Title: Non thermal DM/Misalignment

Speakers: Giovanni Villadoro

Collection: School on Table-Top Experiments for Fundamental Physics

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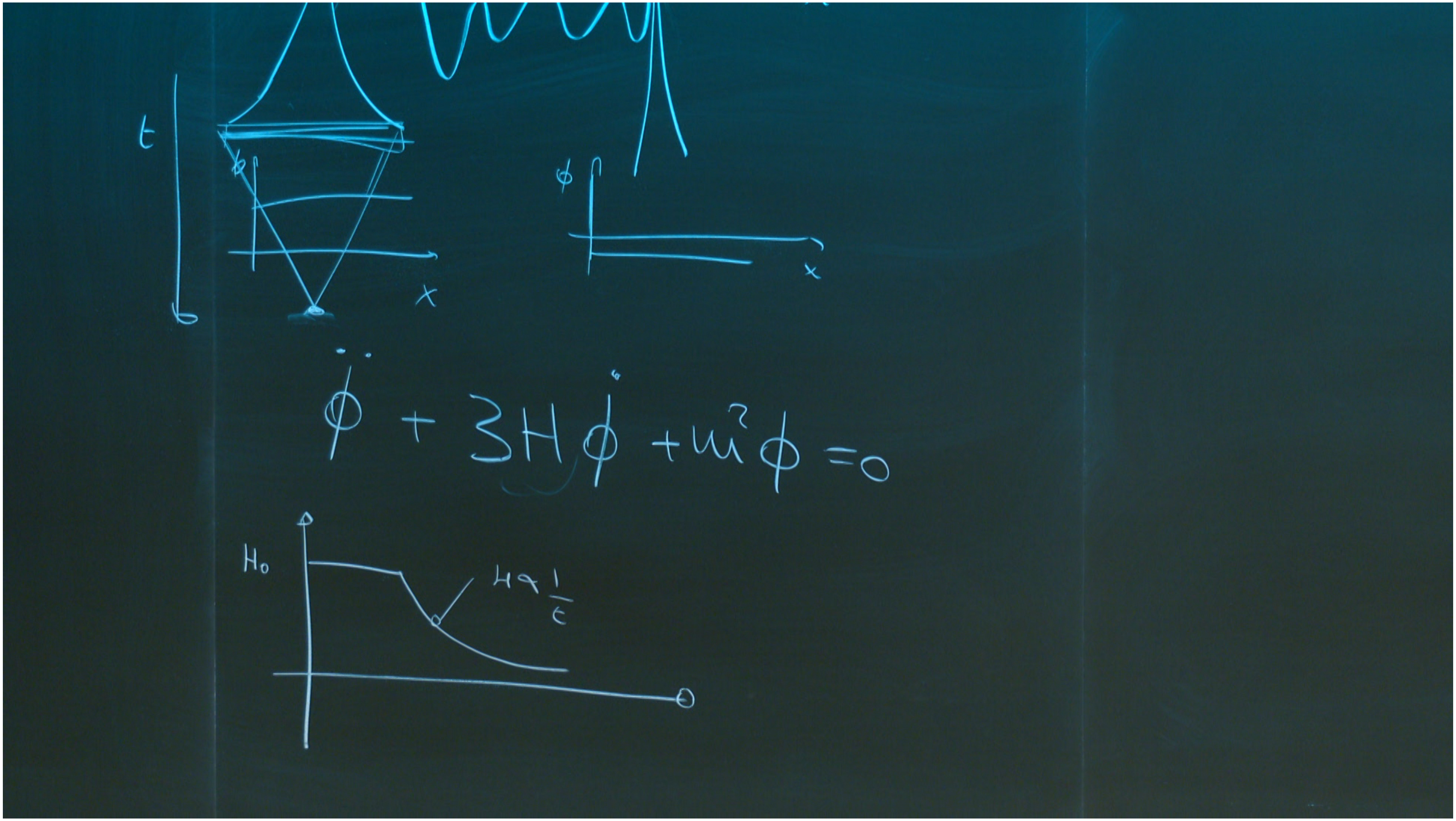
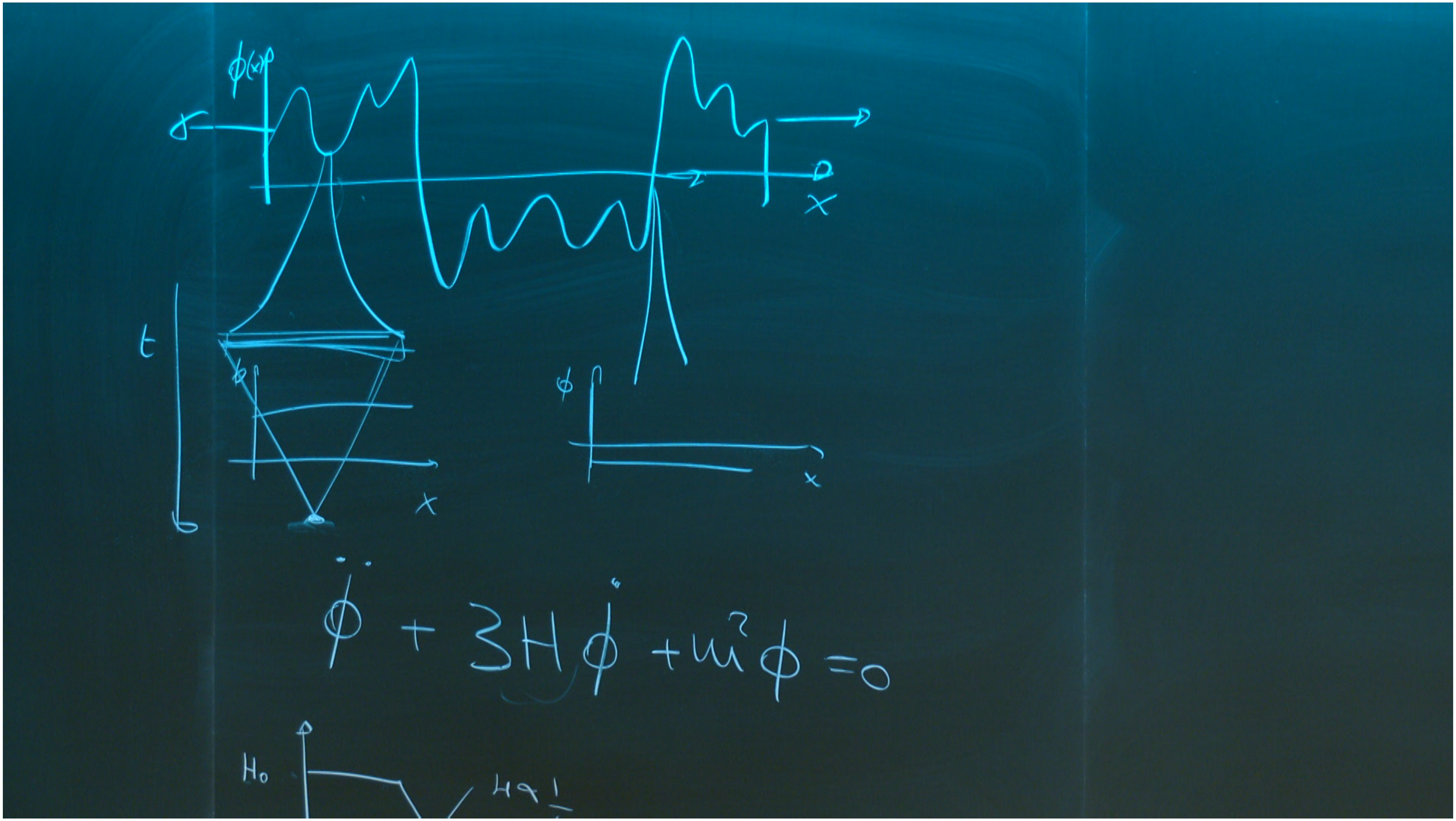
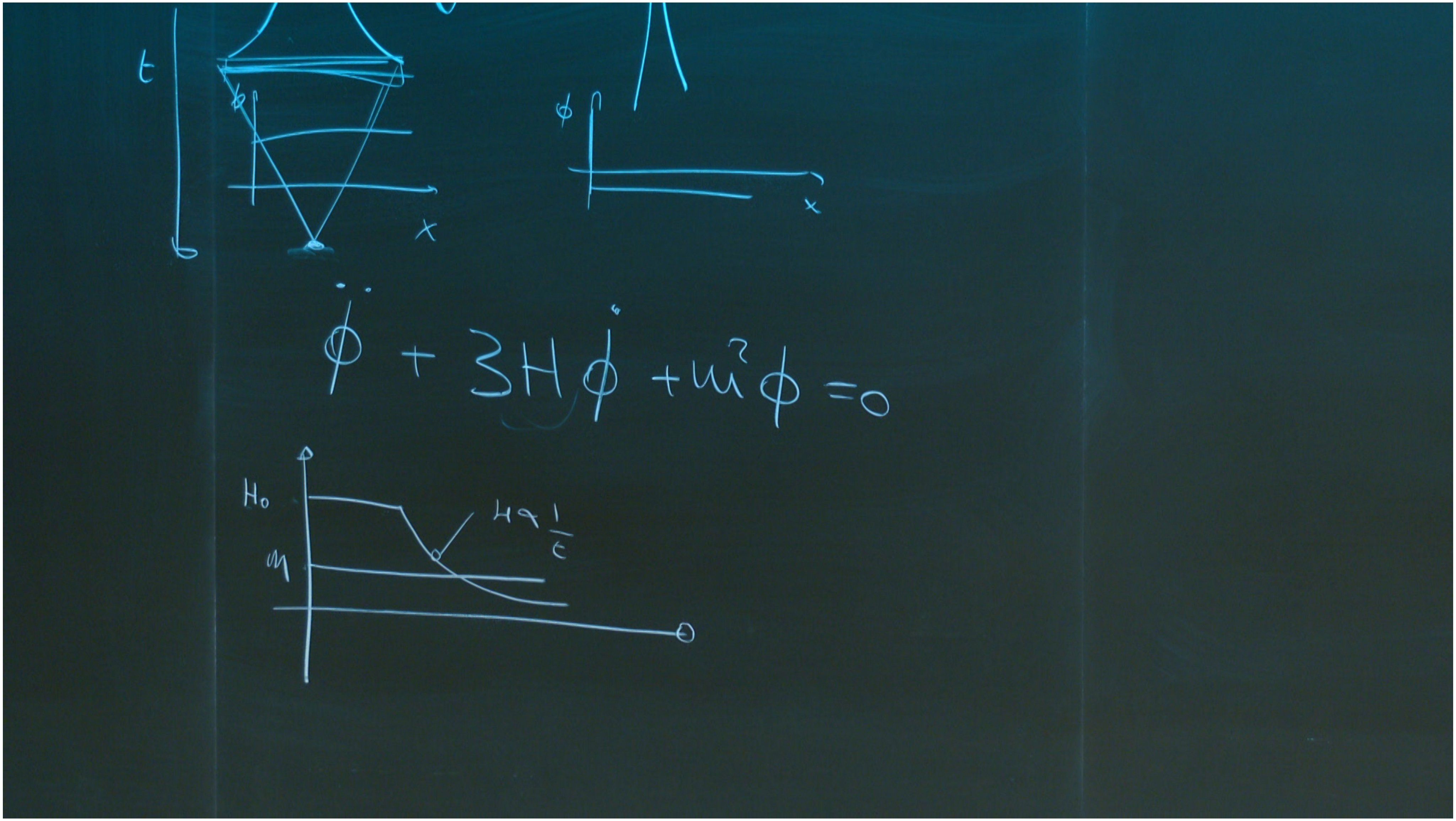
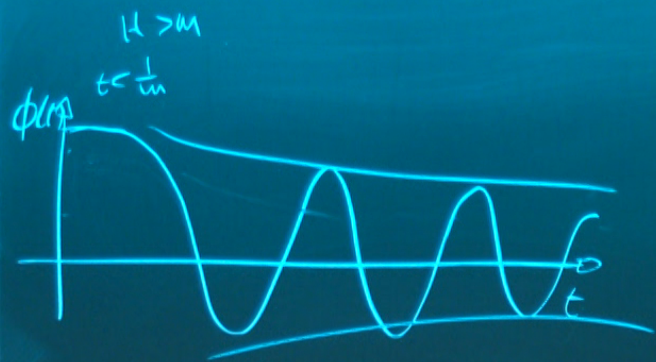
URL: https://pirsa.org/22090008

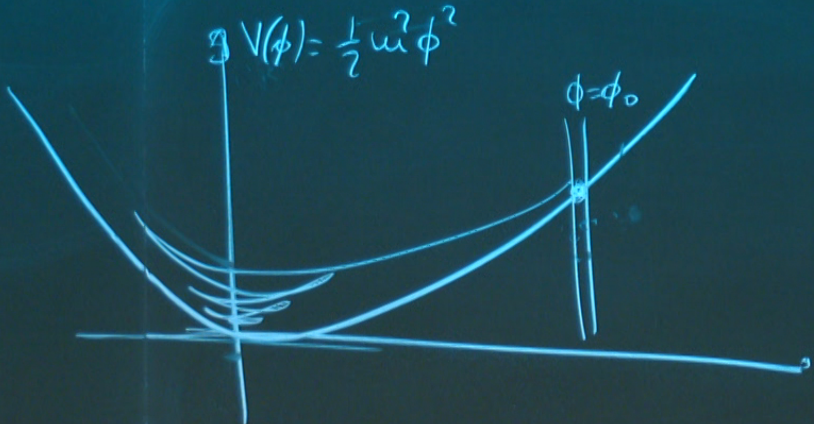

t
ϕ
x
ϕ
x
$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$
H_0
$H \propto \frac{1}{t}$



ϕ(x)
x
t
ϕ
x
ϕ
x
$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$
H_0


t
φ
x
$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$
H_0
m
$H \propto \frac{1}{t}$
t

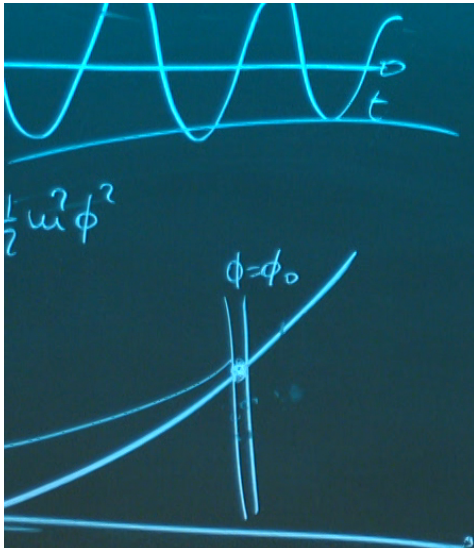




$$\phi(t) \equiv \frac{\psi(t)}{a^{3/2}(t)}$$

$$\ddot{\psi} + \Big(m^2 - \underbrace{\tfrac{3}{2}\dot{H}}_{\frac{1}{t^2}} - \underbrace{\tfrac{9}{4}H^2}_{\frac{1}{t^2}}\Big)\psi = 0$$

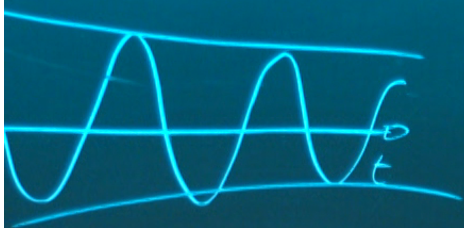
$$\psi = \psi_0 \cos(mt)$$

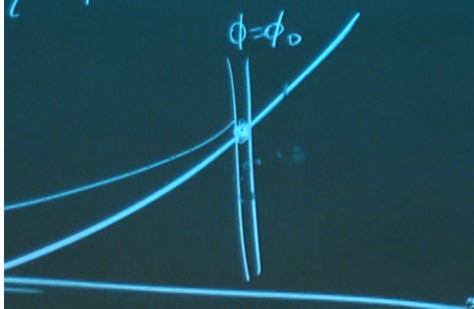


$$\ddot{\psi} + \Big(m^2 - \underbrace{\tfrac{3}{2}\dot{H}}_{\frac{1}{t^2}} - \underbrace{\tfrac{9}{4}H^2}_{\frac{1}{t^2}}\Big)\psi = 0$$

$$\psi = \psi_0 \cos(mt) \qquad t_\star \qquad H(t_\star) = m$$

$$\phi(t) \approx \phi_0 \frac{a_\star^{3/2}}{a^{3/2}(t)} \cos(mt) \qquad H \ll m$$





$$\phi(t) \equiv \frac{\psi(t)}{a^{3/2}(t)}$$

$$\ddot{\psi} + \Big(m^2 - \underbrace{\tfrac{3}{2}\dot{H}}_{\frac{1}{t^2}} - \underbrace{\tfrac{9}{4}H^2}_{\frac{1}{t^2}}\Big)\psi = 0$$

$$\psi = \psi_0 \cos(mt) \qquad t_* \quad H(t_*) = m$$

$$\phi(t) \simeq \phi_0 \frac{a_*^{3/2}}{a^{3/2}(t)} \cos(mt) \qquad H \ll m$$

$$\frac{(t)}{{}^{1/2}(t)}$$

$$-\underbrace{\frac{3}{2}\dot{H}}_{\frac{1}{t^2}}-\underbrace{\frac{9}{4}H^2}_{\frac{1}{t^2}}\Big)\psi=0$$

$t_\star \qquad H(t_\star)=m$

$\cos(mt)$

$$\phi_0\frac{a_\star^{3/2}}{a^{3/2}(t)}\cos(mt) \qquad H\ll m$$

$$\langle\rho\rangle=\frac{1}{2}m^2\phi_0^2\left(\frac{a_\star}{a(t)}\right)^3\propto\frac{1}{a^3}$$

$$n=\frac{\langle\rho\rangle}{m}=\frac{1}{2}m\phi_0^2\left(\frac{a_\star}{a(t)}\right)^3$$

$$\Omega_\phi = \frac{\rho_\phi}{\rho_{TOT}} = \frac{\rho_\phi}{\rho_\gamma}\,\frac{\rho_\gamma}{\rho_{TOT}}$$

$$\Omega_\gamma \simeq 10^{-5}$$

$$= \Omega_\gamma \frac{\frac{1}{2} m^2 \phi_0^2 \left(\frac{a_*}{a}\right)^3}{(\quad)\, T_\gamma^4} \sim \frac{m^2 \phi_0^2}{T_\gamma^4}\,\Omega_\gamma$$

$$S\, a^3 = \text{const}$$

$$= \Omega_\gamma \frac{\frac{1}{2} m^2 \phi_0^2 \left(\frac{a_*}{a}\right)^3}{(\ \ ) T_\gamma^4} \approx \frac{m^2 \phi_0^2}{T_\gamma^4} \Omega_\gamma \left(\frac{T_r}{T_*}\right)^3$$

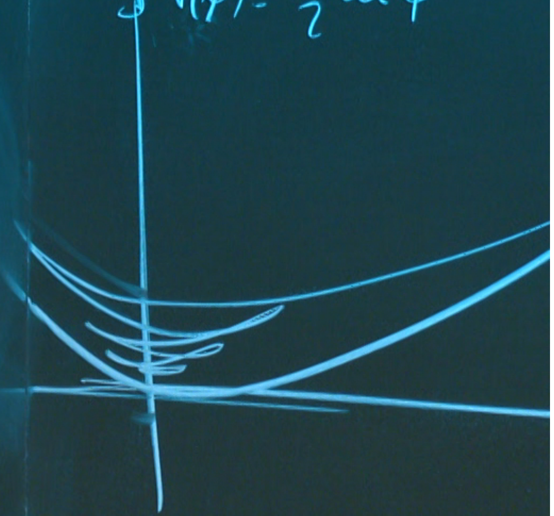
$$S a^3 = \text{const}$$

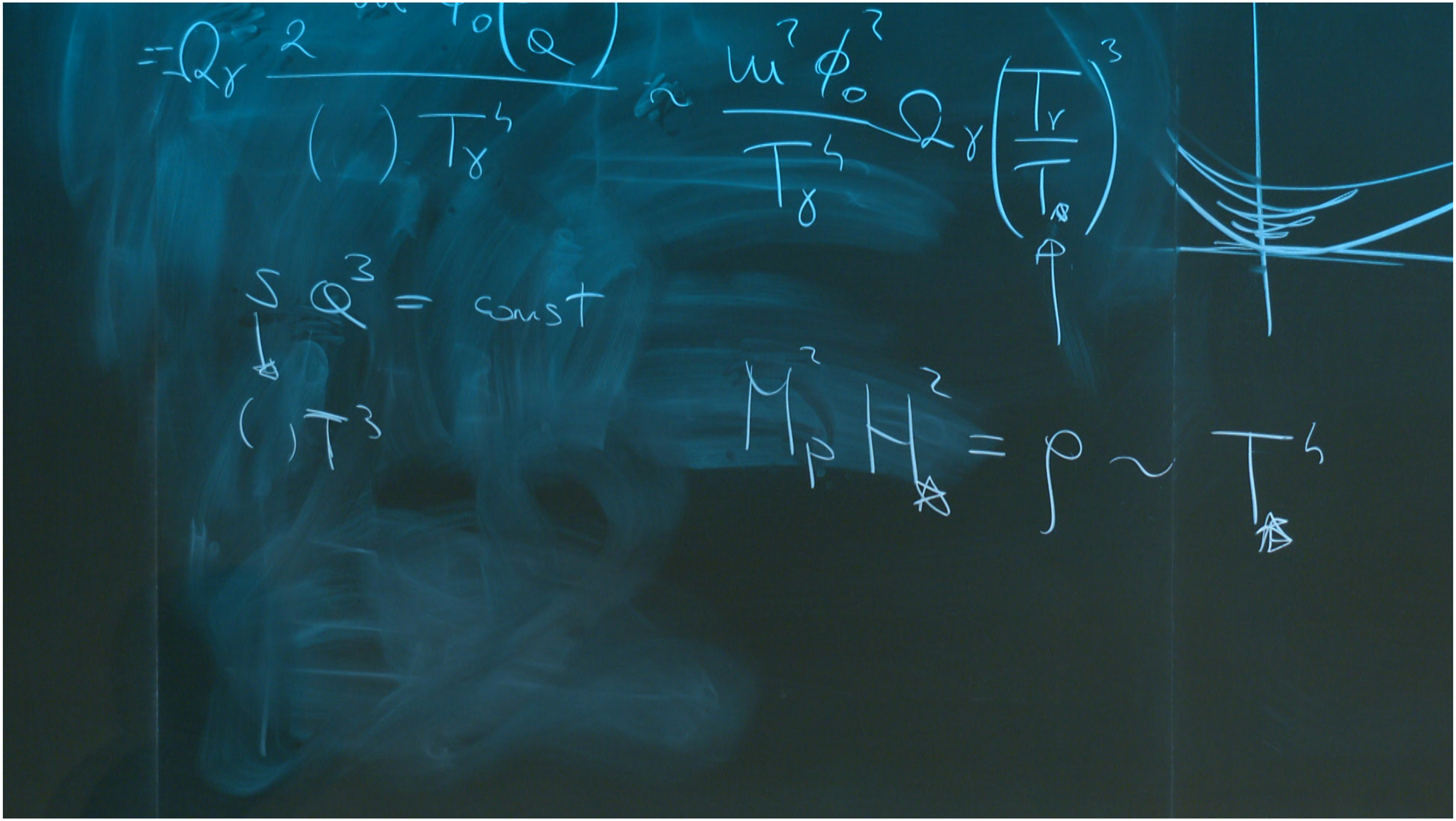
$$\downarrow$$

$$(\ \ ) T^3$$

$$M_p^2 H^2 = \rho \sim T^4$$

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$




S Q^3 = const
( ) T^3
M_p^2 H_*^2 = ρ ~ T_*^4

$$\Omega_\phi \sim \Omega_\gamma \frac{m^2 \phi_0^2}{T_\gamma\, m^{3/2} M_P^{3/2}} \sim \Omega_\gamma \frac{m^{1/2} \phi_0^2}{T_\gamma\, M_P^{3/2}}$$

10^{-5} $\quad$ $10^{-4}\,\mathrm{eV}$ $\quad$ $\sim 10^{27}\,\mathrm{eV}$

$$\sim 0,1 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \left(\frac{\phi_0}{10^{17}\,\mathrm{GeV}}\right)^2$$

$$\left(\frac{T_r}{T_{\phi}}\right)^3$$

10^{-5} $\quad 10^{-4}\,eV$ $\quad \sim 10\,eV$

$$\sim 0.1 \left(\frac{m}{10^{-22}\,eV}\right)^{1/2} \left(\frac{\phi_0}{10^{17}\,GeV}\right)^{2}$$

$$m \in \left(10^{-22} \ldots\ldots 10^{1}\right) eV$$

$$\phi_0 \left(10^{17} \ldots\ldots 10^{11}\right) GeV$$

$$\rho \sim T^{4}$$

$$\Omega_\gamma \frac{m^2\phi_0^2}{T_\gamma\, m^{3/2} M_p^{3/2}} \sim \Omega_\gamma \frac{m^{1/2}\phi_0^2}{T_\gamma\, M_p^{3/2}} = \Omega_\gamma \left(\frac{m}{T_\gamma^2/M_p}\right)^{1/2}\left(\frac{\phi_0}{M_p}\right)^2$$

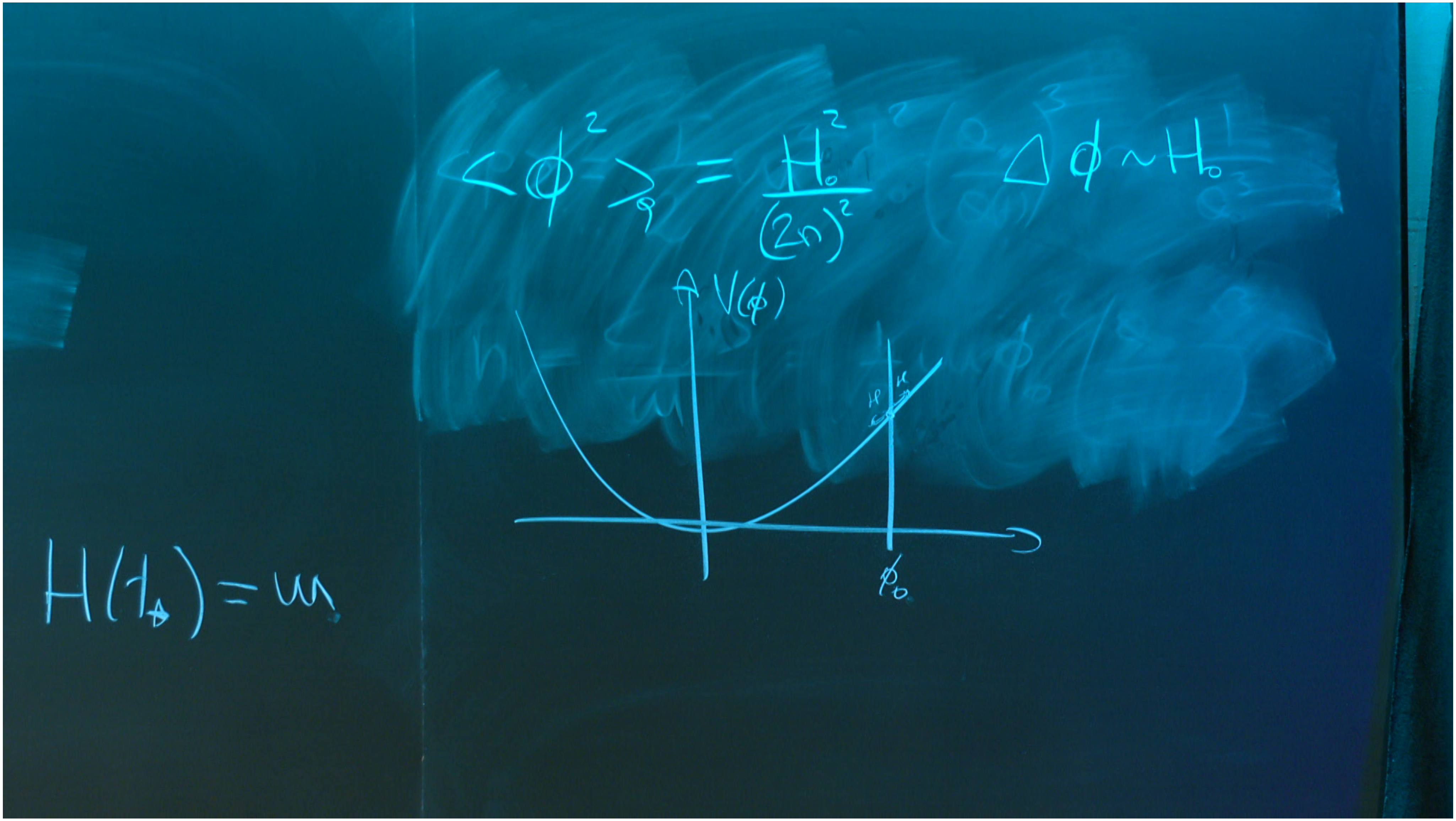
10^{-5} $\quad T_\gamma \sim 10^{-4}\,\mathrm{eV}$ $\quad \sim 10^{-27}\,\mathrm{eV}$ $\quad \sim 10^{18}\,\mathrm{GeV}$

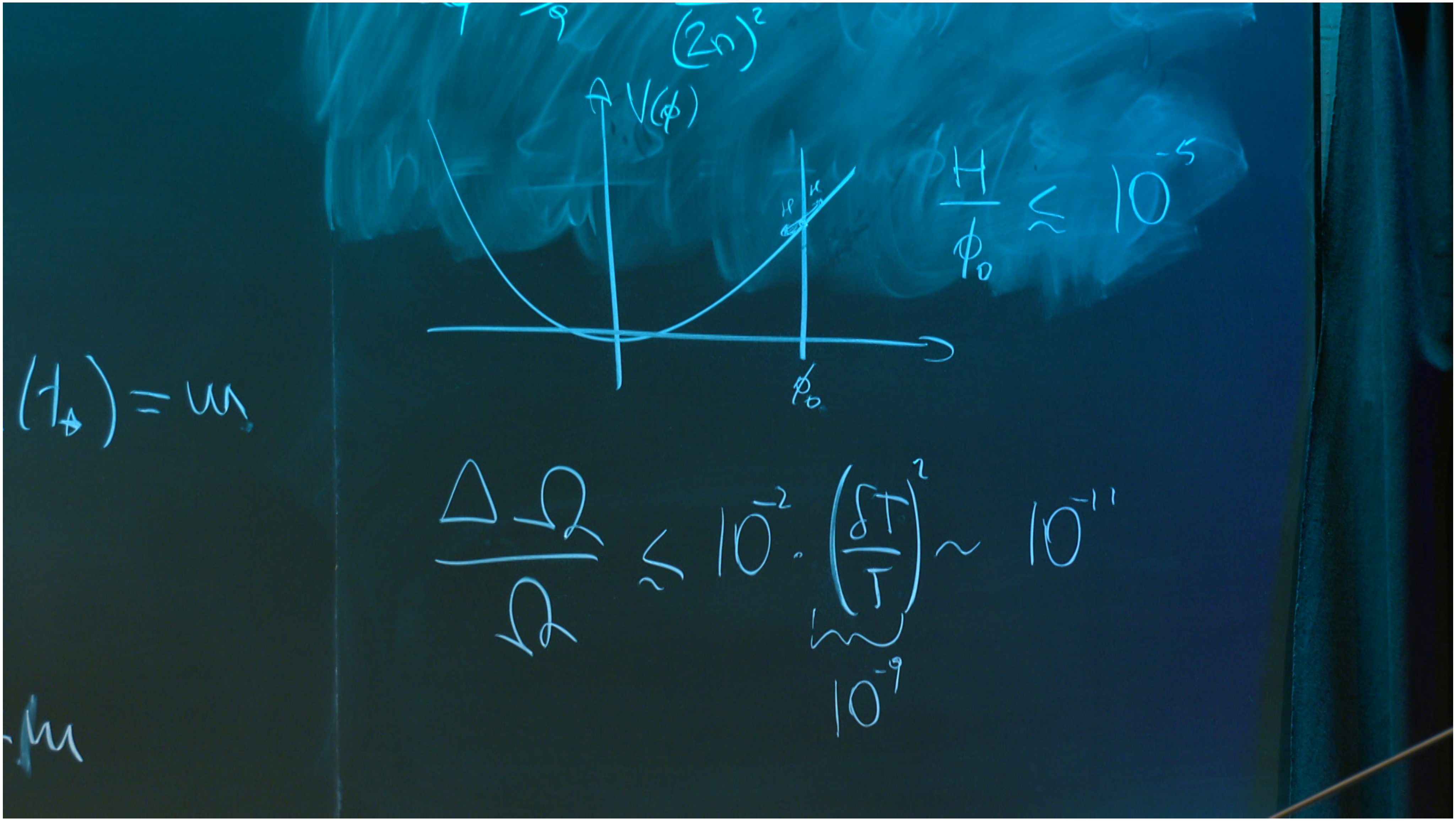
$$0{,}265\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}\left(\frac{\phi_0}{10^{17}\,\mathrm{GeV}}\right)^2$$

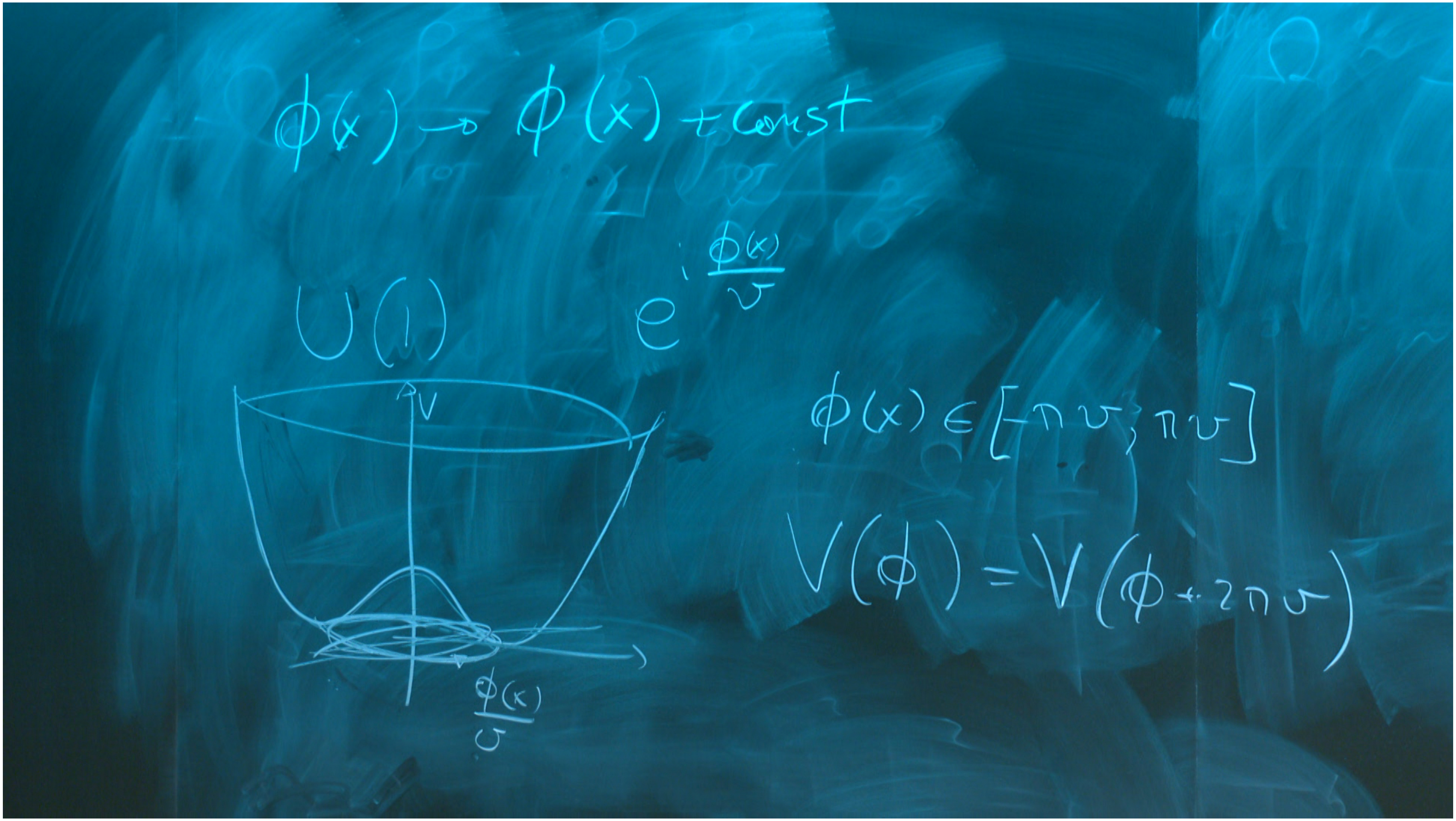
$$m \in \left(10^{-22} \ldots 10^{1}\right)\mathrm{eV}$$

$$t_*$$

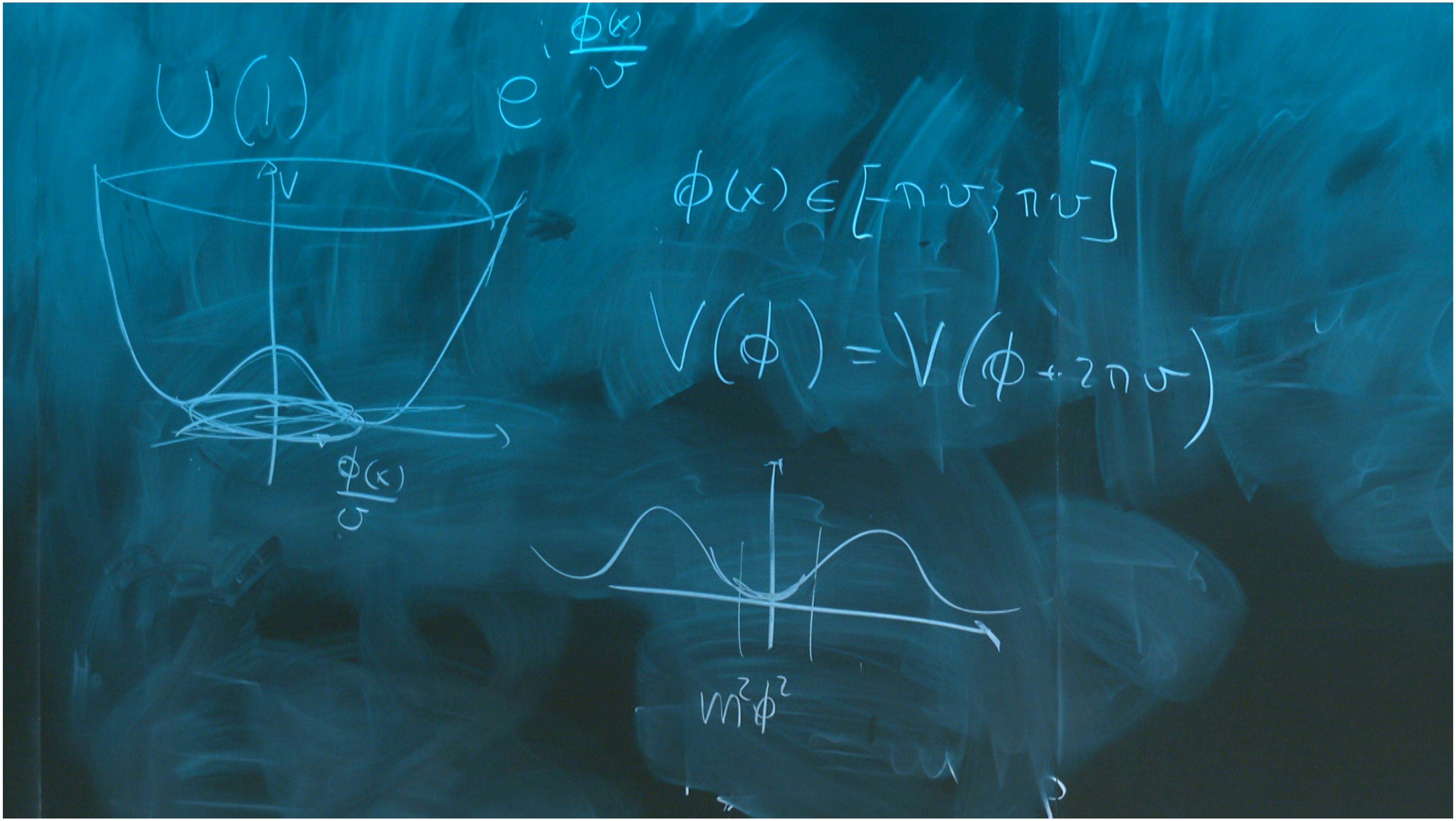
$$\phi_0 \left(10^{17} \ldots 10^{11}\right)\mathrm{GeV}$$

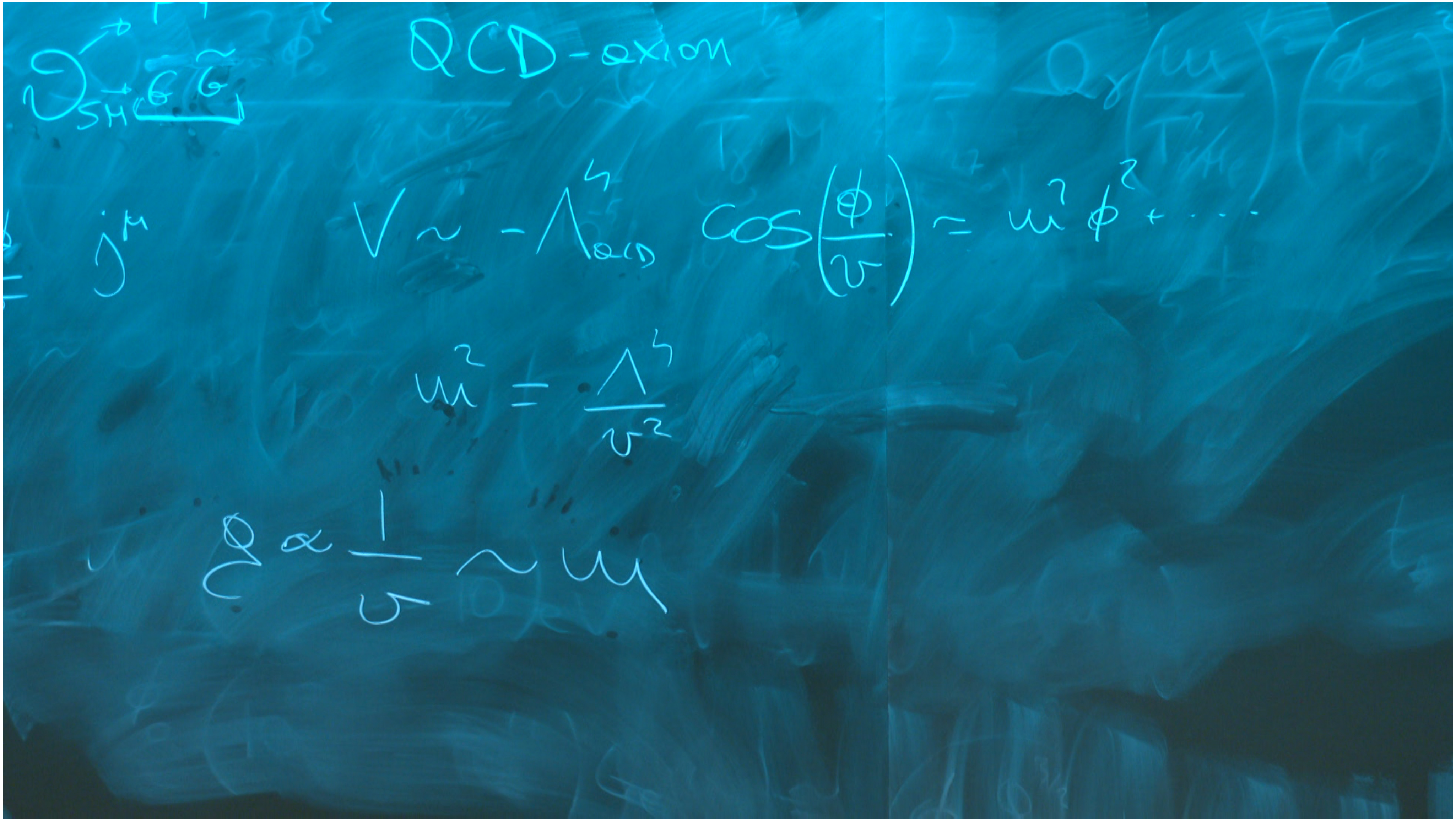

$\langle \phi^2 \rangle_q = \frac{H_0^2}{(2\pi)^2}$
$\Delta \phi \sim H_0$
$V(\phi)$
ϕ_0
$H(t_*) = m$

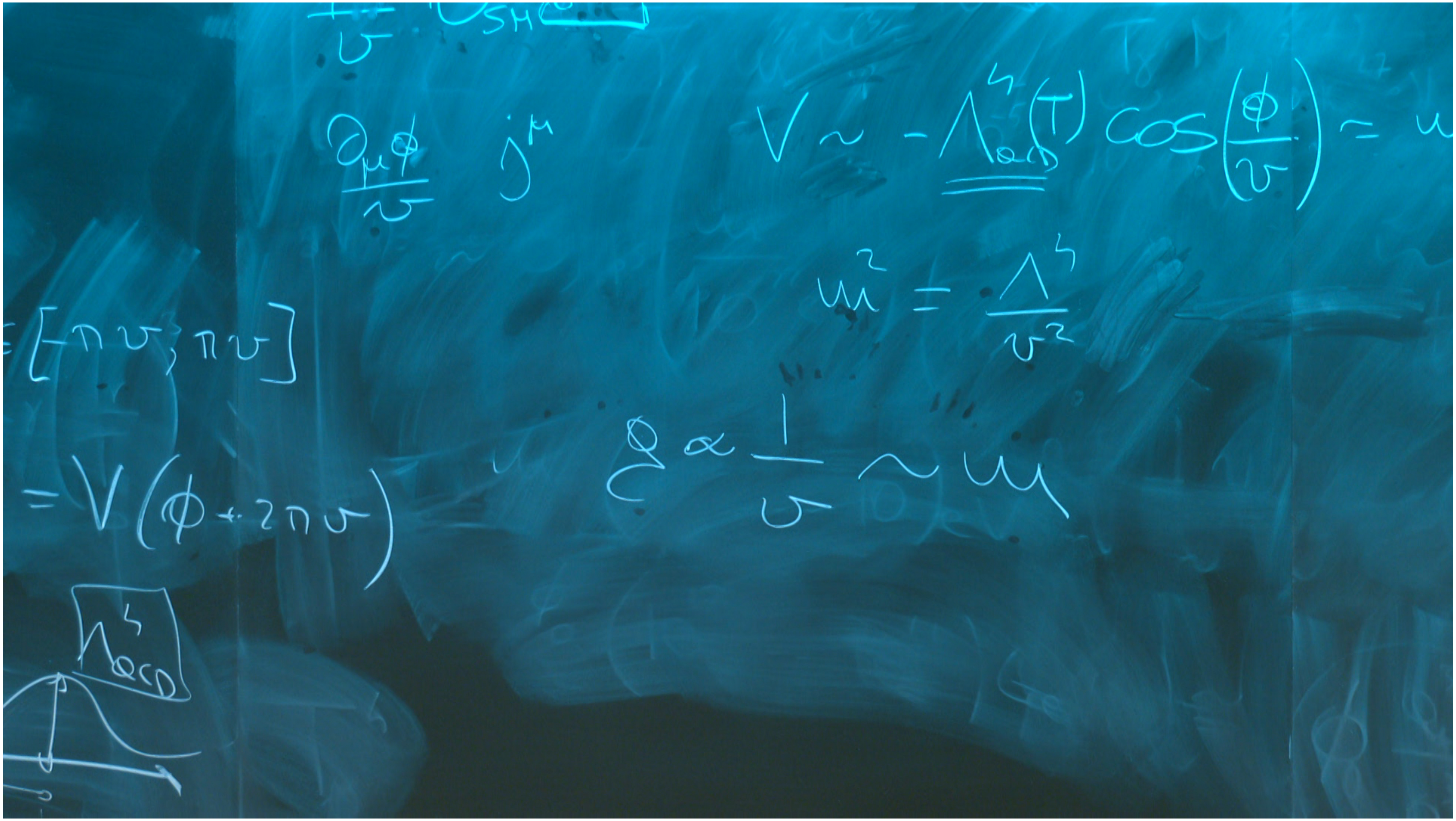

$(2\pi)^2$
$V(\phi)$
ϕ_0
$\frac{H}{\phi_0} \lesssim 10^{-5}$
$\frac{\Delta\Omega}{\Omega} \lesssim 10^{-2} \cdot \left(\frac{\delta T}{T}\right)^2 \sim 10^{-11}$
10^{-9}



$\phi(x) \to \phi(x) + \mathrm{const}$
$U(1)$
$e^{i\frac{\phi(x)}{v}}$
V
$\frac{\phi(x)}{v}$
$\phi(x) \in [-\pi v; \pi v]$
$V(\phi) = V(\phi + 2\pi v)$


U(1)
e^{i φ(x)/v}
V
φ(x)/v
φ(x) ∈ [-πv; πv]
V(φ) = V(φ + 2πv)
m²φ²


QCD-axion
$\partial_{SM} G\tilde{G}$
j^μ
$V \sim -\Lambda_{QCD}^4 \cos\left(\frac{\phi}{v}\right) \simeq m^2\phi^2 + \dots$
$m^2 = \frac{\Lambda^4}{v^2}$
$g \propto \frac{1}{v} \sim m$


$\frac{\partial_\mu \phi}{v}$ j^μ
$V \sim -\Lambda_{QCD}^4(T) \cos\left(\frac{\phi}{v}\right)$
$m^2 = \frac{\Lambda^4}{v^2}$
$[-\pi v, \pi v]$
$= V(\phi + 2\pi v)$
$g \propto \frac{1}{v} \sim m$
Λ_{QCD}^4

j^μ

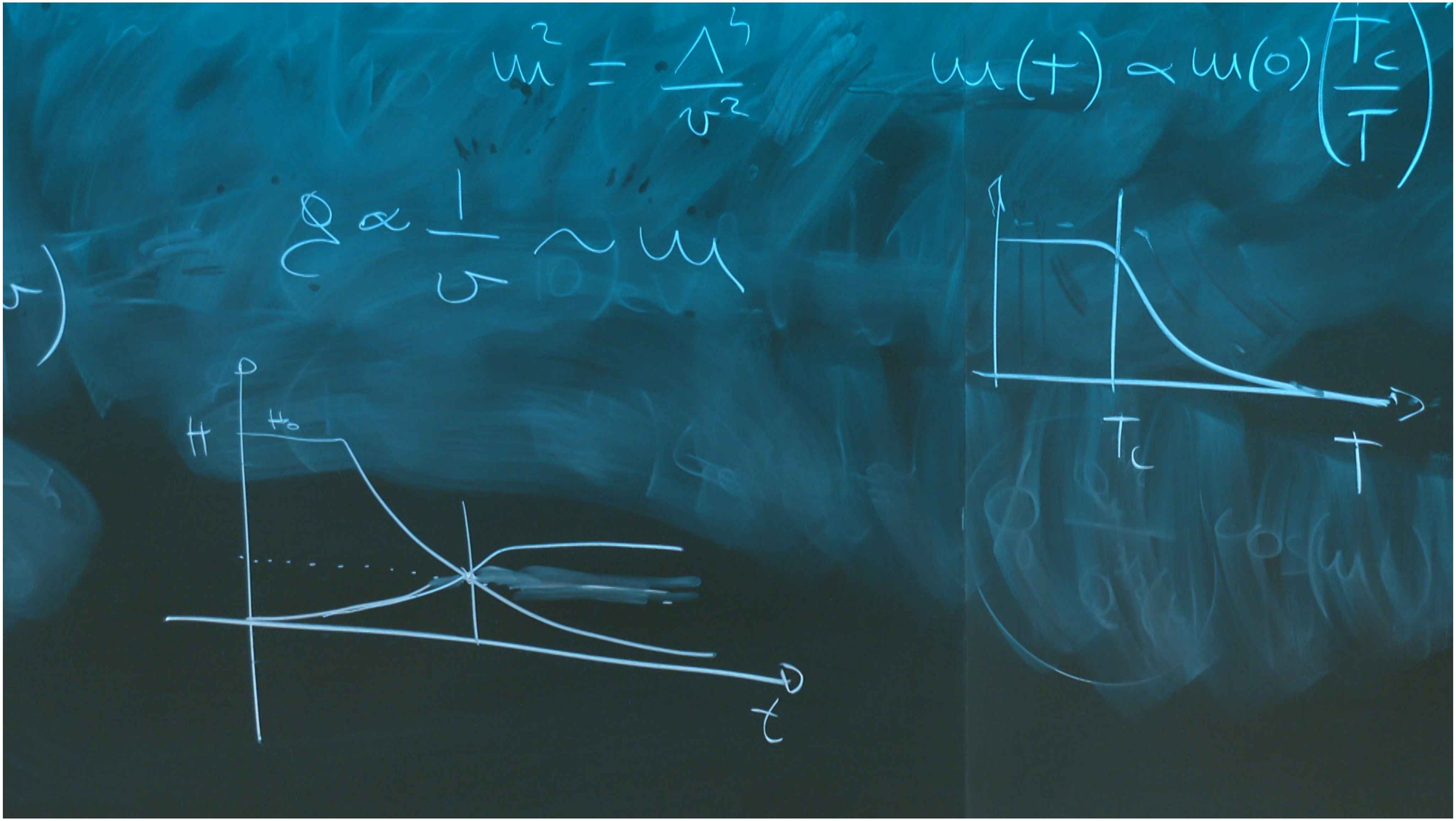
$$V \sim -\Lambda_{QCD}^4(T)\cos\left(\frac{\phi}{v}\right) \simeq m^2\phi^2 + \cdots$$

0,1 GeV

$$m^2 = \frac{\Lambda^4}{v^2} \qquad m(T) \propto m(0)\left(\frac{T_c}{T}\right)^4$$

$$g \propto \frac{1}{v} \sim m$$

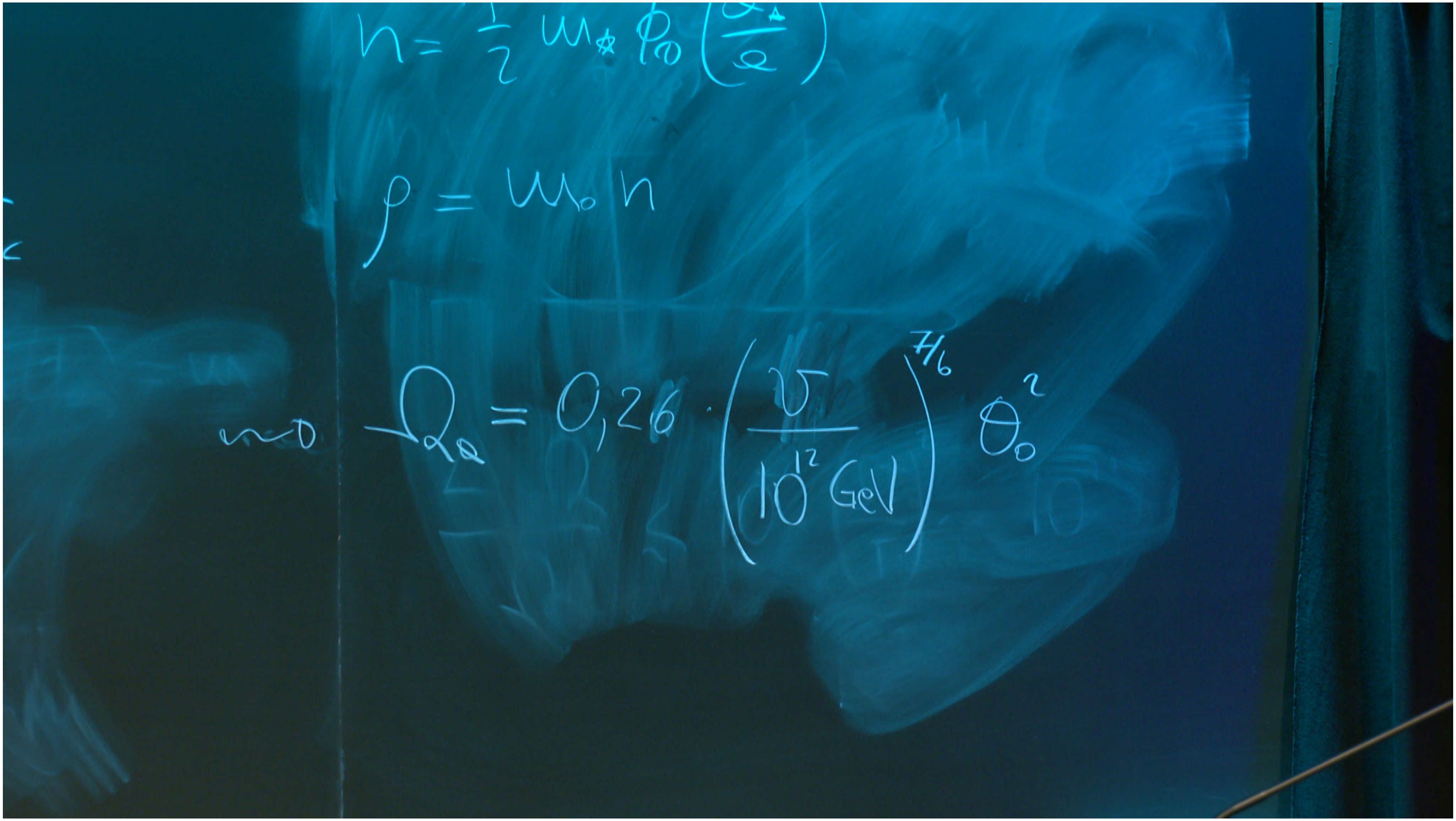
$-\Lambda_{QCD}^4(T)\cos\left(\frac{\phi}{v}\right) \simeq m^2\phi^2+\cdots$
0,1 GeV
$= \frac{\Lambda^4}{v^2}$
$m(T) \propto m(0)\left(\frac{T_c}{T}\right)^4$
$T > T_c$
$\sim m$
T_c
T

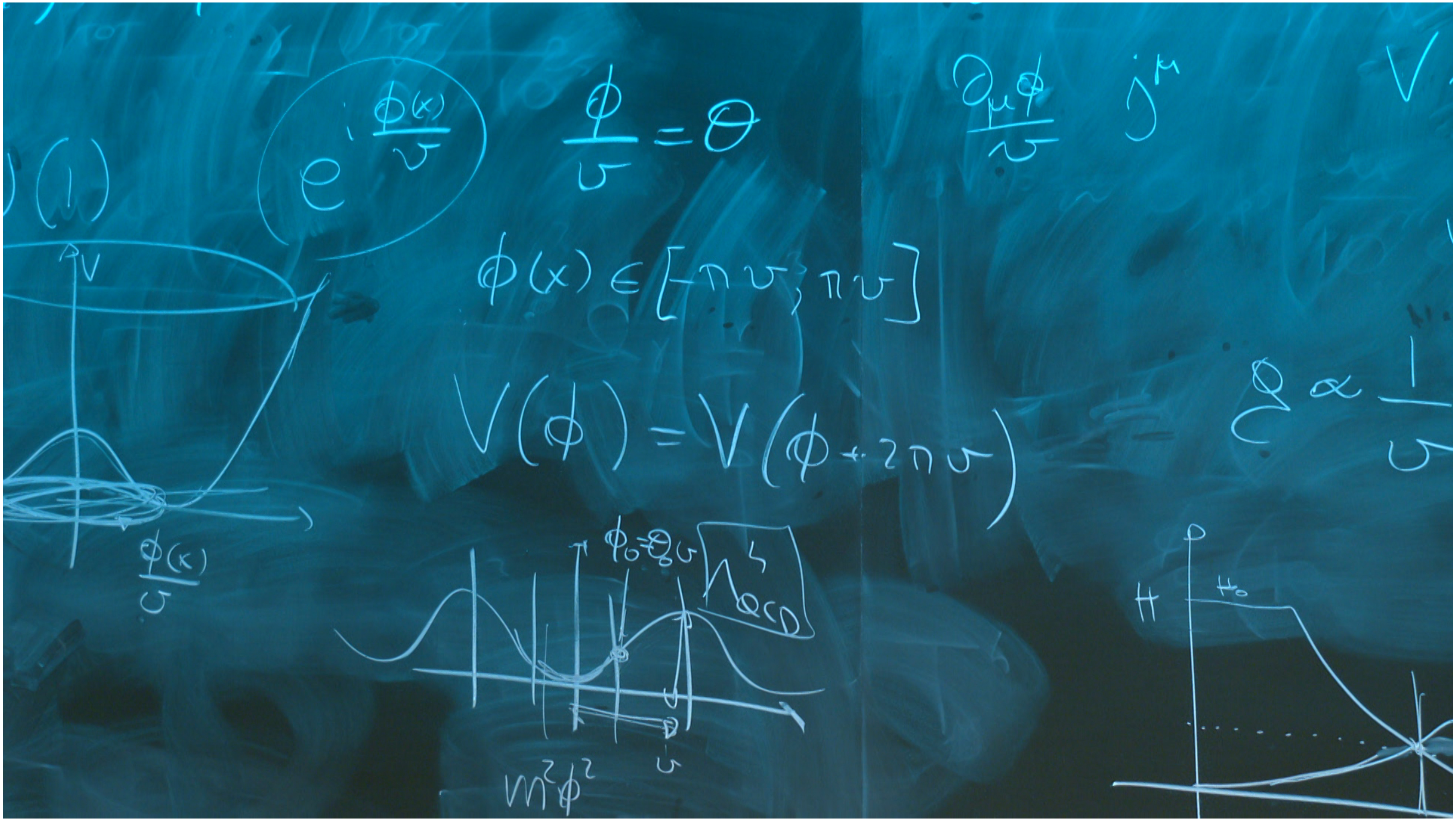

$m^2 = \frac{\Lambda^3}{v^2}$
$m(T) \propto m(0)\left(\frac{T_c}{T}\right)$
$\xi \propto \frac{1}{v} \sim m$
H
H_0
t
T_c
T

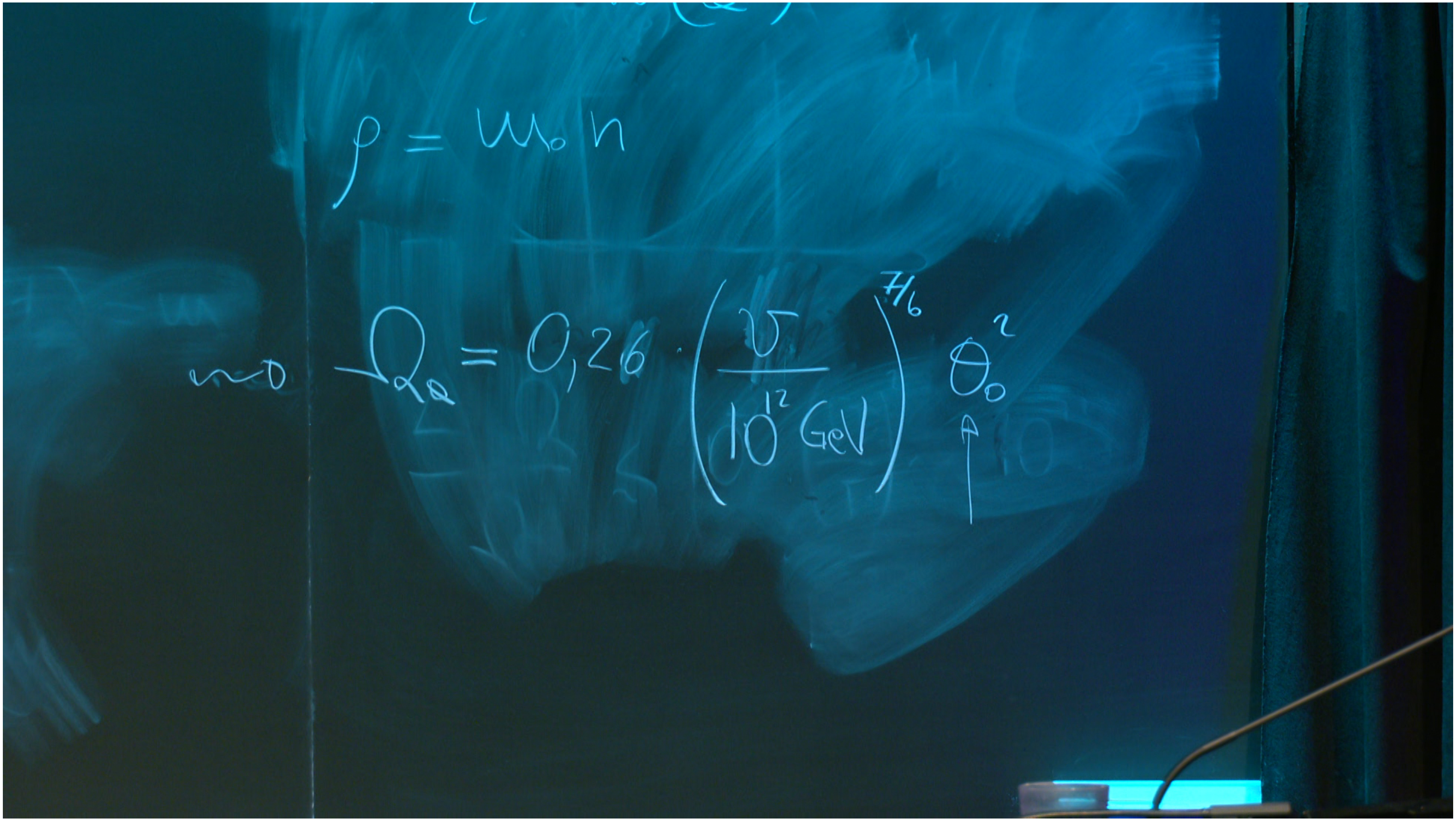
$$\rho = \frac{1}{2} m_* m_* \phi_0^2 \left(\frac{a_*}{a}\right)^3$$

$$n = \frac{1}{2} m_* \phi_0^2 \left(\frac{a_*}{a}\right)^3$$

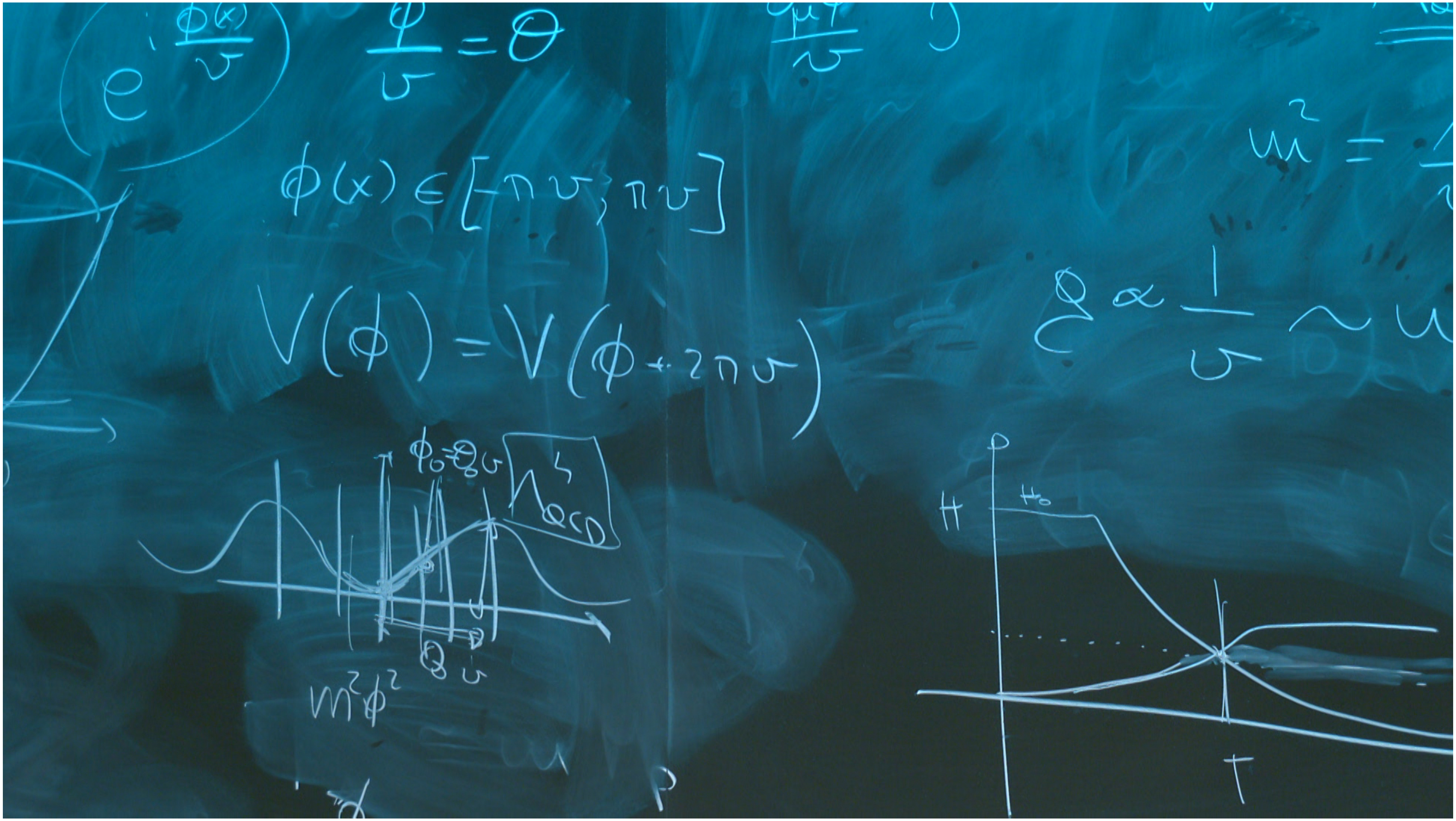
$$\rho = m_0 n$$


$n = \frac{1}{2} m_a \phi_0$
$\rho = m_a n$
$\Omega_a = 0{,}26 \cdot \left(\frac{v}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \theta_0^2$


$e^{i\frac{\phi(x)}{v}}$
$\frac{\phi}{v} = \theta$
$\frac{\partial_\mu \phi}{v}$
j^μ
$\phi(x) \in [-\pi v; \pi v]$
$V(\phi) = V(\phi + 2\pi v)$
$g \propto \frac{1}{v}$
$\phi_0 = \theta_0 v$
Λ_{QCD}
$m^2\phi^2$

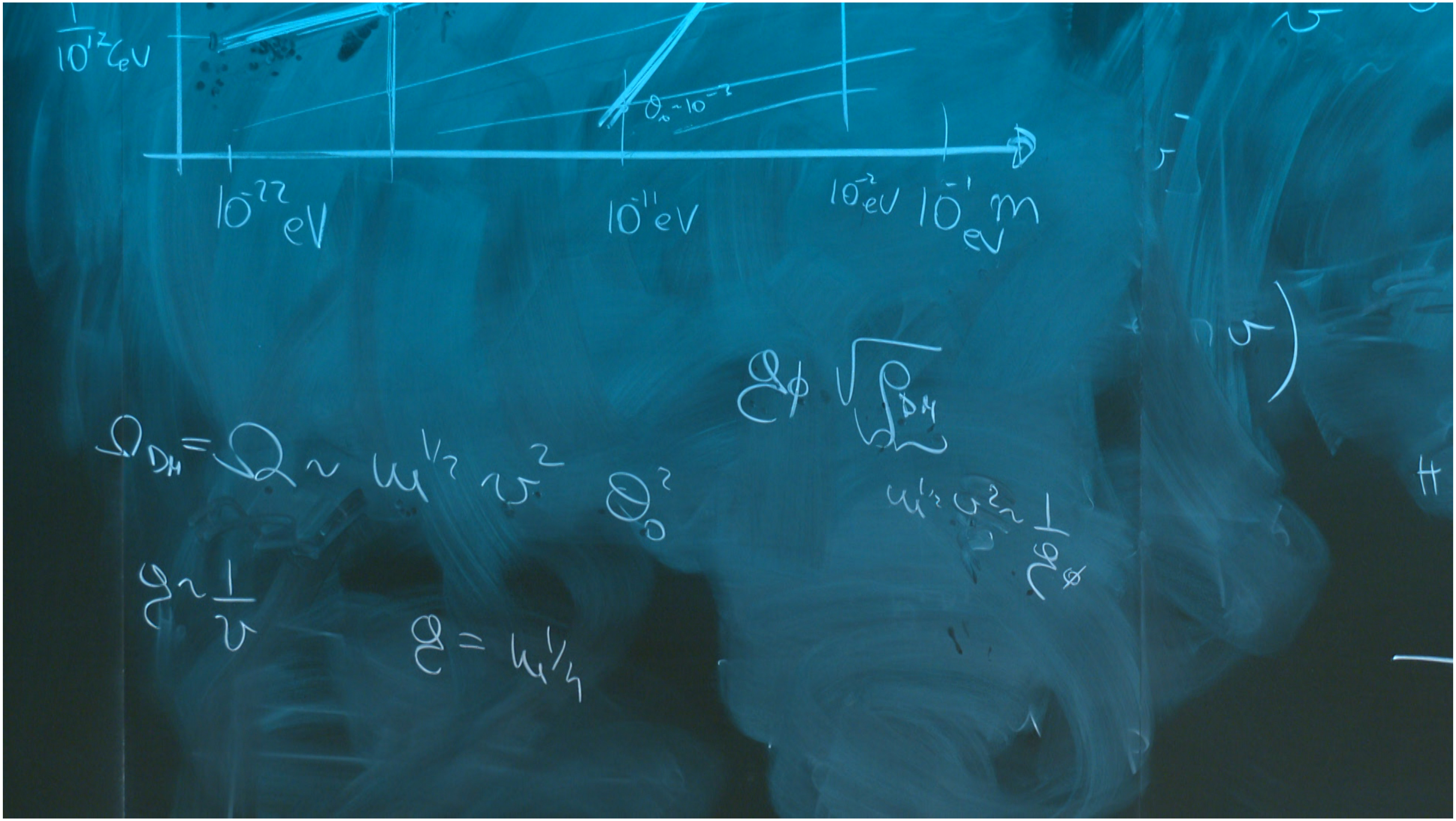


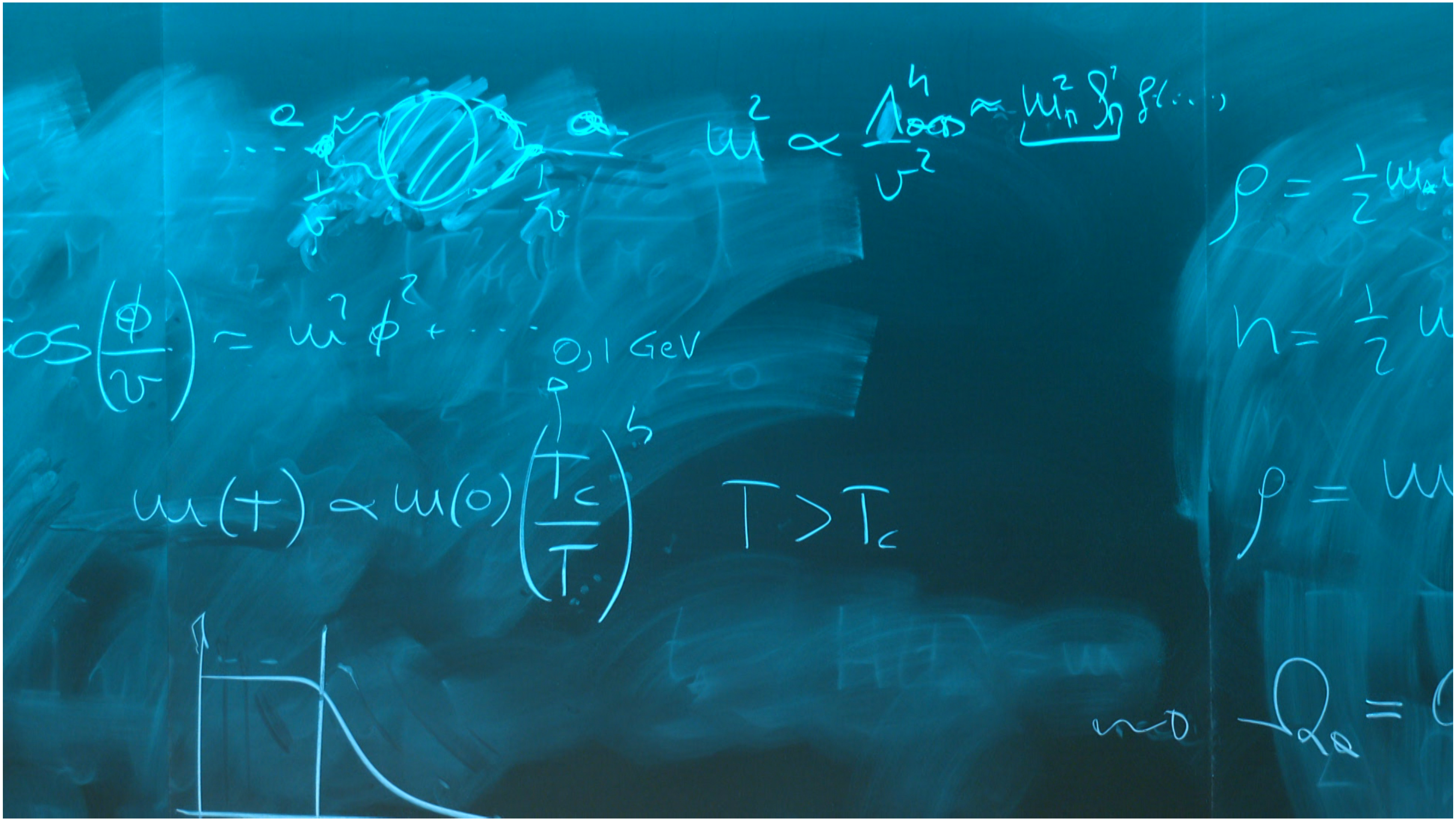
$\rho = m_0 n$
$\Omega_a = 0,26 \cdot \left(\frac{v}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \theta_0^2$



$e^{i\frac{\phi(x)}{v}}$
$\frac{\phi}{v} = \theta$
$\phi(x) \in [-\pi v, \pi v]$
$V(\phi) = V(\phi + 2\pi v)$
$g \propto \frac{1}{v}$
$\phi_0 = \theta_0 v$
Λ_{QCD}
$\theta_0 v$
$m^2\phi^2$
H
H_0
T


θ₀ ~ π
θ₀ = 1
θ₀ = 1
θ₀ ~ 10⁻²
10⁻²² eV
10⁻¹¹ eV
10⁻² eV
10⁻¹ eV
m


10^12 GeV
10^-22 eV
10^-11 eV
10^-2 eV
10^-1 eV
m
θ₀ ~ 10^-3
Ω_DM = Ω ~ m^1/2 v^2 θ₀^2
g_φ √ρ_DM
m^1/2 v^2 ~ 1/g_φ
g ~ 1/v
g = m^1/4



$m^2 \propto \frac{\Lambda^4_{QCD}}{v^2} \approx m_\pi^2 f_\pi^2 f(\ldots)$
$\cos\left(\frac{\phi}{v}\right) \simeq m^2\phi^2 + \ldots$
0,1 GeV
$m(T) \propto m(0)\left(\frac{T_c}{T}\right)^5$
$T > T_c$
$\rho = \frac{1}{2} m$
$n = \frac{1}{2} m$
$\rho = m$
$m \to 0 \quad \Omega_a =$