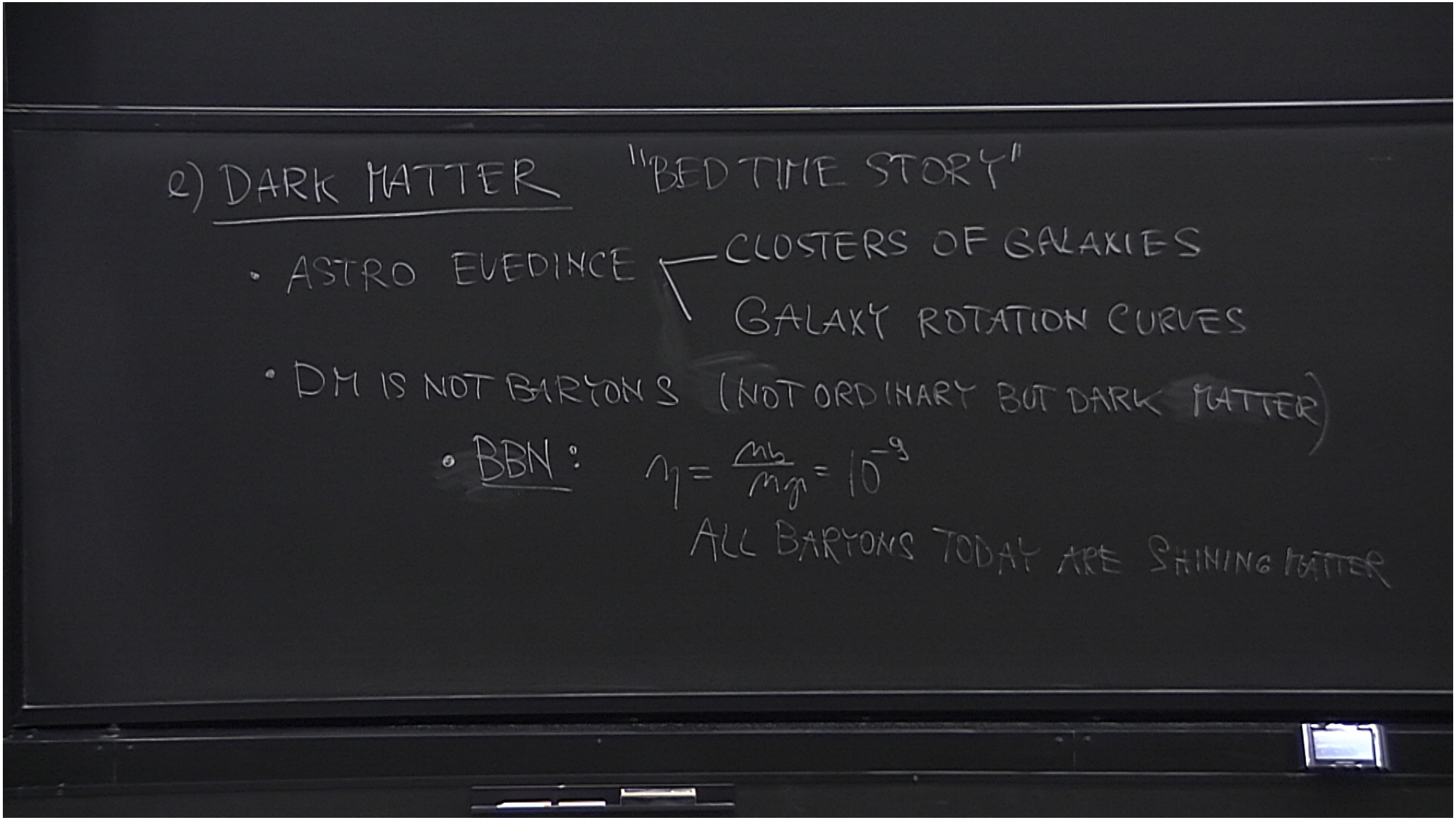
Title: PSI 17/18 - Cosmology - Lecture 8

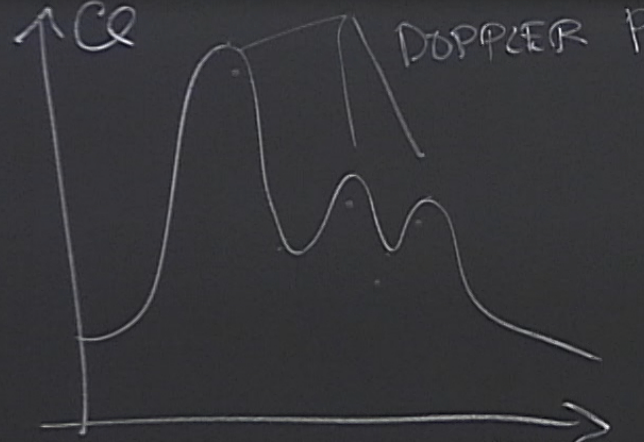
Date: Feb 06, 2018 09:00 AM

URL: http://pirsa.org/18020016

Abstract:


2) DARK MATTER "BED TIME STORY"
• ASTRO EVEDINCE
CLOSTERS OF GALAXIES
GALAXY ROTATION CURVES
• DM IS NOT BARYONS (NOT ORDINARY BUT DARK MATTER)
• BBN: $\eta = \frac{n_b}{n_\gamma} = 10^{-9}$
ALL BARYONS TODAY ARE SHINING MATTER

- CMB PROVIDES ANOTHER INDEPENDENT MEASUREMENT Ω_{DM}



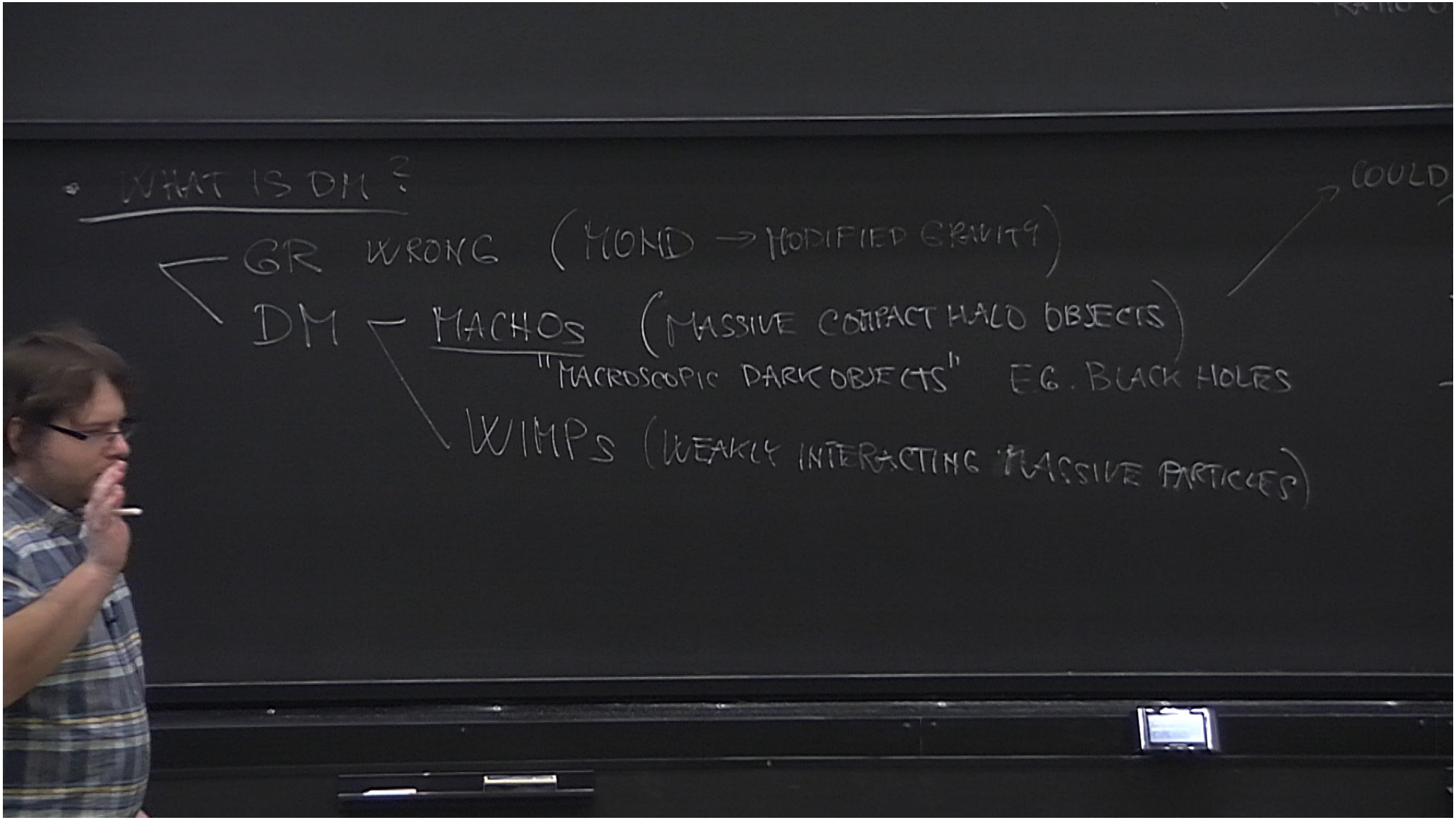
DOPPLER PEAKS = TELL ABOUT Ω_m
OSCILATIONS OF PLASMA
WHEN CMB WAS RELEASED.

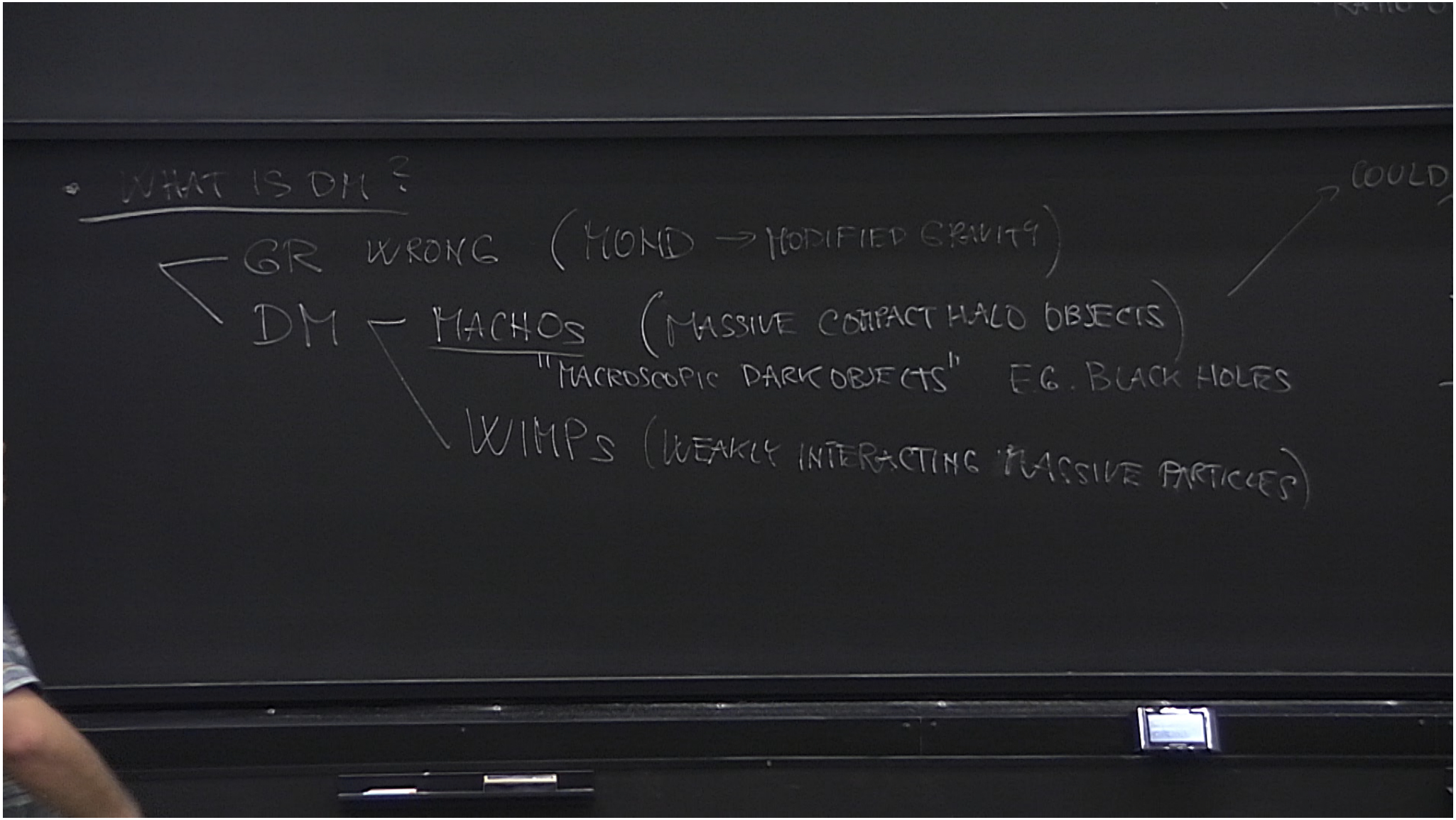
"PLASMA" (BARYONS, PHOTONS)
HAS PRESSURE
GRAV. ATTRACT. } → OSCILLATIONS

DARK MATTER (DECOUPLED)
ONLY ACTS GRAVITATIONALLY:
GRAV. POT. WELLS.

"POSITION OF 1ST PEAK"
$\Omega_m = 0.26$

"RATIO OF 1st/2nd"
$\Omega_b = 0.04$.


WHAT IS DM?
GR WRONG (MOND → MODIFIED GRAVITY)
DM
MACHOs (MASSIVE COMPACT HALO OBJECTS)
"MACROSCOPIC DARK OBJECTS" E.G. BLACK HOLES
WIMPs (WEAKLY INTERACTING MASSIVE PARTICLES)
COULD


WHAT IS DM?
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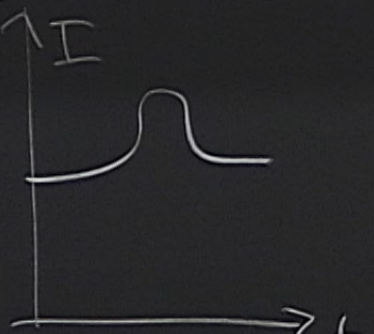
"RATIO OF 1st/2nd"

$R_b = 0.04$.

(DECOUPLED)

ONLY ACTS GRAVITATIONALLY:
GRAV. POT. WELLS.

COULD BE OBSERVED BY GRAV. LENSING



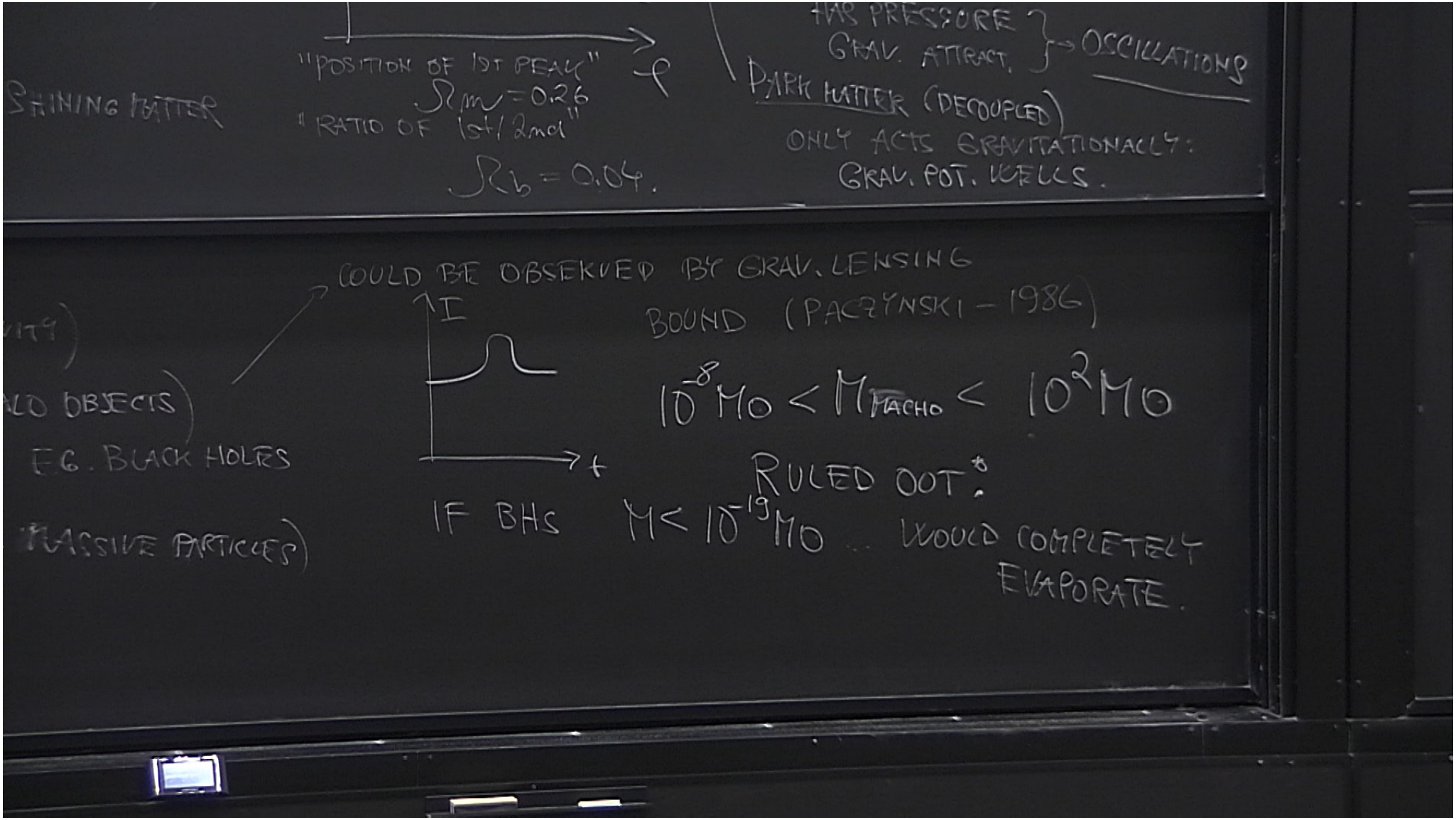
BOUND (PACZYNSKI - 1986)

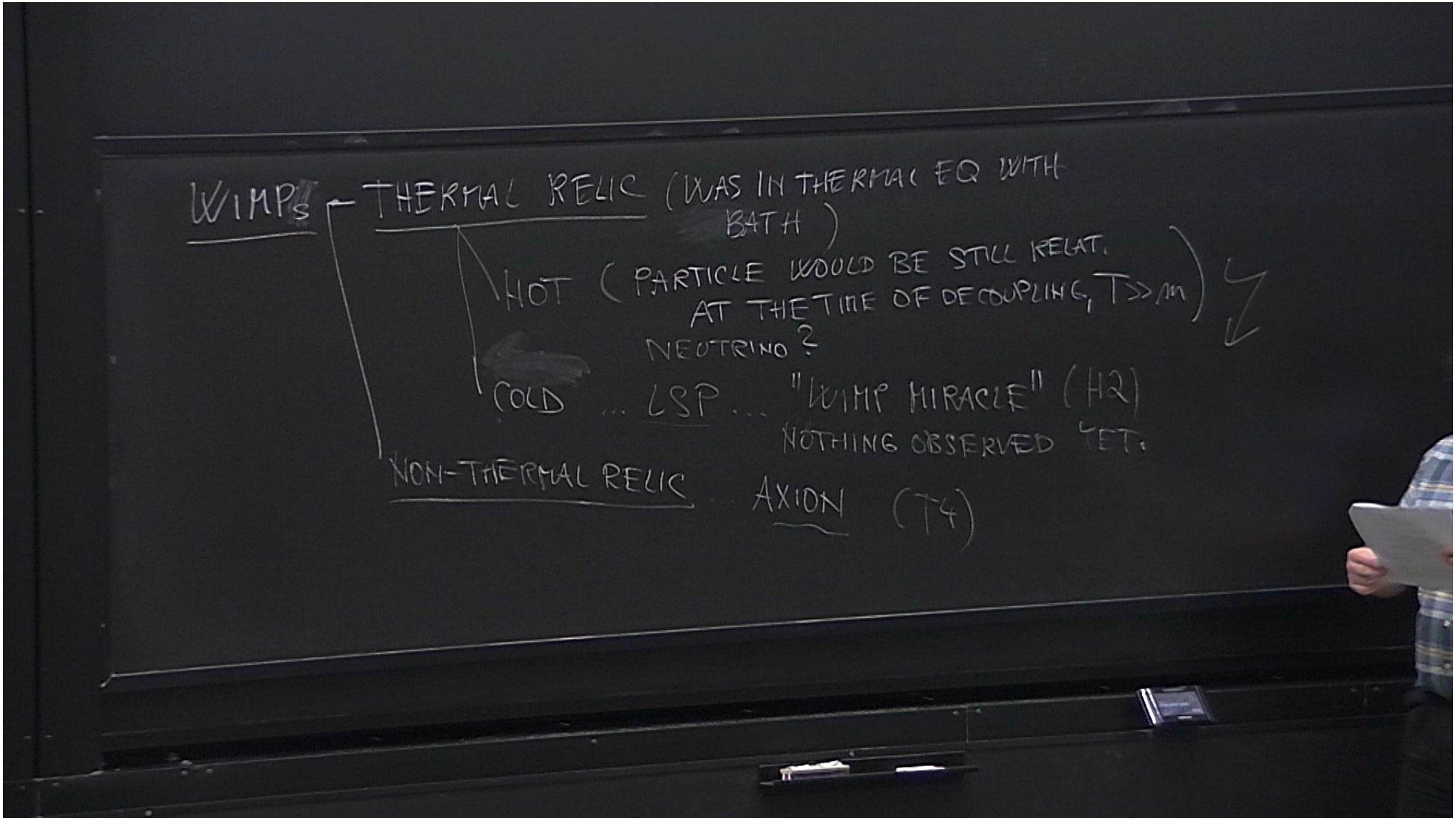
$10^{-8} M_\odot < M_{MACHO} < 10^{2} M_\odot$

RULED OUT!

HOLES

ARTICLES)


"POSITION OF 1ST PEAK"
$\Omega_m = 0.26$
"RATIO OF 1st/2nd"
$\Omega_b = 0.04$.
SHINING MATTER
THR PRESSURE
GRAV. ATTRACT.
OSCILLATIONS
DARK MATTER (DECOUPLED)
ONLY ACTS GRAVITATIONALLY:
GRAV. POT. WELLS.
COULD BE OBSERVED BY GRAV. LENSING
BOUND (PACZYNSKI - 1986)
I
t
$10^{-8} M_\odot < M_{MACHO} < 10^{2} M_\odot$
RULED OUT*
IF BHs $M < 10^{-19} M_\odot$ ... WOULD COMPLETELY EVAPORATE.
E.G. BLACK HOLES


WIMPs
THERMAL RELIC (WAS IN THERMAL EQ WITH BATH)
HOT (PARTICLE WOULD BE STILL RELAT. AT THE TIME OF DECOUPLING, T>>m)
NEUTRINO ?
COLD ... LSP ... "WIMP MIRACLE" (H2)
NOTHING OBSERVED YET.
NON-THERMAL RELIC
AXION (T4)

- HOT THERMAL RELIC IS RULED OUT

- PARTICLE χ, m_χ .. STILL RELAT. AT FREEZE OUT
- FROM FREEZE OUT TILL TODAY

$$\left(\frac{n_\chi}{s}\right)_f = \left(\frac{n_\chi}{s}\right)_{0:\,\text{TODAY}} \Rightarrow n_{\chi,0} = \frac{s_0}{s_f}\, n_{\chi,f}$$

$$s_0 = g_{s,0}\,\frac{2\pi^2}{45}\,T_0^3 \qquad T_0 \leftarrow \text{CMB.}$$

$g_{s,0} \sim 3.7$

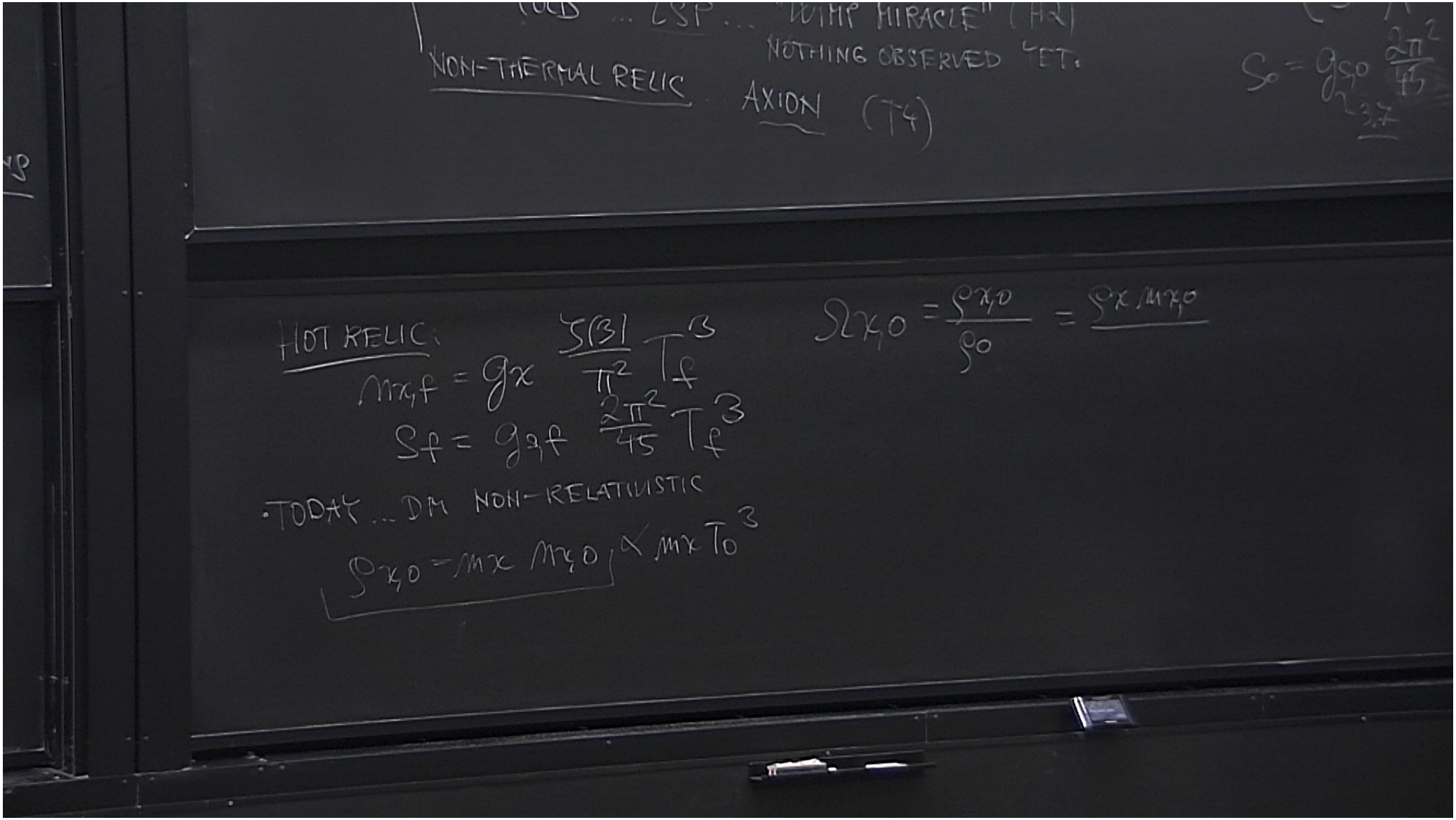
HOT RELIC:

$$n_{\chi,f} = g_\chi \frac{\zeta(3)}{\pi^2} T_f^3$$

$$s_f = g_{*,f} \frac{2\pi^2}{45} T_f^3$$

- TODAY ... DM NON-RELATIVISTIC

$$\rho_{\chi,0} = m_\chi n_{\chi,0}$$


... CSP ... "WIMP MIRACLE" (TR)
NOTHING OBSERVED YET.
NON-THERMAL RELIC
AXION (T4)
HOT RELIC:
$n_{\chi,f} = g_\chi \frac{\zeta(3)}{\pi^2} T_f^3$
$s_f = g_{*,f} \frac{2\pi^2}{45} T_f^3$
$\Omega_{\chi,0} = \frac{\rho_{\chi,0}}{\rho_0} = \frac{g_\chi m_\chi n_{\chi,0}}{\rho_0}$
$s_0 = g_{*,0} \frac{2\pi^2}{45} T_0^3$
3.7
• TODAY ... DM NON-RELATIVISTIC
$\rho_{\chi,0} = m_\chi n_{\chi,0} \propto m_\chi T_0^3$

$$\Omega_{\chi,0} = \frac{\rho_{\chi,0}}{\rho_0} = \frac{m_\chi n_{\chi,0}}{\frac{3H_0^2}{8\pi} M_{pl}^2} \simeq \frac{g_\chi}{g_{s,f}} \frac{0.08}{h^2} \frac{m_\chi}{eV}$$

$$g_{s,0} \simeq 3.91$$

$$H_0 = 100\, h \ \mathrm{km/s/Mpc} \simeq \left(2.13 \times 10^{-42}\right) h \ \mathrm{GeV}$$

$$M_{pl} \simeq 10^{19}\ \mathrm{GeV}, \quad T_0 \simeq 2.35 \times 10^{-13}\ \mathrm{GeV}$$

$$\Omega_{\chi,0} = \frac{\rho_{\chi,0}}{\rho_0} = \frac{m_\chi n_{\chi,0}}{\frac{3H_0^2}{8\pi} M_{Pl}^2} \simeq \frac{g_\chi}{g_{s,f}} \frac{0.08}{h^2} \frac{m_\chi}{eV} \leq \frac{1}{4}$$

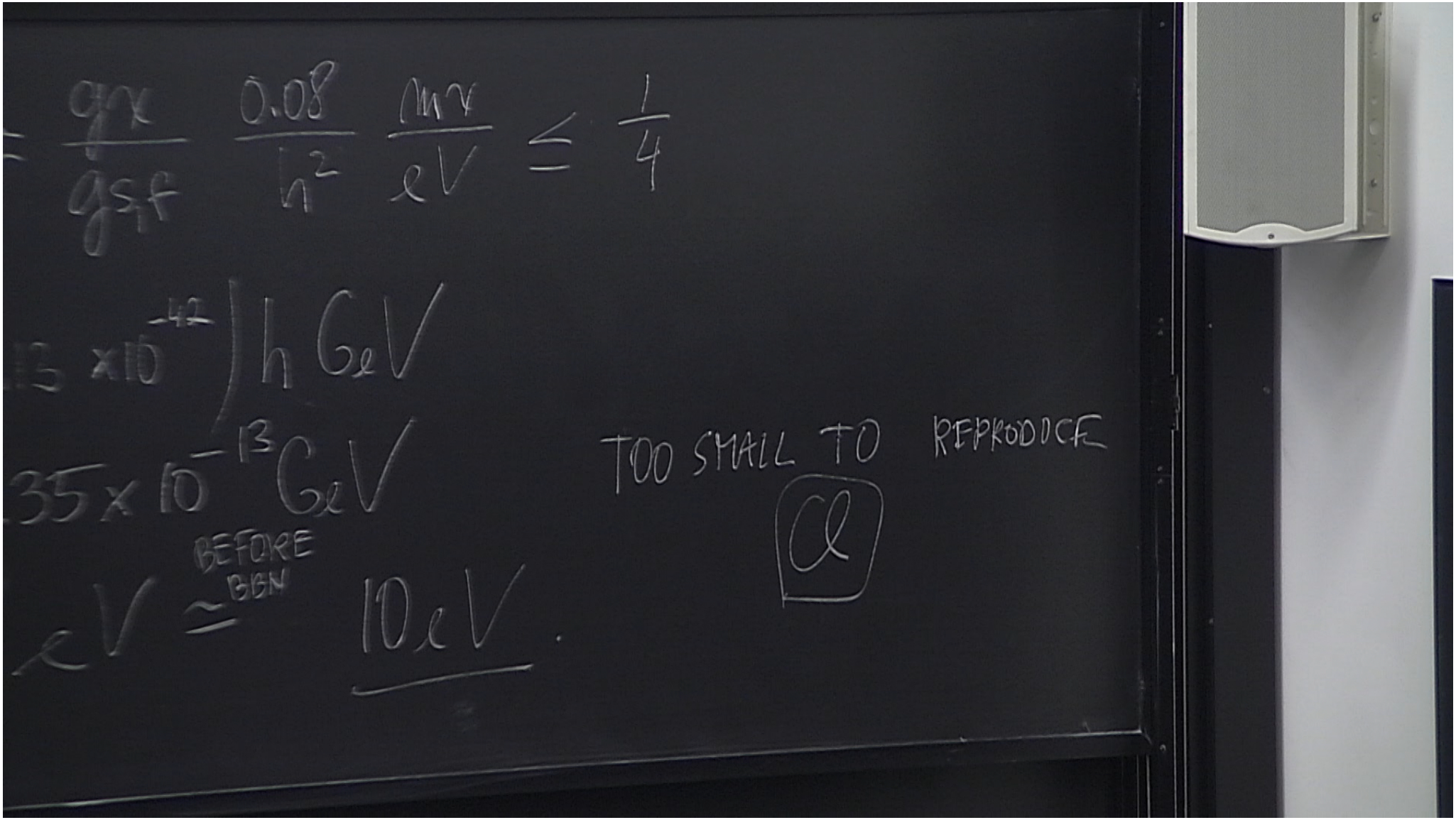
$g_{s,0} \simeq 3.91$

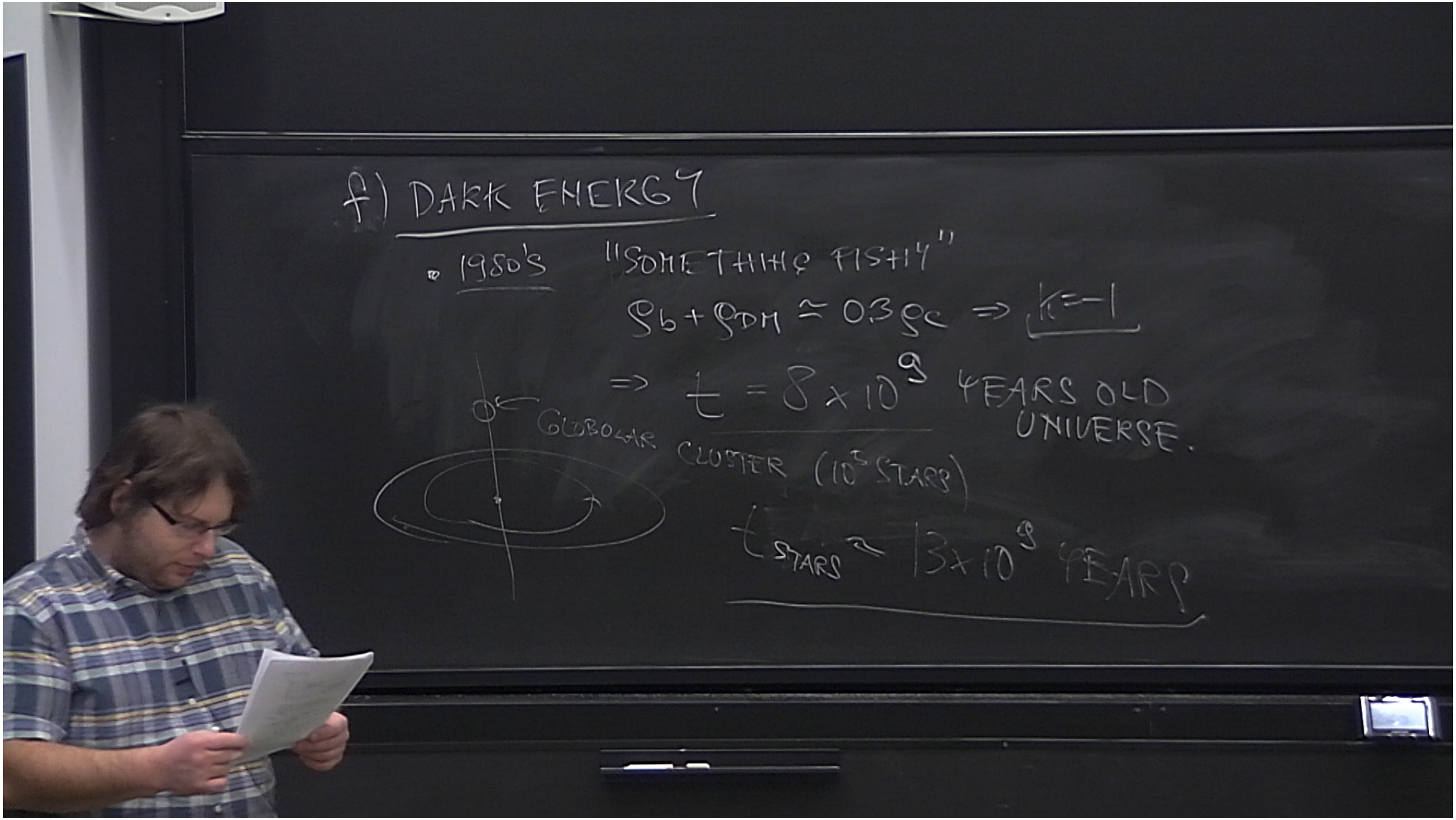
$H_0 = 100\, h$ km/s/Mpc $\simeq \left(2.13 \times 10^{-42}\right) h$ GeV

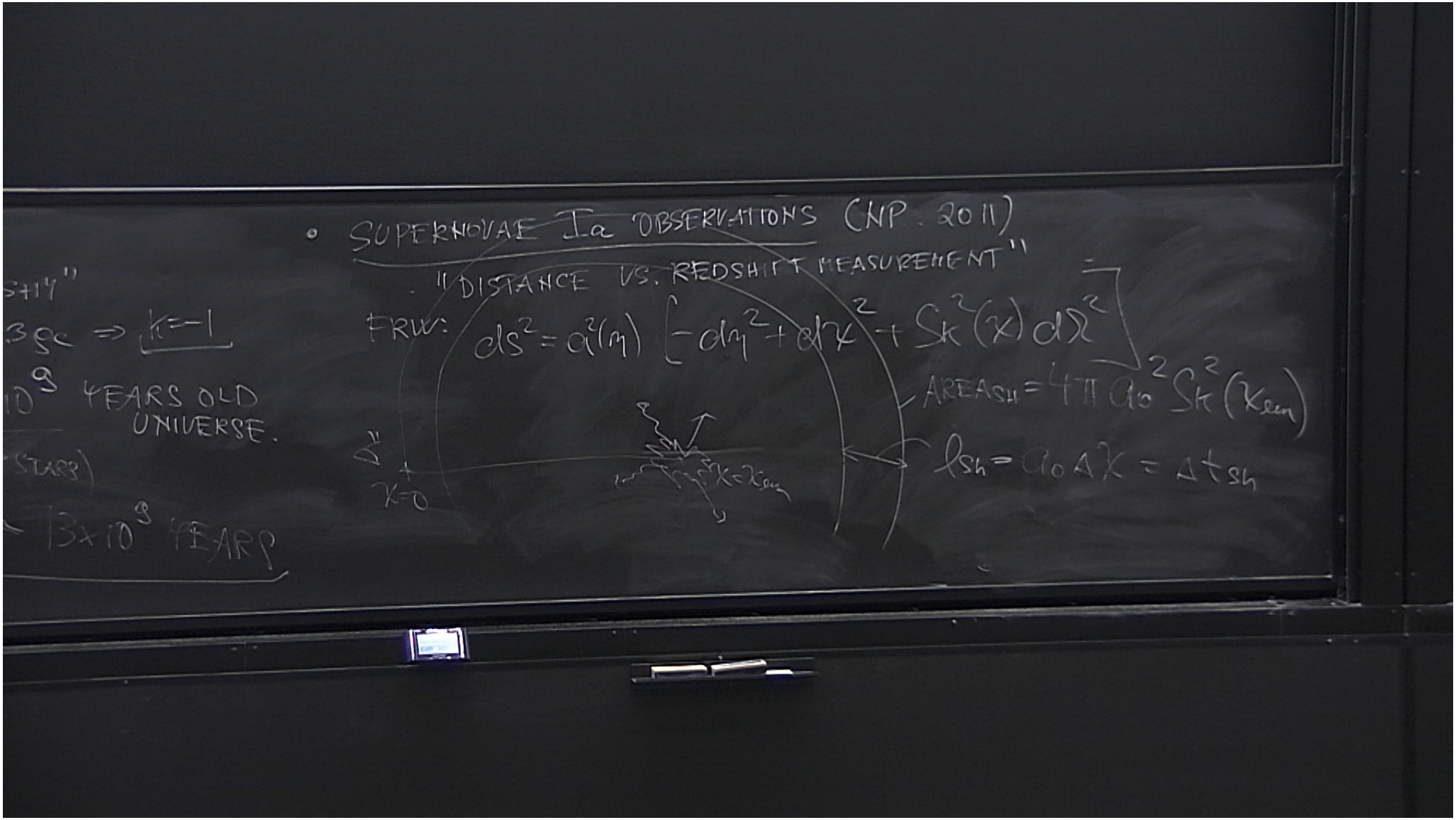
$M_{Pl} \simeq 10^{19}$ GeV $\quad T_0 \simeq 2.35 \times 10^{-13}$ GeV

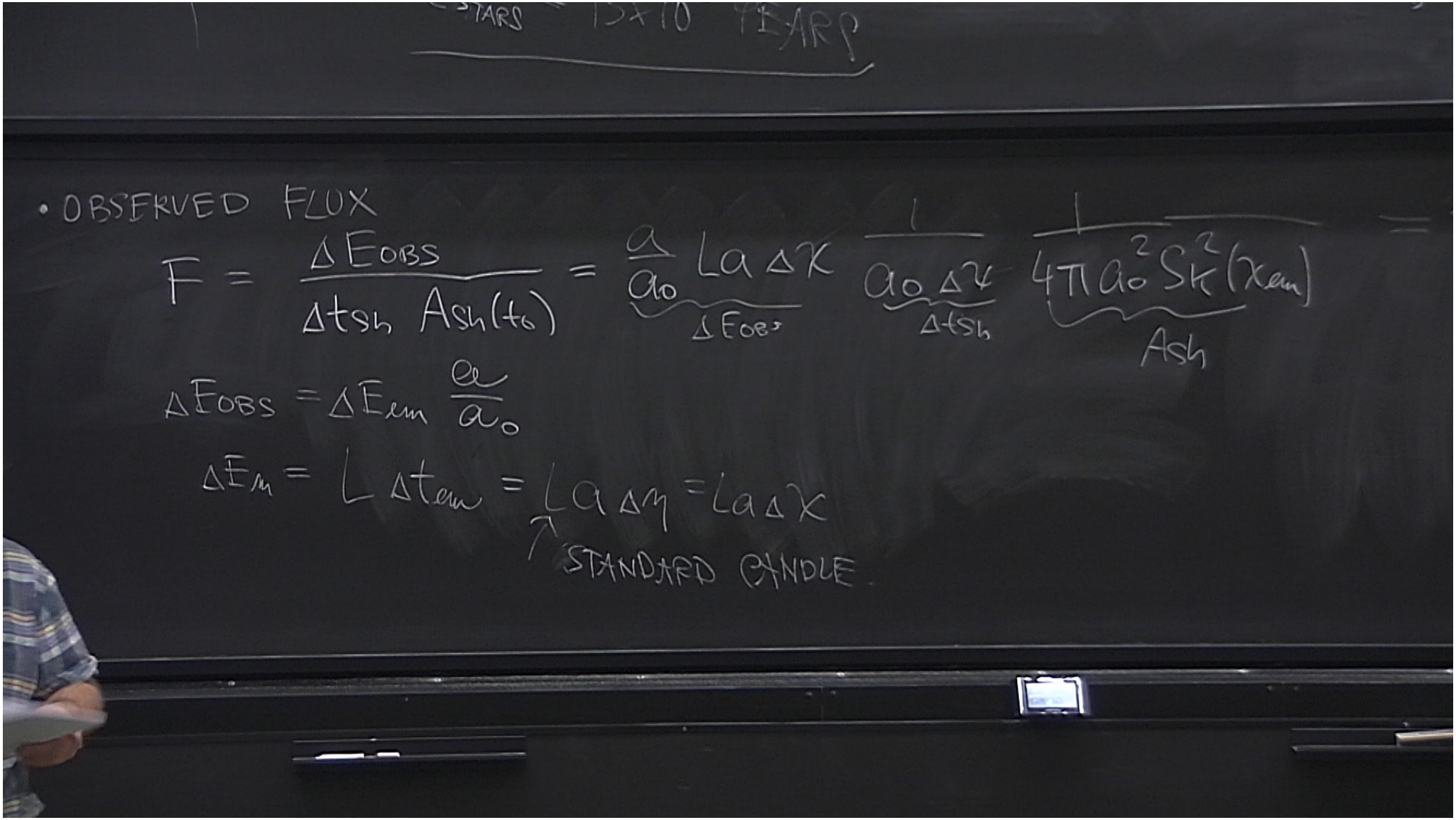
$$m_\chi \leq \frac{1}{4} \frac{h^2}{0.08} \frac{g_{s,f}}{g_\chi} \, eV$$

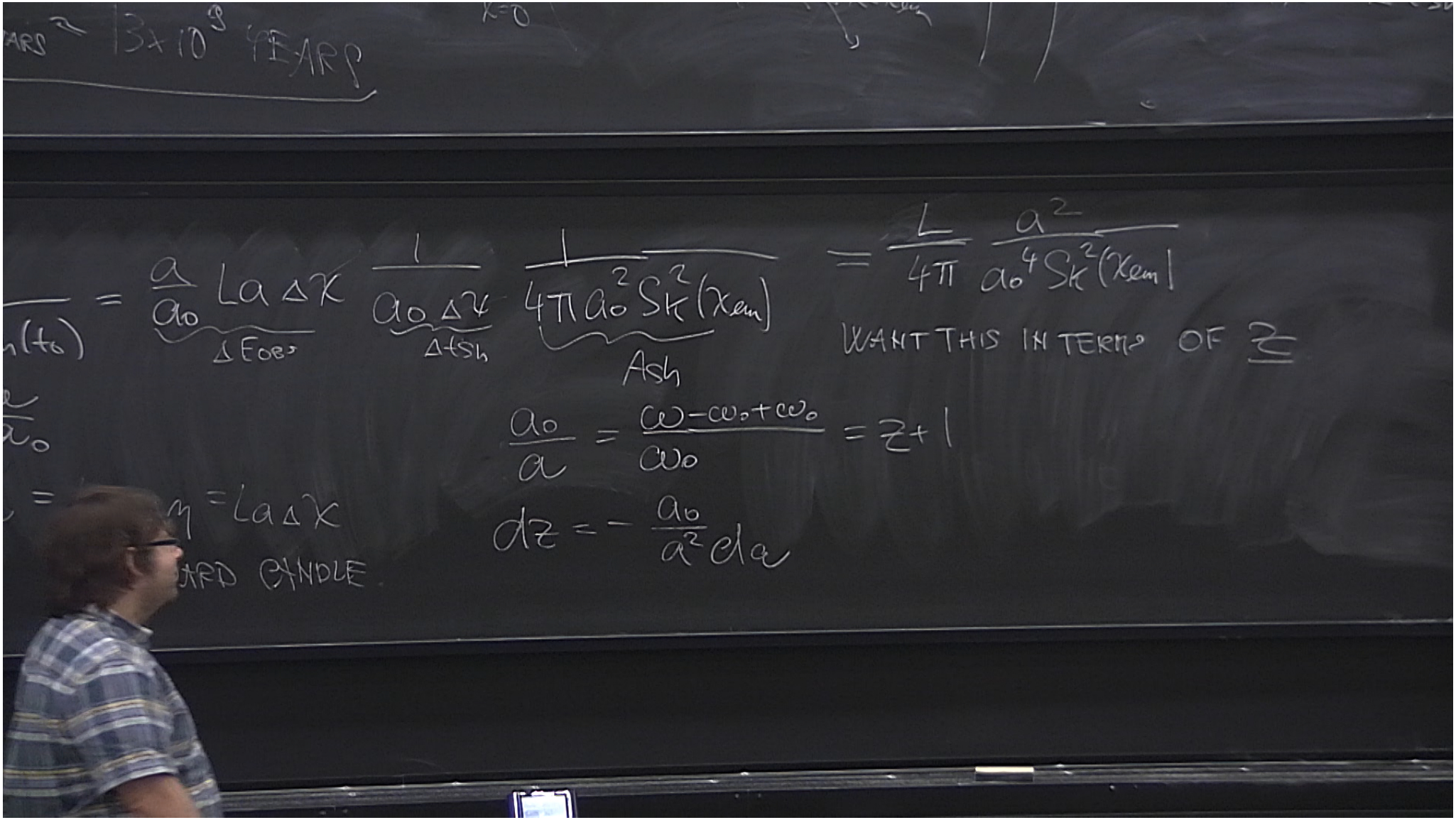
$$\frac{1}{4} \frac{h^2}{0.08} \simeq 1$$

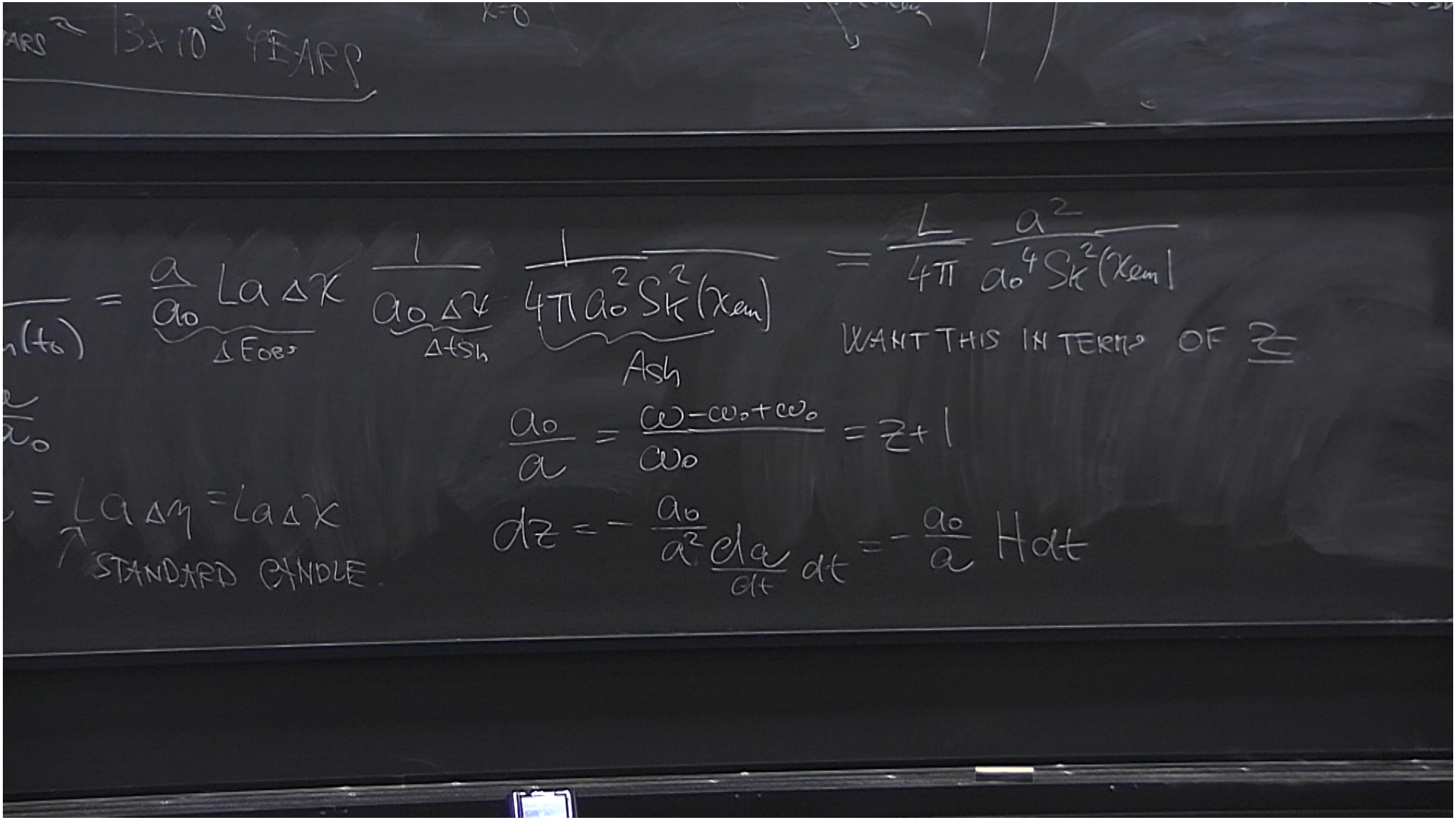

$\frac{g_x}{g_{sf}} \frac{0.08}{h^2} \frac{m_\nu}{eV} \leq \frac{1}{4}$
$\times 10^{-42}$) h GeV
35×10^{-13} GeV
BEFORE BBN
eV
10 eV.
TOO SMALL TO REPRODUCE
(a)


f) DARK ENERGY
• 1980's "SOMETHING FISHY"
$\rho_b + \rho_{DM} \simeq 0.3\rho_c \Rightarrow k=-1$
$\Rightarrow t = 8\times10^9$ YEARS OLD UNIVERSE.
GLOBULAR CLUSTER (10^5 STARS)
$t_{STARS} \simeq 13\times10^9$ YEARS


• SUPERNOVAE Ia OBSERVATIONS (NP. 2011)
"DISTANCE VS. REDSHIFT MEASUREMENT"
FRW: $ds^2 = a^2(\eta)\left[-d\eta^2 + d\chi^2 + S_k^2(\chi)\,d\Omega^2\right]$
$A_{REA_{SH}} = 4\pi a_0^2 S_k^2(\chi_{em})$
$l_{SH} = a_0 \Delta\chi = \Delta t_{SH}$
$\chi = \chi_{em}$
$\chi = 0$
10^9 YEARS OLD UNIVERSE.
3×10^9 YEARS


STARS
• OBSERVED FLUX
$F = \frac{\Delta E_{OBS}}{\Delta t_{sh}\, A_{sh}(t_0)} = \frac{a}{a_0} \underbrace{L a \Delta\chi}_{\Delta E_{obs}} \frac{1}{\underbrace{a_0 \Delta\chi}_{\Delta t_{sh}}} \frac{1}{\underbrace{4\pi a_0^2 S_k^2(\chi_{em})}_{A_{sh}}} =$
$\Delta E_{OBS} = \Delta E_{em} \frac{a}{a_0}$
$\Delta E_m = L \Delta t_{em} = L a \Delta\eta = L a \Delta\chi$
STANDARD CANDLE


$\approx 3\times10^9$ YEARS
$k=0$
$= \frac{a}{a_0} L a \Delta\chi \frac{1}{a_0 \Delta\chi} \frac{1}{4\pi a_0^2 S_k^2(\chi_{em})} = \frac{L}{4\pi} \frac{a^2}{a_0^4 S_k^2(\chi_{em})}$
ΔE_{obs}
Δt_{sh}
A_{sh}
WANT THIS IN TERMS OF z
$\frac{a_0}{a} = \frac{\omega - \omega_0 + \omega_0}{\omega_0} = z+1$
$\eta = La\Delta\chi$
$dz = -\frac{a_0}{a^2} da$


3×10^9 YEARS
k=0
= a/a0 La Δχ 1/(a0 Δχ) 1/(4π a0^2 Sk^2(χem)) = L/4π a^2/(a0^4 Sk^2(χem))
ΔEobs
Δtsh
Ash
WANT THIS IN TERMS OF z
a0/a = (ω−ω0+ω0)/ω0 = z+1
= La Δη = La Δχ
STANDARD CANDLE
dz = − a0/a^2 da/dt dt = − a0/a H dt