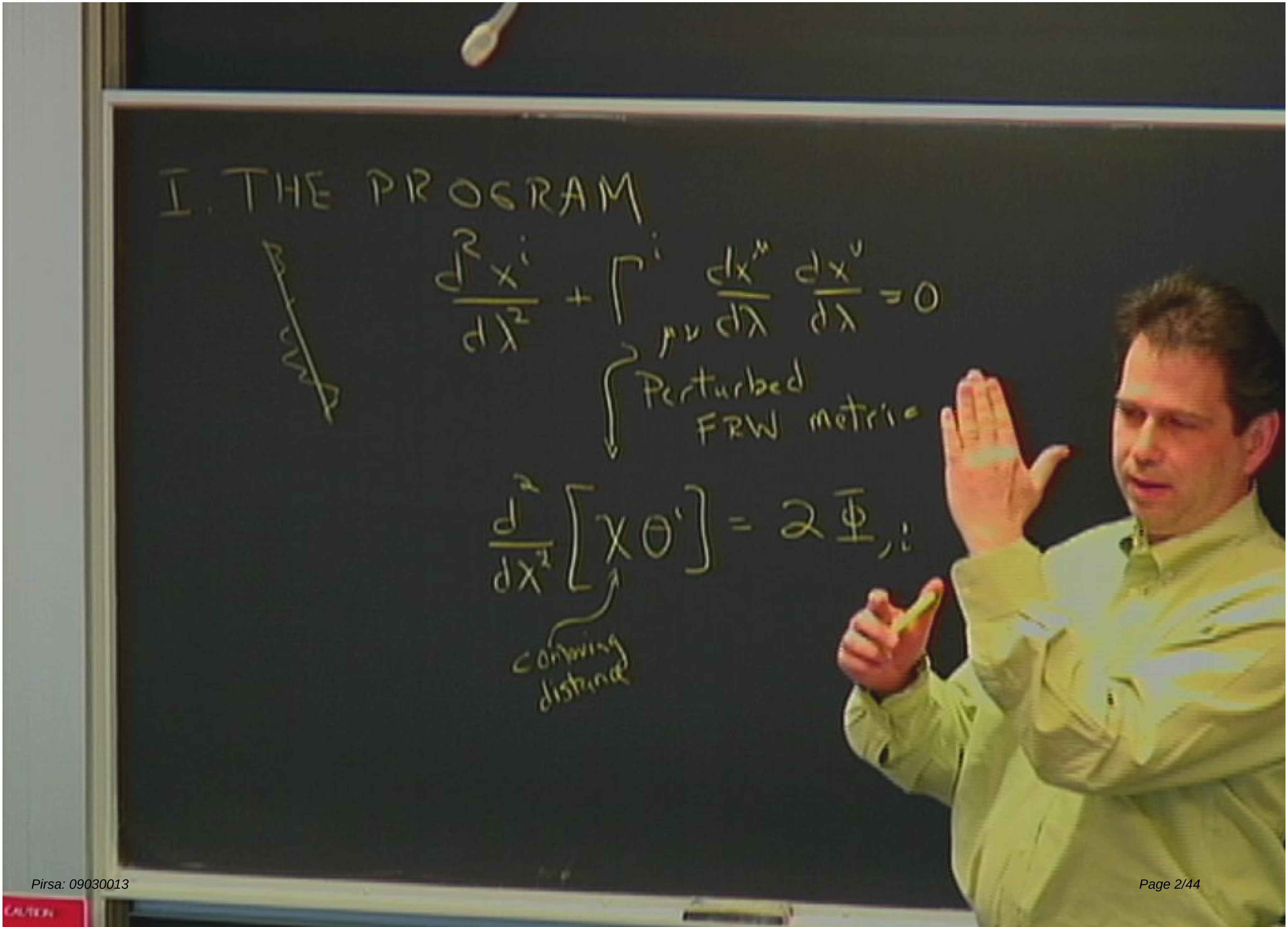
Title: Gravitational Lensing

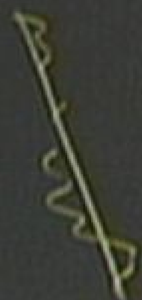
Date: Mar 17, 2009 03:30 PM

URL: http://pirsa.org/09030013

Abstract: Weak lensing has emerged as a powerful probe of fundamental physics such as dark energy and dark matter. After briefly reviewing the standard argument for the power of lensing, I present a variety of surprises: some quantities that are supposedly simple measures of cosmic shear are actually polluted by other effects and some quantities apparently unrelated to lensing are contaminated by lensing. These effects may lead to opportunities to strengthen the constraints lensing will place on dark energy.


I. THE PROGRAM
$\frac{d^2x^i}{d\lambda^2} + \Gamma^i_{\mu\nu}\frac{dx^\mu}{d\lambda}\frac{dx^\nu}{d\lambda} = 0$
Perturbed FRW metric
$\frac{d^2}{d\chi^2}\left[\chi\theta^i\right] = 2\Phi_{,i}$
comoving distance

I. THE PROGRAM



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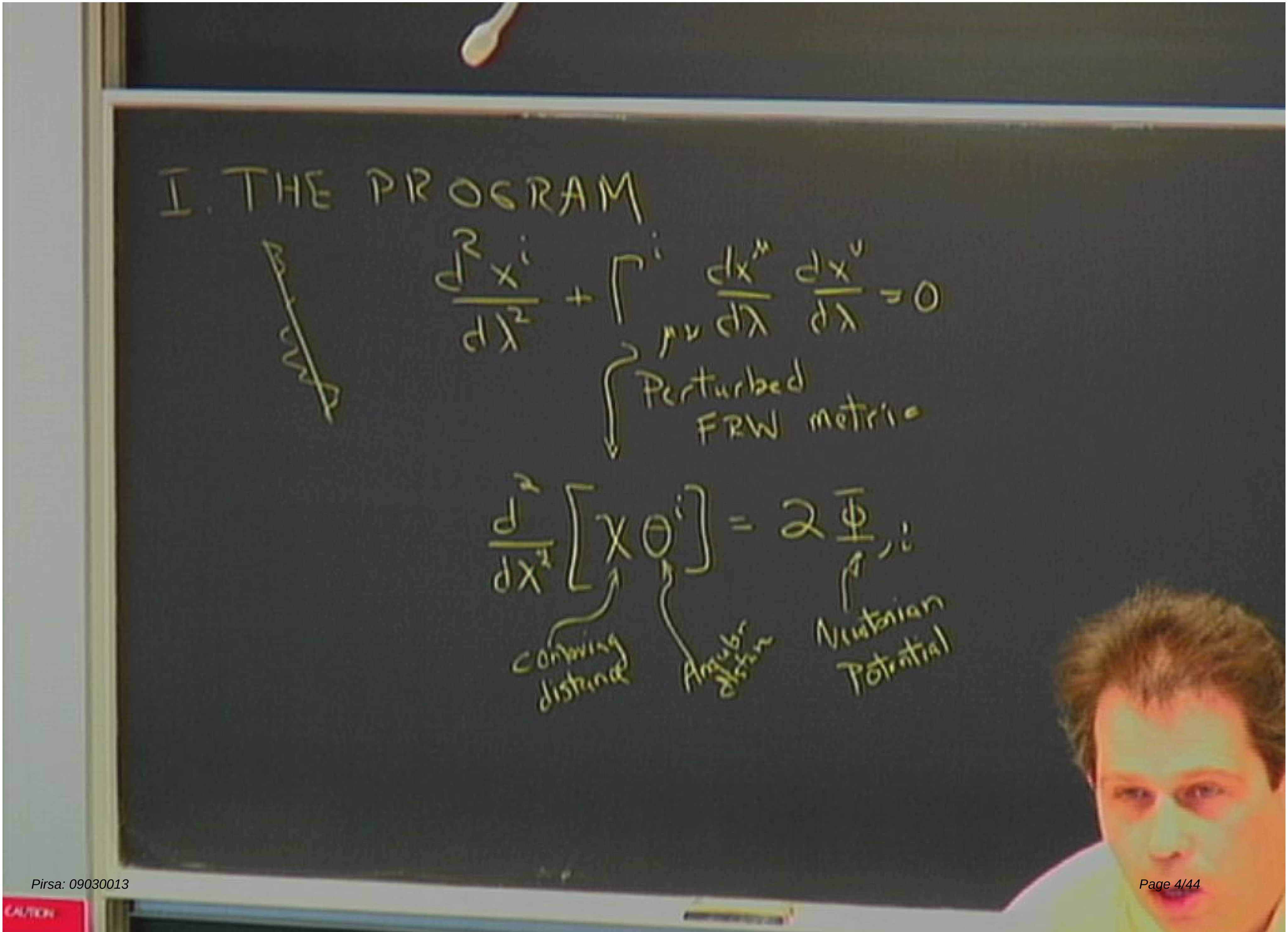
Newtonian Potential



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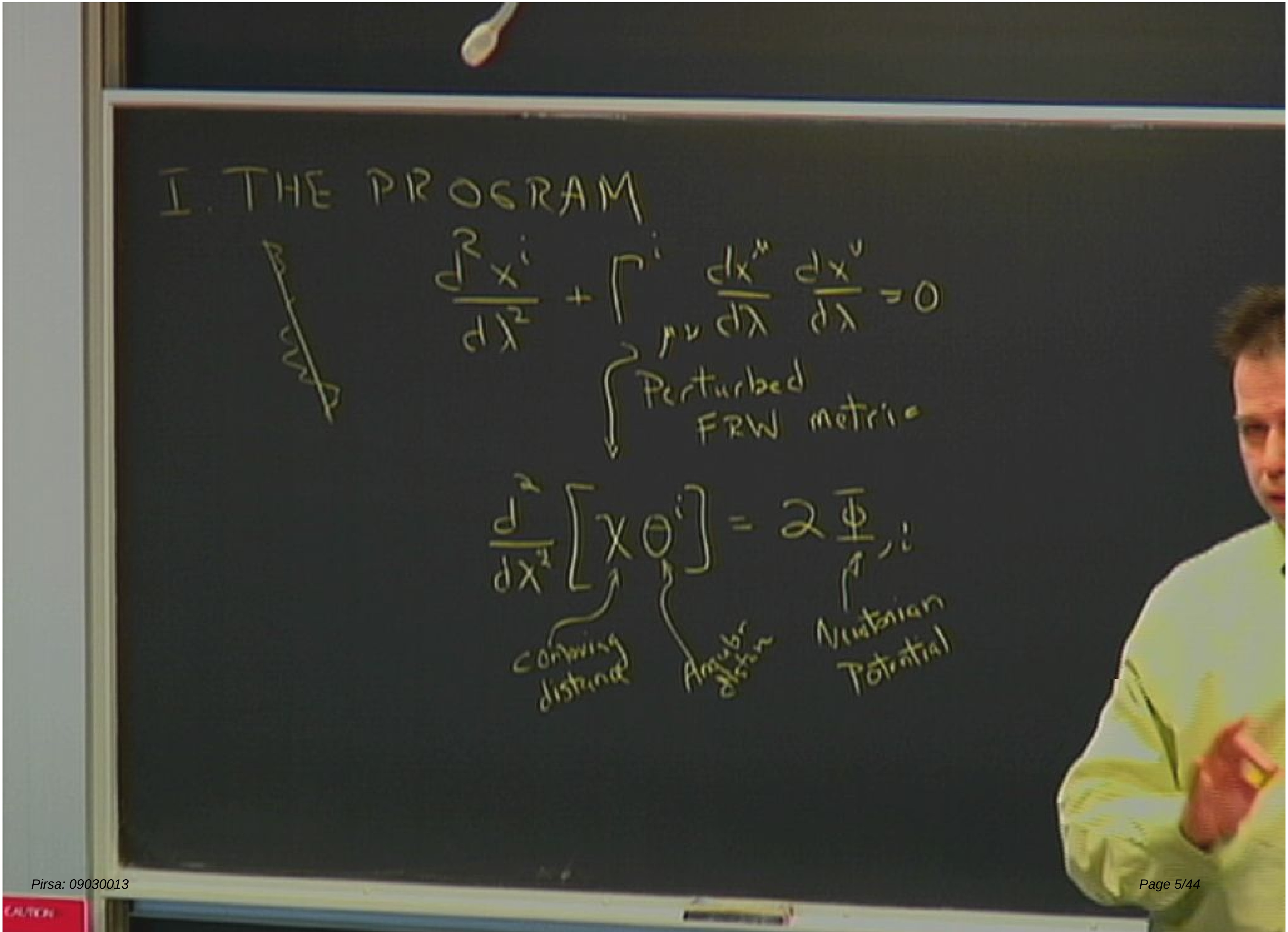
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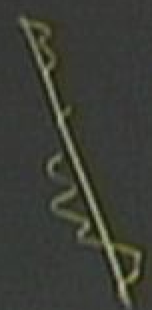

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$\delta\theta^i$

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$$\delta\theta^i = \int_0^{\chi_s} d\chi\, W(\chi,\chi_s)$$

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[illegible]

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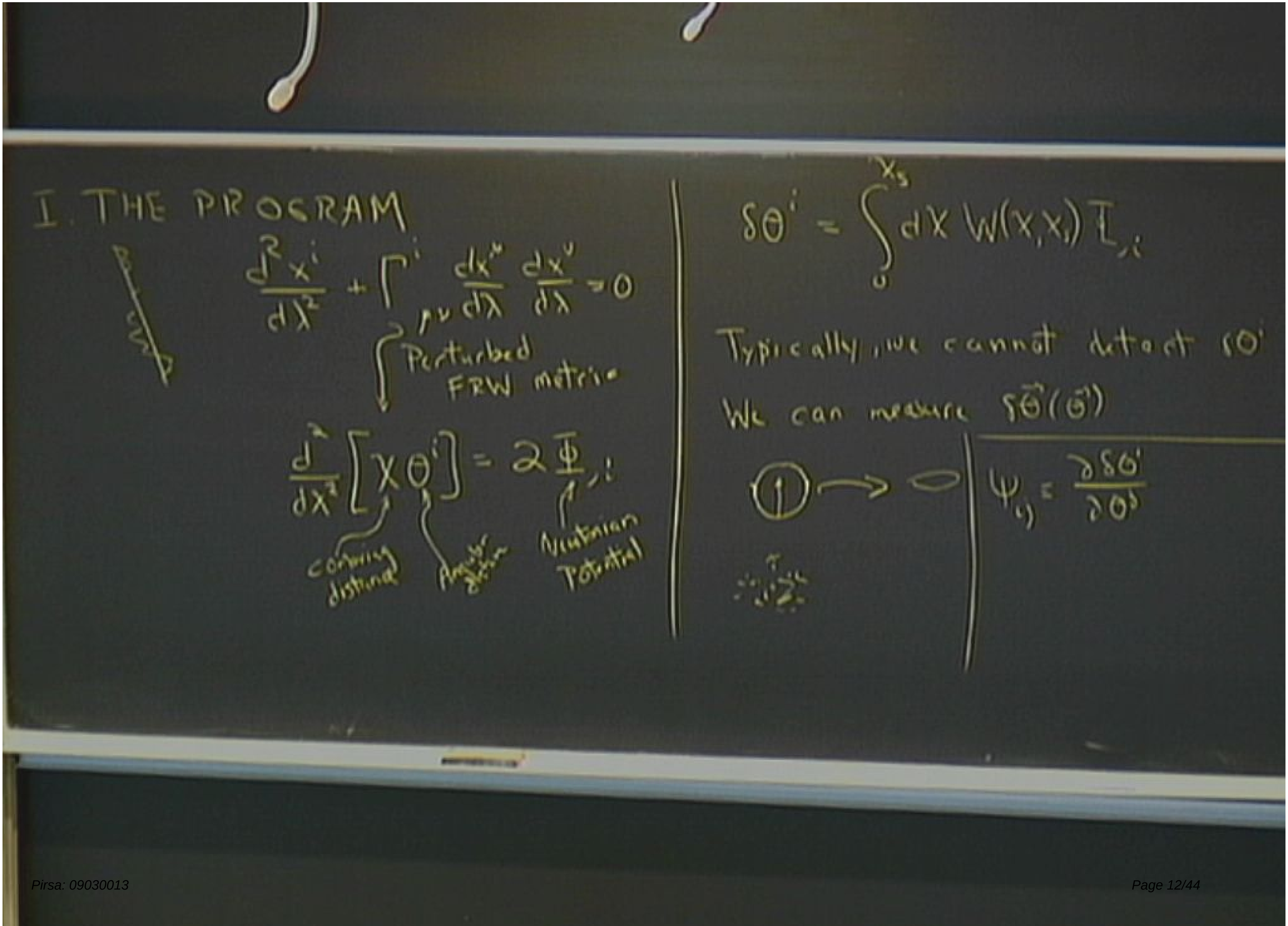
Typically, we cannot detect $\delta\theta^i$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Typically, we cannot detect $\delta\theta^i$
We can measure $\delta\vec{\theta}(\vec{\theta})$
$\psi_{ij} = \frac{\partial\delta\theta^i}{\partial\theta^j}$

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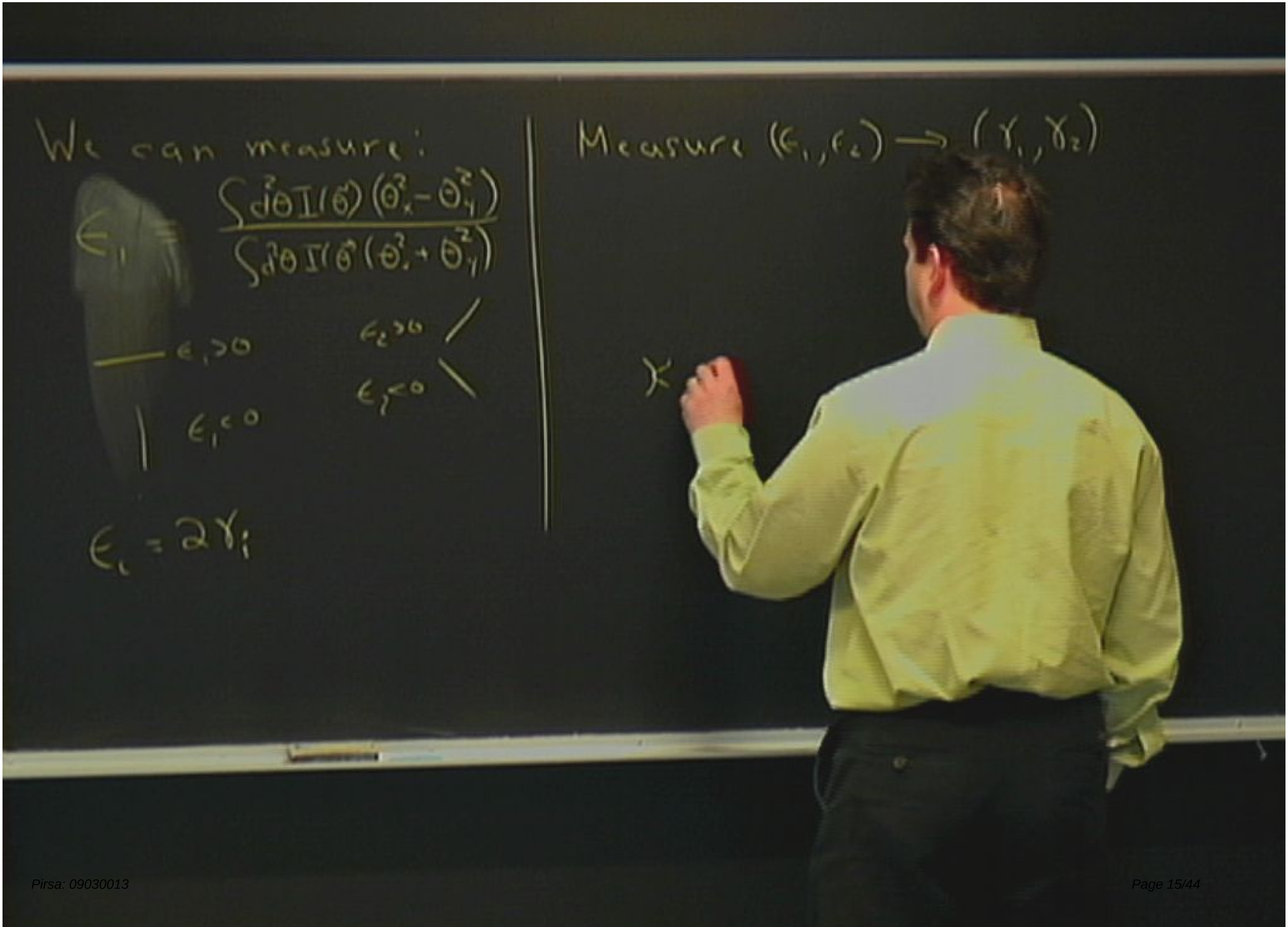
$$\psi_{ij} = \frac{\partial\delta\theta^i}{\partial\theta^j} \equiv \begin{bmatrix} -\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & -\kappa+\gamma_1 \end{bmatrix}$$

We can measure:

$$\epsilon_1 = \frac{\int d^2\theta \, I(\vec{\theta}) \, (\theta_x^2 - \theta_y^2)}{\int d^2\theta \, I(\vec{\theta}) \, (\theta_x^2 + \theta_y^2)}$$

$\epsilon_1 > 0$ $\qquad$ $\epsilon_2 > 0$

$\epsilon_1 < 0$ $\qquad$ $\epsilon_2 < 0$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$\epsilon_1 > 0$
$\epsilon_1 < 0$
$\epsilon_2 > 0$
$\epsilon_2 < 0$
$\epsilon_i = 2\gamma_i$
Measure $(\epsilon_1, \epsilon_2) \longrightarrow (\gamma_1, \gamma_2)$

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Measure $(\epsilon_1, \epsilon_2) \longrightarrow (\gamma_1, \gamma_2)$

$$\downarrow$$

$$\kappa$$

$$\kappa = \int_0^{\chi_s} d\chi\, W(\chi, \chi_s)\, \nabla^2 \Phi$$

We can measure:

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$$\kappa$$

$$(\partial_x^2 - \partial_y^2)\Phi \sim \cos 2\phi\, \kappa$$

$$(\partial_x^2 + \partial_y^2)\Phi$$

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We can measure:

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Measure $(\epsilon_1, \epsilon_2) \longrightarrow (\gamma_1, \gamma_2)$

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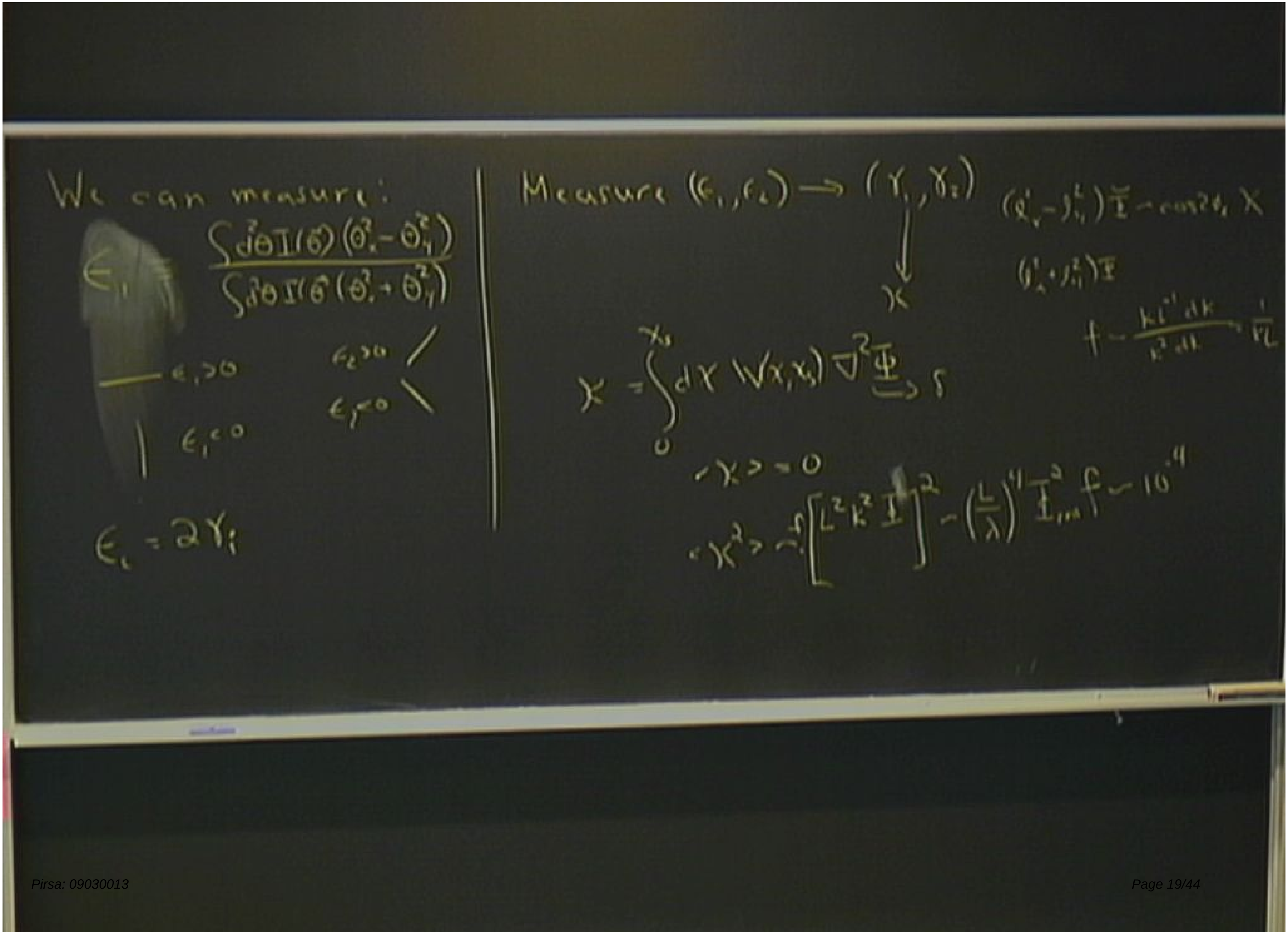
$(\partial_x^2 - \partial_y^2)\Phi \sim \cos 2\theta_i\, \kappa$

$(\partial_x^2 + \partial_y^2)\Phi$

$$\kappa = \int_0^{\chi_s} d\chi\, W(\chi,\chi_s)\, \nabla^2 \Phi \rightarrow \delta$$

$$\langle \kappa \rangle = 0$$

$$\langle \kappa^2 \rangle \sim \left[L^2 k^2 \Phi\right]^2 \sim \left(\frac{L}{\lambda}\right)^4 \Phi_{rms}^2$$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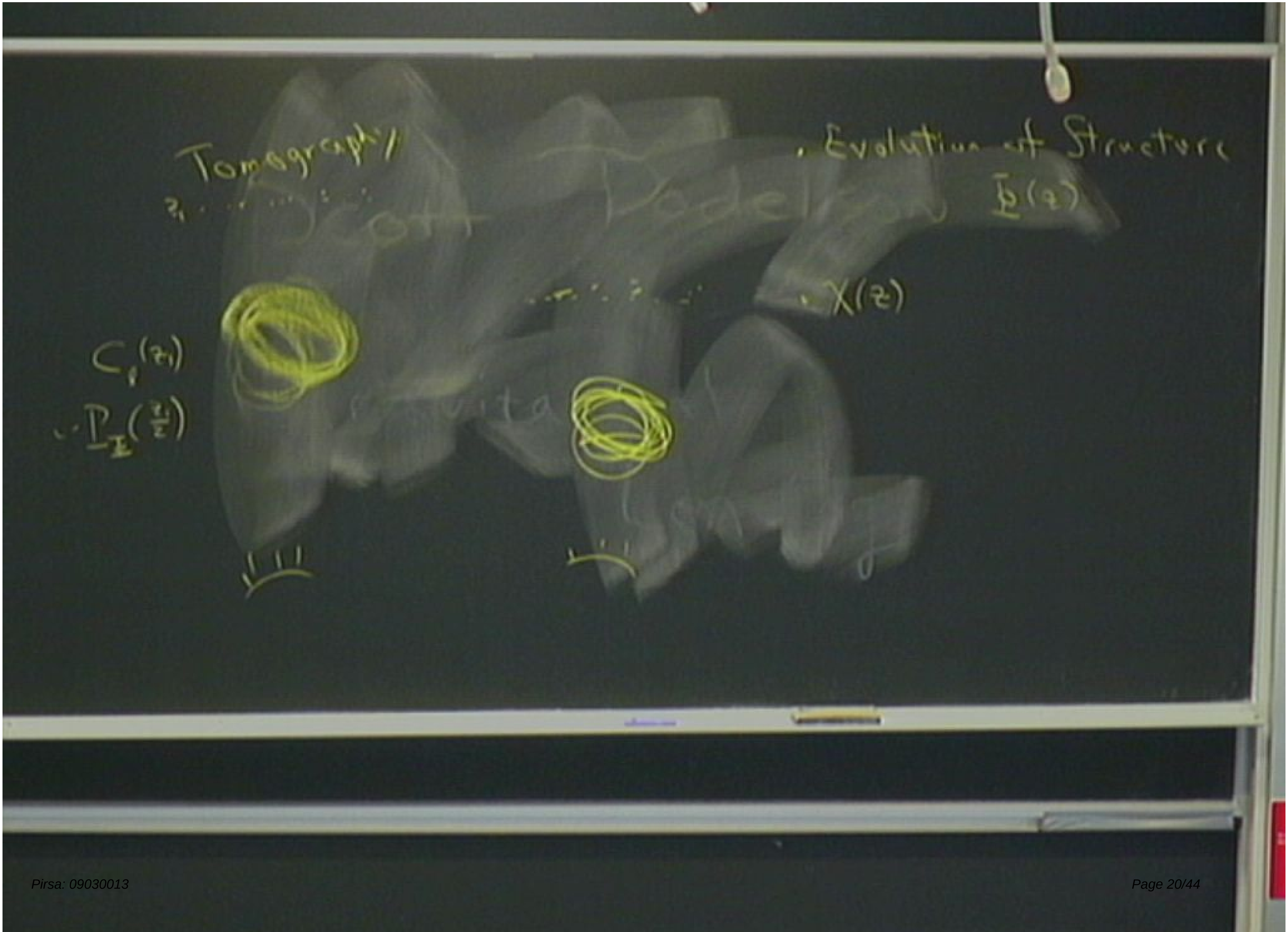
Measure $(\epsilon_1,\epsilon_2)\to(\gamma_1,\gamma_2)$
κ
$\kappa = \int_0^{\chi_s} d\chi\, W(\chi,\chi_s)\nabla^2\Phi$
ρ
$\langle\kappa\rangle = 0$
$\langle\kappa^2\rangle \sim f\left[L^2k^2\Phi\right]^2 \sim \left(\frac{L}{\lambda}\right)^4 \Phi_{rms}^2 f \sim 10^{-4}$
$(\partial_x^2-\partial_y^2)\Phi \sim \cos 2\phi_k\, \kappa$
$(\partial_x^2+\partial_y^2)\Phi$
$f \sim \frac{kL^{-1}dk}{k^2 dk} \sim \frac{1}{kL}$


Tomography
. Evolution of Structure
$\Phi(z)$
. $X(z)$
$C_\ell(z_1)$
. $P_\Sigma(\frac{z_1}{z_2})$

Tomography

z_1 . . . .

$C_\ell(z_1)$

$P_\Sigma\left(\frac{z_1}{z}\right)$

· Evolution of Structure

$\Phi(z)$

· $\chi(z)$

Both of these are very sensitive to dark energy.

Tomography

z_1 ...

$C_\ell(z_1)$

- $P_\Phi(\frac{z_1}{z_2})$

- Evolution of Structure $\Phi(z)$

- $X(z)$

Both of these are very sensitive to dark energy.

Not only DE but also distinguish

DE $\leftrightarrow$ MG $\quad \psi - \Phi$, δ

Tomography

$z_1 \ldots$

$C_\ell(z_1)$

$P_{\Phi}\left(\frac{z_1}{z_2}\right)$

• Evolution of Structure

$\Phi(z)$

• $\chi(z)$

Both of these are very sensitive to dark energy.

Not only DE but also distinguish

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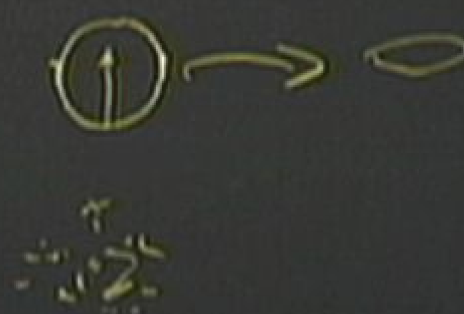
II. YOU THINK YOU'RE MEASURING K, BUT - -

- Beyond Born

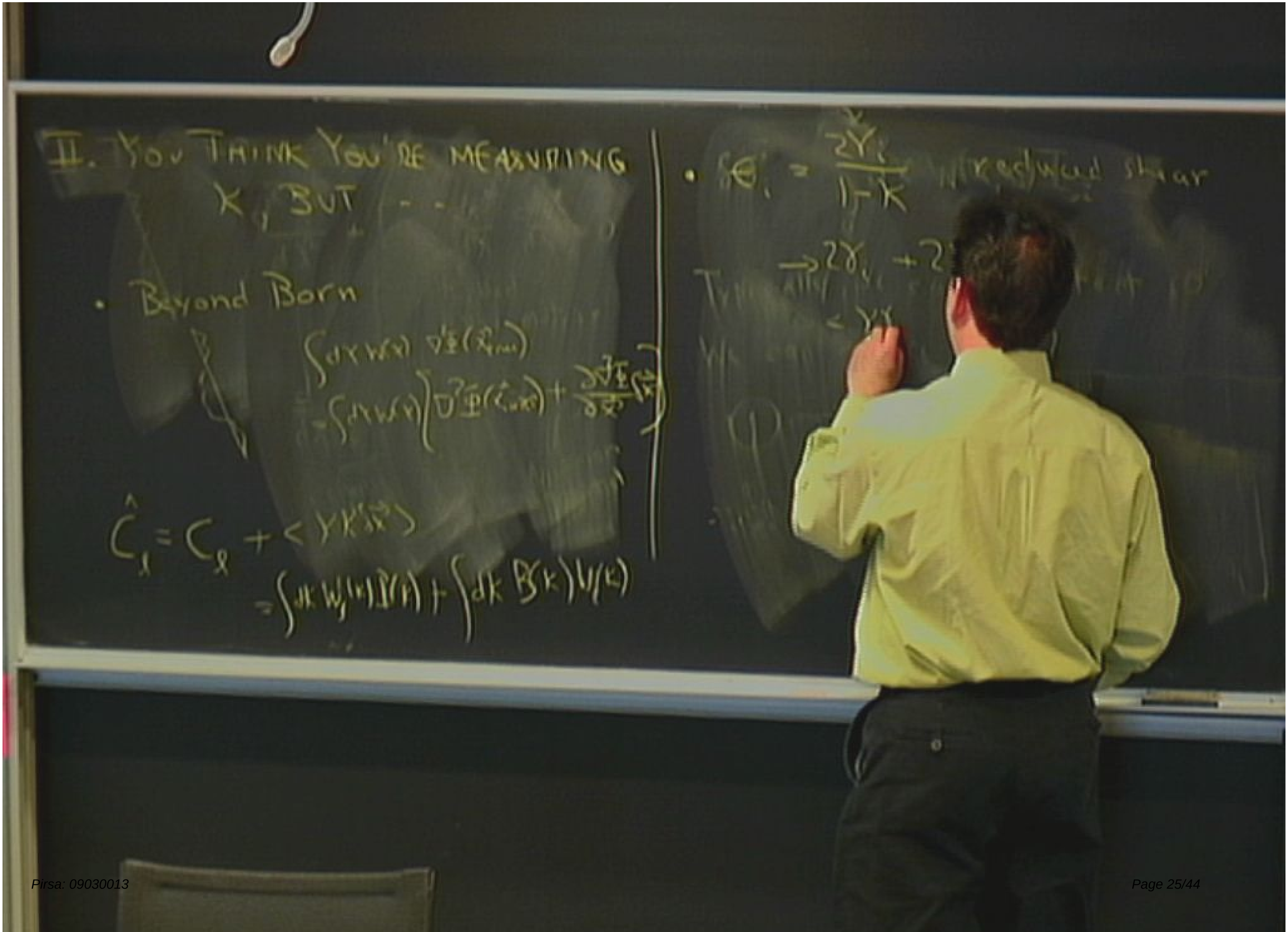
$$\delta\theta^i = \int_0^{X_s} dX\, W($$

Typically, we can

We can measure δ



ψ


II. YOU THINK YOU'RE MEASURING
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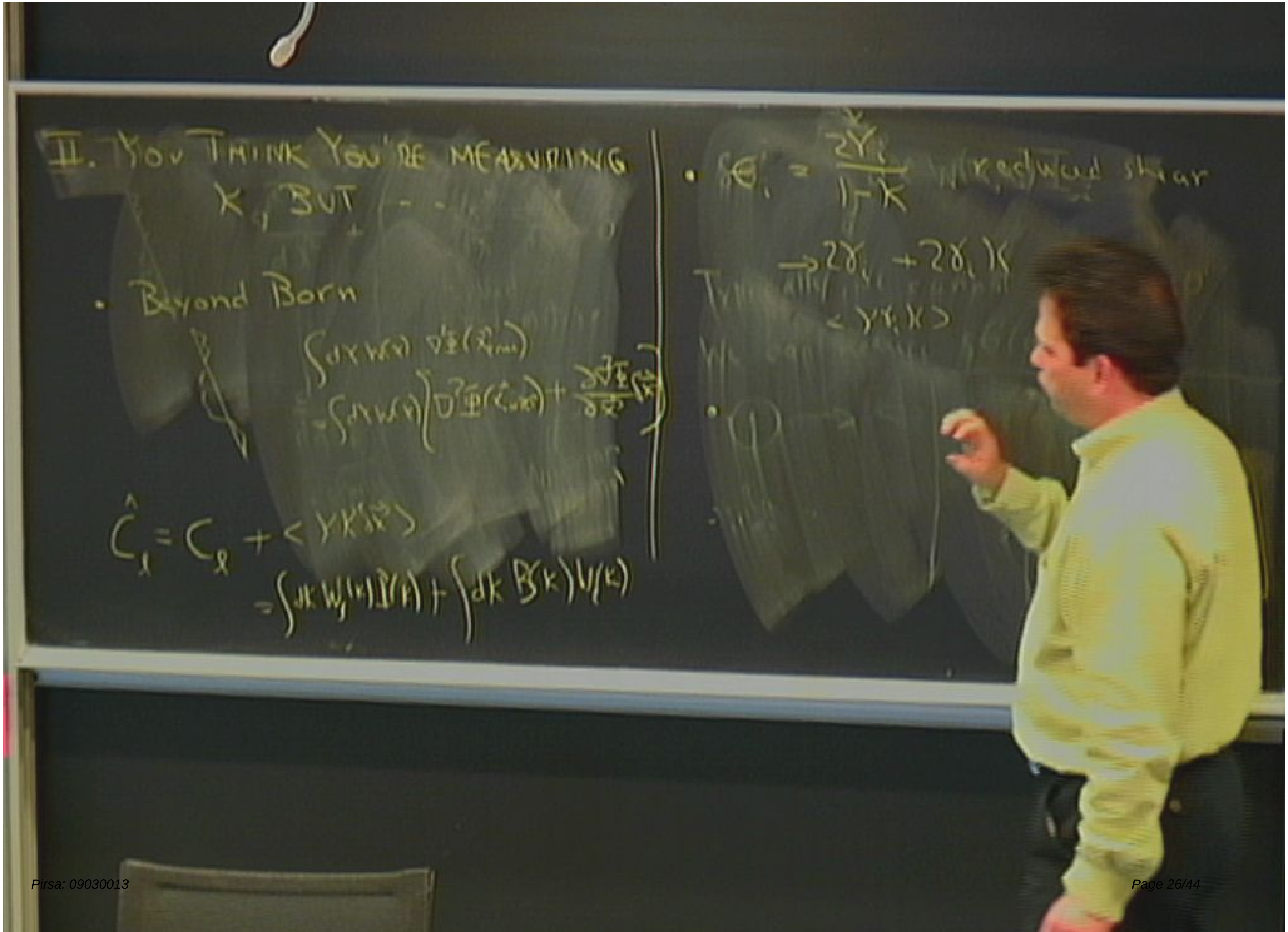
• Beyond Born
reduced shear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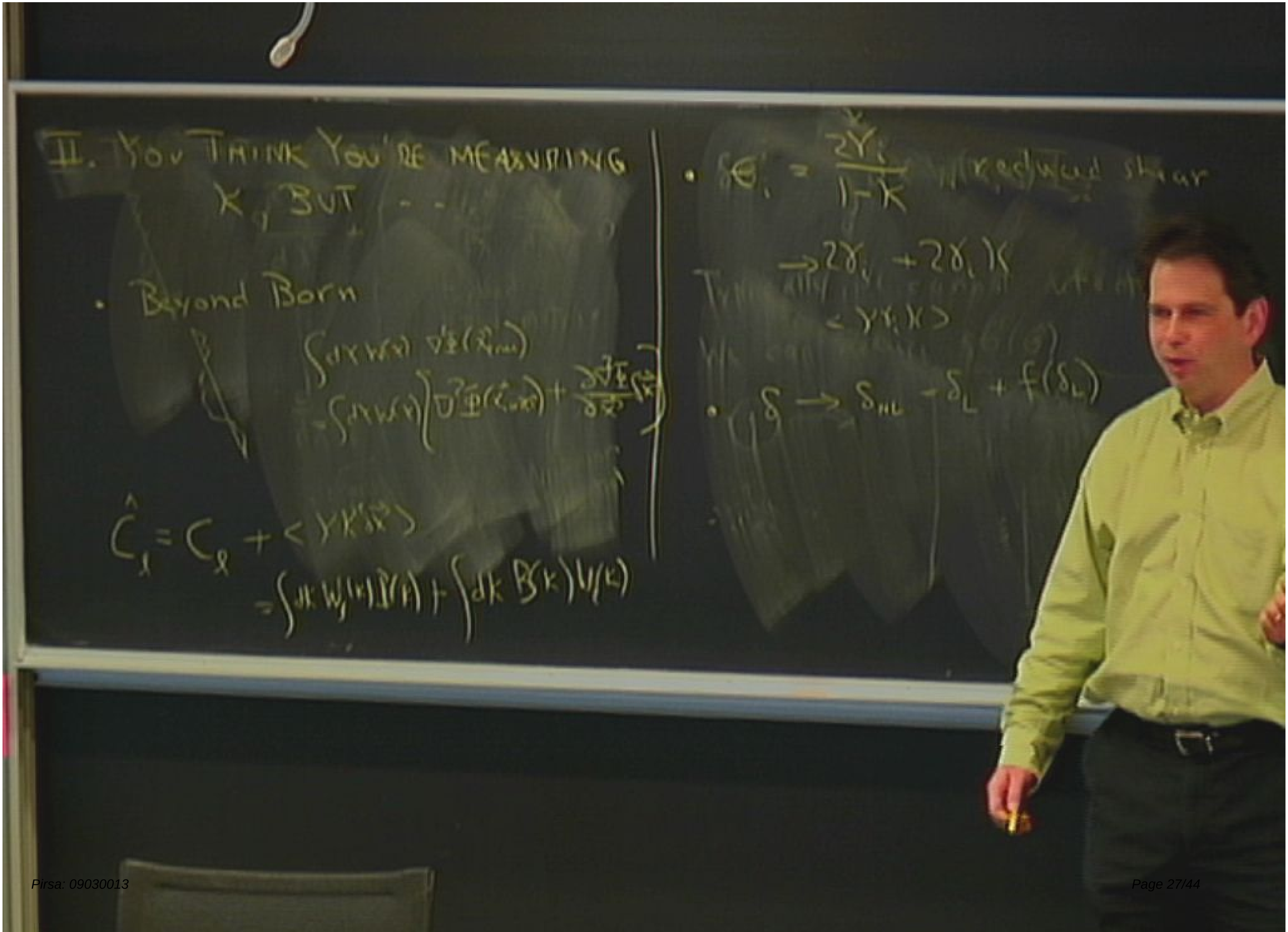
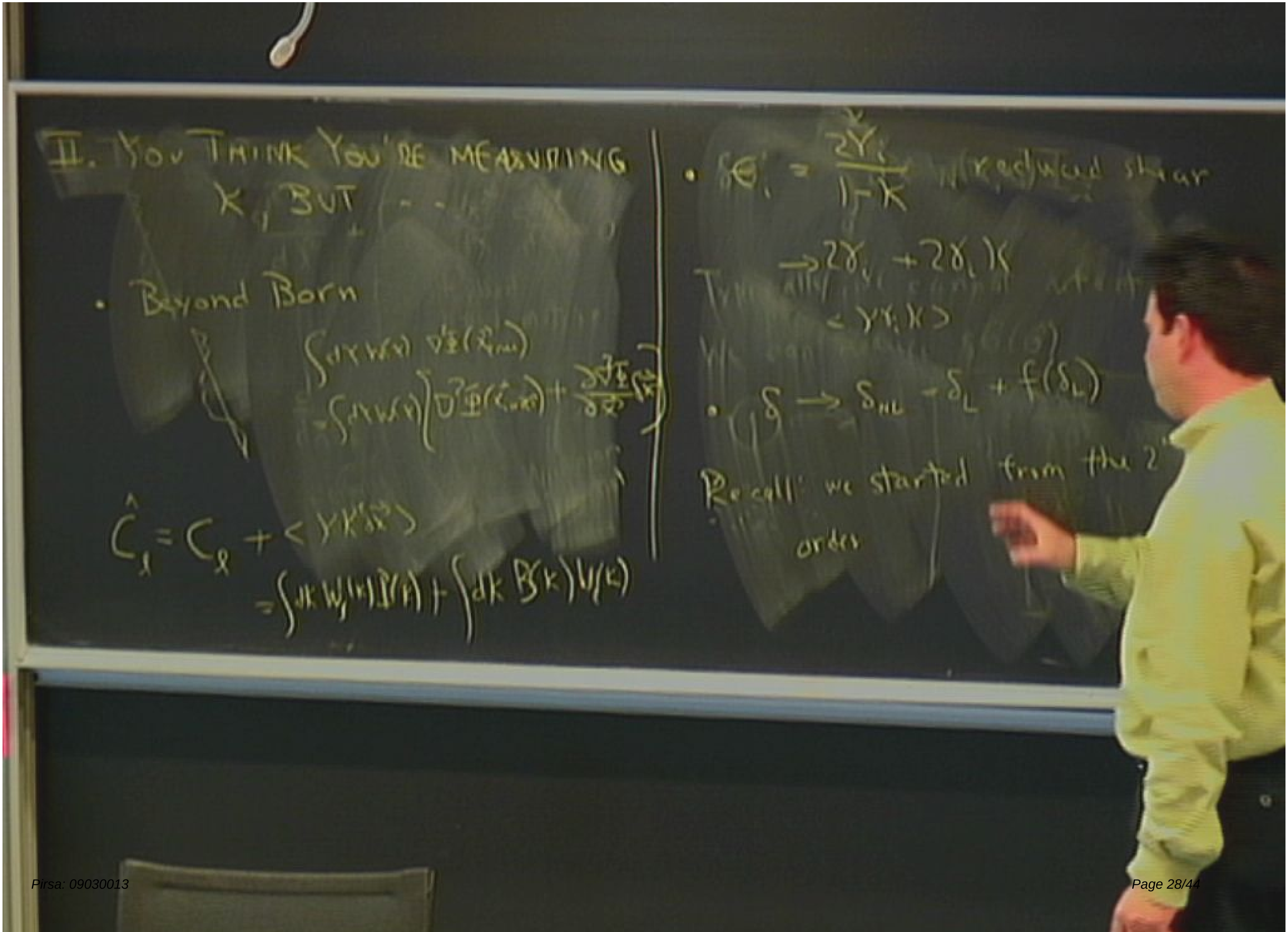
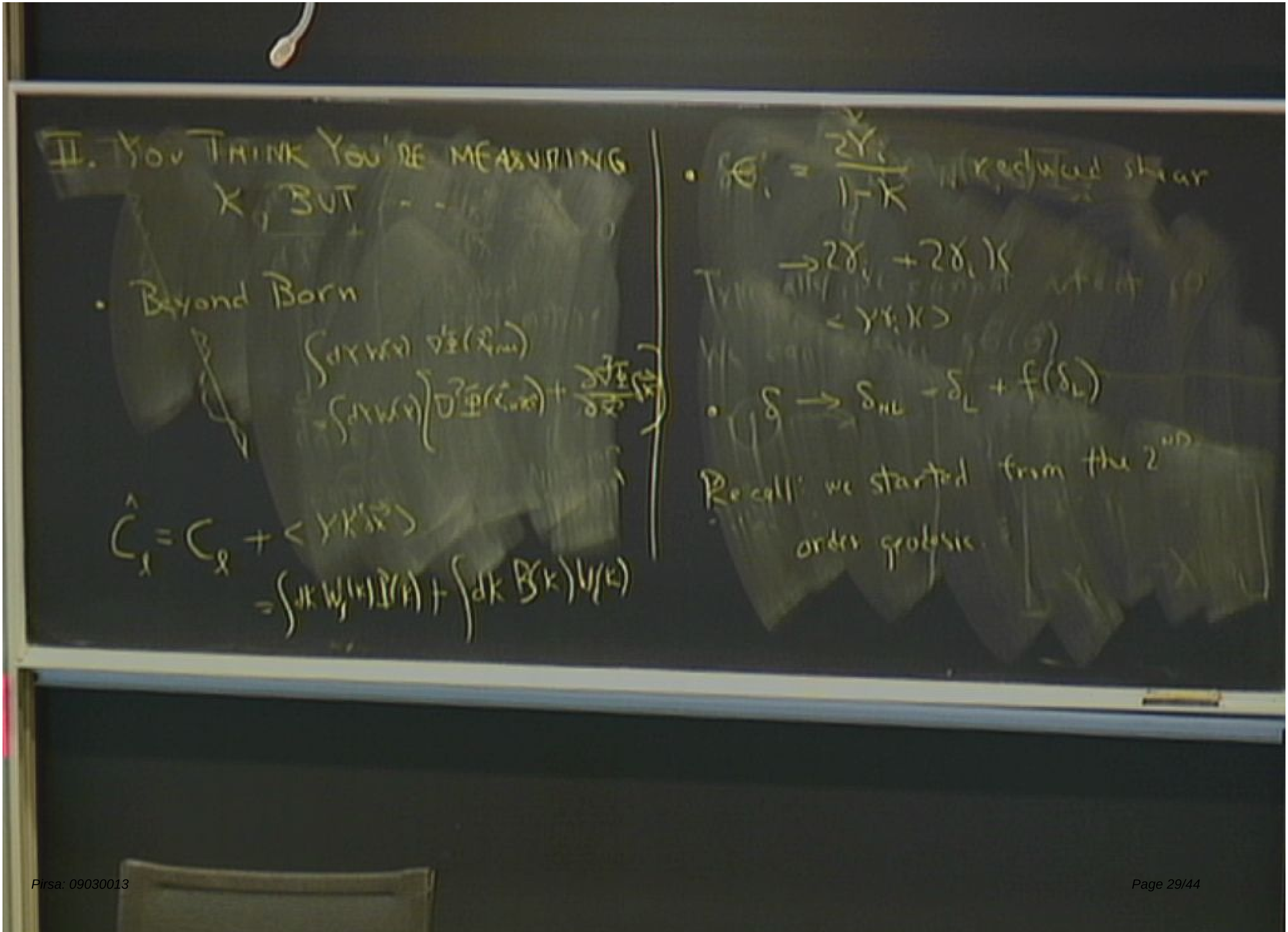

II. YOU THINK YOU'RE MEASURING
κ, BUT - -
• Beyond Born
• δe = 2γ / 1-κ (reduced shear
→ 2γ + 2γ κ
• δ → δ_NL - δ_L + f(δ_L)


II. YOU THINK YOU'RE MEASURING
κ, BUT ...
• Beyond Born
$\int d\chi\, W(\chi)\, \nabla^2\Phi(\vec{x}_{true})$
$= \int d\chi\, W(\chi) \left[\nabla^2\Phi(\vec{x}_{0,\chi}) + \frac{\partial \nabla^2\Phi}{\partial \vec{x}} \delta\vec{x} \right]$
$\hat{C}_\ell = C_\ell + \langle \gamma \kappa \delta x \rangle$
$= \int dk\, W_\ell(k) P(k) + \int dk\, B(k) V(k)$
• $\epsilon_i = \frac{2\gamma_i}{1-\kappa}$ (reduced shear)
$\rightarrow 2\gamma_i + 2\gamma_i \kappa$
$\langle \gamma \gamma_i \kappa \rangle$
• $\delta \rightarrow \delta_{NL} = \delta_L + f(\delta_L)$
Recall: we started from the 2nd order


II. YOU THINK YOU'RE MEASURING
κ, BUT ...
• Beyond Born
• reduced shear
• Recall: we started from the 2nd
order geodesic

II. YOU THINK YOU'RE MEASURING κ, BUT . . .

- Beyond Born

$$\int dx\, W(x)\, \nabla^2\Phi(\vec{x}_{true})$$

$$= \int dx\, W(x) \left[\nabla^2\Phi(\vec{x}_{obs}) + \frac{\partial \nabla^2\Phi}{\partial \vec{x}} \delta\vec{x} \right]$$

$$\hat{C}_\ell = C_\ell + \langle \gamma \kappa' \delta x \rangle$$

$$= \int dk\, W_\ell(k) P(k) + \int dk\, B(k) W(k)$$

- $\delta e_i = \dfrac{2\gamma_i}{1-\kappa}$ reduced shear

$$\rightarrow 2\gamma_i + 2\gamma_i \kappa$$

$$\langle \gamma \gamma_i \kappa \rangle$$

- $\delta \rightarrow \delta_{NL} = \delta_L + f(\delta_L)$

Recall: we started from the 2nd order geodesic.

Only known corrections contribute, at the present level.

Ignoring those corrections,

$\Rightarrow$ systematic errors

$\geq$ statistical errors.

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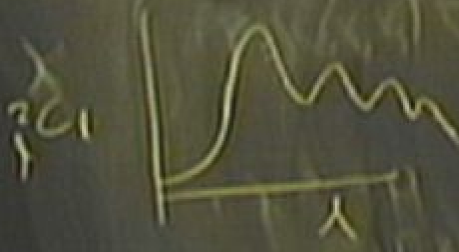
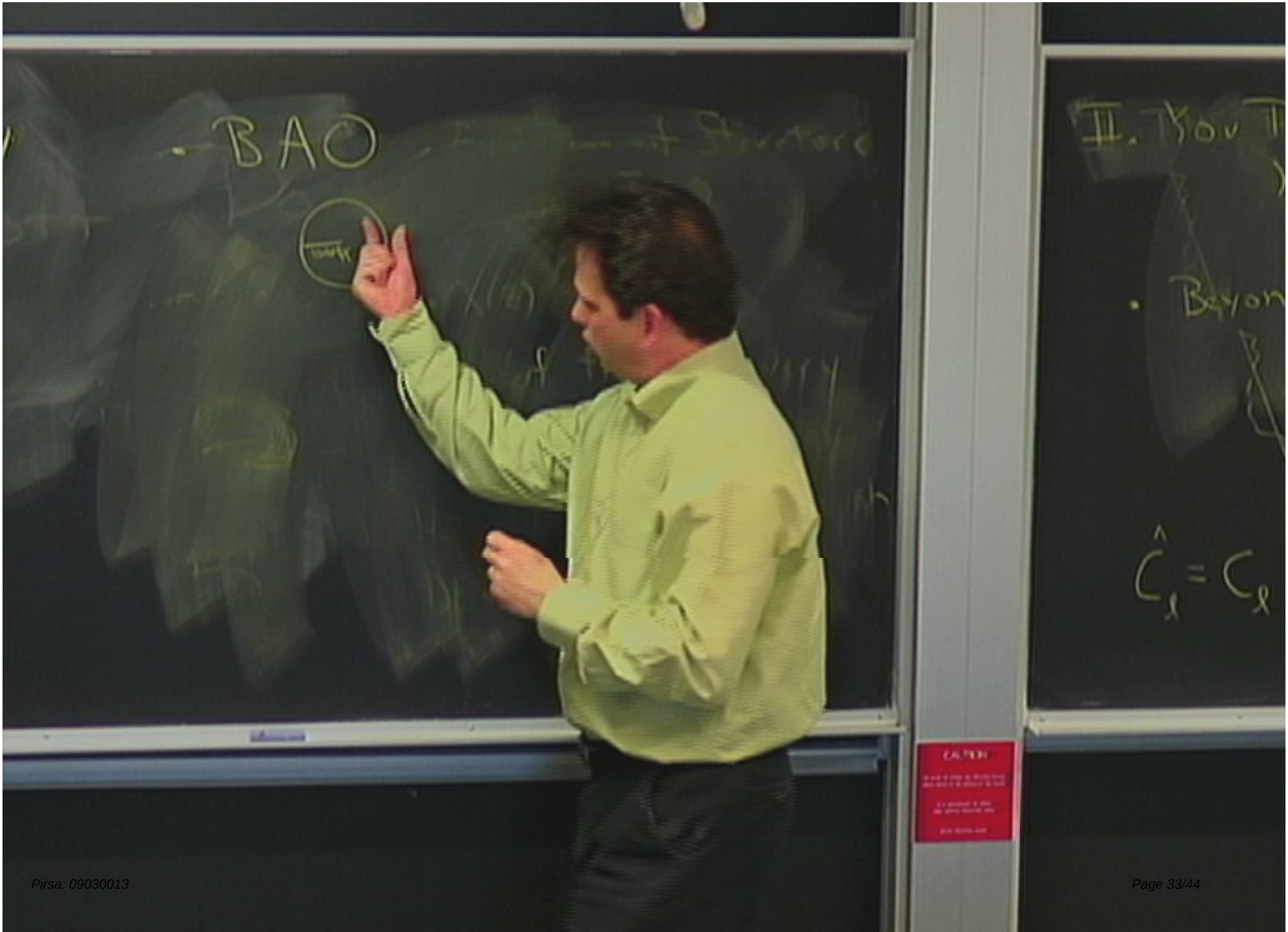
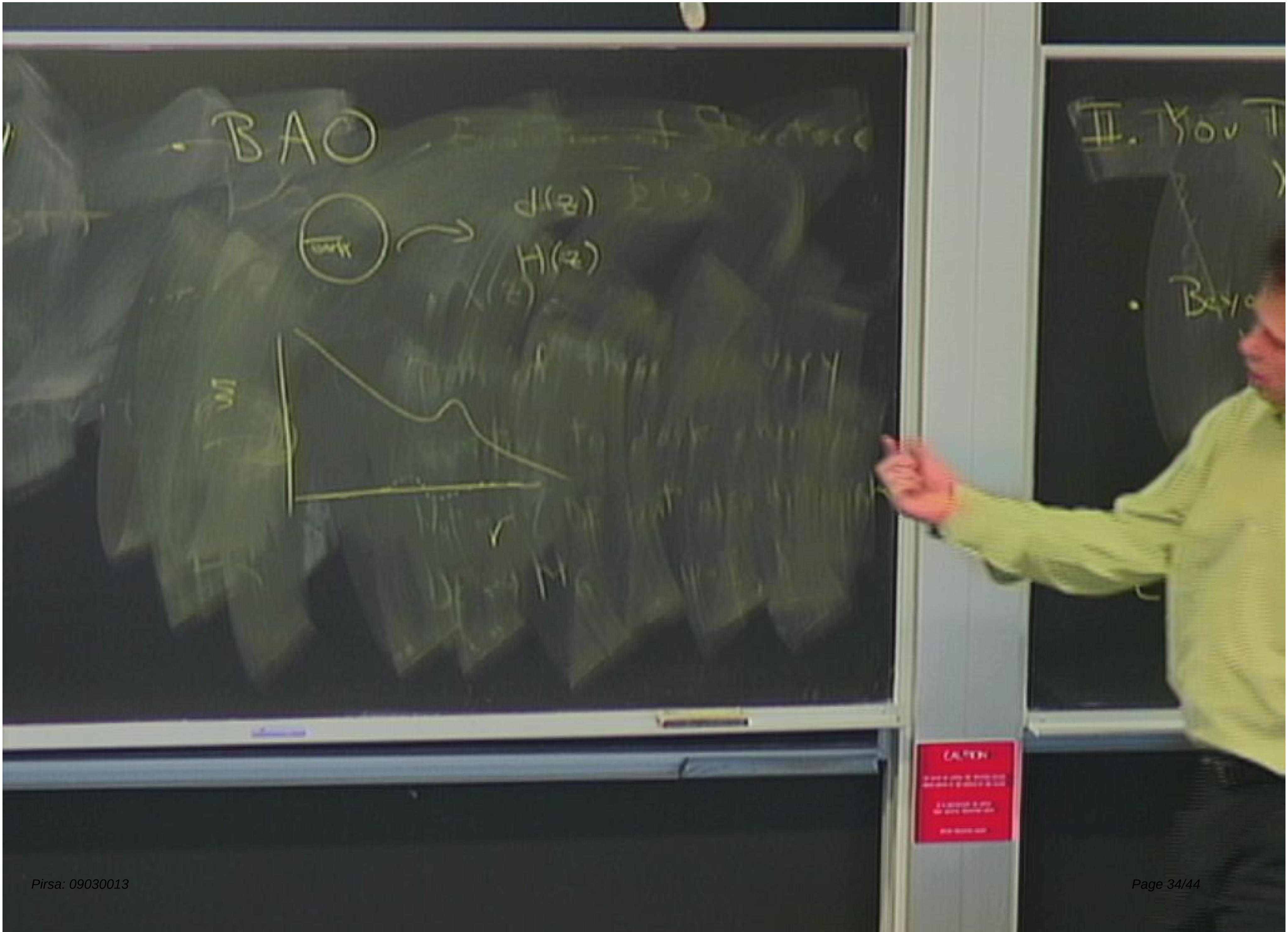
$\gtrsim$ statistical errors.

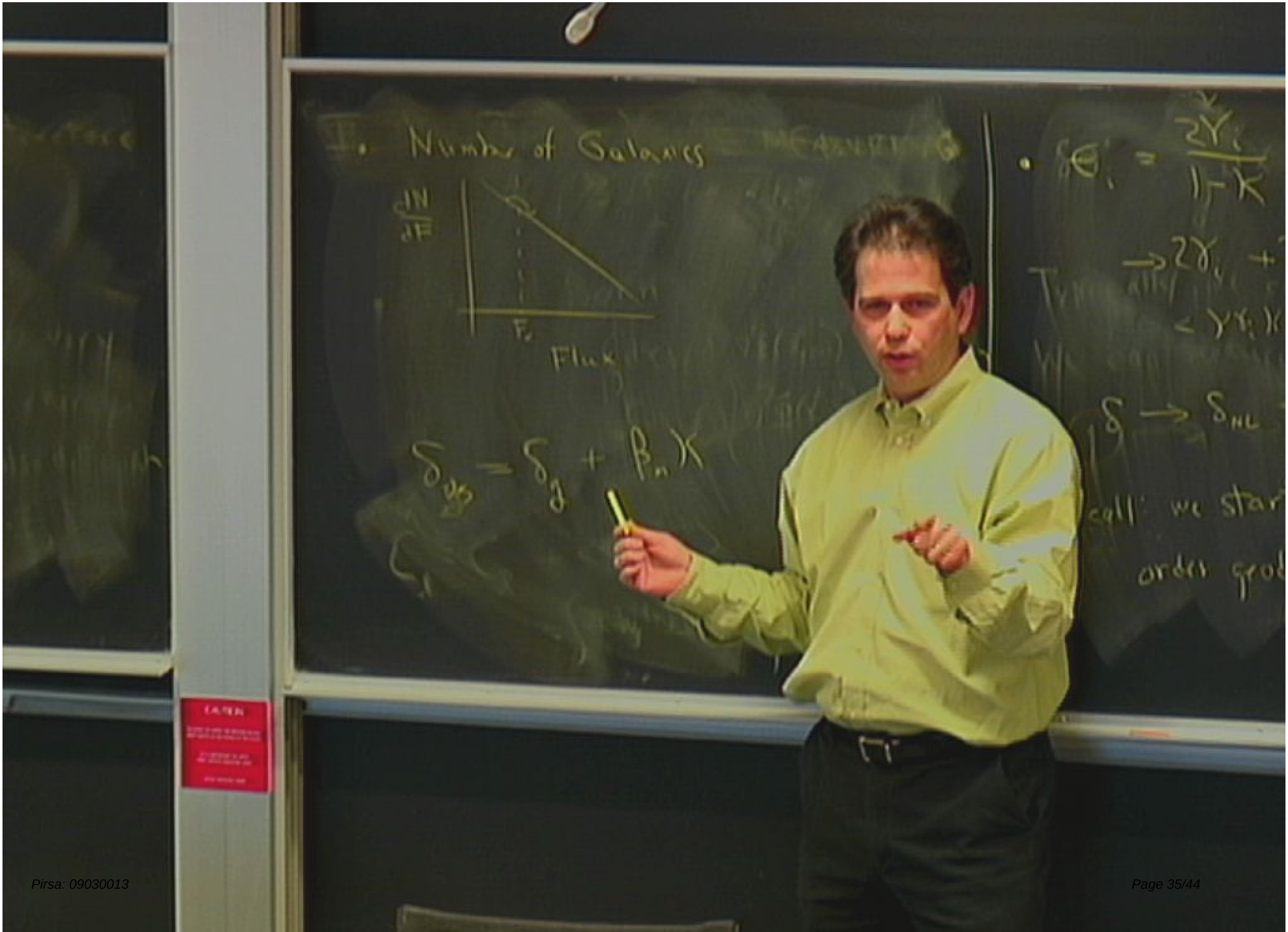
III YOU THINK YOU'RE MEASURING C_ℓ
BUT ....

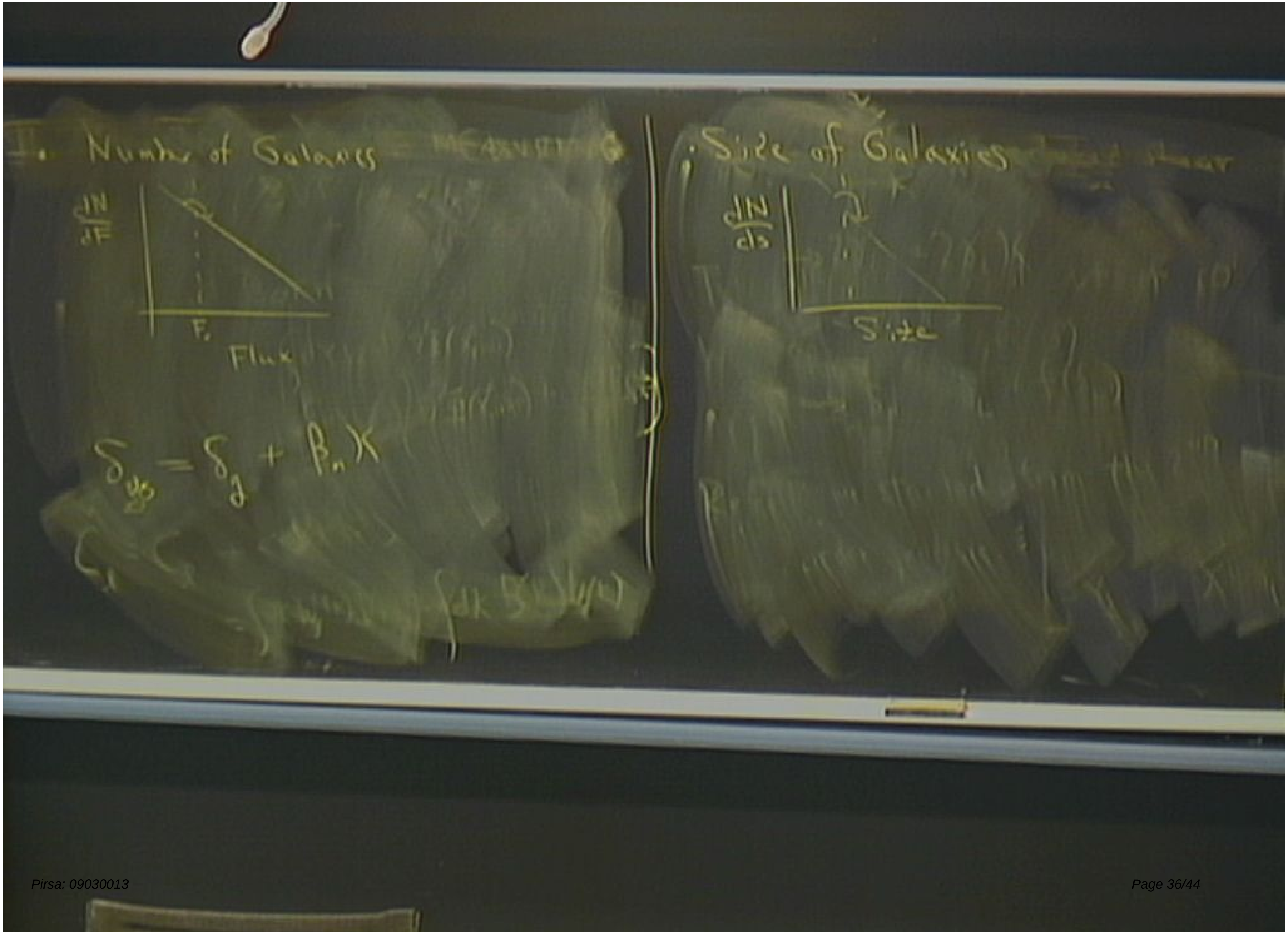
- CMB Lensing



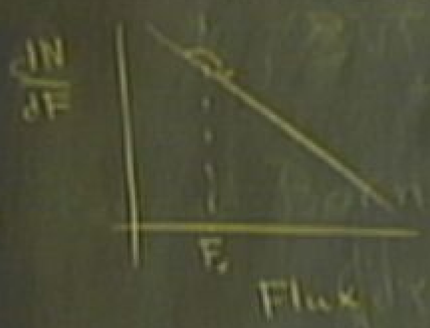

BAO
$\hat{C}_\ell = C_\ell$


BAO
d(z)
H(z)
r


II. Number of Galaxies
dN/dF
Flux
we start

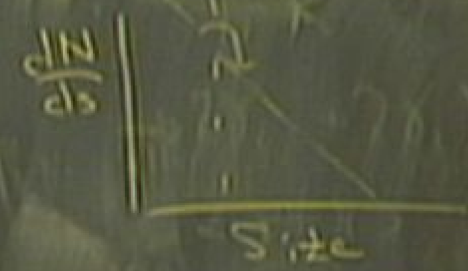

I. Number of Galaxies
dN/dF
F
Flux
δgg = δg + βn κ
Size of Galaxies
dN/ds
Size

I. Number of Galaxies

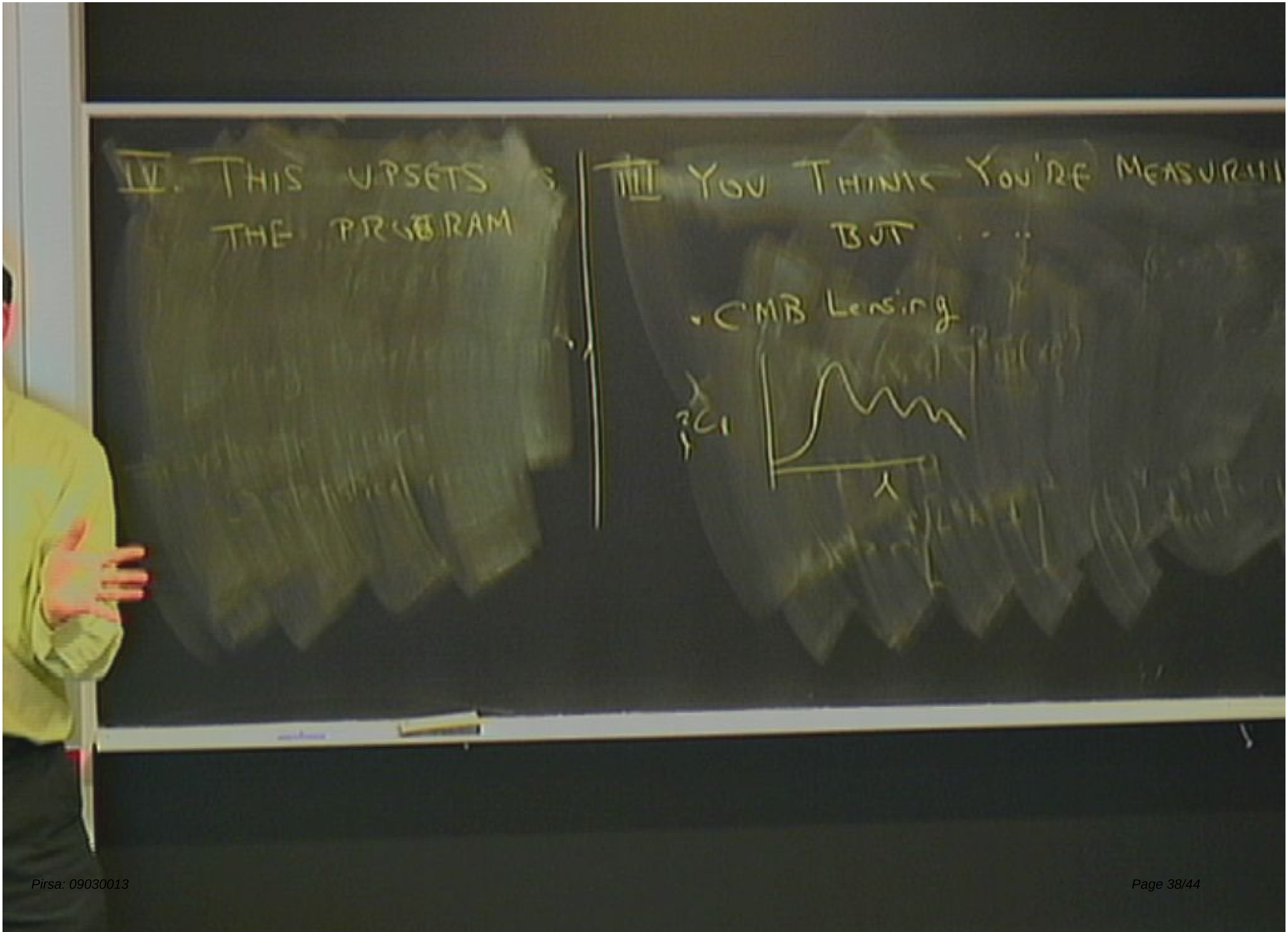


$$\delta_{obs} = \delta_g + \beta_n \kappa$$

Size of Galaxies



$$\Rightarrow \delta_{obs} = \delta_{gal} + q\kappa$$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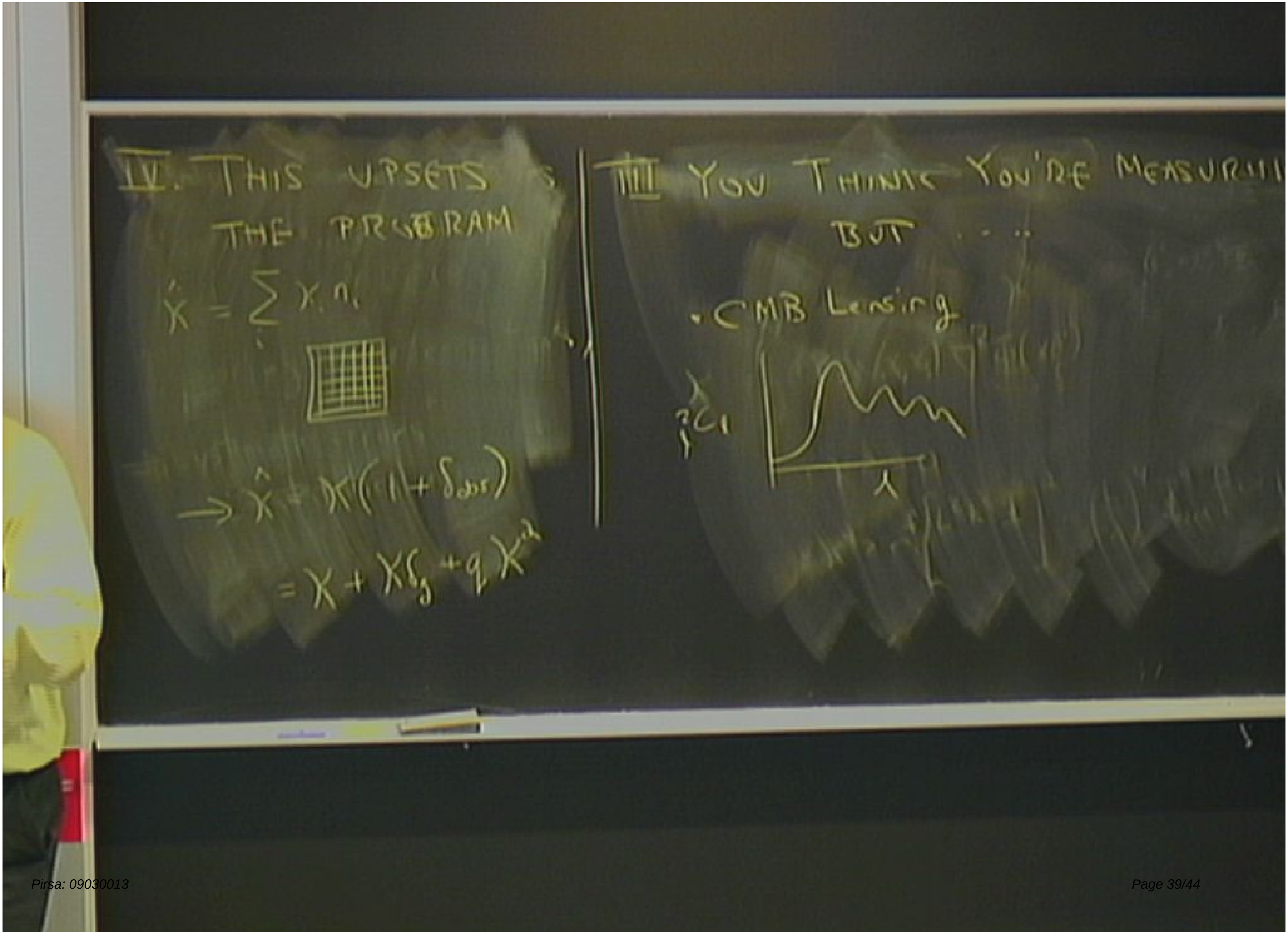
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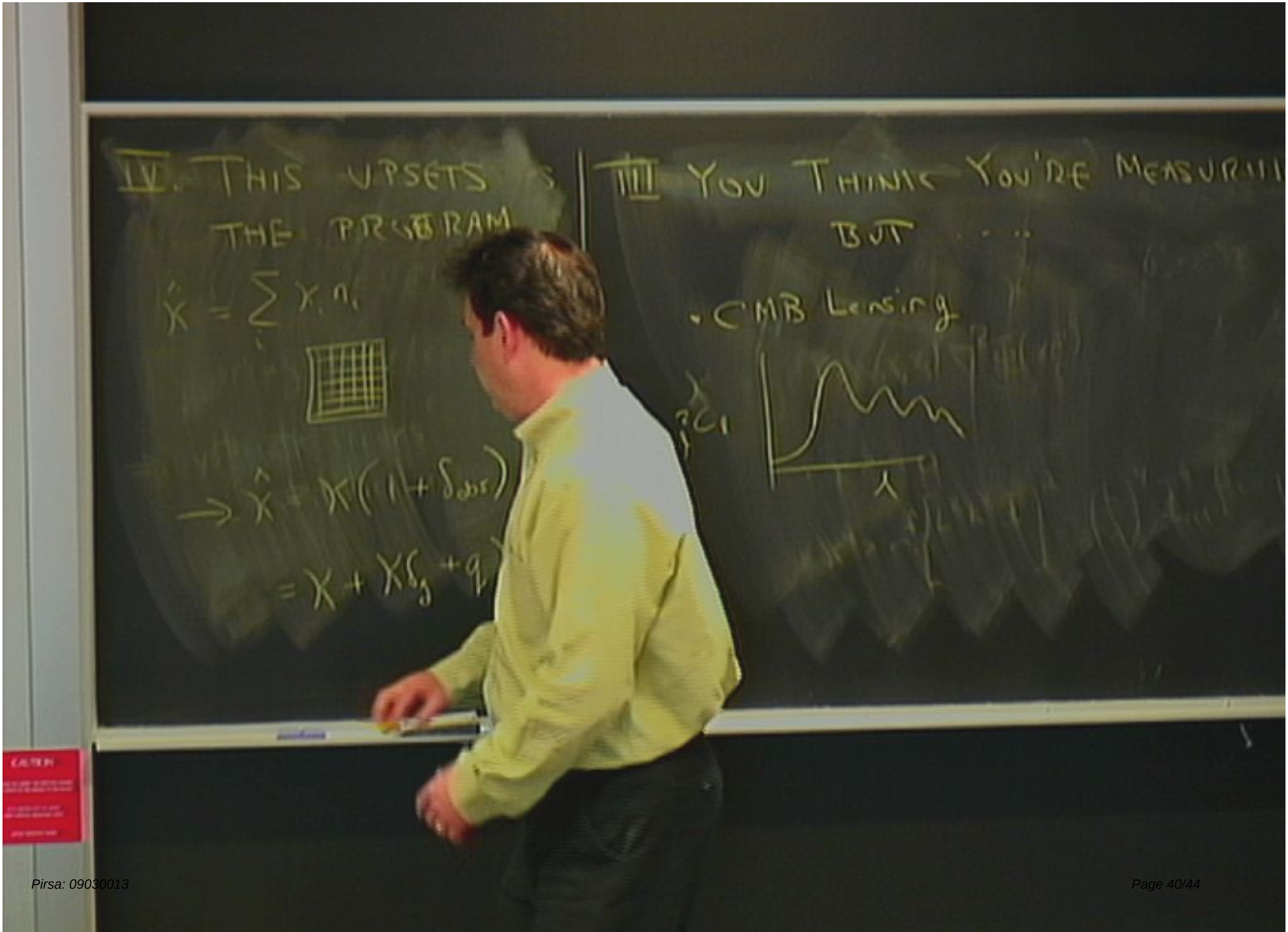
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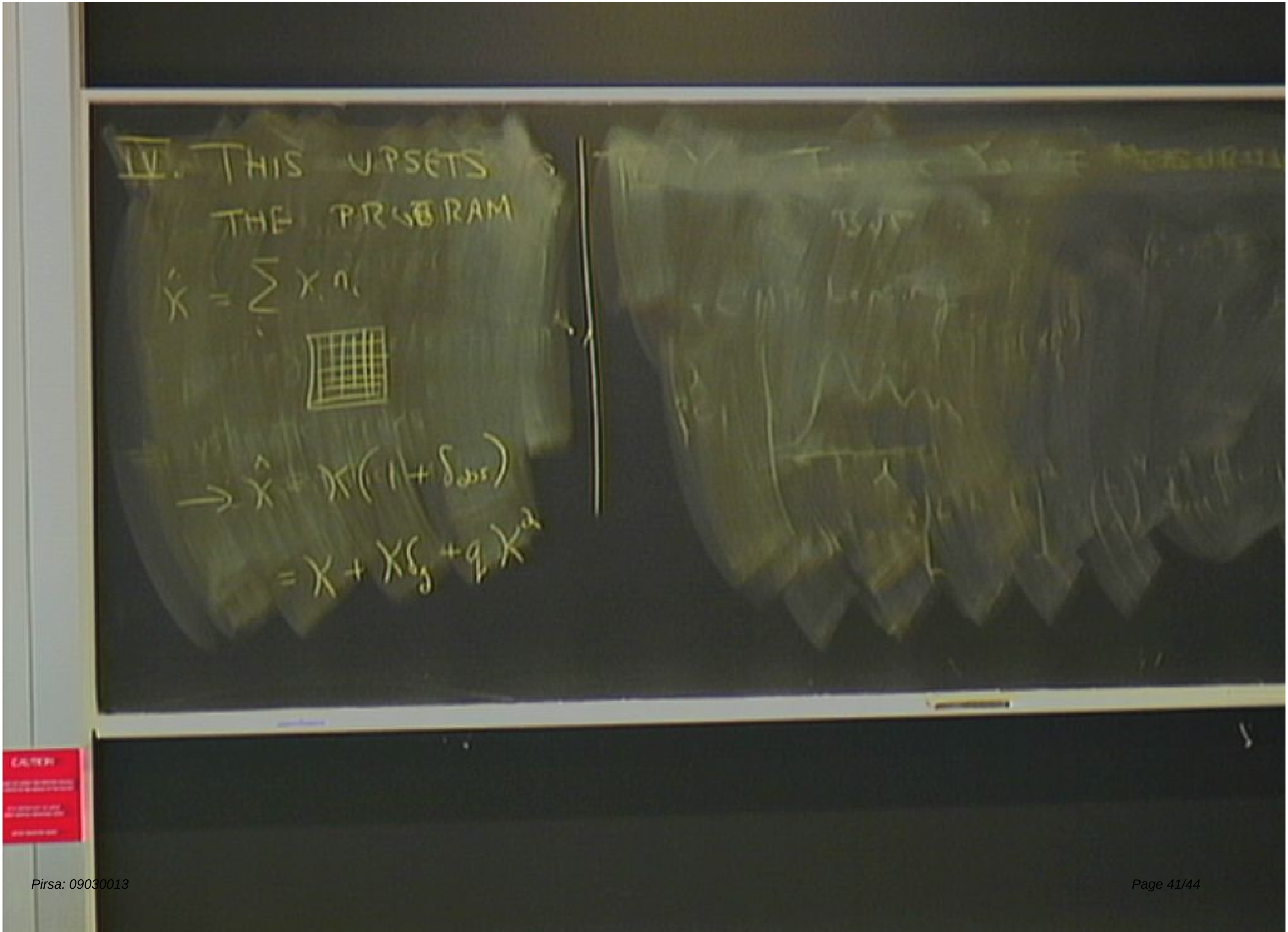
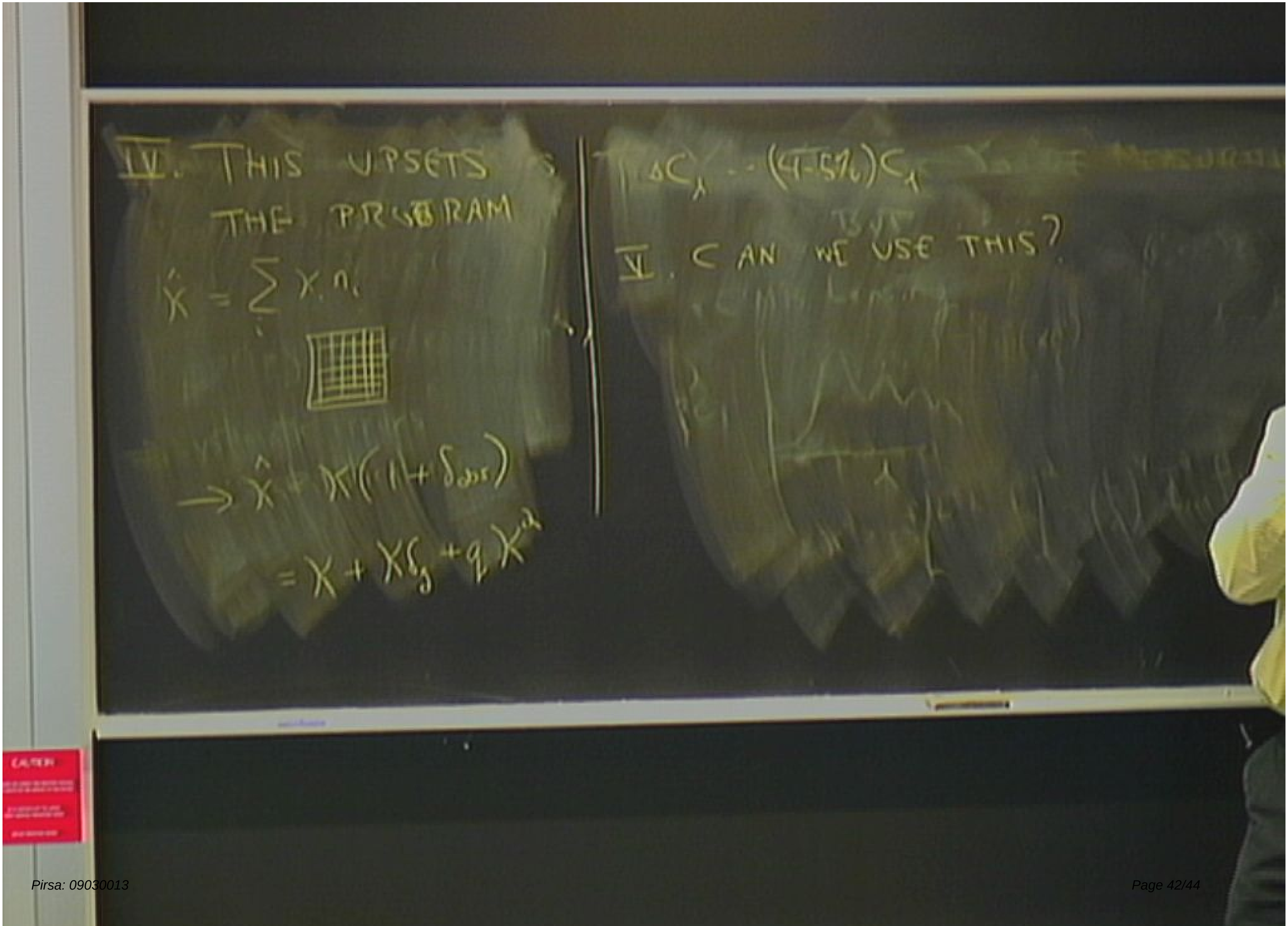
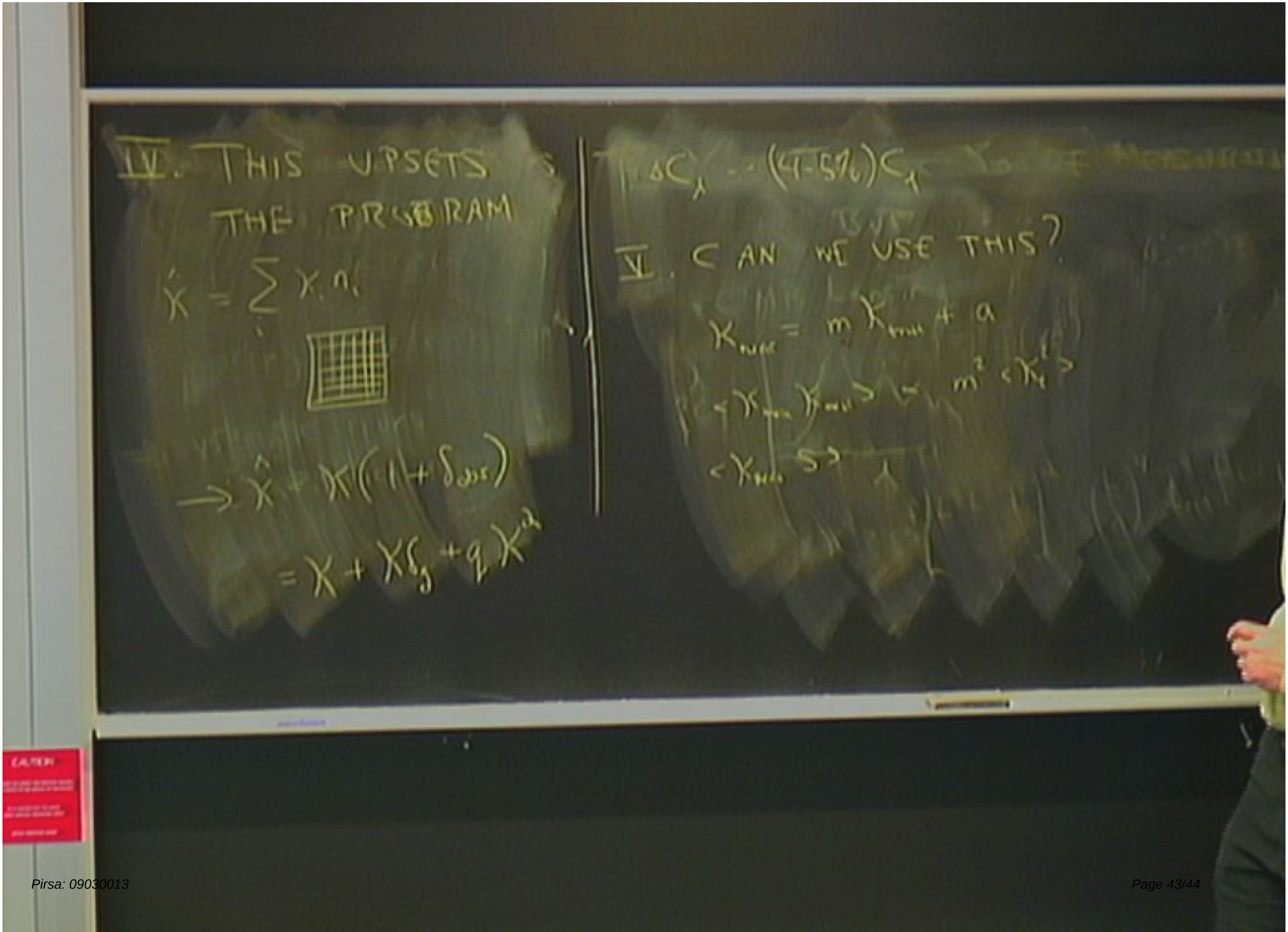

IV. THIS UPSETS
THE PROGRAM
$\hat{x} = \sum_i x_i n_i$
$\rightarrow \hat{x} = x(1 + \delta_{obs})$
$= x + x\delta_g + q x^2$


IV. THIS UPSETS
THE PROGRAM
$\hat{X} = \sum_i x_i n_i$
$\rightarrow \hat{X} = X(1 + \delta_{bias})$
$= X + X\delta_g + q X^2$
$\Delta C_\lambda = (4\text{-}5\%) C_\lambda$
V. CAN WE USE THIS?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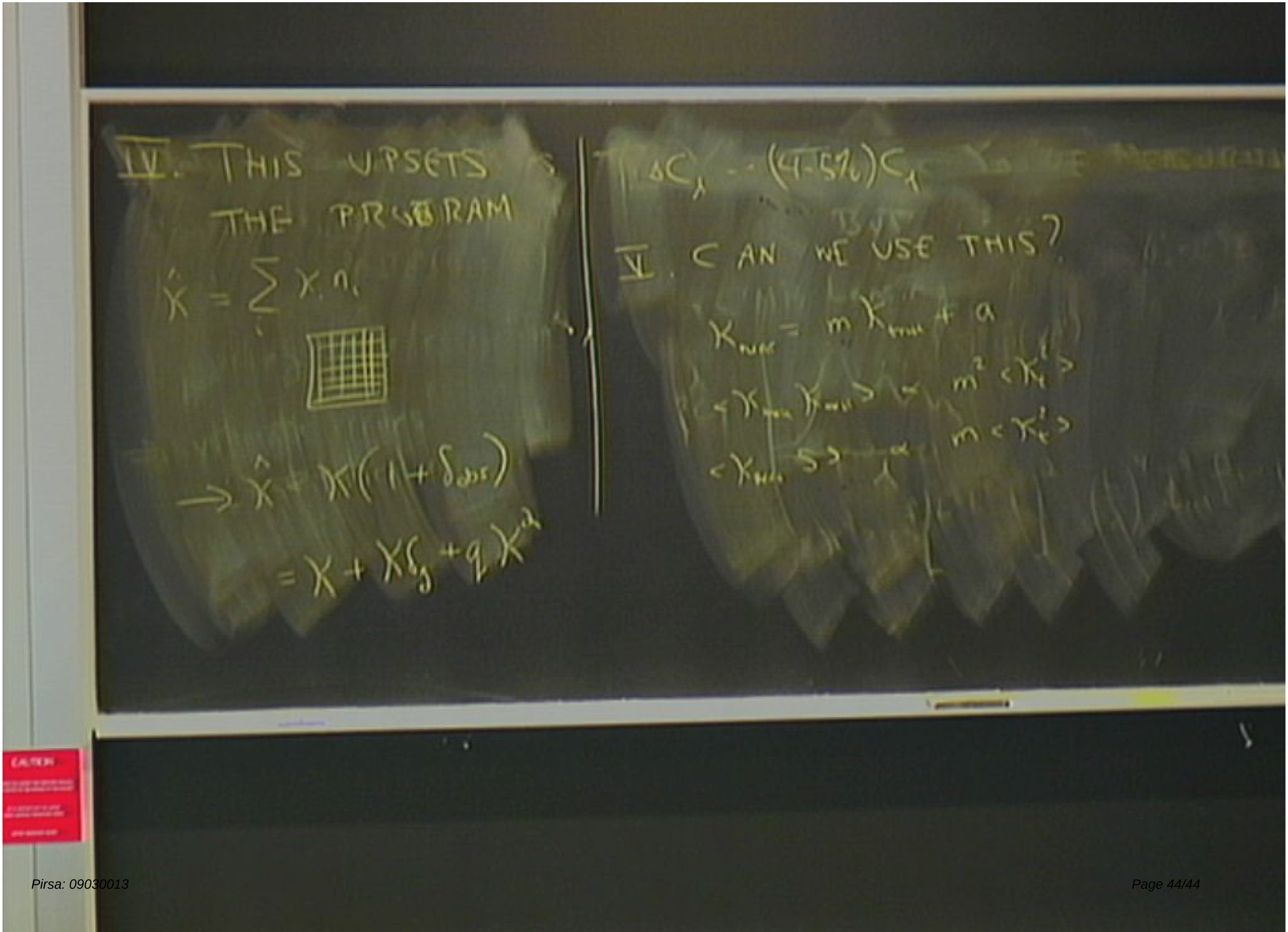
V. CAN WE USE THIS?
CAUTION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