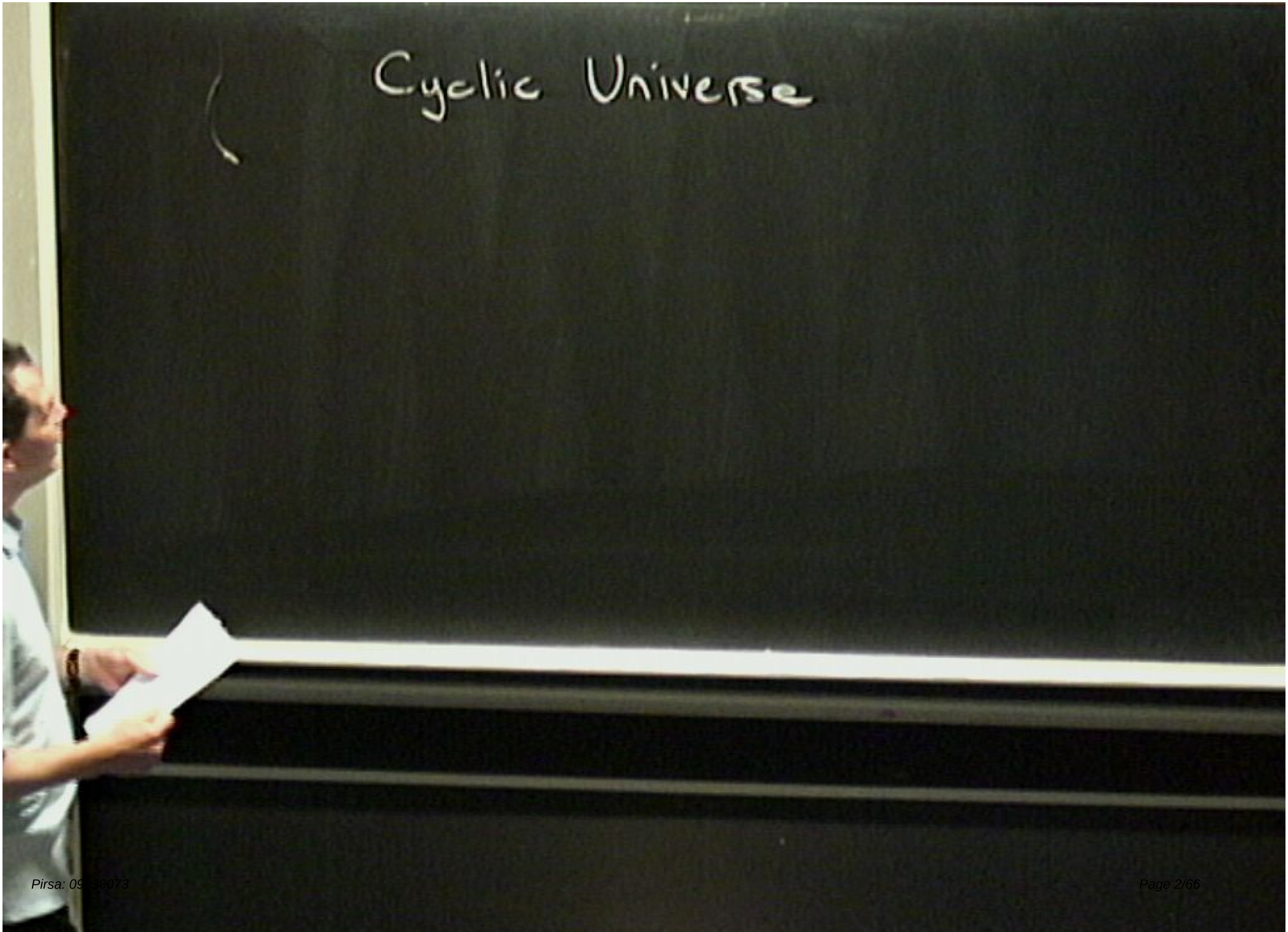
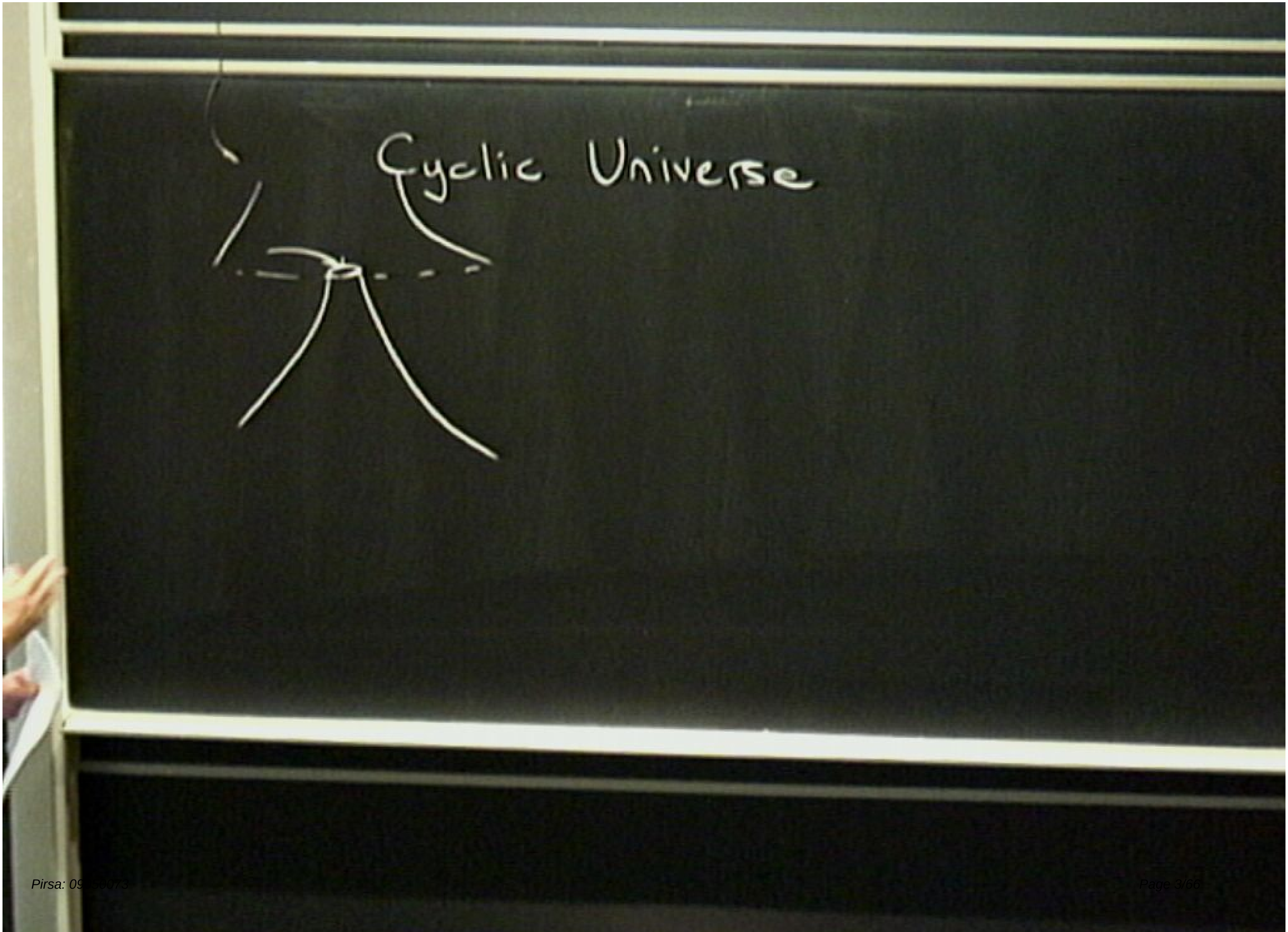
Title: Cyclic Universe

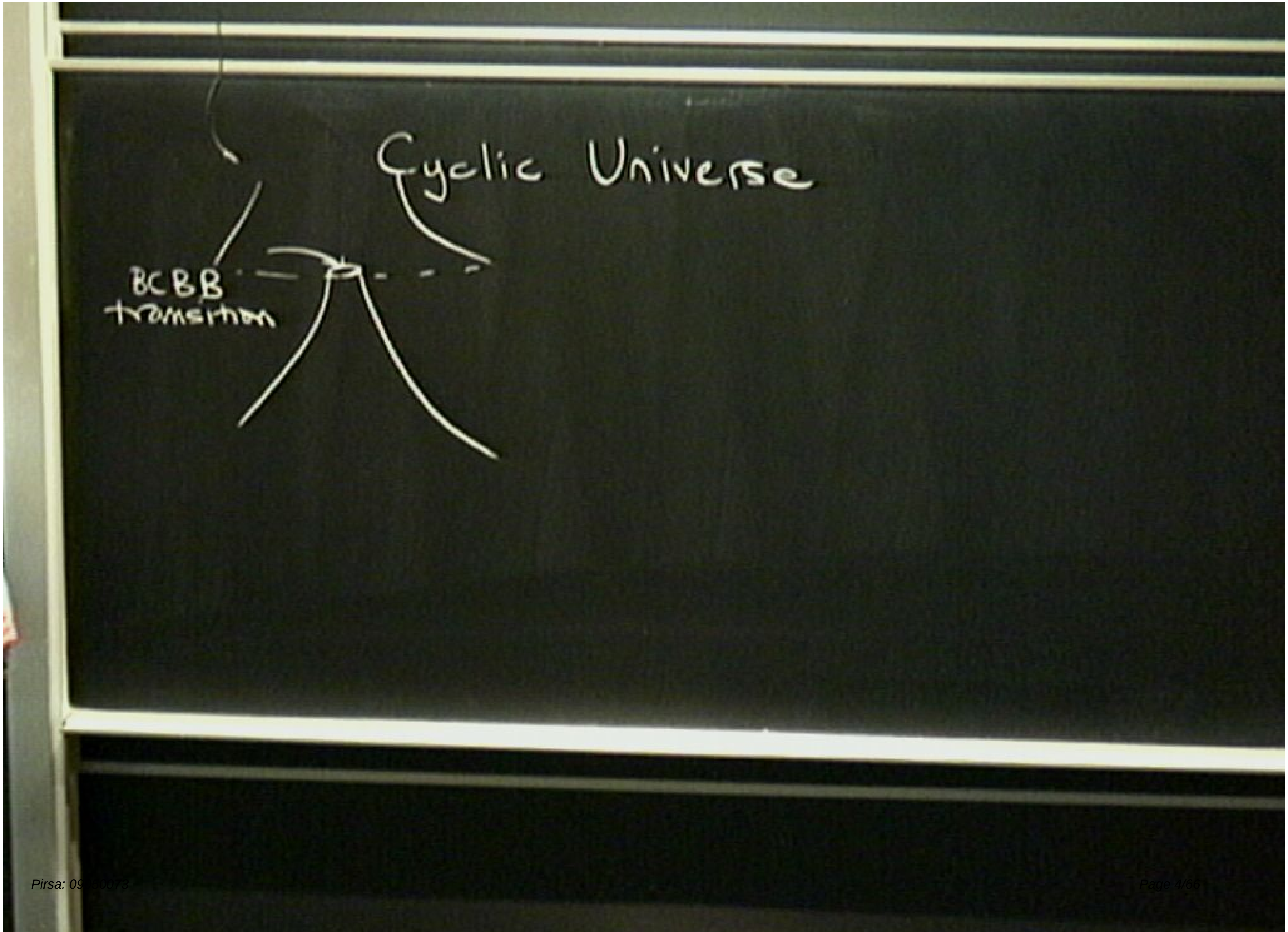
Date: May 25, 2009 04:45 PM

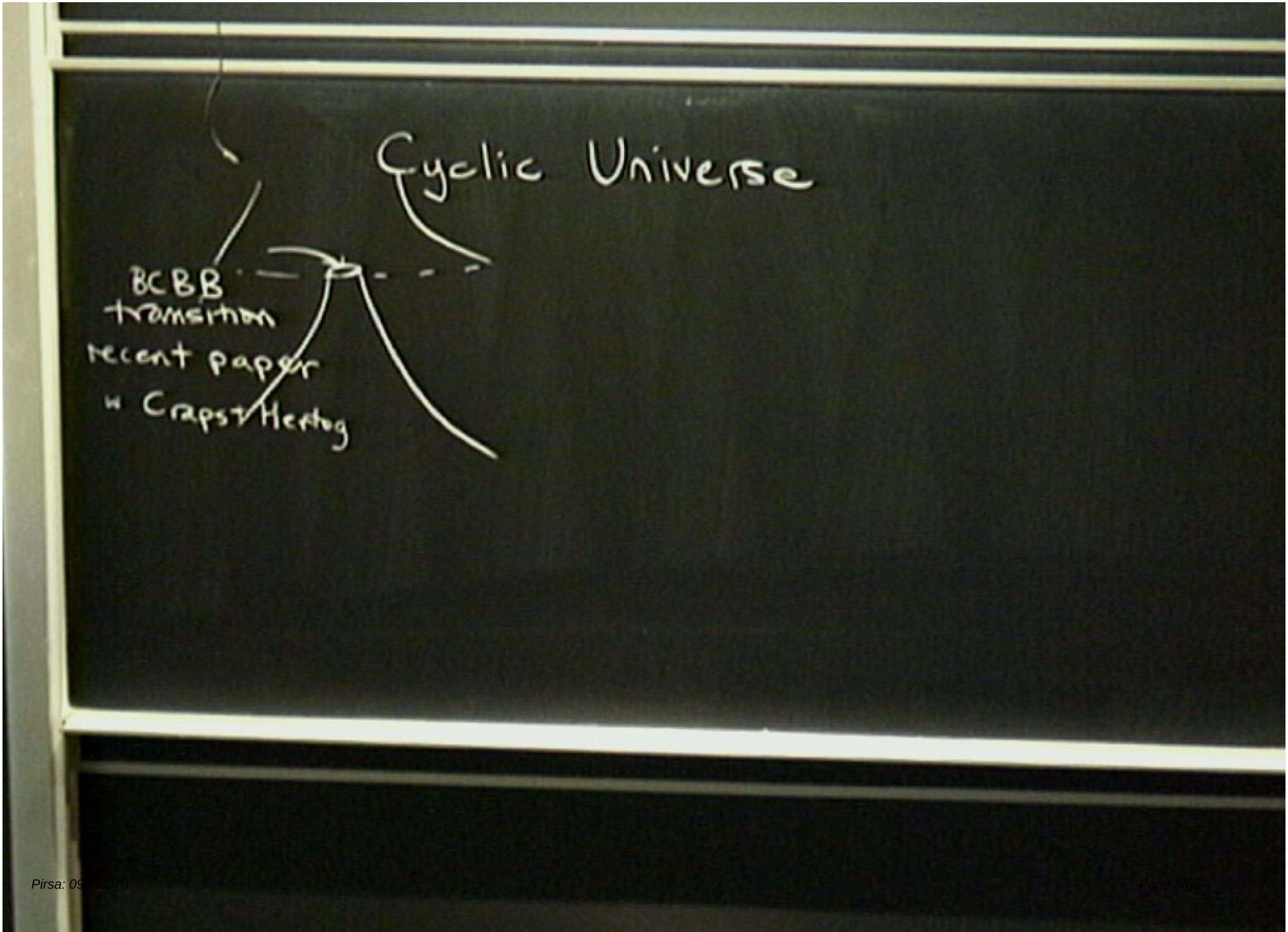
URL: http://pirsa.org/09050073

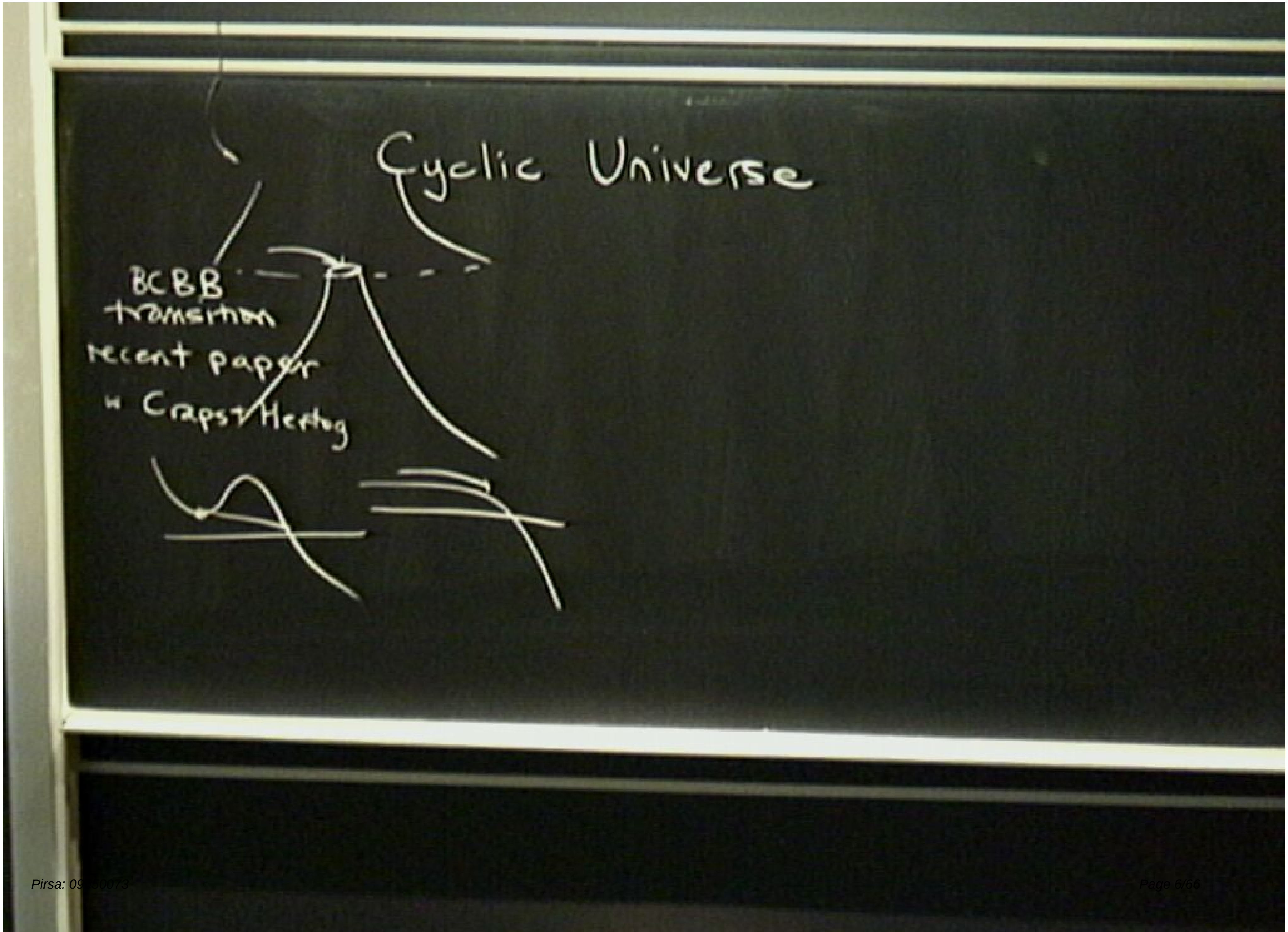
Abstract: TBA


Cyclic Universe


Cyclic Universe


Cyclic Universe
BCBB
transition


Cyclic Universe
BCBB
transition
recent paper
w Craps + Hertog


Cyclic Universe
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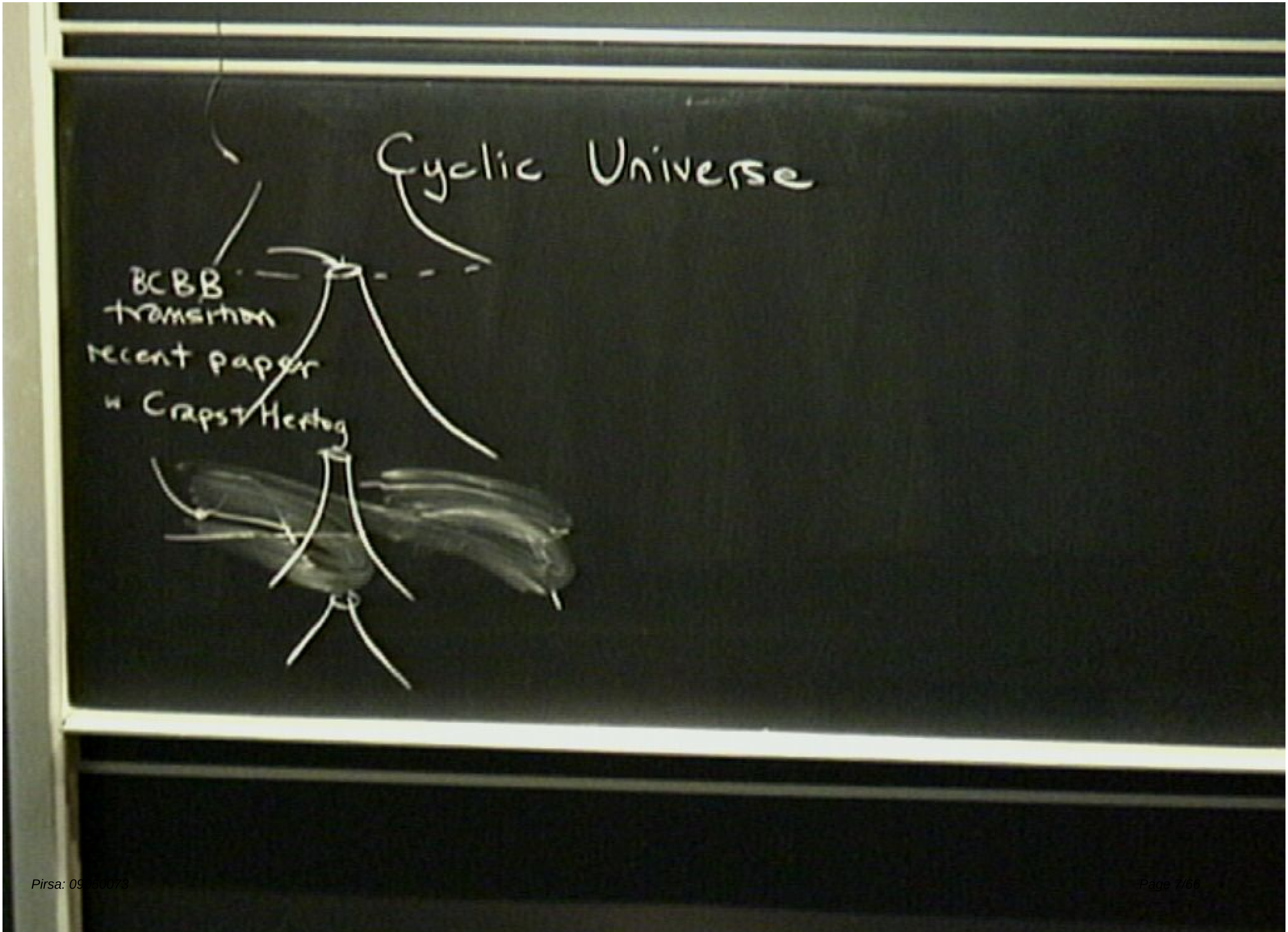
Cyclic Universe
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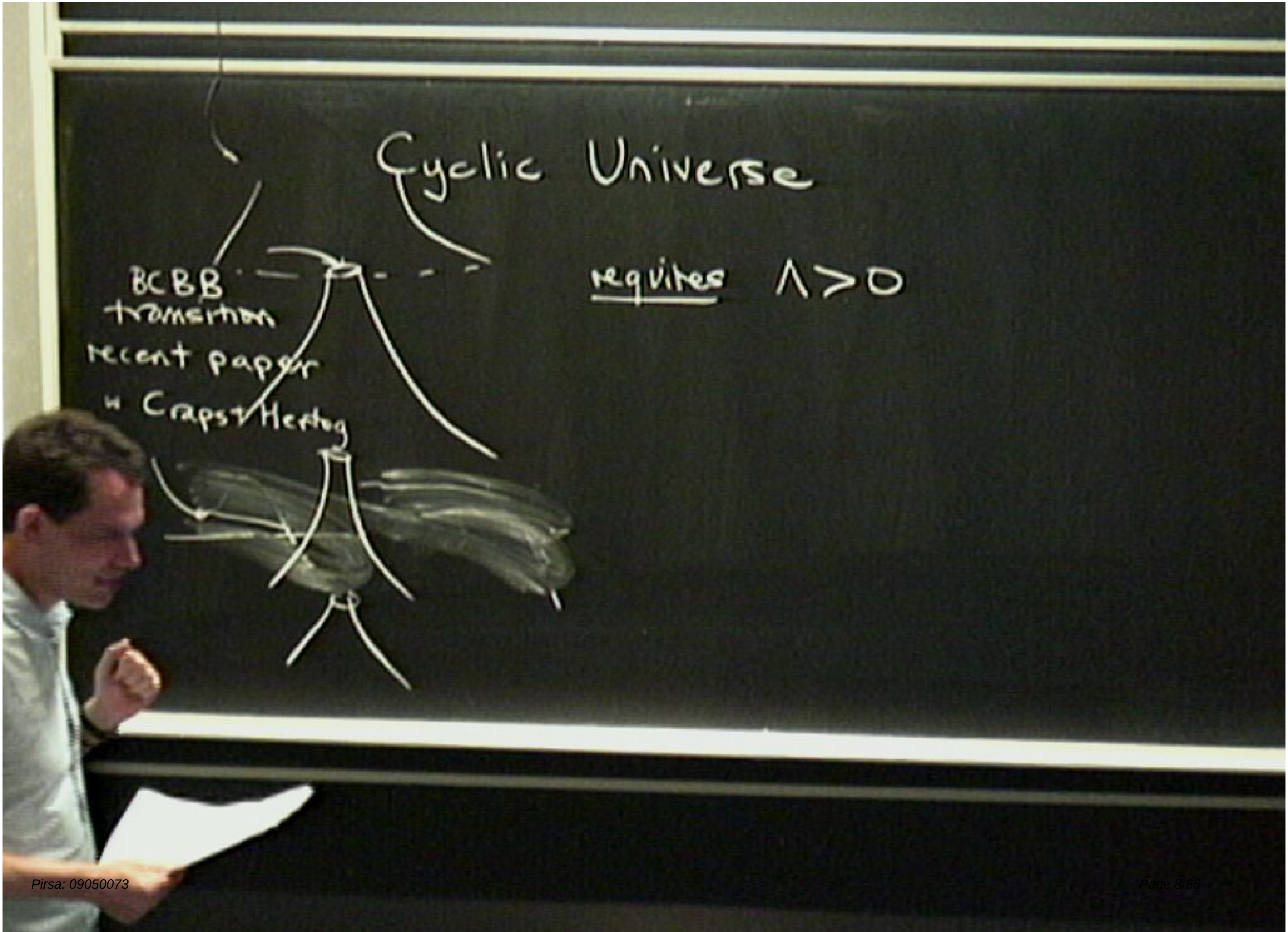
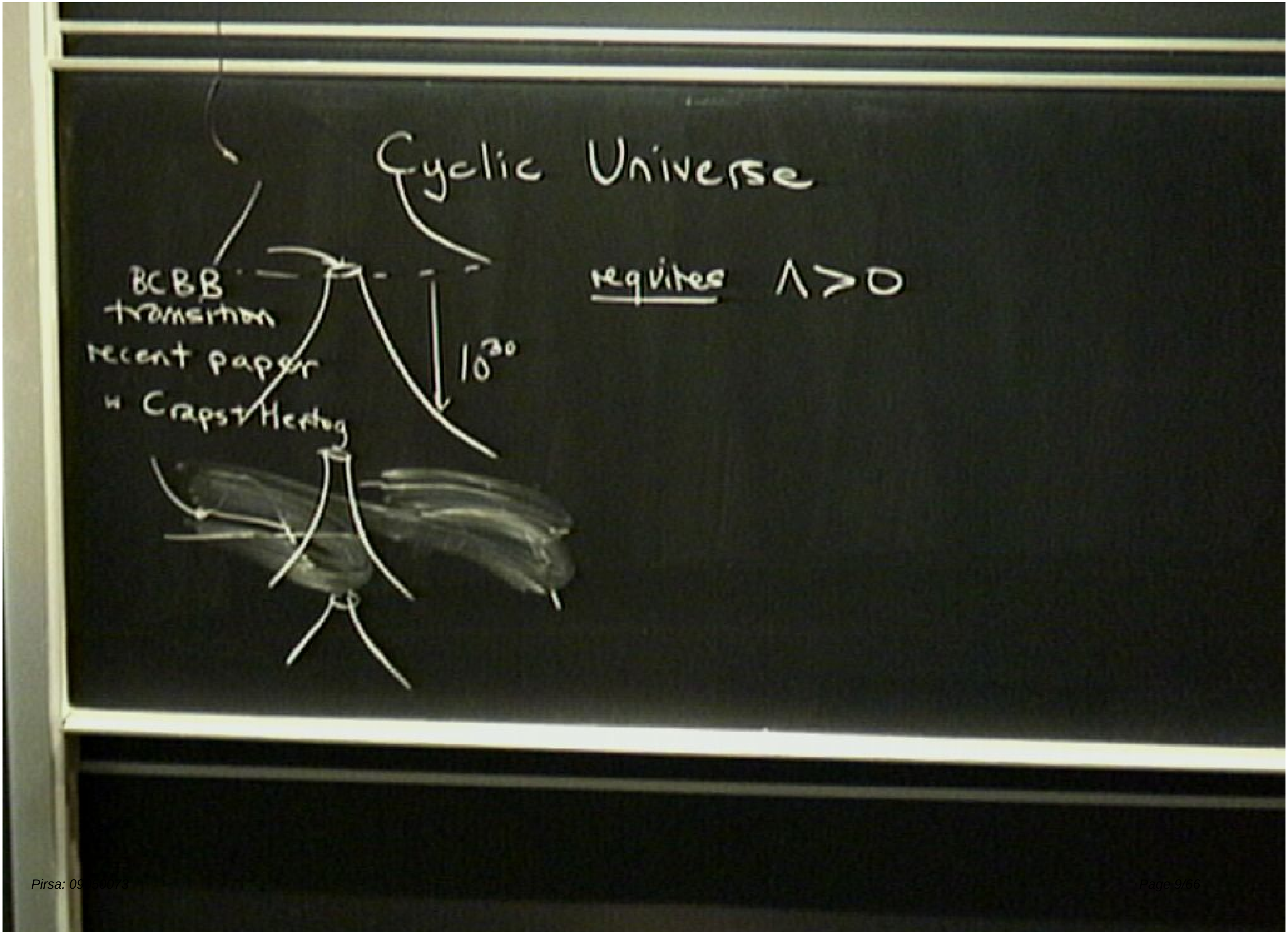
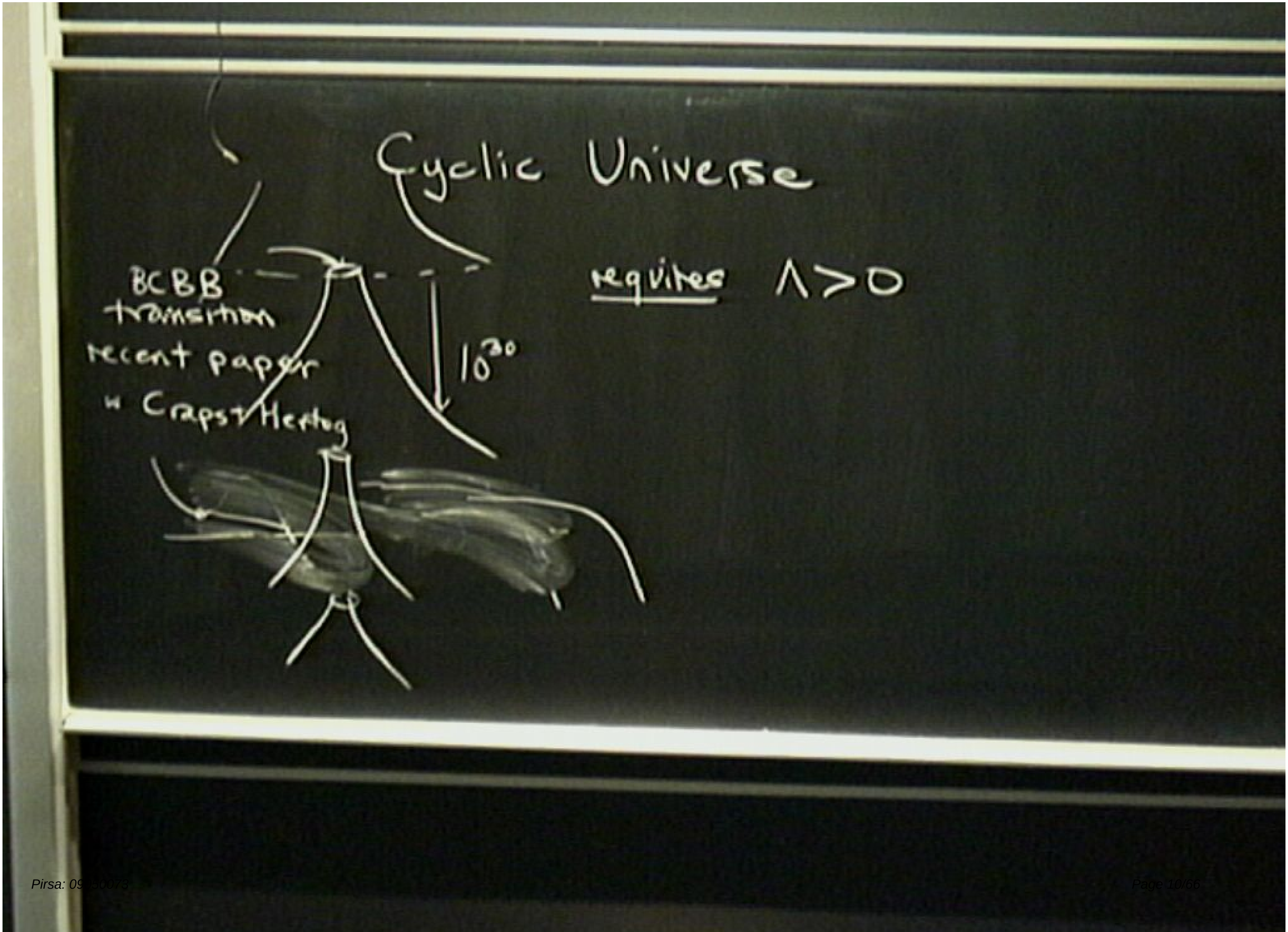
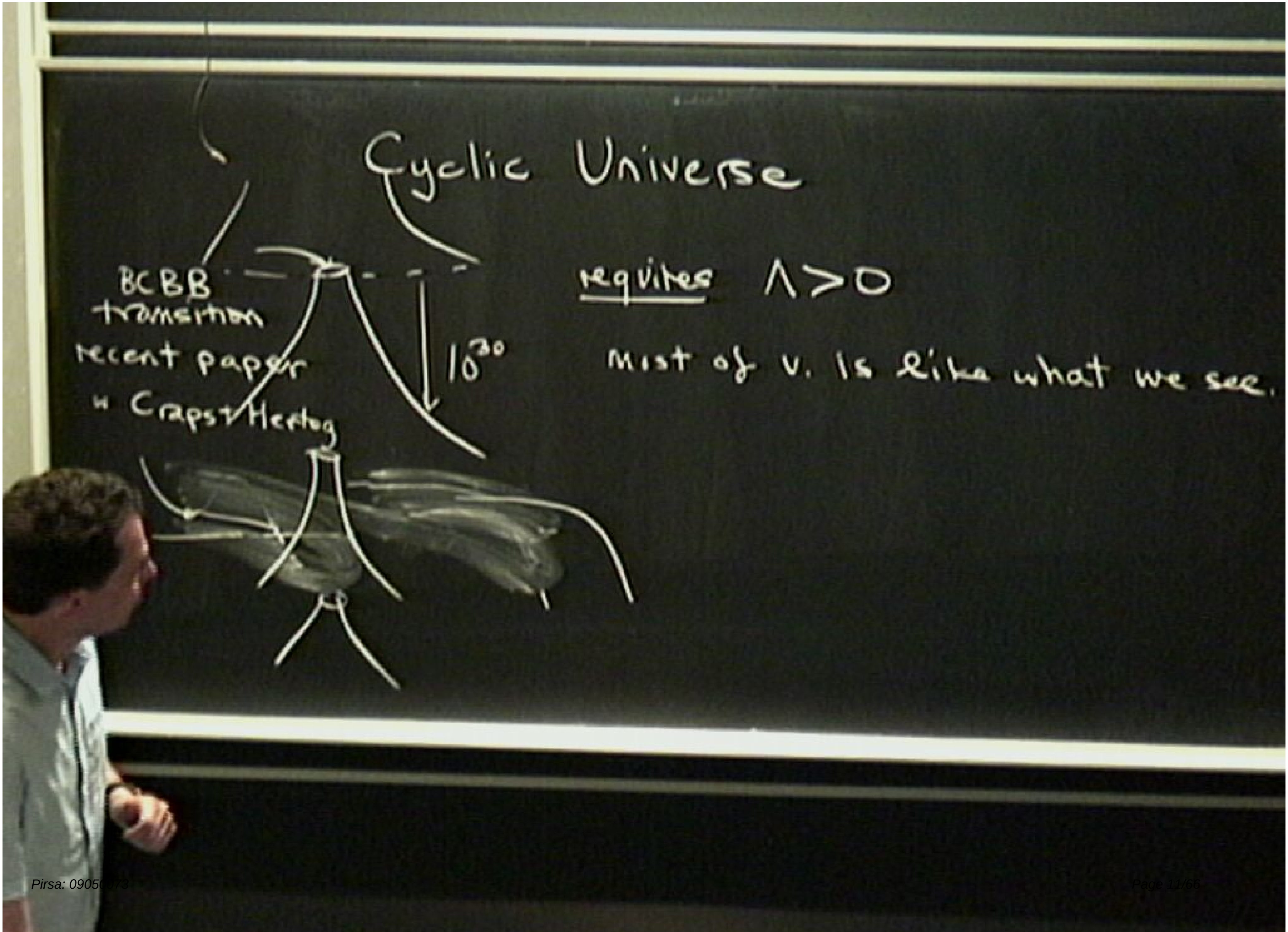
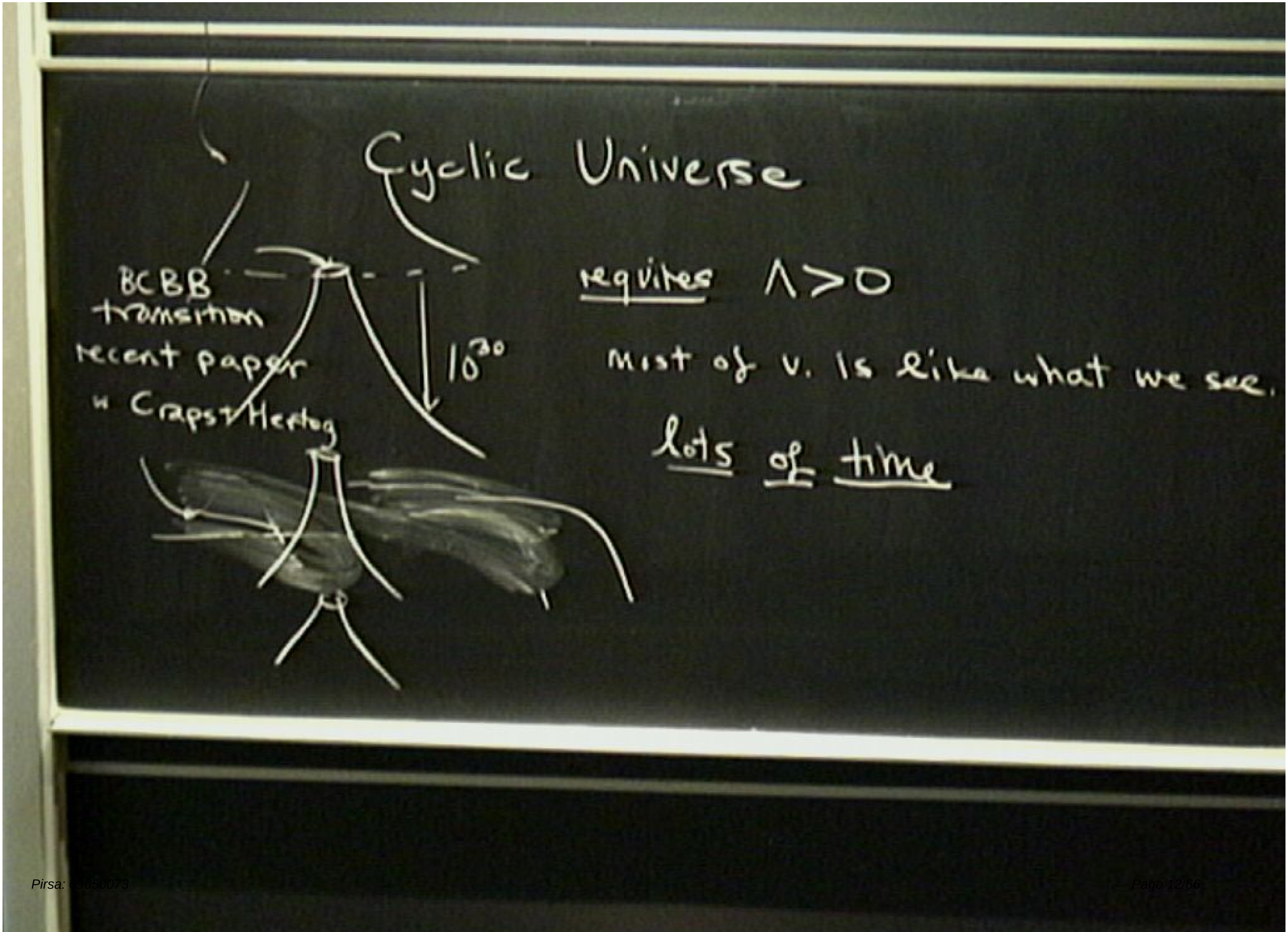

Cyclic Universe
requires Λ>0
BCBB
transition
recent paper
w Craps + Hertog


Cyclic Universe
requires Λ>0
BCBB
transition
recent paper
" Craps + Hertog
10^{30}


Cyclic Universe
requires $\Lambda > 0$
BCBB
transition
recent paper
w Craps + Hertog
10^{30}


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


Cyclic Universe
BCBB transition
recent paper
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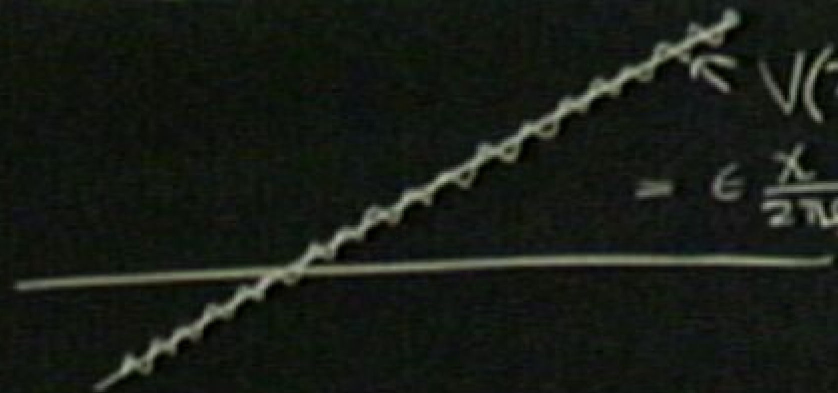
10^30
requires Λ>0
most of U. is like what we see.
lots of time

Steinhardt

(Abbott 1985)

Steinhardt

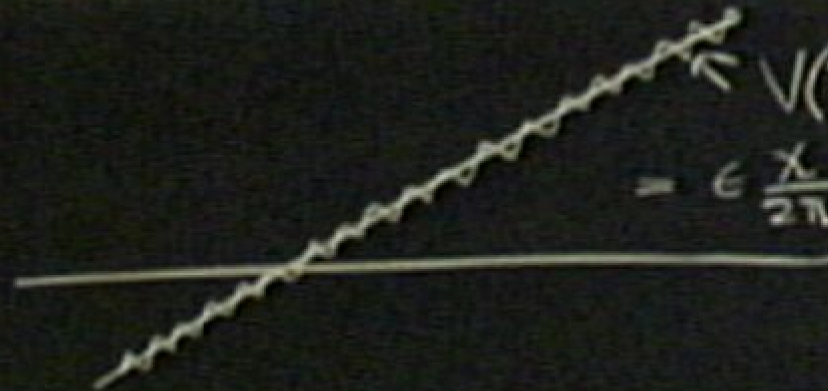
(Abbott 1985)



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

Steinhardt

(Abbott 1985)



$V(\chi)$

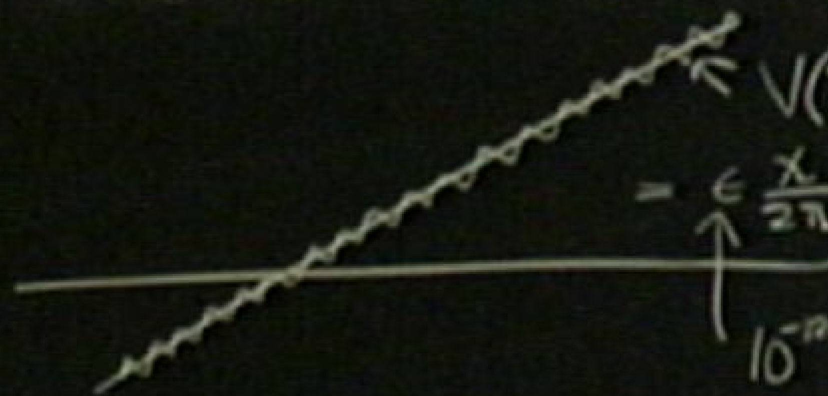
$= \epsilon \frac{\chi}{2\pi f} + M^4 \cos\left(\frac{\chi}{f}\right)$

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

break by ① soft linear term

Steinhardt

(Abbott 1985)



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

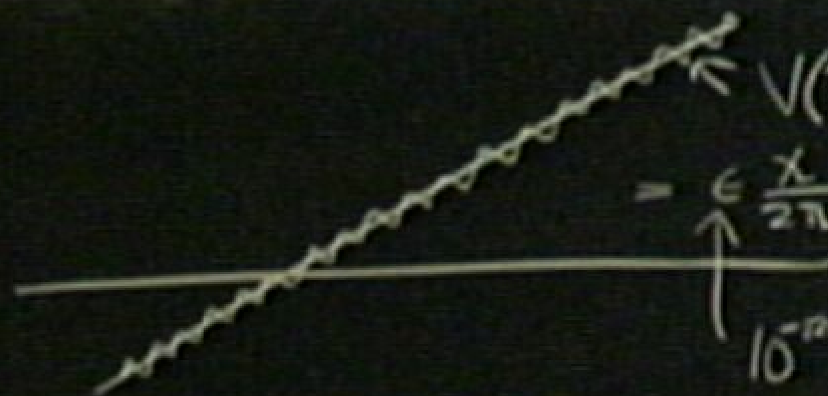
$10^{-120} M_{Pl}^4$ tuned but tech. natural

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

break by ① soft linear term

Steinhardt

(Abbott 1985)



$\swarrow \int \chi F\tilde{F}$

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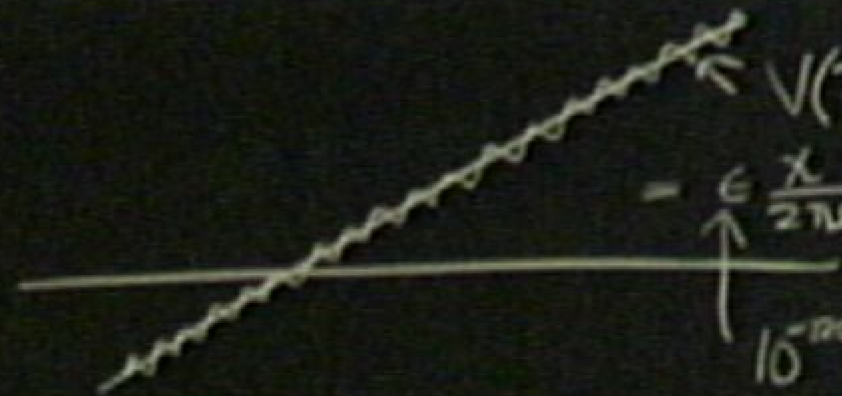

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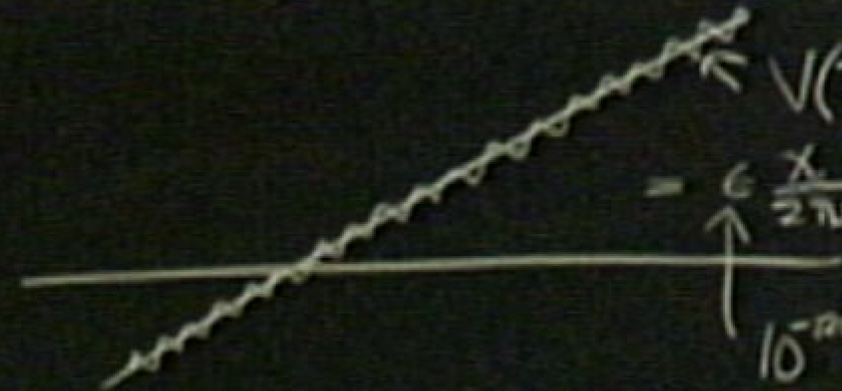
break by ① soft linear term

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

Steinhardt

(Abbott 1985)



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

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

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

tuned but tech. natural

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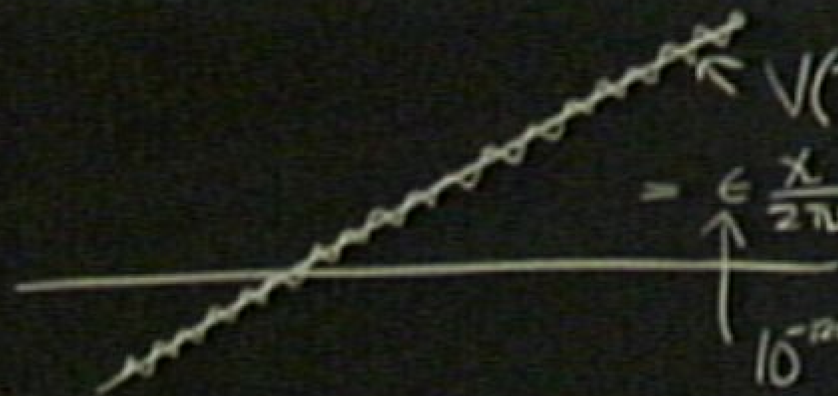
break by ① soft linear term

② nonpert., natural for $M \lll M_{pl}$.

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

Steinhardt

(Abbott 1985)



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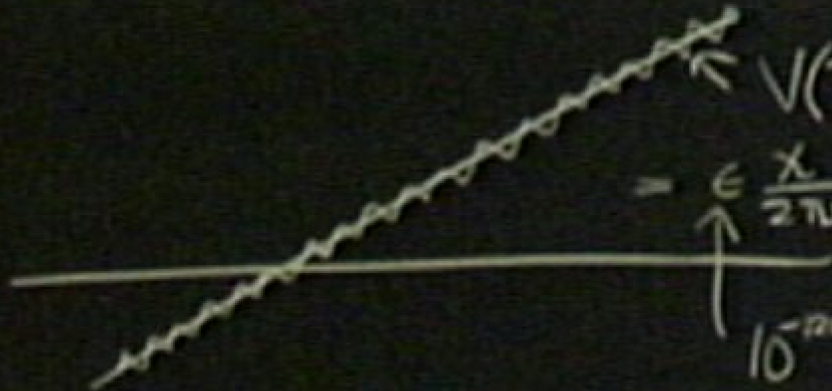
$$M \sim M_{pl}\, e^{-\frac{1}{\alpha(M_{pl})}}$$

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

Steinhardt

(Abbott 1985)



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

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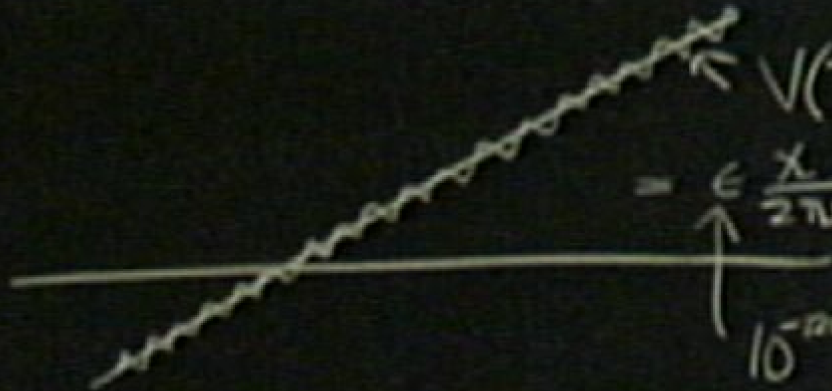

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$\int \frac{\chi}{f} F\tilde{F}$

ϵ: $10^{-120} M_{pl}^4$

tuned but tech. natural

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

break by ① soft linear term

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

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

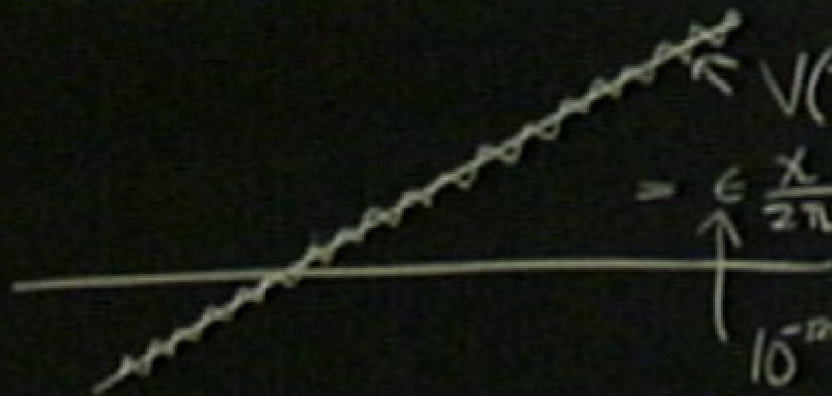
$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_0 < \epsilon$

Steinhardt

(Abbott 1985)



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

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

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

+ anything

tuned but tech. natural

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

break by ① soft linear term

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$0 < V_0 < \epsilon$

(Abbott 1985)

$10^{-120} M_{Pl}^4$ fine tuned but tech. natural

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

break by ① soft linear term

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$\epsilon < M^4$

$\exists$ a minimum w/ V_0

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

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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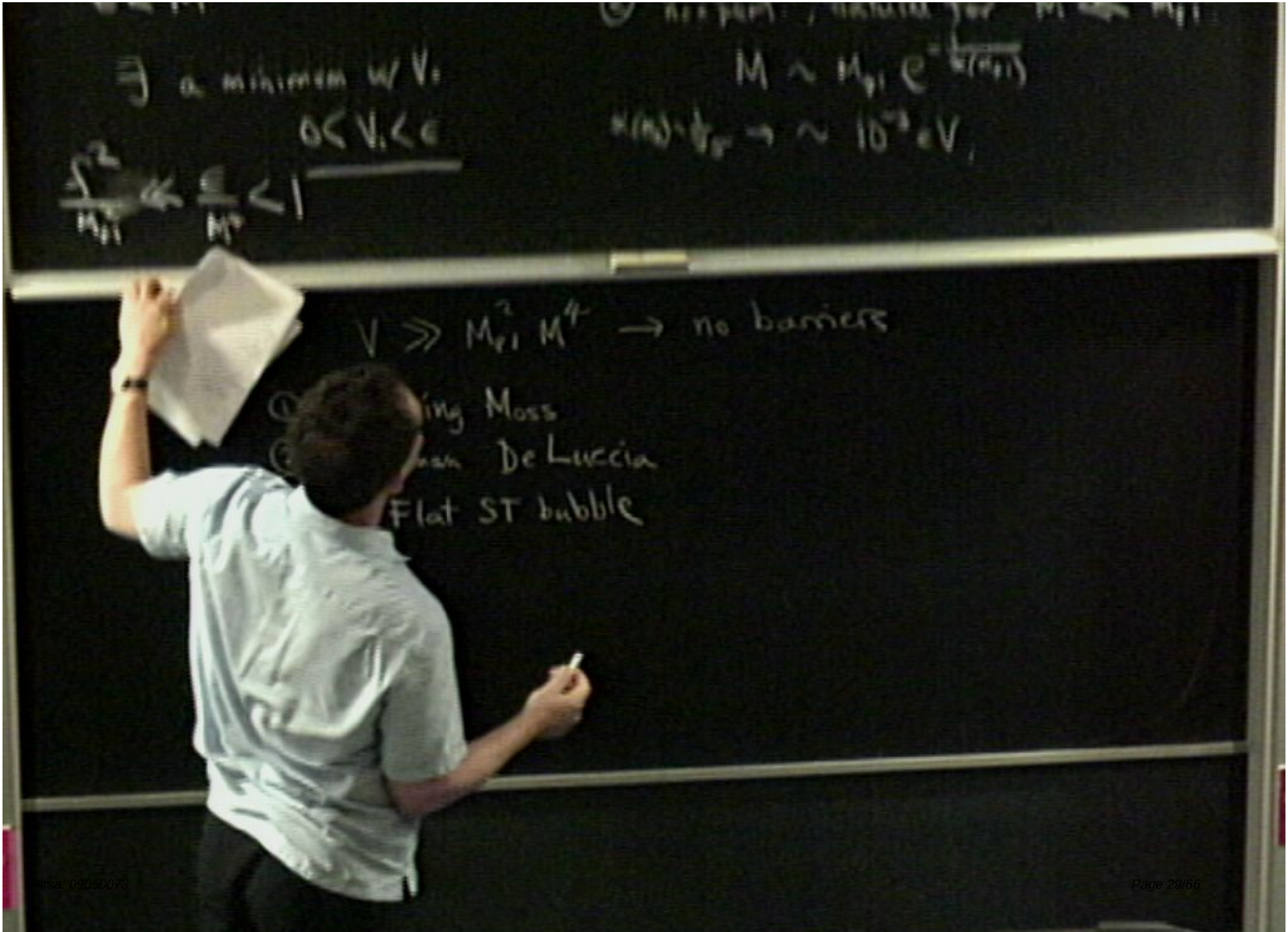
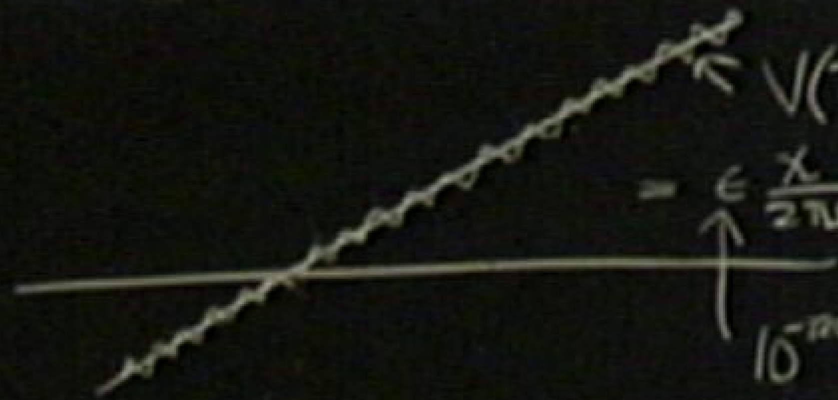
① Hawking Moss

② Coleman De Luccia


a minimum w/ V1
0 < V1 < ε
V ≫ Mpl² M⁴ → no barriers
Moss
De Luccia
Flat ST bubble

Steinhardt

(Abbott 1985)



$V(\chi)$

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

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

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

+ anything

tuned but tech. natural

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

break by ① soft linear term

② nonpert., natural for $M \lll M_{pl}$.

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

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$\epsilon < M^4$

$\exists$ a minimum w/ V_0

$0 < V_0 < \epsilon$

$\frac{f^2}{M_{pl}^2} \lll \frac{\epsilon}{M^4} < 1$

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

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

1. Hawking Moss
2. Coleman De Luccia
3. $\sim$ Flat ST bubble

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

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. $\sim$ Flat ST bubble S_E

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

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

$$S_E = S_0\left(1 - \frac{(V_N + V_{N-1})\,\underbrace{T}_{\text{bubble wall tension}}^{2}}{M_{Pl}^2 \epsilon^2}\right)$$

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

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

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

bubble wall tension

$S_0 \rightarrow \underline{10^{110}}$

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

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

$\propto N$ bubble wall tension

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

$S_0 \rightarrow \underline{10^{110}}$

e.g. $f \sim 10^{4}$ GeV

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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

$$S_E = \underbrace{S_0}_{10^{110}} \left(1 - \frac{(\overbrace{V_N + V_{N-1}}^{\propto N})\overbrace{T}^{\text{bubble wall tension}}{}^2}{M_{Pl}^2 \epsilon^2} \right)$$

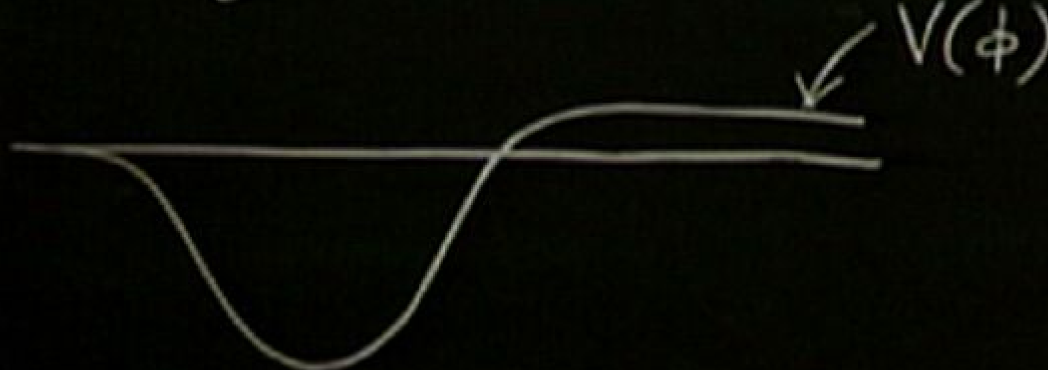
e.g. $f \sim 10^{4}$ GeV

$\frac{\epsilon}{M_{Pl}} = 0.1$

$M \sim 10^{-3}$ eV

rate $\propto \underline{e^{10^{111} N}}$

Empty universe problem!



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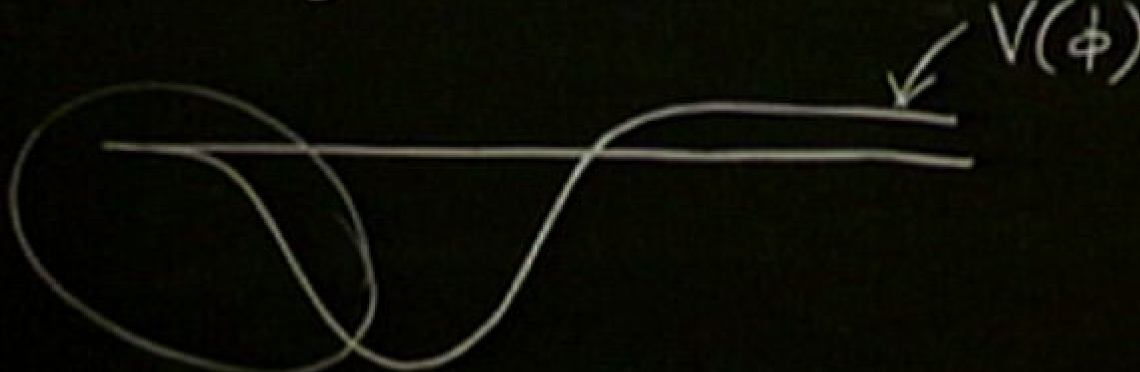
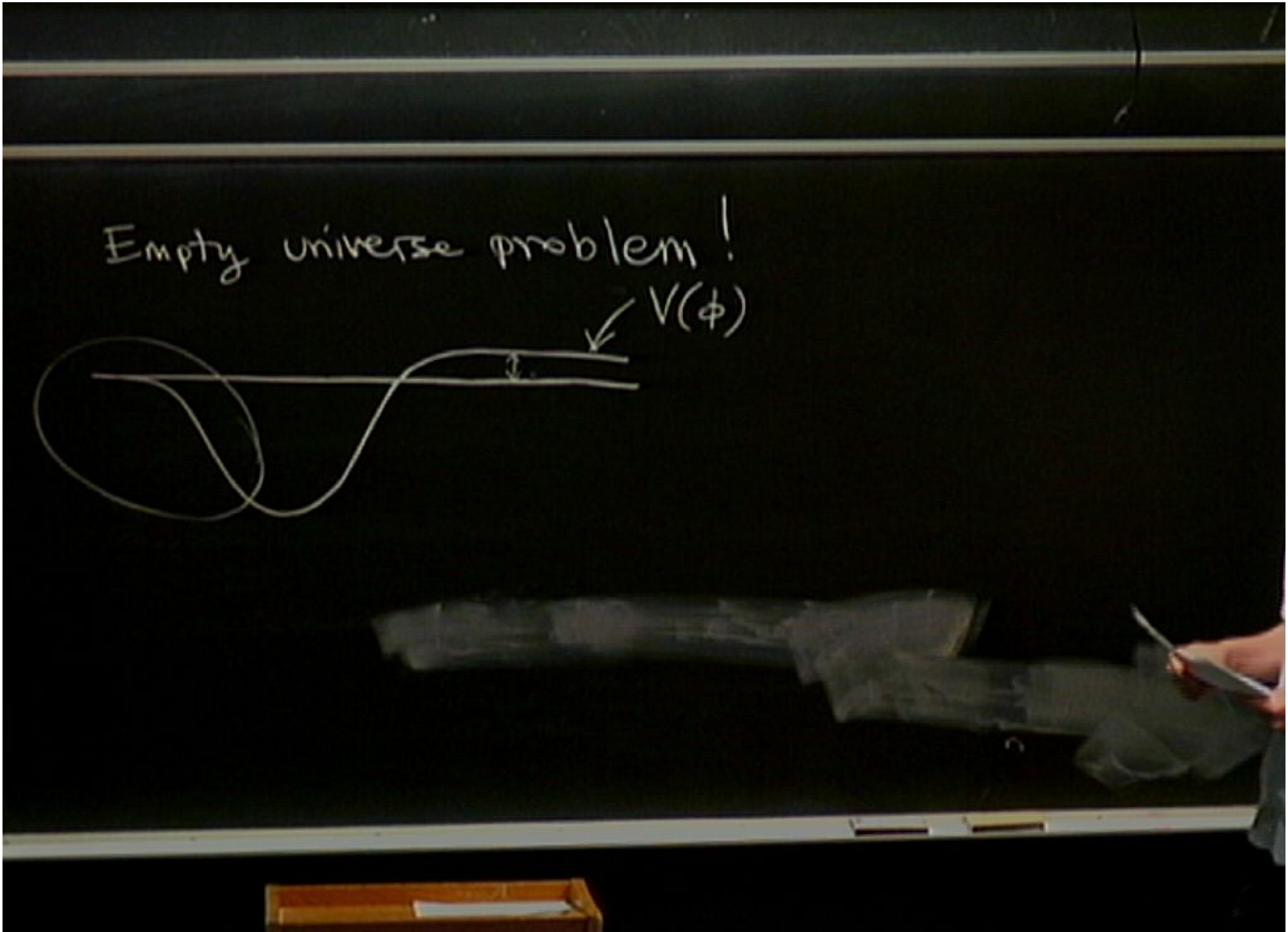
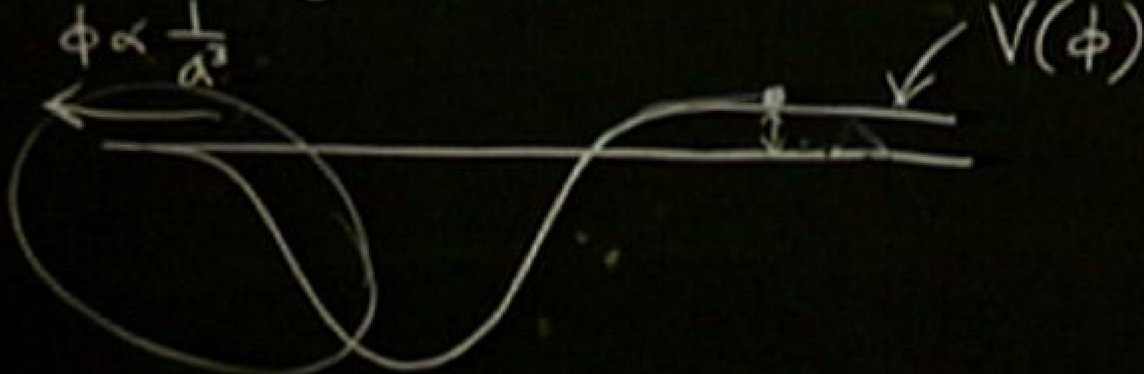



Empty universe problem!
V(ϕ)

Empty universe problem!

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



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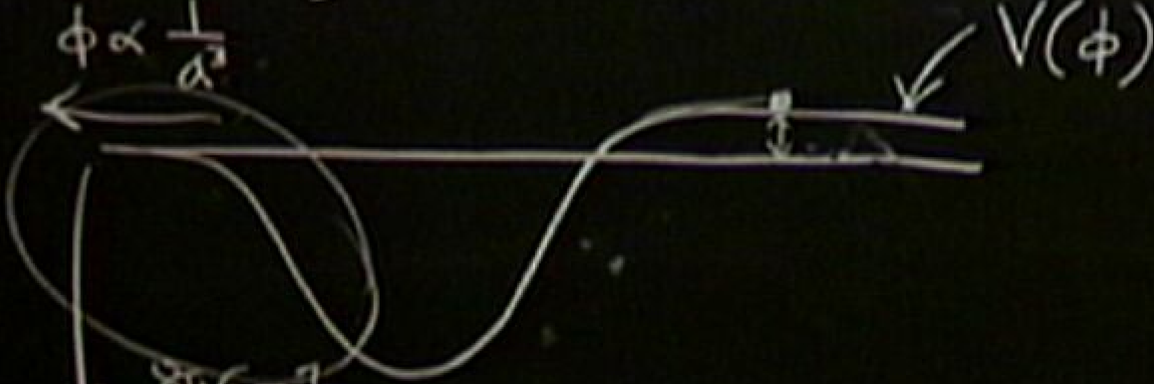
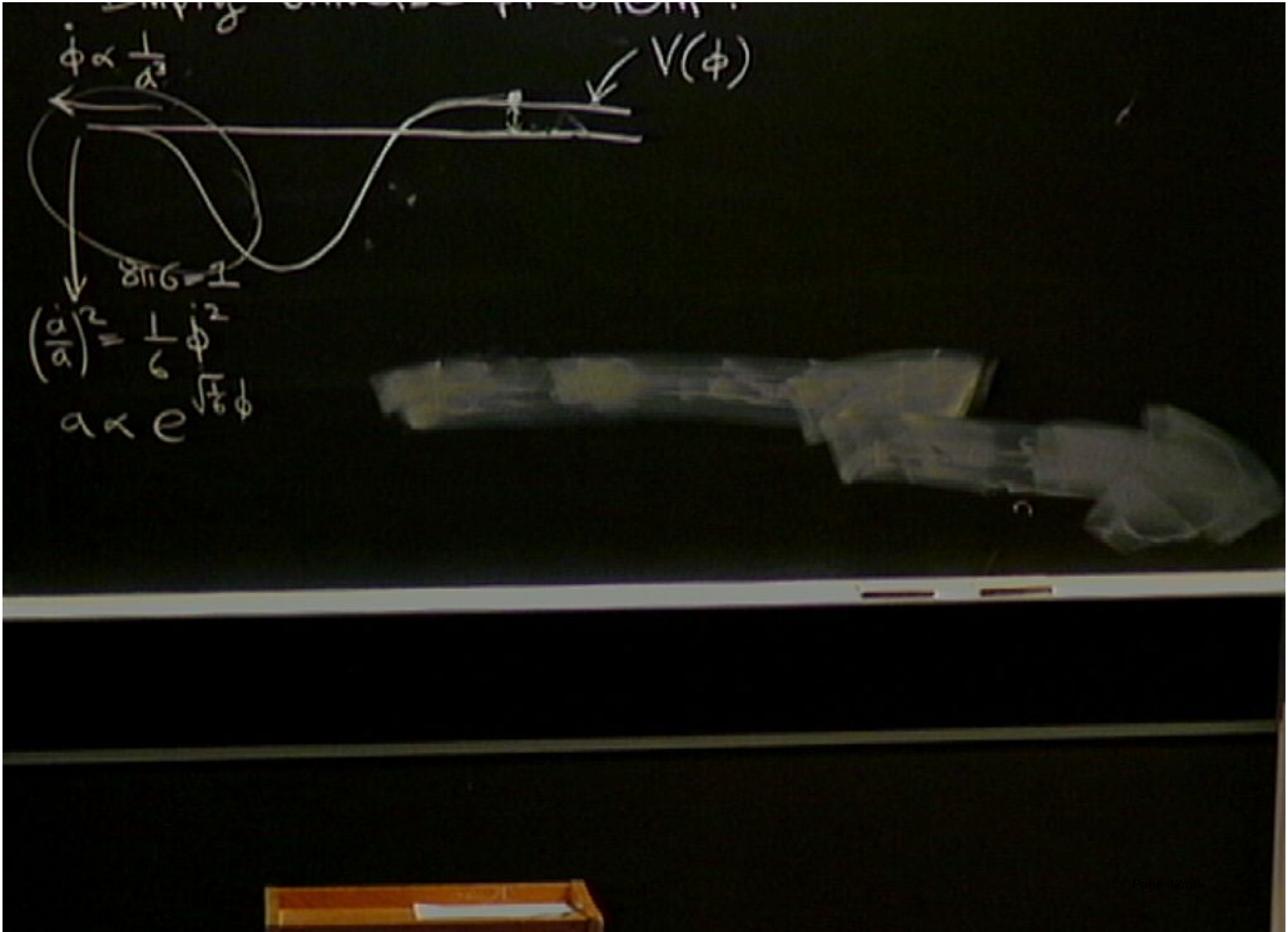
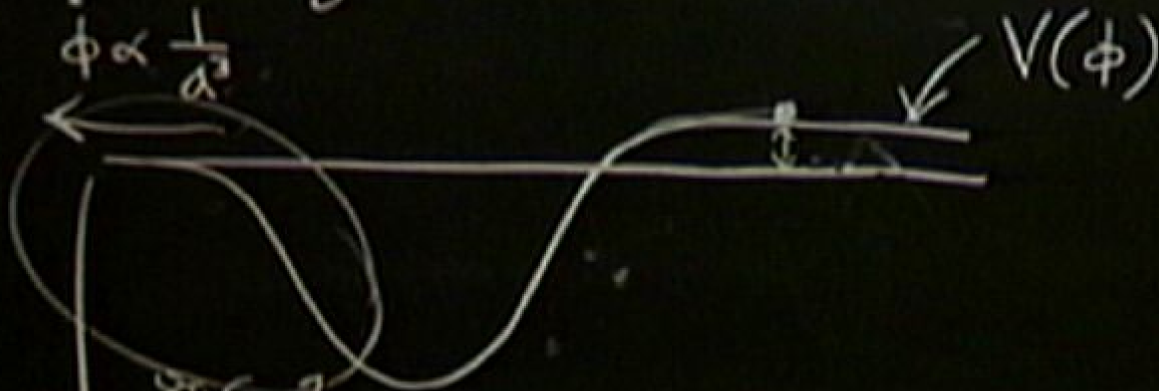


$8\pi G = 1$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$$


$\dot{\phi} \propto \frac{1}{a^3}$
$V(\phi)$
$8\pi G = 1$
$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$

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



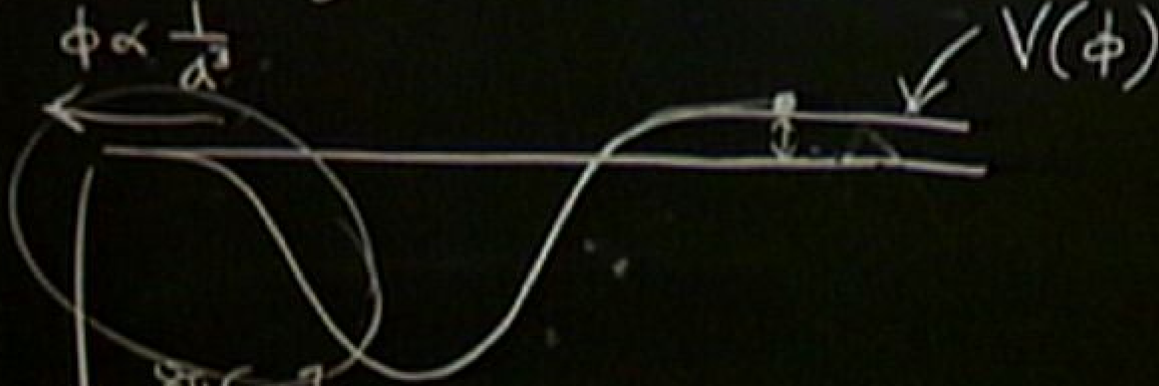
$8\pi G = 1$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$$

$$a \propto e^{\sqrt{\frac{1}{6}}\phi}$$

$$e^{-\sqrt{\frac{2}{3}}\phi}\, g^E_{\mu\nu} = \text{finite at sing?}$$

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



$8\pi G = 1$

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$$g^{5d}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu} = \text{finite at sing?}$$

Empty universe problem!

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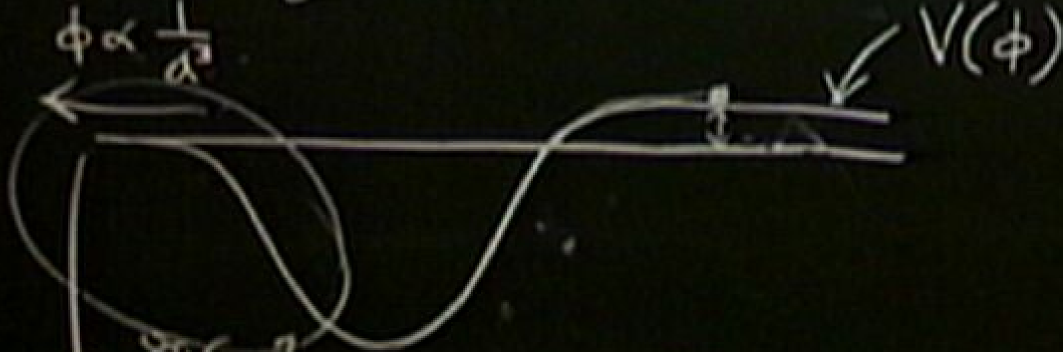

$8\pi G = 1$

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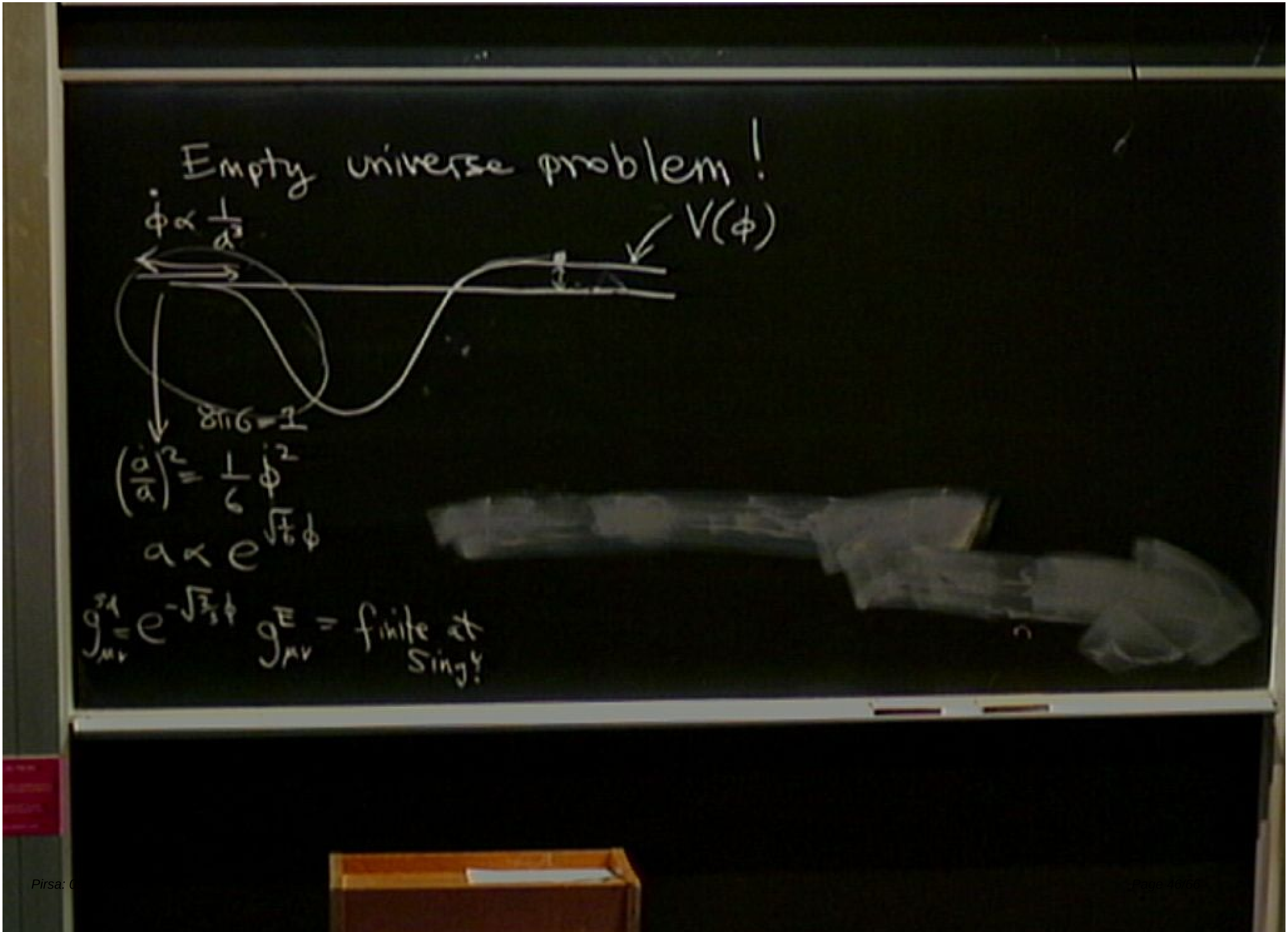
$$g^{SF}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi} g^{E}_{\mu\nu} = \text{finite at sing}^y!$$



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$V(\phi)$
$8\pi G = 1$
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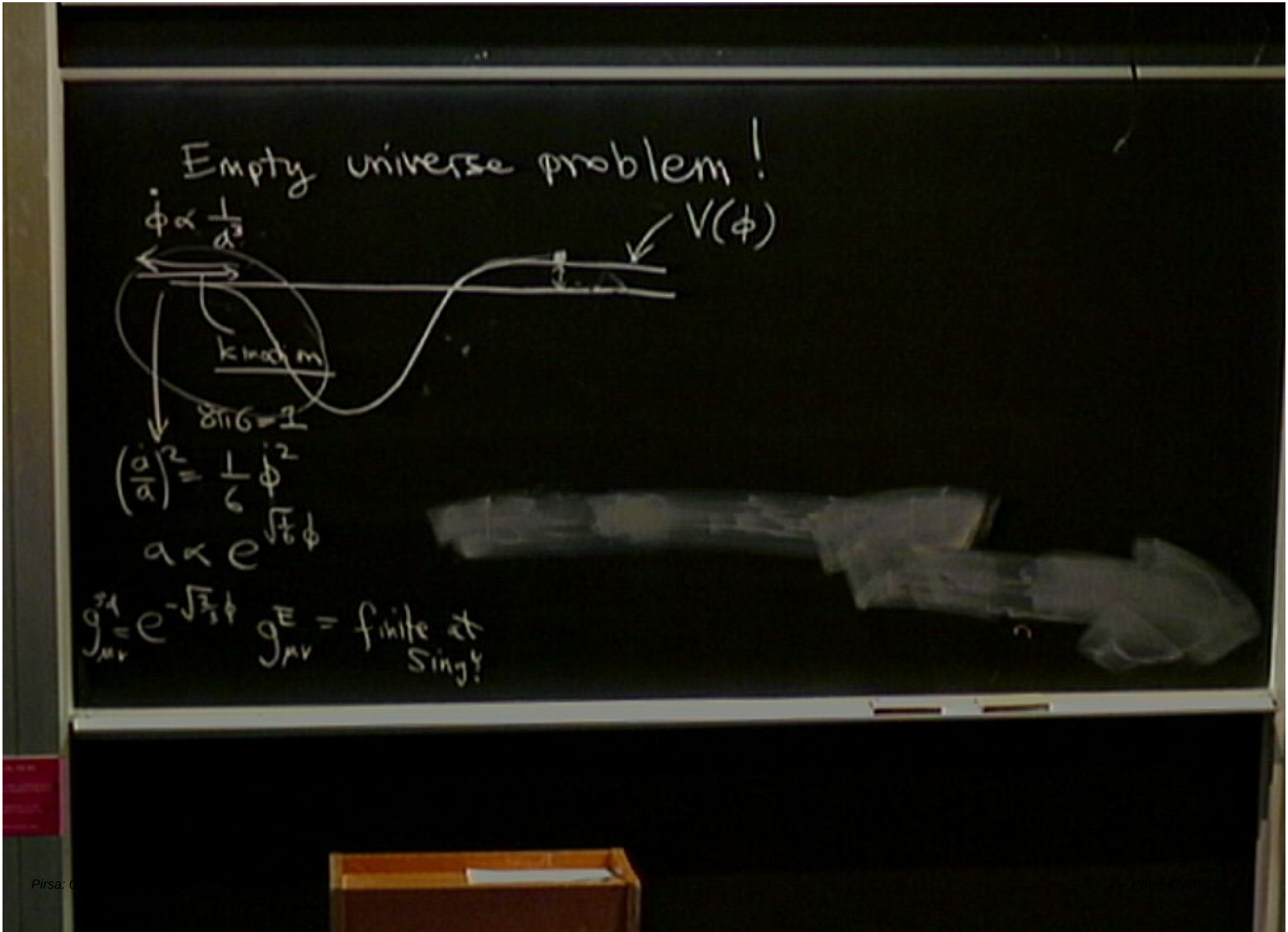
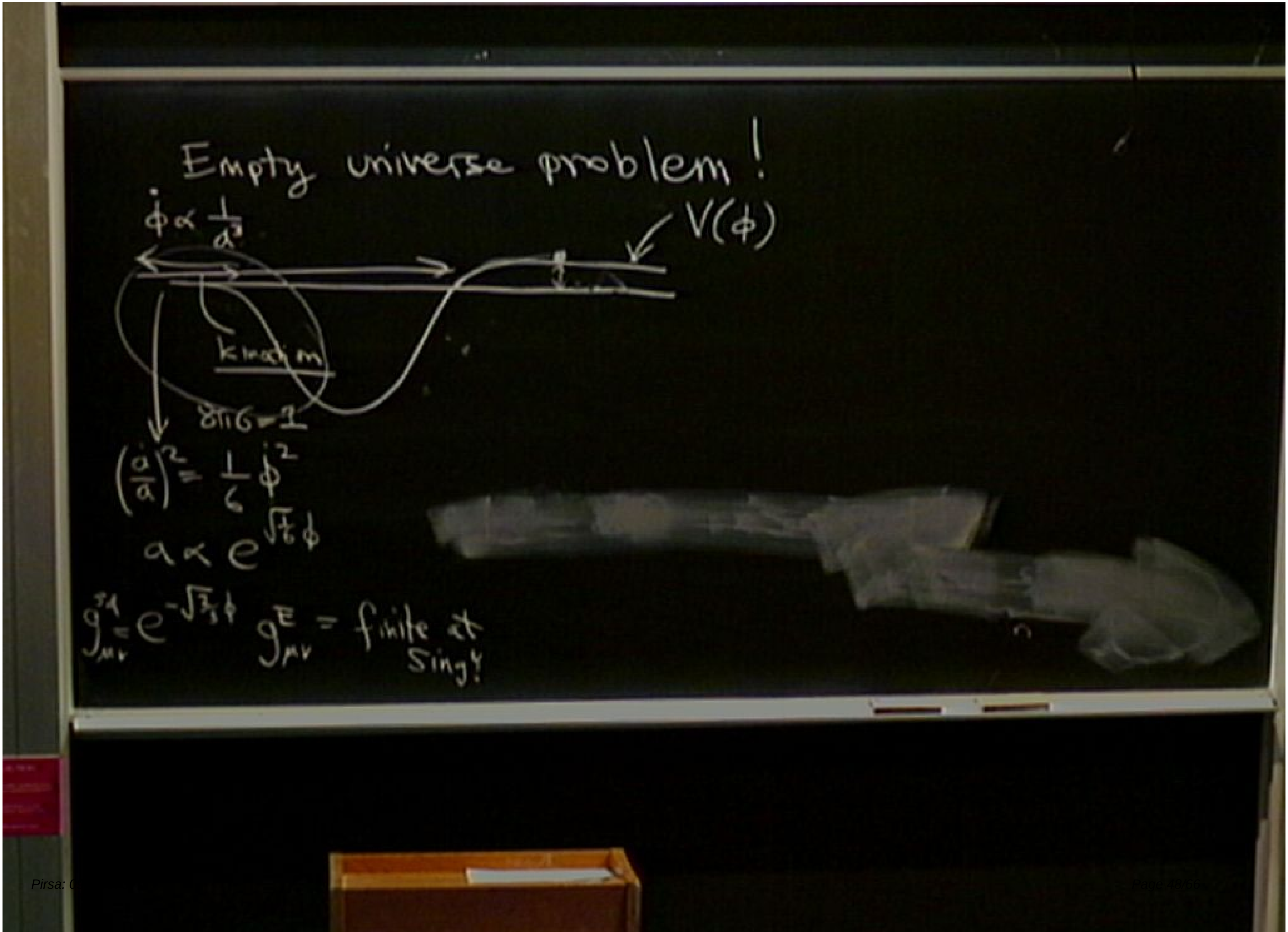
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$
$g_{\mu\nu}^{5d} = e^{-\sqrt{\frac{2}{3}}\phi}\, g_{\mu\nu}^{E}$ = finite at sing!


Empty universe problem!
φ̇ ∝ 1/a³
V(φ)
kination
8πG=1
(ȧ/a)² = 1/6 φ̇²
a ∝ e^{√(1/6) φ}
g_{μν} = e^{-√(2/3) φ} g^E_{μν} = finite at sing!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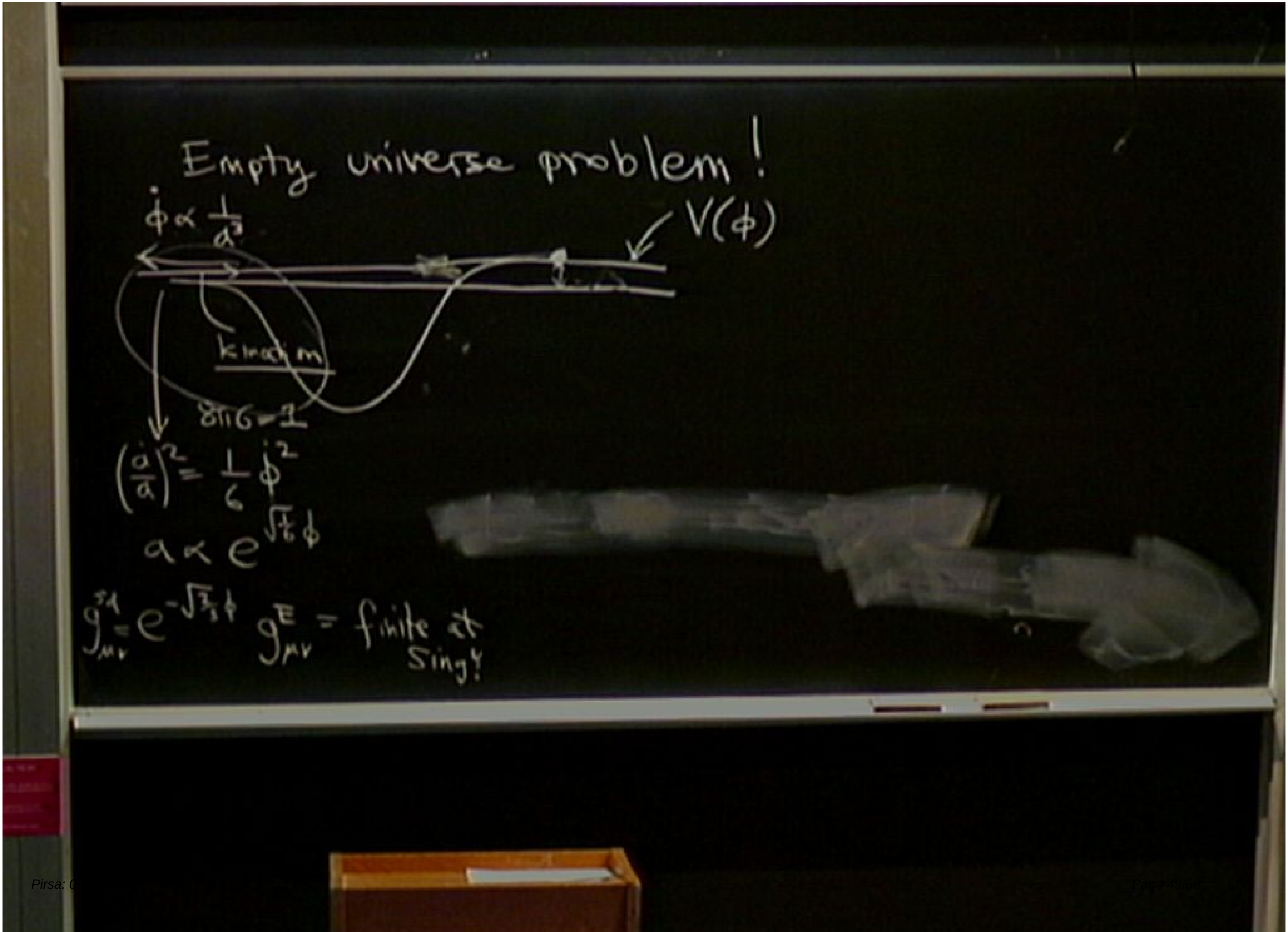

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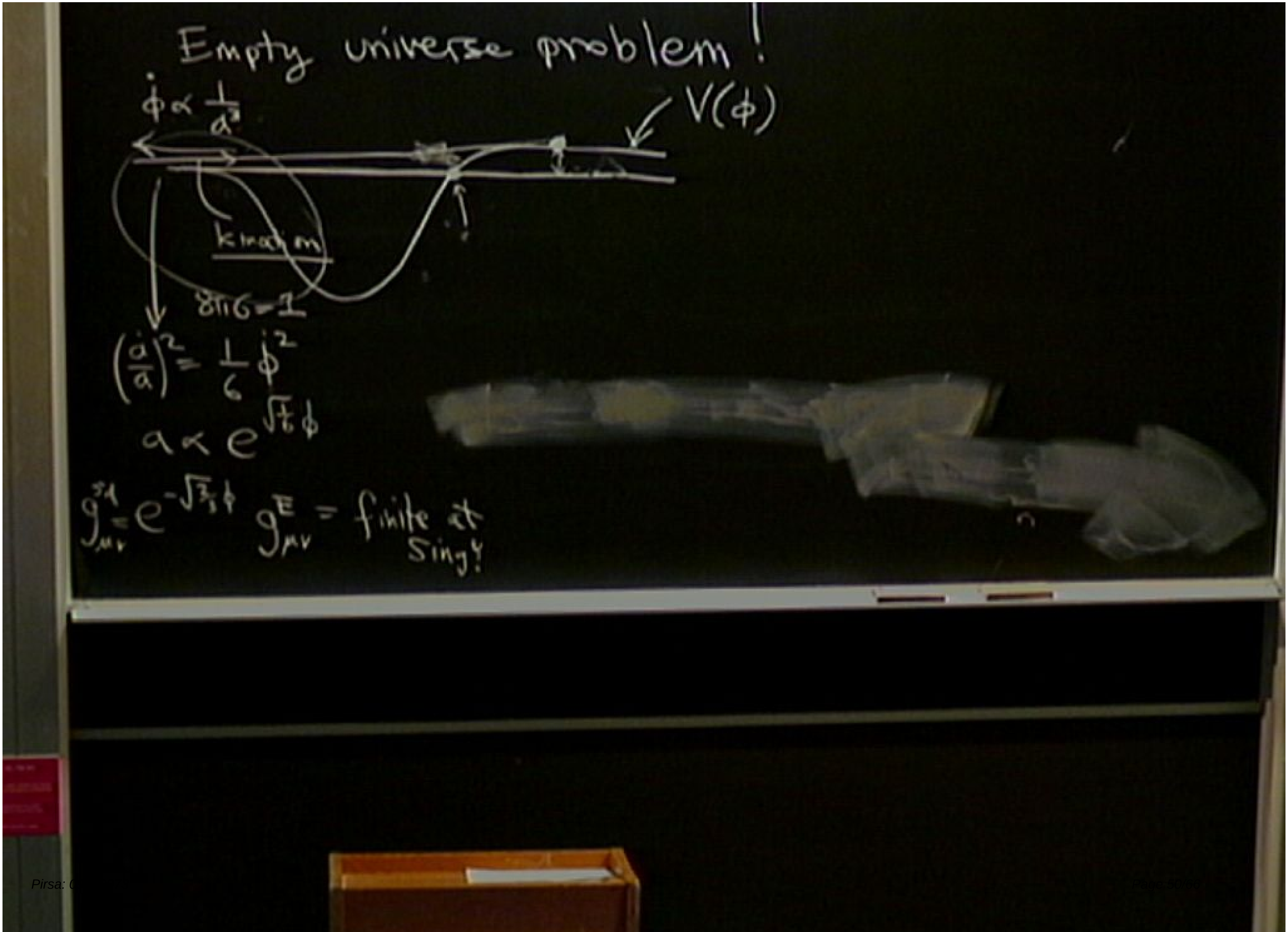
$g^{SA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}$
$g^{E}_{\mu\nu}$ = finite at sing!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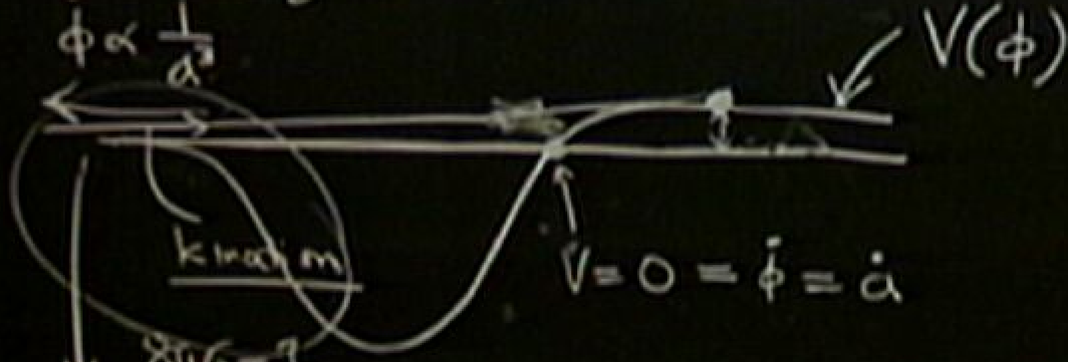
$8\pi G = 1$
$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$
$a \propto e^{\sqrt{\frac{1}{6}}\phi}$
$g^{5d}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing?

Empty universe problem!

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

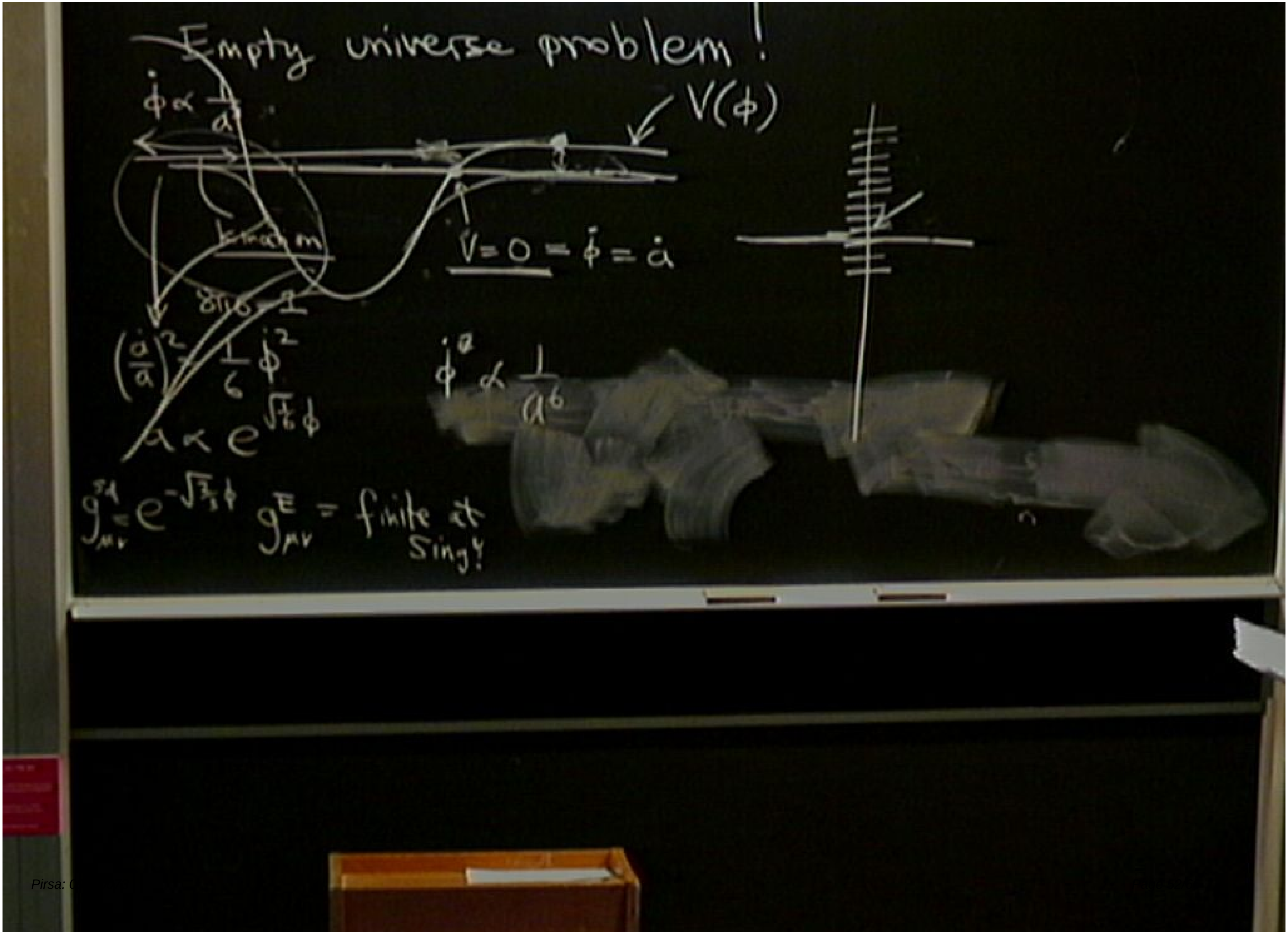


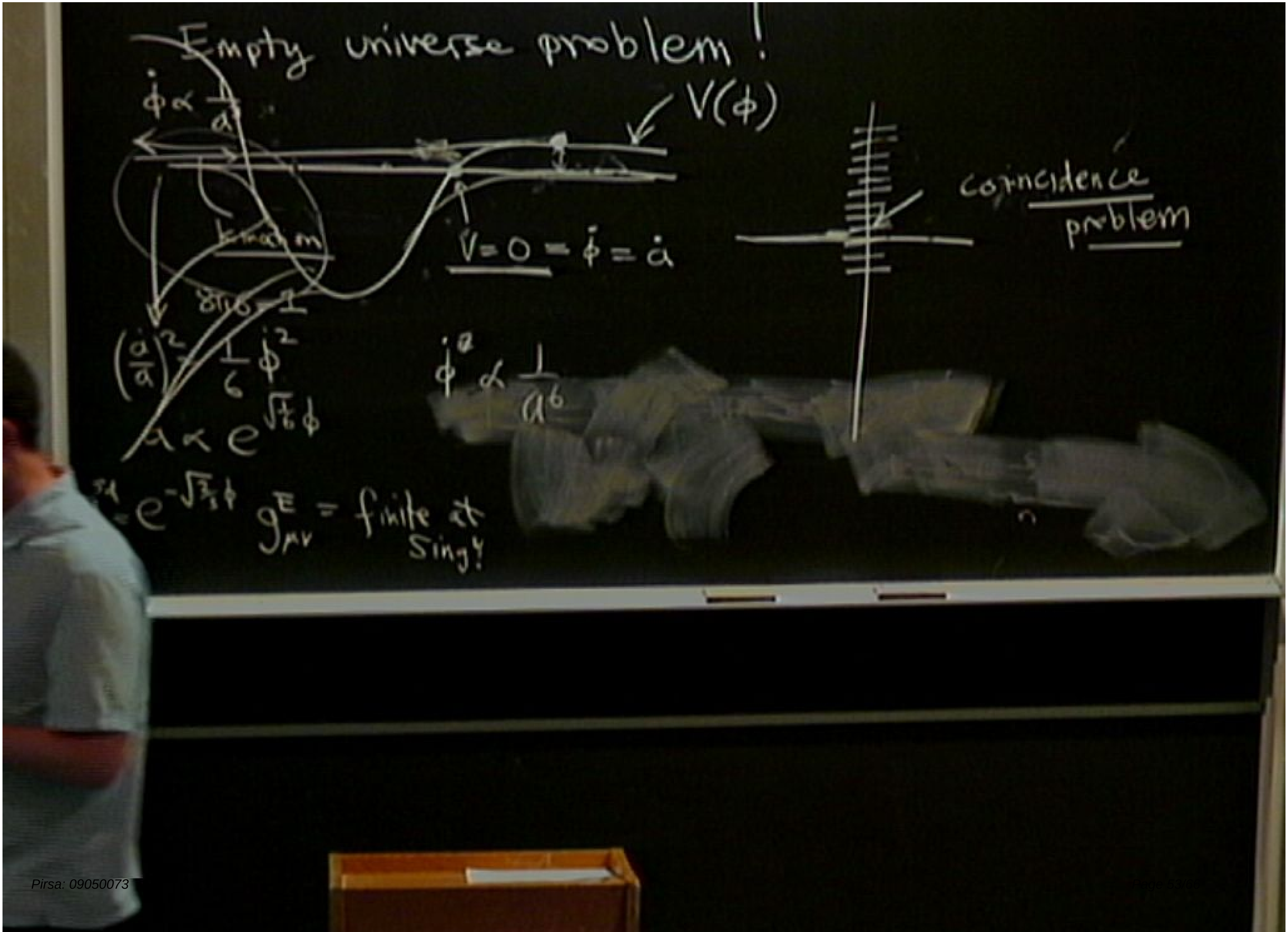
$8\pi G = 1$

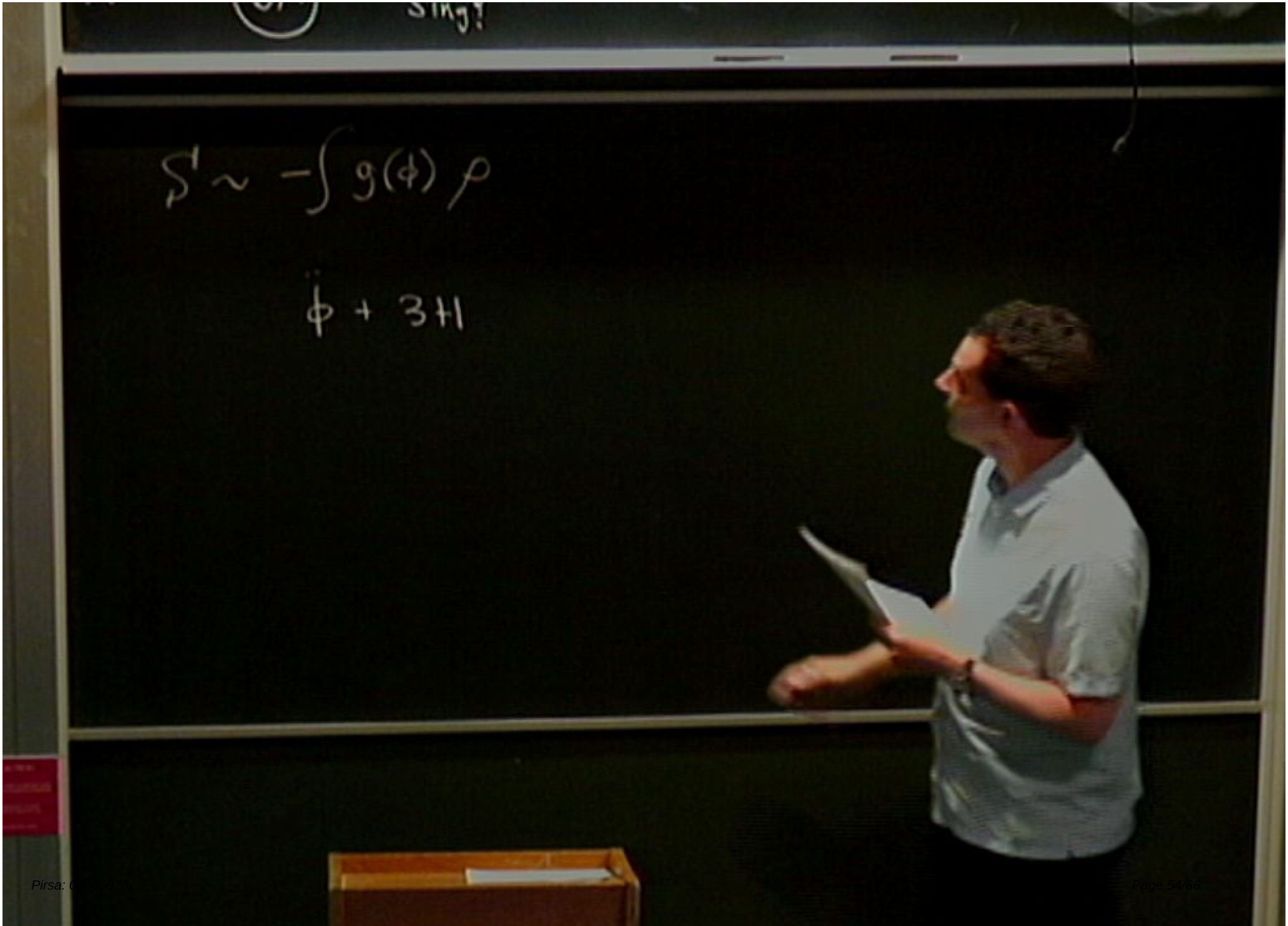
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{6}\dot{\phi}^2$$

$$a \propto e^{\sqrt{\frac{1}{6}}\phi}$$

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


Empty universe problem!
$\dot\phi \propto \frac{1}{a^3}$
$V(\phi)$
kination
$8\pi G = 1$
$V = 0 \Rightarrow \dot\phi = \dot a$
$\left(\frac{\dot a}{a}\right)^2 = \frac{1}{6}\dot\phi^2$
$\dot\phi^2 \propto \frac{1}{a^6}$
$a \propto e^{\sqrt{1/6}\,\phi}$
$g^{SA}_{\mu\nu} = e^{-\sqrt{2/3}\,\phi}\, g^{E}_{\mu\nu}$ = finite at sing'y


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


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

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

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

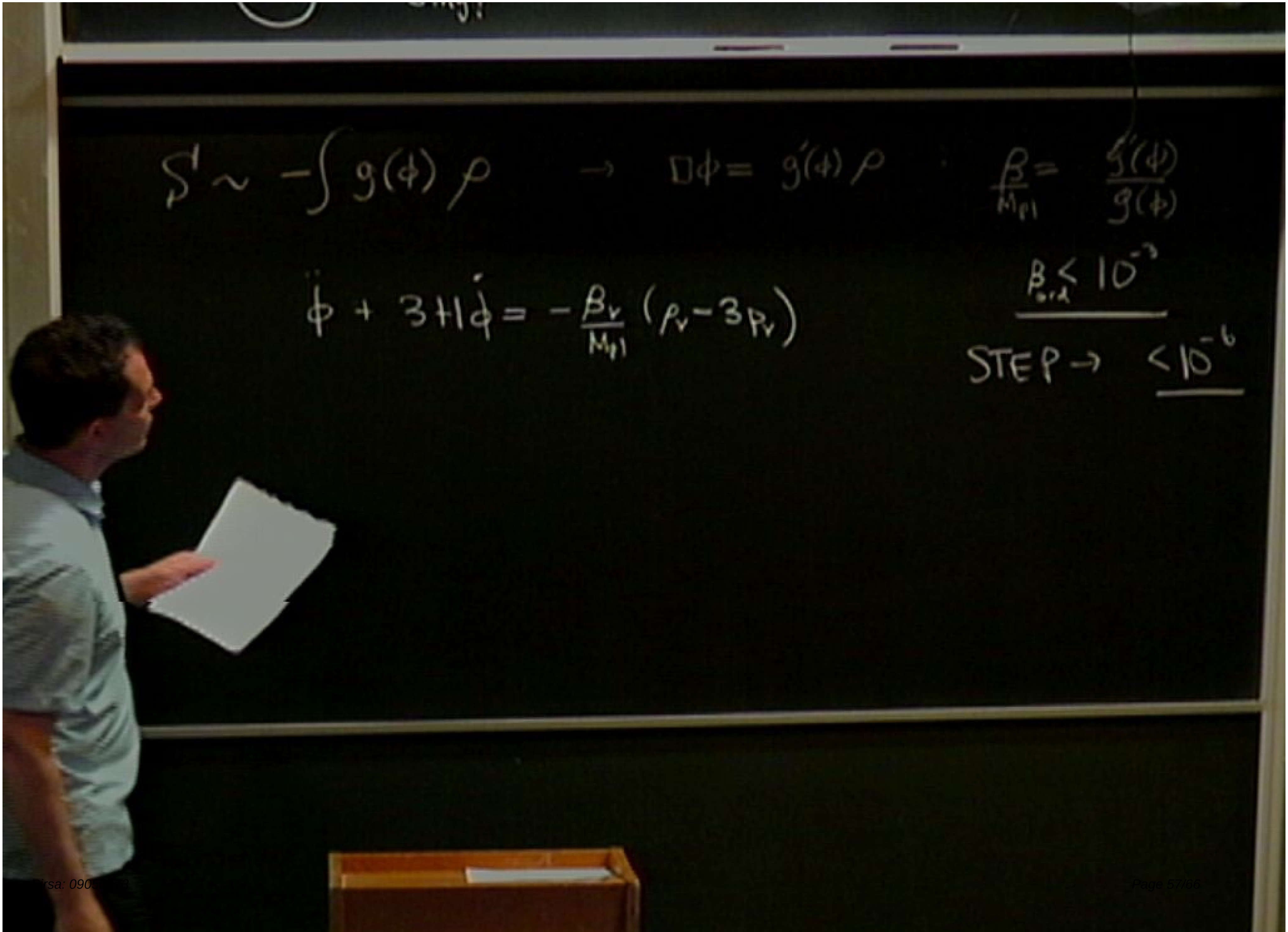
$$S' \sim -\int g(\phi)\,\rho \quad \rightarrow \quad \Box\phi = g'(\phi)\,\rho$$

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

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

$\beta_{\text{ord}} < 10^{-3}$

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


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

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

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

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

$\beta_{ord} < 10^{-3}$

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

$A \propto e^{\ldots}$

$g^{5d}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing!

M_{pl} $g(\phi)$

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_v}{M_{pl}}(\rho_v - 3p_v) + \frac{\beta_c}{M_{pl}}\rho_c$$

$\underline{\beta_{ord} < 10^{-3}}$

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

$A \propto e^{\cdots}$

$g^{JF}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing?

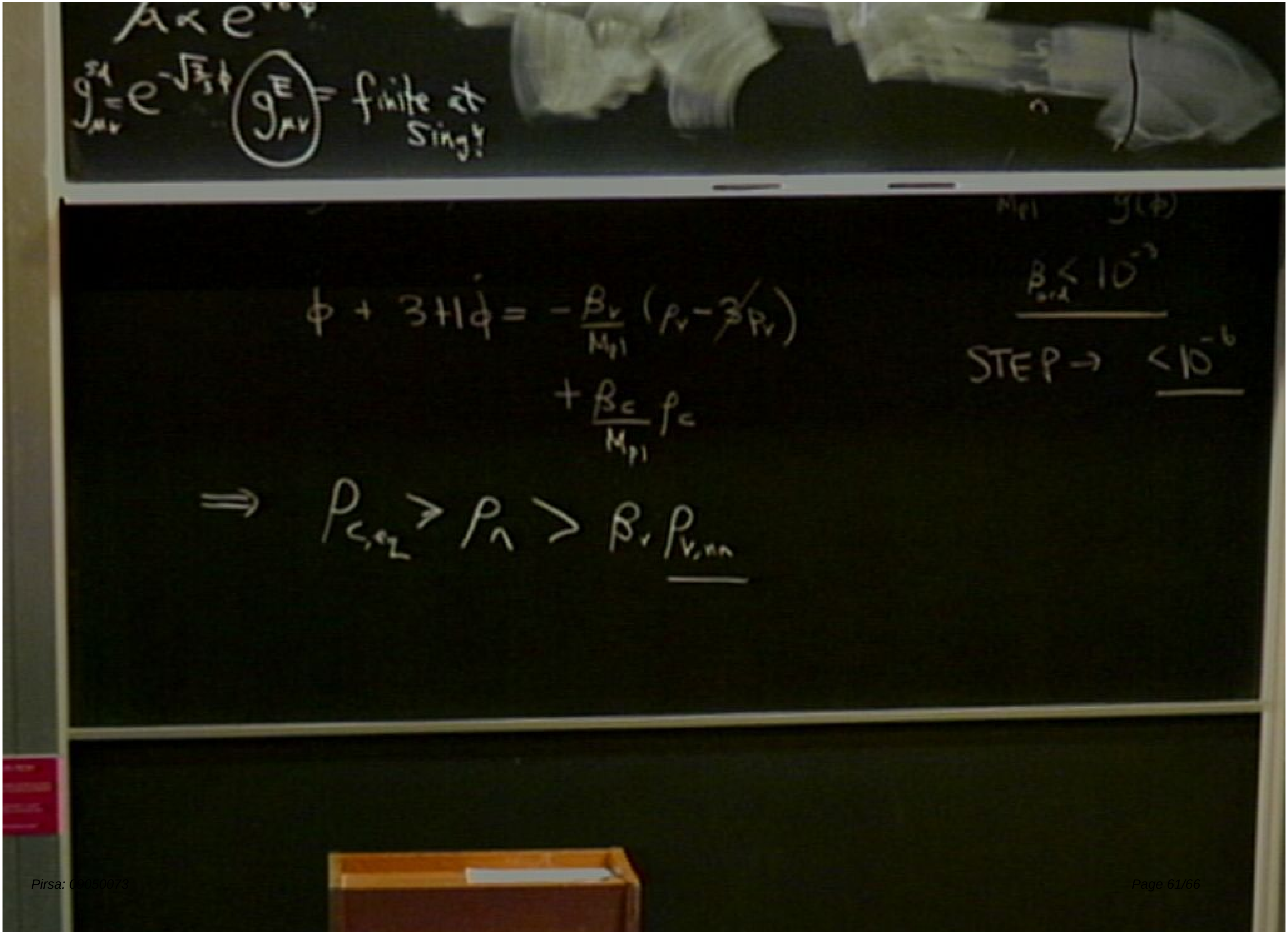
M_{pl} $g(\phi)$

$\beta_{ord} < 10^{-3}$

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

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_v}{M_{pl}}\left(\rho_v - \cancel{3p_v}\right) + \frac{\beta_c}{M_{pl}}\rho_c$$

$$\Longrightarrow \quad \rho_{c,eq} > \rho_\Lambda$$


$g^{SA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing'y
$\ddot\phi + 3H\dot\phi = -\frac{\beta_\nu}{M_{pl}}(\rho_\nu - \cancel{3}p_\nu) + \frac{\beta_c}{M_{pl}}\rho_c$
$\Longrightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nr}$
$\beta_{ord} < 10^{-3}$
STEP $\rightarrow$ $< 10^{-6}$

$A \propto e^{\ldots}$

$g^{5d}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing.y

$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_v}{M_{pl}}(\rho_v - \cancel{3}p_v) + \frac{\beta_c}{M_{pl}}\rho_c$

$\Longrightarrow \rho_{c,eq} > \rho_\Lambda > \beta_v\, \underline{\rho_{v,nn}}$

$\underline{\beta_{ord} < 10^{-3}}$

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

$A \propto e^{\dots}$

$g^{JA}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing'y

M_{pl} $g(\phi)$

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{pl}}\left(\rho_\nu - \cancel{3}p_\nu\right) + \frac{\beta_c}{M_{pl}}\rho_c$$

$\underline{\beta_{ord} < 10^{-3}}$

STEP → $\underline{< 10^{-6}}$

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

$A \propto e^{\cdots}$

$g^{5d}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing.y

M_{pl} $g(\phi)$

$\beta_{ord} < 10^{-3}$

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

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\beta_\nu}{M_{pl}}\left(\rho_\nu - \cancel{3}p_\nu\right) + \frac{\beta_c}{M_{pl}}\rho_c$$

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

$m_\nu > 0.05\,\text{eV}$

$\Lambda \propto e^{\ldots}$

$g^{JF}_{\mu\nu} = e^{-\sqrt{\frac{2}{3}}\phi}\, g^{E}_{\mu\nu}$ = finite at sing?

M_{pl} $g(\phi)$

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

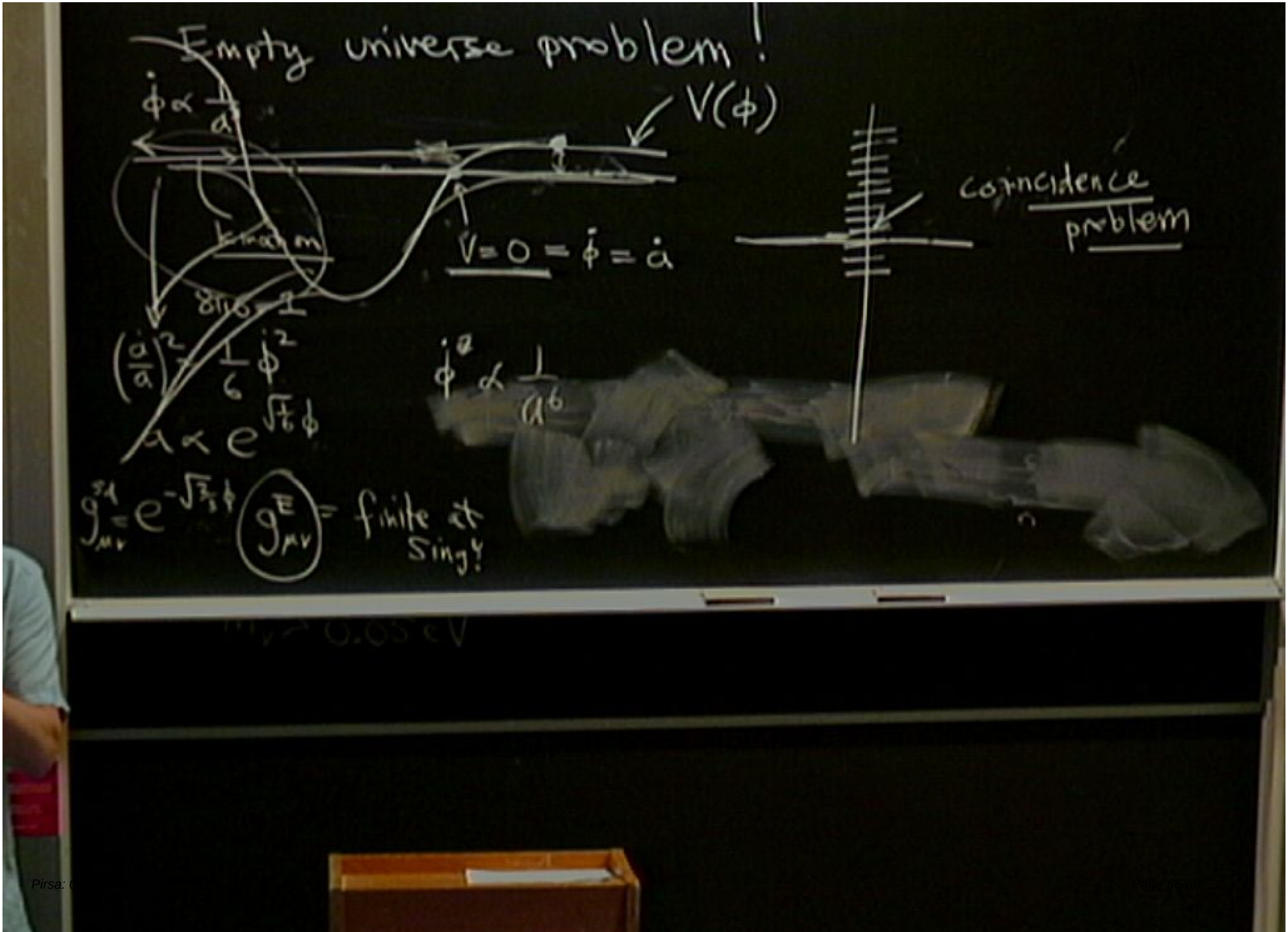
$\Longrightarrow \rho_{c,eq} > \rho_\Lambda > \beta_\nu \rho_{\nu,nn}$

$M_\nu > 0.05\,eV$

$\beta_{ord} < 10^{-3}$

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

Rube Goldberg?



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