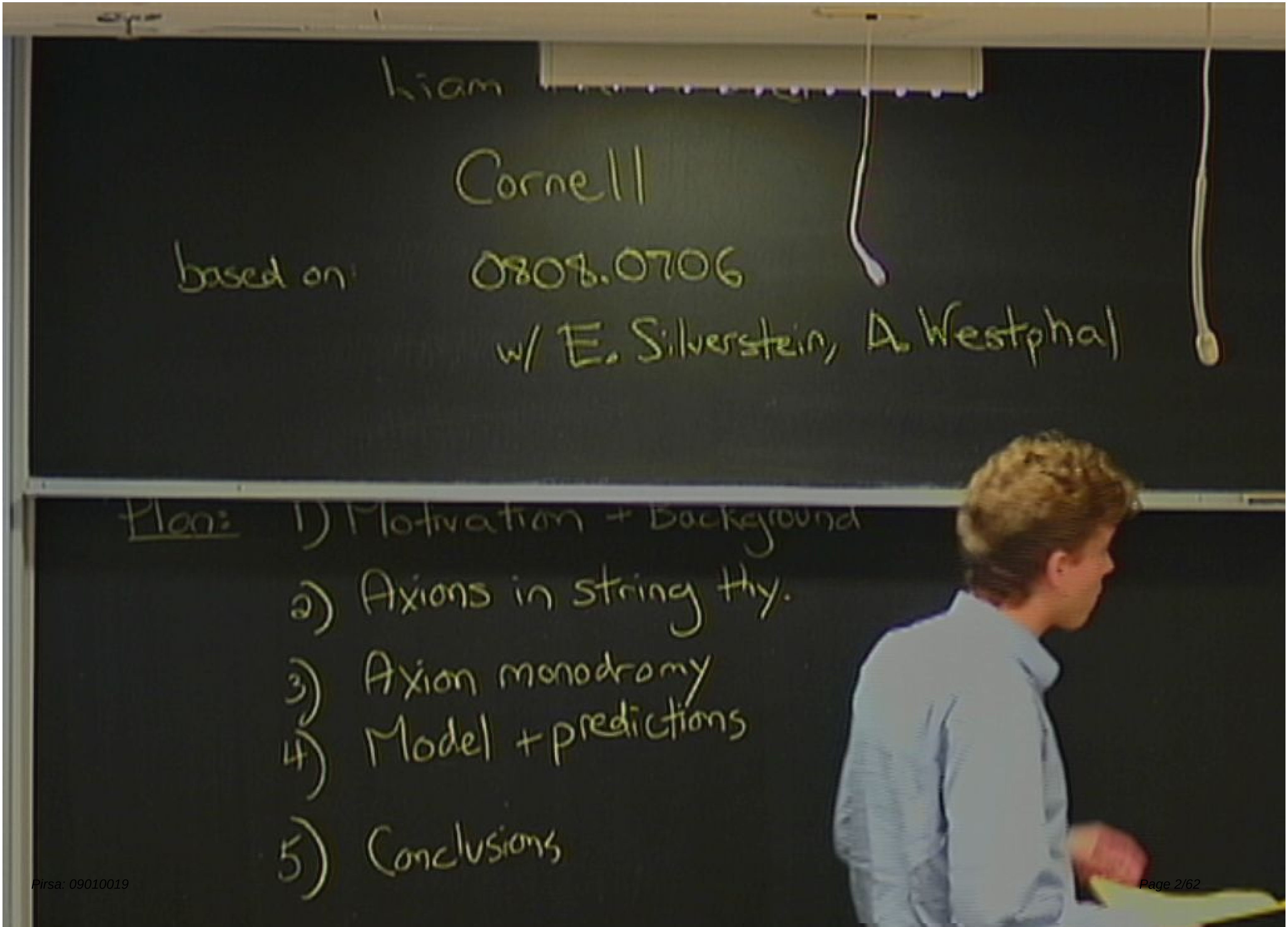
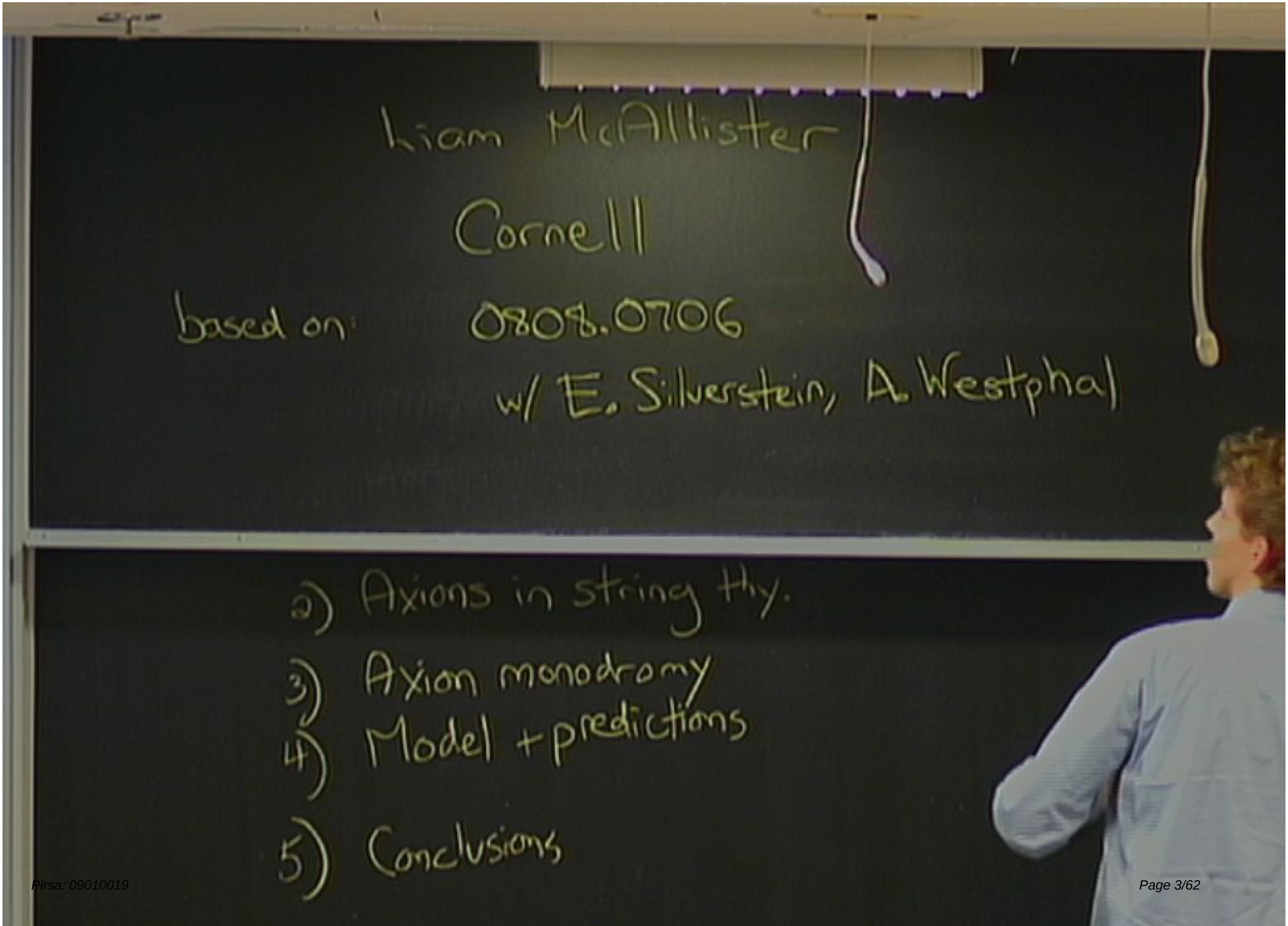
Title: Linear Inflation from Axion Monodromy

Date: Jan 20, 2009 02:00 PM

URL: http://pirsa.org/09010019

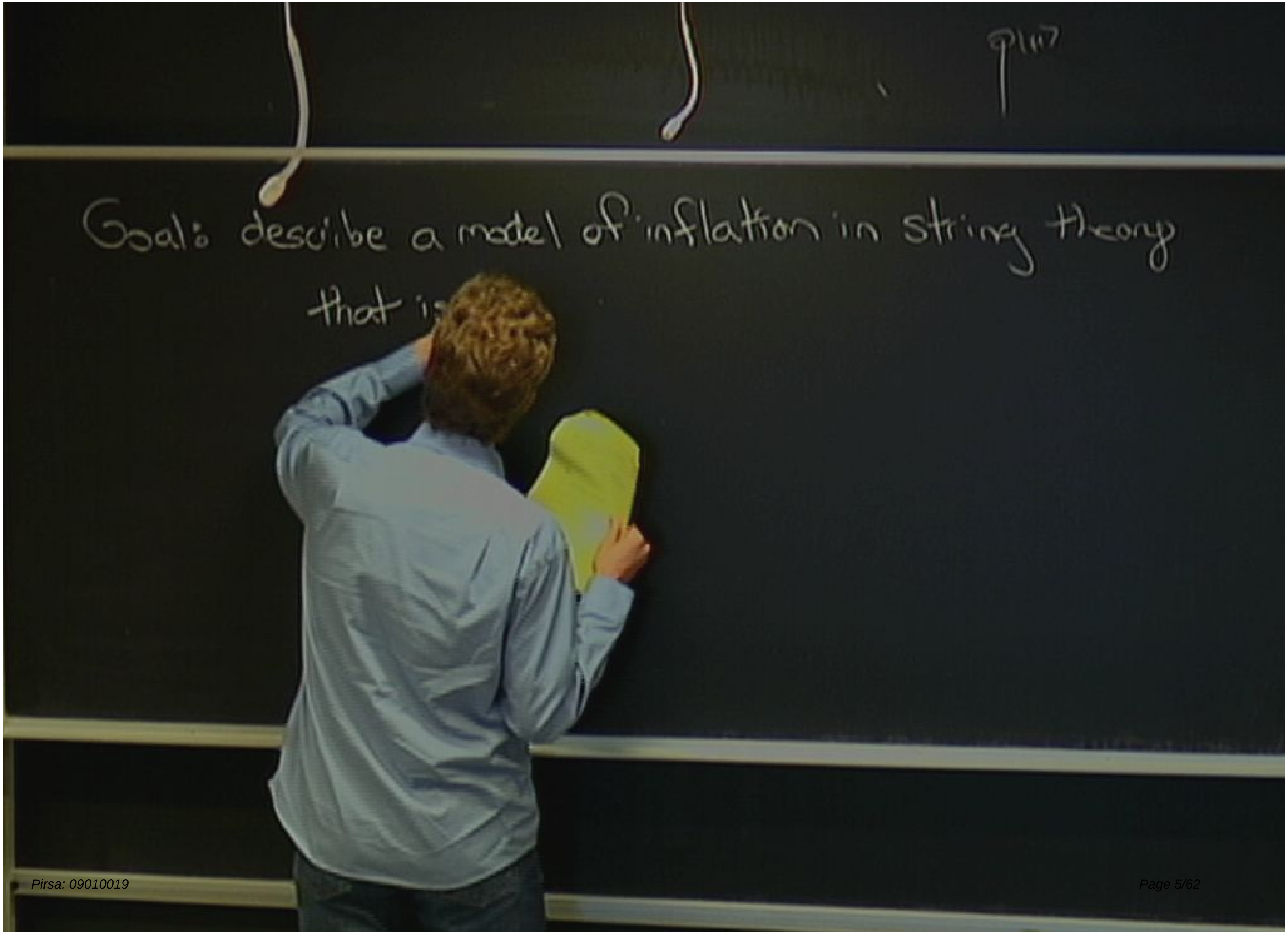
Abstract: Inflationary scenarios with detectable primordial tensor perturbations typically require symmetries that can protect the potential over a super-Planckian field excursion. An old and natural idea is for the inflaton to be an axion protected by a shift symmetry. However, this has appeared difficult to realize in string theory because axion periodicities are sub-Planckian in known examples. I will explain how in compactifications containing wrapped fivebranes, the effective axion range is increased by monodromy: a single axion period can be traversed many times. The resulting potential is approximately linear and can source technically natural large-field inflation. As a result of the all-orders axionic shift symmetry, the potential receives negligible corrections from moduli stabilization.


Liam
Cornell
based on: 0808.0706
w/ E. Silverstein, A. Westphal
Plan: 1) Motivation + Background
2) Axions in string thy.
3) Axion monodromy
4) Model + predictions
5) Conclusions


Liam McAllister
Cornell
based on: 0808.0706
w/ E. Silverstein, A. Westphal
2) Axions in string thy.
3) Axion monodromy
4) Model + predictions
5) Conclusions

Plan:

1) Motivation + Background
2) Axions in string thy.
3) Axion monodromy
4) Model + predictions
5) Conclusions


Goal: describe a model of inflation in string theory
that is

$\phi^{1/7}$

Goal: describe a model of inflation in string theory

that is
- natural
- predicts tensors

Inflation

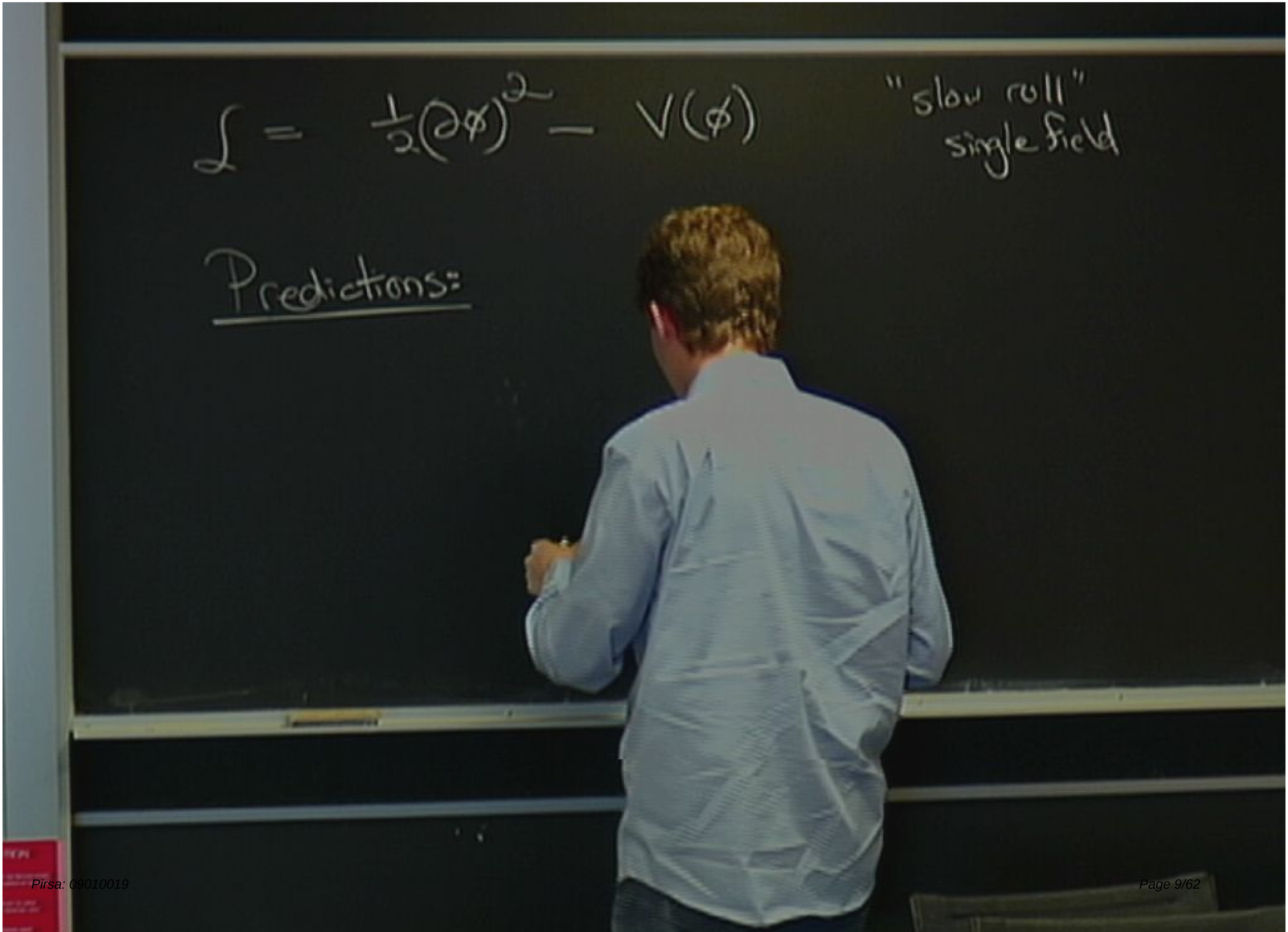
$$ds^2 = -dt^2 + e^{2Ht}\, d\vec{x}^2 \qquad H \approx \text{const.}$$

Inflation

$$ds^2 = -dt^2 + e^{2Ht}\, d\vec{x}^2 \qquad H \approx \text{const.}$$

generic predictions:

- spectrum of scalar perts.
- spectrum of tensor perts.

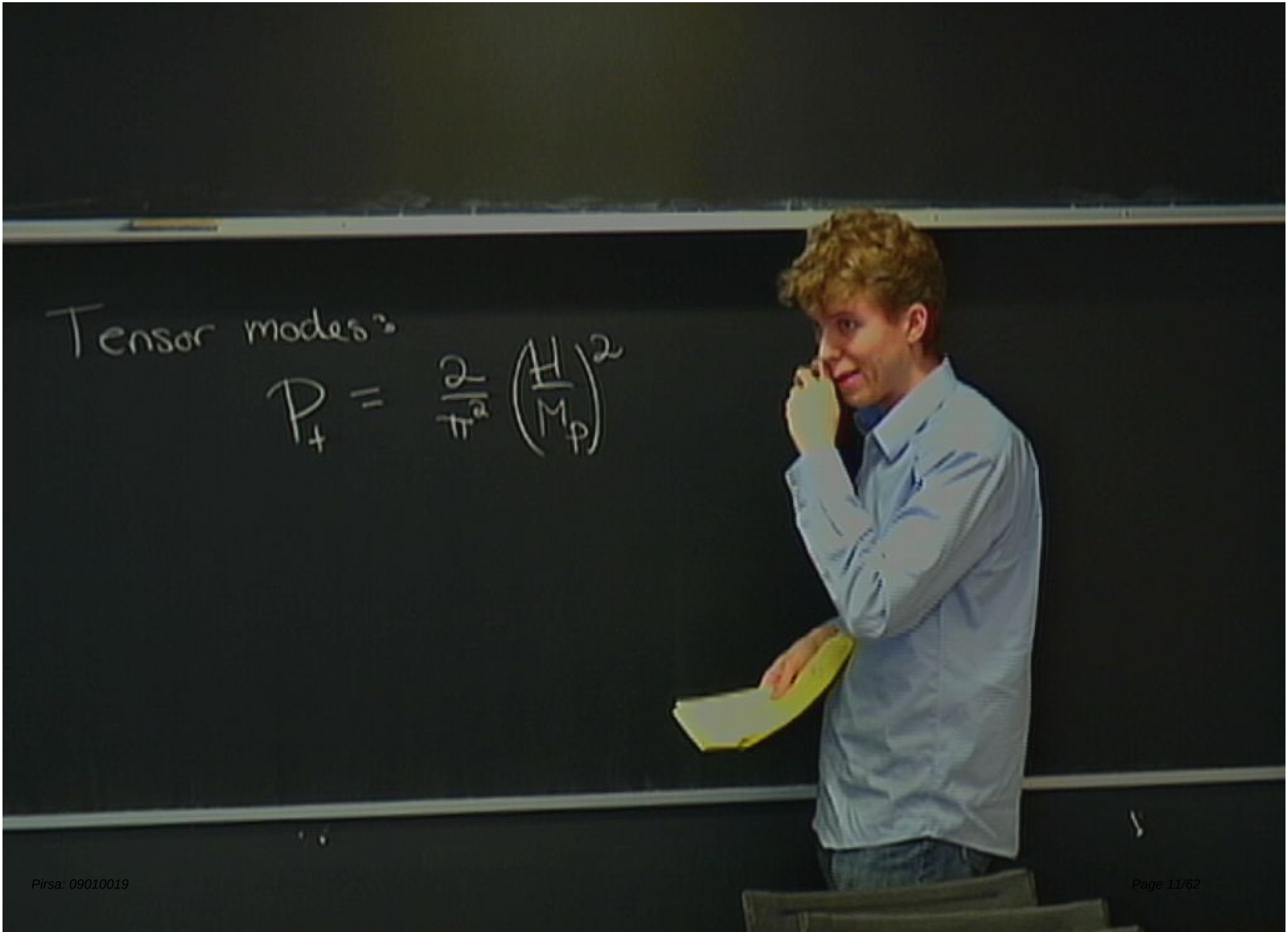

$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$
"slow roll"
single field
Predictions:

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

"slow roll"
single field

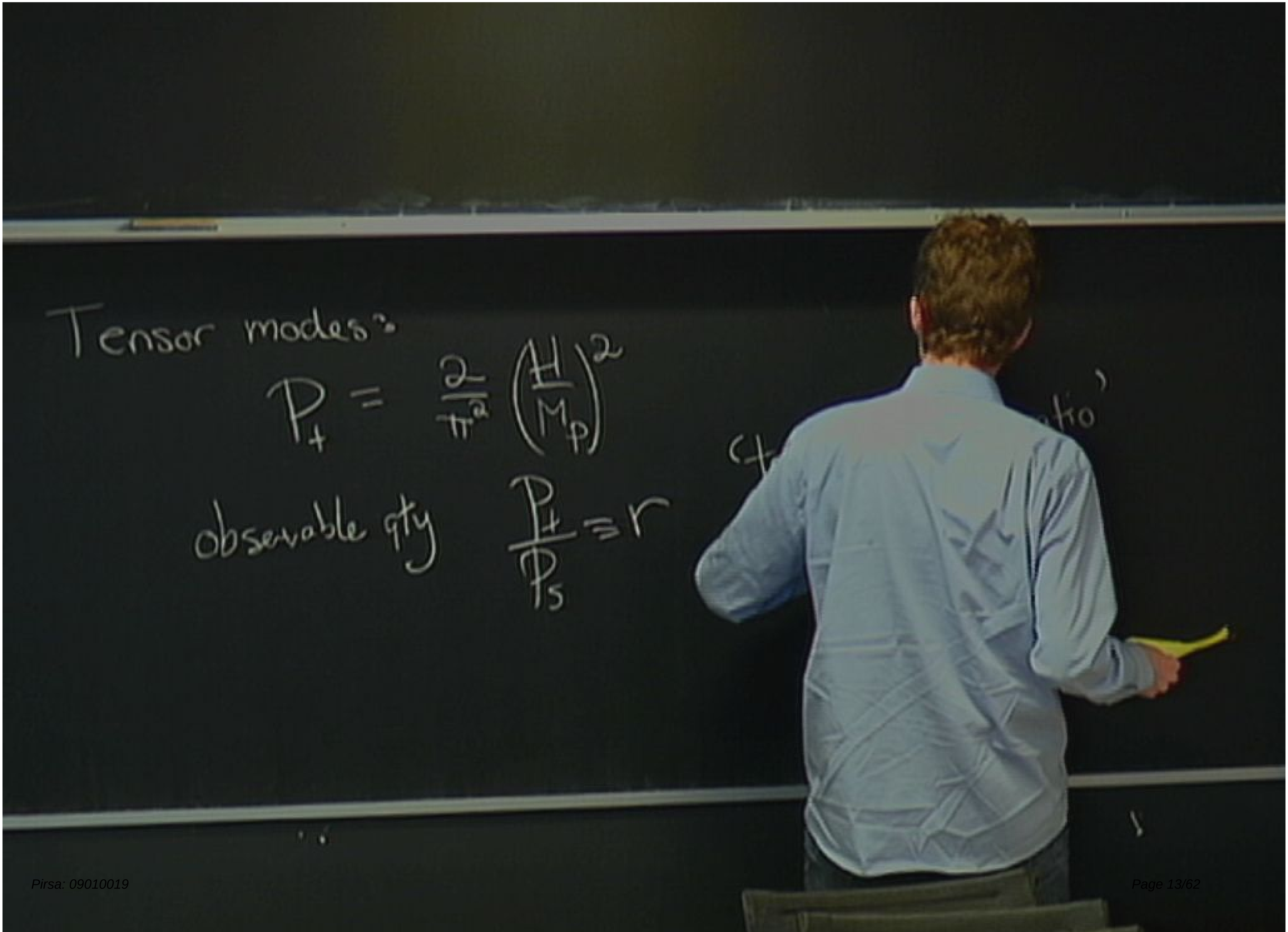
Predictions:

$$P_s(k) = A_s(k_*)\left(k/k_*\right)^{n_s-1+\dots}$$


Tensor modes:
$P_t = \frac{2}{\pi^2}\left(\frac{H}{M_p}\right)^2$

Tensor modes:

$$P_t = \frac{2}{\pi^2}\left(\frac{H}{M_p}\right)^2$$


Tensor modes:
$P_t = \frac{2}{\pi^2}\left(\frac{H}{M_p}\right)^2$
observable qty $\frac{P_t}{P_S} \equiv r$

Tensor modes:

$$P_t = \frac{2}{\pi^2}\left(\frac{H}{M_p}\right)^2$$

'tensor to scalar ratio'

observable qty $\frac{P_t}{P_s} \equiv r$

We know P_s.

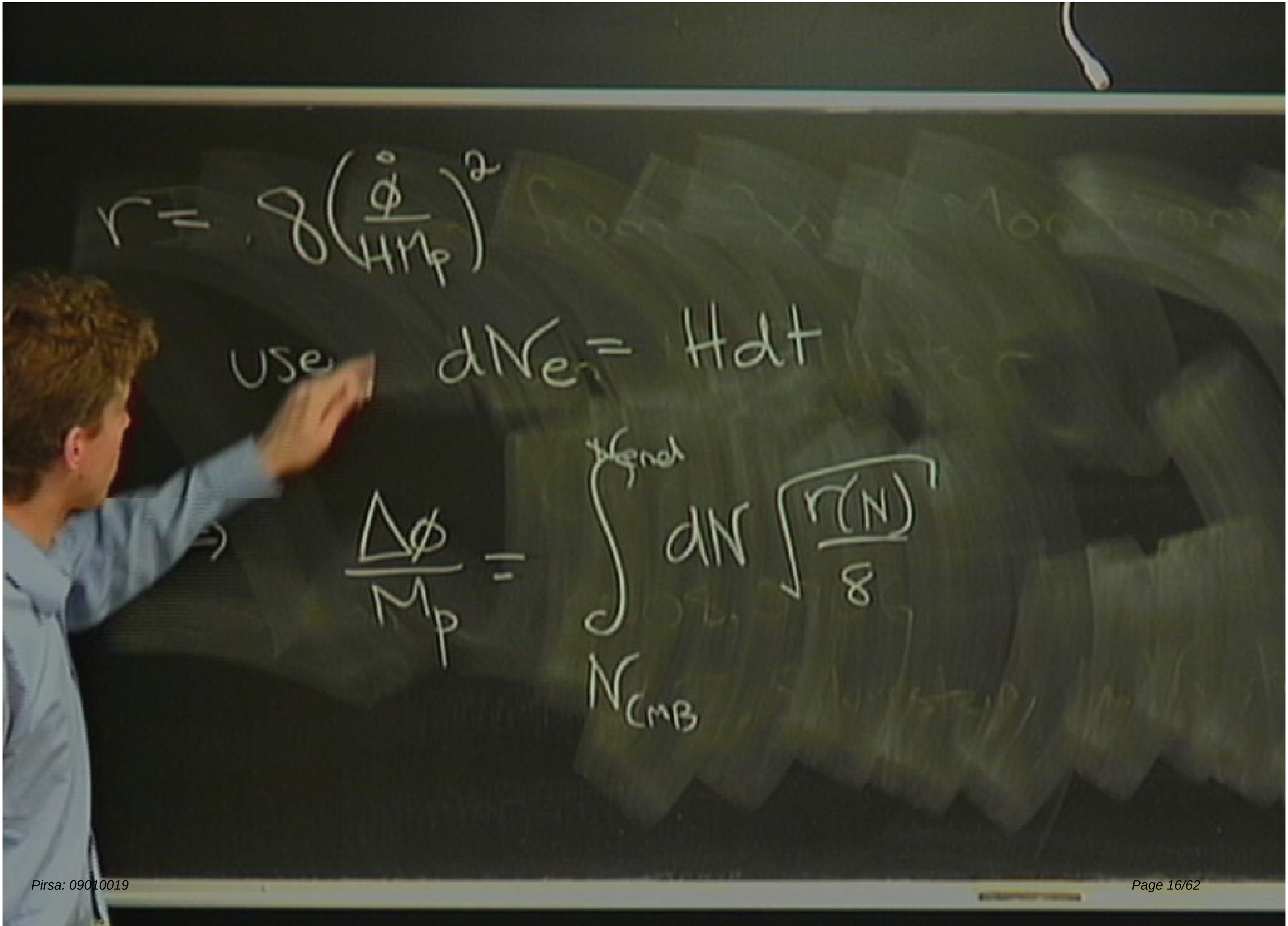
Tensor modes:

$$P_t = \frac{2}{\pi^2}\left(\frac{H}{M_p}\right)^2$$

'tensor to scalar ratio'

observable qty $\frac{P_t}{P_s} \equiv r$

We know P_s.


$r = 8\left(\frac{\dot{\phi}}{H M_p}\right)^2$
use $dN_e = H\,dt$
$\Rightarrow \frac{\Delta\phi}{M_p} = \int_{N_{CMB}}^{N_{end}} dN \sqrt{\frac{r(N)}{8}}$

$$r = 8\left(\frac{\dot{\phi}}{HM_p}\right)^2$$

use $dN_e = H\,dt$

$$\Rightarrow \quad \frac{\Delta\phi}{M_p} = \int_{N_{CMB}}^{N_{end}} dN \sqrt{\frac{r(N)}{8}}$$

$$r = 8\left(\frac{\dot\phi}{H M_p}\right)^2$$

use $dN_e = H\,dt$

$$\Rightarrow \quad \frac{\Delta\phi}{M_p} = \int_{N_{CMB}}^{N_{end}} dN \sqrt{\frac{r(N)}{8}} \approx \sqrt{\frac{r_{CMB}}{8}}\,(60 \ldots 30)$$

$$\Rightarrow \quad \frac{\Delta\phi}{M_p} = \int_{N_{CMB}} dN \sqrt{\frac{r(N)}{8}} \simeq \sqrt{\frac{r_{CMB}}{8}} \left(60 \ldots 30\right)$$

$$\Rightarrow \text{(Lyth)} \qquad \boxed{\frac{\Delta\phi}{M_p} \geq \mathcal{O}(1) \left(\frac{r_{CMB}}{0.01}\right)^{1/2}}$$

lon: 1) Motivation + Background

2) Axions in string thy.

3) Axion monodromy

4) Model + predictions

Central problem: arranging for

$$\left\{ \begin{array}{l} \dfrac{V''}{V} M_p^2 \ll 1 \\ \quad \text{\rotatebox{90}{$\leq$}} \ \ \eta \qquad\qquad \sim 10^{-2} \\ \left(\dfrac{V'}{V}\right)^2 M_p^2 \lll 1 \\ \quad \text{\rotatebox{90}{$\leq$}} \ \ \varepsilon \end{array} \right.$$

$$r = 8\left(\frac{\dot\phi}{H M_p}\right)^2$$

use $dN_e = H\,dt$

$$\Rightarrow \frac{\Delta\phi}{M_p} = \int_{N_{CMB}}^{N_{end}} dN \sqrt{\frac{r(N)}{8}} \approx \sqrt{\frac{r_{CMB}}{8}}\,(60 \ldots 30)$$

$$\Rightarrow (\text{Lyth}) \quad \boxed{\frac{\Delta\phi}{M_p} \geq \mathcal{O}(1)\left(\frac{r_{CMB}}{0.01}\right)^{1/2}}$$

$r < 0.22$

SPIDER, Clover, QUIET, ...

4)

5) Conclusions

<u>Central problem:</u> arranging for

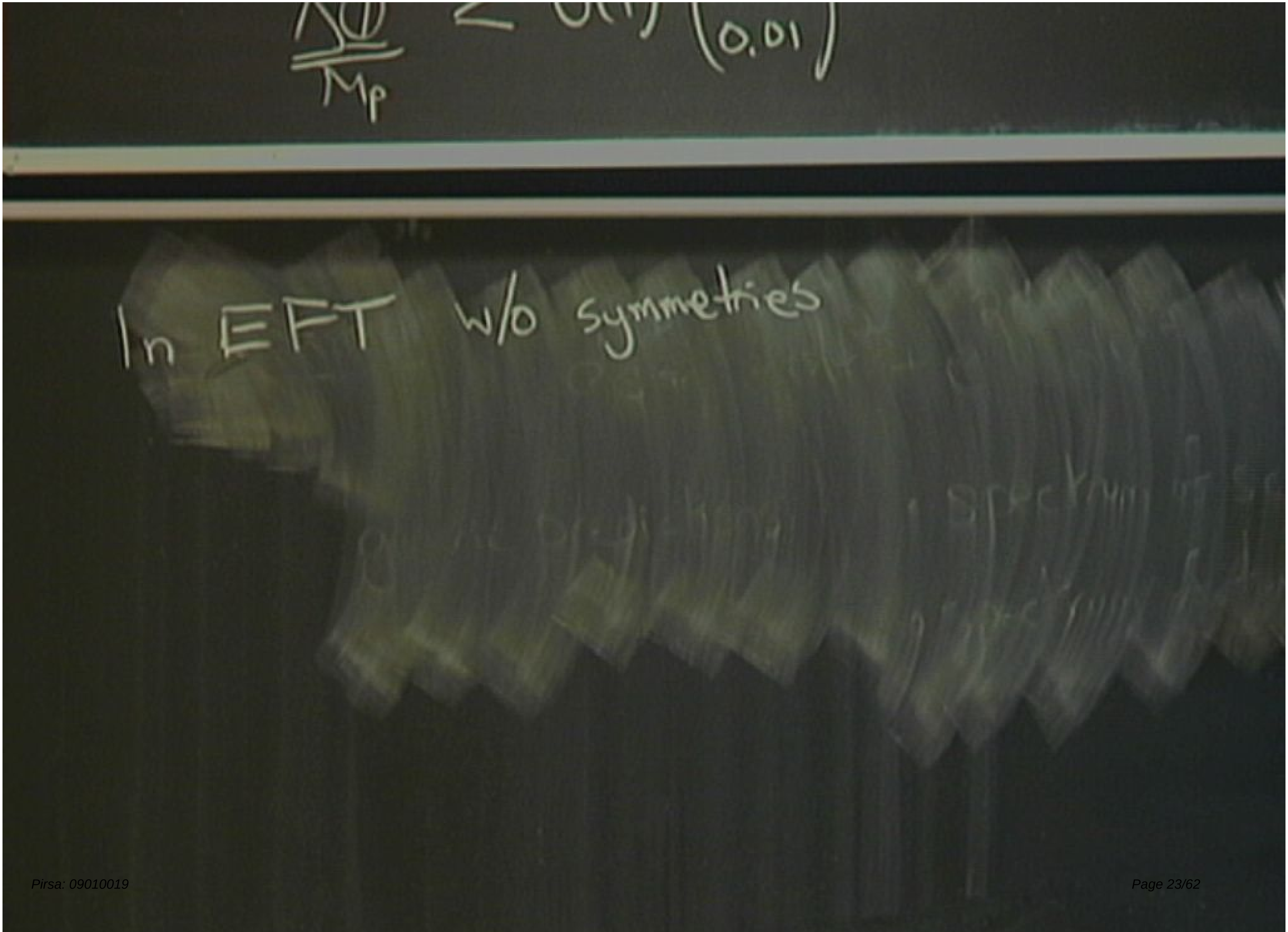
$$\frac{V''}{V} M_p^2 \ll 1 \equiv \eta \sim 10^{-2}$$

(N-flation) $$\left(\frac{V'}{V}\right)^2 M_p^2 \ll 1 \equiv \epsilon$$

$$\sum_{i=1}^{N} \frac{1}{2}(\partial\phi_i)^2 - m^2\phi_i^2$$

$$\Phi \equiv \sqrt{\sum_i \phi_i^2}$$

$$\frac{\Delta\Phi}{M_p} \geq \mathcal{O}(1)\left(\frac{r_{CMB}}{0.01}\right)^{1/2}$$


(0.01)
In EFT w/o symmetries

$$\frac{\Lambda \Phi}{M_p} \lesssim \mathcal{O}(1) \left(\frac{\quad}{0.01}\right)$$

In EFT w/o symmetries except Z_2 $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{k=1}^{\infty} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}}$$

$$\frac{\Lambda\Phi}{M_p} \gtrsim \mathcal{O}(1)\left(\frac{\ldots}{0.01}\right)$$

In EFT w/o symmetries except Z_2 $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{k=1}^{\infty} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}}$$

$$+ \sum_{k=1}^{\infty} \nu_k \frac{(\partial\phi)^{2+2k}}{\Lambda^{2k}} + \cdots$$

In EFT w/o symmetries except $\mathbb{Z}_2$ $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \cancel{\sum_{k=1}^{\infty} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}}}$$

$$+ \sum_{k=1}^{\infty} \mu_k \frac{(\partial\phi)^{2+2k}}{\Lambda^{2k}} + \cdots$$

In EFT w/o symmetries except Z_2 $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \cancel{\frac{1}{2}m^2\phi^2} - \cancel{\frac{1}{4}\lambda\phi^4} - \cancel{\sum_{k=1}^{\infty} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}}}$$

$$+ \sum_{k=1}^{\infty} \nu_k \frac{(\partial\phi)^{2+2k}}{\Lambda^{2k}} + \dots \qquad \phi \to \phi + \text{cnst.}$$

M_p

In EFT w/o symmetries except $\mathbb{Z}_2$ $\phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \cancel{\frac{1}{2}m^2\phi^2} - \cancel{\frac{1}{4}\lambda\phi^4} - \cancel{\sum_{k=1}^{\infty} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}}} \rightarrow \Lambda \sim M_p$$

$$+ \sum_{k=1}^{\infty} \nu_k \frac{(\partial\phi)^{2+2k}}{\Lambda^{2k}} + \dots \qquad \phi \to \phi + \text{const.}$$

Want: continuous symmetry $\phi \to \phi + \text{const.}$

weakly broken by (e.g.) one term, "V"

Want: continuous symmetry $\phi \to \phi + \text{const.}$

weakly broken by (e.g.) one term, V

$\Rightarrow$ should be approx. respected @ "Planck's scale"

Want: continuous symmetry $\phi \to \phi + \text{const.}$

weakly broken by (e.g.) one term, V

$\Rightarrow$ should be approx. respected @ "Planck scale"

- Kawasaki, Yamaguchi, Yanagida
- Hsu, Kallosh, Prokushkin

$$\frac{\Delta\Phi}{M_p} \gtrsim \mathcal{O}(1)\left(\frac{r_{CMB}}{0.01}\right)^{1/2}$$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \cancel{\frac{1}{4}\lambda\phi^4} - \sum_{k=1} \lambda_k \frac{\phi^{4+2k}}{\Lambda^{2k}} \quad \Lambda \sim M_p$$

$$+ \sum_{k=1}^{\infty} \nu_k \frac{(\partial\phi)^{2+2k}}{\Lambda^{2k}} + \cdots \qquad \phi \to \phi + \text{const.}$$

$$V = \mu^{4-\alpha}\phi^{\alpha} \qquad \Delta V \sim \frac{V^2}{M_p^4}$$

Want: continuous symmetry $\phi \to \phi + \text{const.}$

- weakly broken by (e.g.) one term, "V"

$\Rightarrow$ should be approx. respected @ "Planck scale"

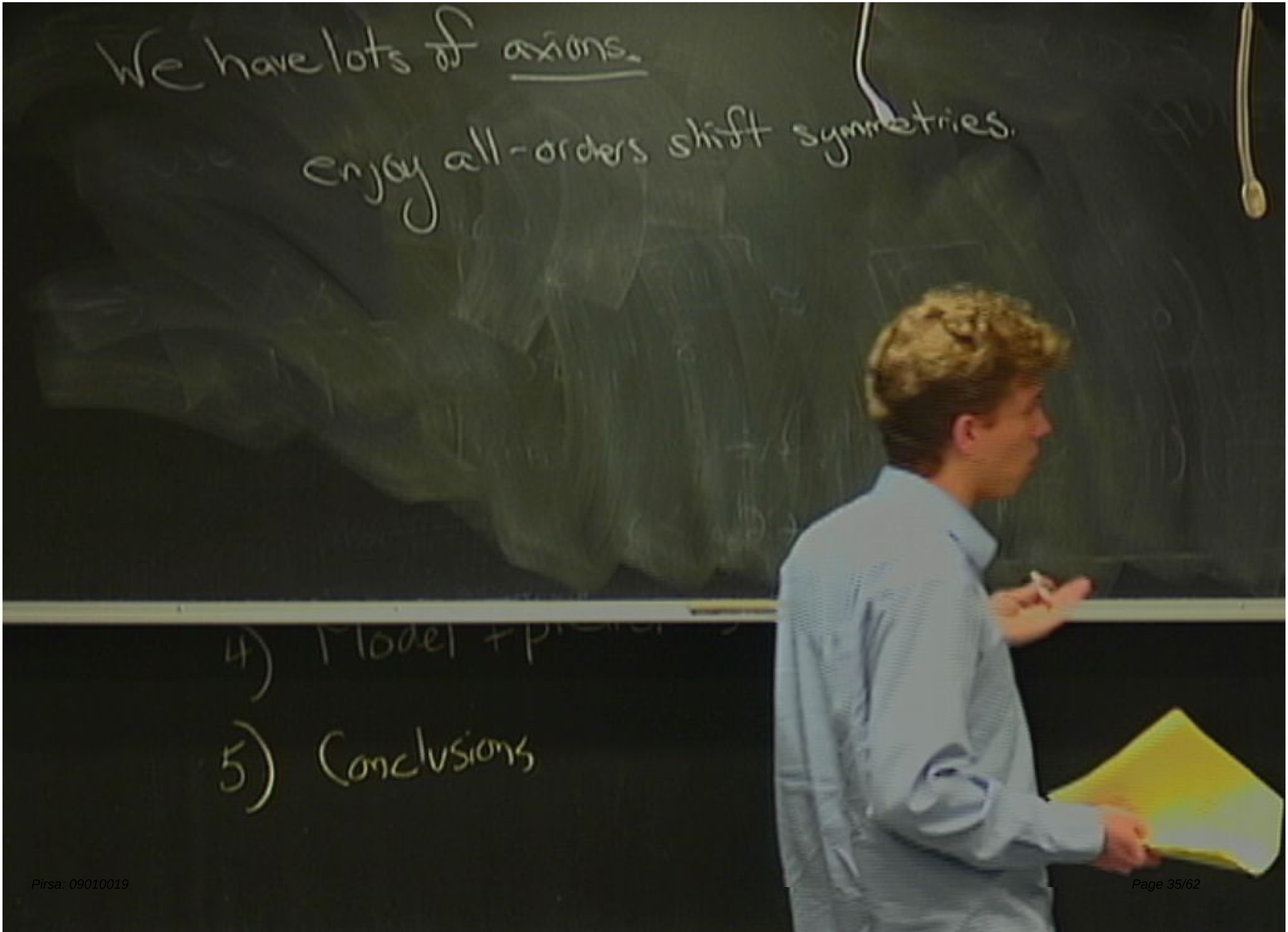
- Kawasaki, Yamaguchi, Yanagida
- Hsu, Kallosh, Prokushkin

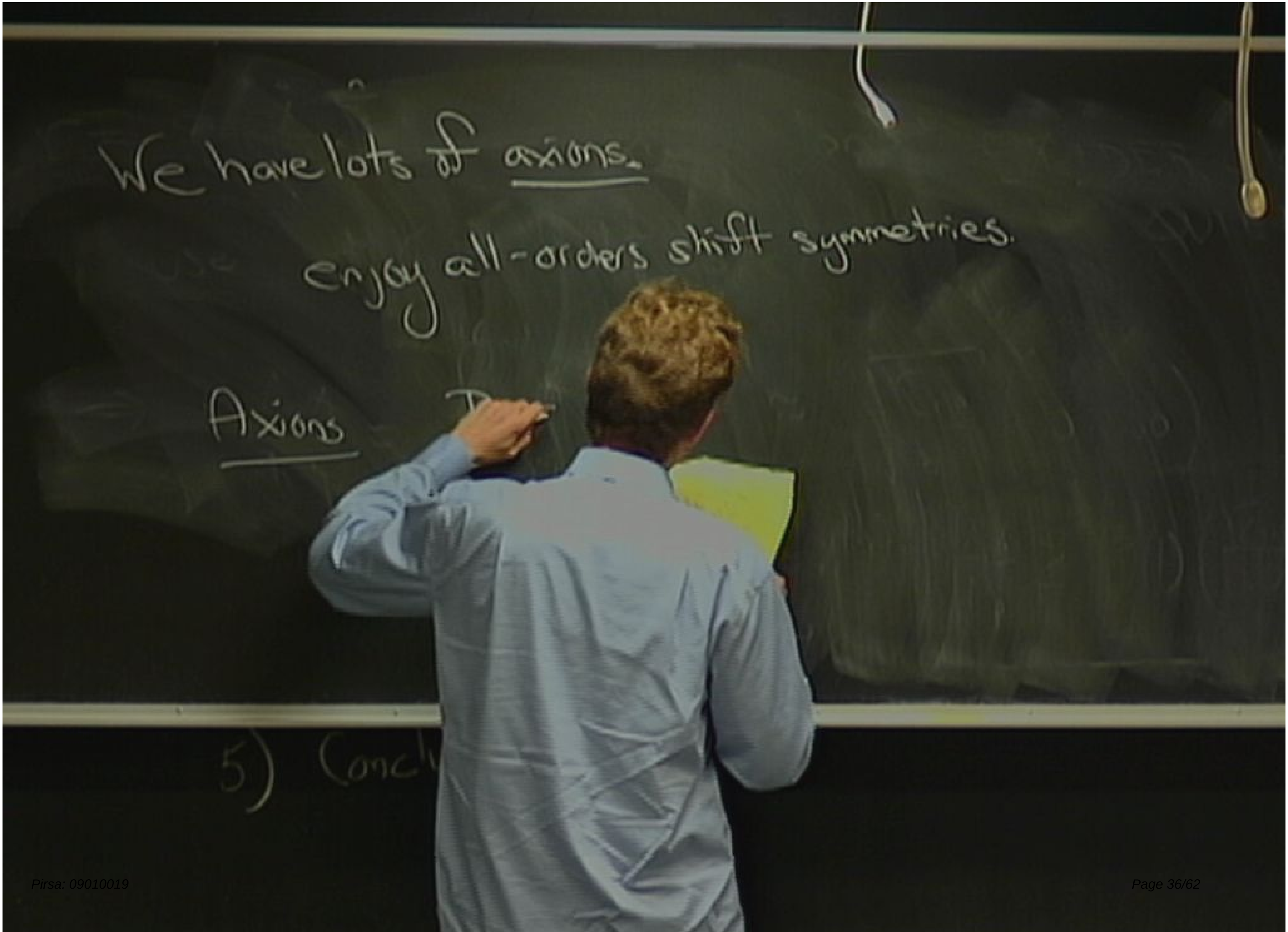
- inflaton is a pNGB.

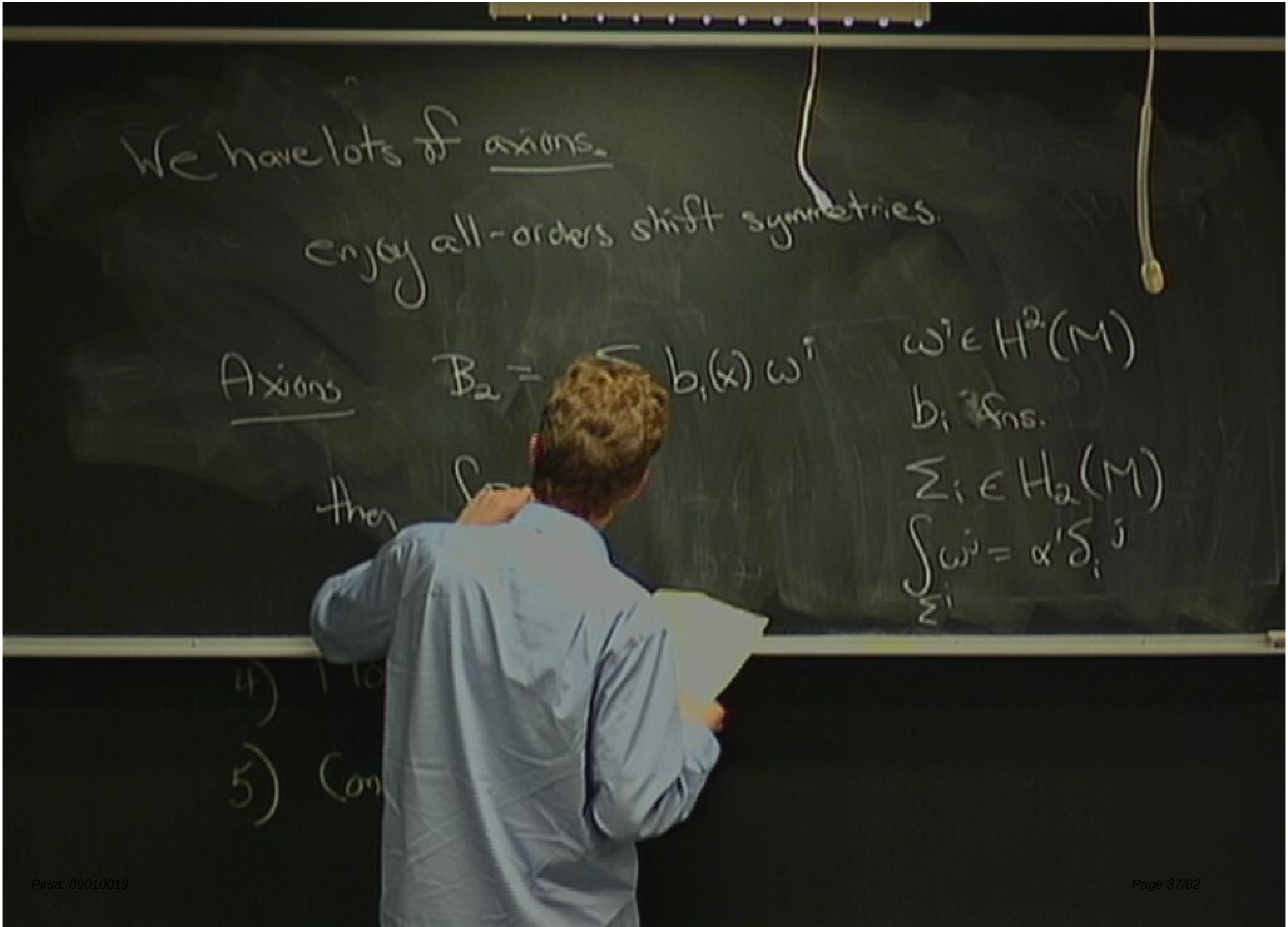
We have lots of axions.

4) Model + p

5) Conclusions


We have lots of axions.
enjoy all-orders shift symmetries.
4) Model
5) Conclusions


We have lots of axions.
enjoy all-orders shift symmetries.
Axions
5) Concl


We have lots of axions.
enjoy all-orders shift symmetries.
Axions
$B_2 = \Sigma\, b_i(x)\,\omega^i$
$\omega^i \in H^2(M)$
b_i fns.
$\Sigma_i \in H_2(M)$
$\int_{\Sigma_i} \omega^j = \alpha' \delta_i^{\ j}$
then
4)
5) Con

We have lots of axions.

enjoy all-orders shift symmetries.

Axions $\quad B_2 = \sum_i b_i(x)\,\omega^i \qquad \omega^i \in H^2(M)$

b_i fns.

then $\int_{\Sigma_i} B = \alpha' b_i \qquad \Sigma_i \in H_2(M)$

$\int_{\Sigma_i} \omega^j = \alpha' \delta_i{}^j$

4) Model + p

5) Conclusions

We have lots of axions.

enjoy all-orders shift symmetries.

Axions $\quad B_2 = \sum_i b_i(x)\,\omega^i \qquad \omega^i \in H^2(M)$

b_i fns.

then $\int_{\Sigma_i} B = \alpha' b_i \qquad \Sigma_i \in H_2(M)$

$b_i \to b_i + (2\pi)^2 \qquad \int_{\Sigma_i} \omega^j = \alpha' \delta_i{}^j$

4) Model + predictions

5) Conclusions

Natural Inflation

$$V = \Lambda^4 \cos\left(\frac{a}{2\pi}\right)$$

$$a \to a + (2\pi)^{2}$$

$$S = \frac{1}{2} f^2 (\partial a)^2 - V$$

decay constant

Natural Inflation

$$V = \Lambda^4 \cos\left(\frac{a}{2\pi}\right)$$

$$a \to a + (2\pi)^2$$

$$S = \frac{1}{2} f^2 (\partial a)^2 - V$$

decay constant

Natural Inflation

$$V = \Lambda^4 \cos\left(\frac{a}{2\pi}\right)$$

$$a \to a + (2\pi)^2$$

$$\eta = -\left(\frac{M_p}{f}\right)^2$$

$$S = \frac{1}{2} f^2 (\partial a)^2 - V$$

decay constant

$$+ \sum_{k=1} D_k \frac{\quad}{\Lambda^{2k}} + \ldots \qquad \phi \to \phi + \text{cons} \qquad 4-\alpha\ \phi^\alpha \qquad \Delta V \sim$$

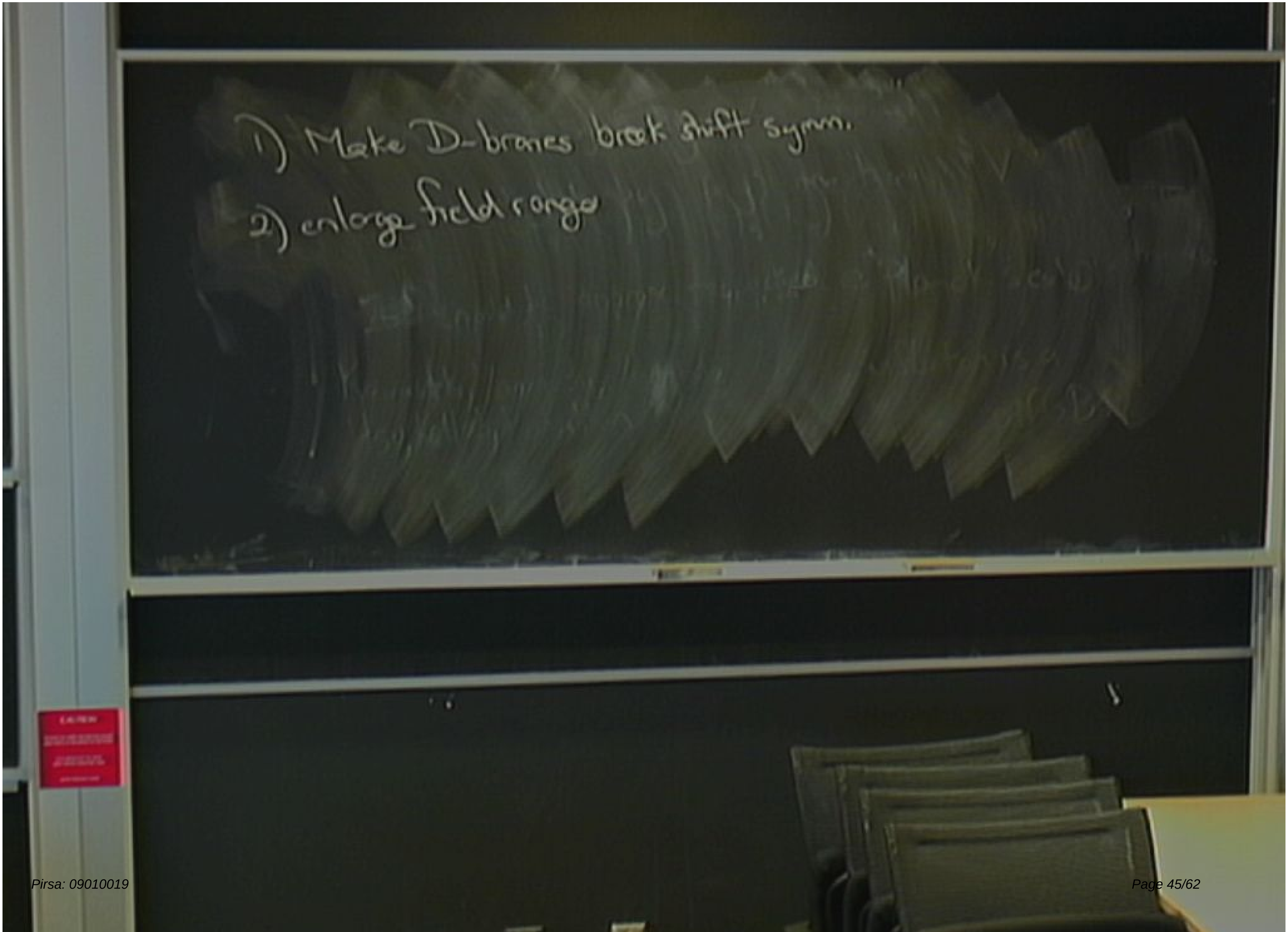
In string theory, f is computable $\frac{1}{2(2\pi)^7 g_s^2 \alpha'^4}\int |H_3|^2$

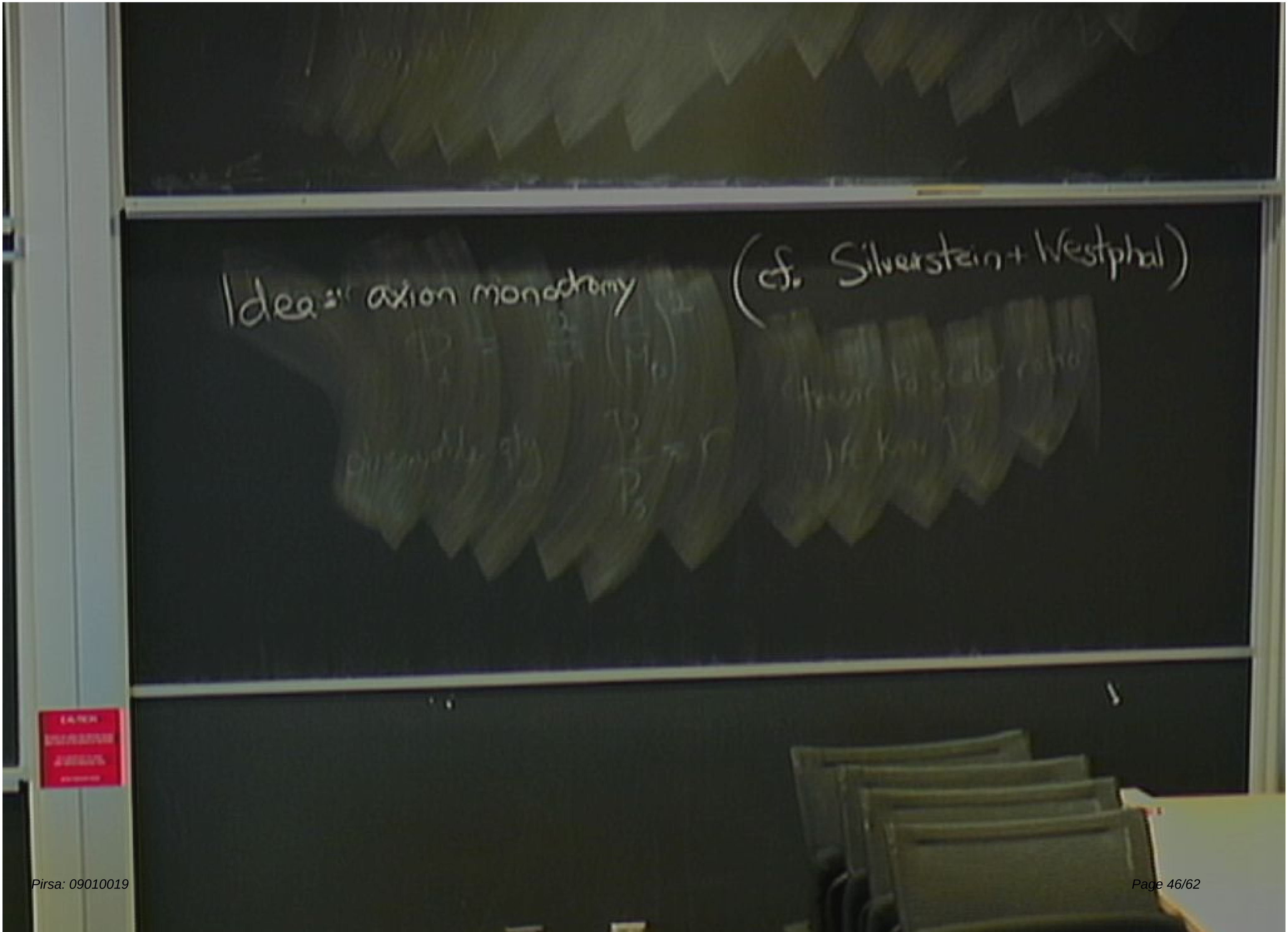
In string theory, f is computable $\frac{1}{2(2\pi)^7 g_s^2 \alpha'^4}\int |H_3|^2$

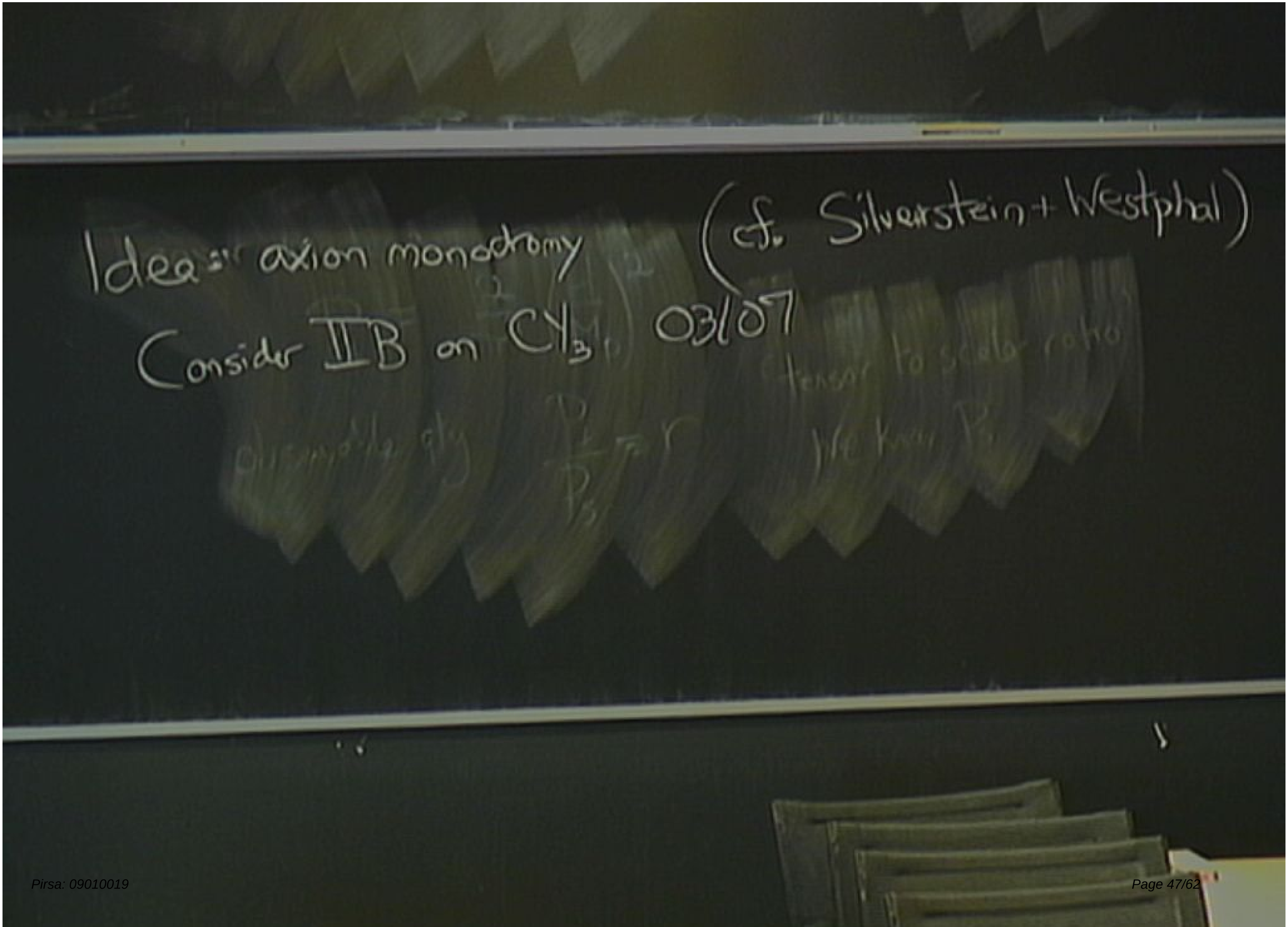
Result: Banks Dine Fox Gorbatov:

$f \ll M_p$ in known, computable limits

$$\frac{f^2}{M_p^2} \sim \frac{1}{L^{\#_1}} g_s^{\#_2} \qquad \#_2 \geq 0, \quad \#_1 > 0$$


1) Make D-branes break shift symm.
2) enlarge field range

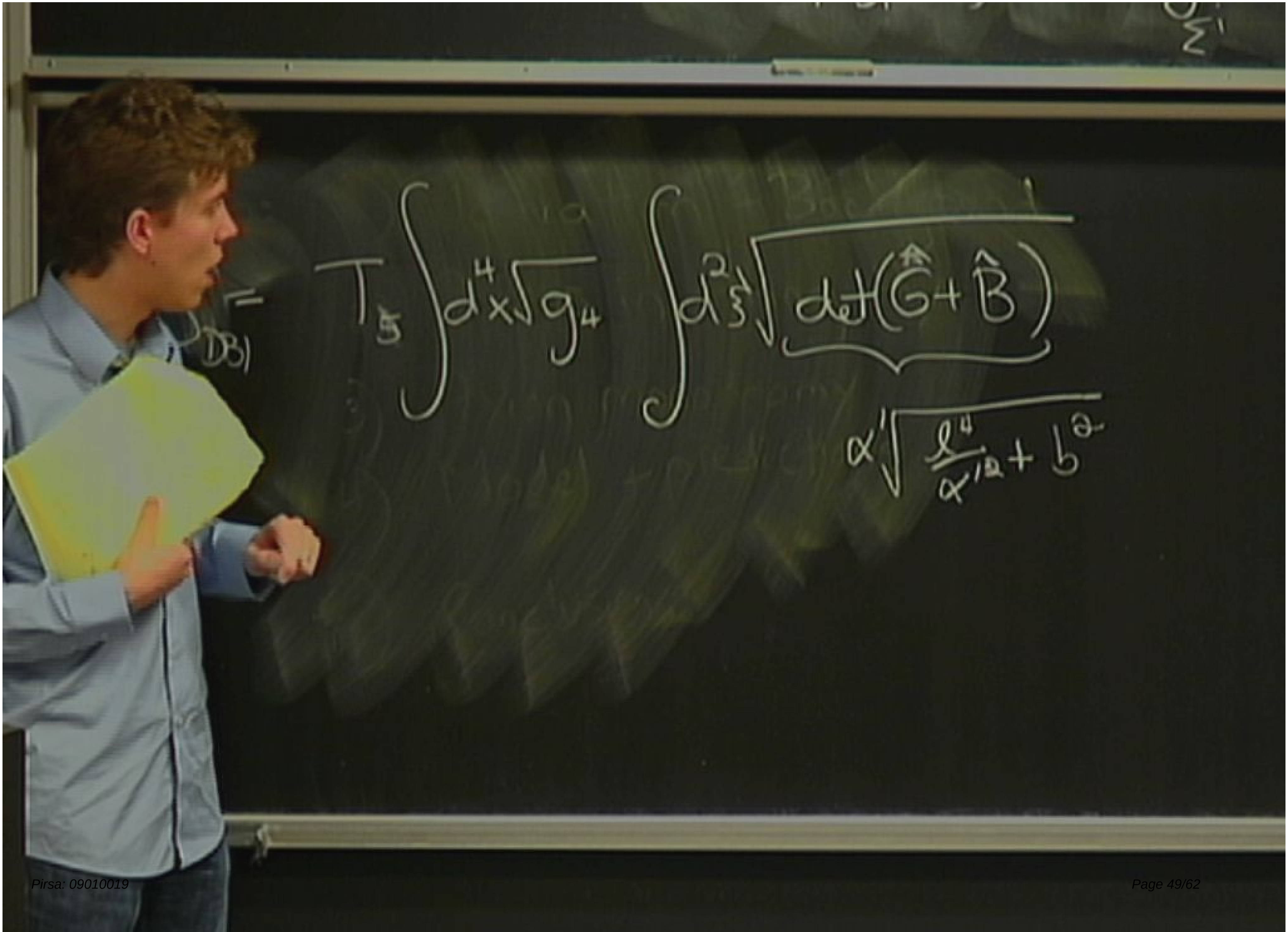

Idea: axion monodromy (cf. Silverstein + Westphal)


Idea: axion monodromy
(cf. Silverstein + Westphal)
Consider IIB on CY3, O3/O7

Idea: axion monodromy (cf. Silverstein + Westphal)

Consider IIB on $CY_3^{(M)}$ 03/07

add a D5-brane wrapping some curve $\Sigma_i \in H_2(M)$


$S_{DBI} = T_5 \int d^4x\sqrt{g_4} \int d^2\xi \underbrace{\sqrt{\det(\hat{G}+\hat{B})}}_{\alpha'\sqrt{\frac{\ell^4}{\alpha'^2}+b^2}}$

$$S_{DB1} = T_5 \int d^4x \sqrt{g_4} \int d^2\xi \sqrt{\underbrace{\det(\hat{G} + \hat{B})}_{\alpha' \sqrt{\frac{\ell^4}{\alpha'^2} + b^2}}}$$

then $\int_{\Sigma_i} B = \alpha' b_i$

$b_i \to b_i + (2\pi)^2$

$\int_{\Sigma^i} \omega^i = \alpha' \delta_i{}^j$

$$S_{DBI} = T_5 \int d^4x \sqrt{g_4} \int d^2\xi \sqrt{\underbrace{\det(\hat{G} + \hat{B})}_{\alpha' \sqrt{\frac{\ell^4}{\alpha'^2} + b^2}}}$$

monodromy

then $\int_{\Sigma_i} B = \alpha' b_i$ $\quad \Sigma_i \in H_2(\ldots)$

$b_i \to b_i + (2\pi)^2$

$\int_{\Sigma_i} \omega^j = \alpha' \delta_i{}^j$

$$S_{DBI} = T_5 \int d^4x \sqrt{g_4} \int d^2\xi \underbrace{\sqrt{\det(\hat{G} + \hat{B})}}_{\alpha' \sqrt{\frac{\ell^4}{\alpha'^2} + b^2}}$$

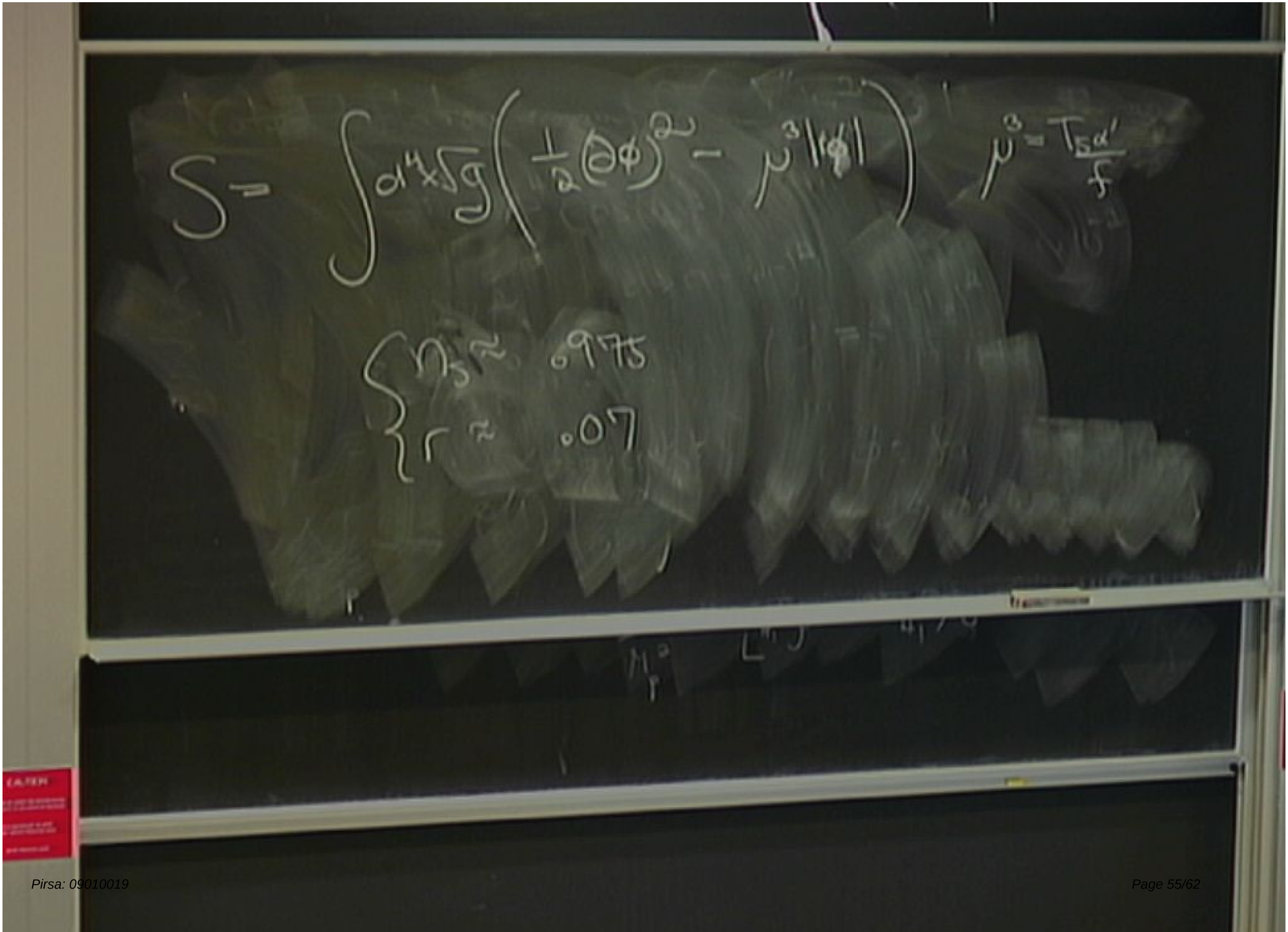
monodromy

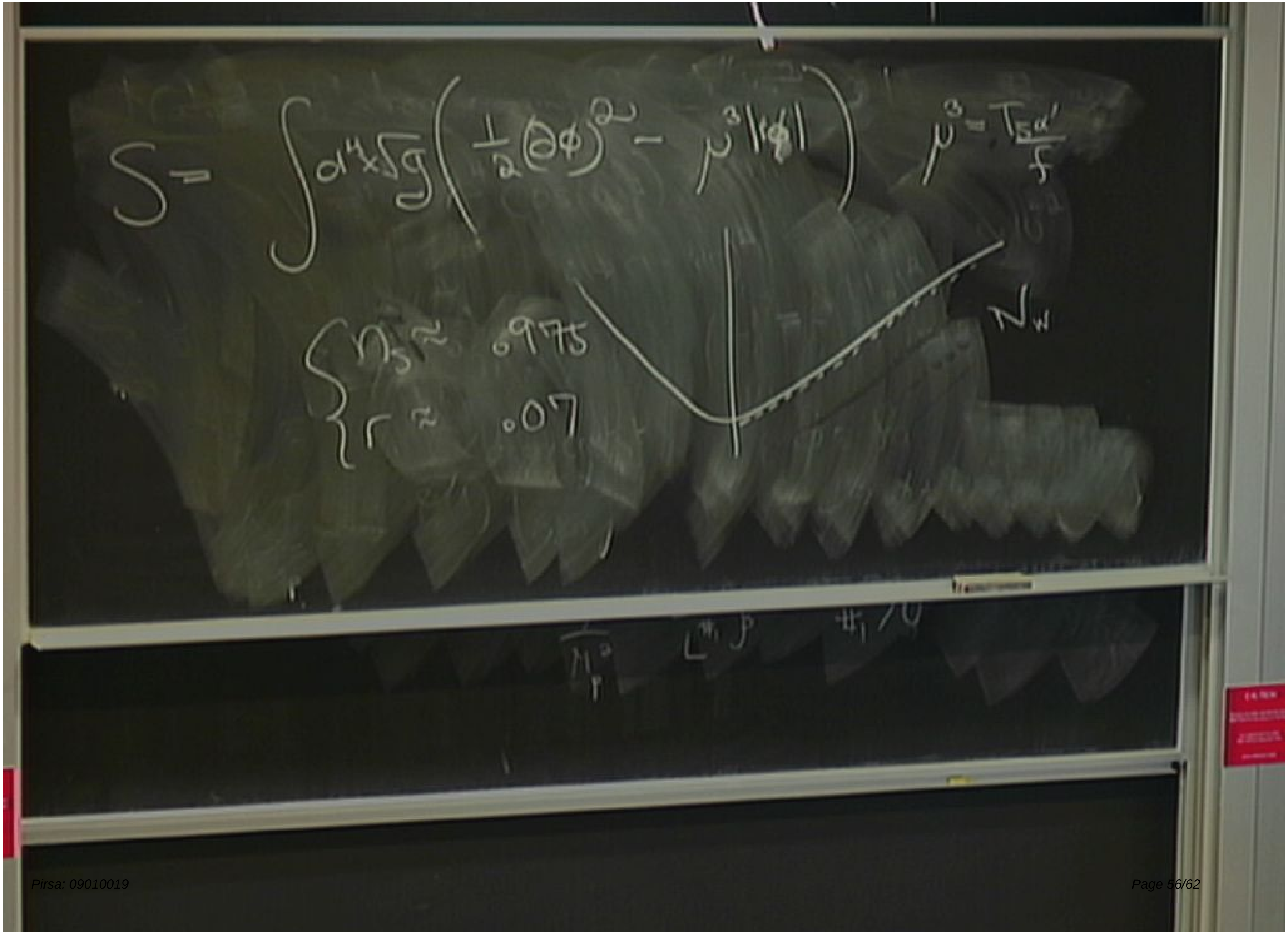
$$\int_{\Sigma_i} \qquad b_i \to b_i + (2\pi)^2 \qquad \int_{\Sigma_i} \omega^j = \alpha' \delta_i^{\ j}$$

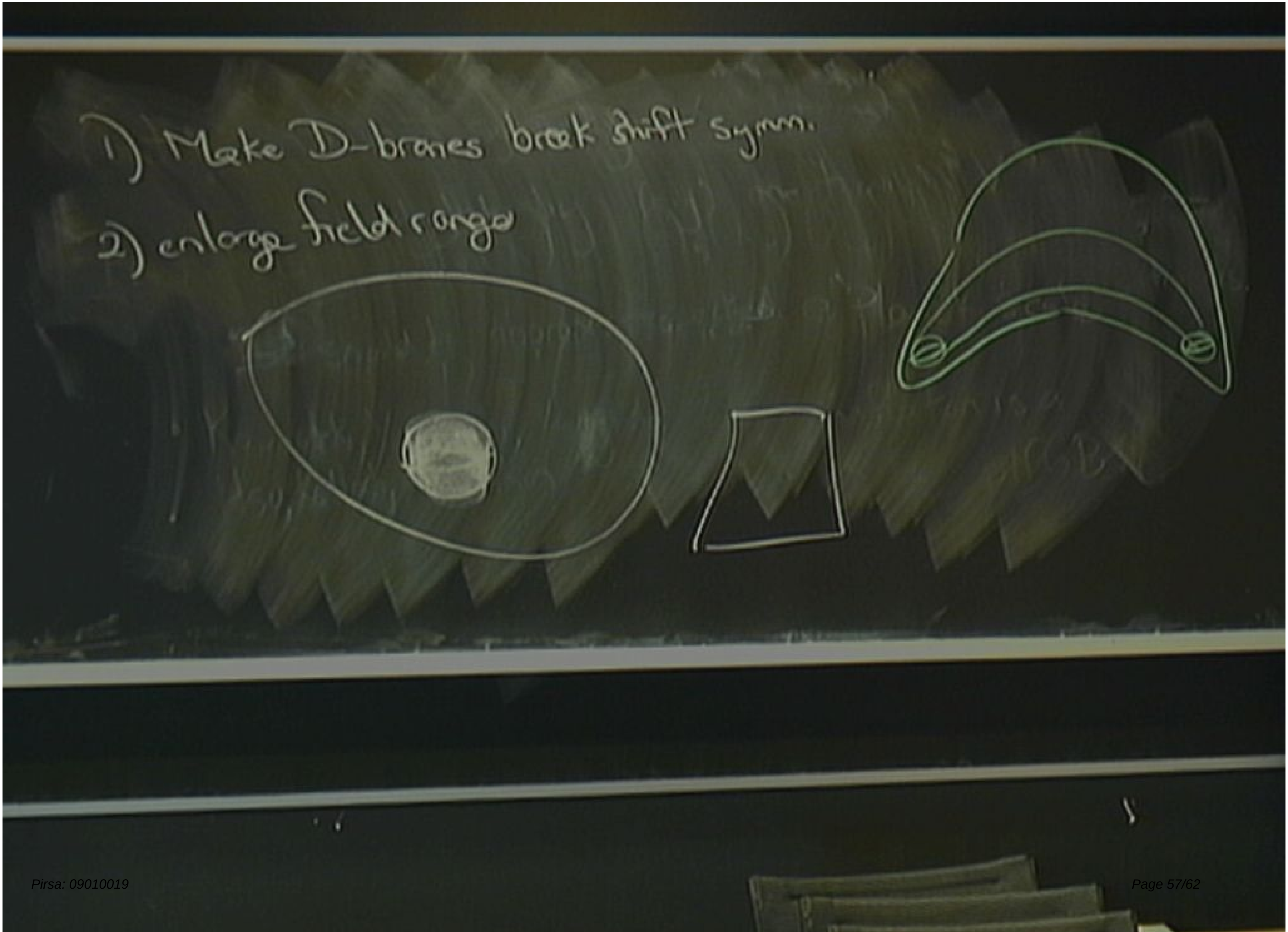
$$S_{D3} = T_5 \int d^4x \sqrt{g_4} \int d^2\xi \sqrt{\underbrace{\det(\hat{G} + \hat{B})}_{\alpha' \sqrt{\frac{\ell^4}{\alpha'^2} + b_i^2}}}$$

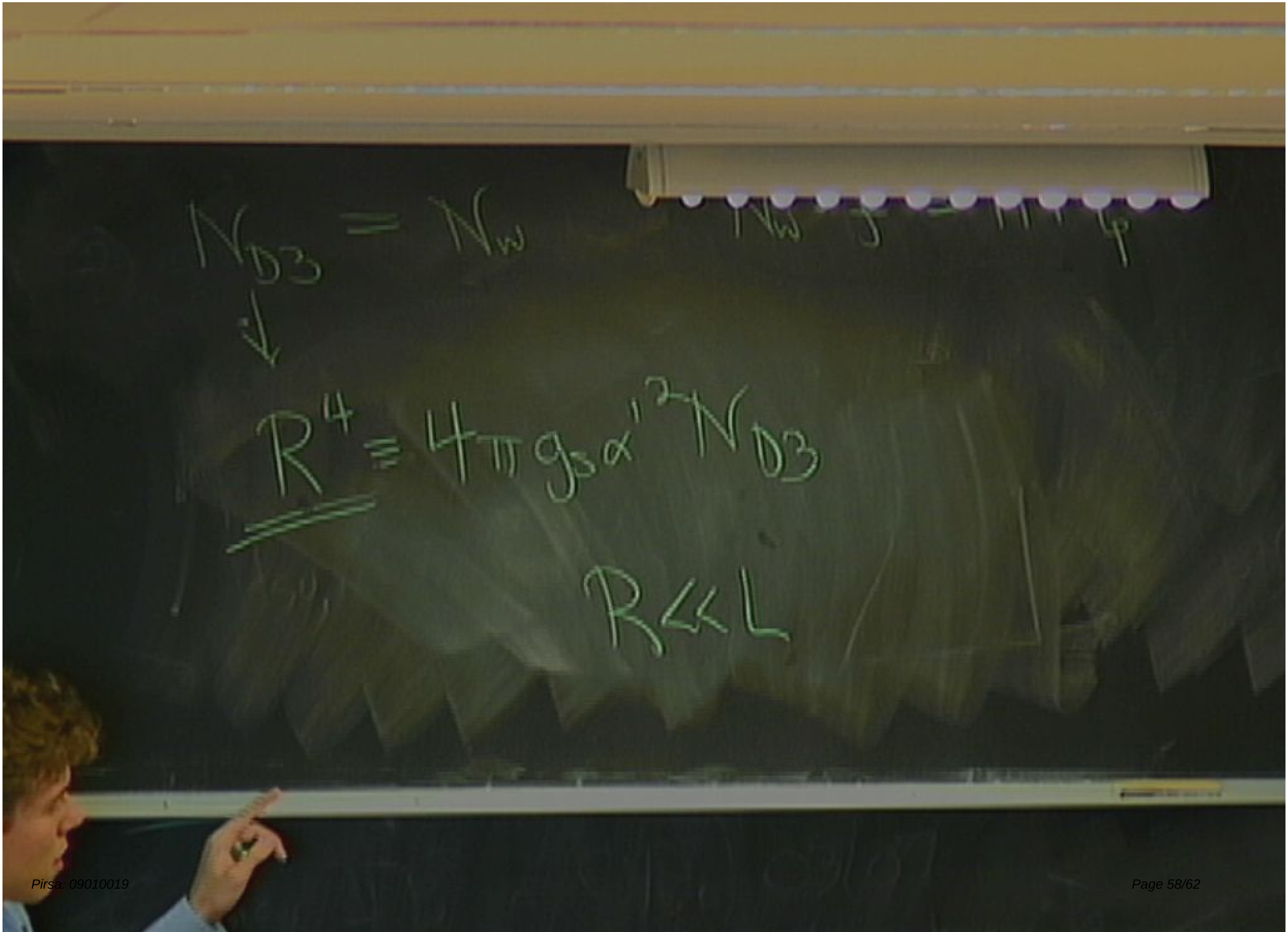
monodromy

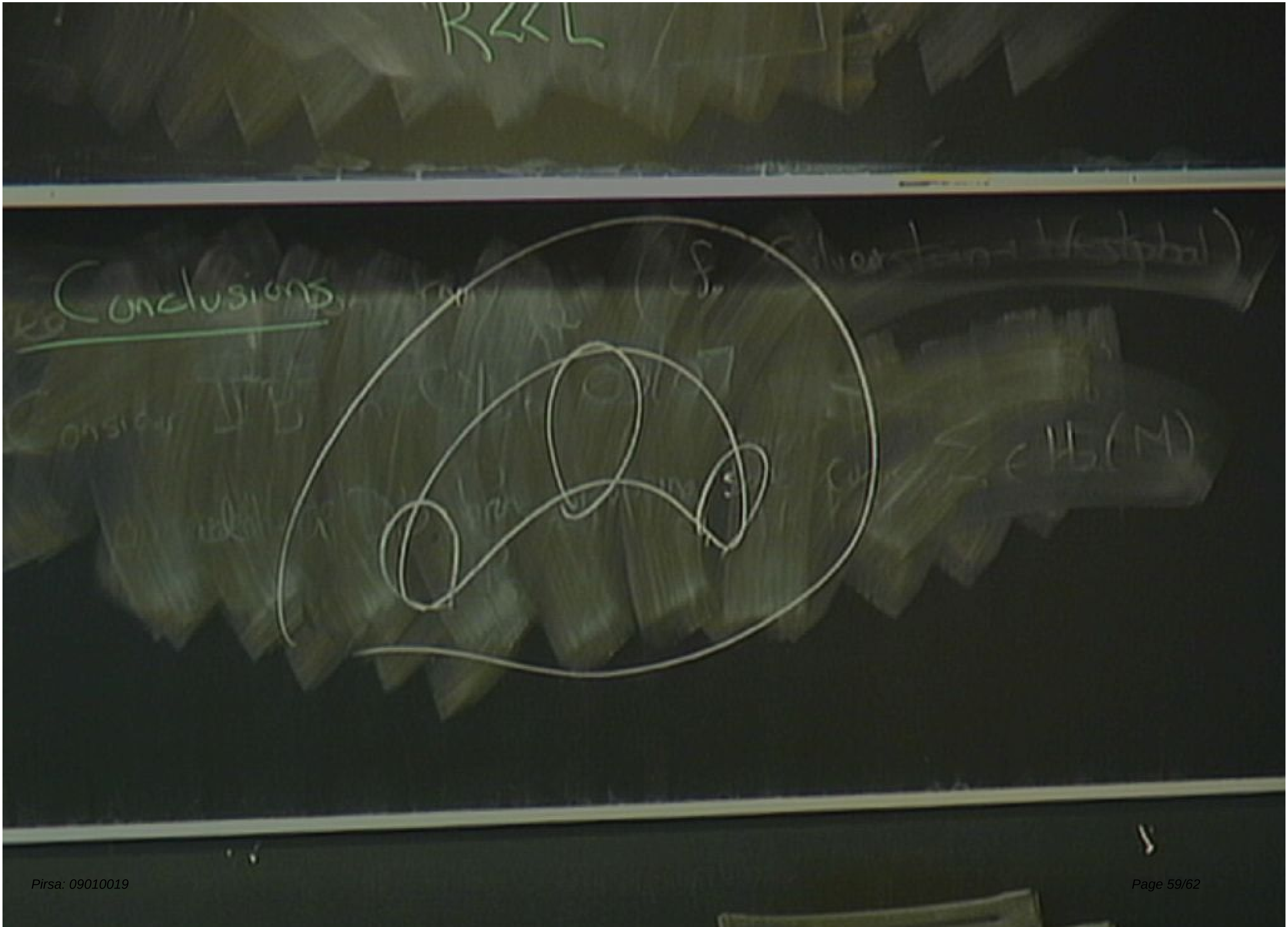
$$S = \int d^4x \sqrt{g} \left(\frac{1}{2}(\partial\phi)^2 - \mu^3 |\phi| \right) \qquad \mu^3 = \frac{T_5 \alpha'}{f}$$


$S = \int d^4x \sqrt{g} \left(\frac{1}{2}(\partial\phi)^2 - \mu^3|\phi| \right)$
$\mu^3 = \frac{T_5 \alpha'}{f}$
$n_s \approx .975$
$r \approx .07$


$S = \int d^4x \sqrt{g} \left(\frac{1}{2}(\partial\phi)^2 - \mu^3 |\phi| \right)$
$\mu^3 = \frac{T_5 \alpha'}{f}$
N_w
$n_s \approx .975$
$r \approx .07$


1) Make D-branes break shift symm.
2) enlarge field range

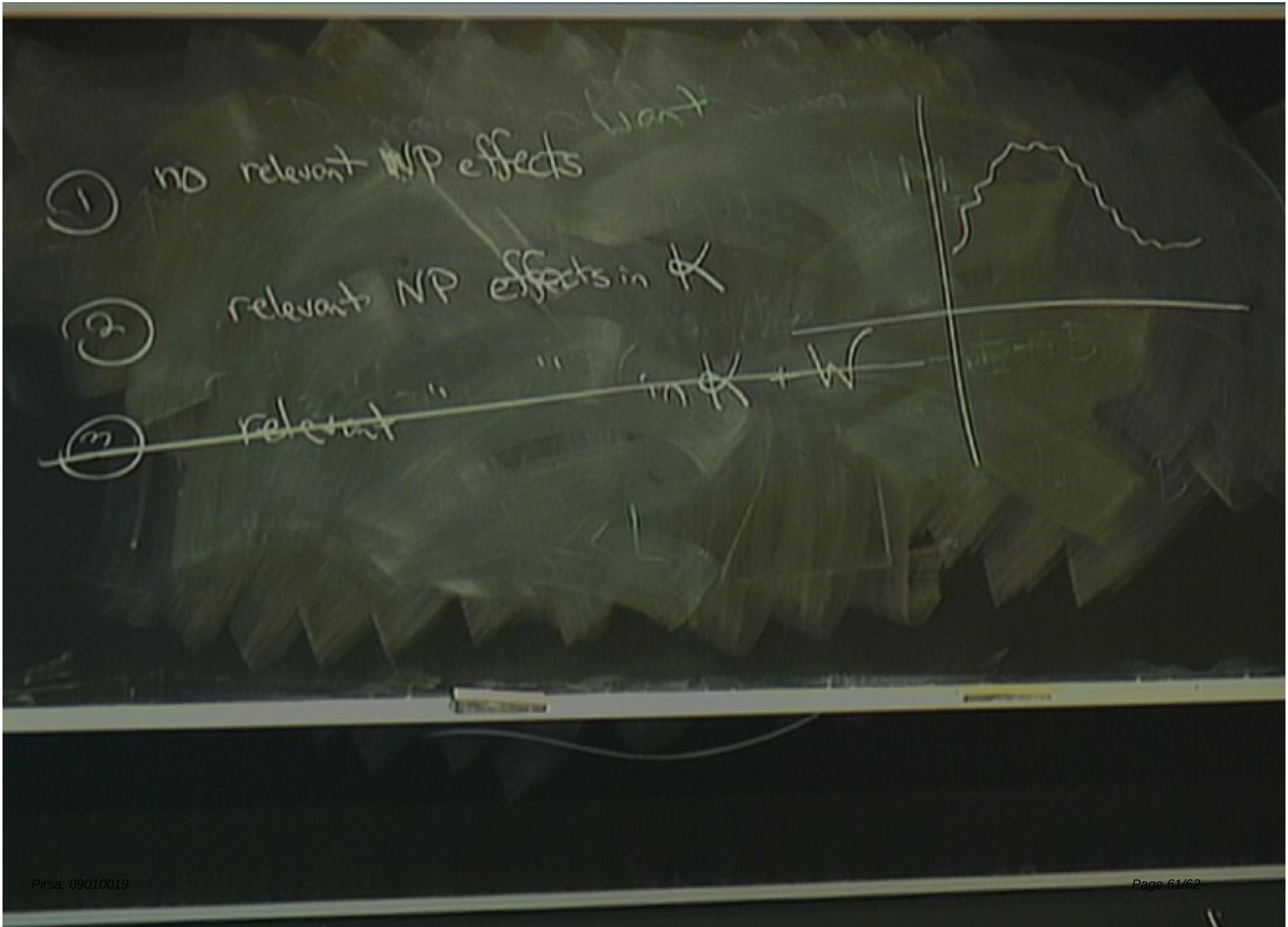

$N_{D3} = N_w$
$R^4 = 4\pi g_s \alpha'^2 N_{D3}$
$R \ll L$


Conclusions

1 no relevant NP effects

2 relevant NP effects in ϵ_K

3 ~~relevant " " in ϵ_K + W~~


① no relevant NP effects
② relevant NP effects in K
" in K + W
③ ~~relevant "~~

want

1. no relevant NP effects
2. relevant NP effects in ϕK
3. ~~relevant " " in $\phi K + W$~~

$f_{ISO} \sim {\sin \atop \cos}(\ln k + \text{phase})$