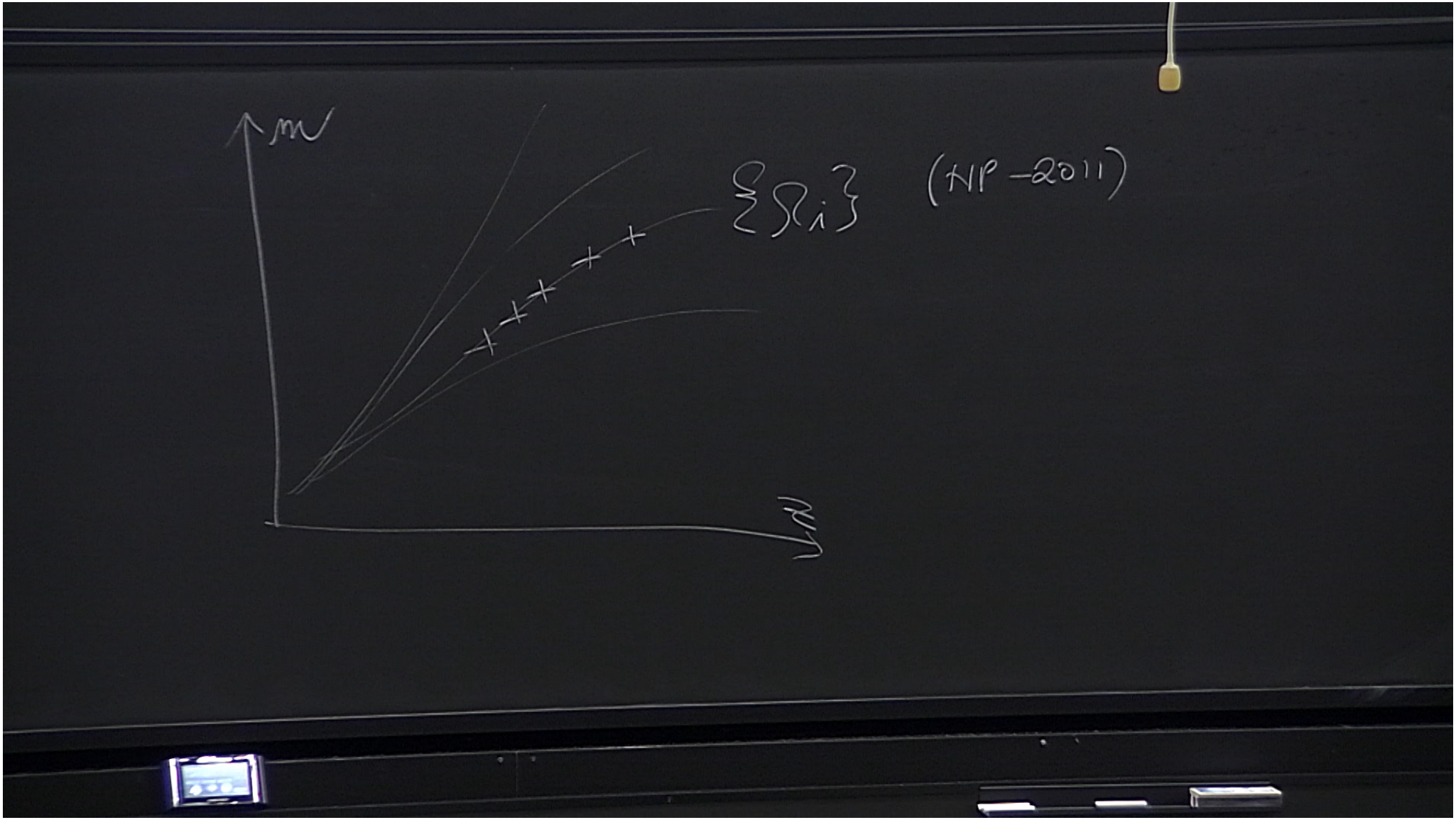
Title: PSI 2016/2017 Cosmology (Review) - Lecture 9

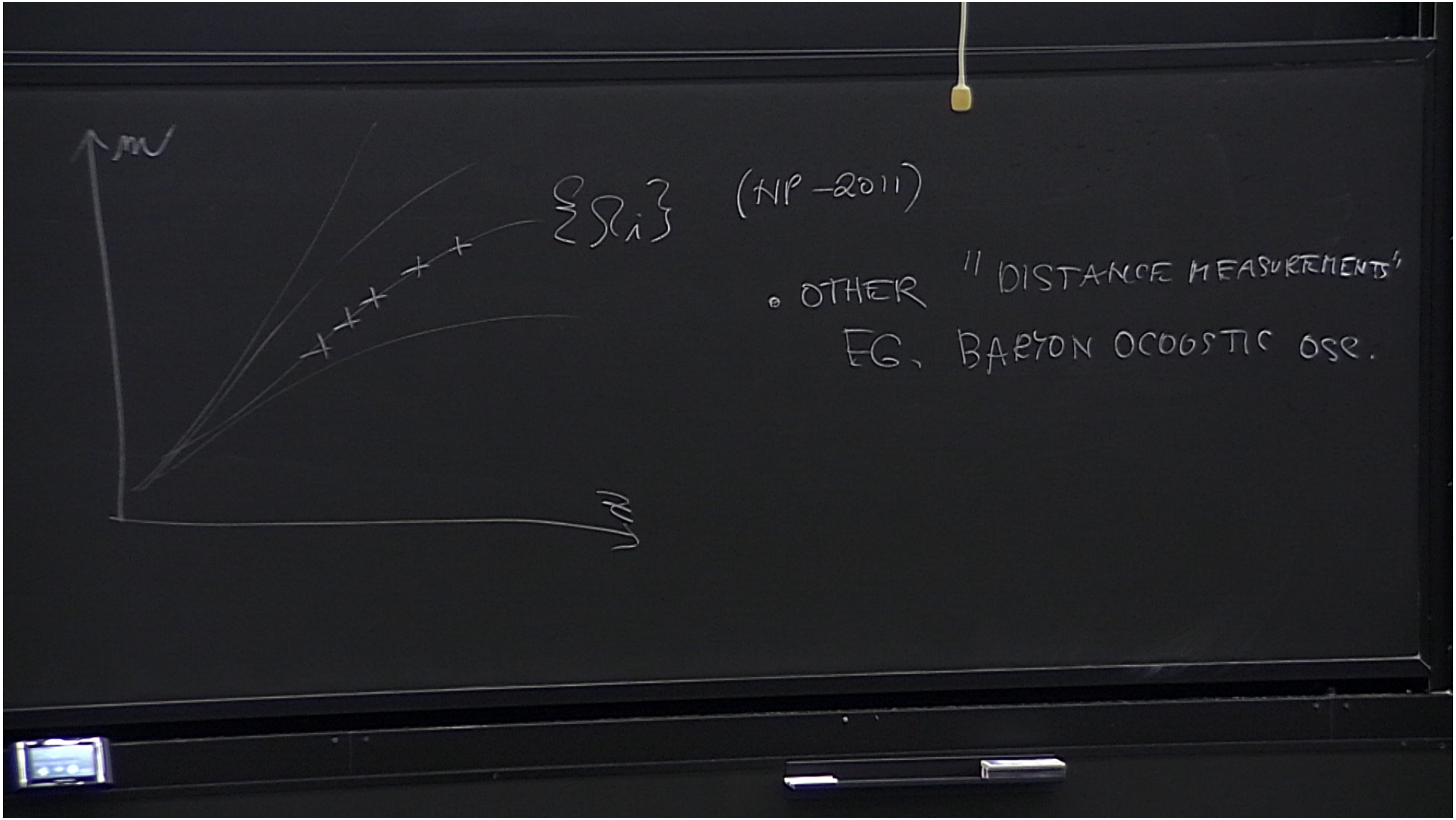
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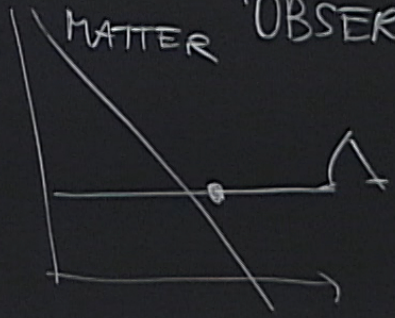
Abstract:


f) DARK ENERGY
OBSERVATIONAL EVIDENCE.
• IF NO DE ⇒ UNIVERSE YOUNGER THAN
SOME STARS IN GLOBULAR CLUSTERS
• SUPERNOVAE Ia OBSERVATION

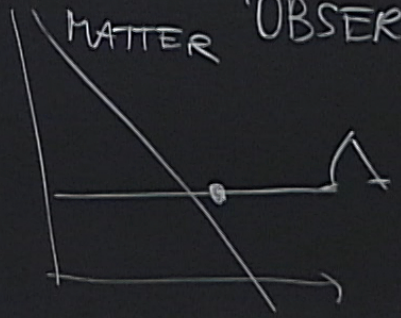

m
{Ωi}
(NP-2011)


mV
{Si} (NP-2011)
• OTHER "DISTANCE MEASUREMENTS"
EG. BARYON OCOUSTIC OSC.

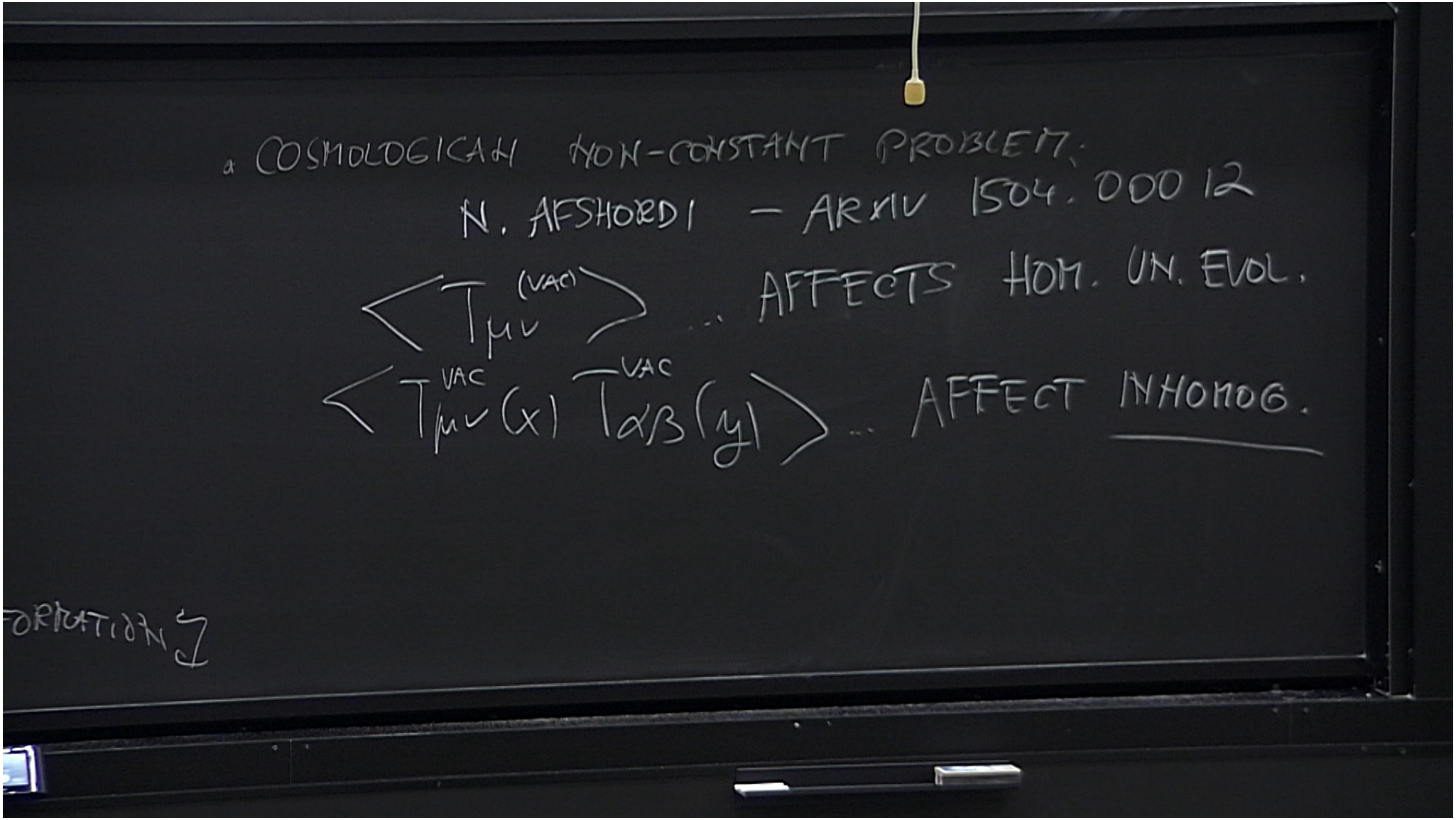
- COSMOLOGICAL CONSTANT PROBLEMS
  - "OLD" $\rho_\Lambda \simeq 10^{-29}\ g/cm^3 \ldots 10^{-120}$
    $\rho_{VACUUM} \simeq O(1)$
    120 MAGNITUDES BIGGER THAN MATTER OBSERVED.
  - "NEW"



- COSMOLOGICAL CONSTANT PROBLEMS
  - "OLD" $\rho_\Lambda \simeq 10^{-29}\ g/cm^3 \ldots 10^{-120}$
    $\rho_{VACUUM} \simeq O(1)$
    120 MAGNITUDES BIGGER THAN OBSERVED,
  - "NEW"



IF VALUE OF Λ DIFFERENT => STRUCTURE FORMATION ↘


a COSMOLOGICAL NON-CONSTANT PROBLEM:
N. AFSHORDI - ARXIV 1504.00012
$\langle T_{\mu\nu}^{(VAC)} \rangle$ .. AFFECTS HOM. UN. EVOL.
$\langle T_{\mu\nu}^{VAC}(x)\, T_{\alpha\beta}^{VAC}(y) \rangle$ .. AFFECT INHOMOG.
FORMATION

a COSMOLOGICAL NON-CONSTANT PROBLEM:

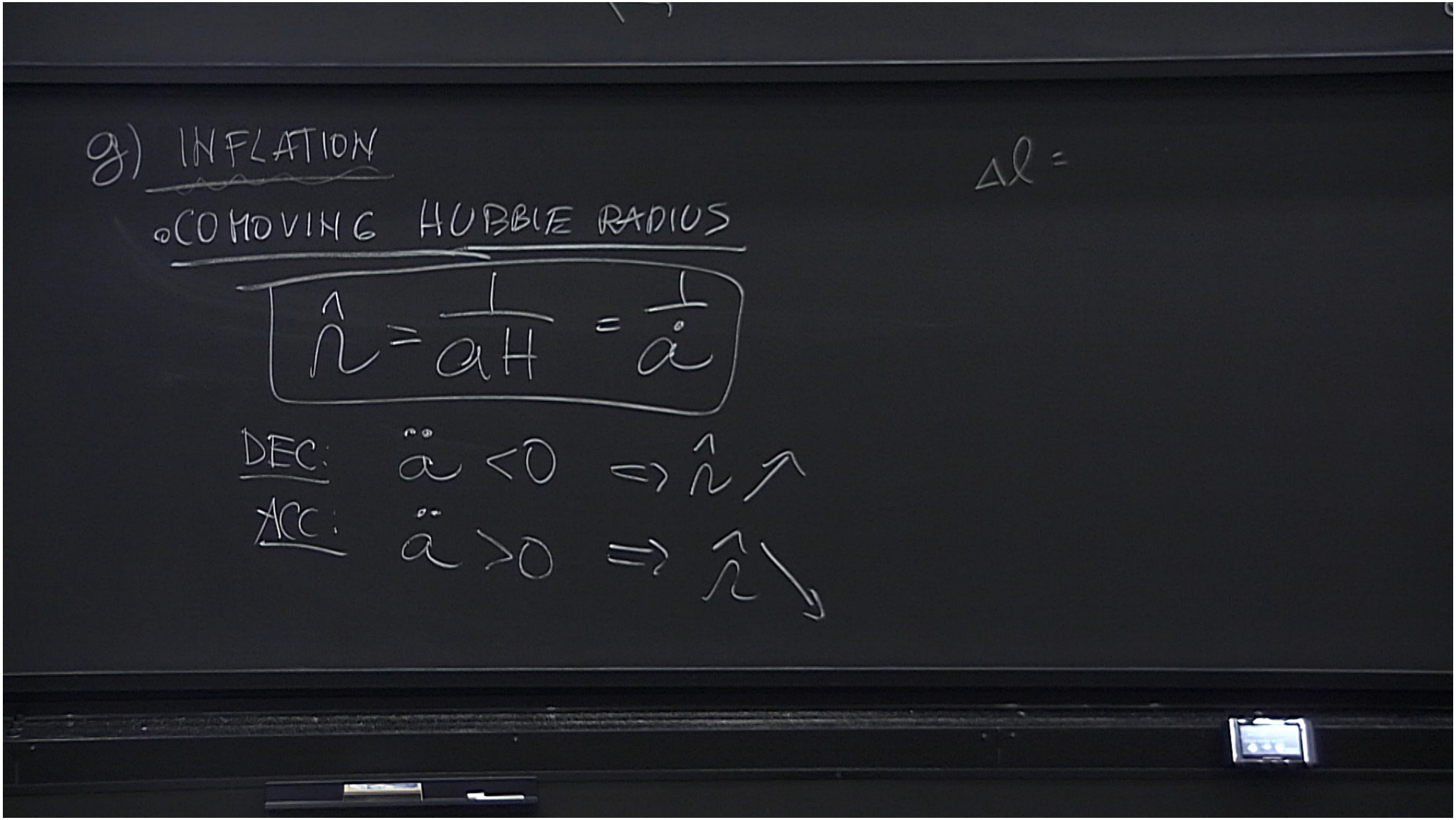
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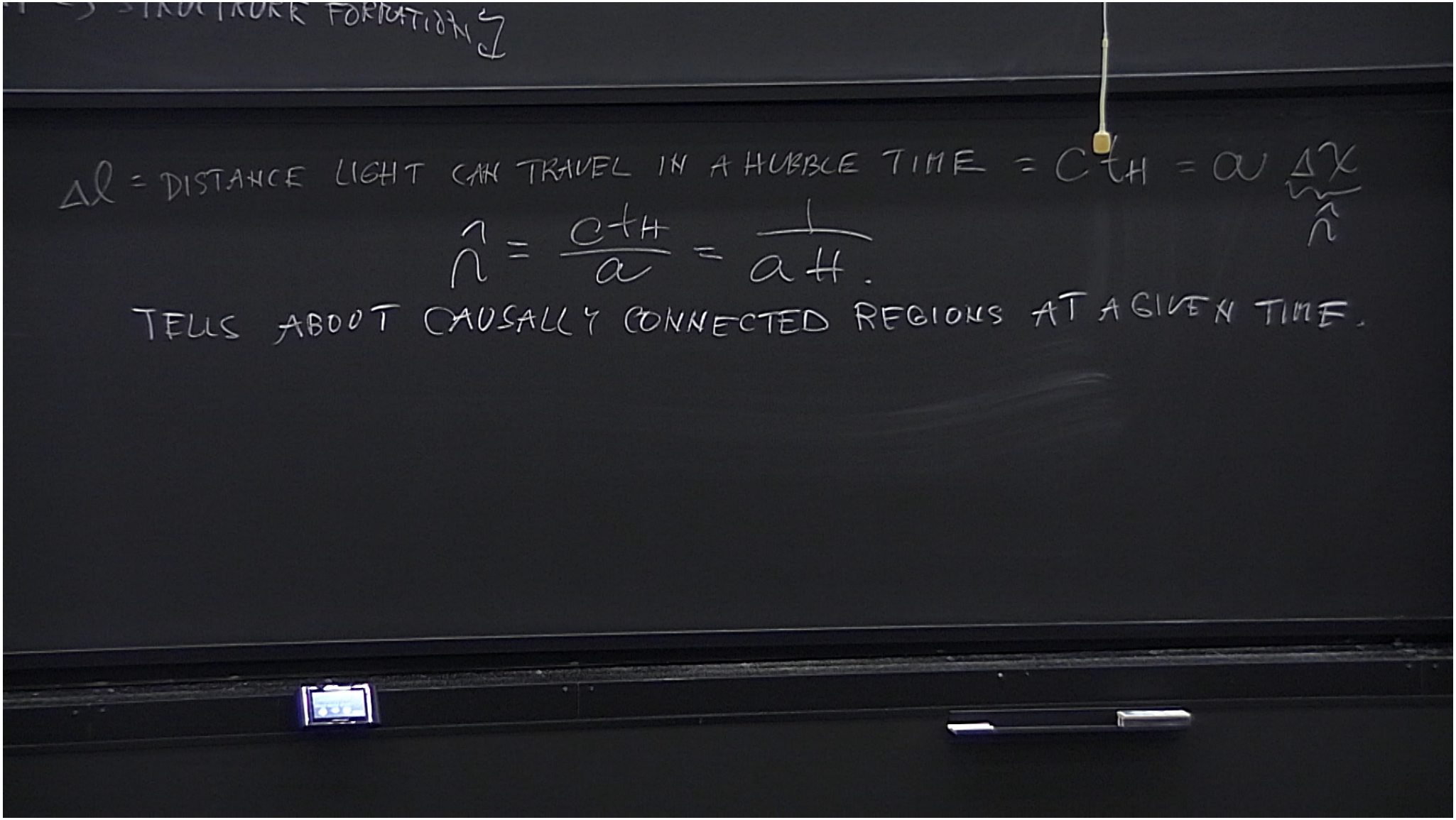
$\langle T_{\mu\nu}^{(VAC)} \rangle$ .. AFFECTS HOM. UN. EVOL.

$\langle T_{\mu\nu}^{VAC}(x)\, T_{\alpha\beta}^{VAC}(y) \rangle$ .. AFFECT INHOMOG.

MORE SEVERE ?

FORMATION ?


g) INFLATION
• COMOVING HUBBLE RADIUS
$\hat{r} = \frac{1}{aH} = \frac{1}{\dot{a}}$
DEC: $\ddot{a} < 0 \Rightarrow \hat{r} \nearrow$
ACC: $\ddot{a} > 0 \Rightarrow \hat{r} \searrow$
$\Delta l =$


STRUCTURE FORMATION
Δl = DISTANCE LIGHT CAN TRAVEL IN A HUBBLE TIME = $c t_H = a \Delta\chi$
$\hat{\eta}$
$\hat{\eta} = \frac{c t_H}{a} = \frac{1}{aH}$.
TELLS ABOUT CAUSALLY CONNECTED REGIONS AT A GIVEN TIME.

$\Rightarrow$ STRUCTURE FORMATION $\downarrow$

Δl = DISTANCE LIGHT CAN TRAVEL IN A HUBBLE TIME $= c t_H = a \Delta\chi$

$\hat{n}$

$$\hat{n} = \frac{c t_H}{a} = \frac{1}{a H}.$$

TELLS ABOUT CAUSALLY CONNECTED REGIONS AT A GIVEN TIME.

CF: $\chi > \chi_{\text{PARTICLE-HORIZON}}$ .... NEVER COULD HAVE COMMUNICATED



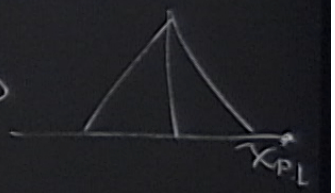
$\Rightarrow$ STRUCTURE FORMATION $\Rightarrow$

Δl = DISTANCE LIGHT CAN TRAVEL IN A HUBBLE TIME $= c t_H = a \Delta\chi$, with $\Delta\chi = \hat{r}$

$$\hat{r} = \frac{c t_H}{a} = \frac{1}{a H}.$$

TELLS ABOUT CAUSALLY CONNECTED REGIONS AT A GIVEN TIME.

CF:
- $\chi > \chi_{PARTICLE-HORIZON}$ .... NEVER COULD HAVE COMMUNICATED
- $\chi > \hat{r}$



$\Rightarrow$ STRUCTURE FORMATION $\Rightarrow$

Δl = DISTANCE LIGHT CAN TRAVEL IN A HUBBLE TIME $= c t_H = a \Delta\chi$

$$\hat{r} = \frac{c t_H}{a} = \frac{1}{a H}.$$

TELLS ABOUT CAUSALLY CONNECTED REGIONS AT A GIVEN TIME.

CF: • $\chi > \chi_{PARTICLE-HORIZON}$ .... NEVER COULD HAVE COMMUNICATED

• $\chi > \hat{r}$ .... CANNOT COMMUNICATE "NOW"



- INFLATION : BEFORE RAD ERA STARTED THERE WAS A PERIOD WHEN UNIVERSE EXPANDED LIKE CRAZY ($\ddot{a} > 0$)

$$\ddot{a} > 0 \iff \frac{d\hat{n}}{dt} < 0$$

- **INFLATION** = BEFORE RAD ERA STARTED THERE WAS A PERIOD WHEN UNIVERSE EXPANDED LIKE CRAZY ($\ddot{a} > 0$)

$$\ddot{a} > 0 \iff \frac{d\hat{r}}{dt} < 0$$

NUMBER OF E-FOLDS N

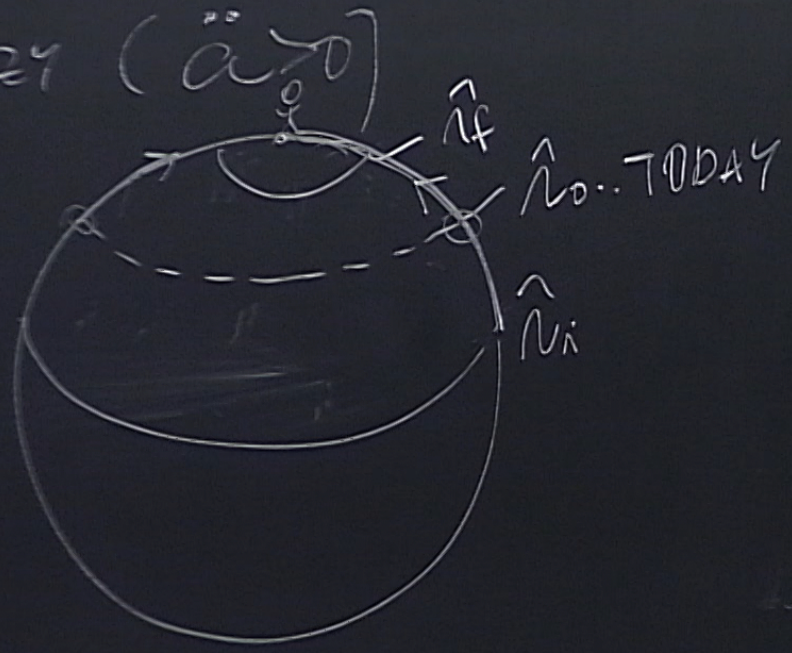
$$e^N = \frac{\hat{\lambda}_i}{\hat{\lambda}_f}$$

$\hat{\lambda}_i$ ← INITIAL

$\hat{\lambda}_f$ ← FINAL

D THERE WAS A PERIOD

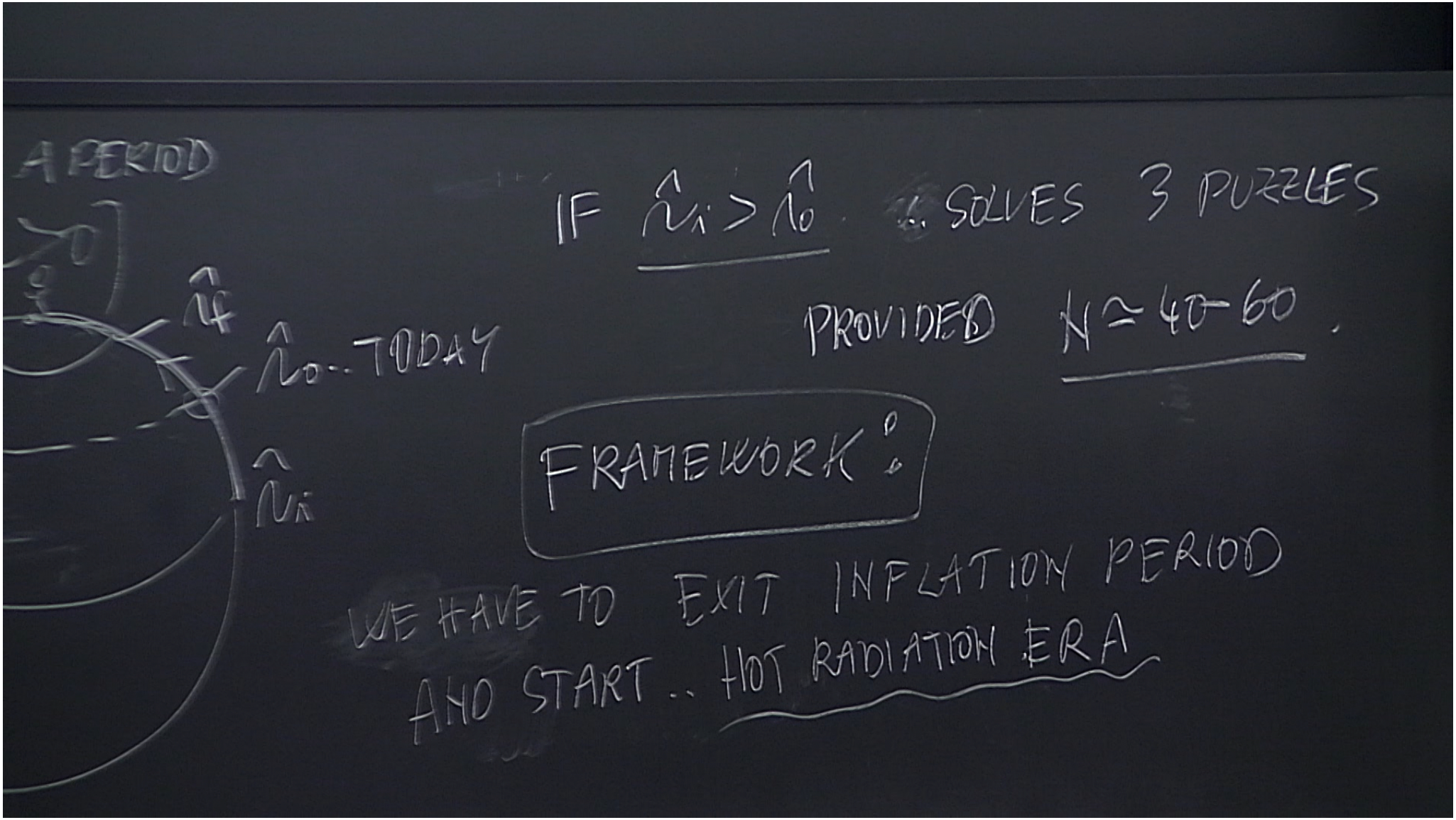
CRAZY ($\ddot{a} > 0$)

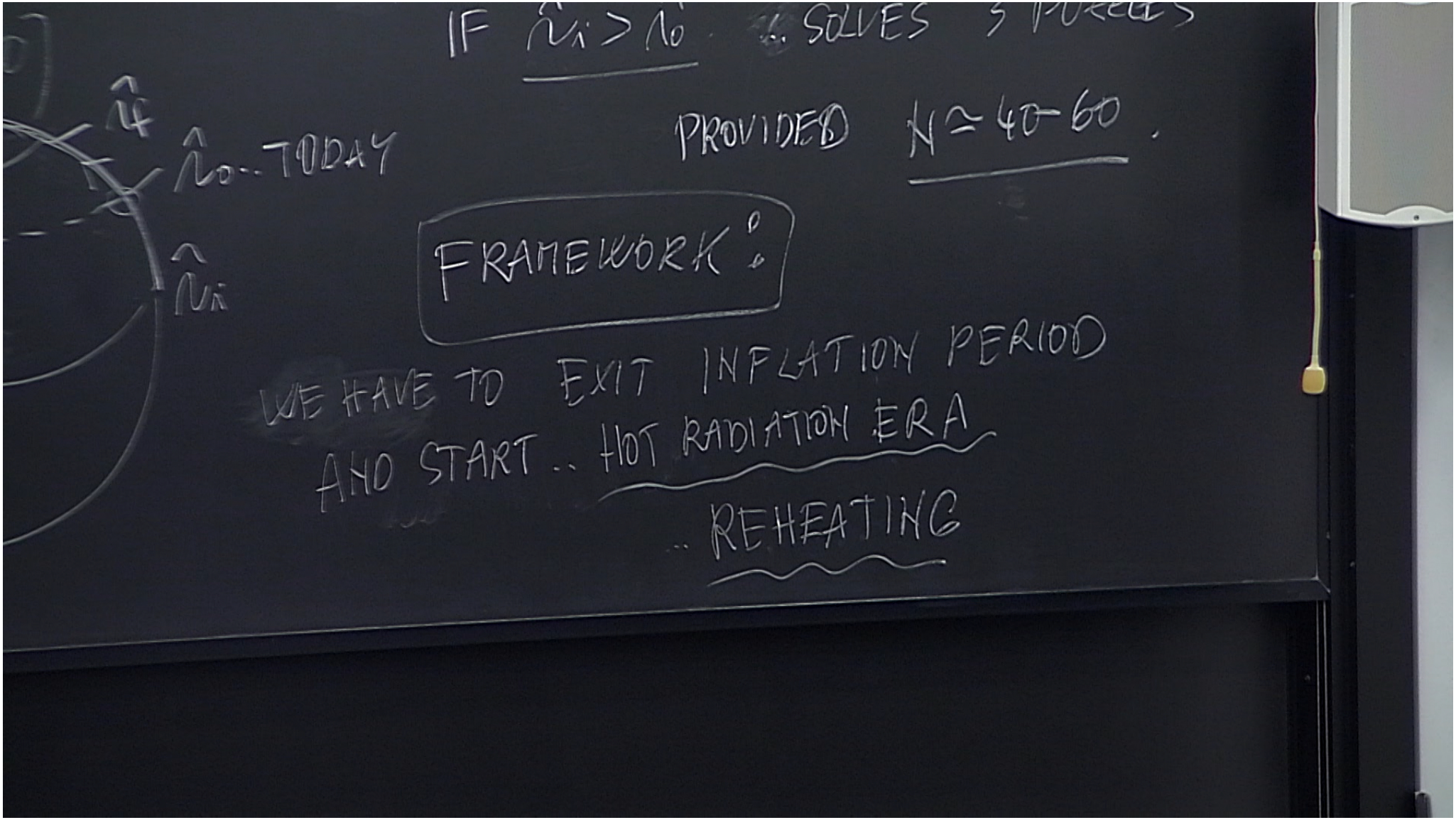


IF $\hat{\Lambda}_i > \hat{\Lambda}_0$ .. SOLVES 3 PUZZLES

PROVIDED $N \simeq 40\text{-}60$.

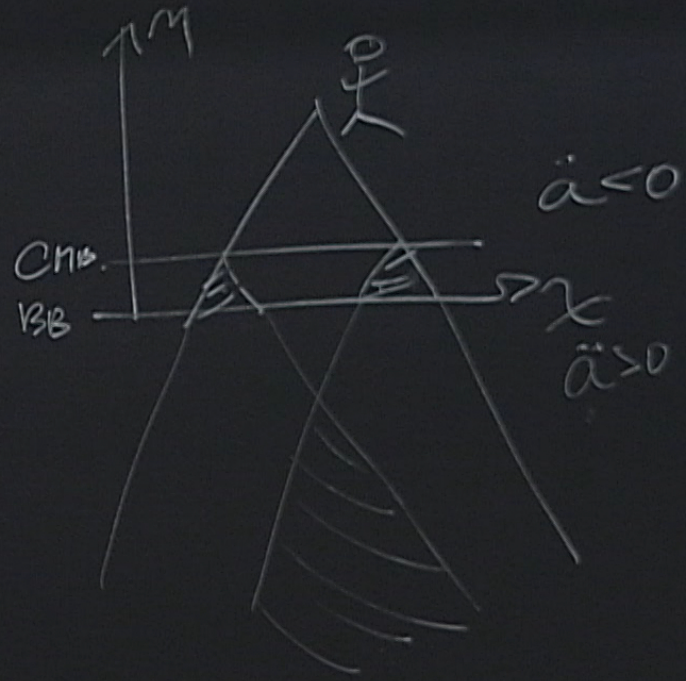
FRAMEWORK?


A PERIOD
IF $\hat{\Lambda}_i > \hat{\Lambda}_0$ .. SOLVES 3 PUZZLES
PROVIDED $N \simeq 40-60$.
$\hat{\Lambda}_f$
$\hat{\Lambda}_0$ .. TODAY
$\hat{\Lambda}_i$
FRAMEWORK :
WE HAVE TO EXIT INFLATION PERIOD
AND START .. HOT RADIATION ERA


IF $\hat{\Omega}_i > \hat{\Omega}_0$ .. SOLVES
PROVIDED $N \simeq 40-60$.
$\hat{\Omega}_0$ .. TODAY
FRAMEWORK :
WE HAVE TO EXIT INFLATION PERIOD
AND START .. HOT RADIATION ERA
.. REHEATING

• 3 PUZZLE :

• HORIZON PROBLEM



• FLATNESS PROBLEM

$\rho = \rho_c$ (1+

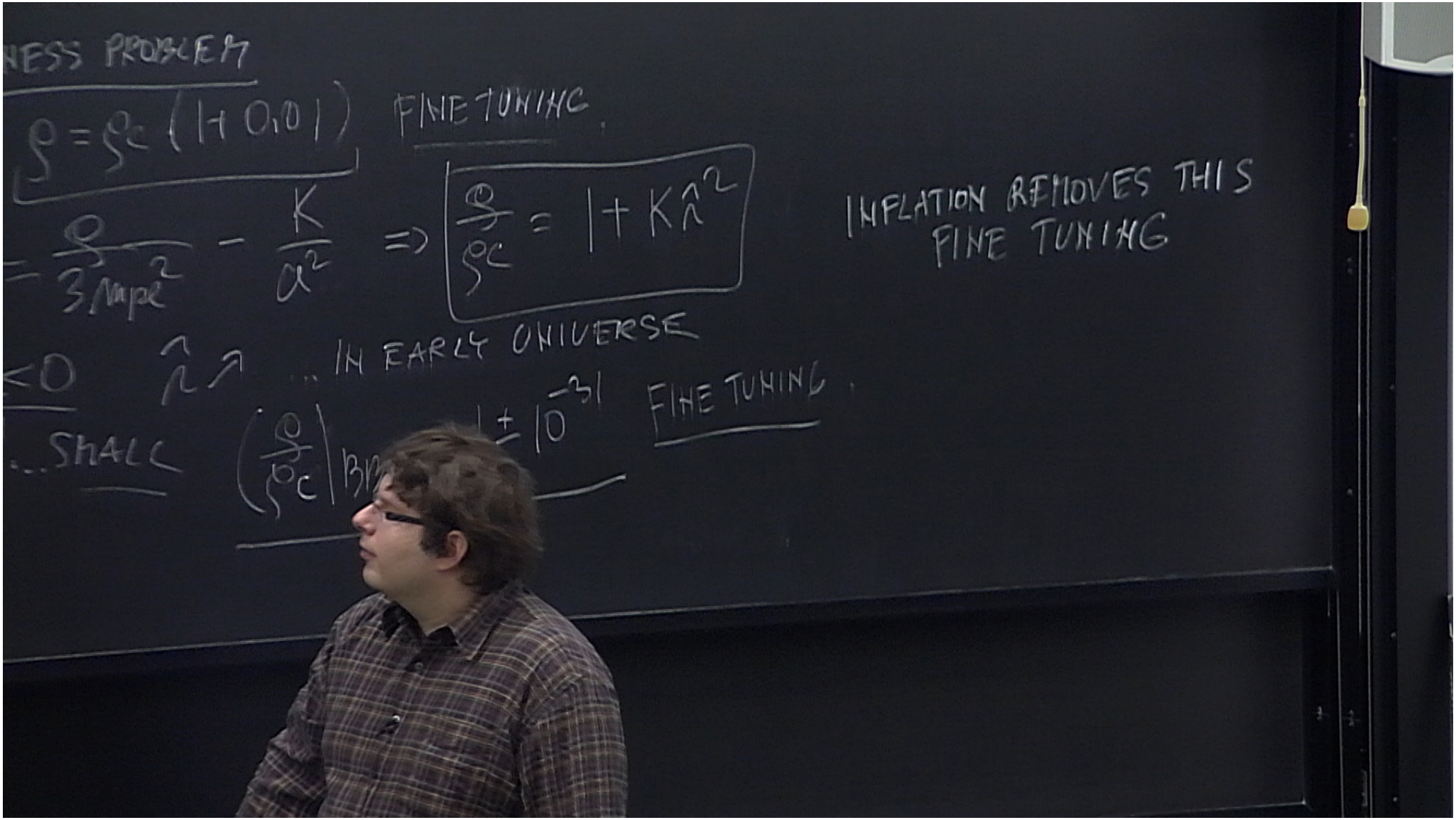
- FLATNESS PROBLEM

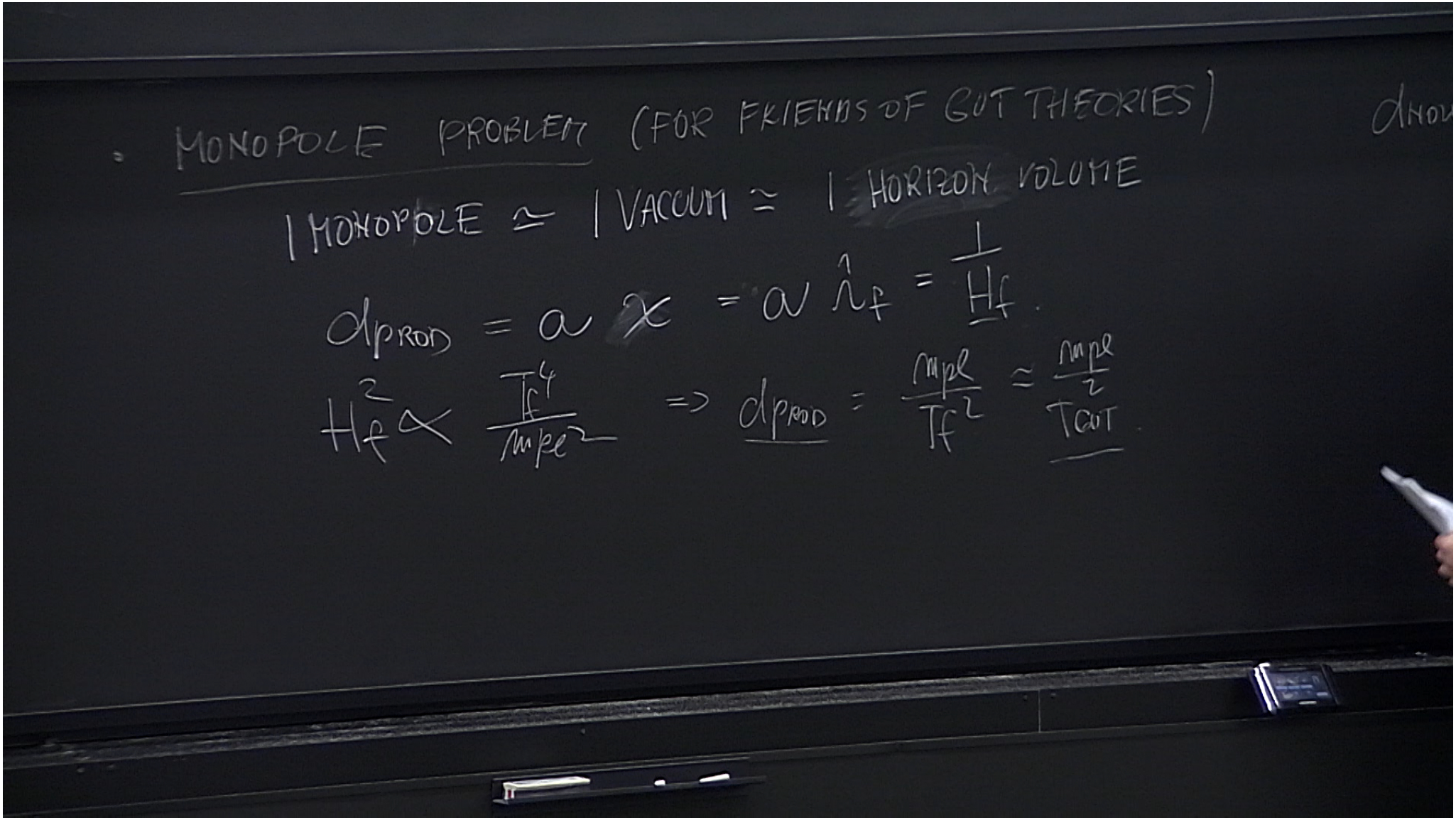
$\rho = \rho_c (1 + 0{,}01)$ FINE TUNING.

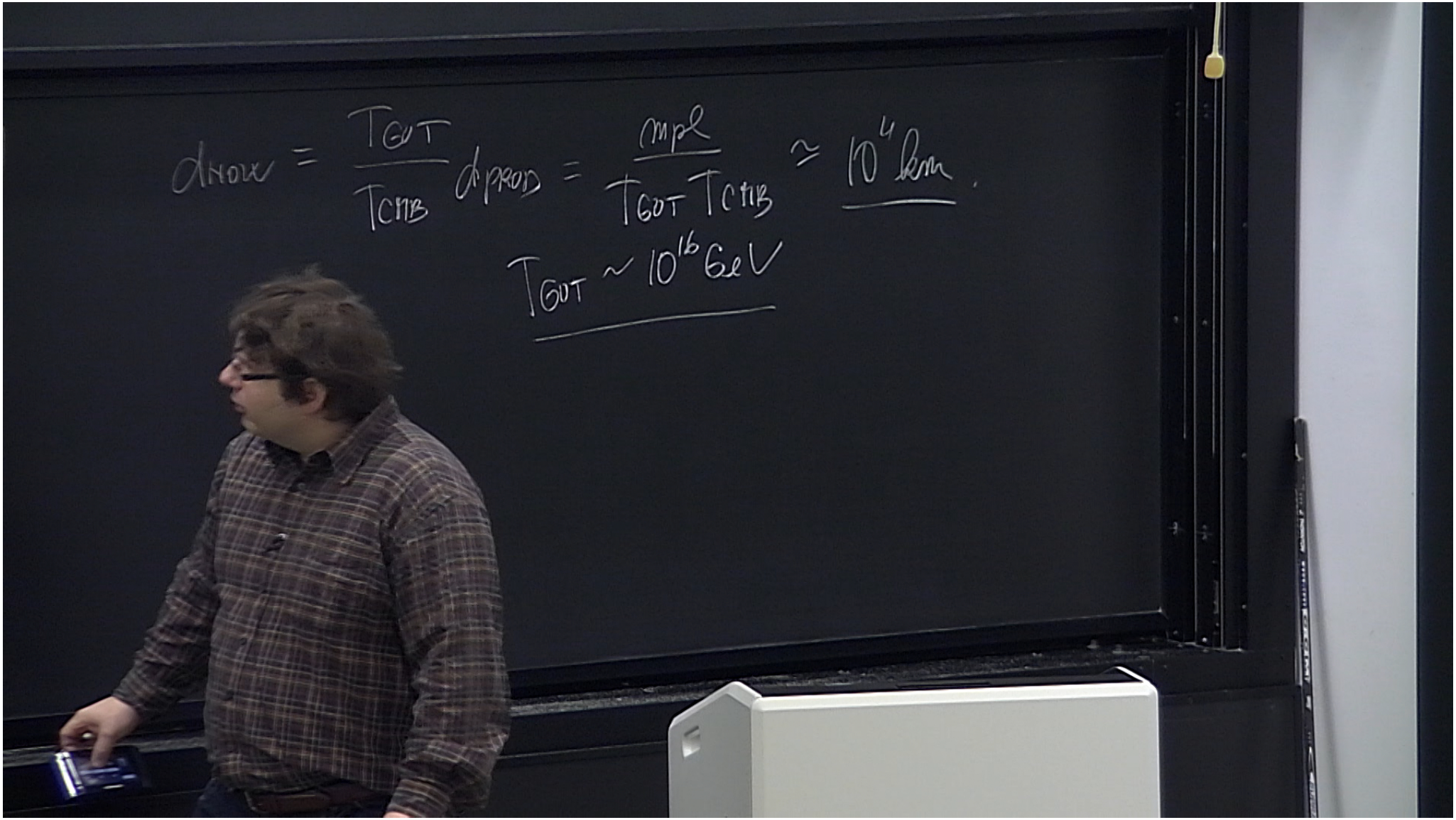
$$H^2 = \frac{\rho}{3 M_{pl}^2} - \frac{K}{a^2} \Rightarrow \boxed{\frac{\rho}{\rho_c} = 1 + K\hat{\lambda}^2}$$

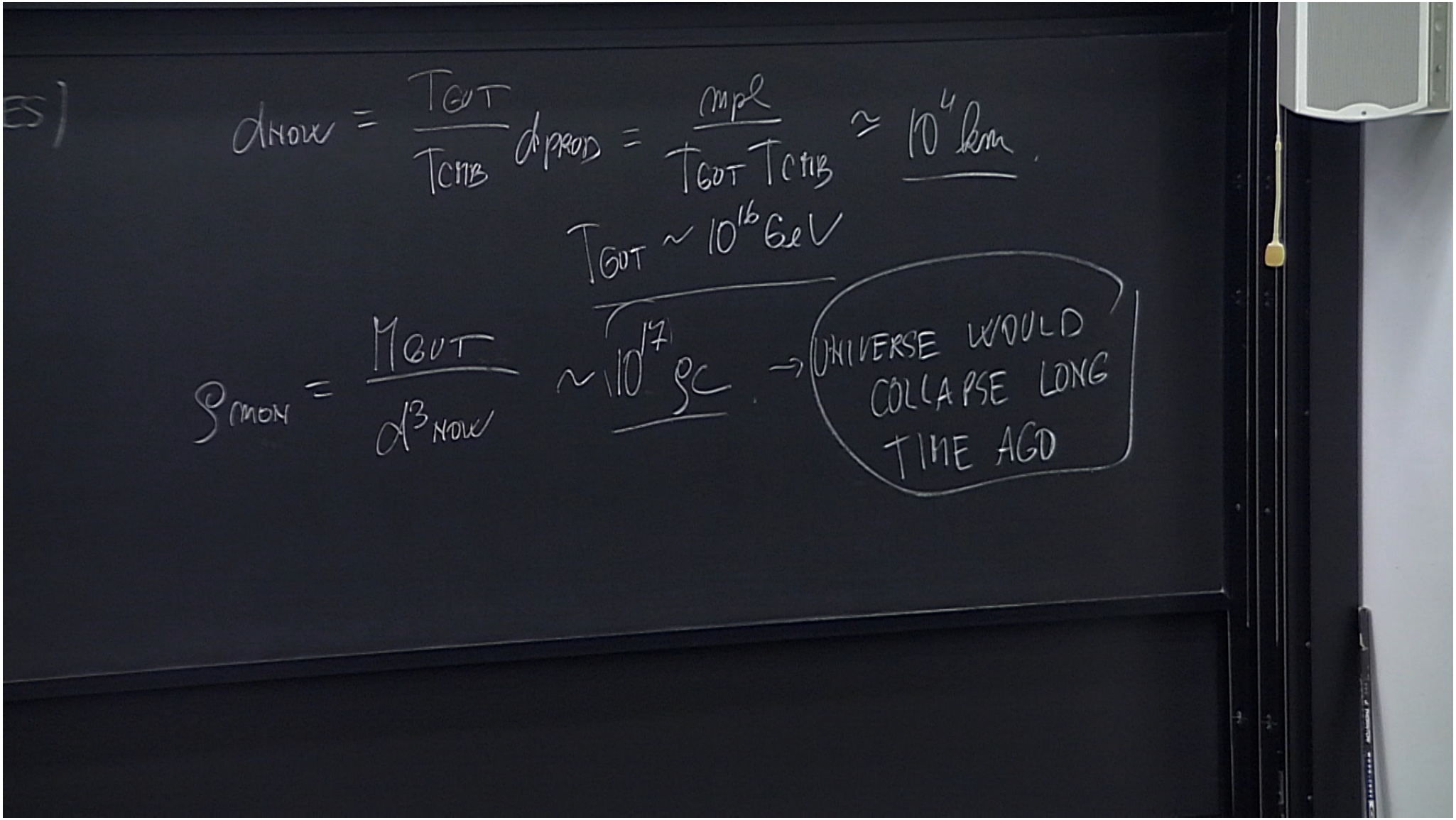
IF $\ddot{a} < 0$ $\hat{\lambda}$ ↗ ... IN EARLY UNIVERSE

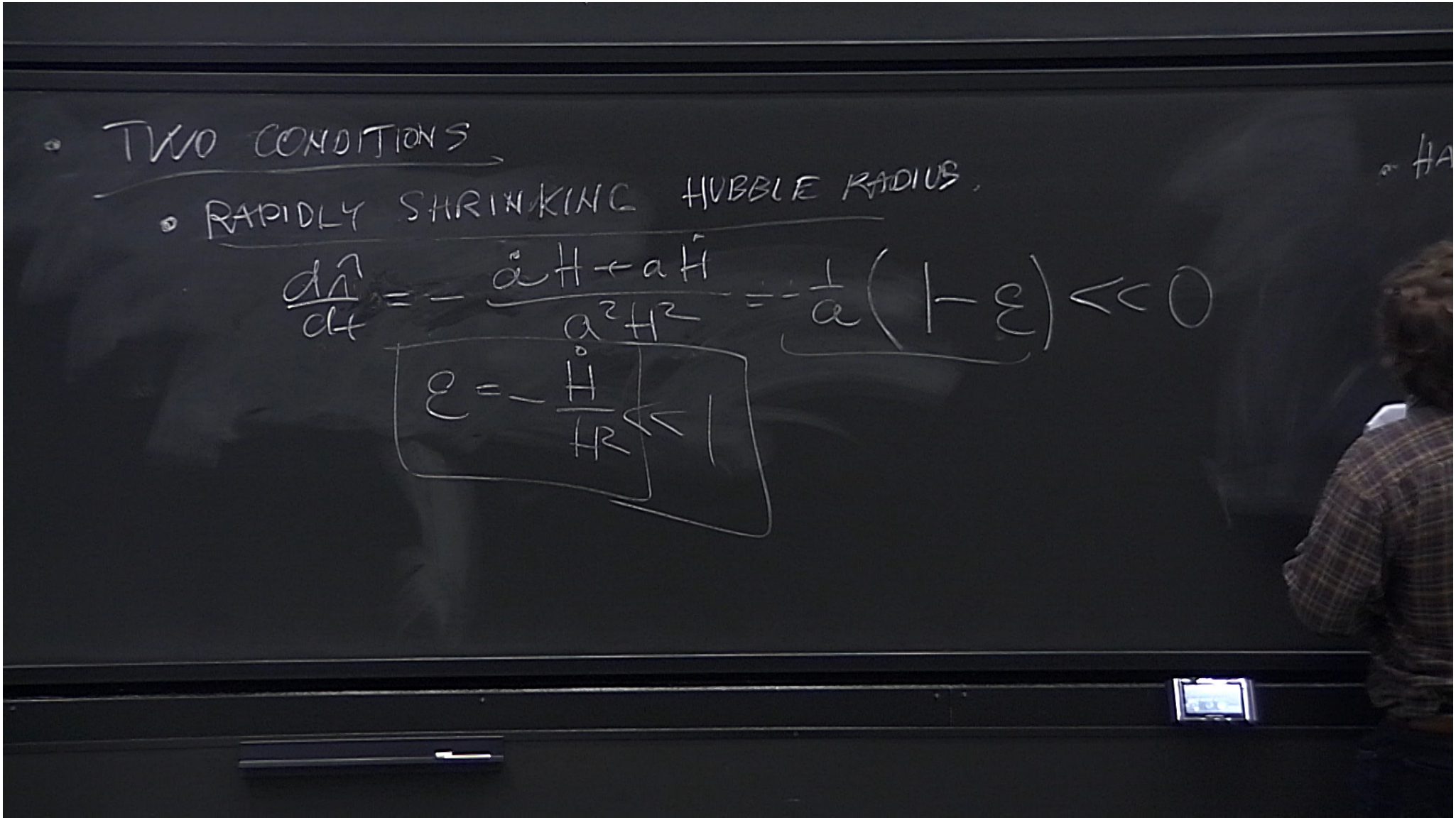
$\hat{\lambda}$ ... SMALL $\left(\frac{\rho}{\rho_c}\right)_{BBN} \simeq 1 \pm 10^{-31}$ FINE TUNING.


NESS PROBLEM
$\rho = \rho_c (1 + 0.01)$ FINE TUNING.
$\frac{\rho}{3 M_{pl}^2} - \frac{K}{a^2} \Rightarrow \boxed{\frac{\rho}{\rho_c} = 1 + K\hat{\Lambda}^2}$
INFLATION REMOVES THIS FINE TUNING
< 0 $\hat{\Lambda} \nearrow$ ... IN EARLY UNIVERSE
... SMALL $\left(\frac{\rho}{\rho_c}\right)$ $\pm 10^{-31}$ FINE TUNING.


MONOPOLE PROBLEM (FOR FRIENDS OF GUT THEORIES)
| MONOPOLE ≃ | VACCUM ≃ | HORIZON VOLUME
$d_{PROD} = a\,\chi = a\,\hat{\lambda}_f = \frac{1}{H_f}$
$H_f^2 \propto \frac{T_f^4}{m_{pl}^2} \Rightarrow d_{PROD} = \frac{m_{pl}}{T_f^2} \simeq \frac{m_{pl}}{T_{CUT}^2}$


$d_{NOW} = \frac{T_{GUT}}{T_{CMB}} d_{PROD} = \frac{m_{pl}}{T_{GUT} T_{CMB}} \simeq 10^4\,km.$
$T_{GUT} \sim 10^{16}\,GeV$


$d_{NOW} = \frac{T_{GUT}}{T_{CMB}} d_{PROD} = \frac{m_{pl}}{T_{GUT} T_{CMB}} \simeq 10^4\,km$
$T_{GUT} \sim 10^{16}\,GeV$
$\rho_{MON} = \frac{M_{GUT}}{d^3_{NOW}} \sim 10^{17}\,g/c$
UNIVERSE WOULD COLLAPSE LONG TIME AGO


• TWO CONDITIONS
• RAPIDLY SHRINKING HUBBLE RADIUS.
$\frac{d\tilde{\lambda}}{dt} = -\frac{\dot{a}H + a\dot{H}}{a^2H^2} = -\frac{1}{a}(1-\varepsilon) < 0$
$\varepsilon = -\frac{\dot{H}}{HR} < 1$

$\langle T^{VAC}_{\mu\nu}(x)\, T^{VAC}_{\rho\sigma}(y) \rangle$ AFFECT INHOMOG

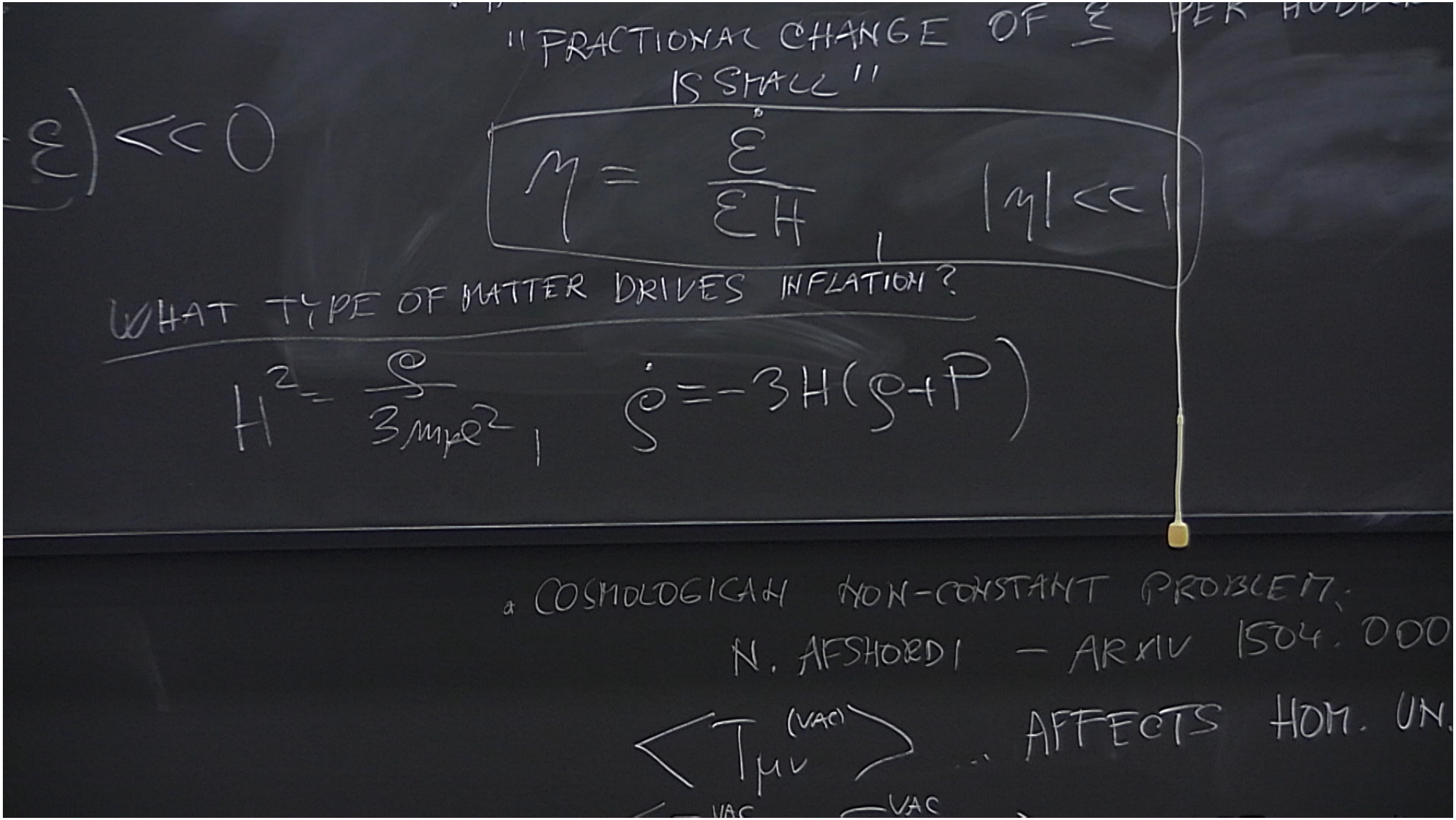
- HAS TO LAST SUFFICIENTLY LONG $\simeq$ "FRACTIONAL CHANGE OF $\dot{\varepsilon}$ PER HUBBLE TIME IS SMALL"

$$\eta = \frac{\dot{\varepsilon}}{\varepsilon H}, \quad |\eta| \ll 1$$

... NEVER COULD HAVE COMMUNICATED

... CANNOT COMMUNICATE [illegible]



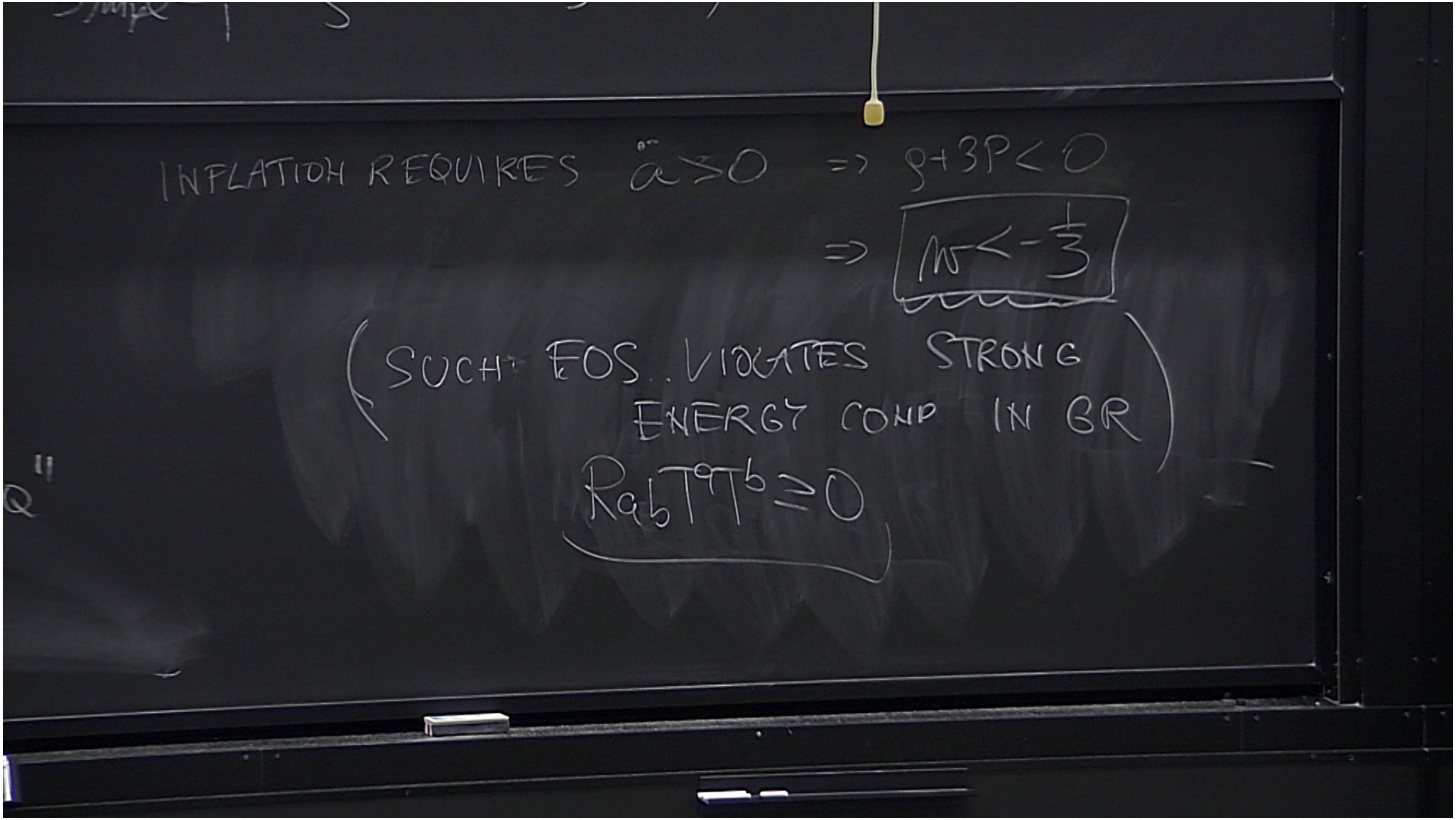

"FRACTIONAL CHANGE OF $\dot{\varepsilon}$ IS SMALL"
$\dot{\varepsilon}) \ll 0$
$\eta = \frac{\dot{\varepsilon}}{\varepsilon H}, \quad |\eta| \ll 1$
WHAT TYPE OF MATTER DRIVES INFLATION?
$H^2 = \frac{\rho}{3M_{pl}^2}, \quad \dot{\rho} = -3H(\rho + P)$
a COSMOLOGICAL NON-CONSTANT PROBLEM:
N. AFSHORDI - ARXIV 1504.000
$\langle T_{\mu\nu}^{(VAC)} \rangle$ .. AFFECTS HOM. UN.

$$2H\dot{H} = 2H\left(\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2}\right) = 2H\left(\frac{\ddot{a}}{a} - \frac{\rho}{3M_{pl}^2}\right)$$

$$= \frac{\dot{\rho}}{3M_{pl}^2} = \frac{-3H(\rho+P)}{3M_{pl}^2}$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{1}{6M_{pl}^2}(\rho+3P)}$$

"ACCELERATION EQ"


INFLATION REQUIRES $\ddot{a} > 0$ $\Rightarrow$ $\rho + 3P < 0$
$\Rightarrow$ $w < -\frac{1}{3}$
(SUCH EOS VIOLATES STRONG ENERGY COND IN GR
$R_{ab} T^{a} T^{b} \geq 0$)