Title: Particle Physics Lecture

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Collection: Particle Physics

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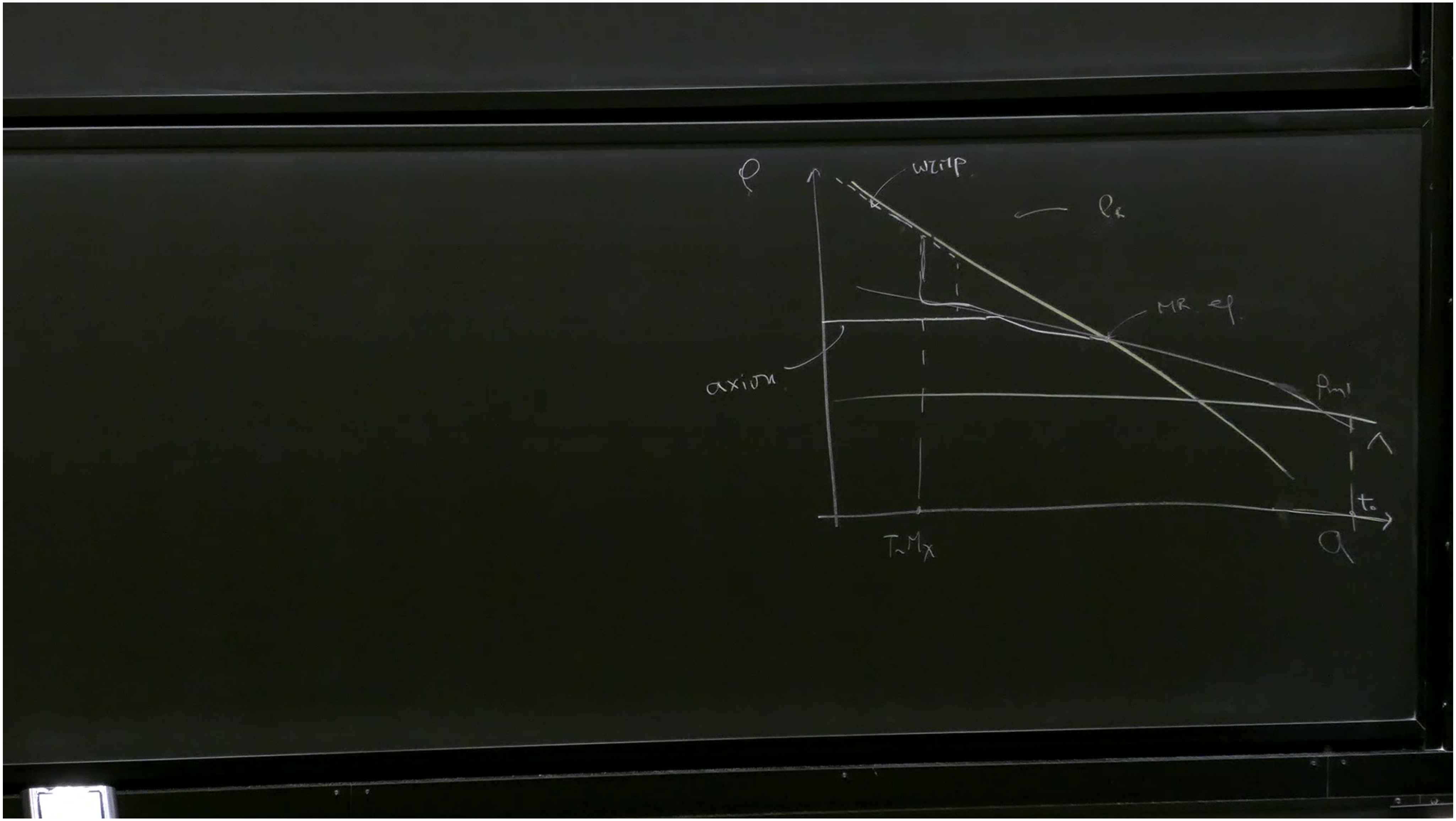
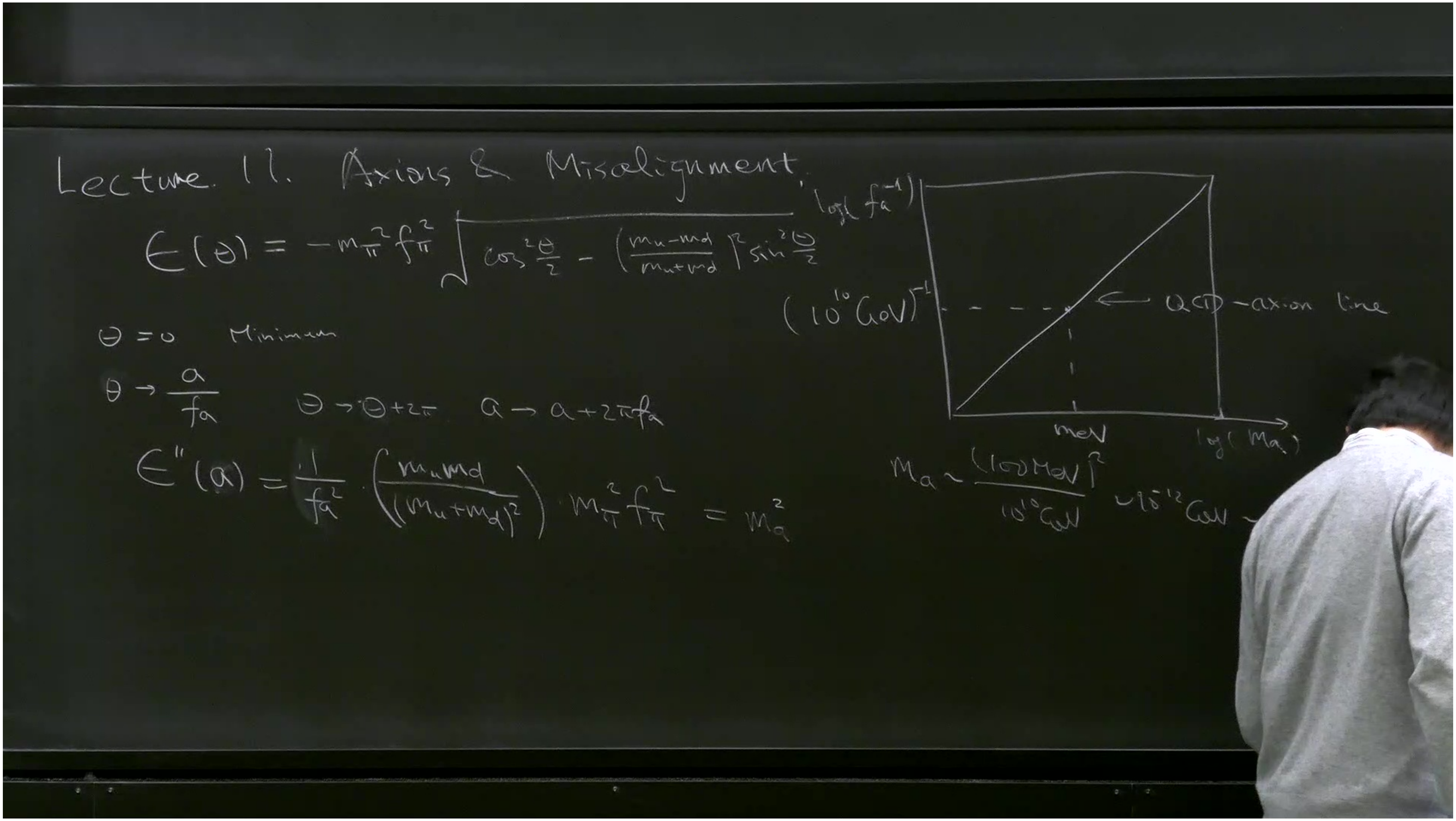
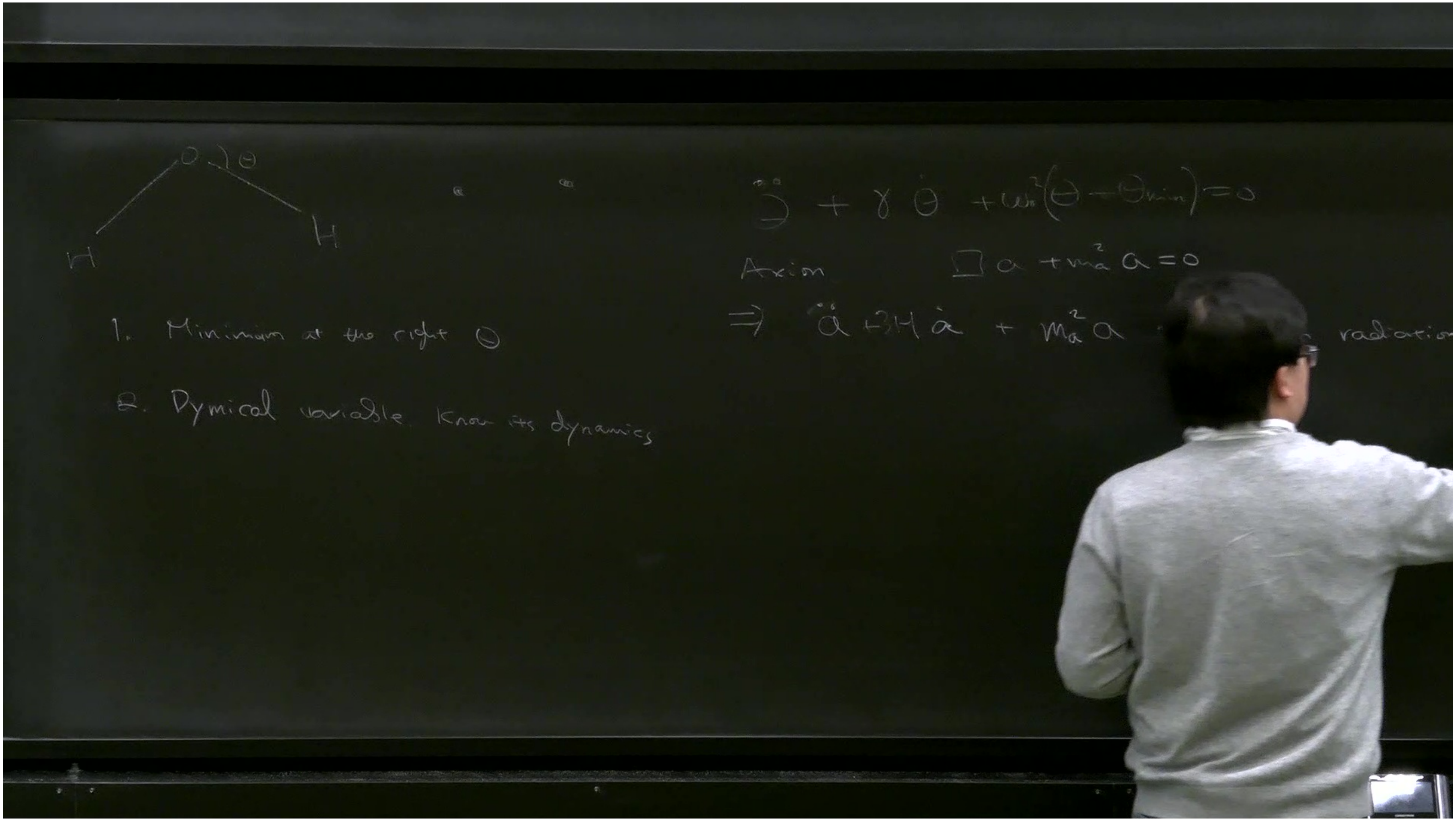
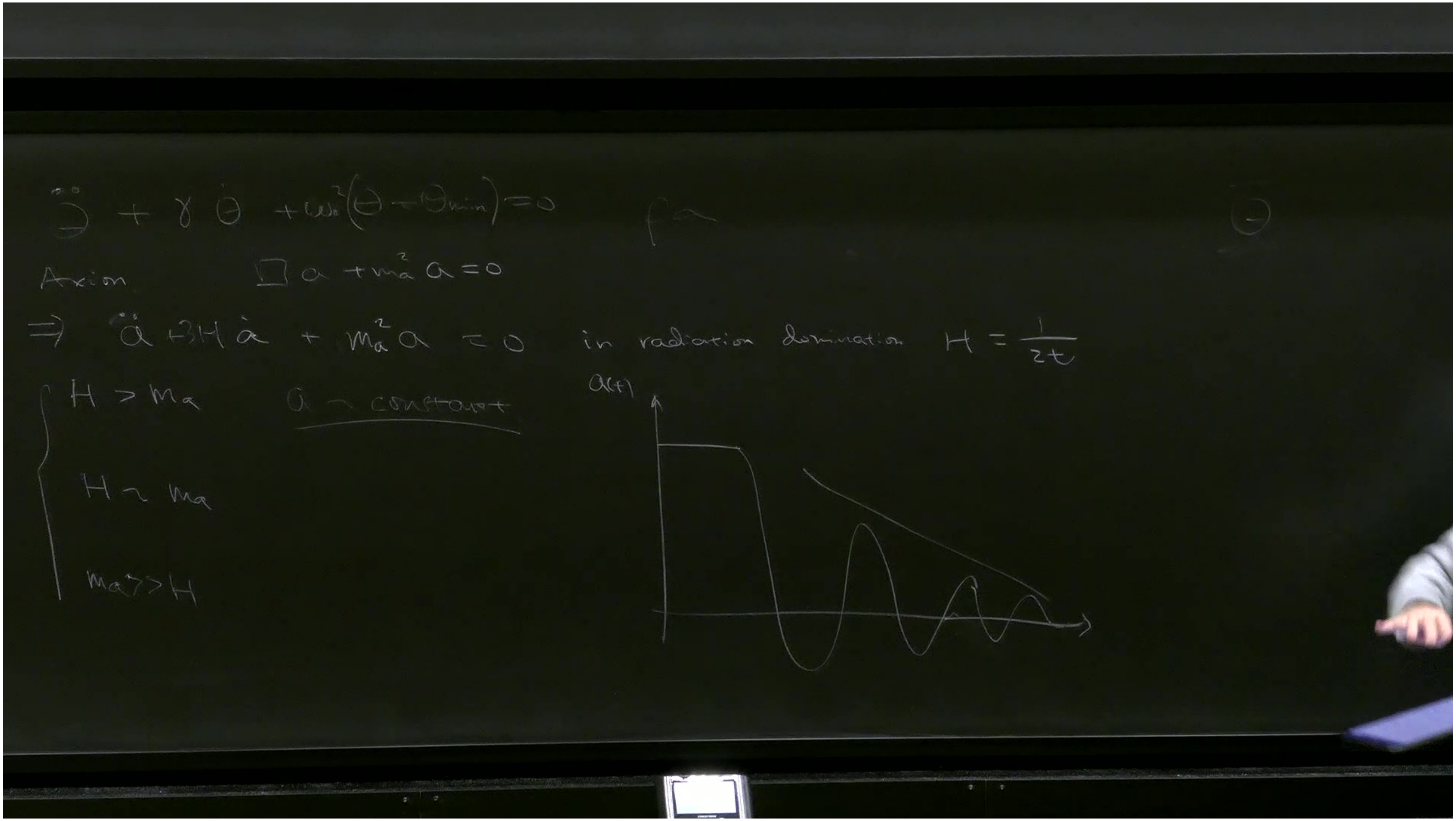


ρ
wimp
ρ_r
MR eq.
axion
ρ_m
Λ
t_0
$T \sim M_X$
a

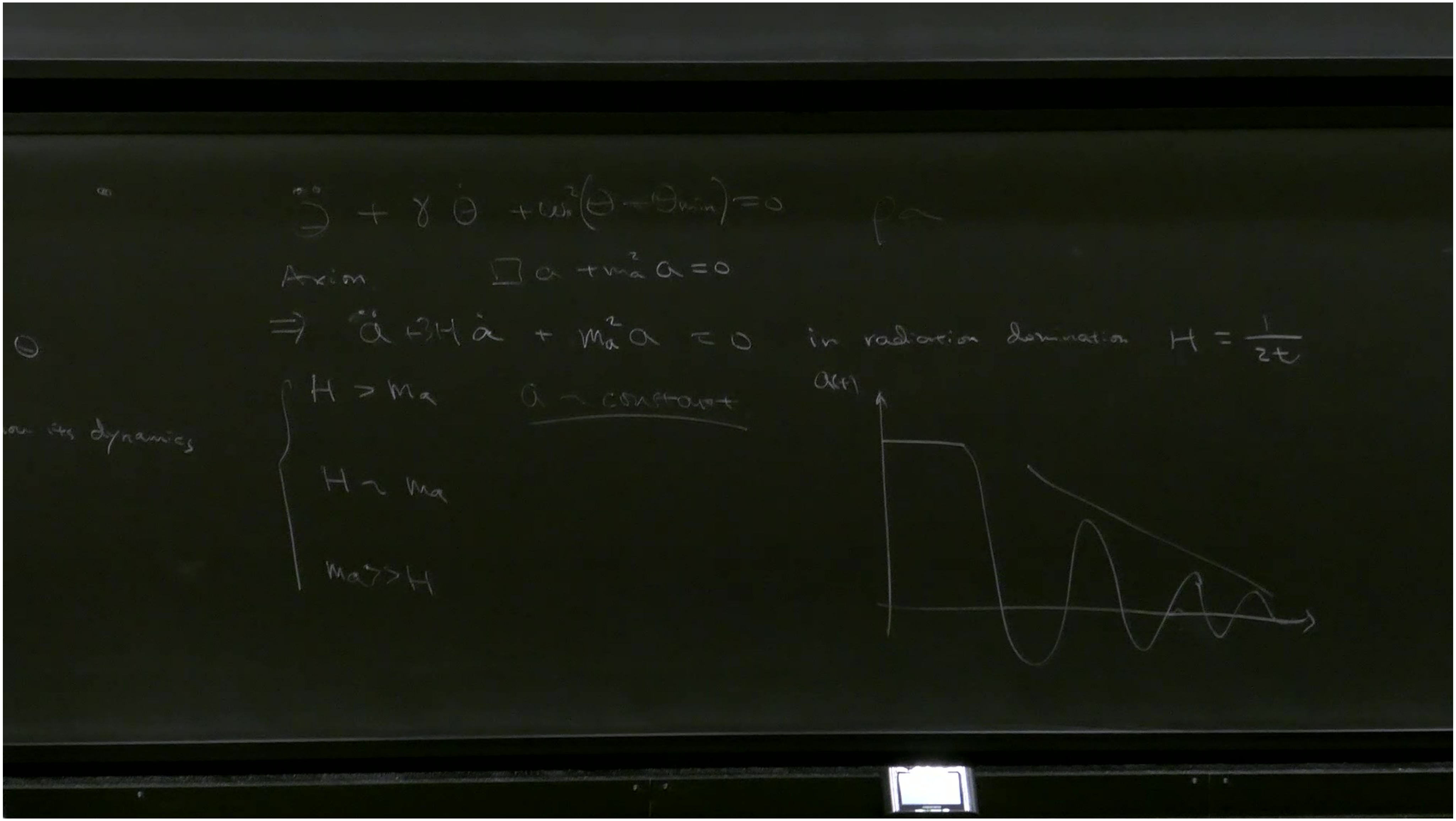

Lecture 11. Axions & Misalignment.
$E(\theta) = -m_\pi^2 f_\pi^2 \sqrt{\cos^2\frac{\theta}{2} - \left(\frac{m_u - m_d}{m_u + m_d}\right)^2 \sin^2\frac{\theta}{2}}$
$\theta = 0$ Minimum
$\theta \to \frac{a}{f_a}$
$\theta \to \theta + 2\pi$ $a \to a + 2\pi f_a$
$E''(a) = \frac{1}{f_a^2}\left(\frac{m_u m_d}{(m_u+m_d)^2}\right) m_\pi^2 f_\pi^2 = m_a^2$
$\log(f_a^{-1})$
$(10^{10}\,\mathrm{GeV})^{-1}$
QCD-axion line
meV
$\log(m_a)$
$m_a \sim \frac{(100\,\mathrm{MeV})^2}{10^{10}\,\mathrm{GeV}} \sim 10^{-12}\,\mathrm{GeV}$

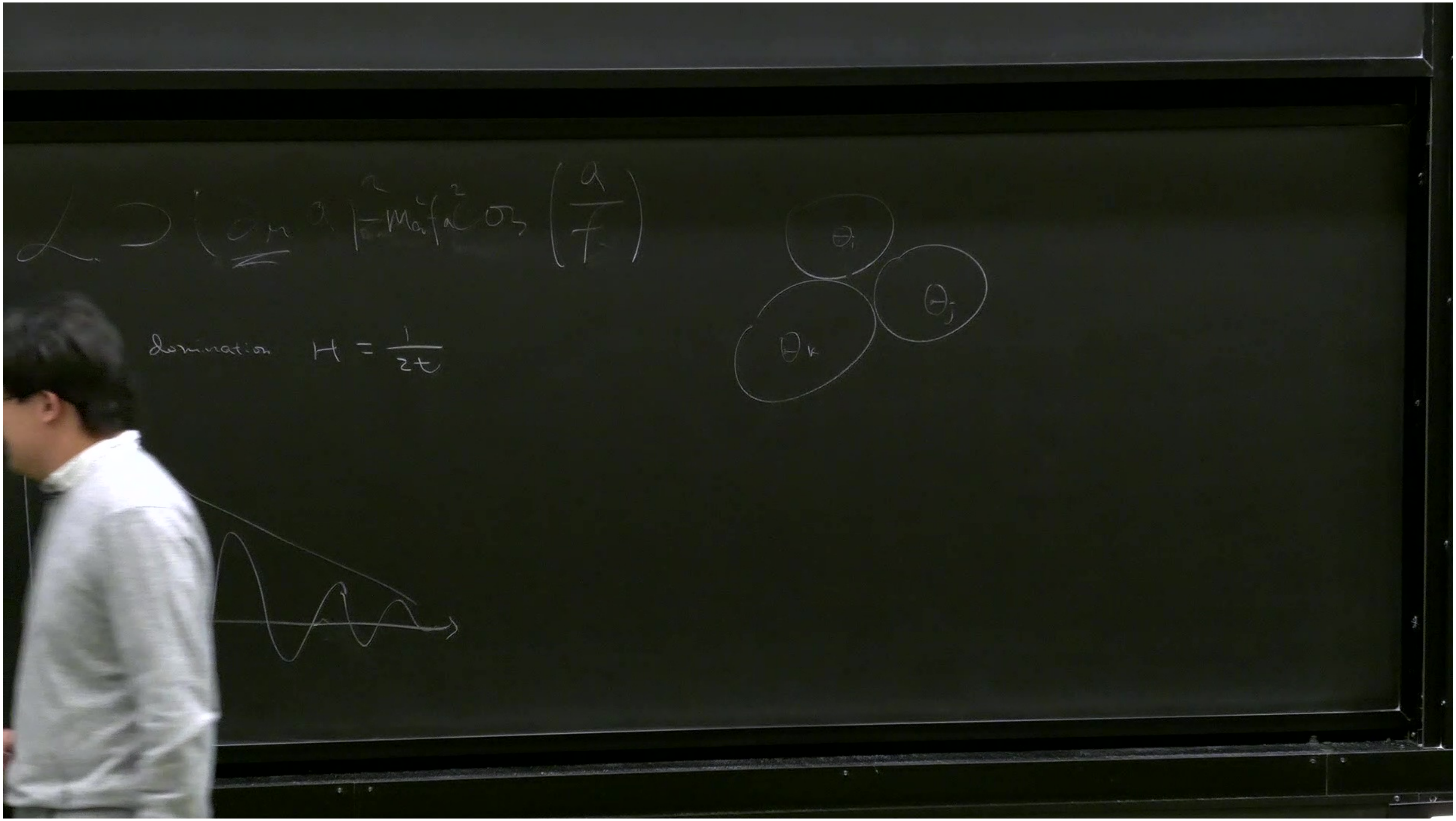


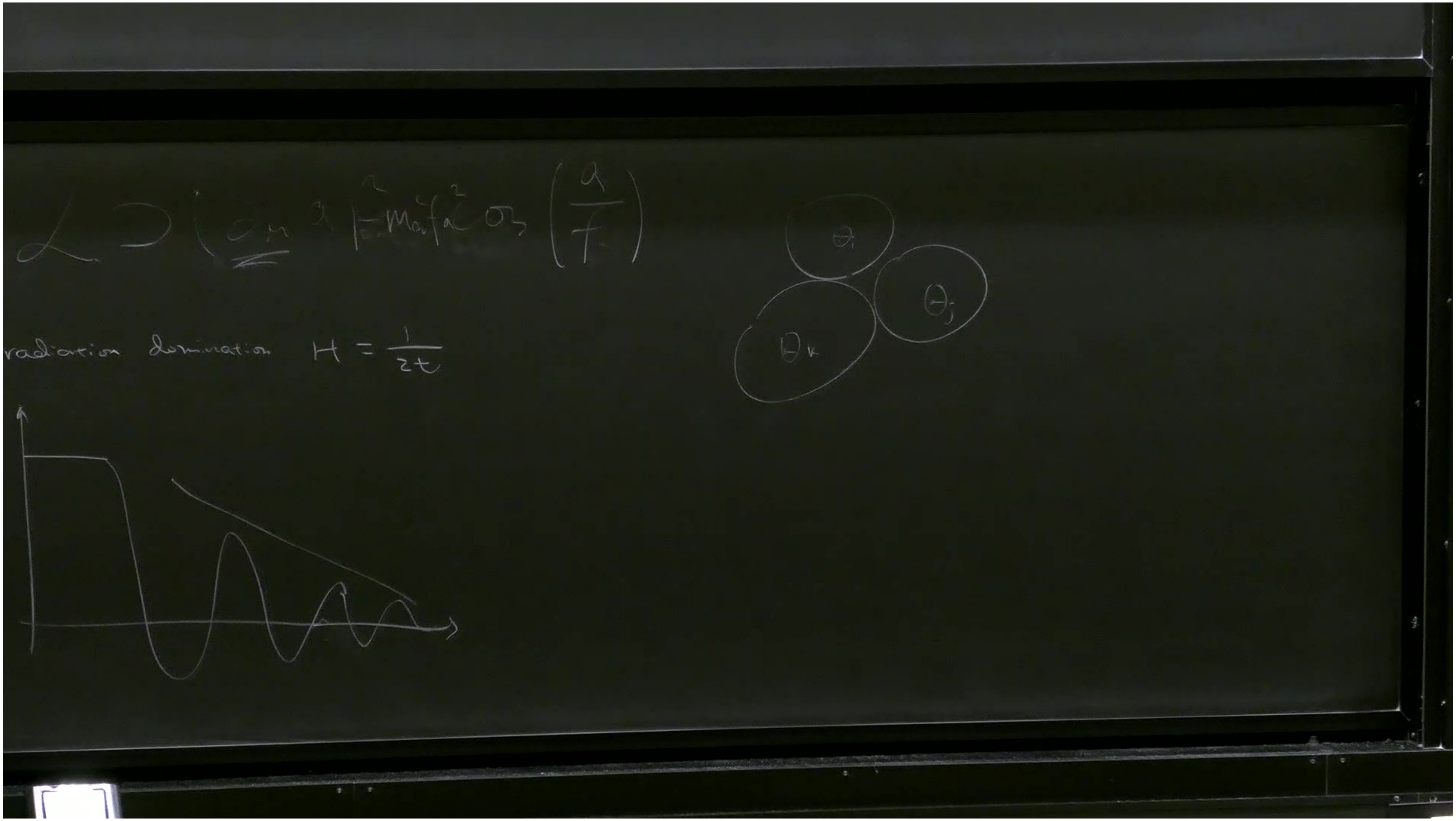
H
H
$\ddot{\theta} + \gamma \dot{\theta} + \omega_0^2(\theta - \theta_{min}) = 0$
Axion
$\Box a + m_a^2 a = 0$
$\Rightarrow \ddot{a} + 3H\dot{a} + m_a^2 a$
radiation
1. Minimum at the right θ
2. Dymical variable. Know its dynamics

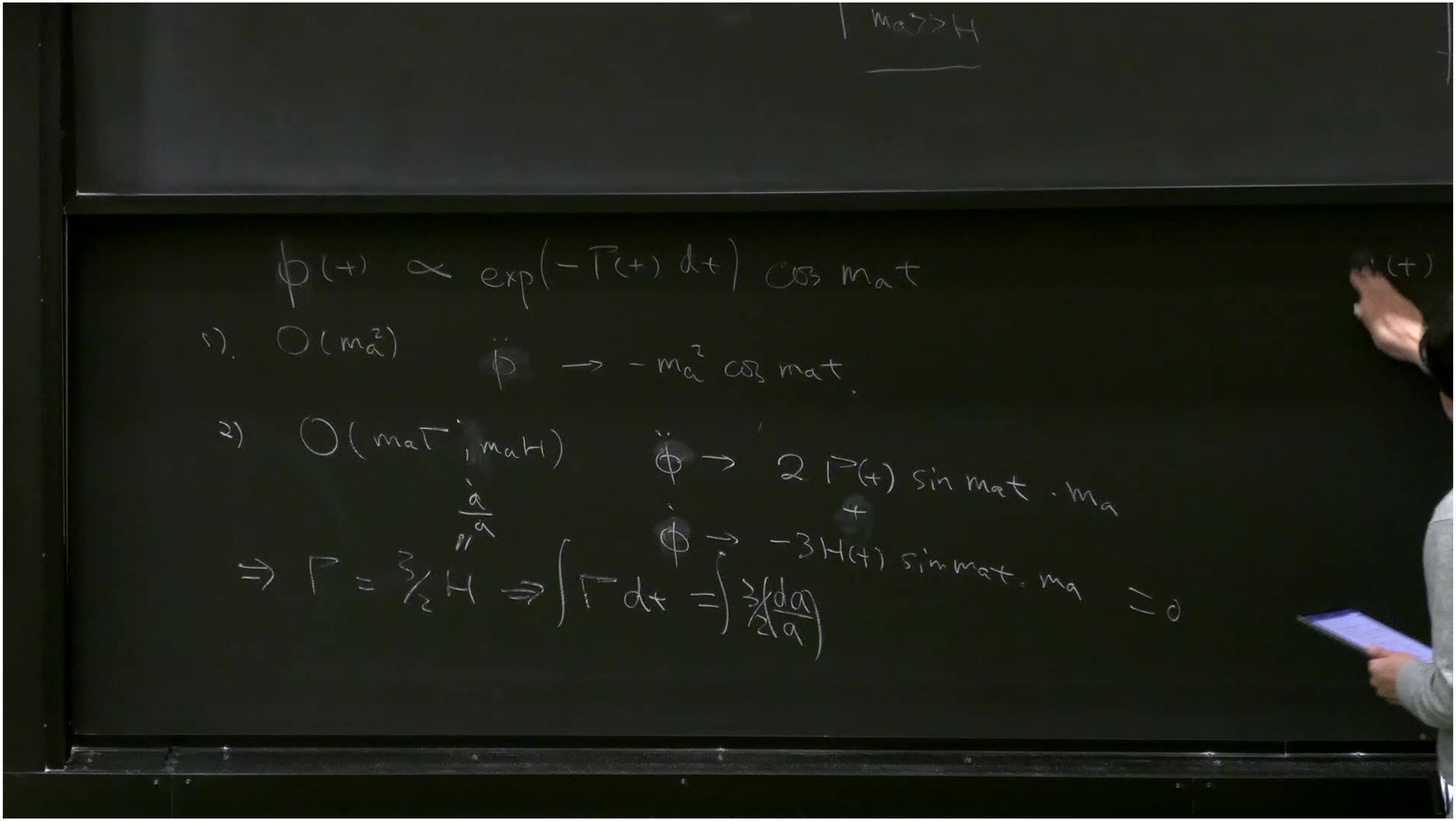


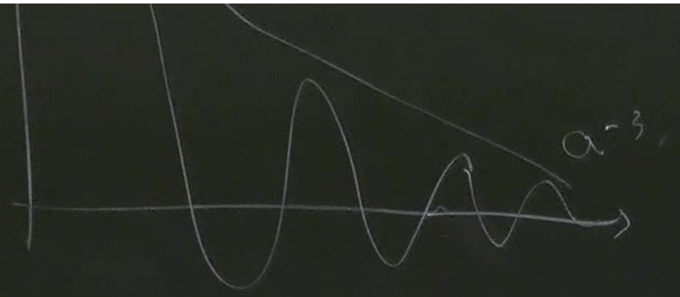
$\ddot{\theta} + \gamma\dot{\theta} + \omega_0^2(\theta - \theta_{min}) = 0$
f_a
Axion
$\Box a + m_a^2 a = 0$
$\Rightarrow \ddot{a} + 3H\dot{a} + m_a^2 a = 0$
in radiation domination $H = \frac{1}{2t}$
$H > m_a$
$a \sim$ constant
$H \sim m_a$
$m_a >> H$
$a(t)$


θ̈ + γ θ̇ + ω²(θ − θmin) = 0
Axion
□a + ma² a = 0
⇒ ä + 3H ȧ + ma² a = 0
in radiation domination H = 1/2t
H > ma
a ~ constant
H ~ ma
ma >> H
a(t)
its dynamics


domination
H = 1/2t
θi
θj
θk


radiation domination H = 1/2t
θi
θj
θk


ma >> H
φ(t) ∝ exp(−Γ(t) dt) cos ma t
(t)
1). O(ma²)   φ̈ → −ma² cos mat.
2) O(maΓ, maH)   φ̈ → 2Γ(t) sin mat · ma
ȧ/a
+
φ̇ → −3H(t) sin mat · ma   = 0
⇒ Γ = 3/2 H ⇒ ∫Γ dt = ∫ 3/2 (da/a)



$$\phi(t) \simeq \left(\frac{a(H=m_a)}{a(t)}\right)^{3/2} \phi_0 \cos m_a t$$

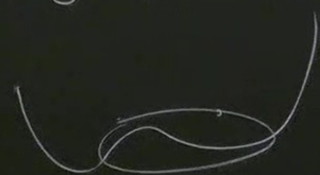
$$\rho_\phi = (\partial_t \phi)^2 + m_a^2 \phi^2$$

$$= \left(\frac{a(H=m_a)}{a(t)}\right)^3 \cdot \underbrace{m_a^2 \phi_0^2}_{} \quad \rho_0$$

This behavior is DM.

What is the density?

$\phi \to \phi + 2\pi f_a$



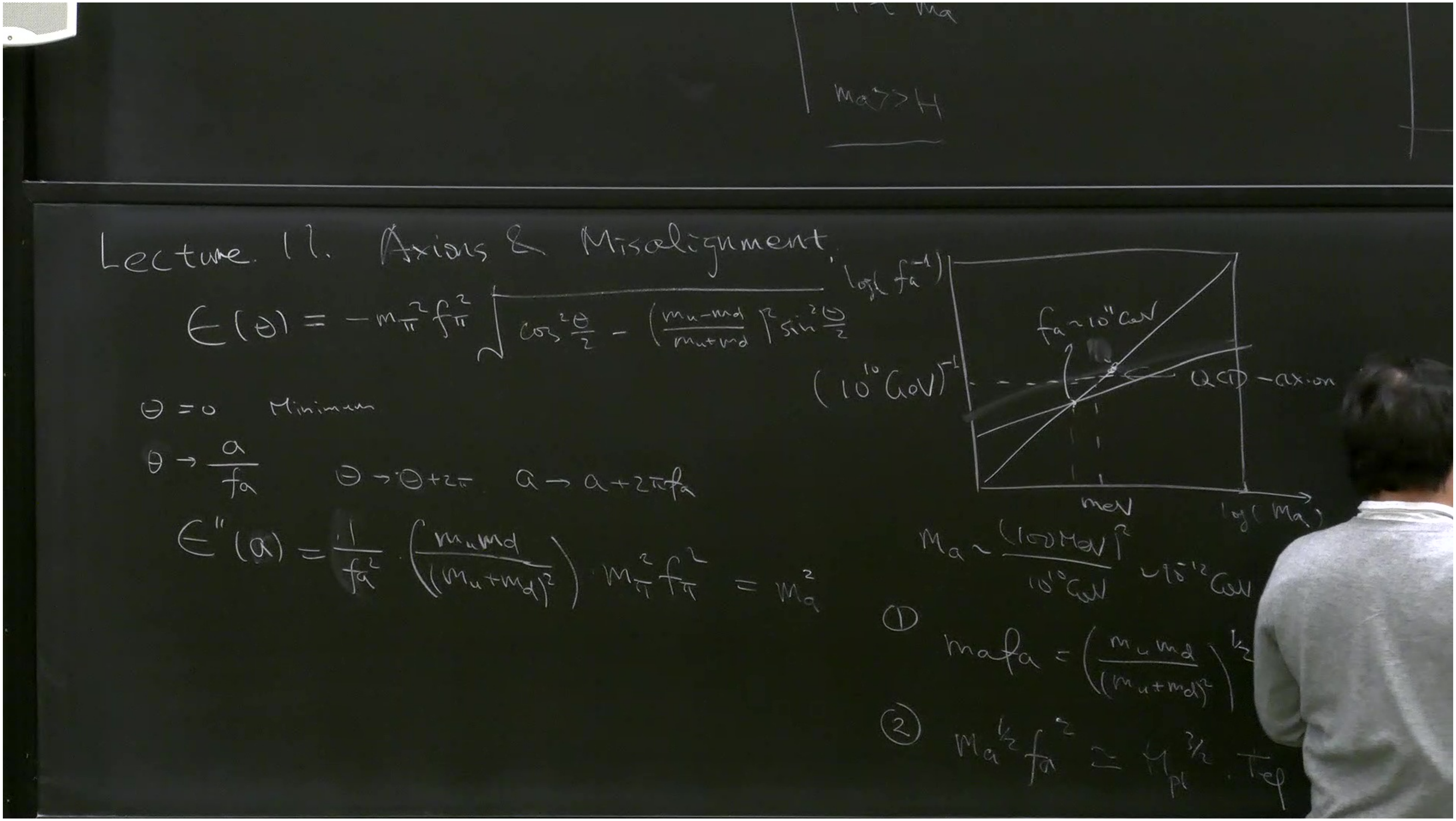
$\left[\theta_i - \theta_{min}^{"0"}\right] \sim 1 = \overline{\theta_i}$

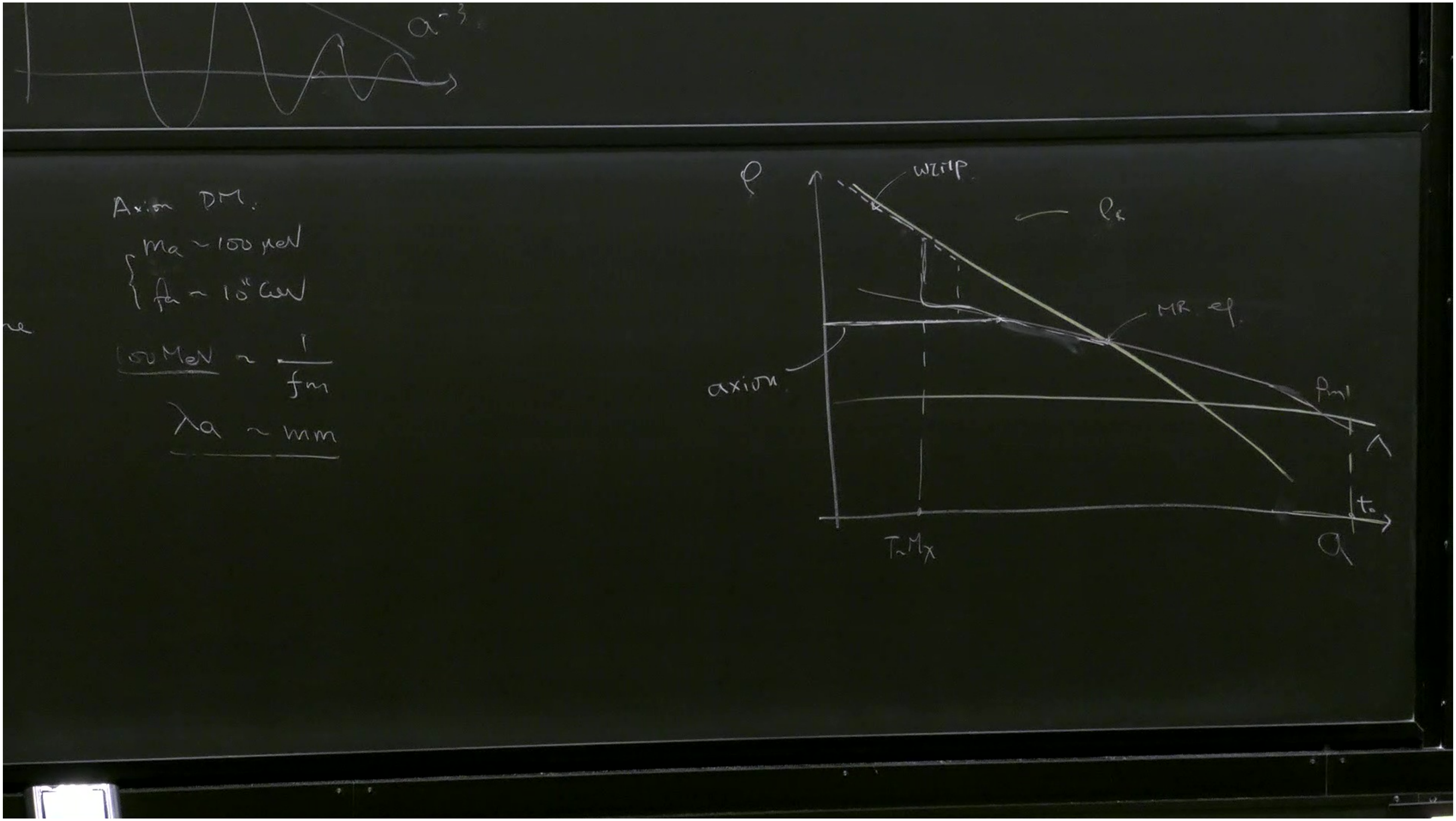
Initial condition persist until $m_a \simeq H$

$\rho_\phi = m_a^2 f_a^2 \cdot \overline{\theta_i}^2$ $\quad n_\phi(t) = m_a f_a^2 \overline{\theta_i}^2 \cdot \left(\frac{T(t)}{T(H=m_a)}\right)^3$

$\rho_M = \rho_\gamma$ @ MR equality.

$$\left.\frac{\rho_a}{\rho_\gamma}\right|_{T=T_{eq}} = \left(\frac{n_\phi}{n_\gamma}\right) \cdot \frac{m_\phi}{T_{eq}} = \frac{m_a^{1/2} \cdot f_a^2 \overline{\theta_i}^2}{M_{pl}^{3/2} \cdot T_{eq}} \sim 1$$


Ma >> H
Lecture 11. Axions & Misalignment.
E(θ) = −mπ² fπ² √(cos² θ/2 − ((mu−md)/(mu+md))² sin² θ/2)
θ = 0 Minimum
θ → a/fa   θ → θ+2π   a → a+2πfa
E''(a) = 1/fa² (mu md/(mu+md)²) mπ² fπ² = ma²
log(fa⁻¹)
fa ~ 10¹¹ GeV
(10¹⁰ GeV)⁻¹
QCD−axion
meV
log(Ma)
Ma ~ (100 MeV)²/10¹⁰ GeV ~ 10⁻¹² GeV
① mafa = (mu md/(mu+md)²)^½
② Ma^½ fa² ≃ Mpl^3/2 . Teq


a^-3
Axion DM:
m_a ~ 100 μeV
f_a ~ 10^11 GeV
100 MeV ~ 1/fm
λ_a ~ mm
ρ
WIMP
ρ_r
MR eq.
axion
ρ_ml
Λ
t_0
T~M_X
a

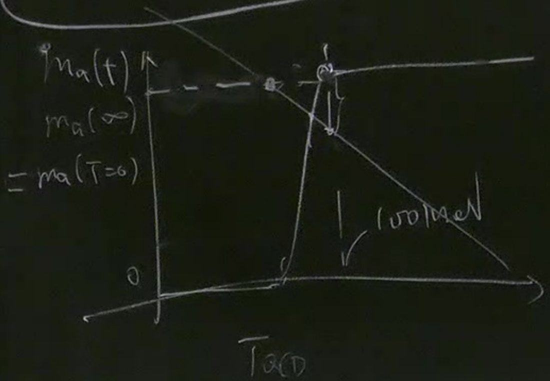
In reality m_a is not a constant if it is from QCD.

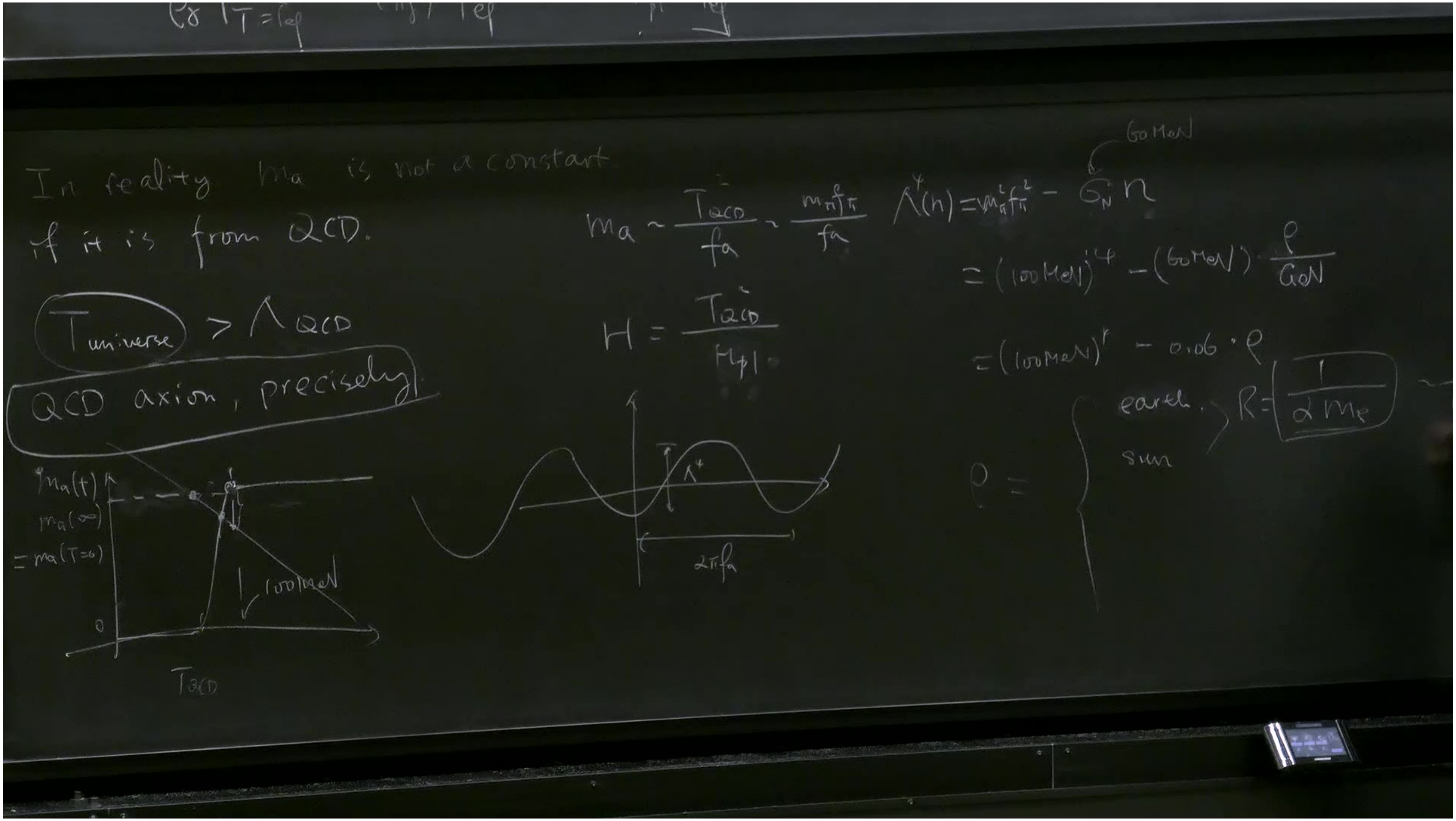
$T_{universe} > \Lambda_{QCD}$

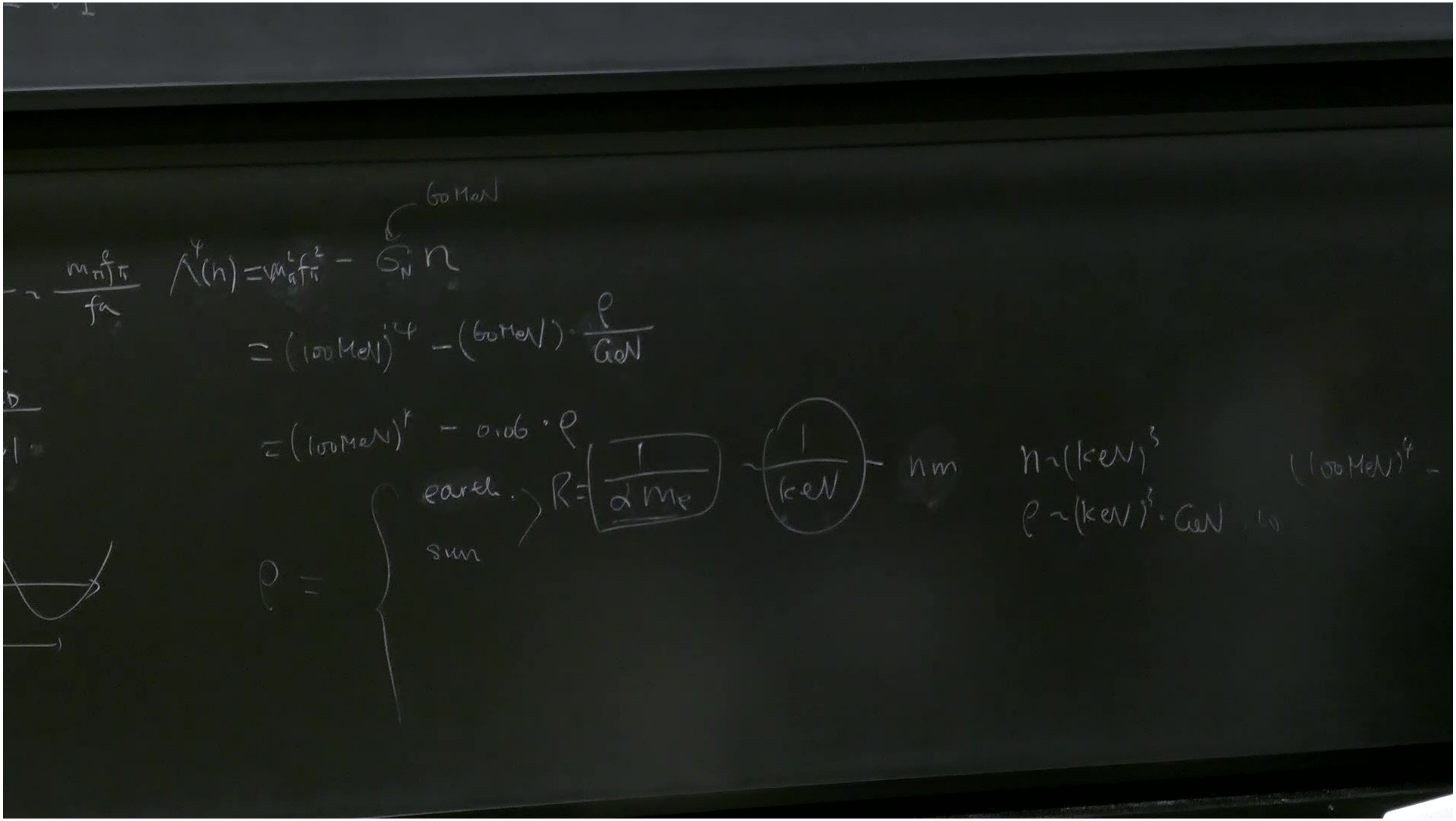
QCD axion, precisely

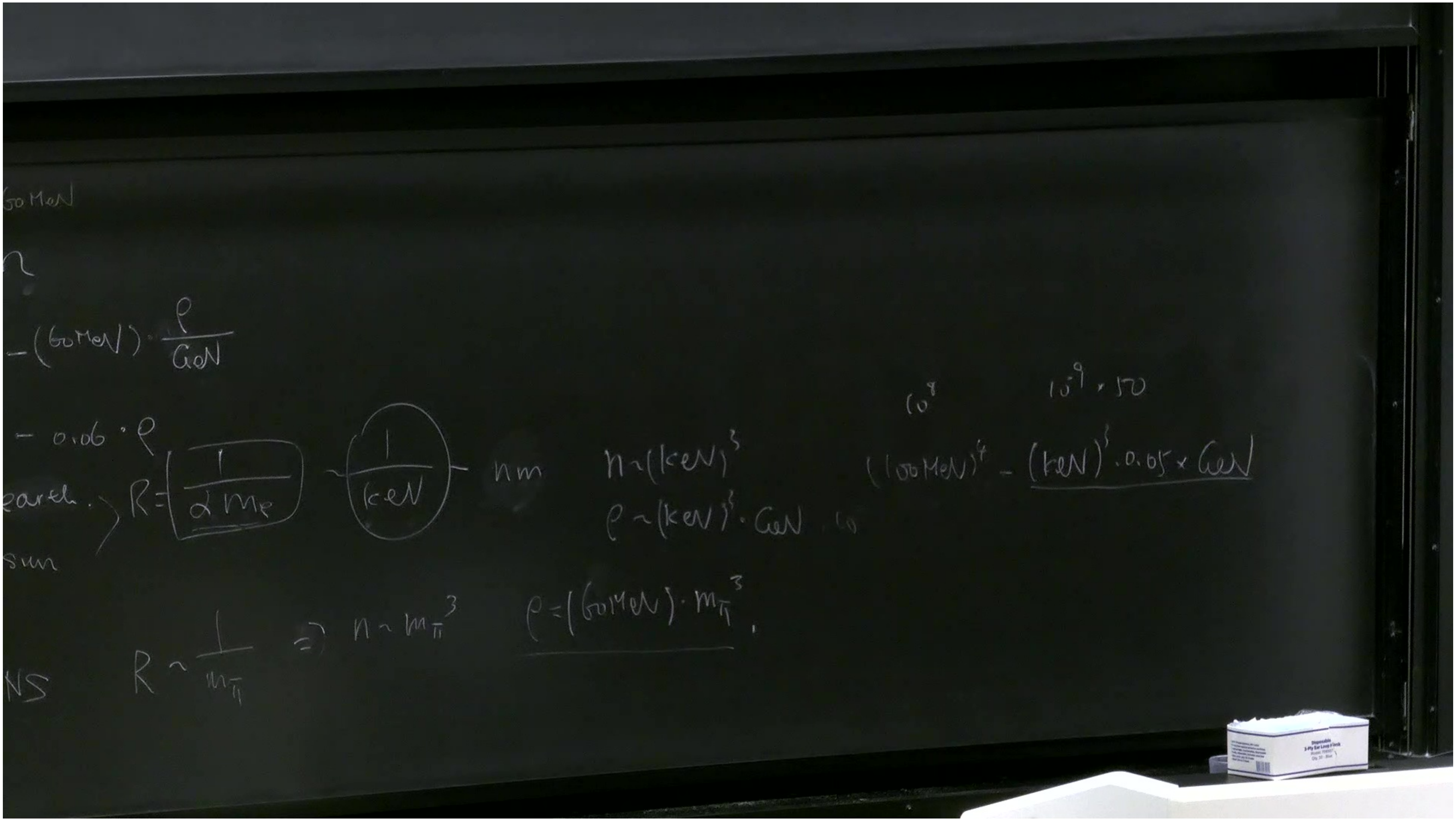
$$m_a \sim \frac{T_{QCD}^2}{f_a} \sim \frac{m_\pi f_\pi}{f_a}$$

$$H = \frac{T_{QCD}^2}{M_{pl}}$$

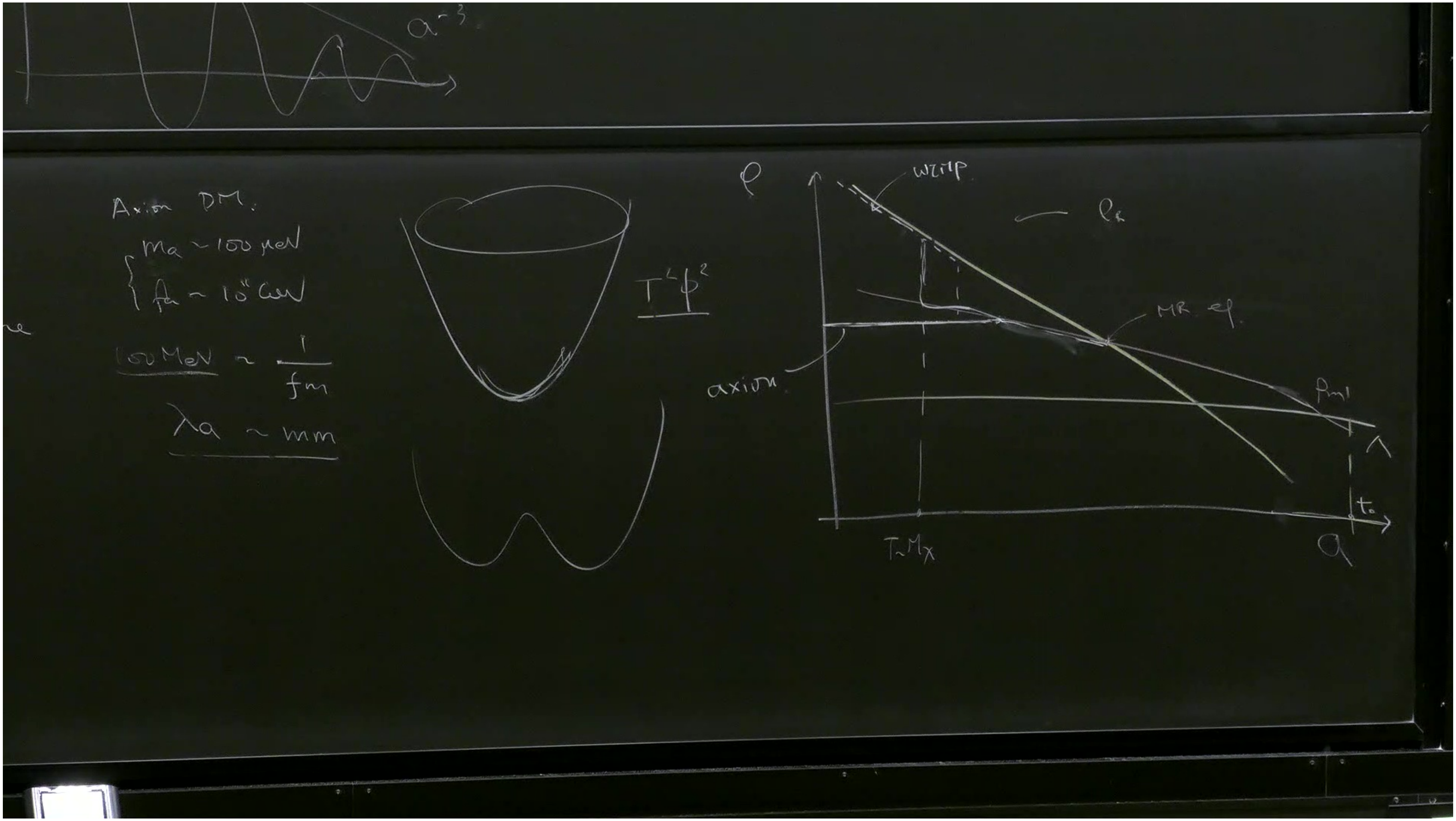



In reality ma is not a constant
if it is from QCD.
Tuniverse > Λ QCD
QCD axion, precisely.
ma(t)
ma(∞)
= ma(T=0)
100MeV
TQCD
ma ~ TQCD²/fa ~ mπ²fπ²/fa
H = TQCD²/Mpl
Λ⁴
2πfa
60MeV
Λ⁴(n) = mπ²fπ² − σN n
= (100MeV)⁴ − (60MeV)³ · ρ/GeV
= (100MeV)⁴ − 0.06 · ρ
earth
sun
R = 1/(α me)
ρ =


60 MeV
Λ⁴(n) = m_π² f_π² − σ_N n
m_π f_π / f_a
= (100 MeV)⁴ − (60 MeV) · ρ / GeV
= (100 MeV)⁴ − 0.06 · ρ
earth
sun
ρ =
R = 1 / α m_e ~ 1 / keV ~ nm
n ~ (keV)³
ρ ~ (keV)³ · GeV
(100 MeV)⁴



60 MeV
(60 MeV) · ρ / GeV
0.06 · ρ
earth
sun
R = 1 / α m_e ~ 1 / keV ~ nm
n ~ (keV)^3
ρ ~ (keV)^3 · GeV
10^8
10^9 × 50
(100 MeV)^4 ~ (keV)^3 · 0.05 × GeV
NS
R ~ 1 / m_π ⇒ n ~ m_π^3
ρ = (60 MeV) · m_π^3


a^-3
Axion DM:
ma ~ 100 μeV
fa ~ 10^11 GeV
100 MeV ~ 1/fm
λa ~ mm
T²φ²
ρ
WIMP
ρR
MR eq.
axion
Λ
t0
a
T~MX