Title: Cosmological Variations

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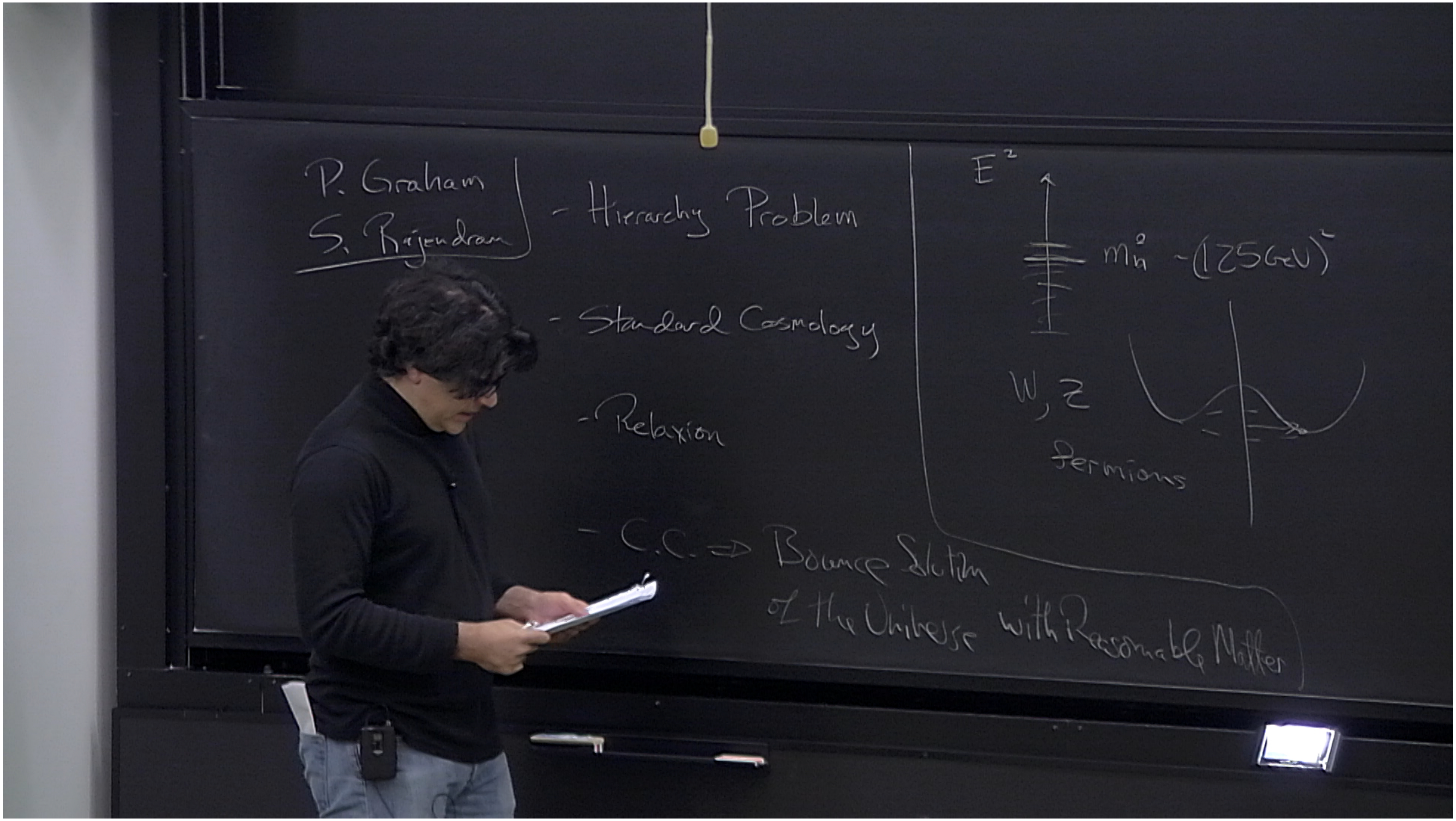
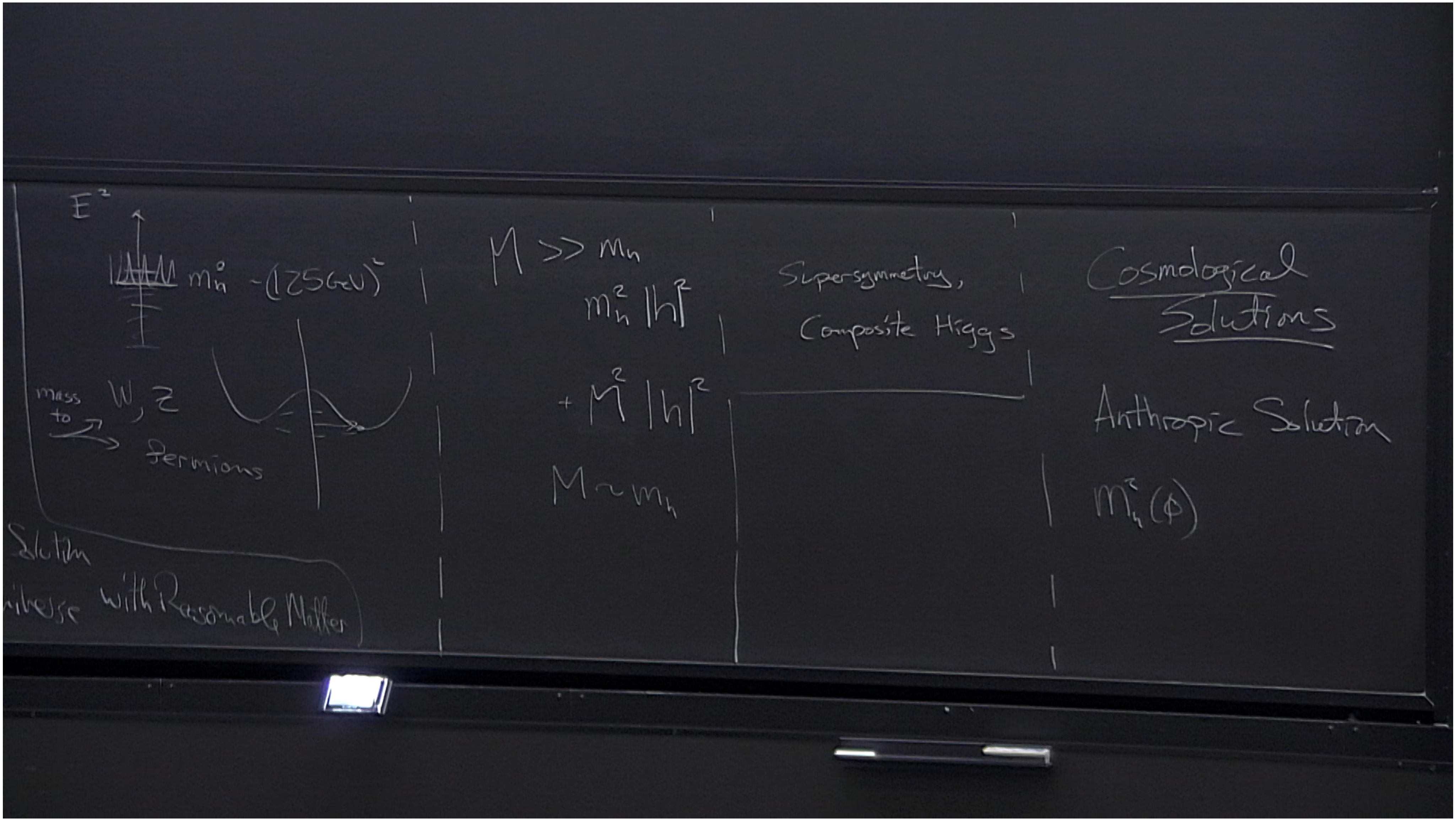
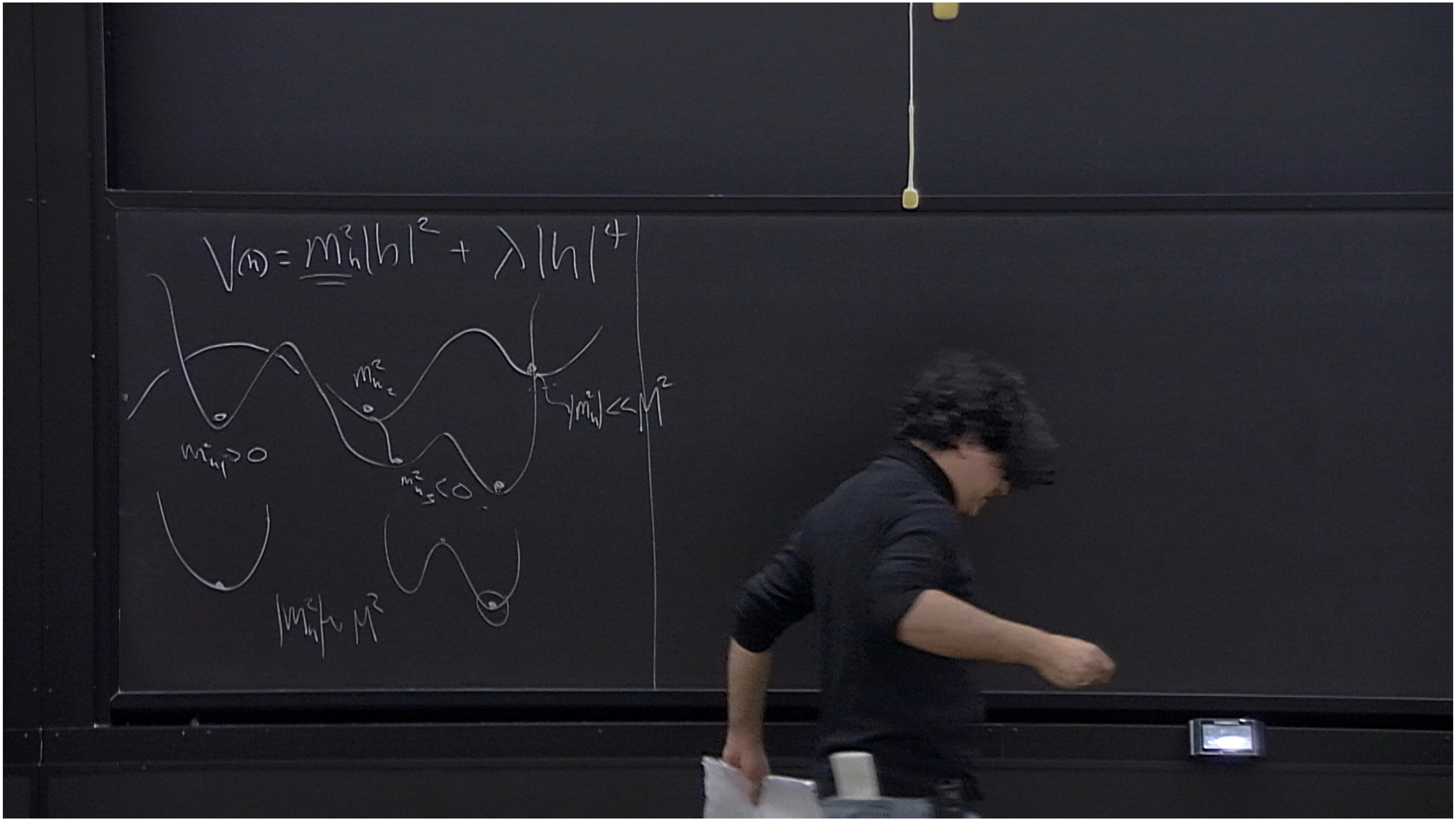
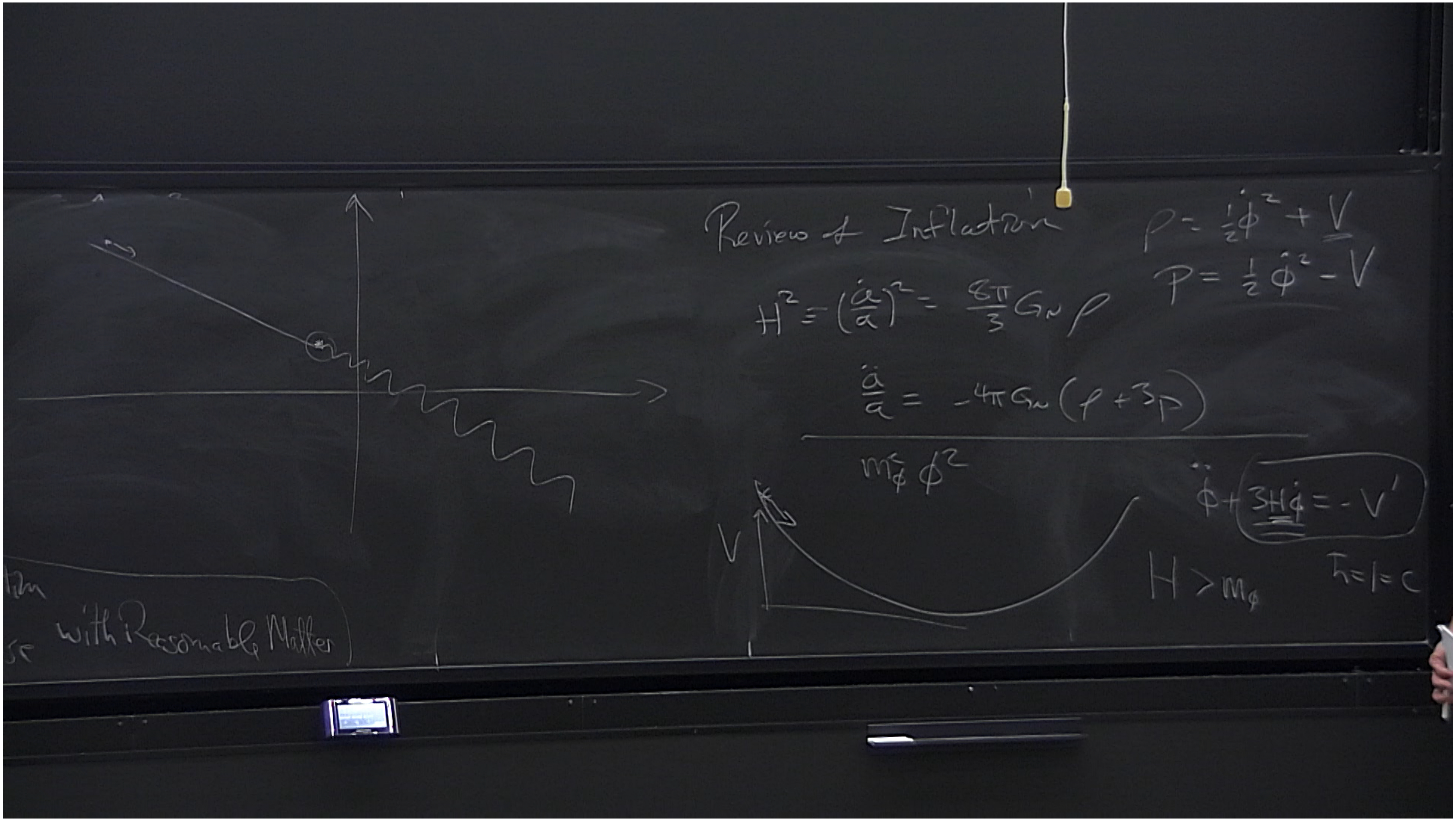
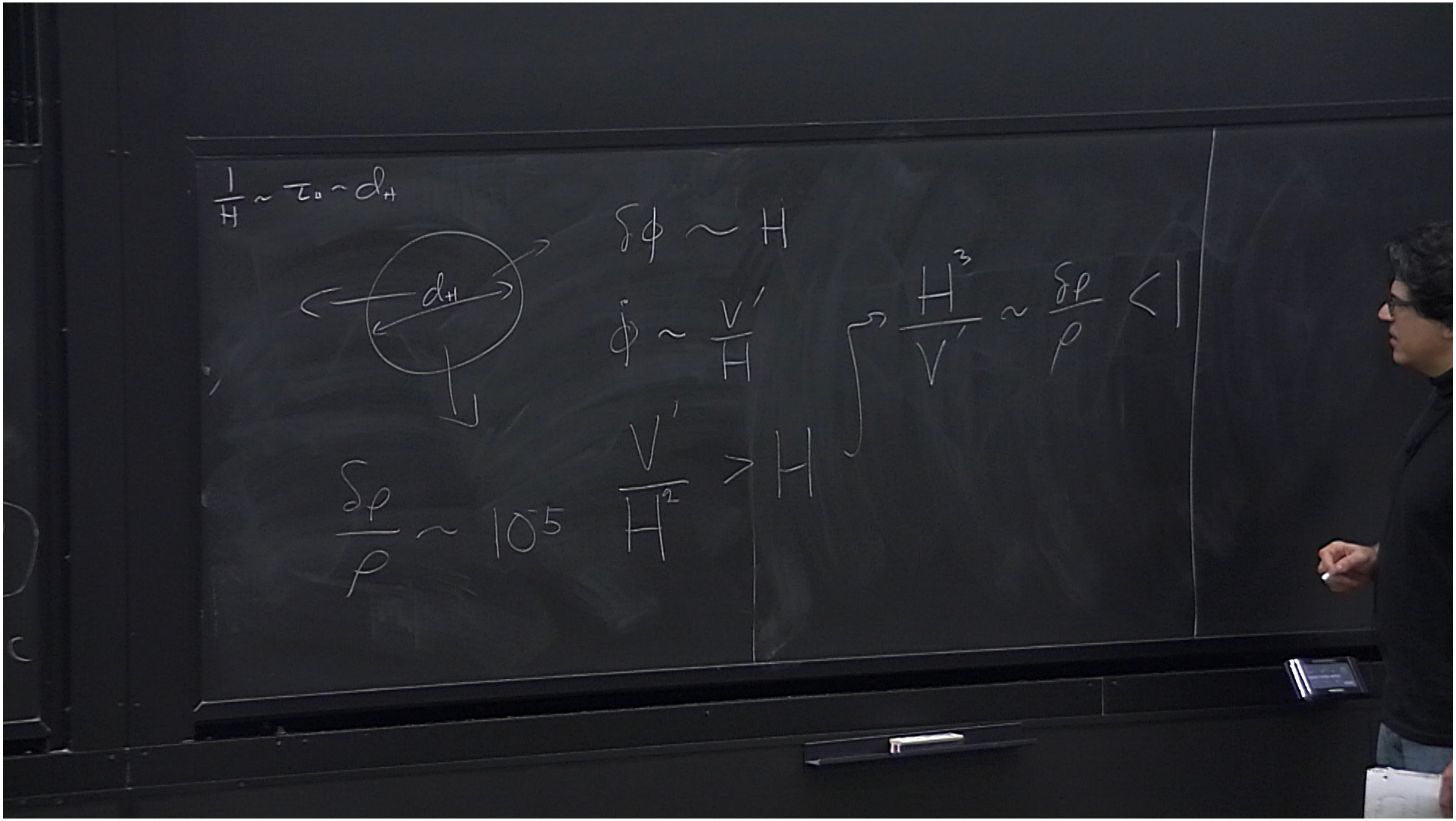
Abstract: <p>I present three possible non-standard additions to cosmology. First I show that a very long early period of inflation could exist in which parameters evolve, or 'relax', to seemingly fine-tuned values. Next, I show that even if cosmic inflation existed, a period after inflation with anisotropic stress can dramatically affect super-horizon modes and thus the imprint on the cosmic microwave background. Finally, I show that cosmological singularities can be avoided by a bounce without using exotic matter that violates the Null Energy Condition, but by the addition of vorticity in compact extra dimensions.</p>


P. Graham
S. Rajendran
- Hierarchy Problem
- Standard Cosmology
- Relaxion
- C.C. ⇒ Bounce Solution of the Universe with Reasonable Matter
E^2
$m_h^2 \sim (125\,\mathrm{GeV})^2$
W, Z
fermions


E^2
$m_h^2 \sim (125\,\mathrm{GeV})^2$
mass to
W, Z
fermions
Solution
with Reasonable Matter
$M \gg m_h$
$m_h^2 |h|^2$
$+ M^2 |h|^2$
$M \sim m_h$
Supersymmetry,
Composite Higgs
Cosmological Solutions
Anthropic Solution
$m_h^2(\phi)$


$V(h) = m_h^2|h|^2 + \lambda|h|^4$
$m_{h_1}^2 > 0$
$m_{h_2}^2$
$m_{h_3}^2 < 0$
$|m_h^2| \ll M^2$
$|m_h^2| \sim M^2$


Review of Inflation
$\rho = \frac{1}{2}\dot{\phi}^2 + V$
$P = \frac{1}{2}\dot{\phi}^2 - V$
$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho$
$\frac{\ddot{a}}{a} = -4\pi G_N (\rho + 3p)$
$m_\phi^2 \phi^2$
V
$\ddot{\phi} + 3H\dot{\phi} = -V'$
$H > m_\phi$
$\hbar = 1 = c$
with Reasonable Matter


$\frac{1}{H} \sim \tau_0 \sim d_H$
d_H
$\delta\phi \sim H$
$\dot{\phi} \sim \frac{V'}{H}$
$\frac{H^3}{V'} \sim \frac{\delta\rho}{\rho} < 1$
$\frac{V'}{H^2} > H$
$\frac{\delta\rho}{\rho} \sim 10^{-5}$

Review of Inflation

$$\rho = \tfrac{1}{2}\dot{\phi}^2 + \underline{\underline{V}}$$

$$P = \tfrac{1}{2}\dot{\phi}^2 - V$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho$$

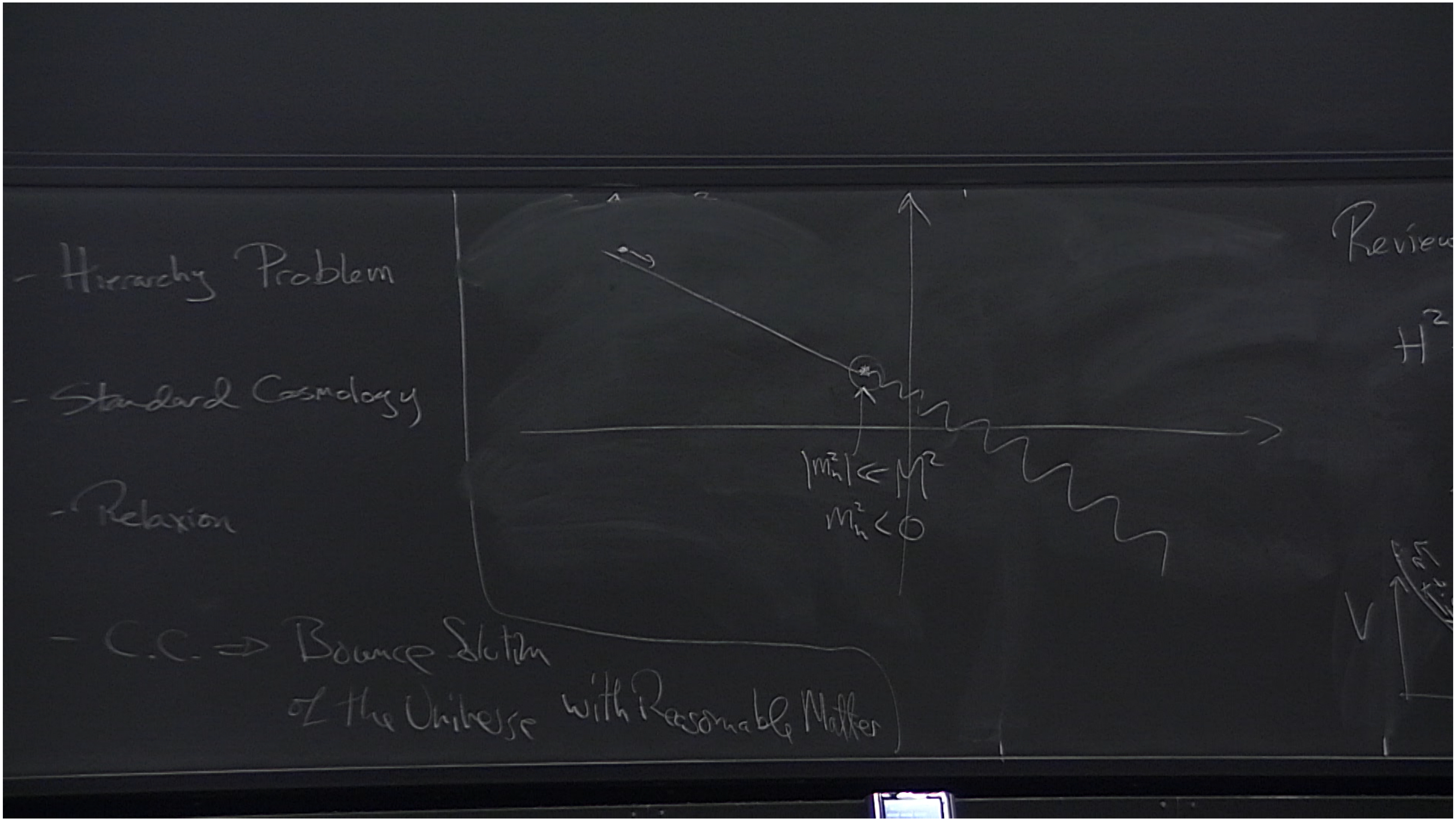
$$\frac{\ddot{a}}{a} = -4\pi G_N (\rho + 3p)$$

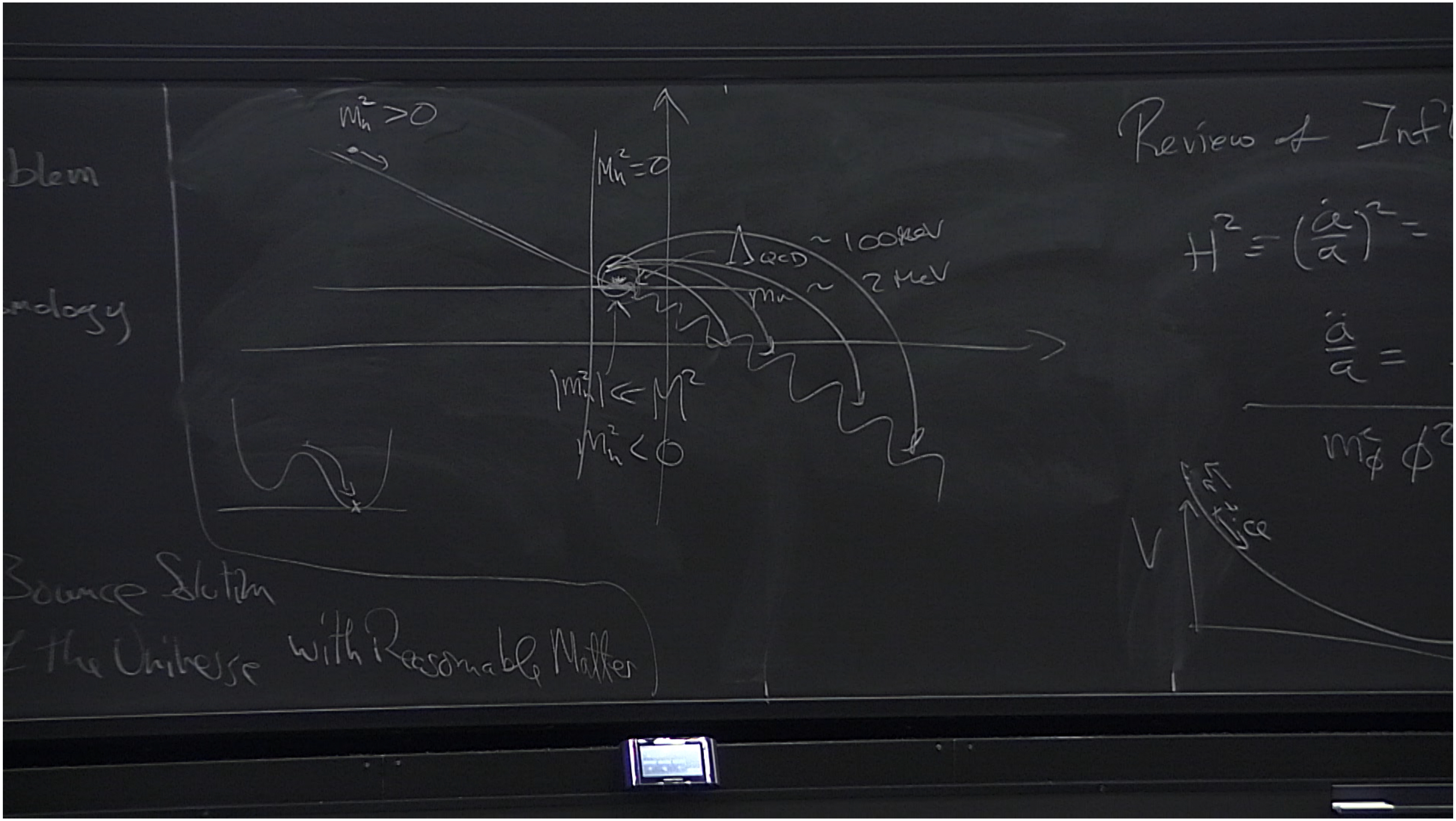
$$m_\phi^2 \phi^2$$

$$\boxed{\ddot{\phi} + 3\underline{\underline{H}}\dot{\phi} = -V'}$$

$$H > m_\phi$$

$$\hbar = 1 = c$$

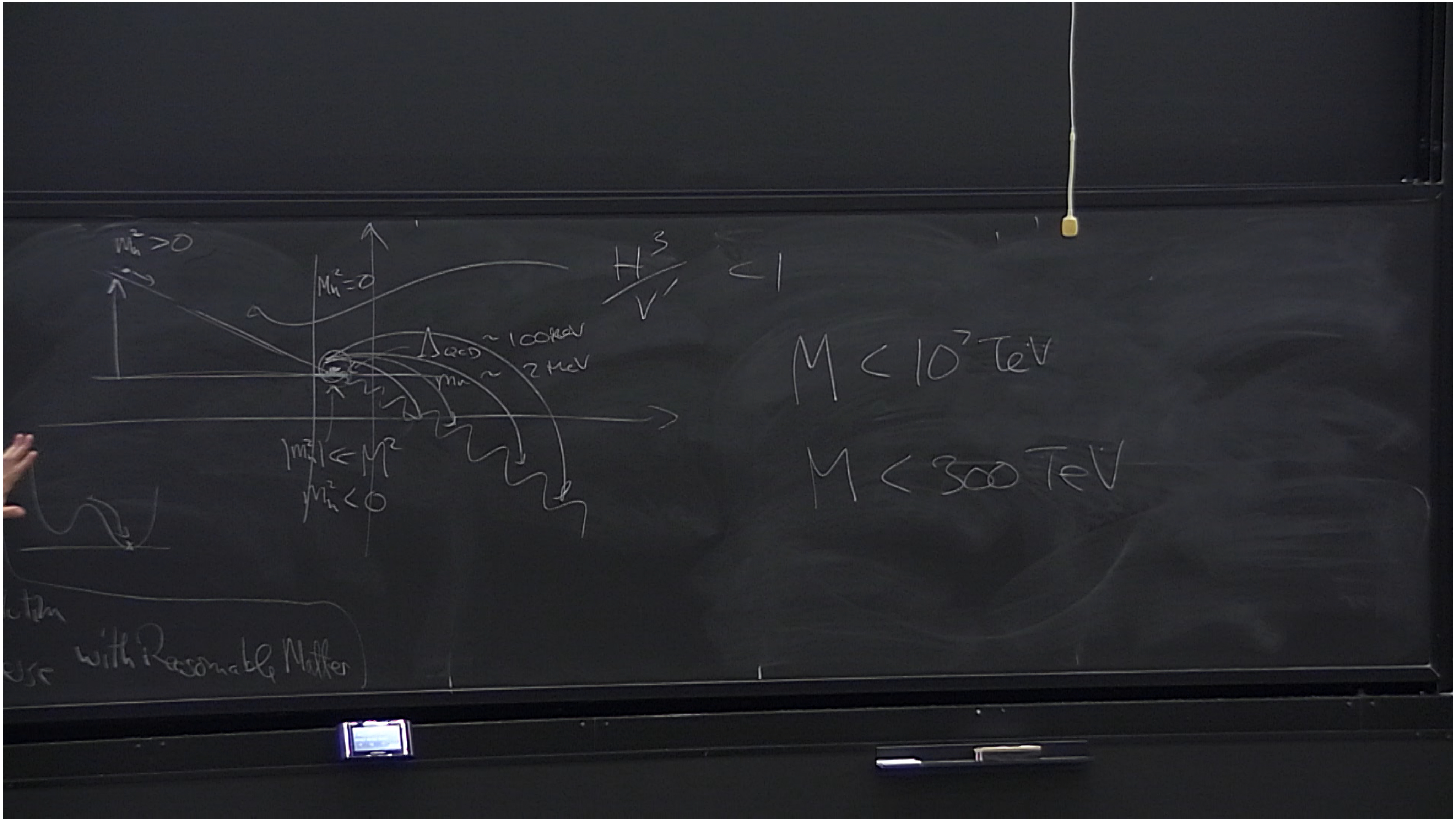

- Hierarchy Problem
- Standard Cosmology
- Relaxion
- C.C. ⇒ Bounce Solution of the Universe with Reasonable Matter
|m_h^2| ≪ M^2
m_h^2 < 0
Review
H^2
V

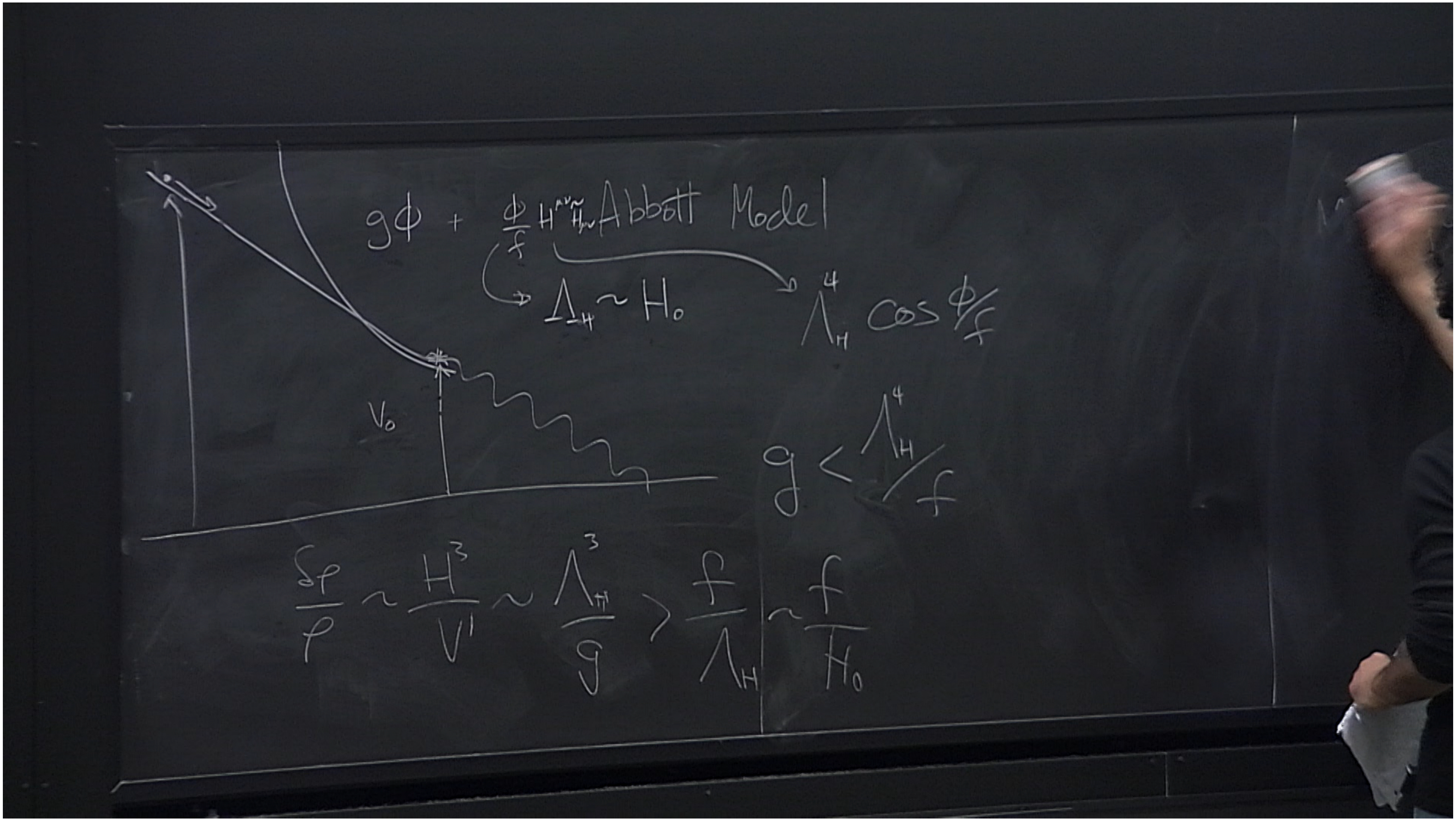

blem
mology
Bounce Solution
the Universe with Reasonable Matter
Review of Inf
$m_h^2 > 0$
$M_h^2 = 0$
$\Lambda_{QCD} \sim 100\,keV$
$m_h \sim 2\,MeV$
$|m_h^2| \ll M^2$
$m_h^2 < 0$
$H^2 = \left(\frac{\dot{a}}{a}\right)^2 =$
$\frac{\ddot{a}}{a} =$
$m_\phi^2 \phi^2$
V

$$\sim \frac{\delta\rho}{\rho} < 1$$

$$\left(M^2 + g\phi\right)h^2 + \underline{gM^2\phi} + \frac{\phi}{f_a}\, G^{\mu\nu} G^{\alpha\beta} \varepsilon_{\mu\nu\alpha\beta}$$

$$+ \Lambda_{QCD}^3\, m_u\, \mathcal{F}\left(\phi / 2\pi f_\phi\right)$$


$m_h^2 > 0$
$m_h^2 = 0$
$\frac{H^3}{V'} < 1$
$\Lambda_{QCD} \sim 100\,\text{MeV}$
$m_u \sim 2\,\text{MeV}$
$|m_h^2| \ll M^2$
$m_h^2 < 0$
$M < 10^7\,\text{TeV}$
$M < 300\,\text{TeV}$
with Reasonable Matter


$g\phi + \frac{\phi}{f} H^{\mu\nu}\tilde{H}_{\mu\nu}$ Abbott Model
$\Lambda_H \sim H_0$
$\Lambda_H^4 \cos \phi/f$
V_0
$g < \Lambda_H^4 / f$
$\frac{\delta\rho}{\rho} \sim \frac{H^3}{V'} \sim \frac{\Lambda_H^3}{g} > \frac{f}{\Lambda_H} \sim \frac{f}{H_0}$

$\cos \phi/f$

Λ_H^4 / f

Empty Universe! $\rightarrow$ Want to Refill!

$$\boxed{P = w\rho} \qquad w = -1$$

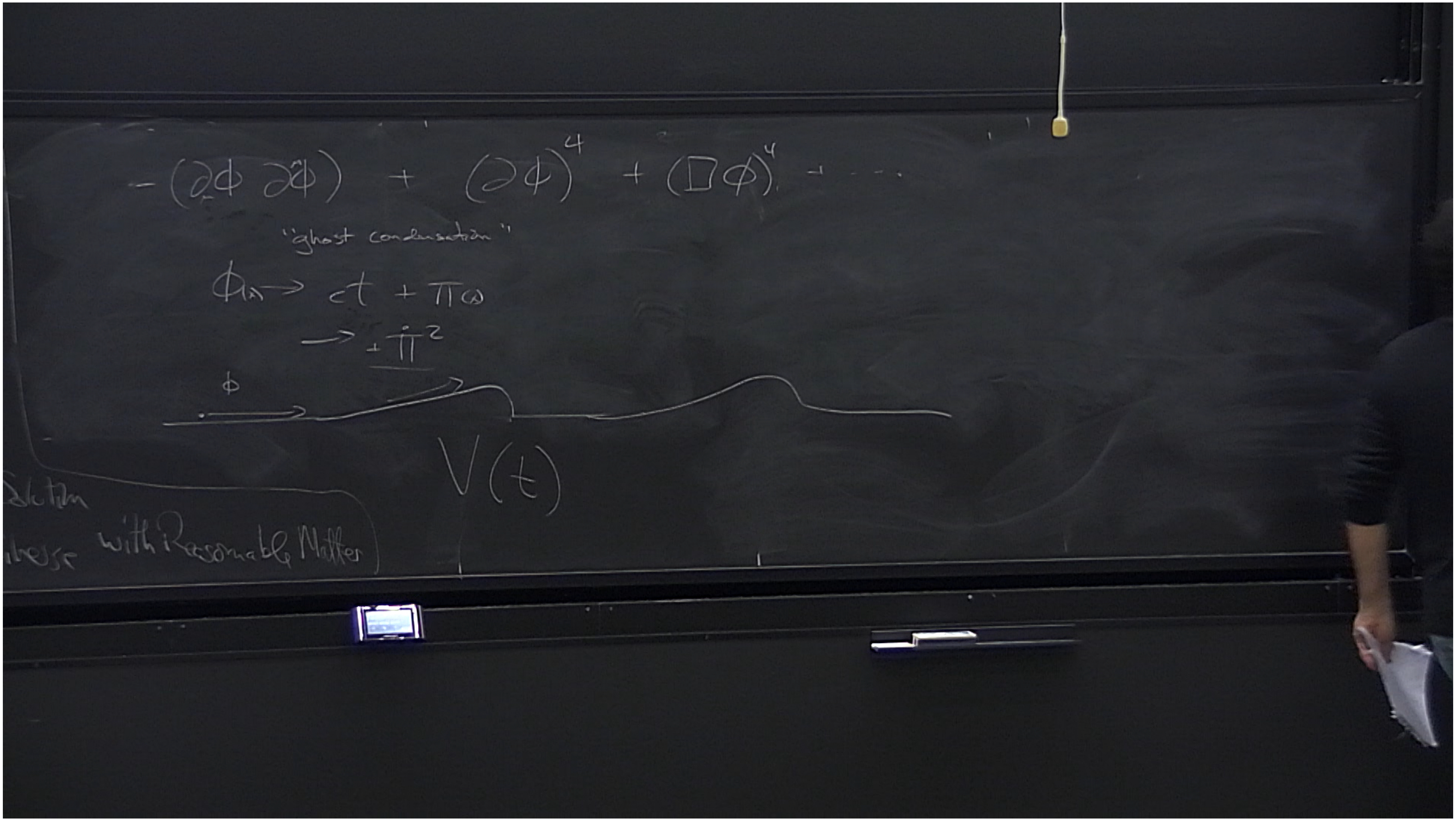
ρ to increase

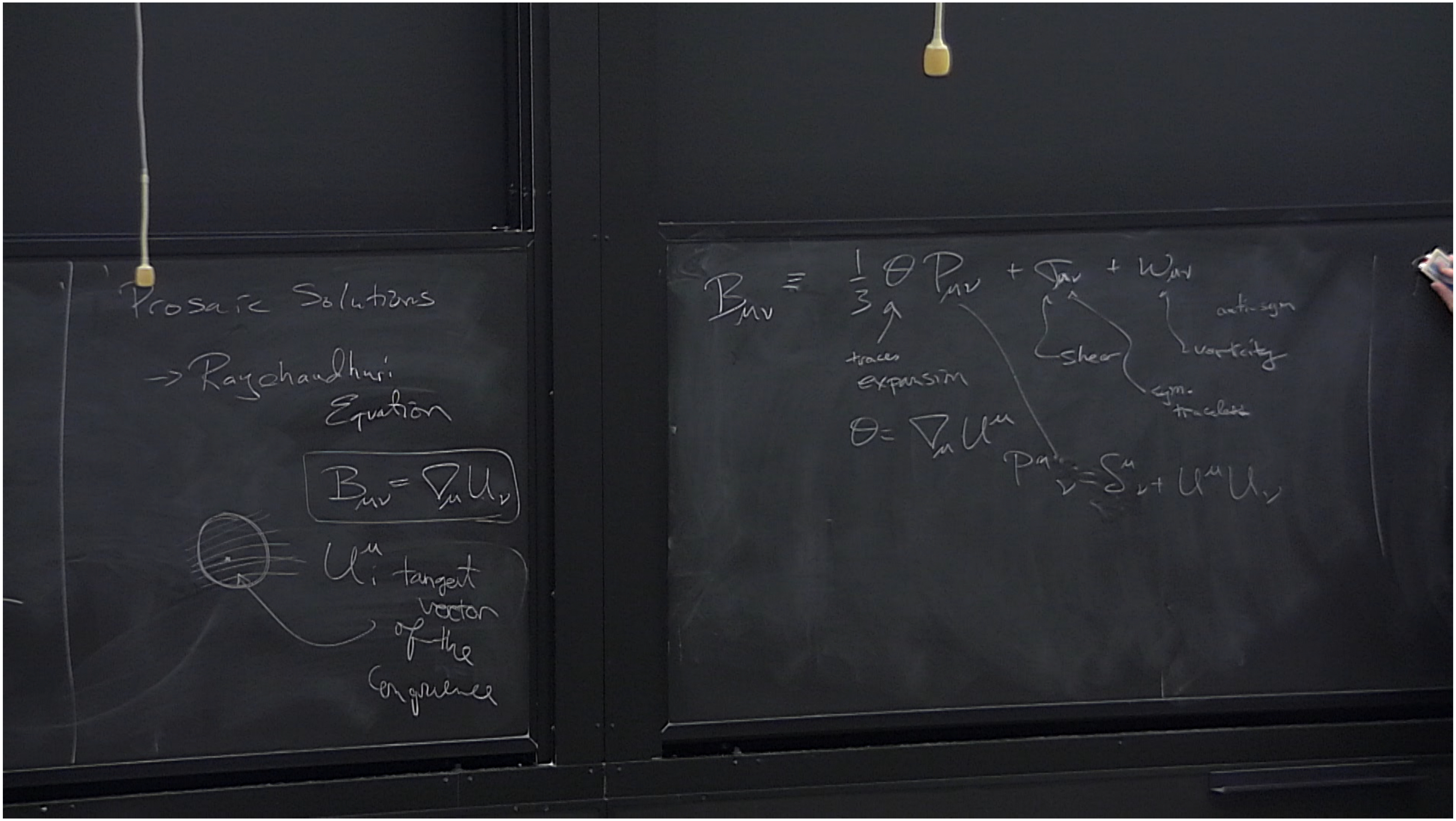
$$H^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi}{3} G_N \rho$$

$$\frac{\dot\rho}{\rho} = -3(1+w)\frac{\dot a}{a}$$

$w < -1$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$


$-(\partial\phi\,\partial\phi) + (\partial\phi)^4 + (\Box\phi)^4 + \dots$
"ghost condensation"
$\phi(x) \to ct + \pi(x)$
$\to + \dot{\pi}^2$
ϕ
$V(t)$
with Reasonable Matter


Prosaic Solutions
→ Raychaudhuri Equation
$B_{\mu\nu} = \nabla_\mu U_\nu$
U^μ: tangent vector of the congruence
$B_{\mu\nu} \equiv \frac{1}{3}\theta P_{\mu\nu} + \sigma_{\mu\nu} + \omega_{\mu\nu}$
traces expansion
shear
sym. traceless
anti-sym
vorticity
$\theta = \nabla_\mu U^\mu$
$P^\mu{}_\nu = \delta^\mu{}_\nu + U^\mu U_\nu$

$$\rho + p \geq 0 \;;\; \rho + 3p \geq 0$$

$$\frac{d\theta}{d\tau} = -\frac{1}{3}\theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \underline{\omega_{\mu\nu}\omega^{\mu\nu}} - R_{\mu\nu}U^\mu U^\nu$$

Strong Energy Condition

$$R_{\mu\nu} = 8\pi G_N \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right)$$

$$\frac{d\theta}{d\tau} \leq -\frac{1}{3}\theta^2 \Longrightarrow \frac{1}{\theta} = \frac{1}{\theta_0} + \frac{1}{3}\tau$$

$$\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T^\lambda{}_\lambda\right) U^\mu U^\nu > 0$$

$$\theta_0 < 0$$

oblem

osmology

$$\frac{d\Theta}{d\lambda} = -\frac{1}{2}\Theta^2 - \hat{\sigma}_{\mu\nu}\hat{\sigma}^{\mu\nu} + \hat{\omega}_{\mu\nu}\hat{\omega}^{\mu\nu} - R_{\mu\nu}k^\mu k^\nu$$

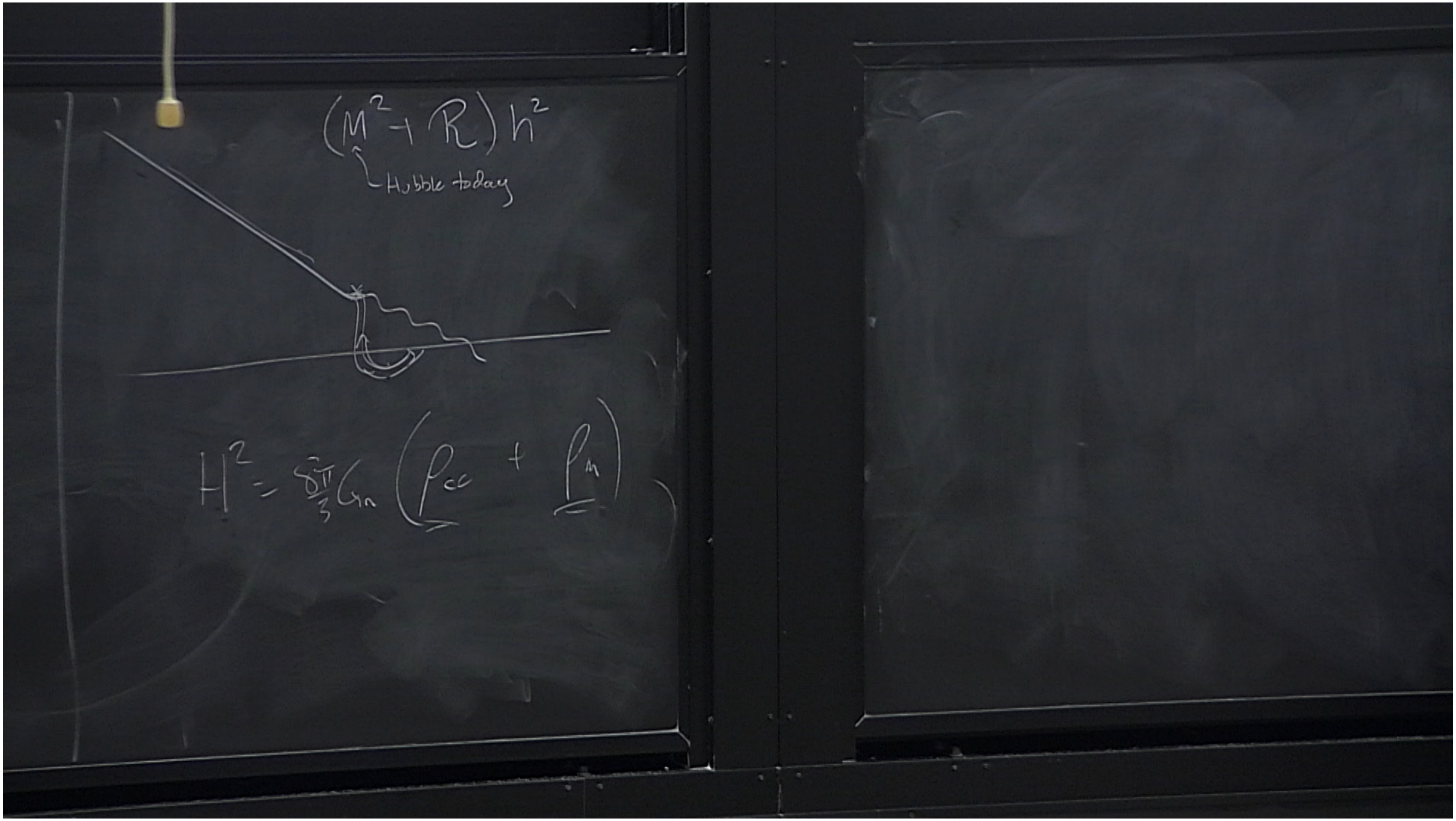
$\rho + P \geq 0$

$$8\pi G_N \left(T_{\mu\nu} - \cancel{\tfrac{1}{2} g_{\mu\nu} T^\lambda{}_\lambda}\right) k^\mu k^\nu$$

$$= 8\pi G_N T_{\mu\nu} k^\mu k^\nu < 0$$

Violates NEC

Bounce Solution of the Universe with Reasonable Matter


$(M^2 + R)h^2$
Hubble today
$H^2 = \frac{8\pi}{3} G_N (\rho_{cc} + \rho_m)$

Kerr Metric – locally it has $\omega_{\mu\nu} \neq 0$

$$ds^2 = -\left(1 - \frac{2GMr}{\rho^2(r,\theta)}\right) dt^2$$

Stationary

$$- \frac{2GMar\sin^2\theta}{\rho^2(r,\theta)} \left(2\, dt\, d\phi\right)$$

Not Static

$$+ \cdots$$

$$\frac{d\theta}{d\tau}$$

$$\frac{d\theta}{d\tau}$$

Gödel Metric.

Homogeneous, Not isotropic $\Rightarrow$ Rotating Dust

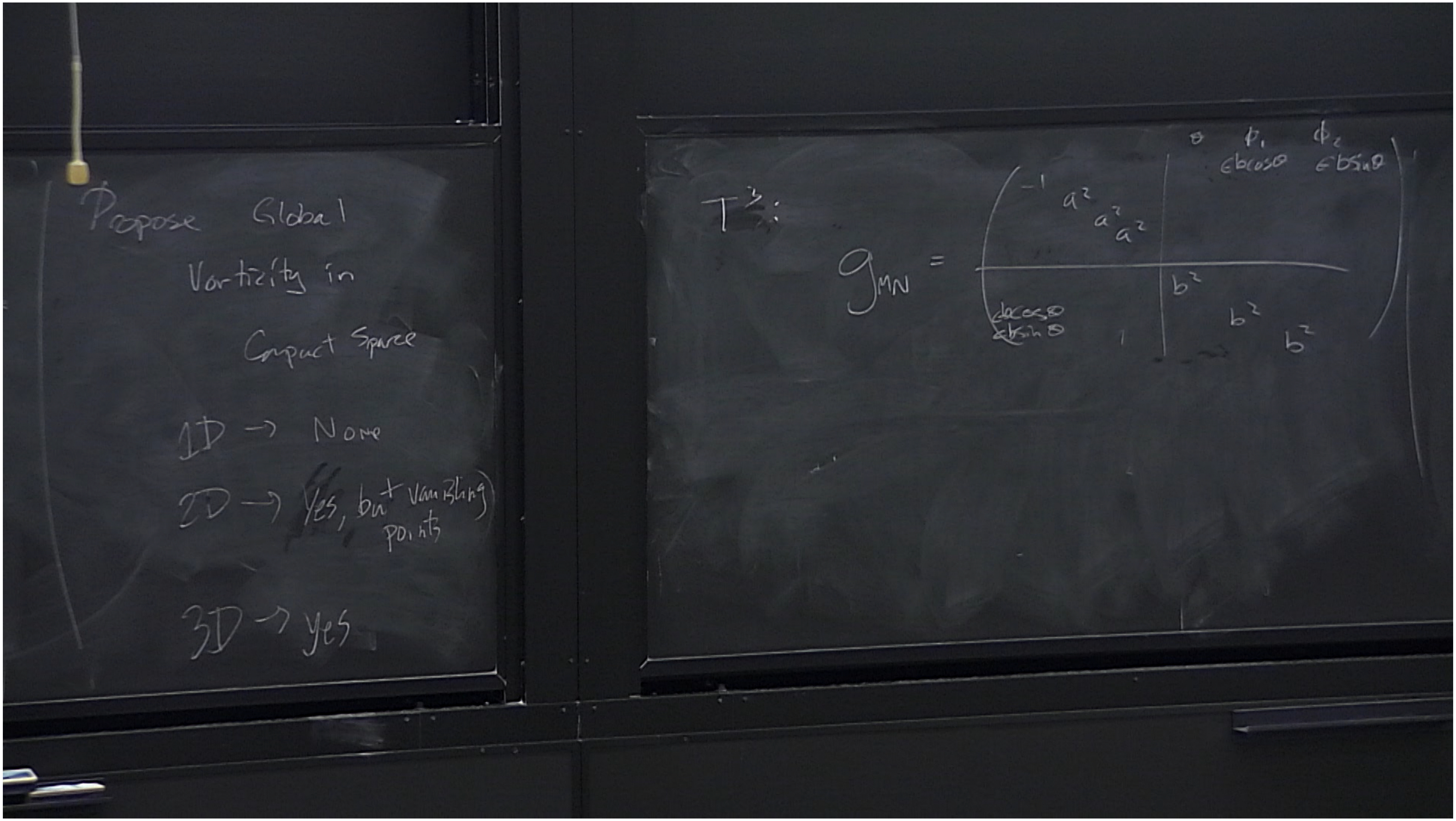
$$ds^2 = -dt^2 + dr^2 + dz^2 - (\sinh^4 r - \sinh^2 r)\, d\phi^2 - 2\sqrt{2}\sinh^2 r\, d\phi\, dt$$

$r = R,\ z = 0,\ t = -\alpha\phi$

Small $\alpha \Rightarrow$ CTC

Solution

...iverse with Reasonable Matter


Propose Global
Vorticity in
Compact Space
1D → None
2D → Yes, but vanishing points
3D → yes
T³:
g_MN =
θ φ₁ φ₂
-1
a²
a²
a²
b²
b²
b²
εb cos θ
εb sin θ
1