Title: PSI 2015/2016 Cosmology - Lecture 7

Date: Feb 09, 2016 11:30 AM

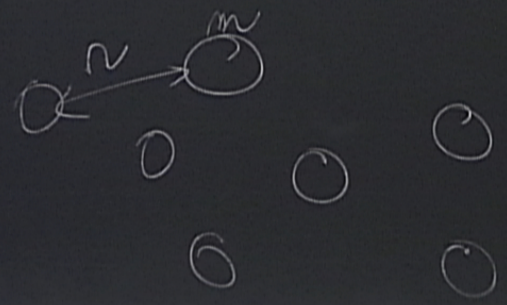
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Abstract:

2) DARK MATTER "BED TIME STORY"

- WHY DO MOST COSMOLOGISTS BELIEVE THERE IS DM?

- 1930's FRITZ ZWICKY ... CLUSTERS OF GALAXIES



= STATISTICALLY STEADY, S.S. SELF GRAVITATING SYSTEM OF N OBJECTS ($M_0 = m$

$\propto$ AVERAGE ORBITAL VEL $\langle v \rangle^2$

$E = \frac{1}{2} N m \sigma^2$, $U = -\frac{1}{2} N(N-1) \frac{G_N m^2}{r}$

VIRIAL THEOREM: $E = -\frac{U}{2}$

ES

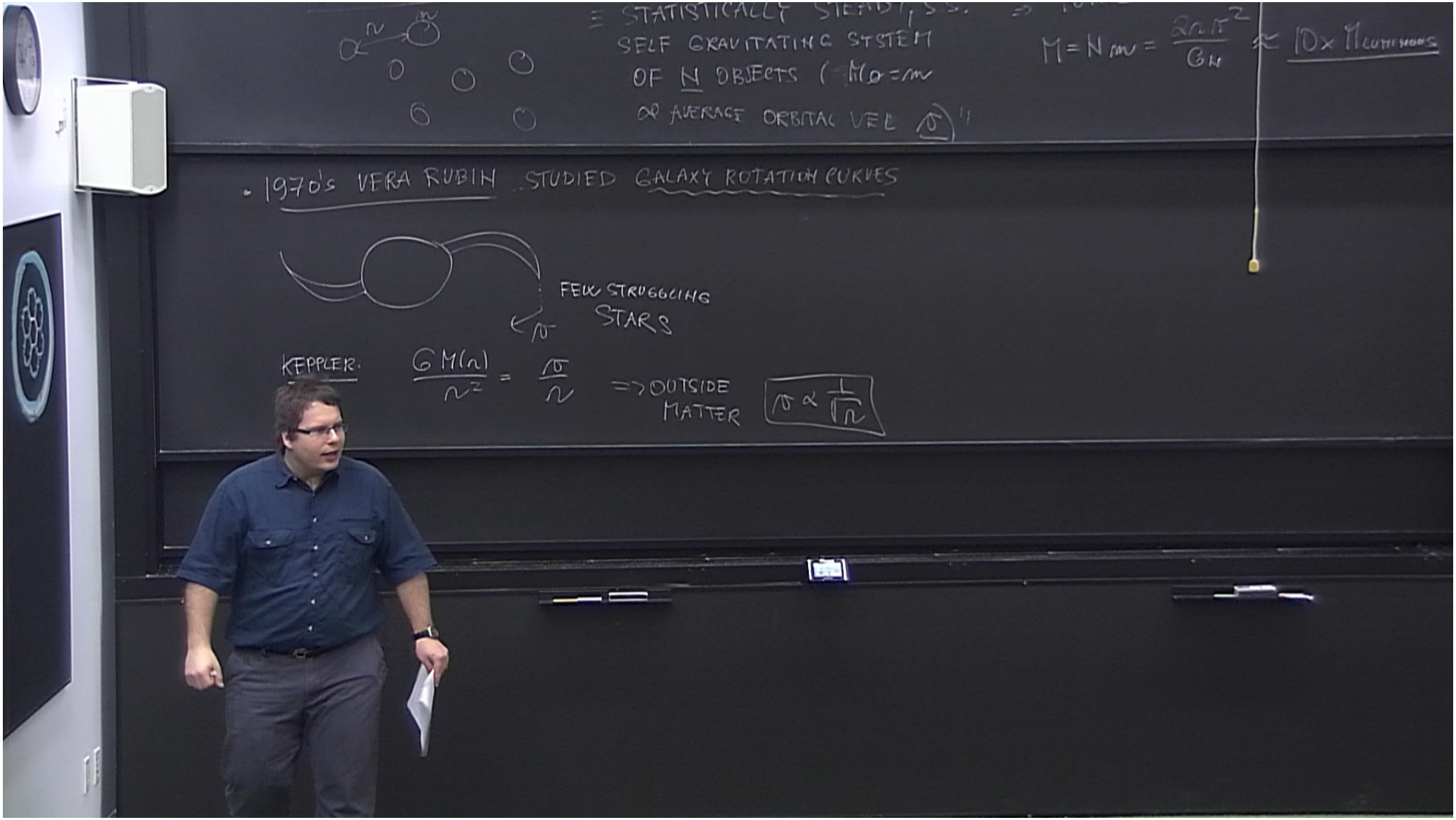
ADY, S.S. $\Rightarrow$ TOTAL DYNAMICAL MASS

TSTEM

$D = m$

$M = N m = \frac{2 r \sigma^2}{G_N} \approx 10 \times$ LUMINOUS

EL (D) 11


= STATISTICALLY STEADY, S.S.
SELF GRAVITATING SYSTEM
OF N OBJECTS (M_O = m
& AVERAGE ORBITAL VEL v
M = N m = 2r v^2 / G
≈ 10x MILKY WAYS
• 1970's VERA RUBIN STUDIED GALAXY ROTATION CURVES
FEW STRUGGLING STARS
KEPPLER: GM(r)/r^2 = v^2/r
=> OUTSIDE MATTER
v ∝ 1/√r

DM ?

30's FRITZ ZWICKY ... CLUSTERS OF GALAXIES

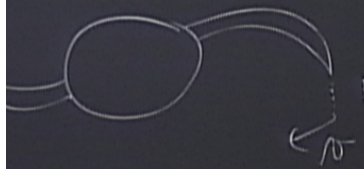
= STATISTICALLY STEADY, S.S.
SELF GRAVITATING SYSTEM
OF N OBJECTS ($M_O = m$
∝ AVERAGE ORBITAL VEL σ)

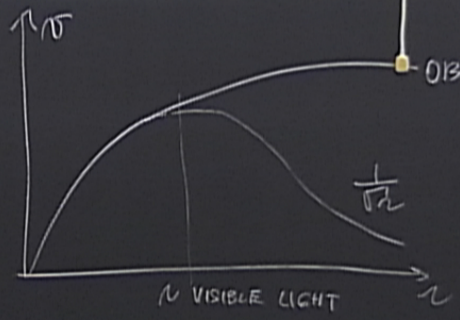
VIRIAL THEOREM: $E = -\frac{U}{2}$

⇒ TOTAL DYNAMICAL MASS

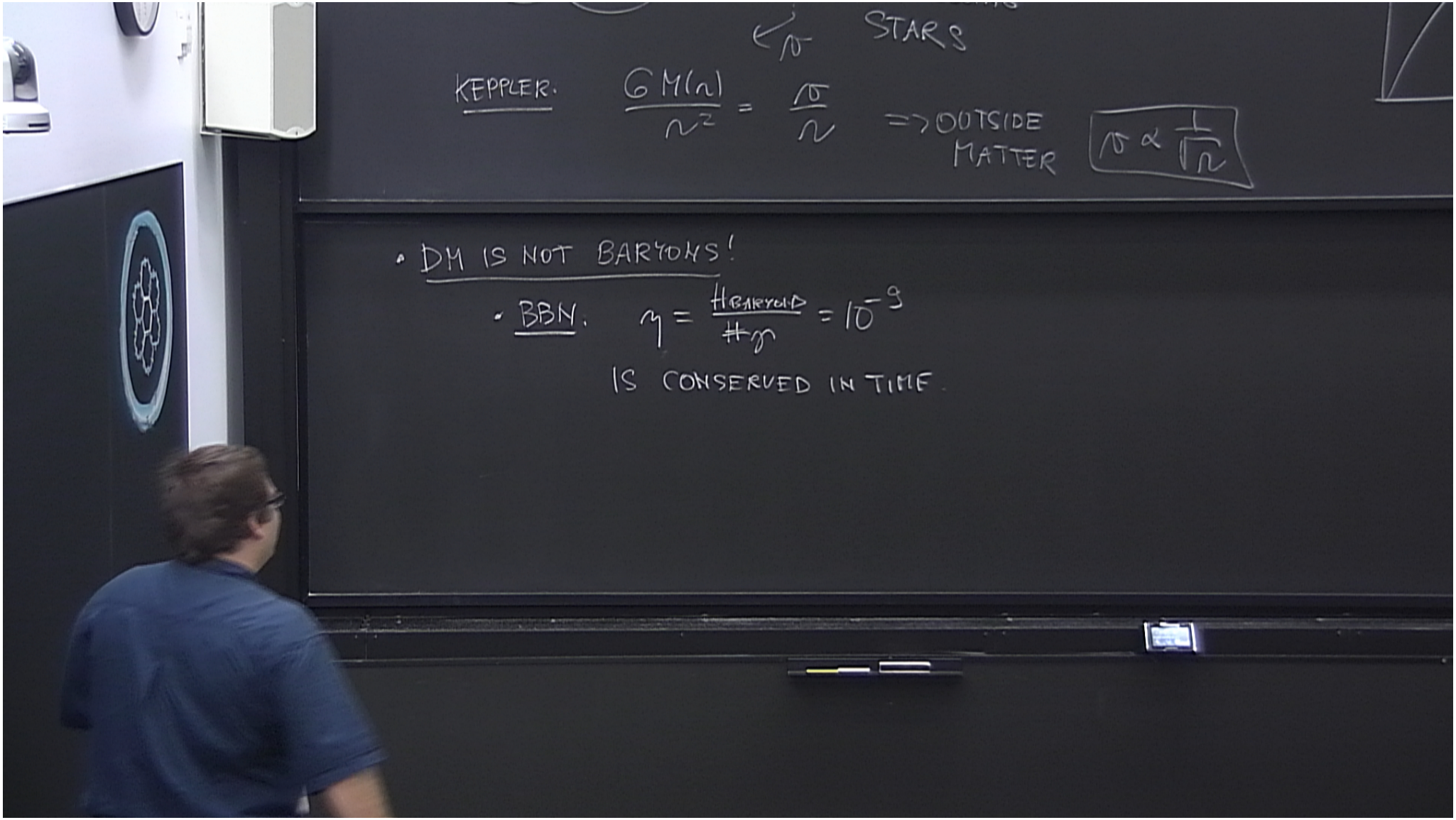
$M = N m = \frac{2 r \sigma^2}{G}$ ≈ 10 × (LUMINOUS)

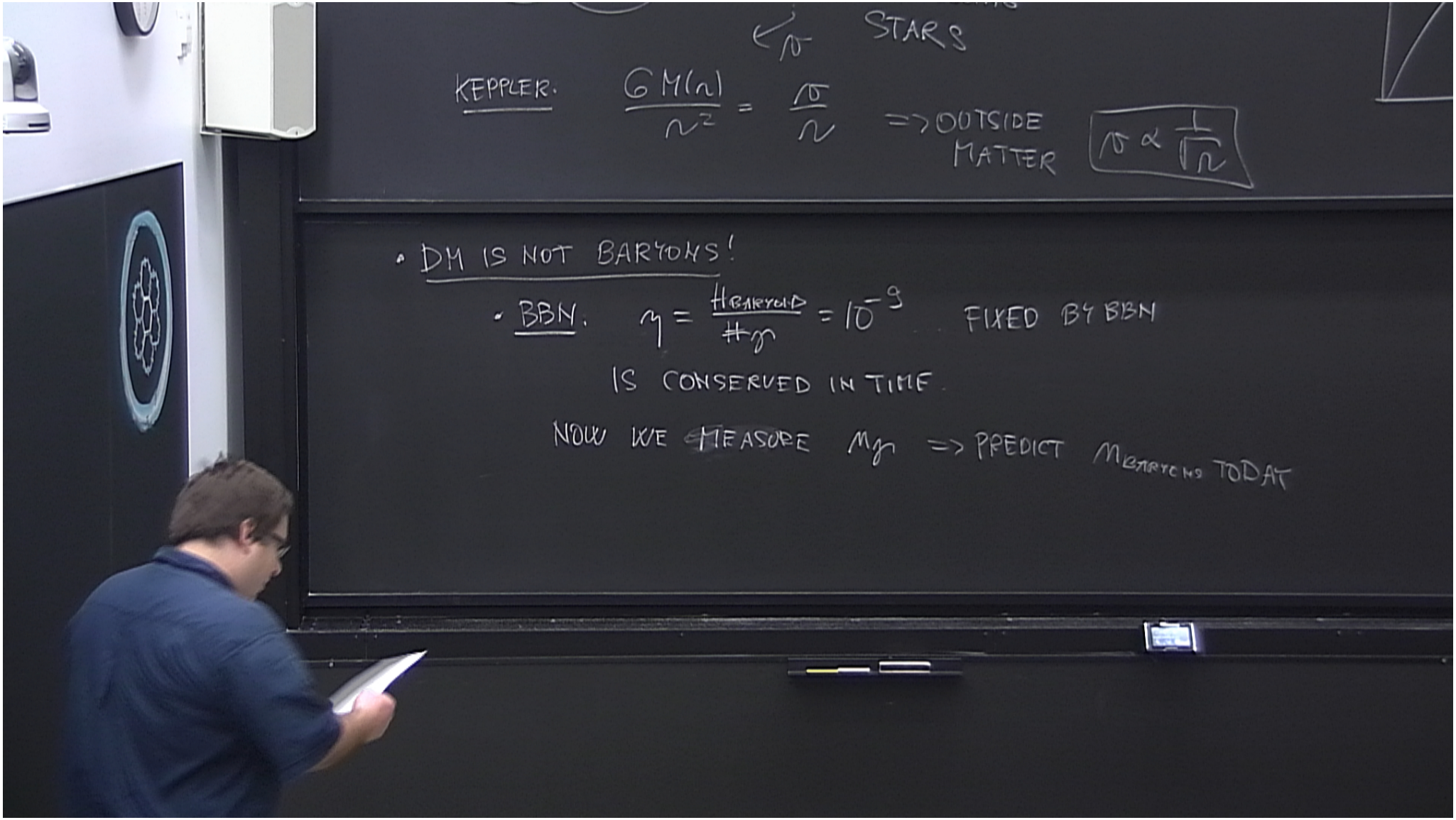
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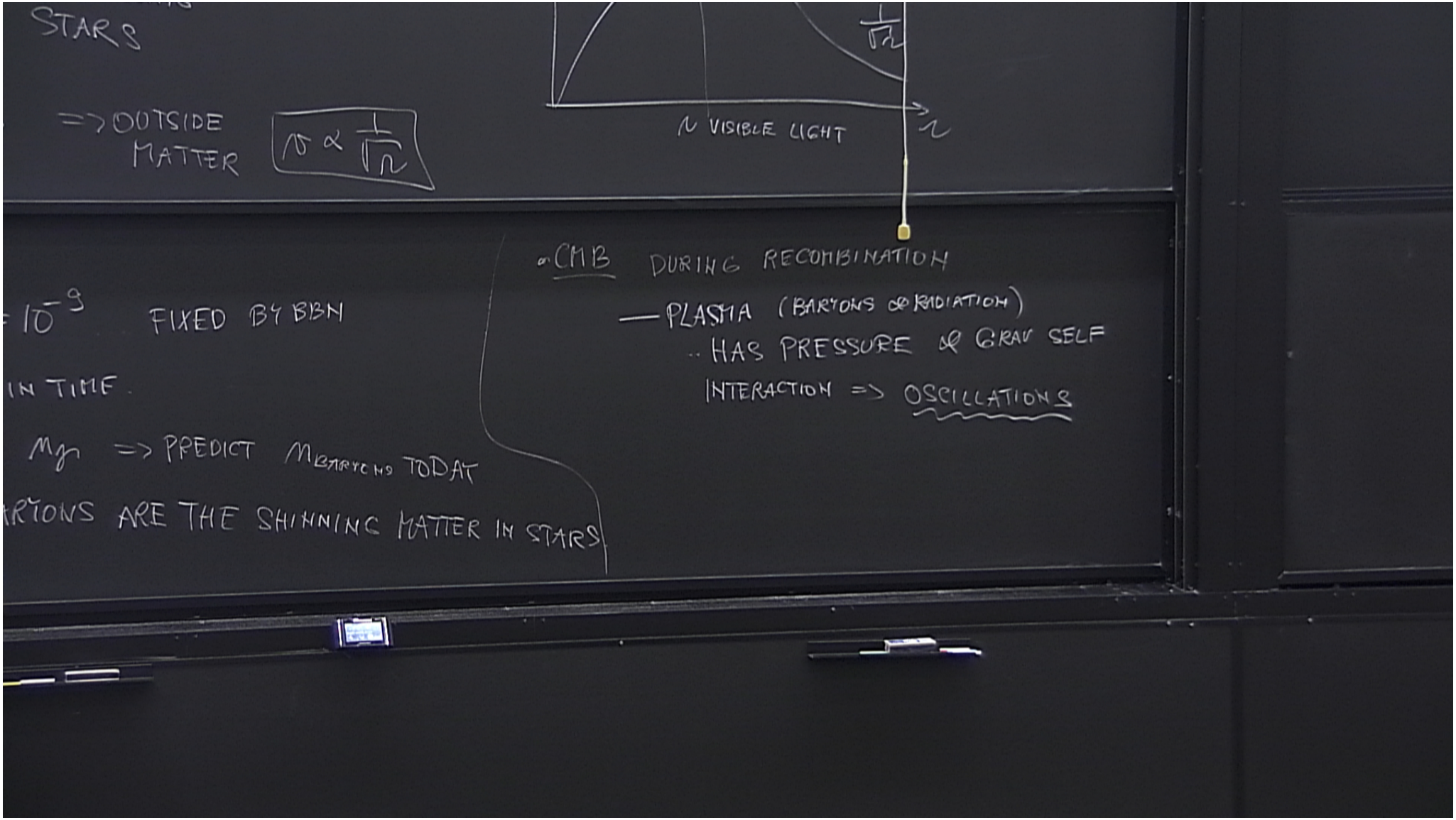


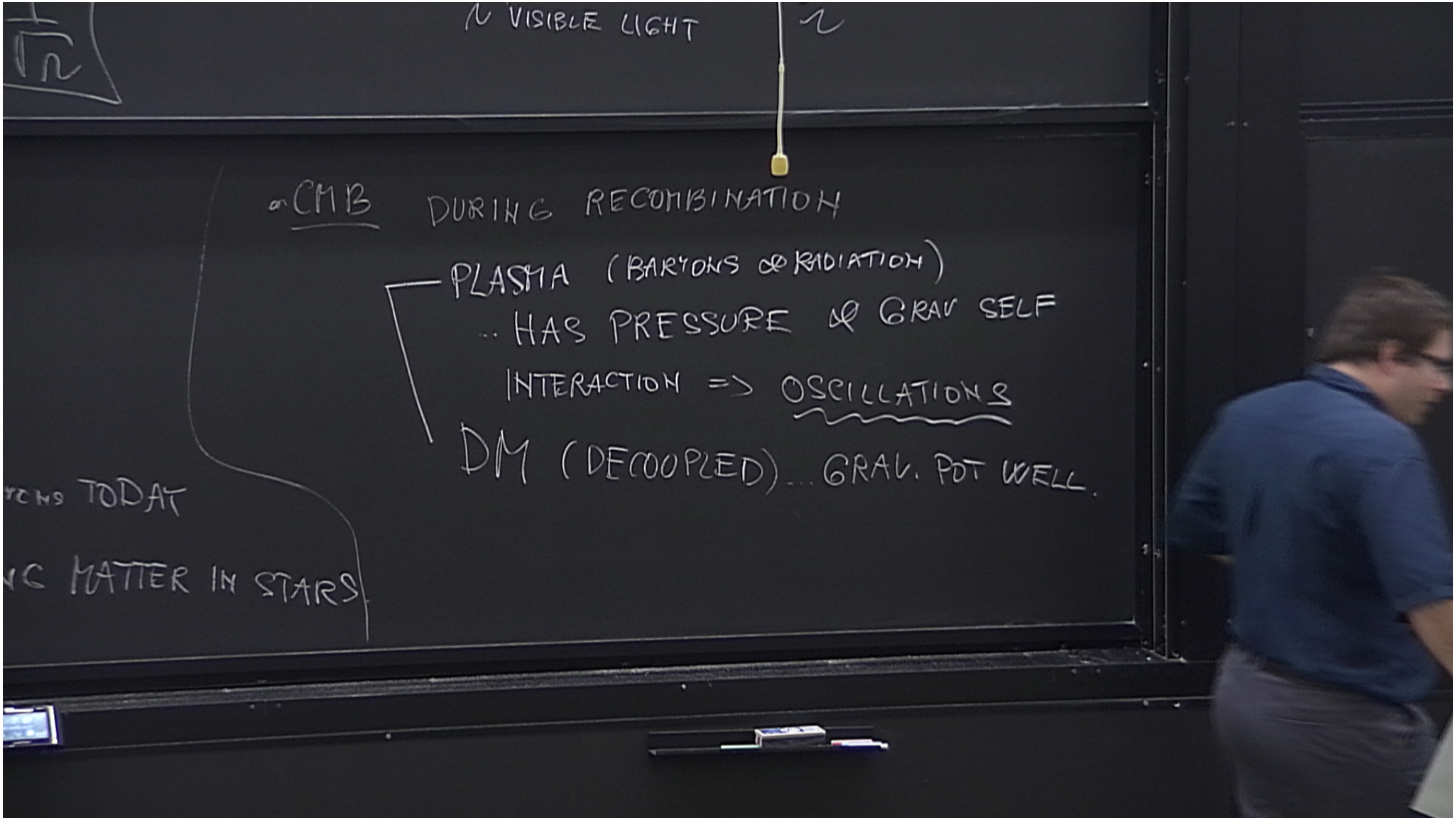


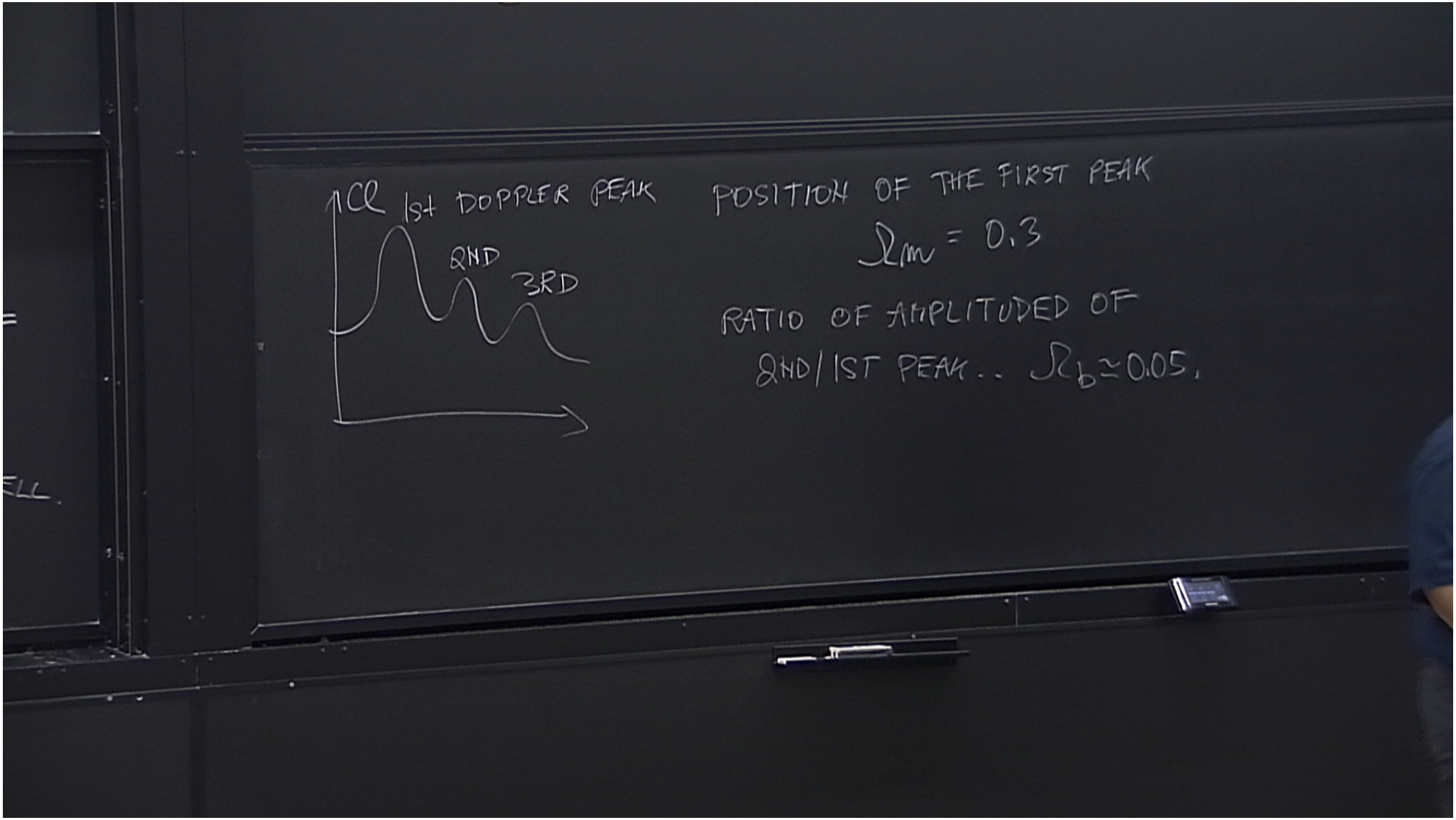
ER. $\frac{G M(r)}{r^2} = \frac{\sigma}{r}$ ⇒ OUTSIDE MATTER $\sigma \propto \frac{1}{\sqrt{r}}$

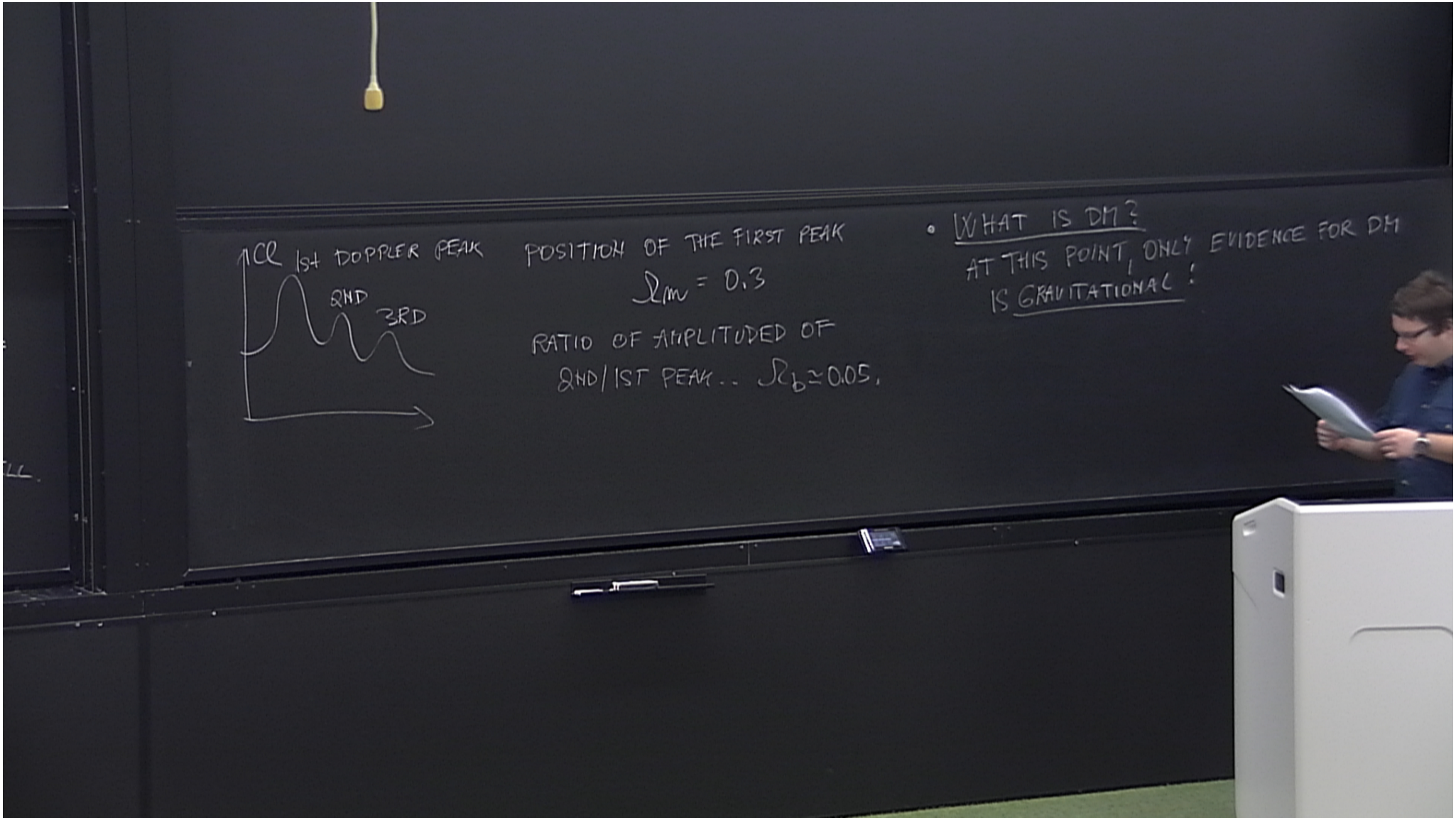

STARS
KEPPLER. $\frac{GM(r)}{r^2} = \frac{v}{r}$ => OUTSIDE MATTER $v \propto \frac{1}{\sqrt{r}}$
• DM IS NOT BARYONS!
• BBN. $\eta = \frac{\#_{BARYONS}}{\#_\gamma} = 10^{-9}$
IS CONSERVED IN TIME

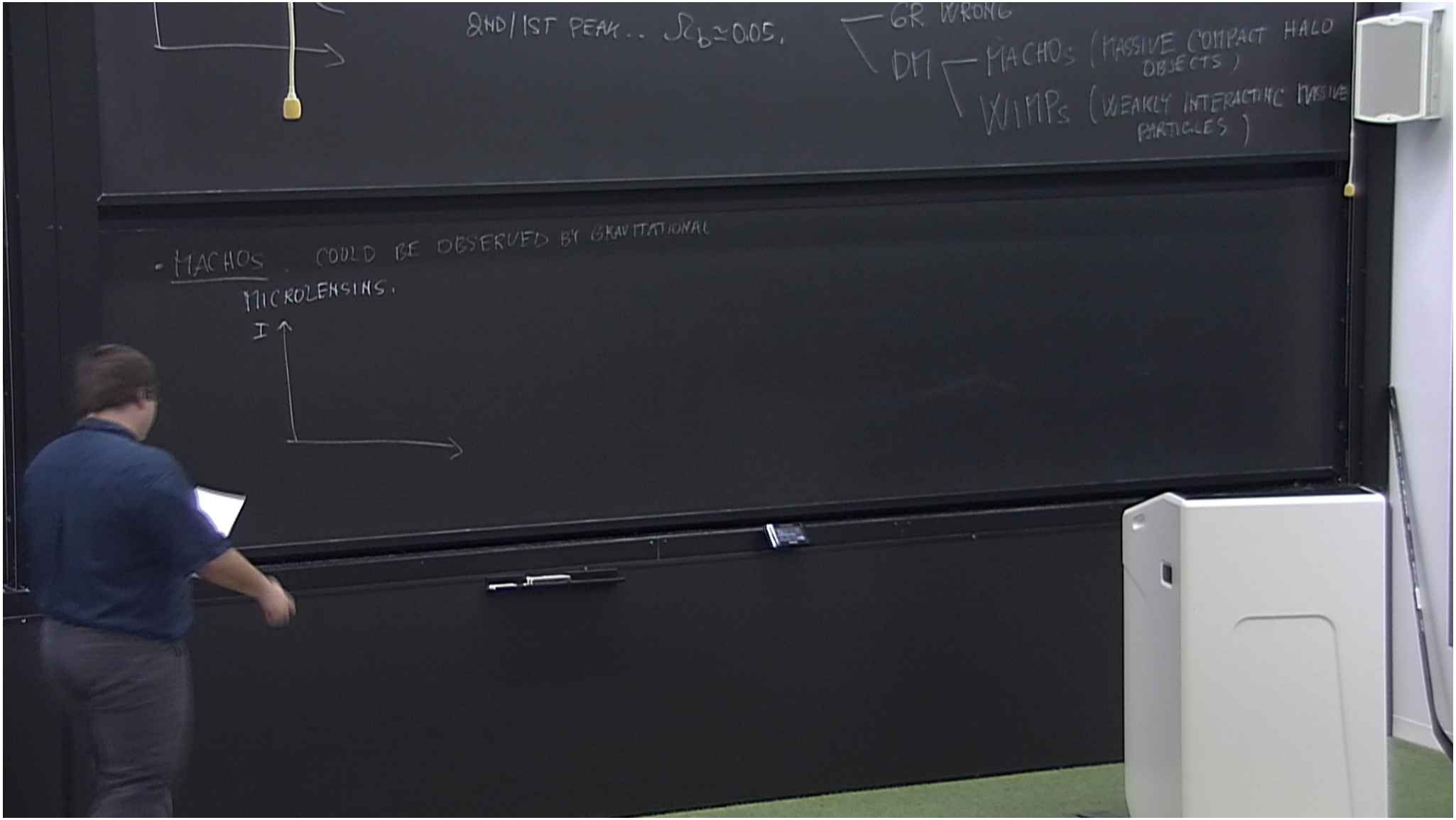

STARS
KEPPLER. $\frac{GM(r)}{r^2} = \frac{v^2}{r}$ => OUTSIDE MATTER $v \propto \frac{1}{\sqrt{r}}$
• DM IS NOT BARYONS!
• BBN. $\eta = \frac{n_{BARYONS}}{n_\gamma} = 10^{-9}$ FIXED BY BBN
IS CONSERVED IN TIME
NOW WE MEASURE M_γ => PREDICT $M_{BARYONS}$ TODAY

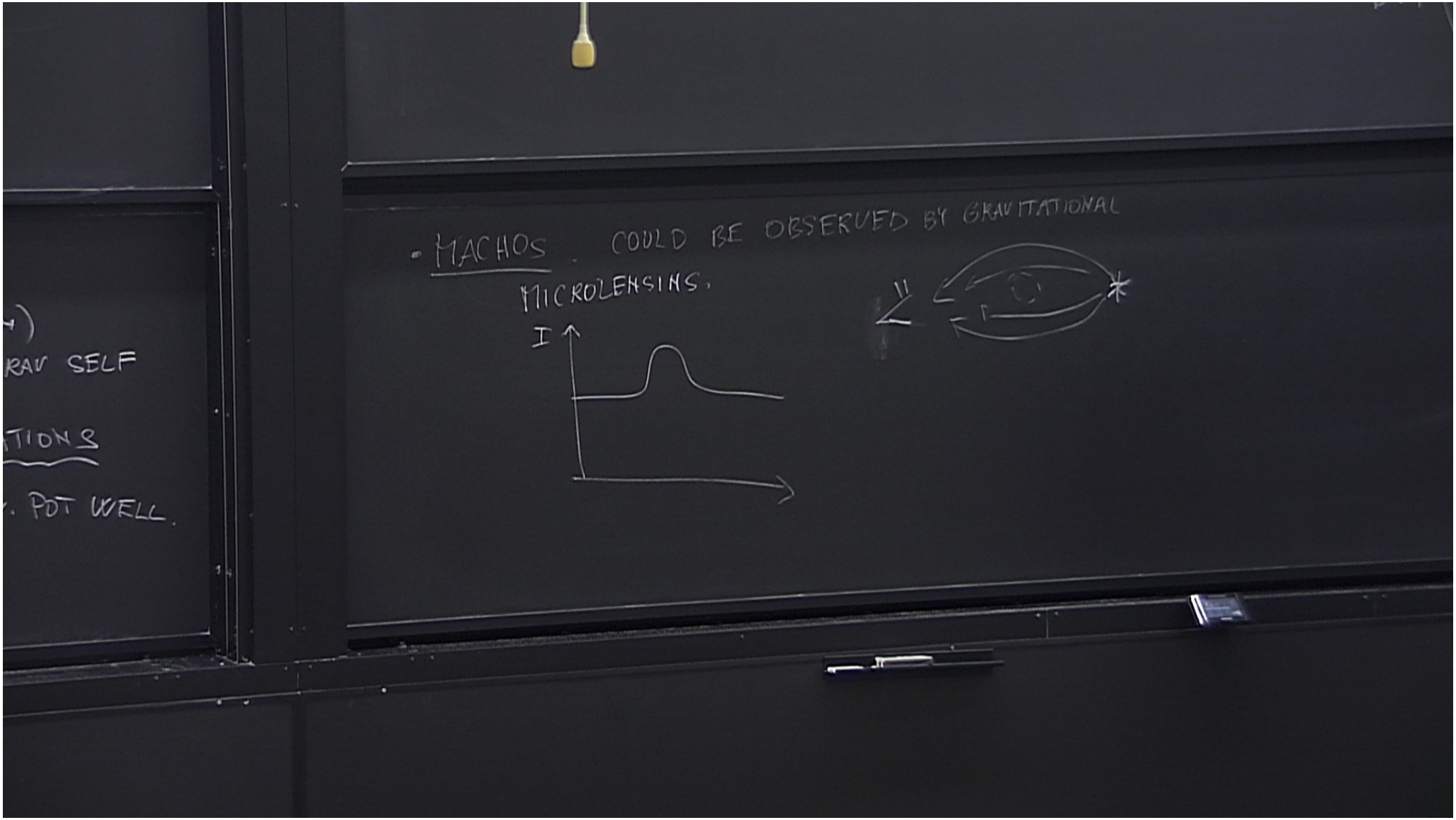

STARS
=> OUTSIDE MATTER
$n \propto \frac{1}{r^2}$
$\frac{1}{r^2}$
ν VISIBLE LIGHT
ν
10^{-9} FIXED BY BBN
IN TIME
$M_{\odot}$ => PREDICT $M_{BARYONS}$ TODAY
ARYONS ARE THE SHINING MATTER IN STARS
CMB DURING RECOMBINATION
— PLASMA (BARYONS & RADIATION)
.. HAS PRESSURE & GRAV SELF
INTERACTION => OSCILLATIONS


VISIBLE LIGHT
CMB DURING RECOMBINATION
PLASMA (BARYONS & RADIATION)
.. HAS PRESSURE & GRAV SELF
INTERACTION => OSCILLATIONS
DM (DECOUPLED) ... GRAV. POT WELL.
TODAT
MATTER IN STARS

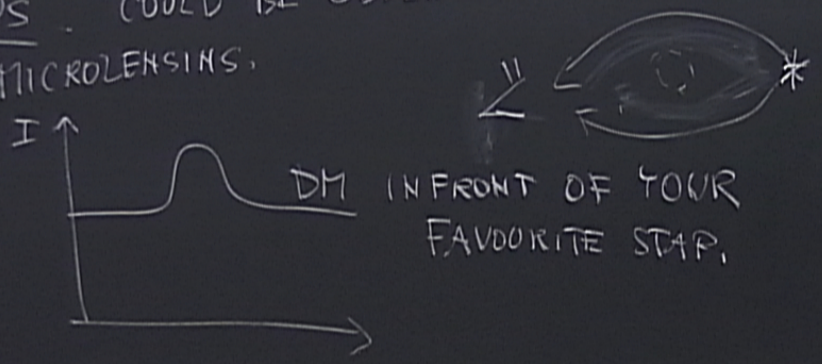

C_ℓ
1st DOPPLER PEAK
2ND
3RD
POSITION OF THE FIRST PEAK
$\Omega_m = 0.3$
RATIO OF AMPLITUDED OF
2ND/1ST PEAK.. $\Omega_b \simeq 0.05$.


C_l
1st DOPPLER PEAK
2ND
3RD
POSITION OF THE FIRST PEAK
$\Omega_m = 0.3$
RATIO OF AMPLITUDED OF
2ND/1ST PEAK.. $\Omega_b \simeq 0.05$.
• WHAT IS DM?
AT THIS POINT, ONLY EVIDENCE FOR DM
IS GRAVITATIONAL!

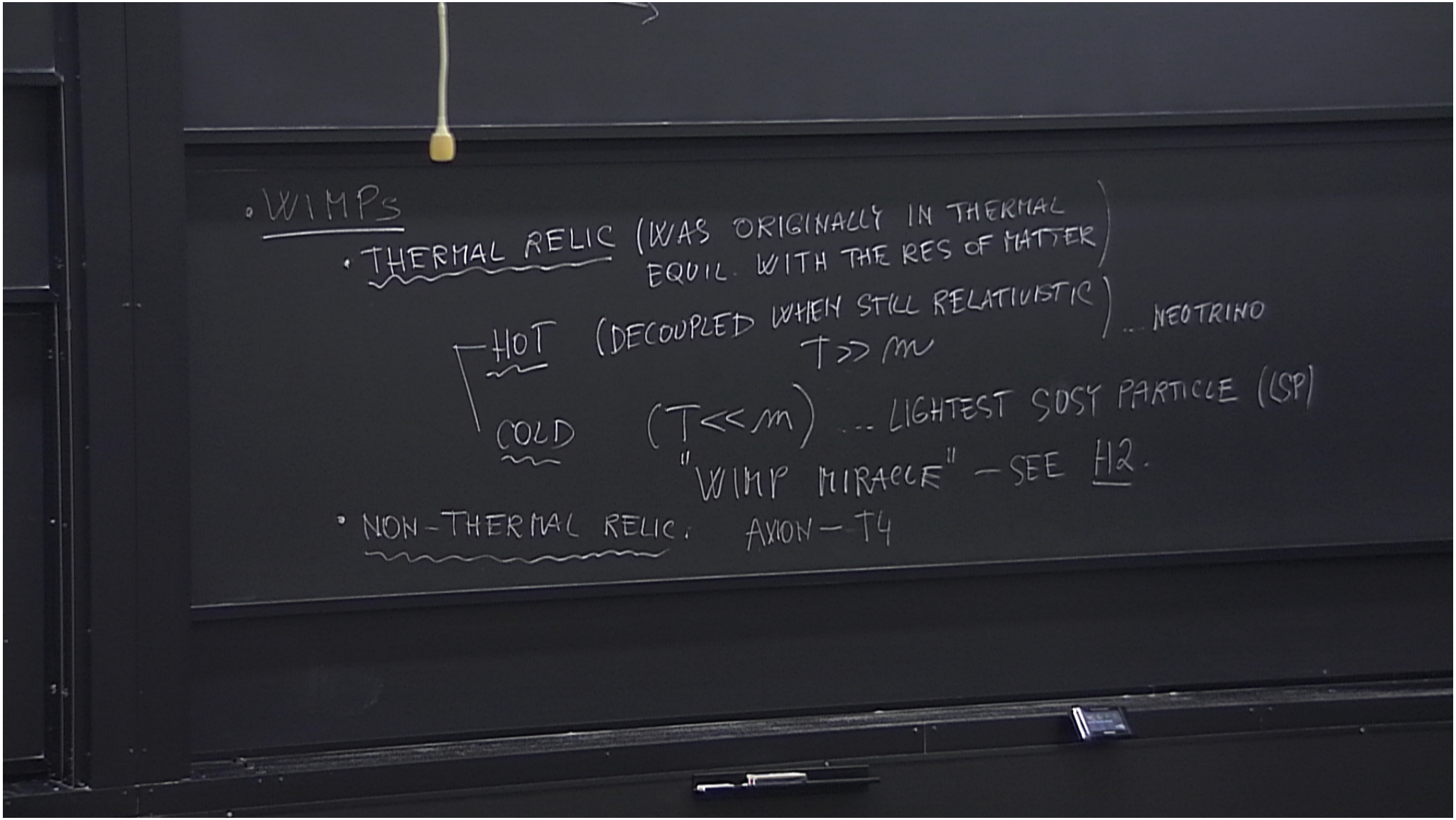

2ND/1ST PEAK.. $\Omega_b \simeq 0.05$.
GR WRONG
DM
MACHOs (MASSIVE COMPACT HALO OBJECTS)
WIMPs (WEAKLY INTERACTING MASSIVE PARTICLES)
- MACHOs COULD BE OBSERVED BY GRAVITATIONAL
MICROLENSING.
I

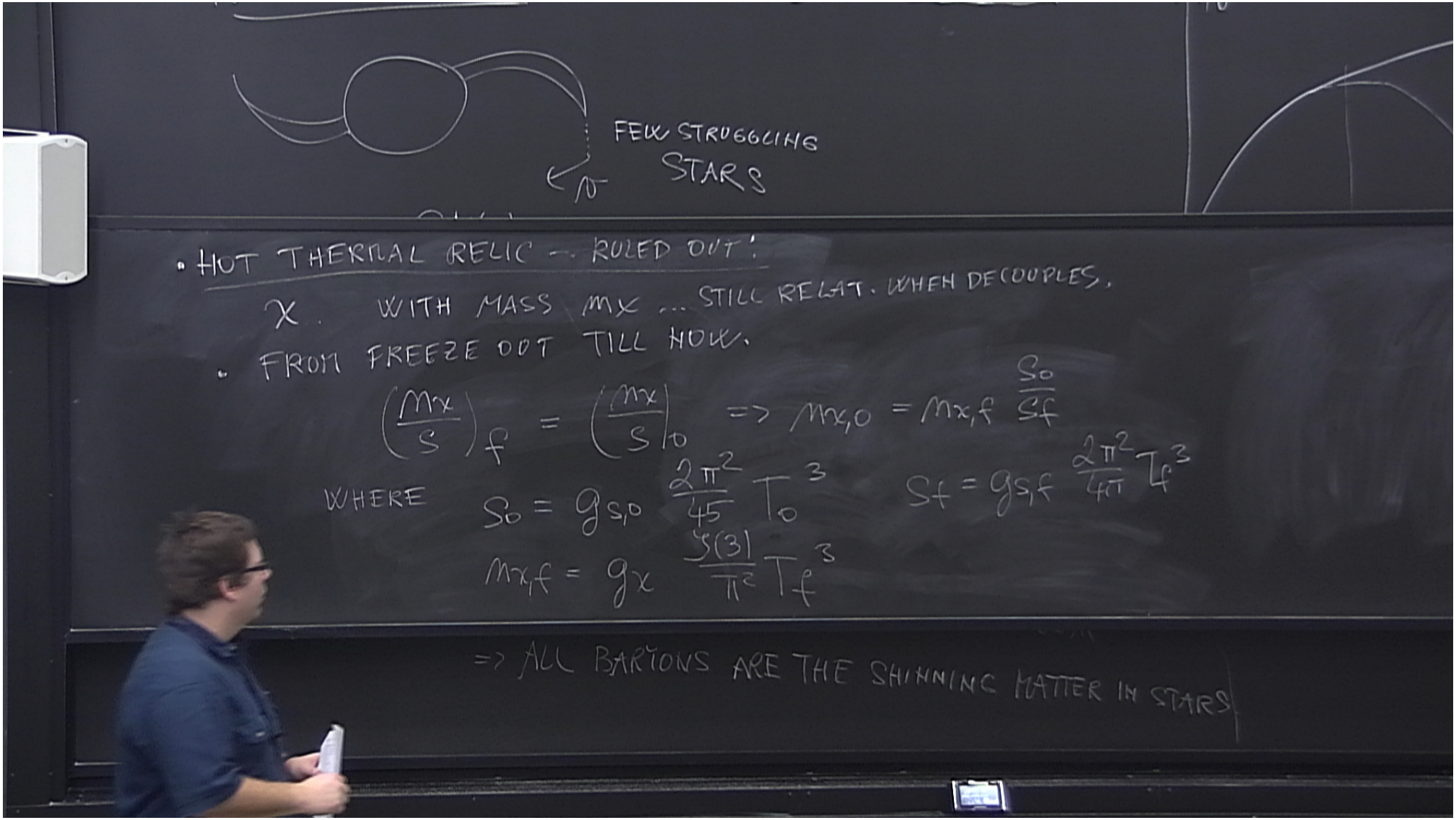

• MACHOS COULD BE OBSERVED BY GRAVITATIONAL
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I
RAV SELF
TIONS
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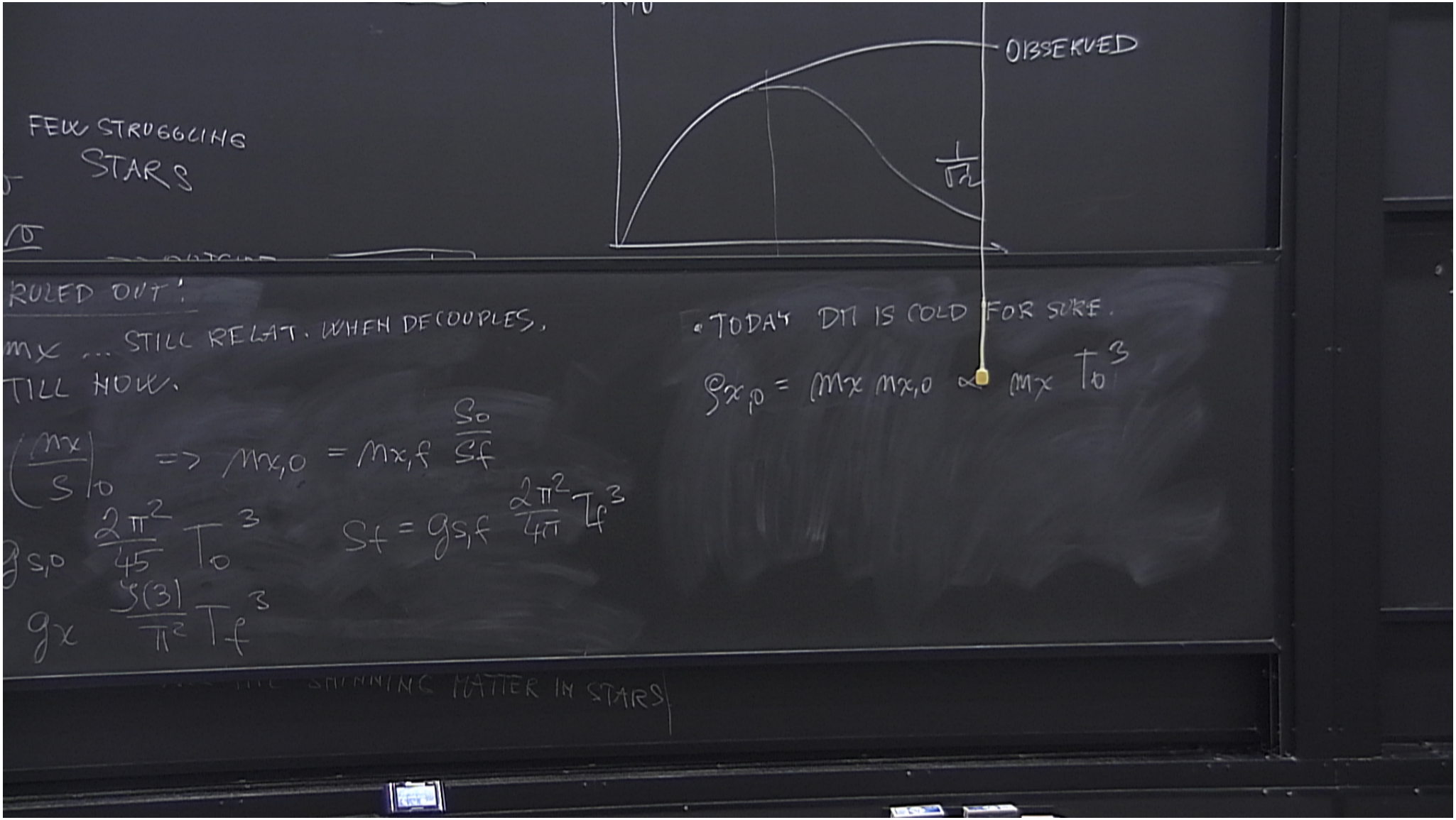
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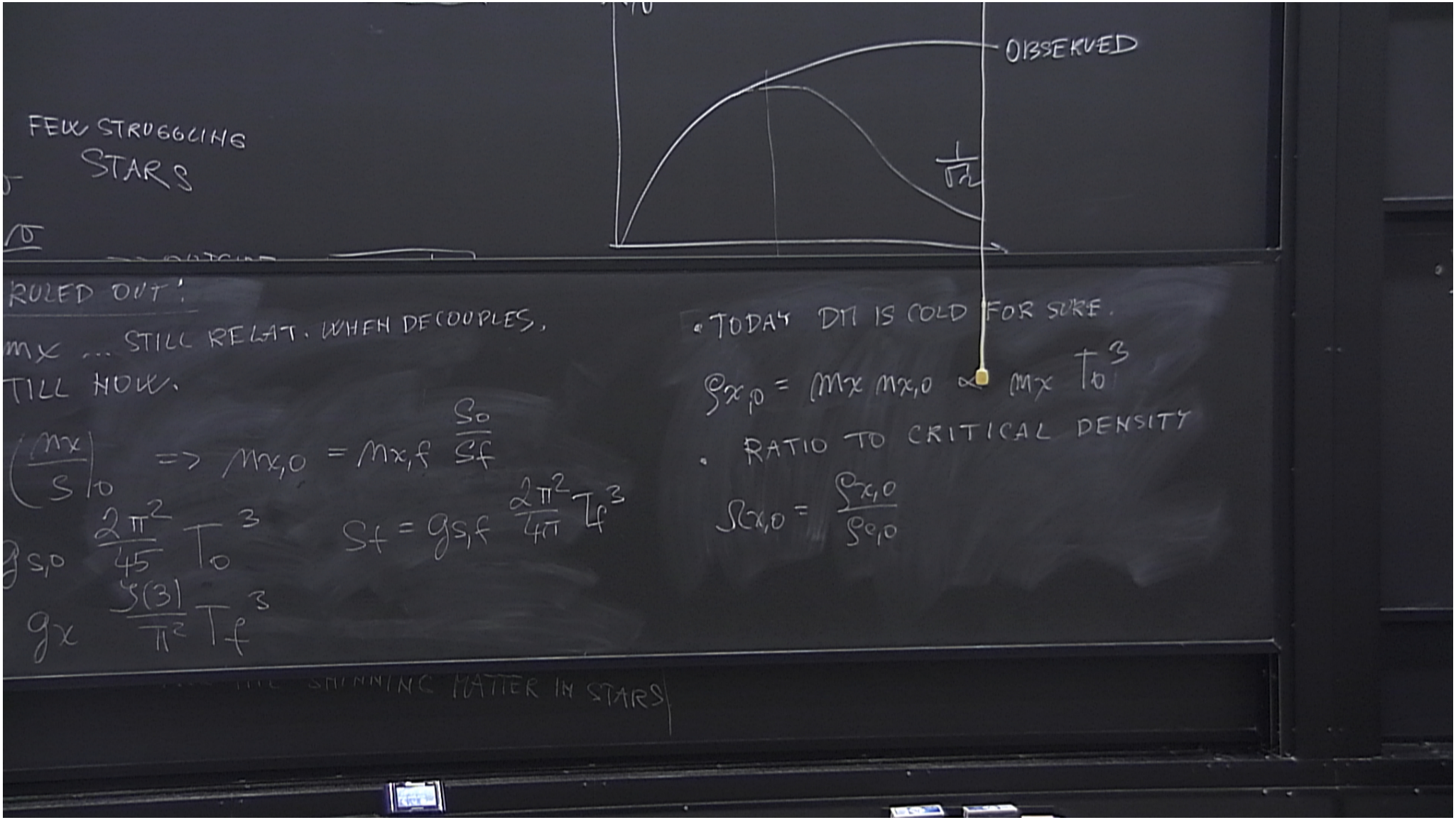


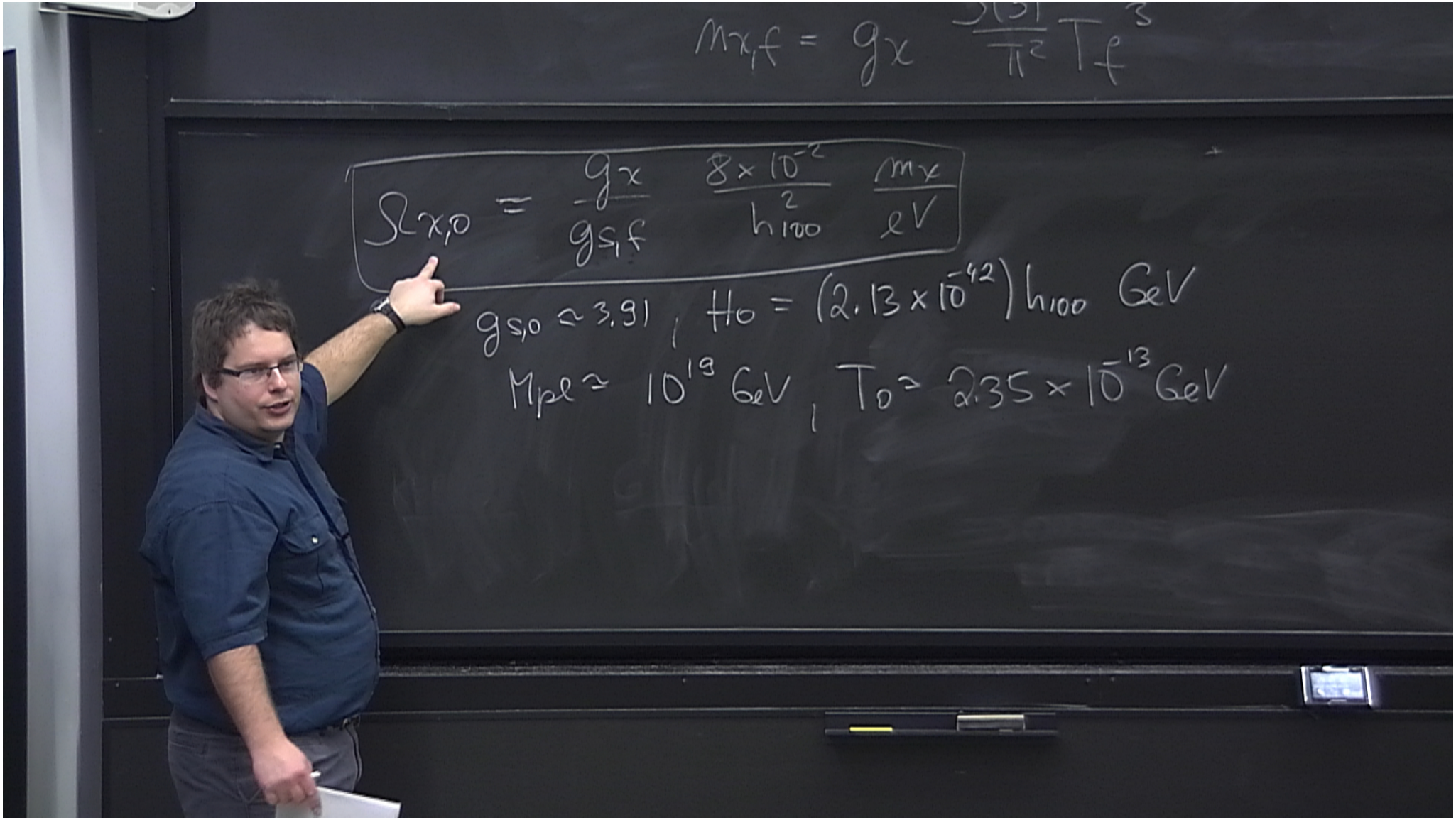
=> • $10^{-5} M_\odot < M < 10^{2} M_\odot$ RULED OUT.
• $10^{-18} M_\odot$ BHs WOULD ALREADY HAWKING EVAP.
• THERE IS STILL WINDOW. PRIMORDIAL BHs

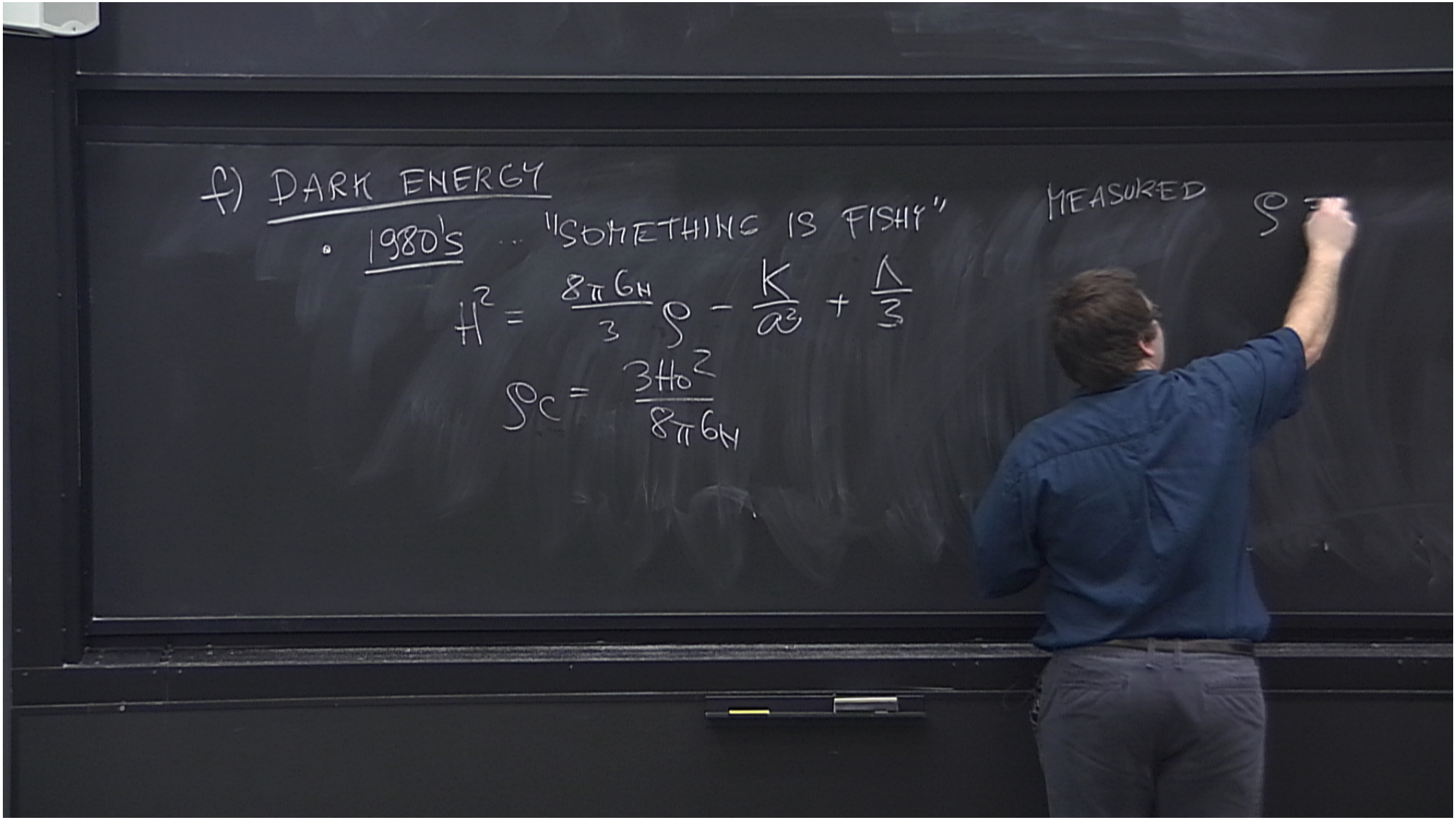

• WIMPs
• THERMAL RELIC (WAS ORIGINALLY IN THERMAL EQUIL. WITH THE RES OF MATTER)
HOT (DECOUPLED WHEN STILL RELATIVISTIC $T \gg m$) ... NEOTRINO
COLD ($T \ll m$) ... LIGHTEST SUSY PARTICLE (LSP)
"WIMP MIRACLE" – SEE H2.
• NON-THERMAL RELIC: AXION – T4

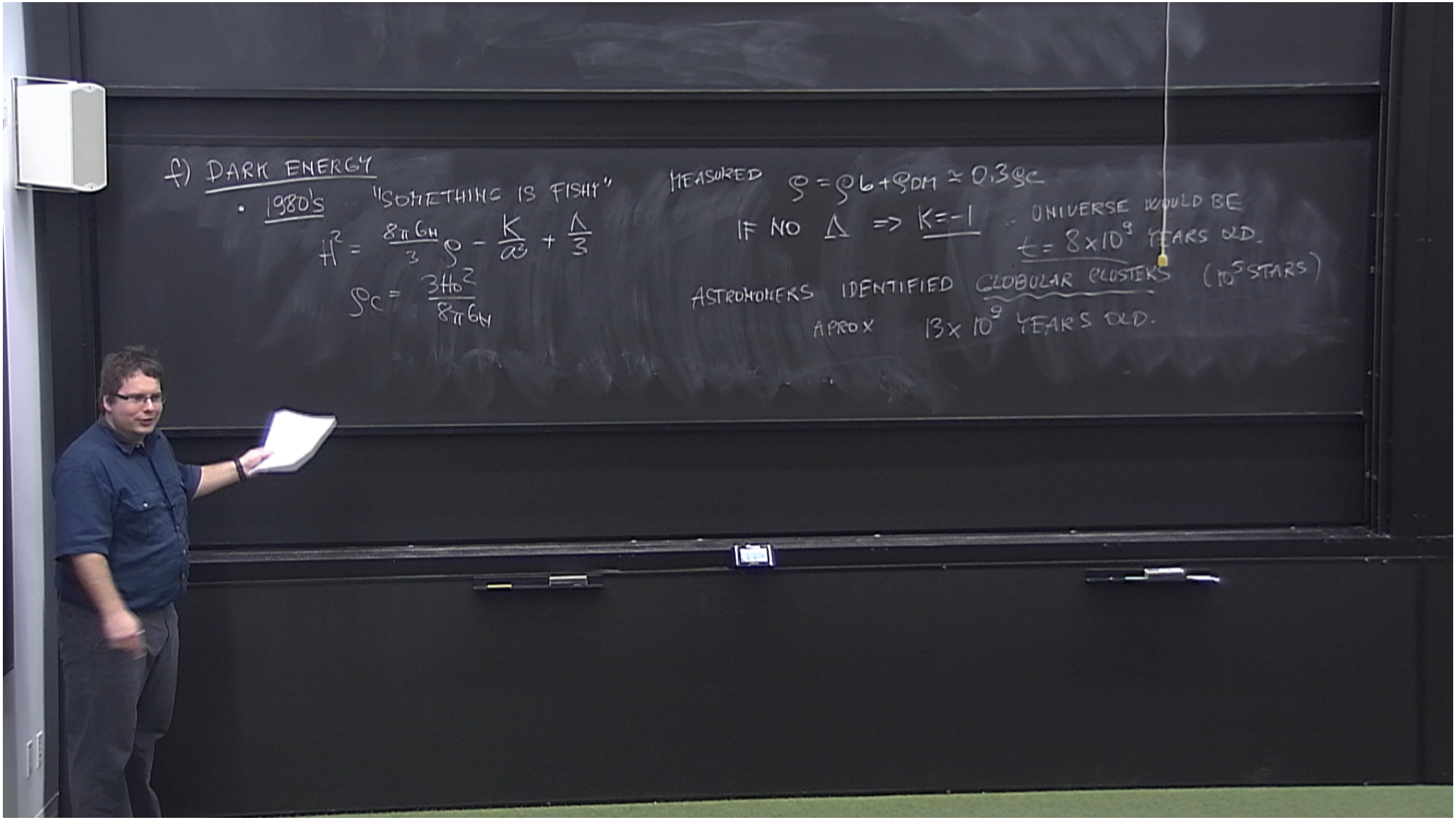

FEW STRUGGLING STARS
• HOT THERMAL RELIC -- RULED OUT!
χ WITH MASS m_χ ... STILL RELAT. WHEN DECOUPLES.
• FROM FREEZE OUT TILL NOW.
$\left(\frac{m_\chi}{s}\right)_f = \left(\frac{m_\chi}{s}\right)_0 \Rightarrow m_{\chi,0} = m_{\chi,f}\frac{s_0}{s_f}$
WHERE $s_0 = g_{s,0}\frac{2\pi^2}{45}T_0^3$ $s_f = g_{s,f}\frac{2\pi^2}{45}T_f^3$
$m_{\chi,f} = g_\chi \frac{\zeta(3)}{\pi^2}T_f^3$
⇒ ALL BARYONS ARE THE SHINING MATTER IN STARS


OBSERVED
FEW STRUGGLING STARS
RULED OUT!
• TODAY DM IS COLD FOR SURE.
STUNNING MATTER IN STARS


OBSERVED
FEW STRUGGLING STARS
RULED OUT!
mx ... STILL RELAT. WHEN DECOUPLES,
TILL NOW.
$\left(\frac{n_x}{s}\right)_0 \Rightarrow n_{x,0} = n_{x,f}\frac{s_0}{s_f}$
$g_{s,0}\ \frac{2\pi^2}{45}T_0^3 \qquad s_f = g_{s,f}\frac{2\pi^2}{45}T_f^3$
$g_x\ \frac{\zeta(3)}{\pi^2}T_f^3$
• TODAY DM IS COLD FOR SURE.
$\rho_{x,0} = m_x n_{x,0} \propto m_x T_0^3$
• RATIO TO CRITICAL DENSITY
$\Omega_{x,0} = \frac{\rho_{x,0}}{\rho_{c,0}}$


$n_{x,f} = g_x \frac{3\zeta(3)}{\pi^2} T_f^3$
$\Omega_{x,0} = \frac{g_x}{g_{s,f}} \frac{8\times10^{-2}}{h_{100}^2} \frac{m_x}{eV}$
$g_{s,0} \simeq 3.91$, $H_0 = (2.13\times10^{-42})\, h_{100}$ GeV
$M_{pl} \simeq 10^{19}$ GeV , $T_0 \simeq 2.35\times10^{-13}$ GeV


f) DARK ENERGY
• 1980's ... "SOMETHING IS FISHY"
MEASURED
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$
$\rho_c = \frac{3H_0^2}{8\pi G_N}$


f) DARK ENERGY
• 1980's "SOMETHING IS FISHY"
$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$
$\rho_c = \frac{3H_0^2}{8\pi G}$
MEASURED $\rho = \rho_b + \rho_{DM} \simeq 0.3\rho_c$
IF NO Λ => $k=-1$. UNIVERSE WOULD BE $t = 8\times10^9$ YEARS OLD.
ASTRONOMERS IDENTIFIED GLOBULAR CLUSTERS (10^5 STARS)
APROX 13×10^9 YEARS OLD.