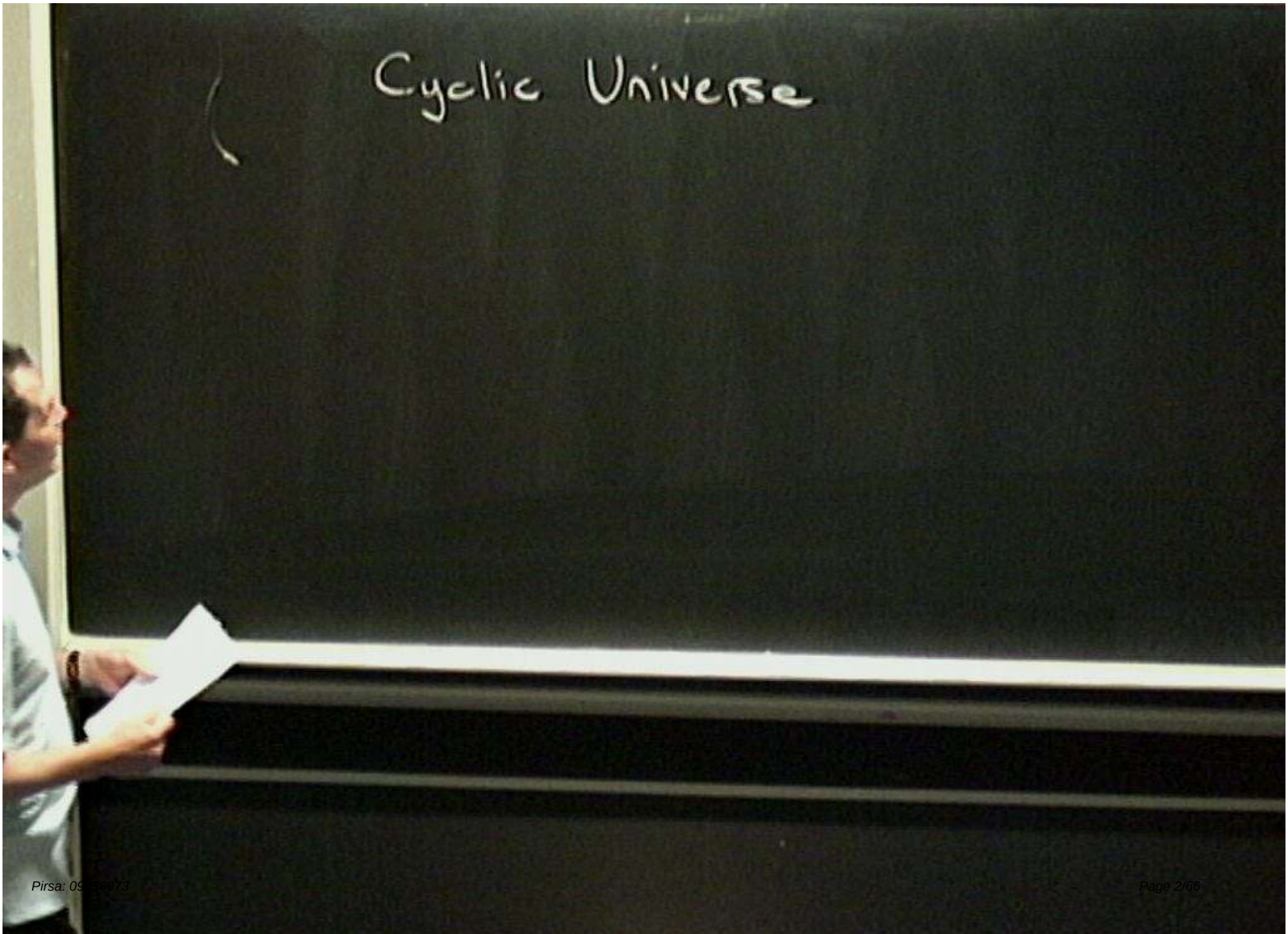
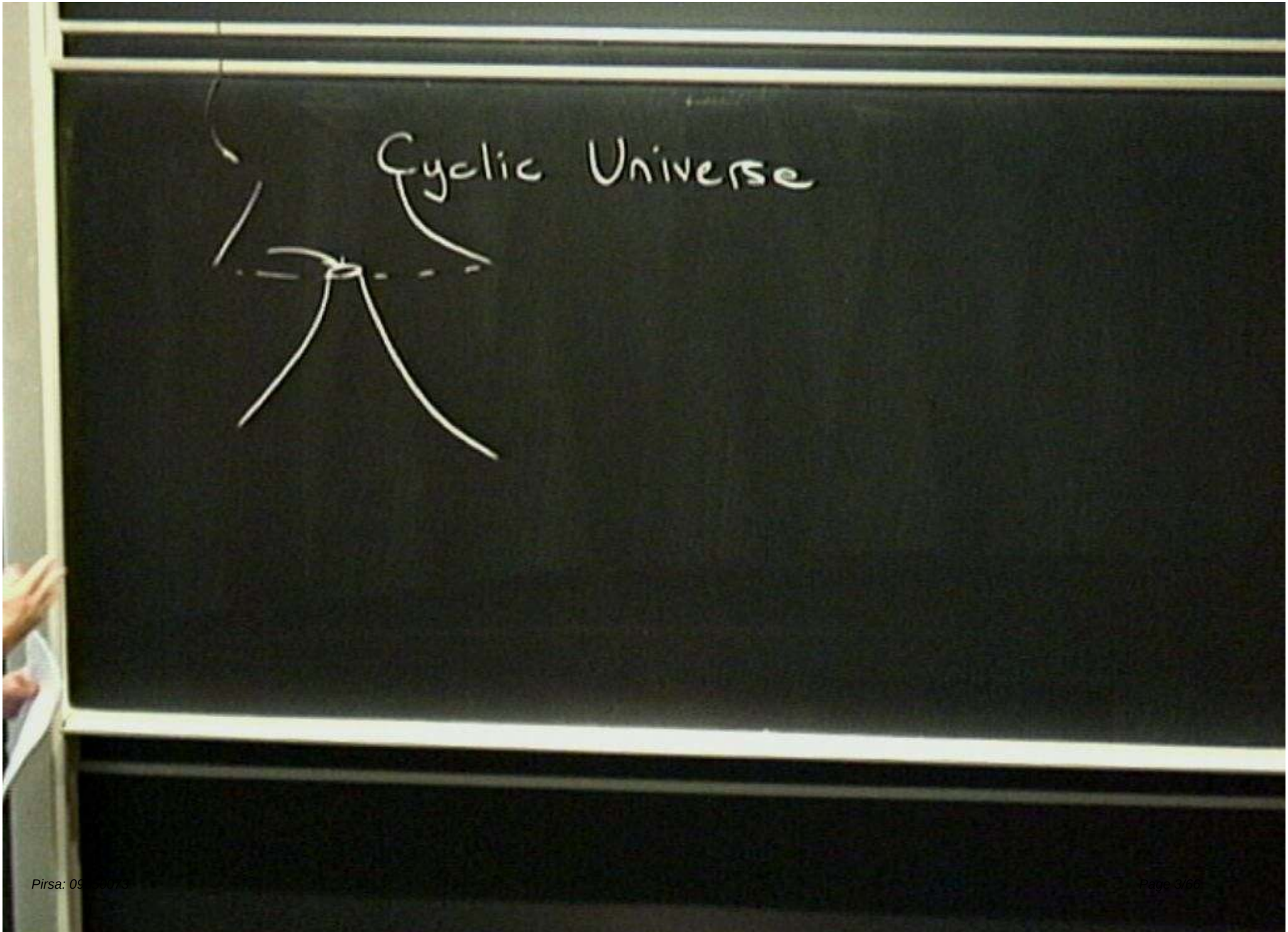
Title: Cyclic Universe

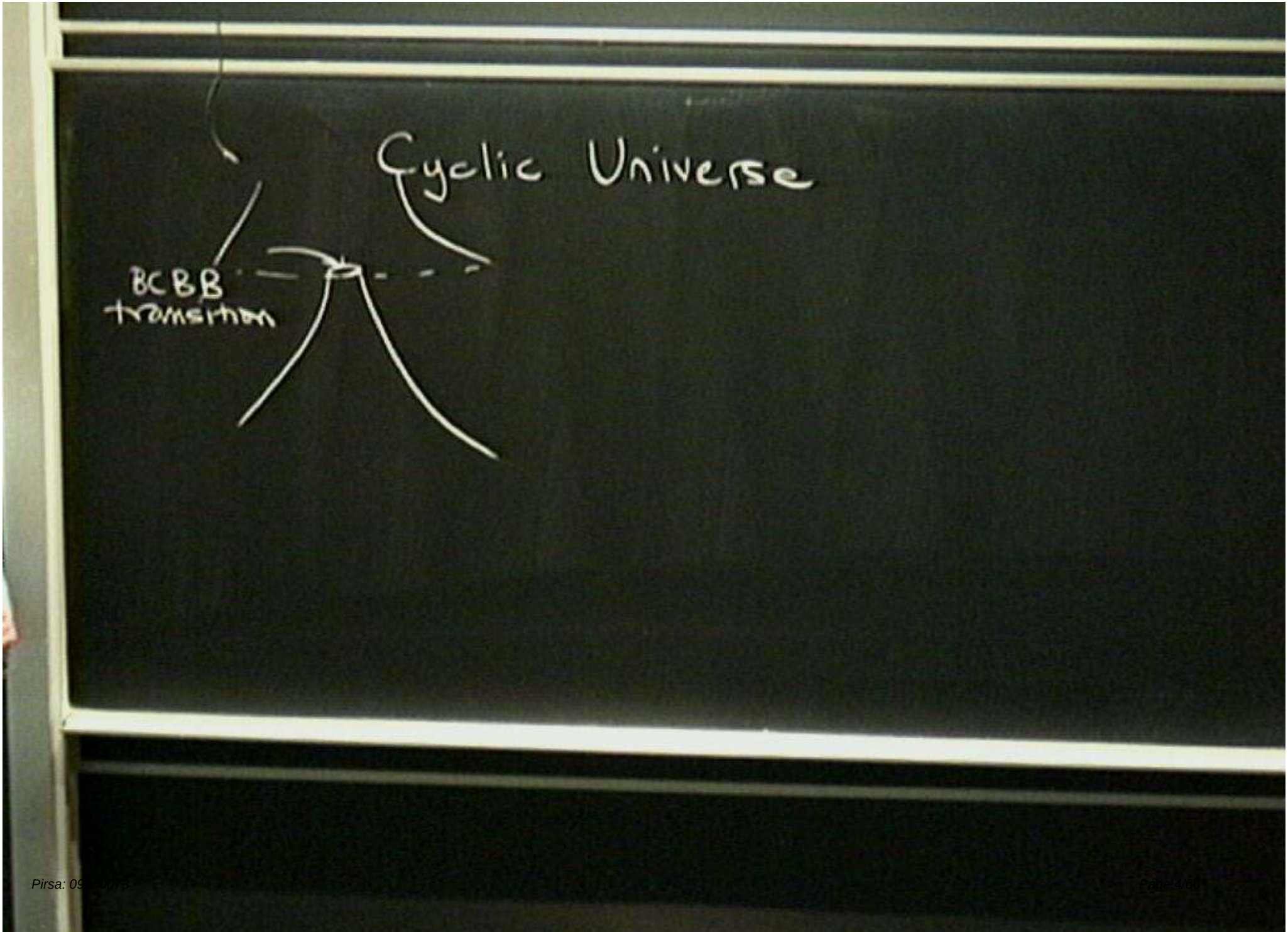
Date: May 25, 2009 04:45 PM

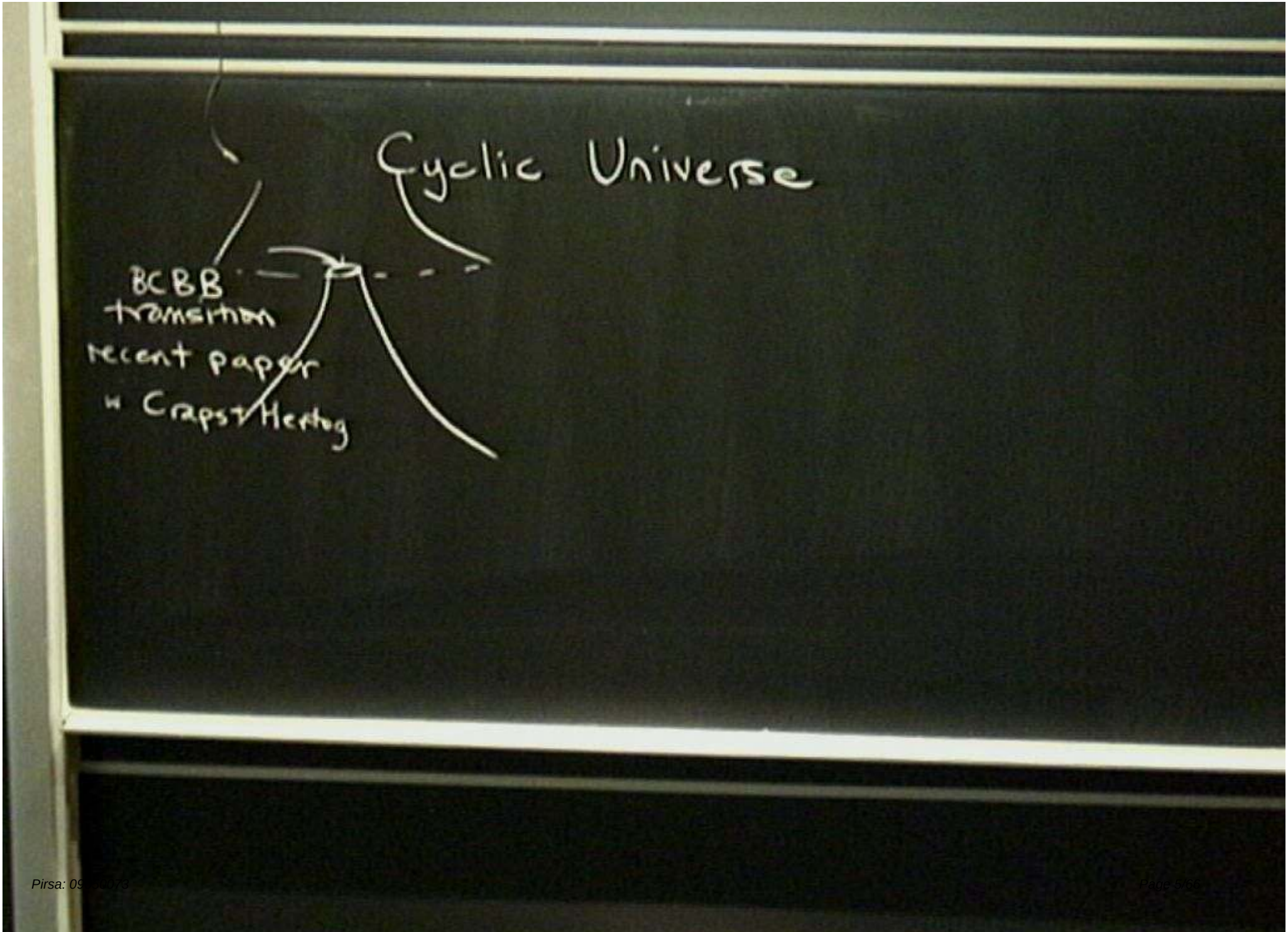
URL: http://pirsa.org/09050073

Abstract: TBA

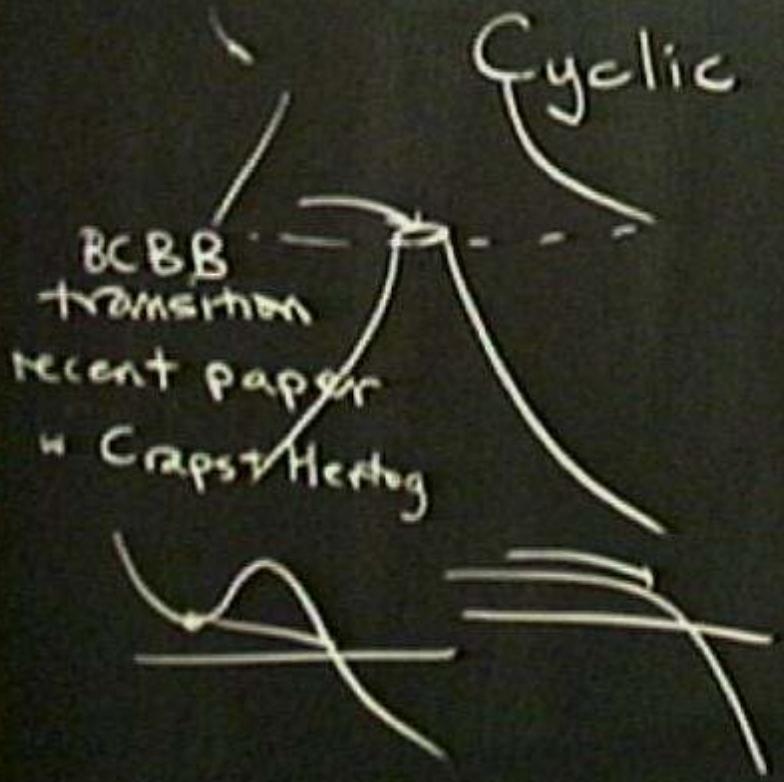

Cyclic Universe


Cyclic Universe

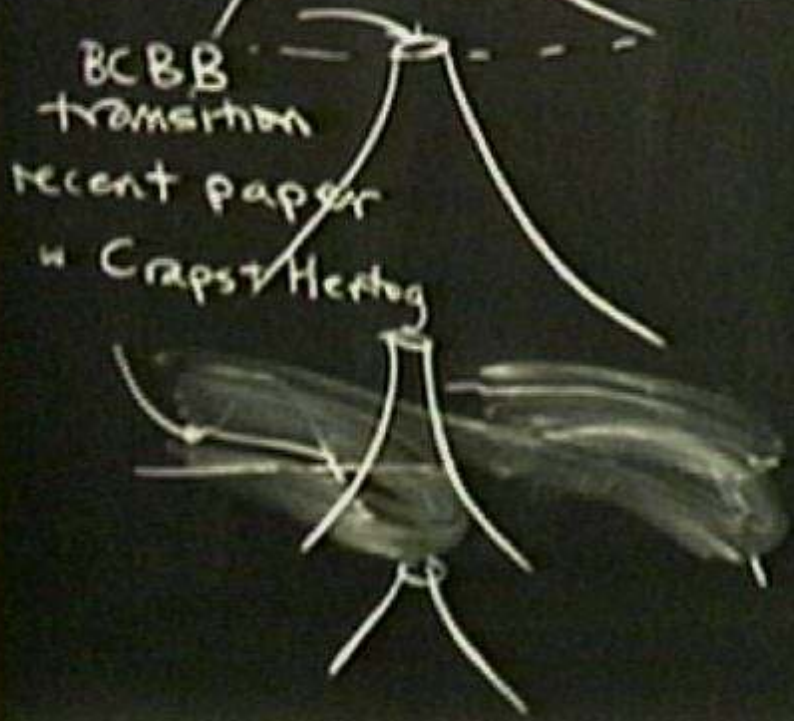

Cyclic Universe
BCBB
transition

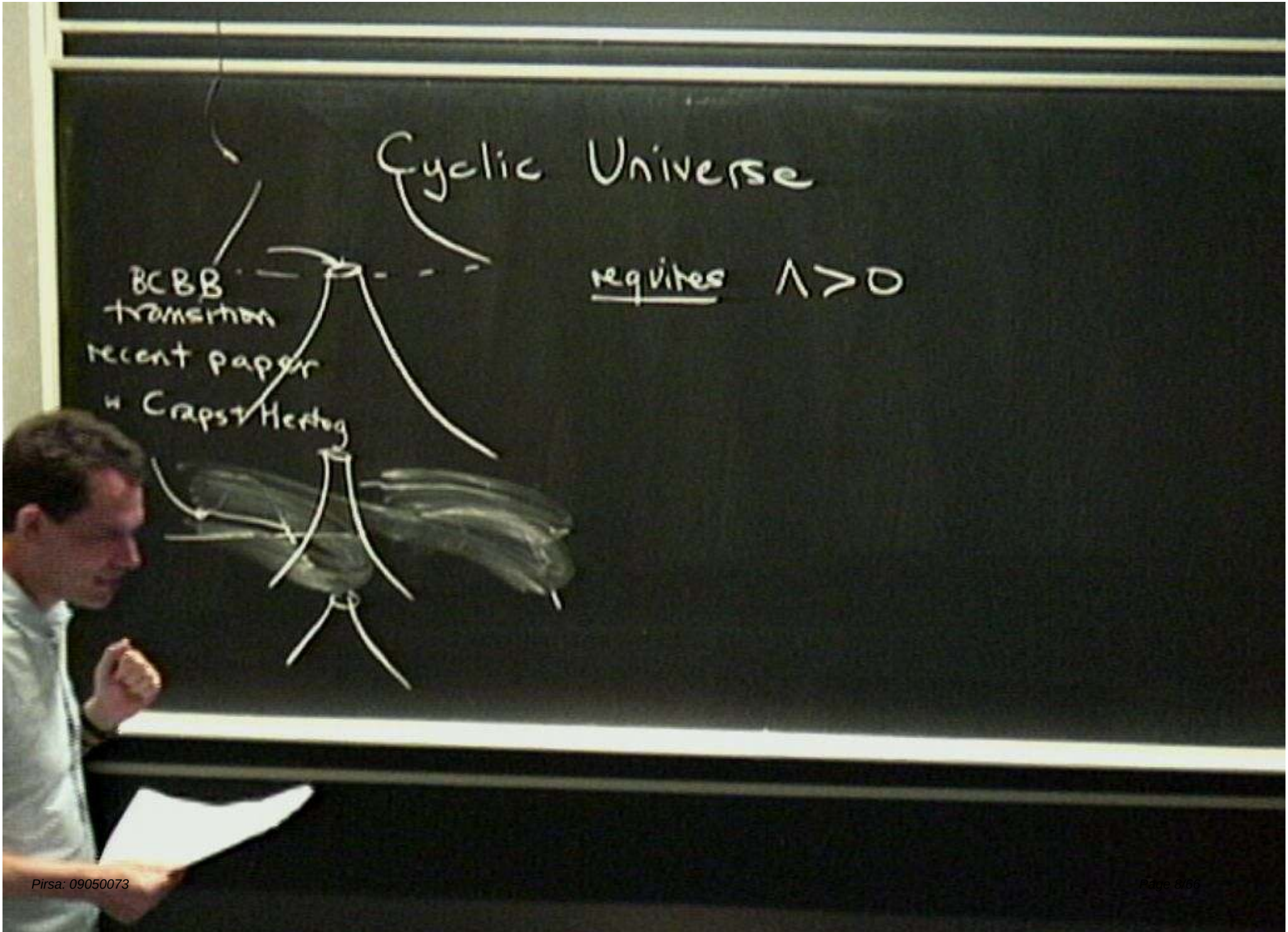

Cyclic Universe
BCBB
transition
recent paper
w Craps + Herlog

Cyclic Universe

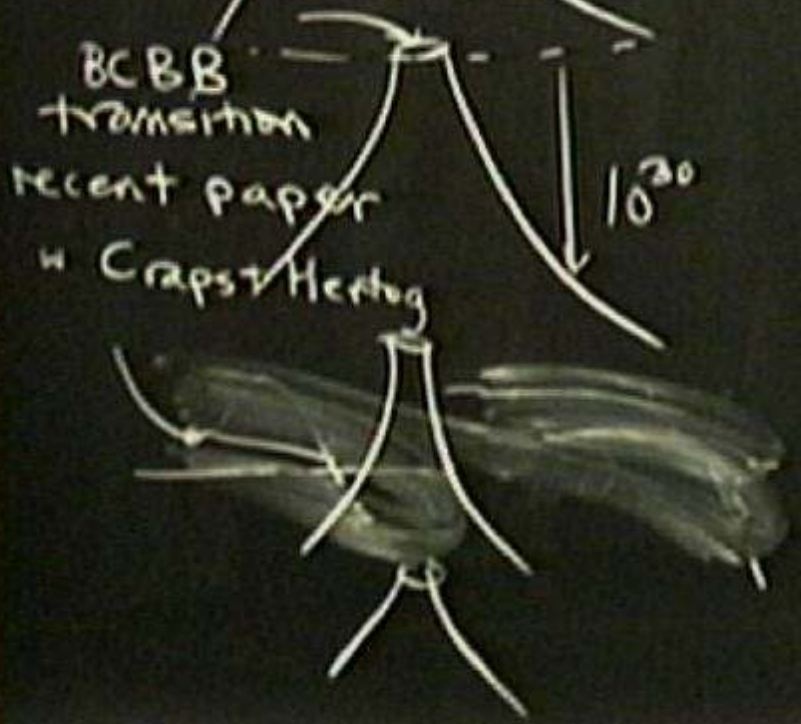


Cyclic Universe



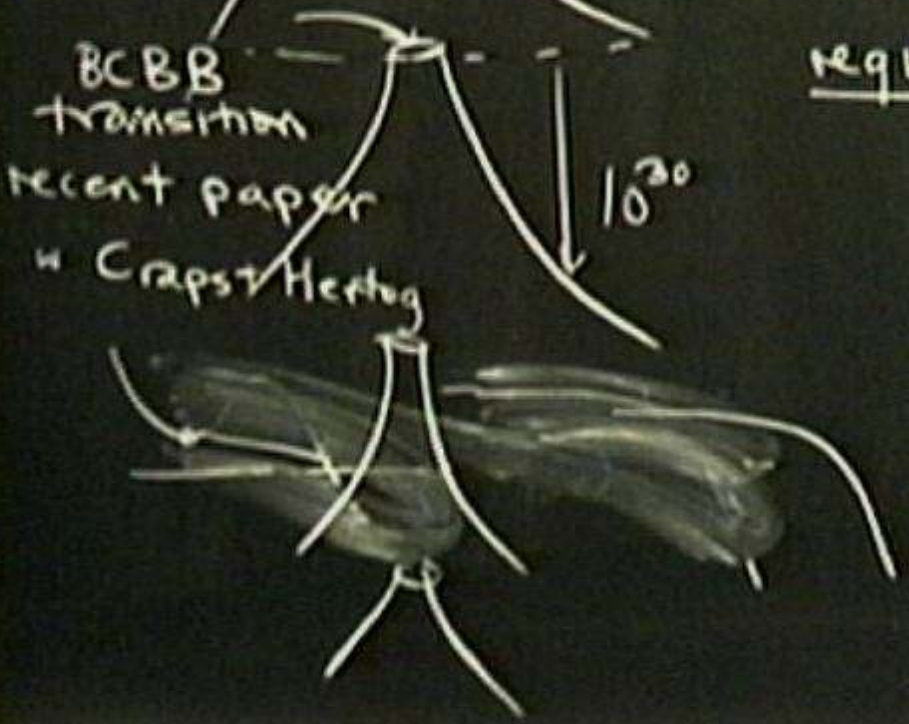

Cyclic Universe
requires Λ>0
BCBB
transition
recent paper
w Crapst/Herlog

Cyclic Universe

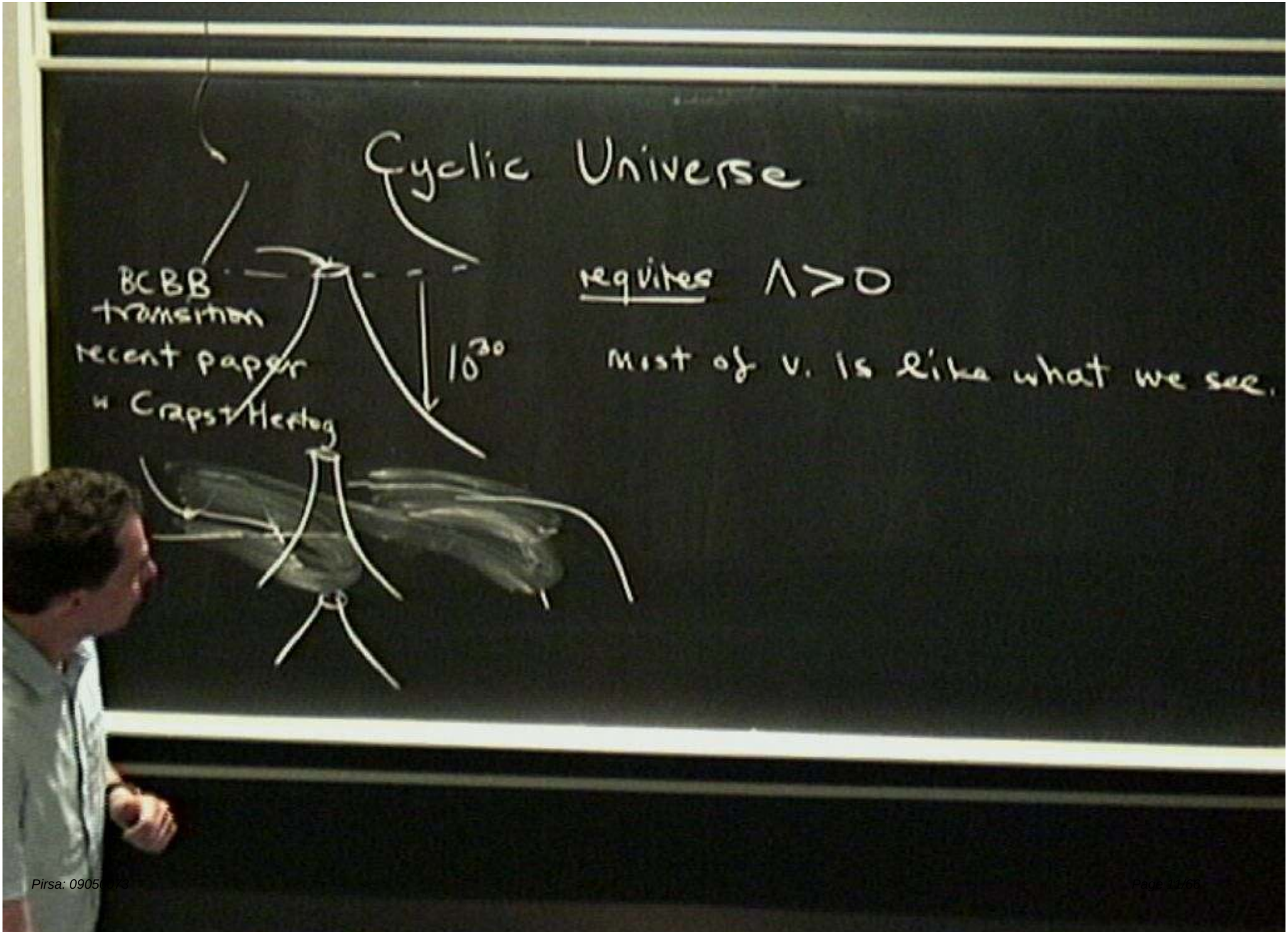


requires $\Lambda > 0$

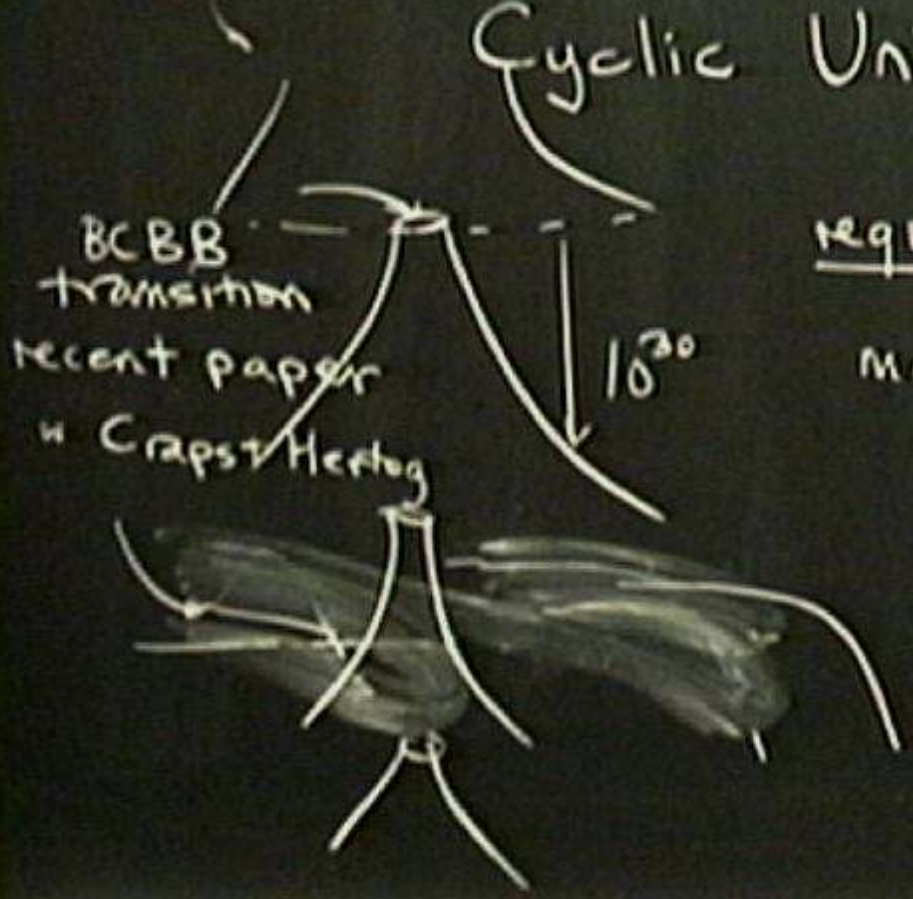
Cyclic Universe



requires $\Lambda > 0$


Cyclic Universe
requires $\Lambda > 0$
BCBB transition
recent paper
w Craps/Herlog
10^{30}
Most of U. is like what we see.

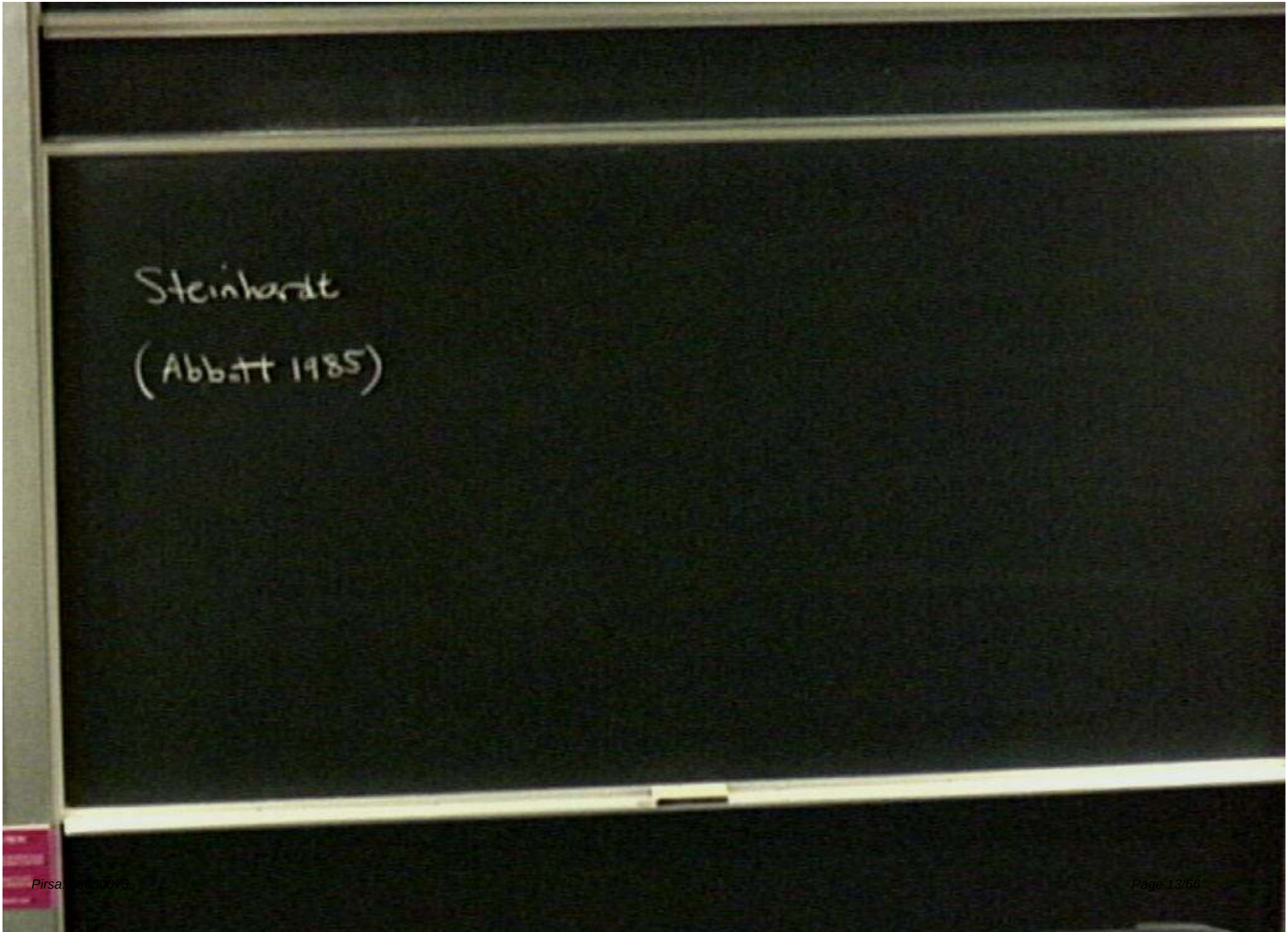
Cyclic Universe



requires $\Lambda > 0$

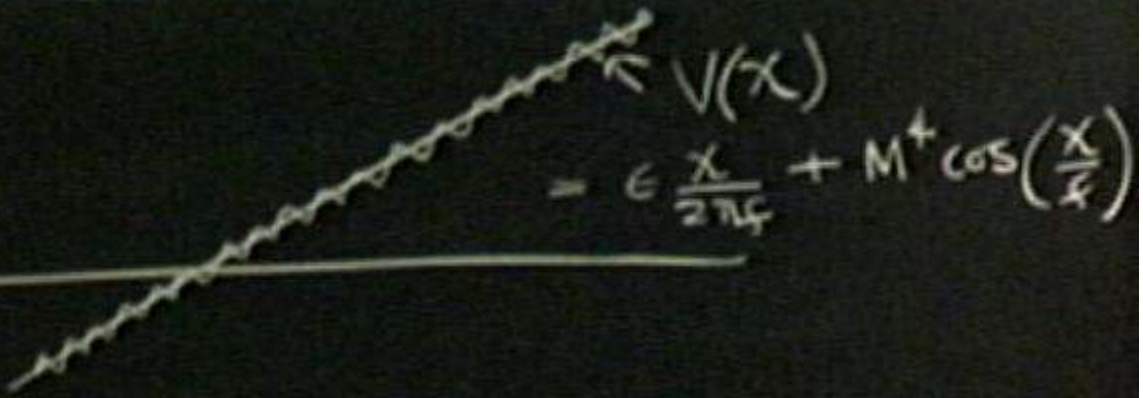
Most of V. is like what we see.

lots of time


Steinhardt
(Abbott 1985)

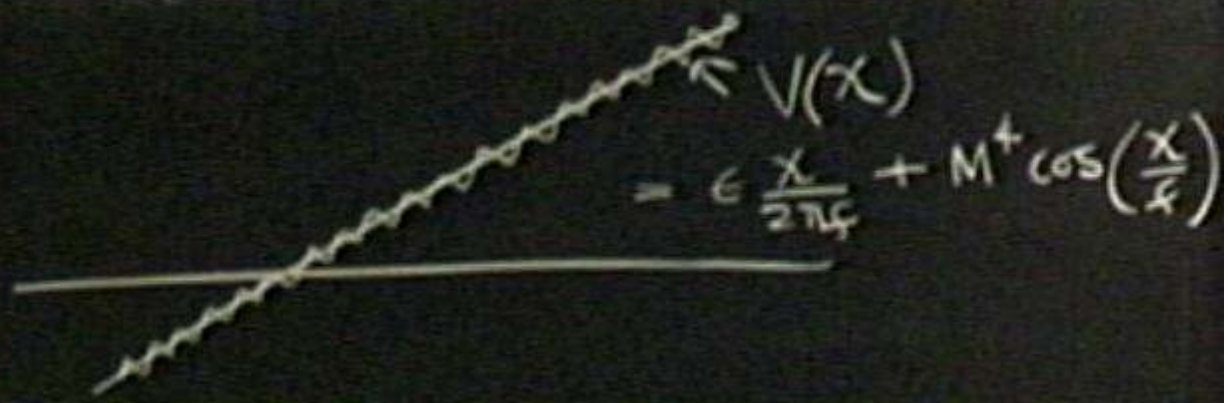
Steinhardt

(Abbott 1985)



Steinhardt

(Abbott 1985)

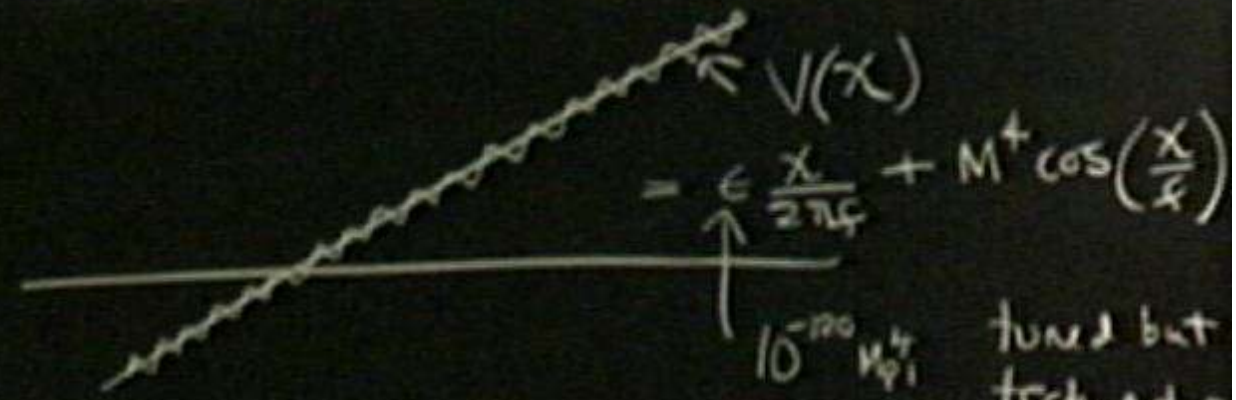


$\chi \to \chi + \text{const}$

break by ① soft linear term

Steinhardt

(Abbott 1985)



tuned but
tech. natural

$\chi \to \chi + \text{const}$

break by ① soft linear term

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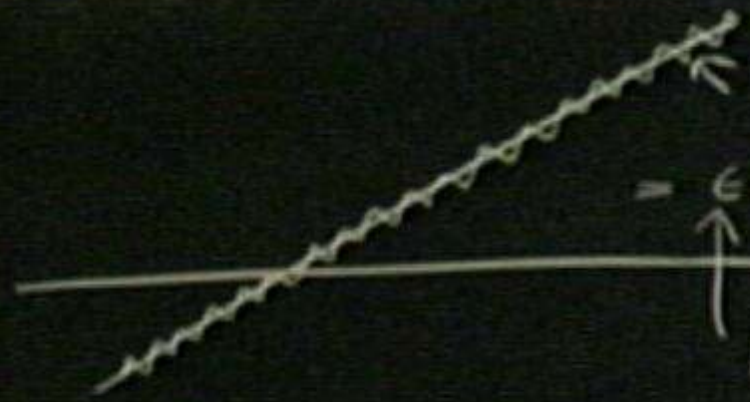

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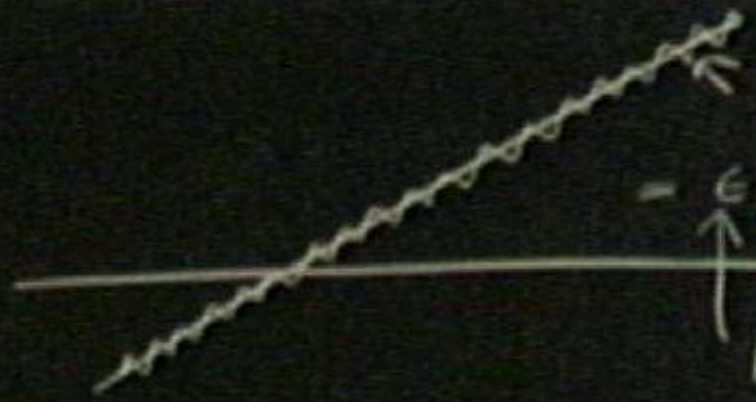


$+ M^4 \cos\left(\frac{\chi}{f}\right)$

tuned but
tech. natural

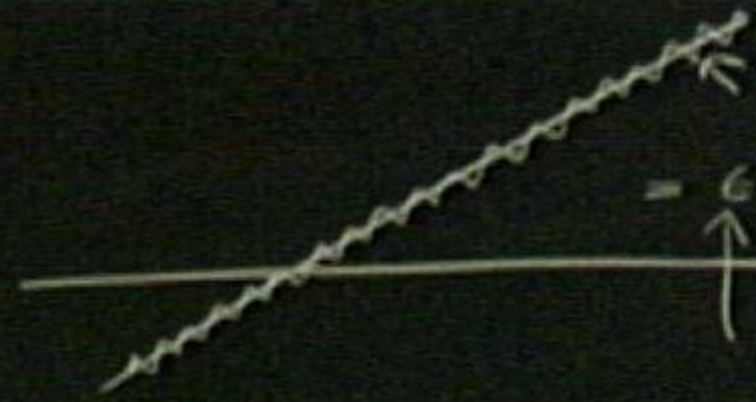
$\chi \to \chi + \text{const}$

break by ① soft linear term

② non-pert., natural for $M \ll M_{Pl}$.

Steinhardt

(Abbott 1985)



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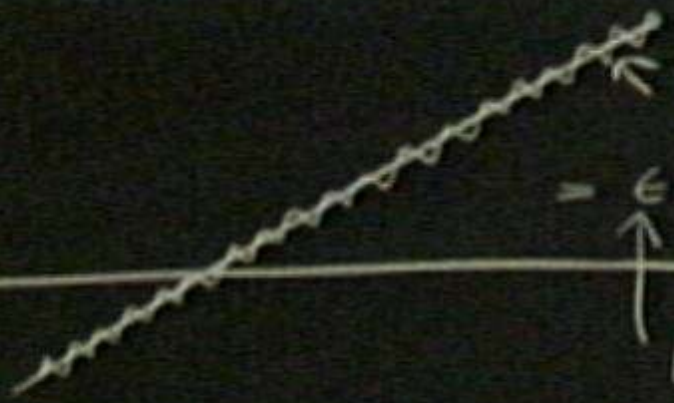
break by ① soft linear term

② non pert., natural for $M \ll M_{Pl}$.

$M \sim M_{Pl} e^{-\frac{1}{N(M_{Pl})}}$

Steinhardt

(Abbott 1985)



$\int \frac{\chi}{f} F\tilde{F}$

$+ M^4 \cos\left(\frac{\chi}{f}\right)$

tuned but tech. natural

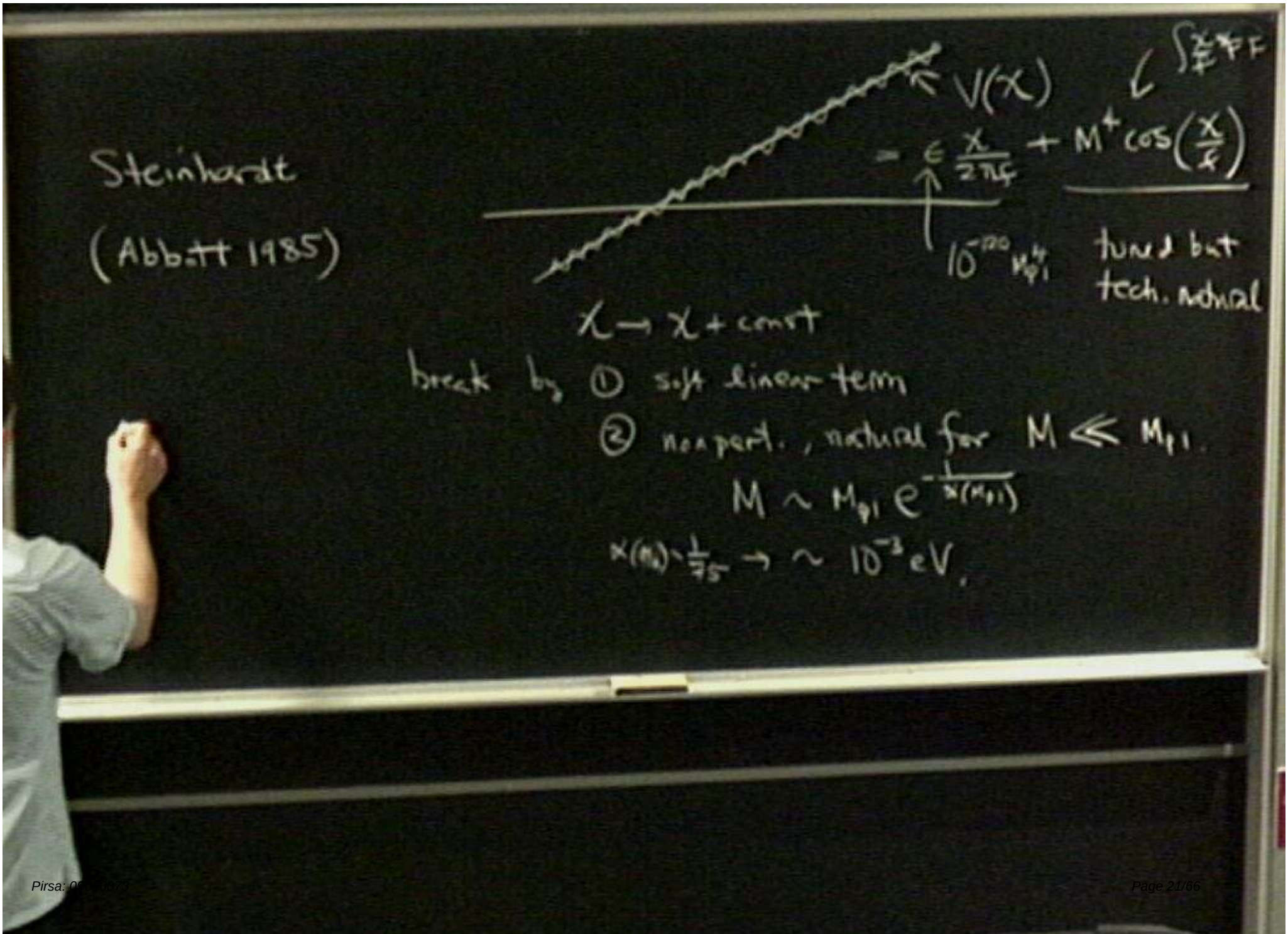
$\chi \to \chi + \text{const}$

break by ① soft linear term

② non pert., natural for $M \ll M_{Pl}$.

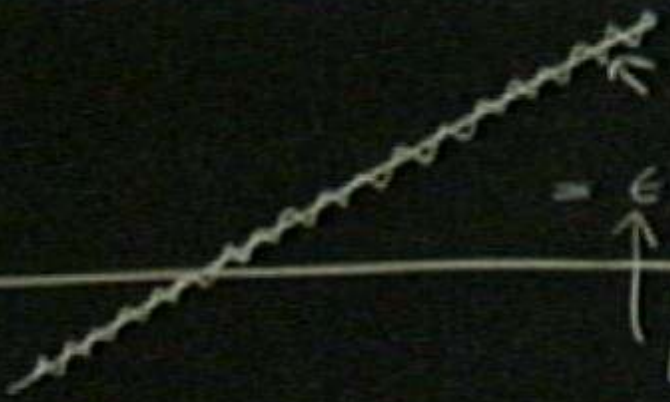
$$M \sim M_{Pl} e^{-\frac{1}{\alpha(M_{Pl})}}$$

$\alpha(M_{Pl}) \sim \frac{1}{25} \to \sim 10^{-3}\,eV.$


Steinhardt
(Abbott 1985)
V(χ)
$= \epsilon \frac{\chi}{2\pi f}$
$+ M^4 \cos\left(\frac{\chi}{f}\right)$
$\int \frac{\chi}{f} F\tilde{F}$
$10^{-120} M_{Pl}^4$
tuned but tech. natural
$\chi \to \chi + \text{const}$
break by ① soft linear term
② non pert., natural for $M \ll M_{Pl}$.
$M \sim M_{Pl} e^{-\frac{1}{\alpha(M_{Pl})}}$
$\alpha(M_{Pl}) \sim \frac{1}{25} \to \sim 10^{-3}\,\text{eV}$.

Steinhardt

(Abbott 1985)



tuned but tech. natural

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break by ① soft linear term

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$M \sim M_{Pl} e^{-\frac{1}{\alpha(M_{Pl})}}$

$\alpha(M_{Pl}) \sim \frac{1}{25} \to \sim 10^{-3}\,eV.$

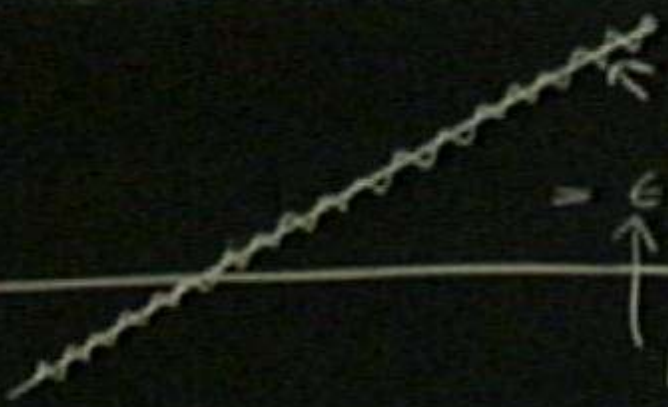
$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_0 < \epsilon$

Steinhardt

(Abbott 1985)



$V(\chi) = \epsilon \frac{\chi}{2\pi f} + M^4 \cos\left(\frac{\chi}{f}\right)$ ← $\int \frac{\chi}{f} \neq F$

tuned but technically natural

$\chi \to \chi + \text{const}$

break by ① soft linear term

② non-pert., natural for $M \ll M_{pl}$.

$M \sim M_{pl} e^{-\frac{1}{\alpha(M_{pl})}}$

$\alpha(M_{pl}) \sim \frac{1}{75} \to \sim 10^{-3}\,\text{eV}$.

$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_0 < \epsilon$

(Abbott 1985)

$10^{-120} M_{Pl}^4$

tuned but tech. natural

$\chi \to \chi + \text{const}$

break by ① soft linear term

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$\alpha(M_{Pl}) \sim \frac{1}{35} \to \sim 10^{-3}\,\text{eV}$.

$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_1 < \epsilon$

$\frac{f^2}{M_{Pl}^2} \ll \frac{\epsilon}{M^4} < 1$

Scenario: imagine starting with $V \gg \epsilon$

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$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers

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① Hawking Moss

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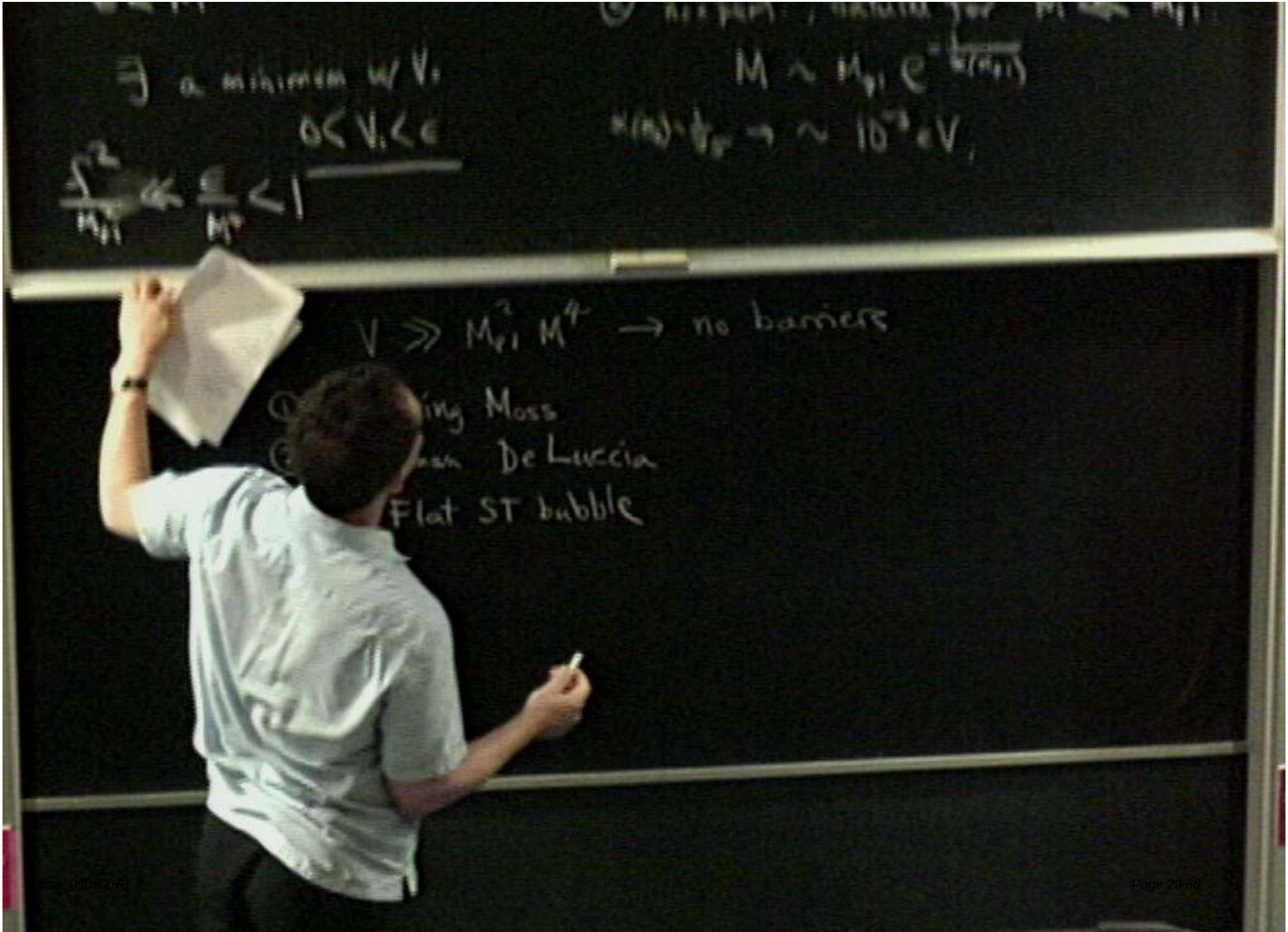
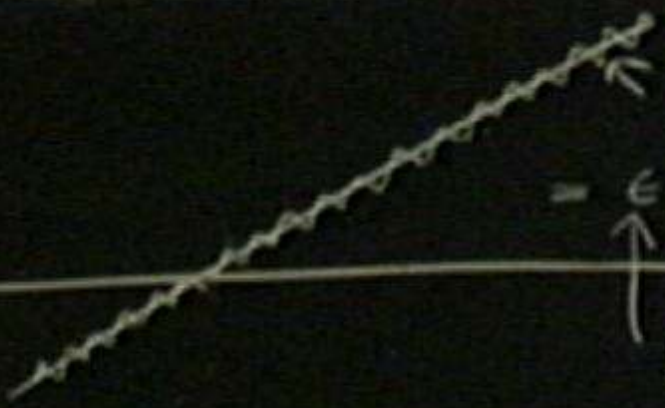
① Hawking Moss
② Coleman De Luccia


a minimum w/ V
$0 < V_1 < \epsilon$
$M \sim M_{Pl}\, e^{-\frac{1}{\epsilon(\phi)}}$
$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers
ing Moss
am De Luccia
Flat ST bubble

Steinhardt

(Abbott 1985)



$+ M^4 \cos\left(\frac{\chi}{f}\right)$

tunneling but tech. natural

$\chi \to \chi + \text{const}$

break by ① soft linear term

② non-pert., natural for $M \ll M_{Pl}$.

$M \sim M_{Pl} e^{-\frac{1}{\alpha(M_{Pl})}}$

$\alpha(M_{Pl}) \sim \frac{1}{75} \to \sim 10^{-3}\,\text{eV}$.

$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_0 < \epsilon$

$\frac{f^2}{M_{Pl}^2} \ll \frac{\epsilon}{M^4} < 1$

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Scenario: imagine starting with $V \gg \epsilon$

$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers

① Hawking Moss
② Coleman De Luccia
③ ~ Flat ST bubble

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② Coleman De Luccia
③ ~ Flat ST bubble S_E

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① Hawking Moss
② Coleman De Luccia
③ ~ Flat ST bubble

$$S_E = S_0\left(1 - \frac{(V_{N+1} V_{N-1})\, T^2}{M_{Pl}^2 \epsilon^2}\right)$$

bubble wall tension

$\frac{A}{M_{Pl}^2} \ll \frac{\epsilon}{M^4} < 1$

Scenario: imagine starting with $V \gg \epsilon$

$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers

① Hawking Moss
② Coleman De Luccia
③ ~ Flat ST bubble

$S_E = S_0\left(1 - \frac{(V_{N+1} V_{N-1})}{M_{Pl}^2 \epsilon^2} T^2\right)$

bubble wall tension

e.g. $f \sim 10^{16}$ GeV
$\frac{\epsilon}{M_{Pl}} = 0.1$
$M \sim 10^{-3}$ eV

10^{110}

Scenario: imagine starting with $V \gg \epsilon$

$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers

① Hawking Moss
② Coleman De Luccia
③ ~ Flat ST bubble

$$S_E = S_0\left(1 - \frac{(V_{N+1} V_{N-1})\, T^2}{M_{Pl}^2 \epsilon^2}\right)$$

$\propto N$; bubble wall tension

e.g. $f \sim 10^{14}$ GeV
$\frac{\epsilon}{M_4} = 0.1$
$M \sim 10^{-3}$ eV

$S_0 \sim 10^{110}$

Scenario: imagine starting with $V \gg \epsilon$

$V \gg M_{Pl}^2 M^4 \rightarrow$ no barriers

① Hawking Moss
② Coleman De Luccia
③ ~ Flat ST bubble

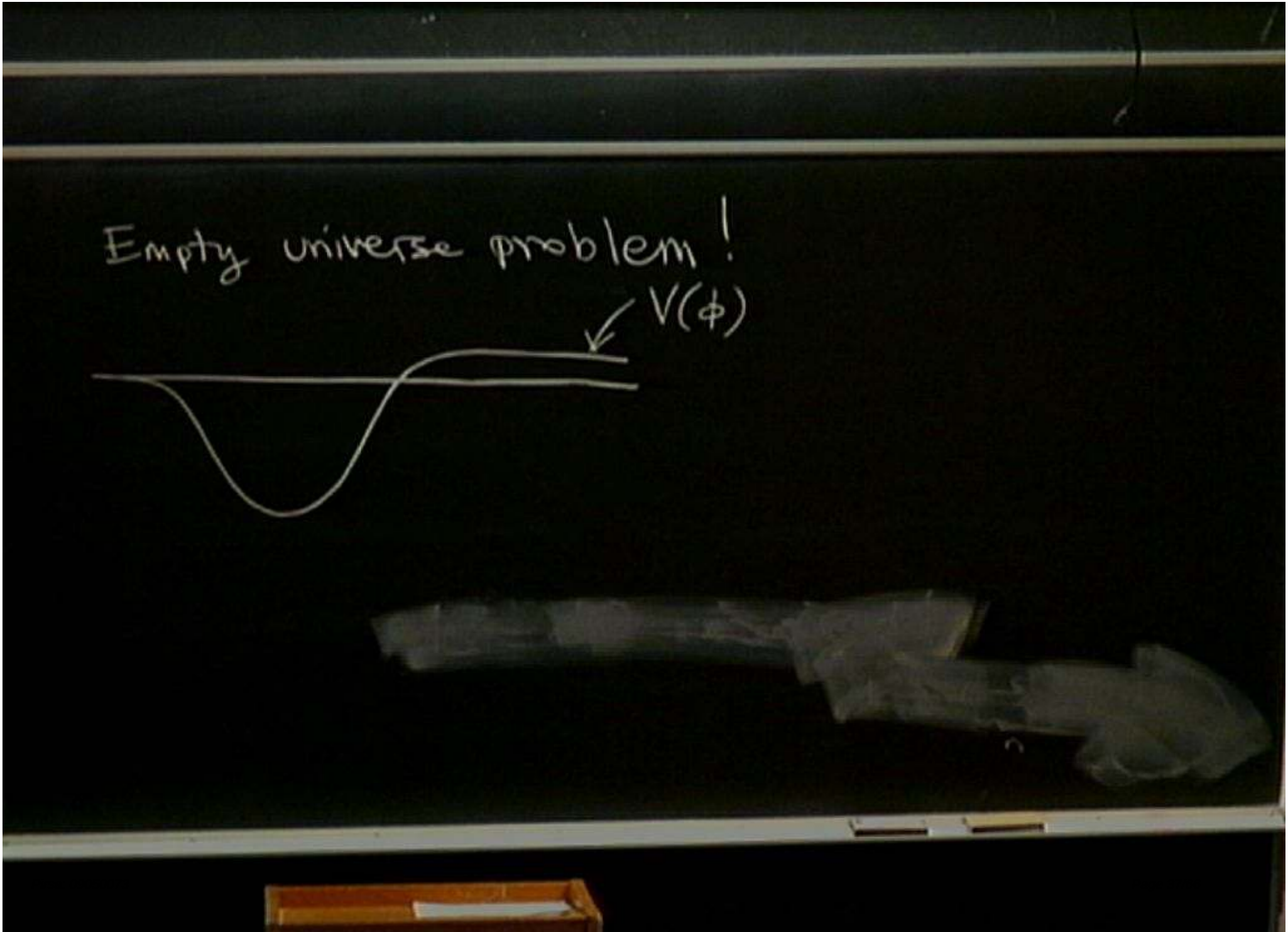
rate $\propto e^{10^{11} N}$

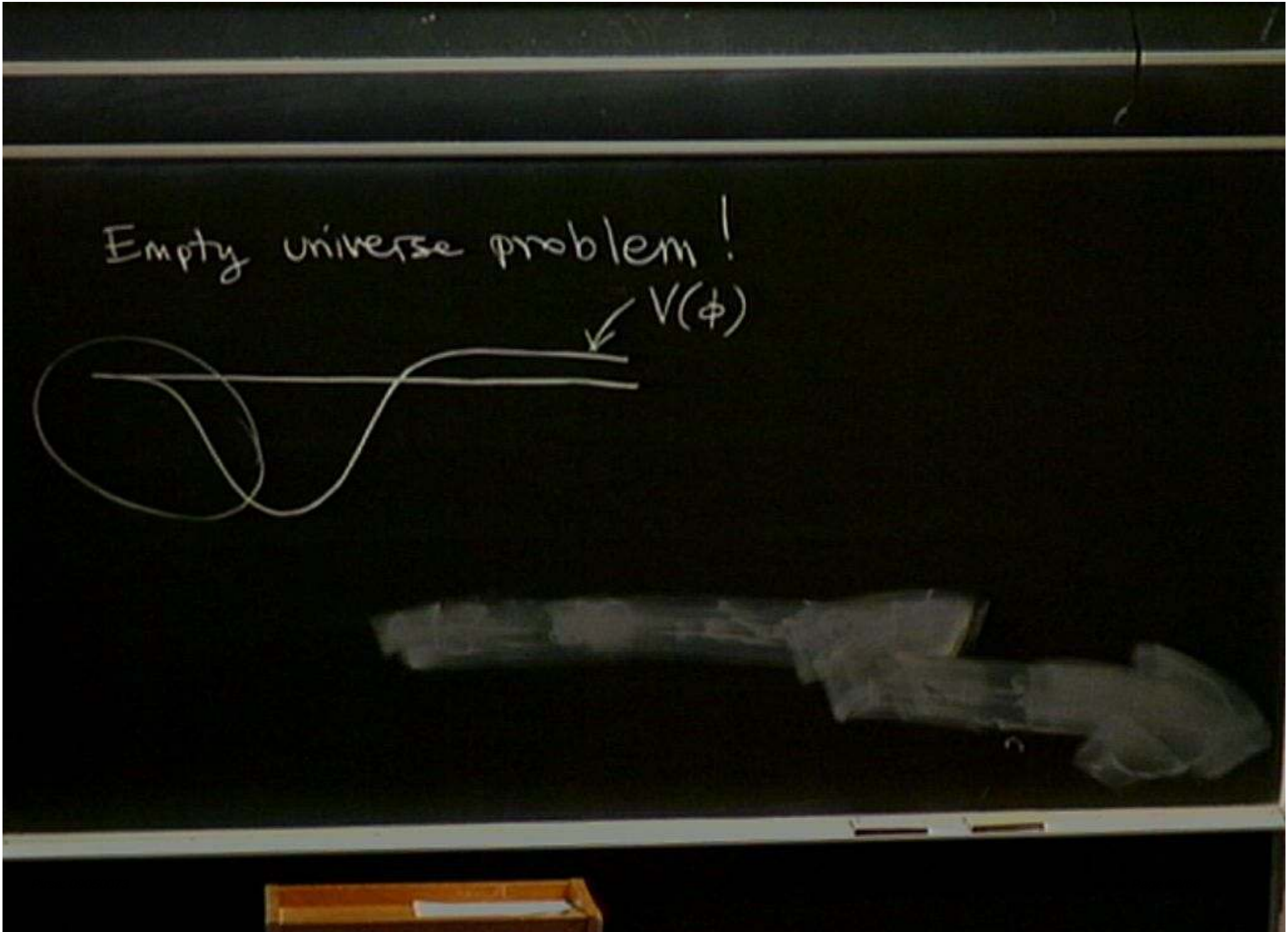
e.g. $f \sim 10^{4}$ GeV
$\frac{\phi}{M_{Pl}} = 0.1$
$M \sim 10^{-3}$ eV

$S_E = S_0 \left(1 - \frac{(V_{N+1} V_{N-1})\, T^2}{M_{Pl}^2 \epsilon^2}\right)$

$\propto N$; bubble wall tension

$\rightarrow 10^{110}$


Empty universe problem !
V(φ)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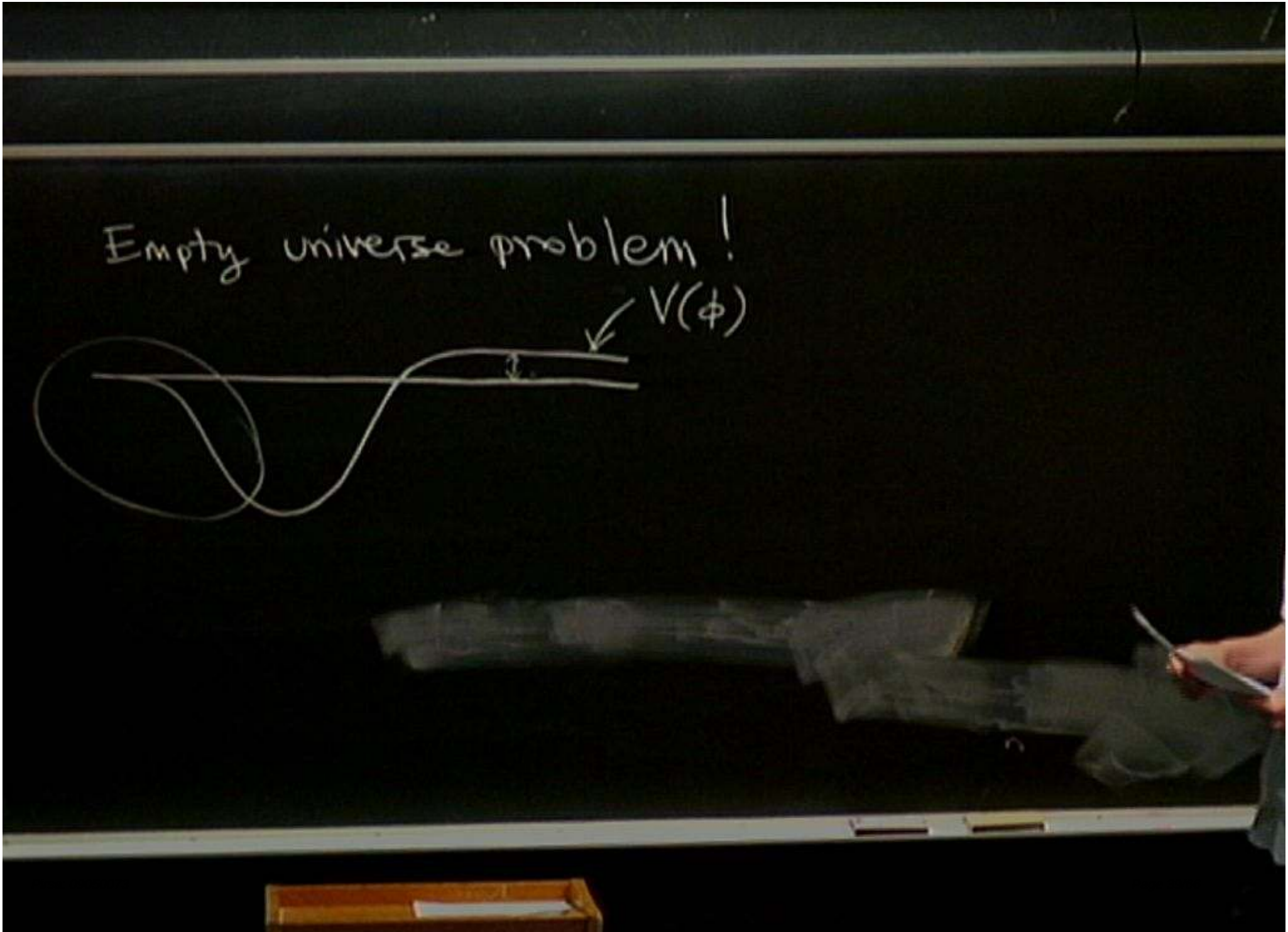
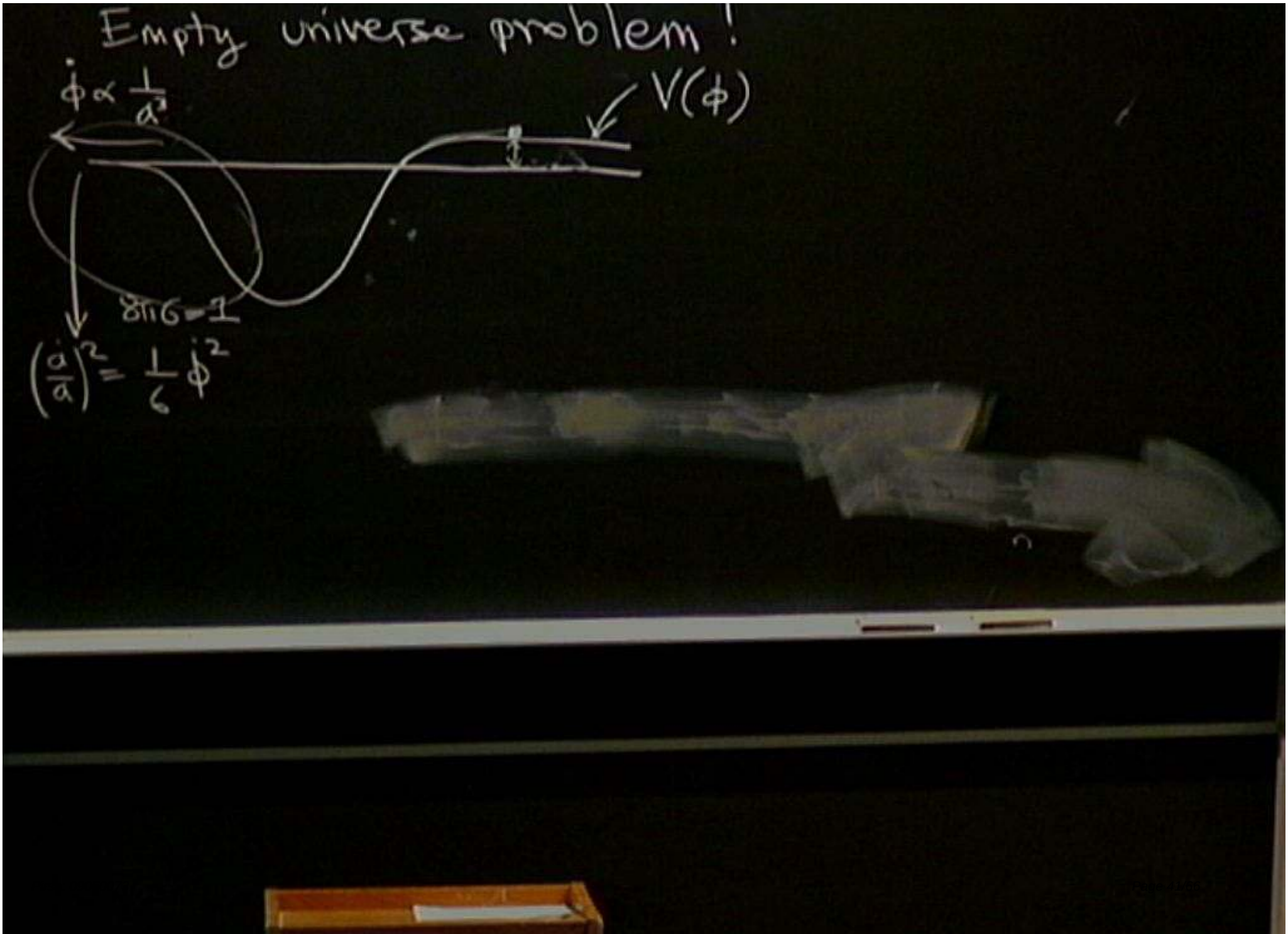
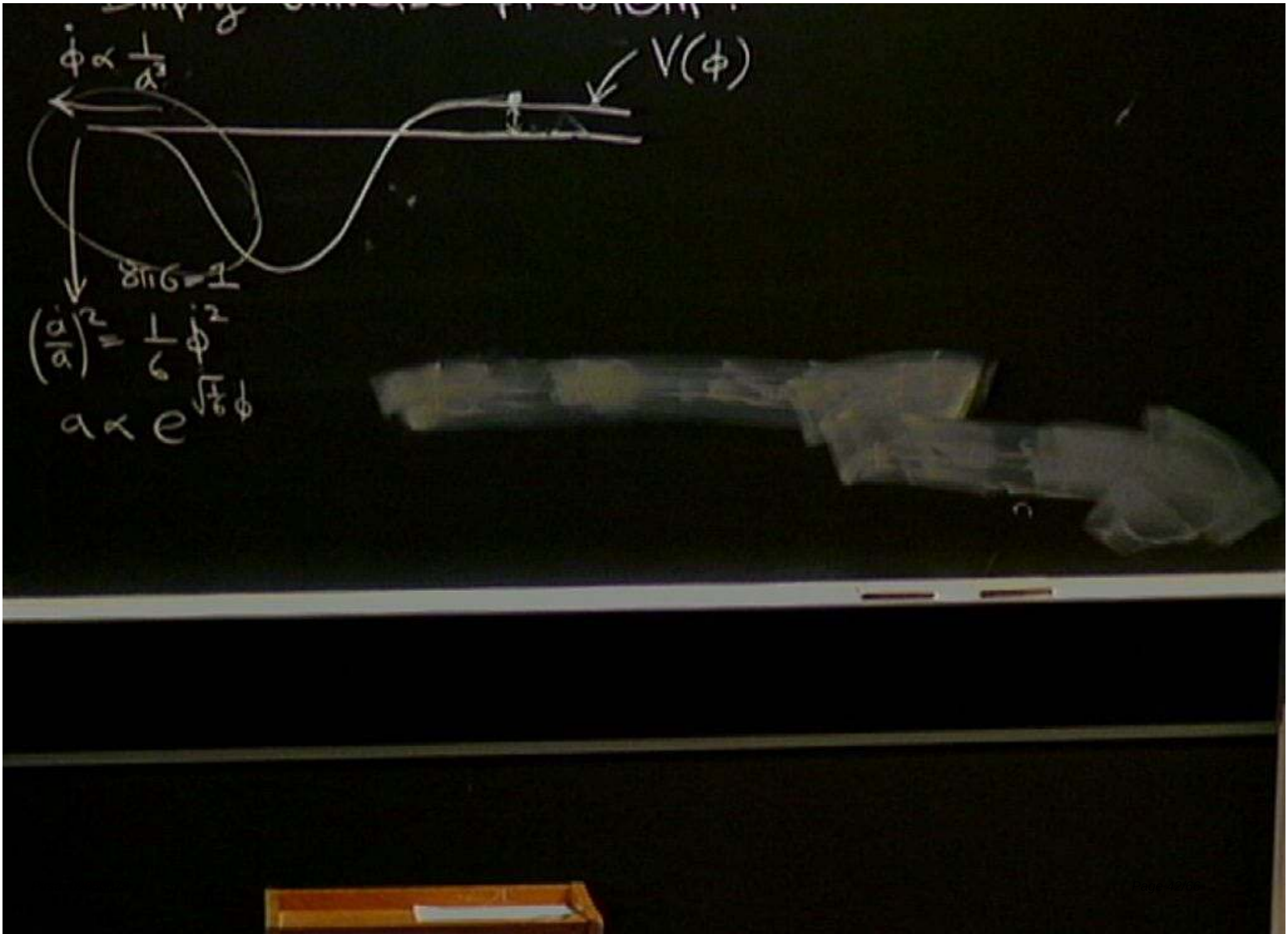

Empty universe problem !
V(φ)

Empty universe problem !

$\dot{\phi} \propto \frac{1}{a^3}$


Empty universe problem!
$\dot{\phi} \propto \frac{1}{a^3}$
$V(\phi)$
$8\pi G = 1$
$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$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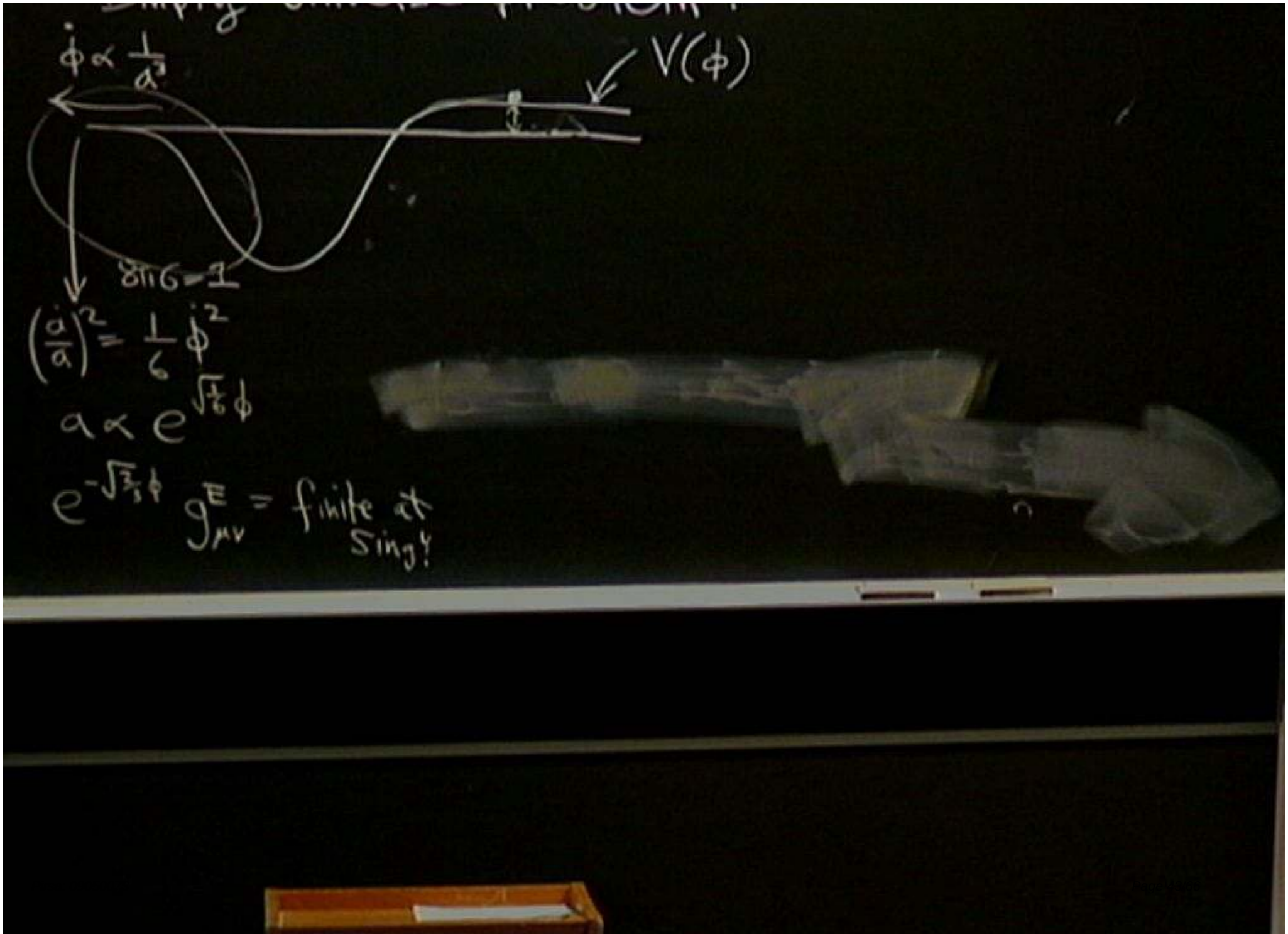
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$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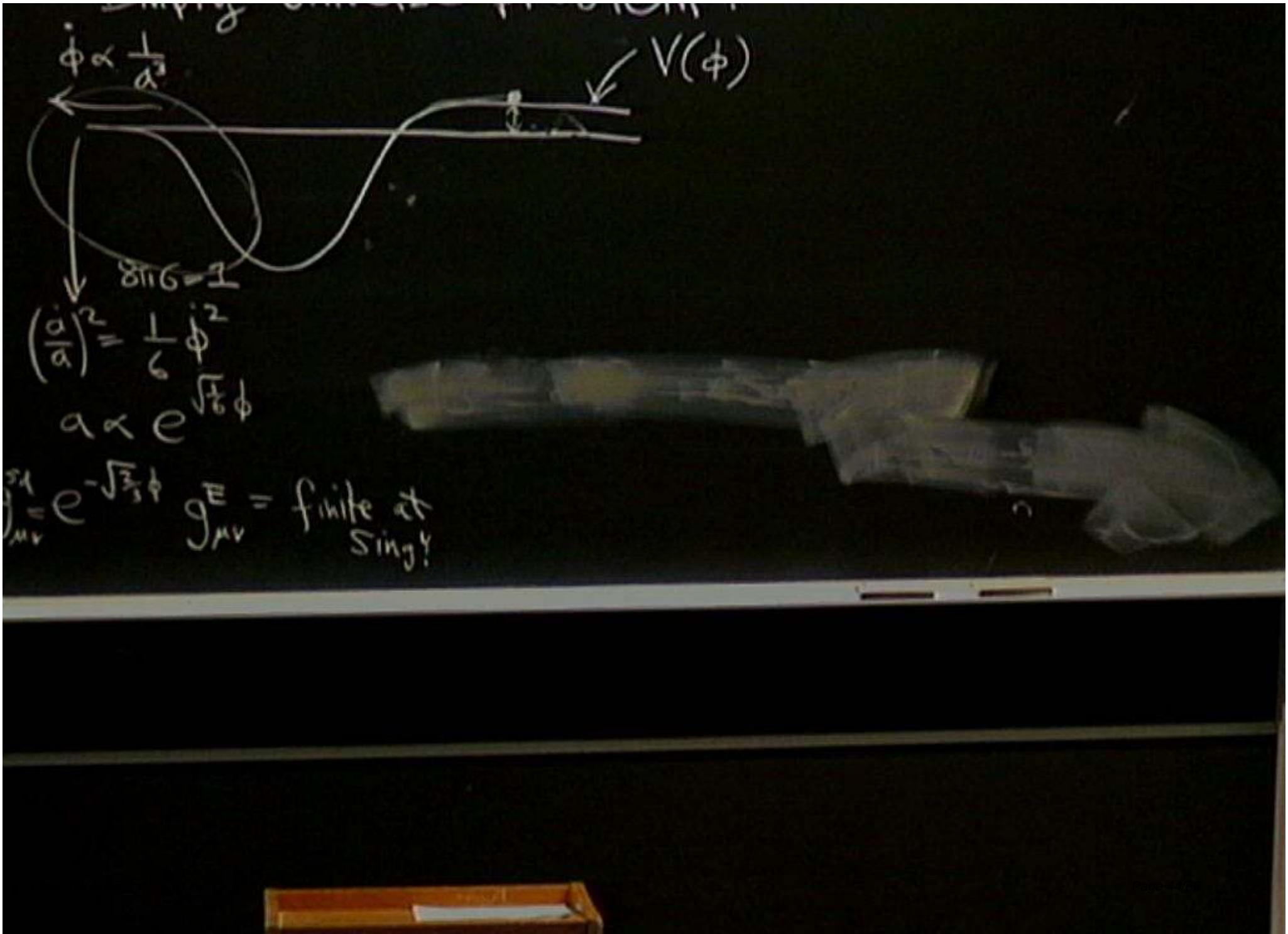
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$
$e^{-\sqrt{\frac{3}{5}}\phi}$
$g^E_{\mu\nu}$ = finite at Sing!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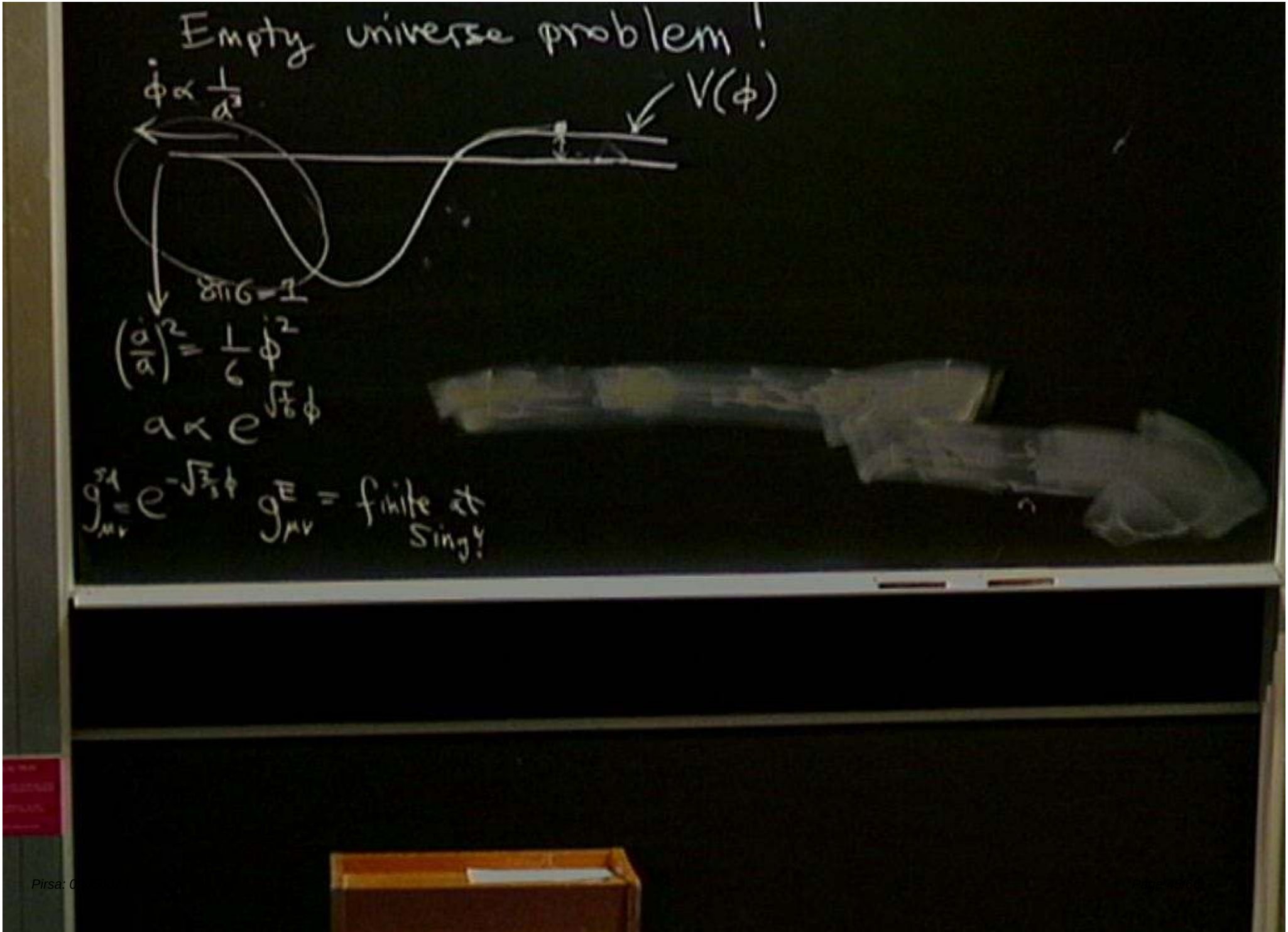
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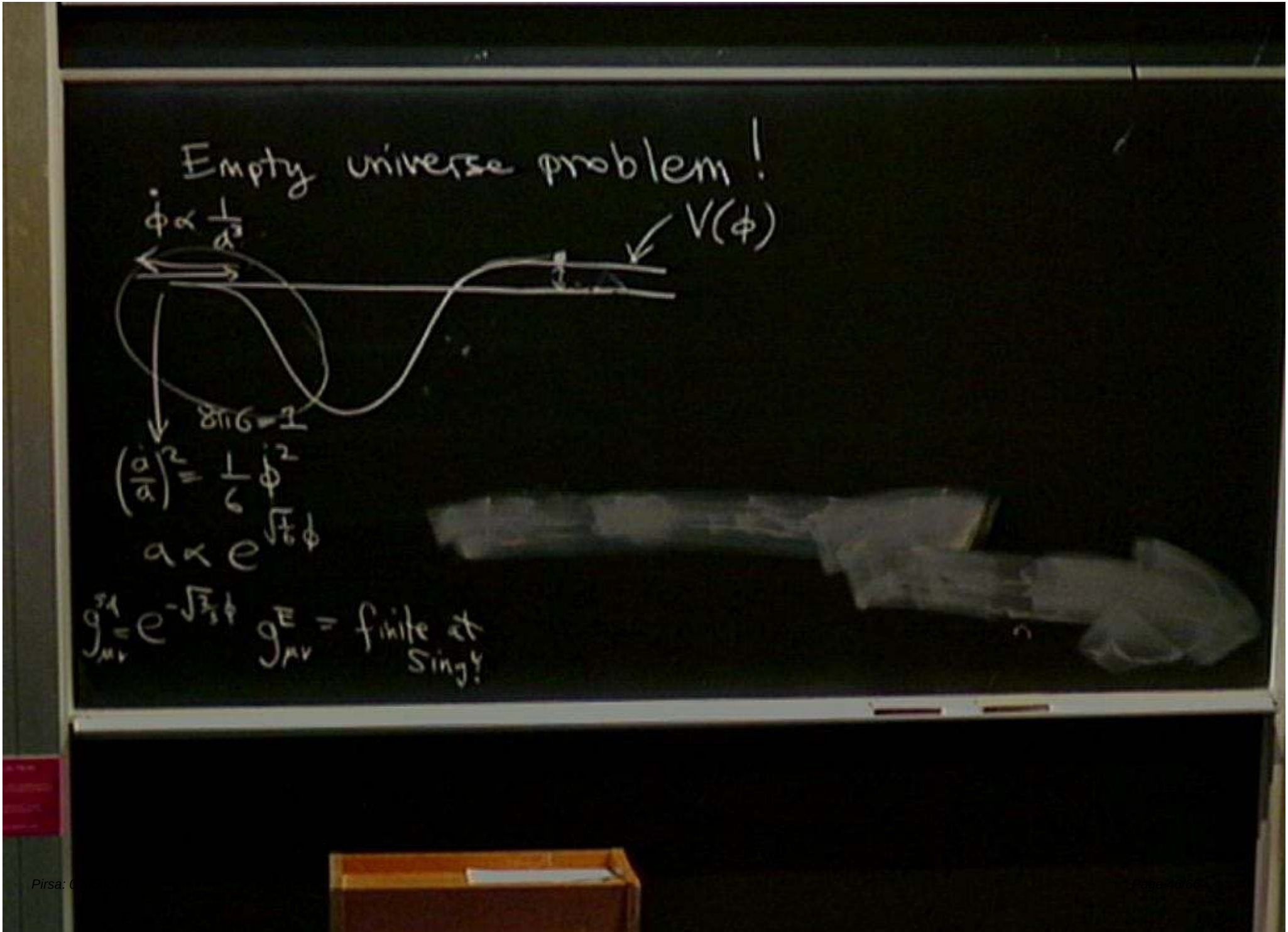
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$
$g^{\text{FRW}}_{\mu\nu} = e^{-\sqrt{\frac{1}{3}}\phi}$
$g^{E}_{\mu\nu}$ = finite at Sing!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$g^{S1}_{\mu\nu} = e^{-\sqrt{\frac{1}{3}}\phi}$
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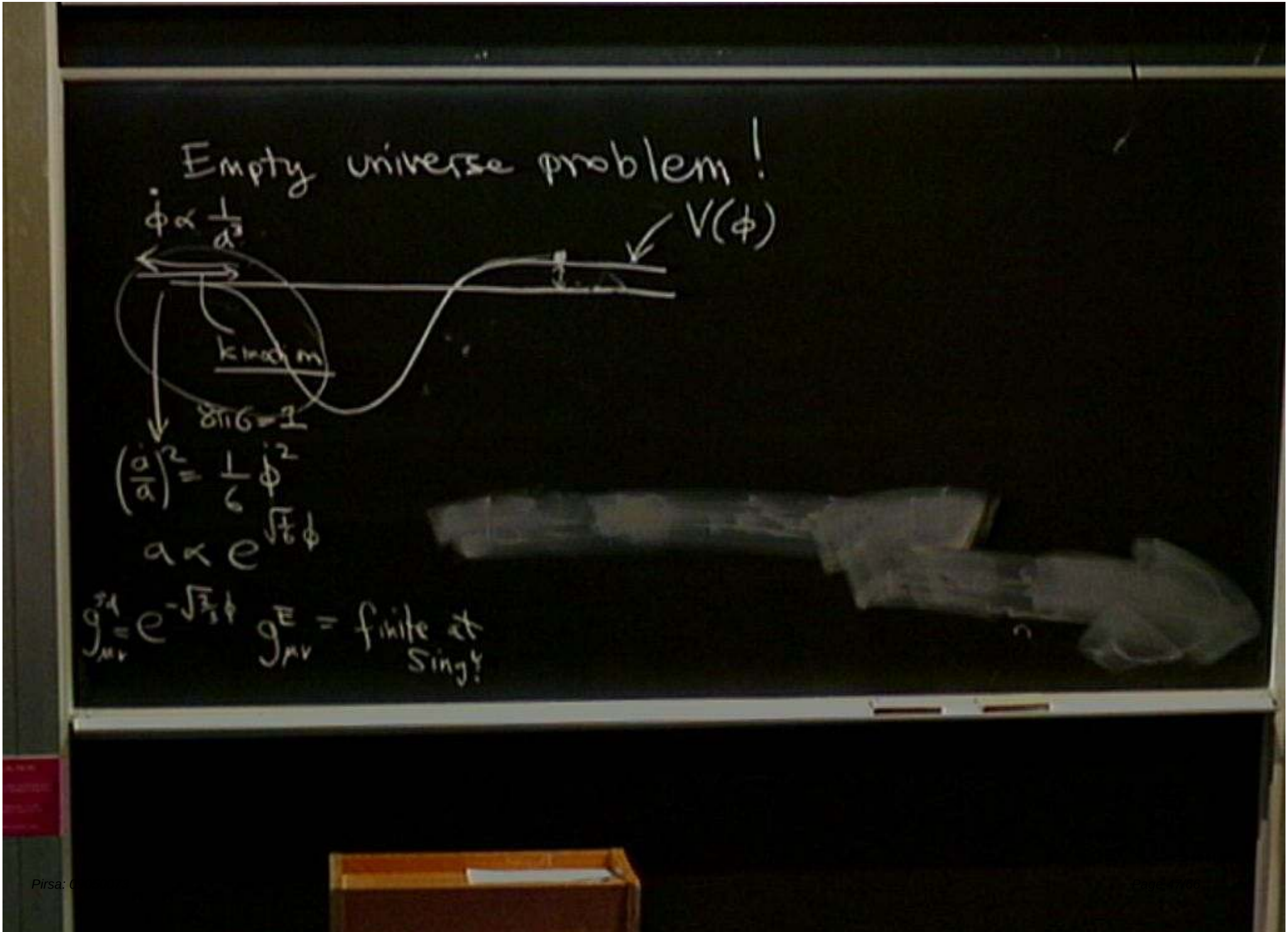
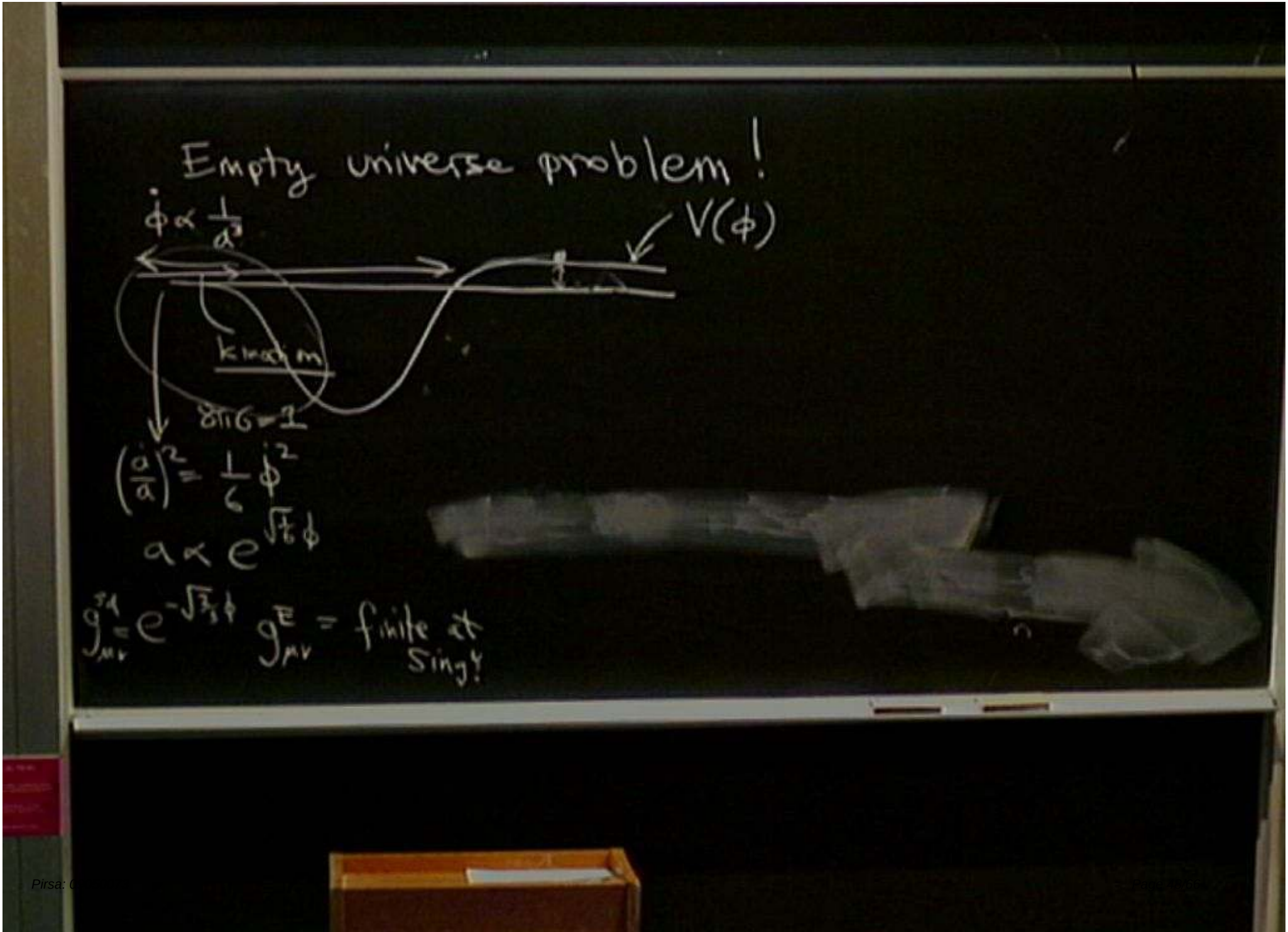

Empty universe problem !
$\dot{\phi} \propto \frac{1}{a^3}$
$V(\phi)$
kinetic
$8\pi G = 1$
$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$
$g^{\text{Jordan}}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$
$g^{E}_{\mu\nu}$ = finite at Sing!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$g^{\text{Jordan}}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{\text{Einstein}}_{\mu\nu}$
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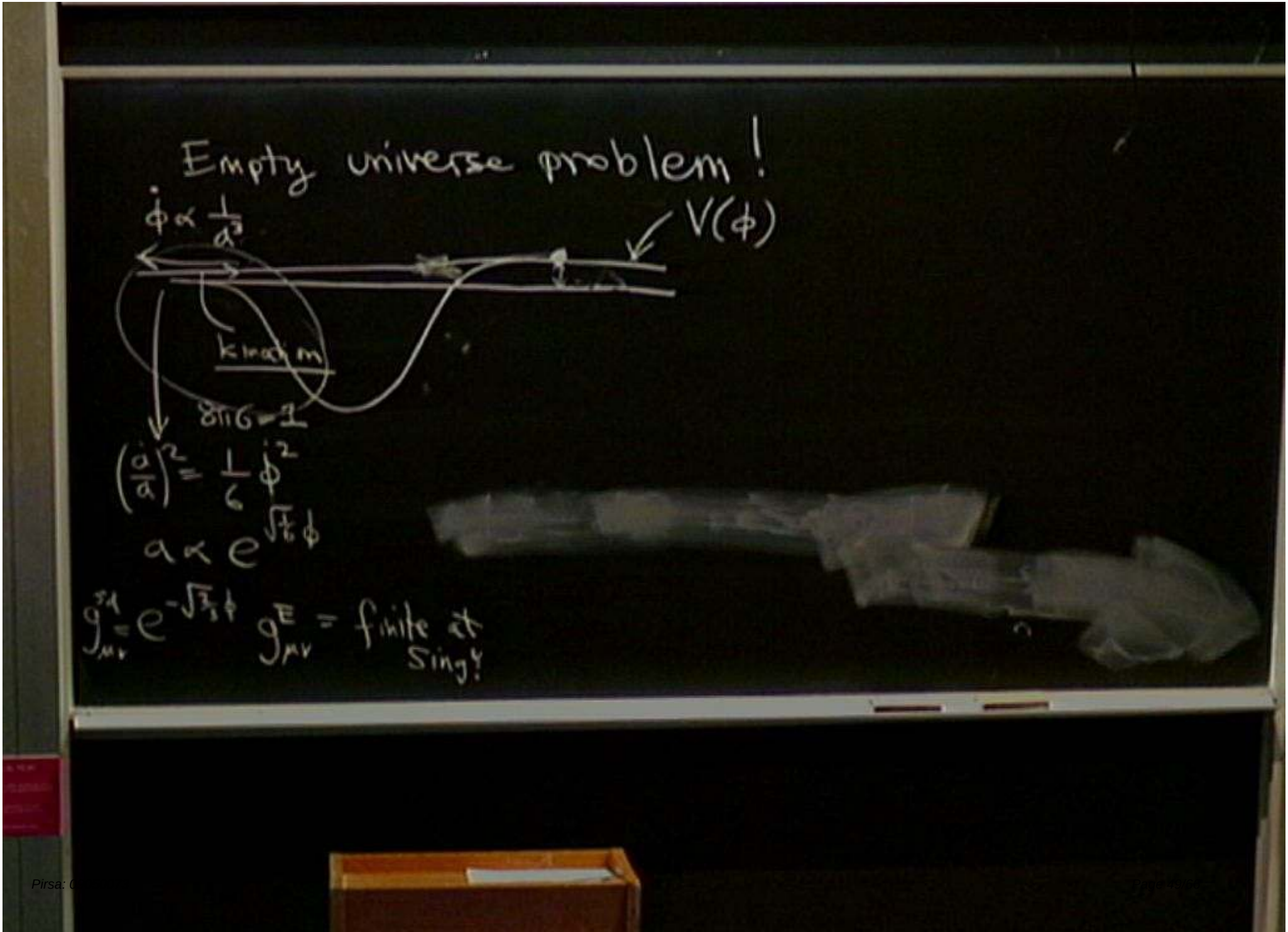
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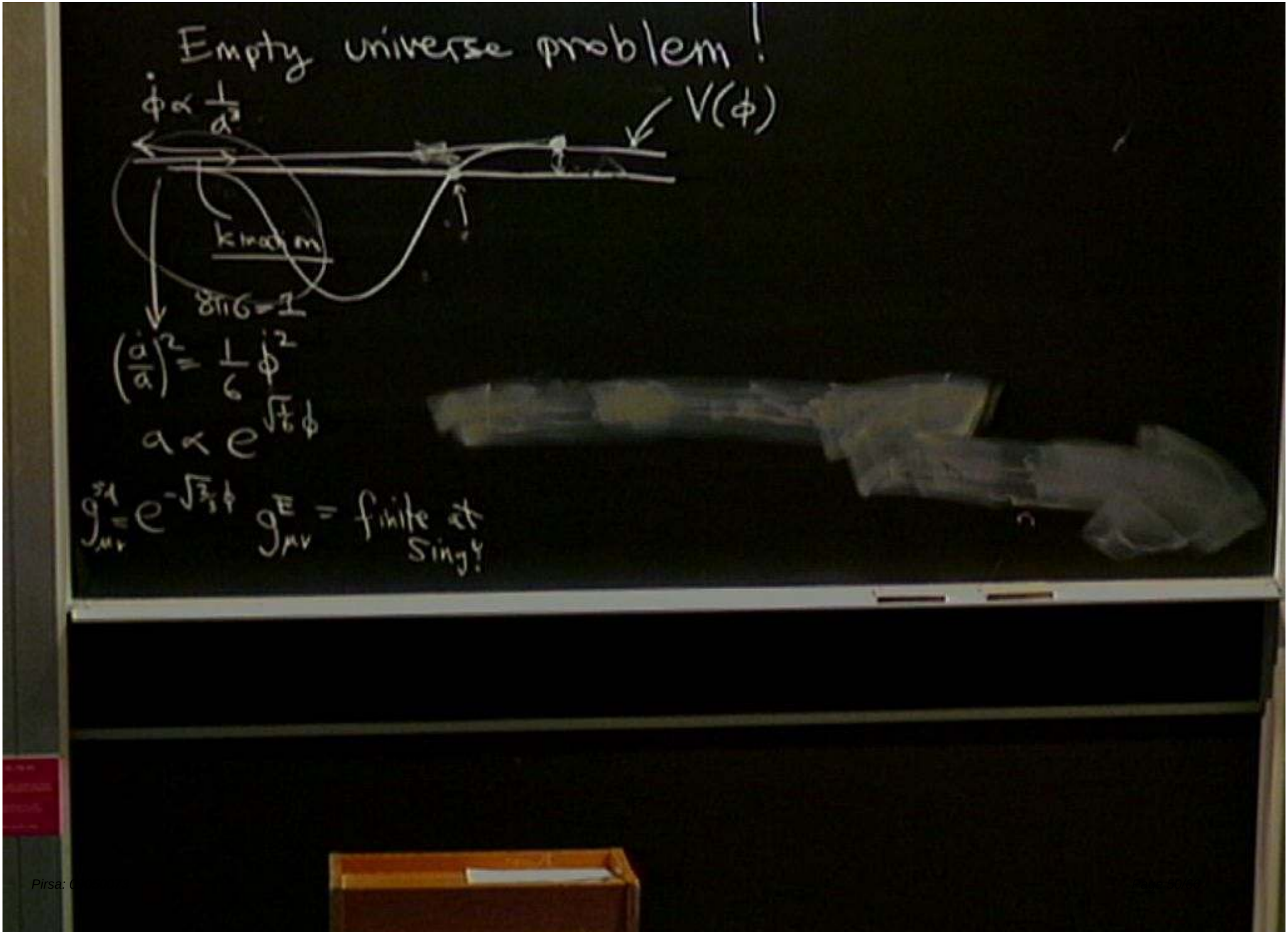
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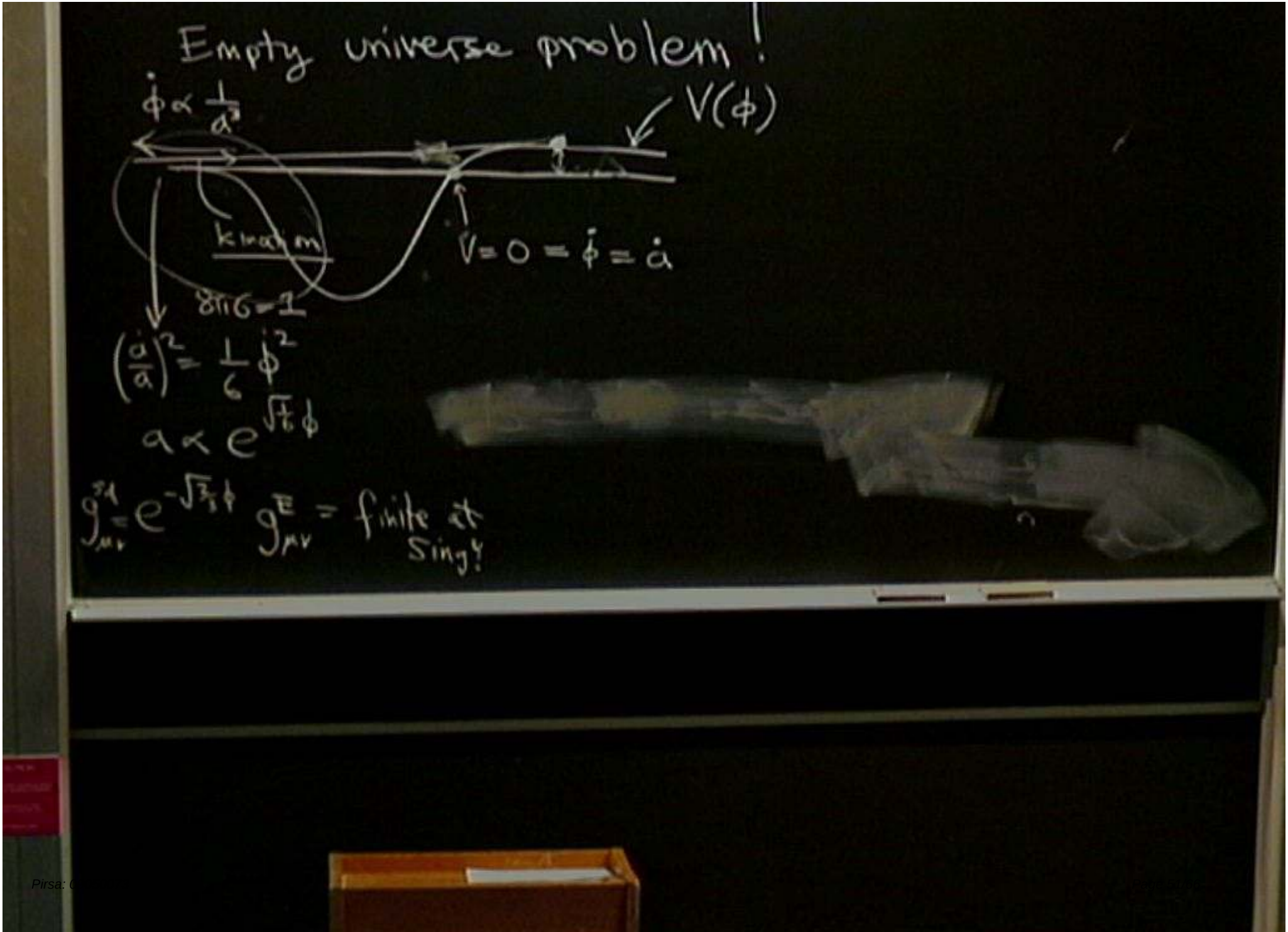
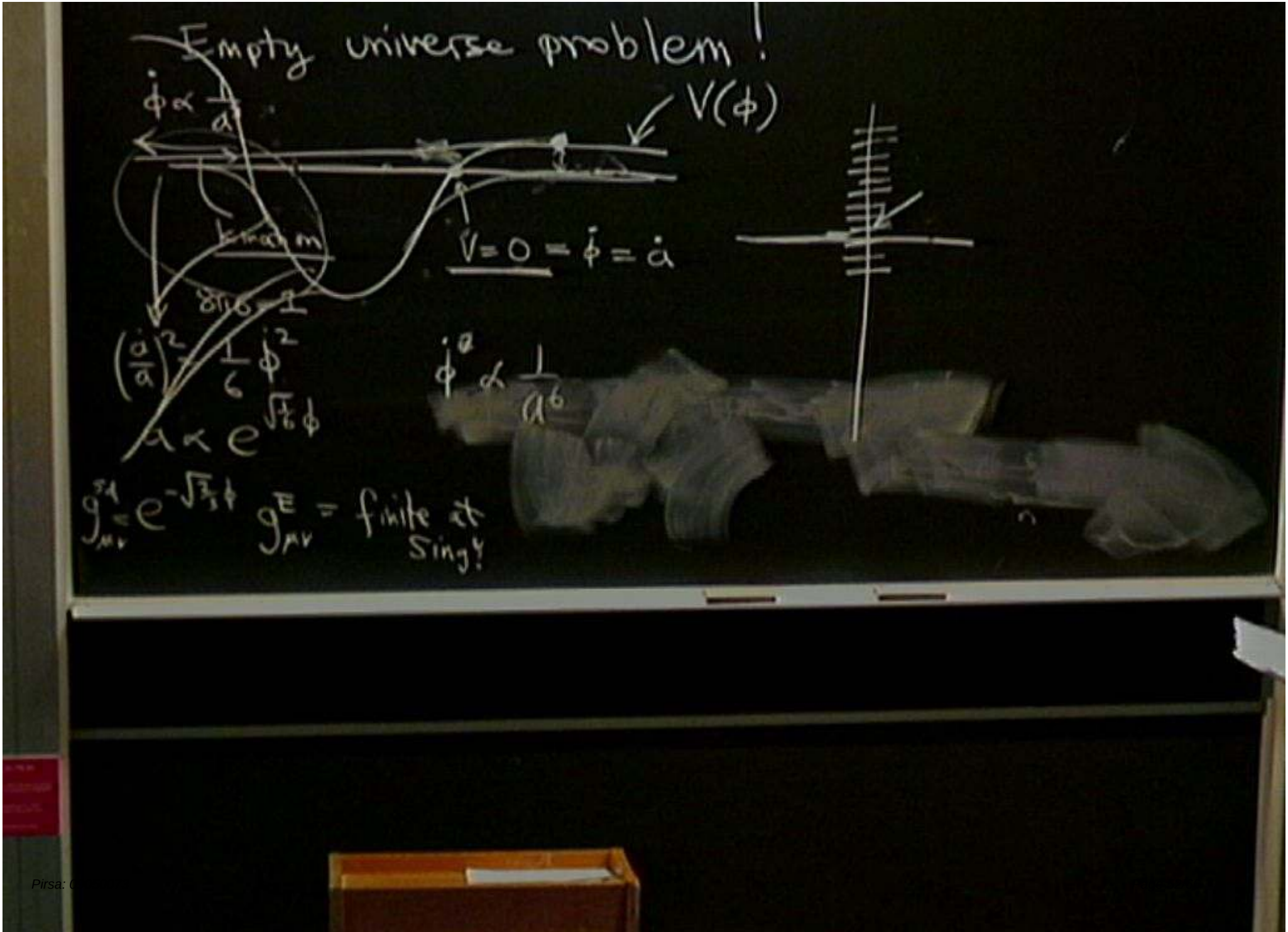
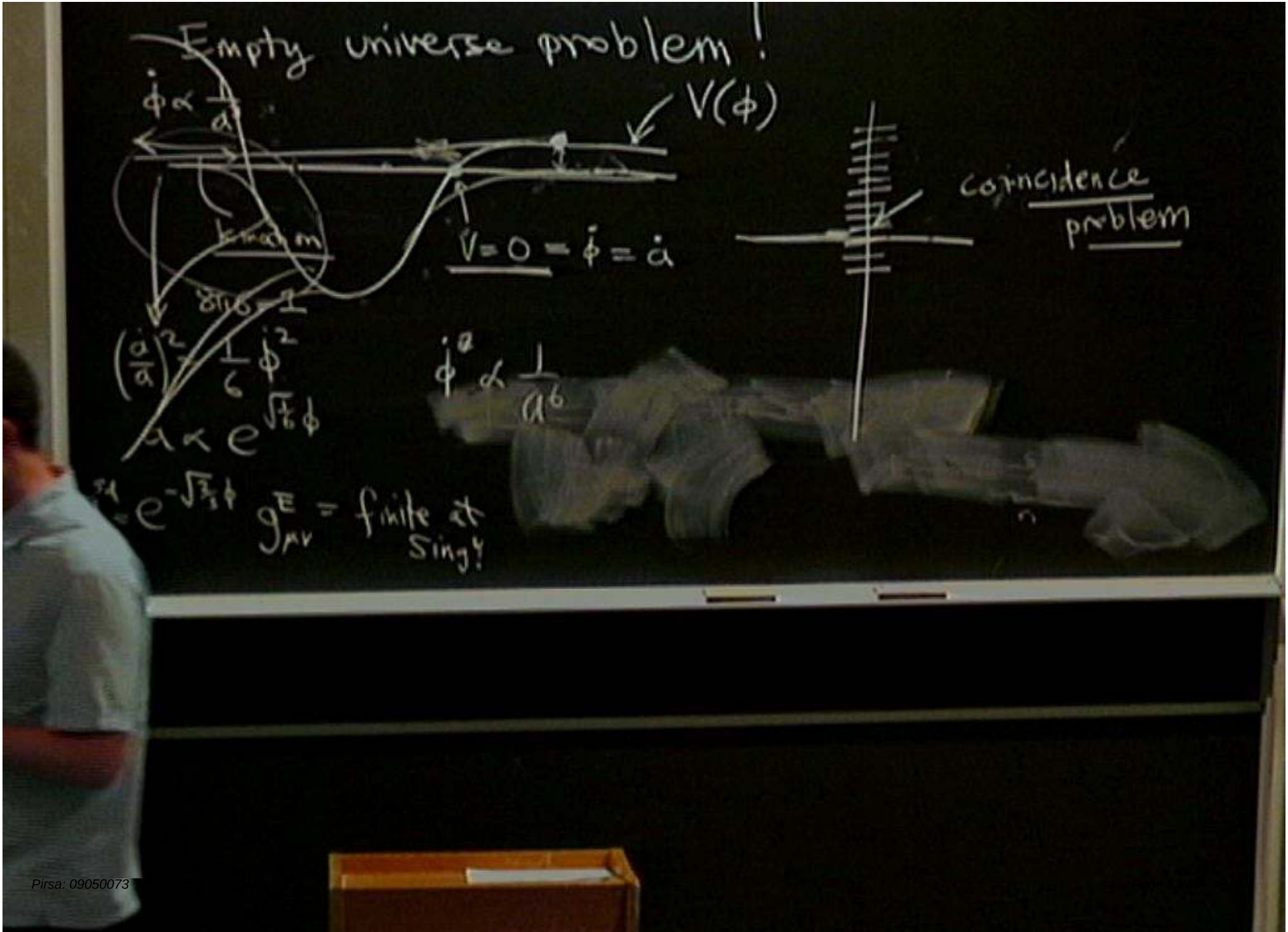
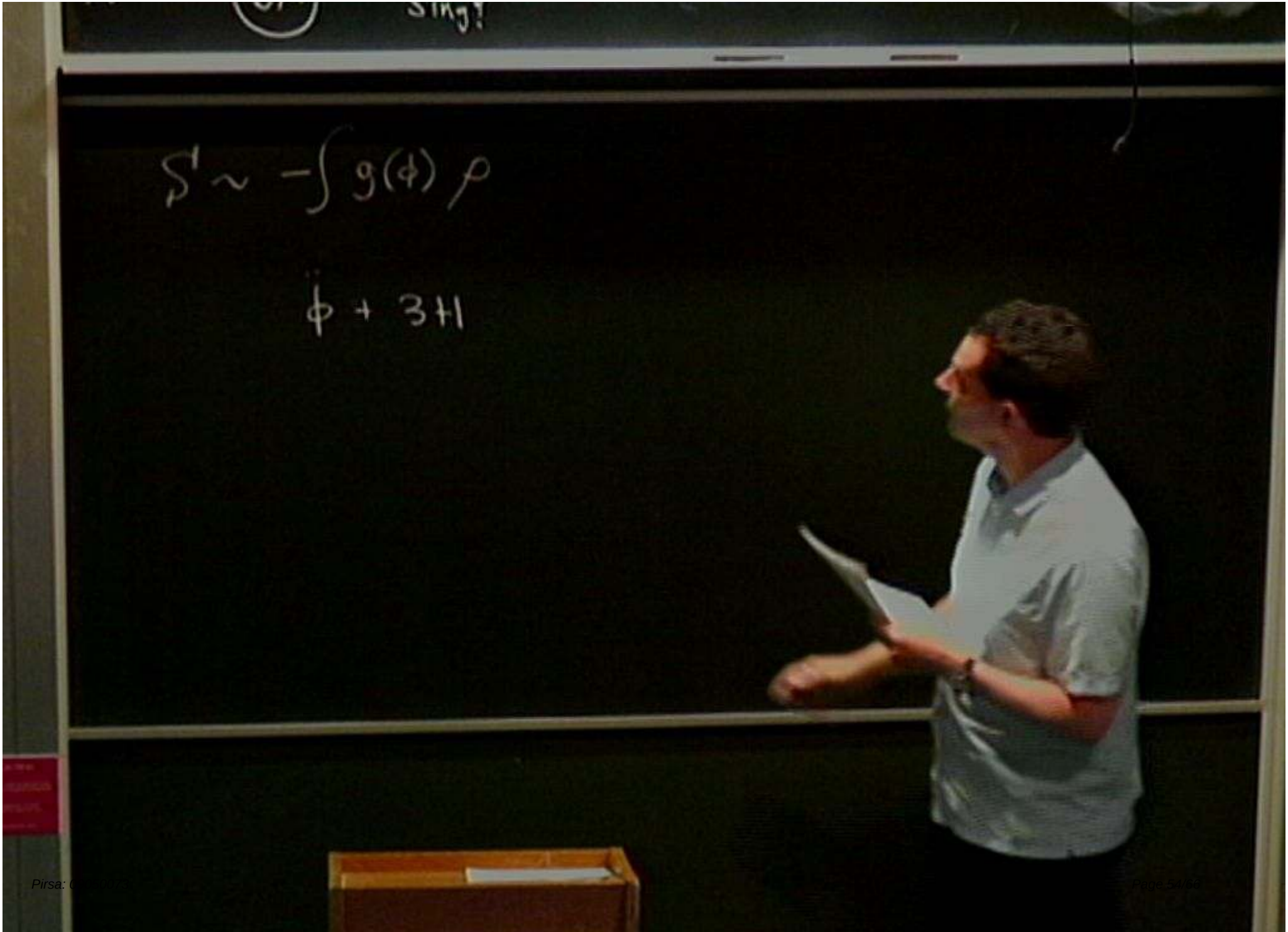

Empty universe problem!
$\dot\phi \propto \frac{1}{a^3}$
$V(\phi)$
kinetic
$V=0=\dot\phi=\dot a$
$8\pi G=1$
$\left(\frac{\dot a}{a}\right)^2=\frac{1}{6}\dot\phi^2$
$a\propto e^{\sqrt{\frac{1}{6}}\phi}$
$g^{\text{sing}}_{\mu\nu}=e^{-\sqrt{\frac{1}{3}}\phi}$
$g^{E}_{\mu\nu}$ = finite at Sing!


Empty universe problem !
V(φ)
V=0 ⇒ φ̇ = ȧ
φ̇ ∝ 1/a
φ̇ ∝ 1/a⁶
g_μν = finite at Sing!



Pirsa: 09050073


$S' \sim -\int g(\phi)\,\rho$
$\ddot{\phi} + 3H\dot{\phi}$

$S' \sim -\int g(\phi)\,\rho \quad \rightarrow \quad \Box\phi = g'(\phi)\,\rho \qquad \frac{\beta}{M_{Pl}} = \frac{g'(\phi)}{g(\phi)}$

$\ddot{\phi} + 3H\dot{\phi}$

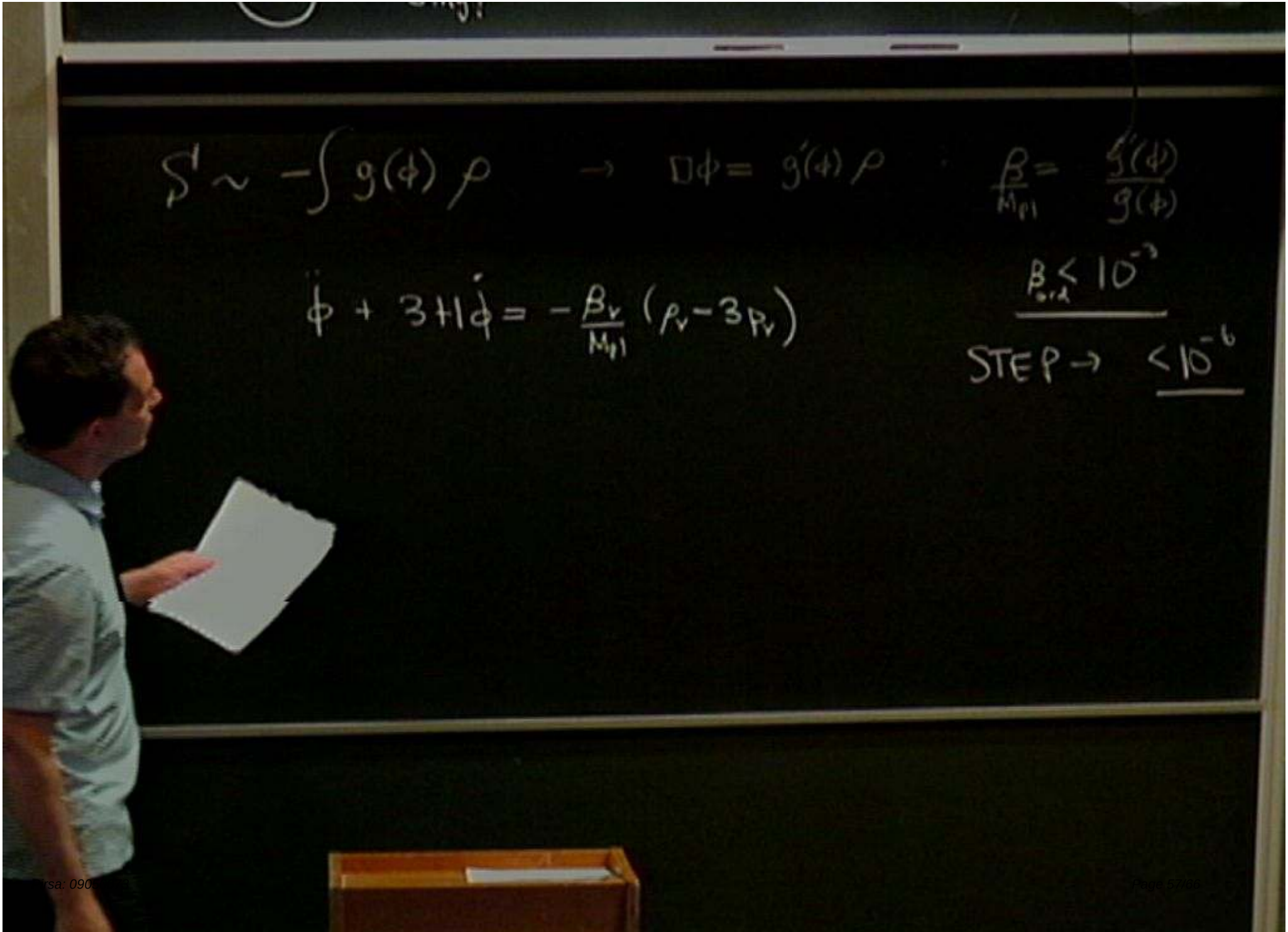
$S' \sim -\int g(\phi)\,\rho \quad \rightarrow \quad \Box\phi = g'(\phi)\,\rho$

$\frac{\beta}{M_{Pl}} = \frac{g'(\phi)}{g(\phi)}$

$\dot{\phi} + 3H$

$\beta_{0.2} \lesssim 10^{-3}$

STEP $\rightarrow$ $< 10^{-6}$


$S' \sim -\int g(\phi)\rho \rightarrow \Box\phi = g'(\phi)\rho$
$\frac{\beta}{M_{Pl}} = \frac{g'(\phi)}{g(\phi)}$
$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu)$
$\beta_{0+2} < 10^{-3}$
STEP → $< 10^{-6}$

$S' \sim -\int g(\phi)\,\rho \quad \rightarrow \quad \Box\phi = g'(\phi)\,T^{\lambda}{}_{\lambda}$: $\frac{\beta}{M_{Pl}} = \frac{g'(\phi)}{g(\phi)}$

$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu)$

$\frac{\beta_{0\nu\beta\beta} < 10^{-3}}{}$

STEP $\rightarrow$ $\underline{< 10^{-6}}$

$A \propto e^{\dots}$

$g^{st}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$ $g^{E}_{\mu\nu}$ = finite at Sing!

M_{Pl} $g(\phi)$

$$\dot{\phi} + 3H\dot{q} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu) + \frac{\beta_c}{M_{Pl}}\rho_c$$

$\beta_{\nu,c} < 10^{-3}$

STEP → $< 10^{-6}$

$A \propto e^{\dots}$

$g^{EA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{Pl}}}$ $g^{E}_{\mu\nu}$ = finite at Sing!

M_{Pl} $g(\phi)$

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu) + \frac{\beta_c}{M_{Pl}}\rho_c$$

$\beta_{\nu,\lambda} < 10^{-3}$

STEP → $< 10^{-6}$

$\Rightarrow \rho_{c,eq} > \rho_\Lambda$

$A \propto e^{\dots}$

$g^{SA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$ $g^{E}_{\mu\nu}$ = finite at Sing!

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu) + \frac{\beta_c}{M_{Pl}}\rho_c$$

$$\Rightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nr}$$

M_{Pl} $g(\phi)$

$\beta_{\nu\Lambda} \lesssim 10^{-3}$

STEP → $< 10^{-6}$

$A \propto e^{\dots}$

$g^{st}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$ $g^{E}_{\mu\nu}$ = finite at Sing!

$\ddot{\phi} + 3(1+1)\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu)$

$+ \frac{\beta_c}{M_{Pl}}\rho_c$

$\Rightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nn}$

M_{Pl} $g(\phi)$

$\beta_{\nu,\Lambda} < 10^{-3}$

STEP → $< 10^{-6}$

$A \propto e^{\dots}$

$g^{St}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$ $\boxed{g^{E}_{\mu\nu}}$ = finite at Sing!

M_{Pl} $g(\phi)$

$\beta_{\nu\lambda} \lesssim 10^{-3}$

STEP → $\lesssim 10^{-6}$

$$\ddot{\phi} + 3(1+1)\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu) + \frac{\beta_c}{M_{Pl}}\rho_c$$

$$\Rightarrow \boxed{\rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nr}}$$

$A \propto e^{\dots}$

$g^{St}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$ $g^{E}_{\mu\nu}$ = finite at Sing!

$\ddot{\phi} + 3(1+1)\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu)$

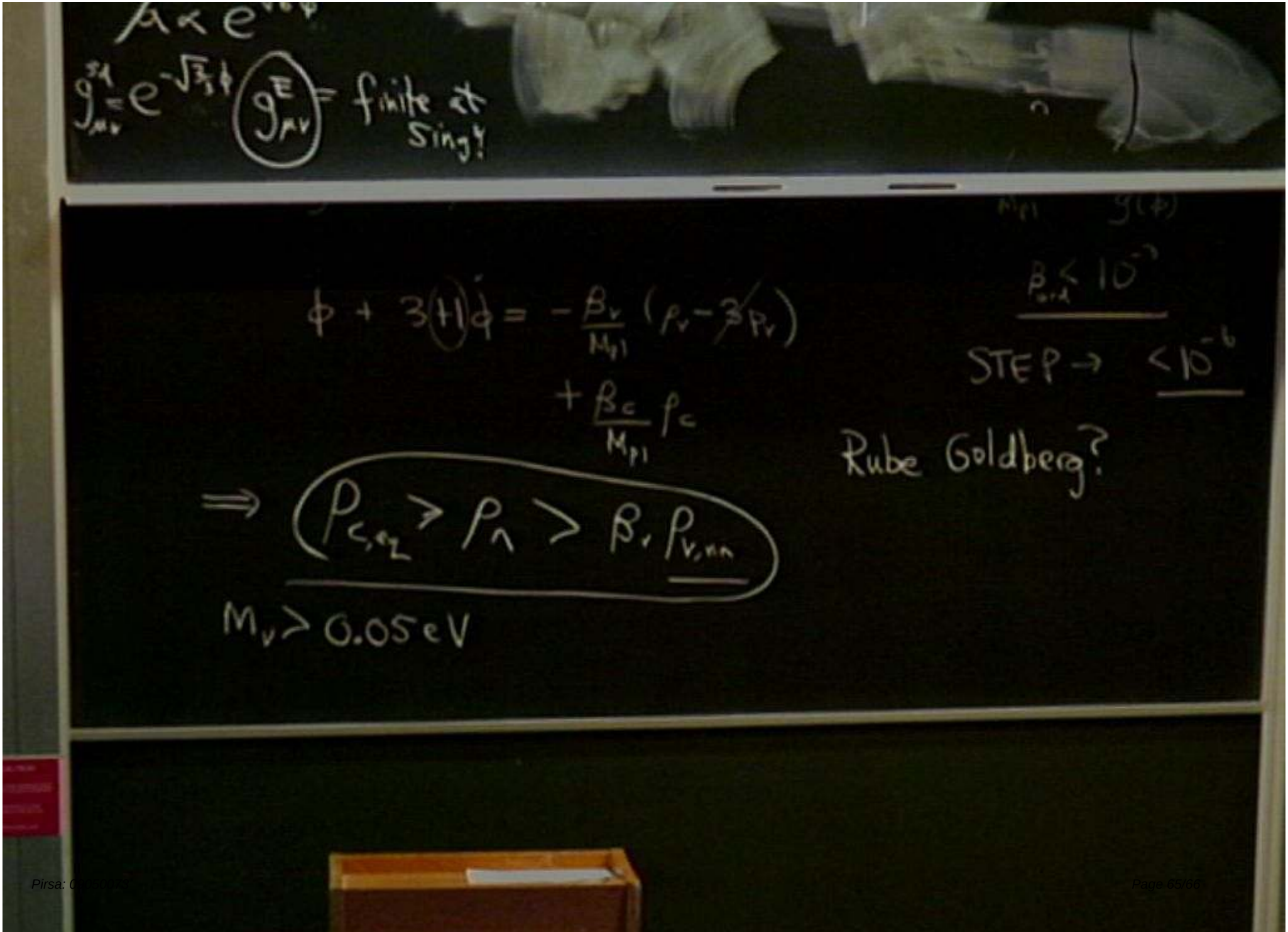
$+ \frac{\beta_c}{M_{Pl}}\rho_c$

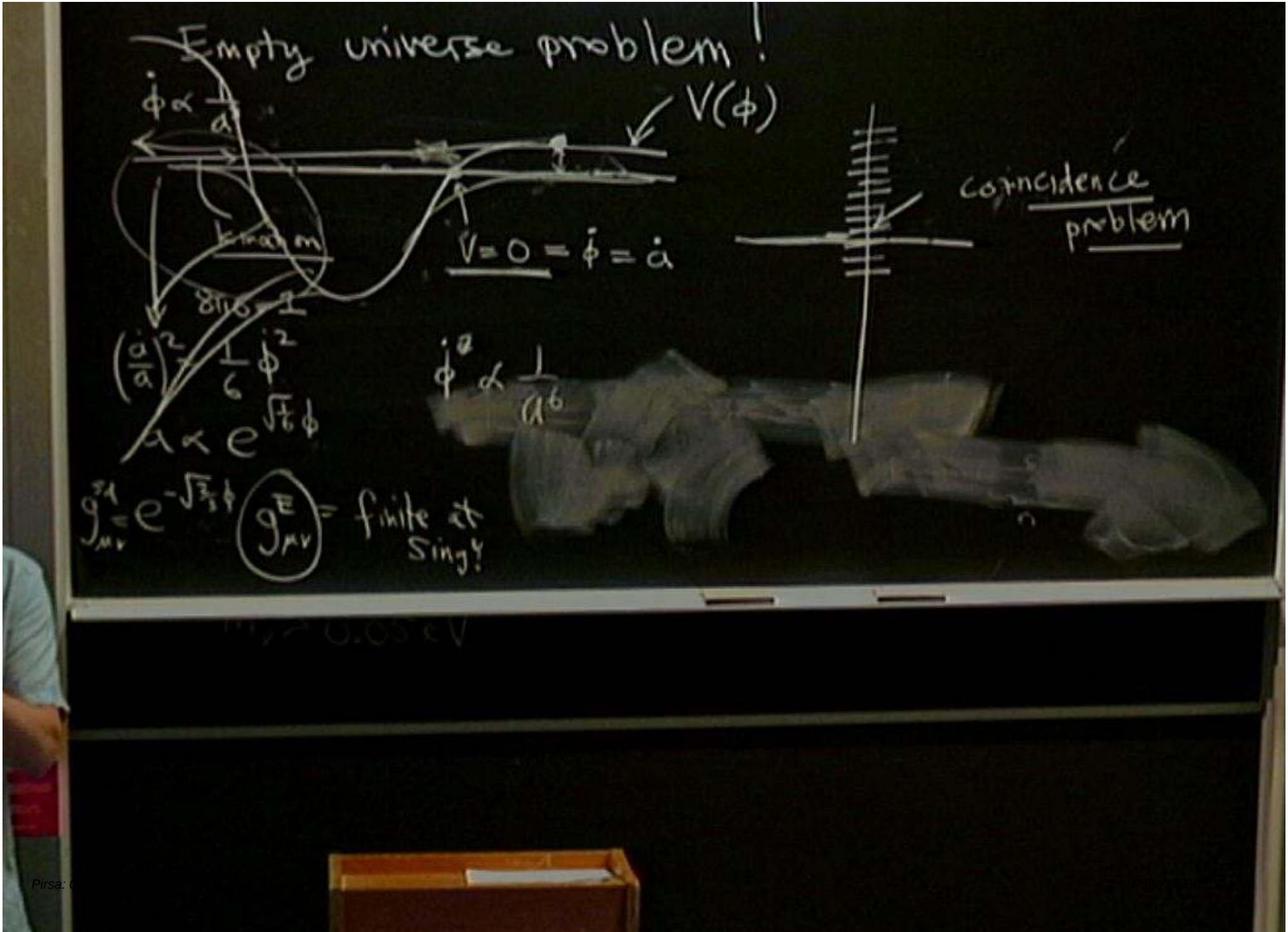
$\Rightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nr}$

$M_\nu > 0.05\,eV$

$\beta_{0\nu} < 10^{3}$

STEP → $< 10^{-6}$


$A \propto e^{\dots}$
$g^{SA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$
$g^{E}_{\mu\nu}$ = finite at Sing?
$\ddot{\phi} + 3(1+1)\dot{\phi} = -\frac{\beta_\nu}{M_{Pl}}(\rho_\nu - 3P_\nu)$
$+ \frac{\beta_c}{M_{Pl}}\rho_c$
$\Rightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nr}$
$M_\nu > 0.05\,eV$
$\beta_{0,\nu} < 10^{-3}$
STEP $\rightarrow$ $< 10^{-6}$
Rube Goldberg?


Empty universe problem !
V(φ)
coincidence problem
V=0 = φ̇ = ȧ
finite at Sing!