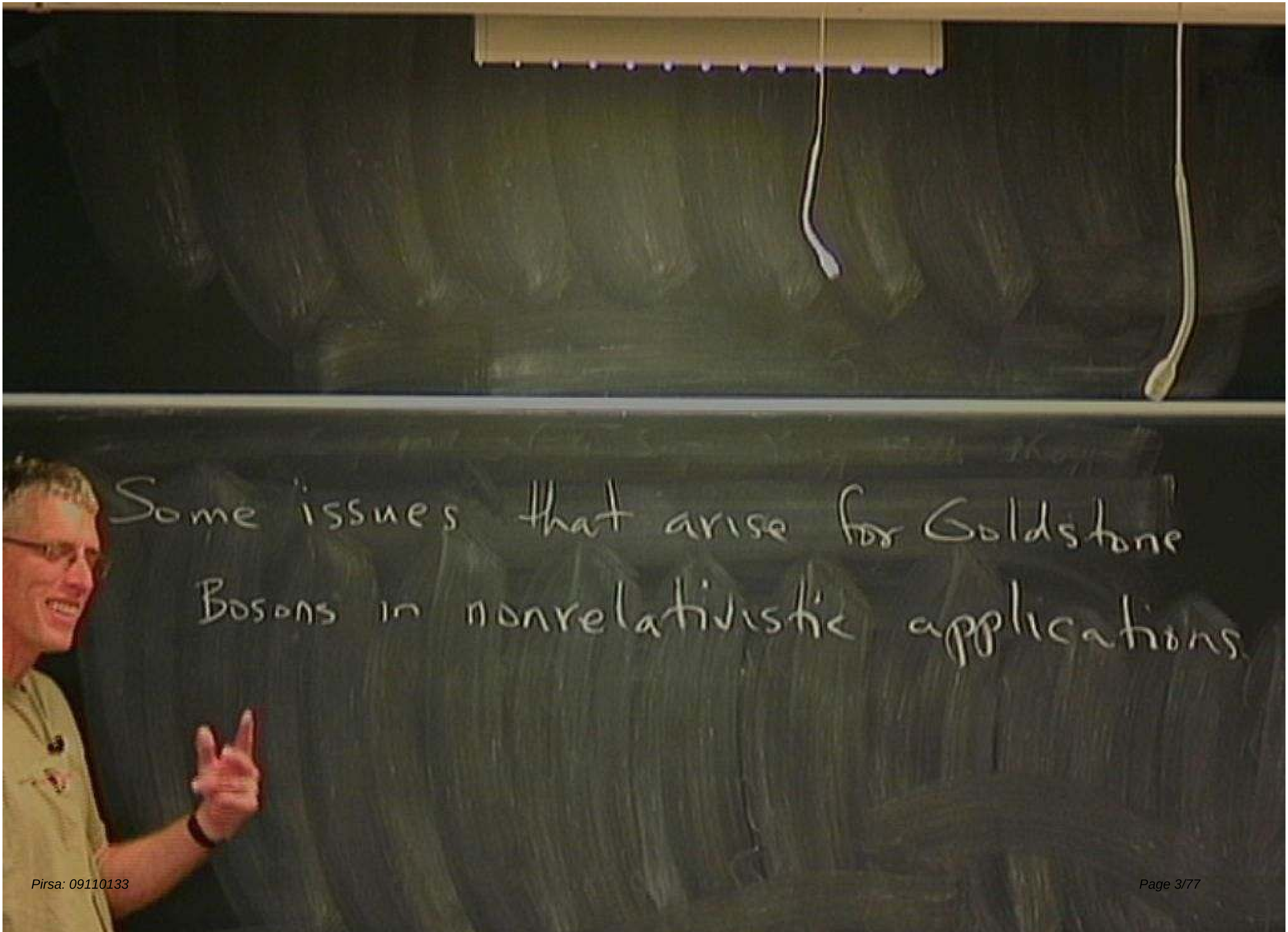
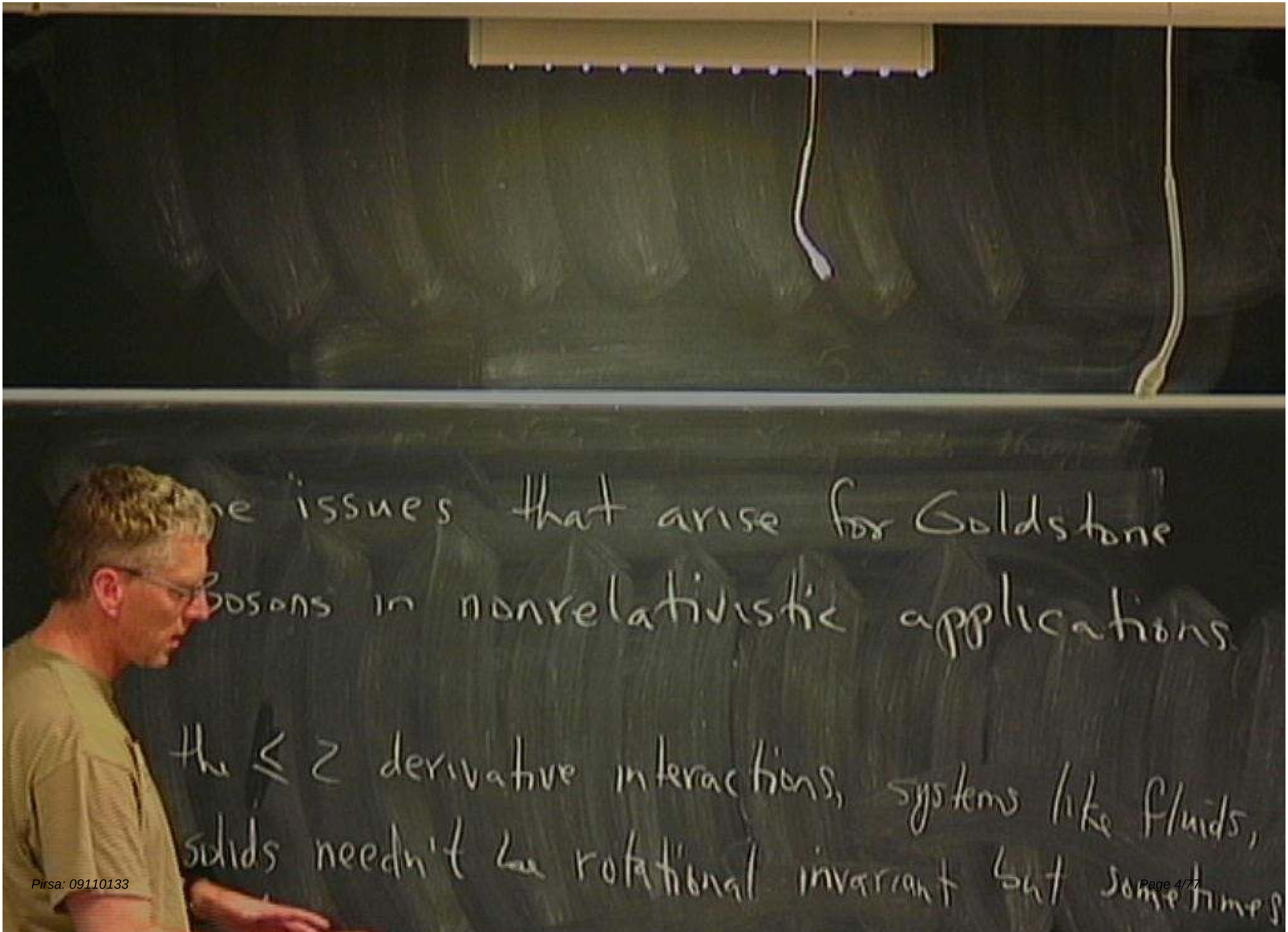
Title: Introduction to Effective Field Theory - Lecture 8C

Date: Nov 11, 2009 03:30 PM

URL: http://pirsa.org/09110133

Abstract:


Some issues that arise for Goldstone
Bosons in nonrelativistic applications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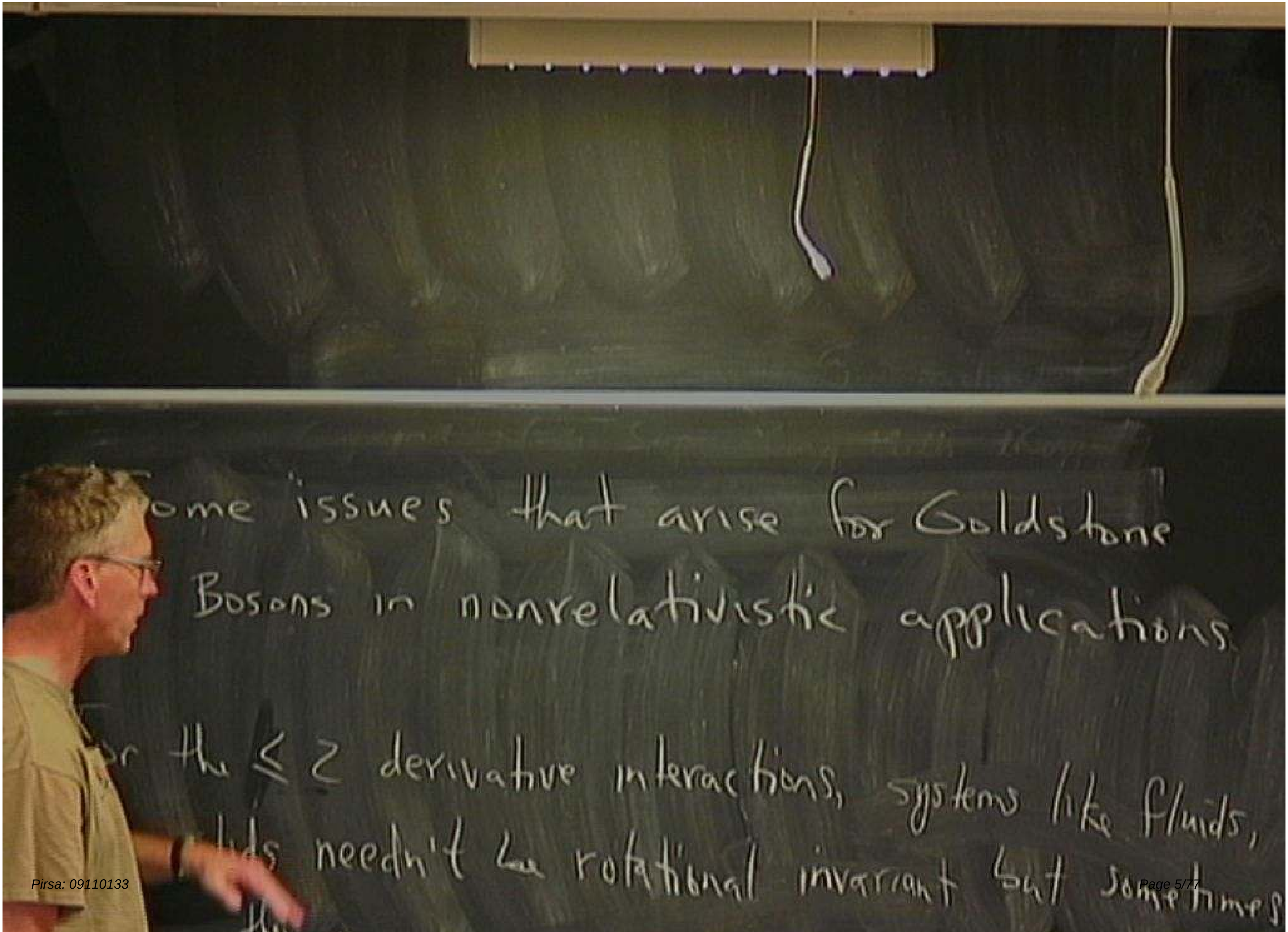
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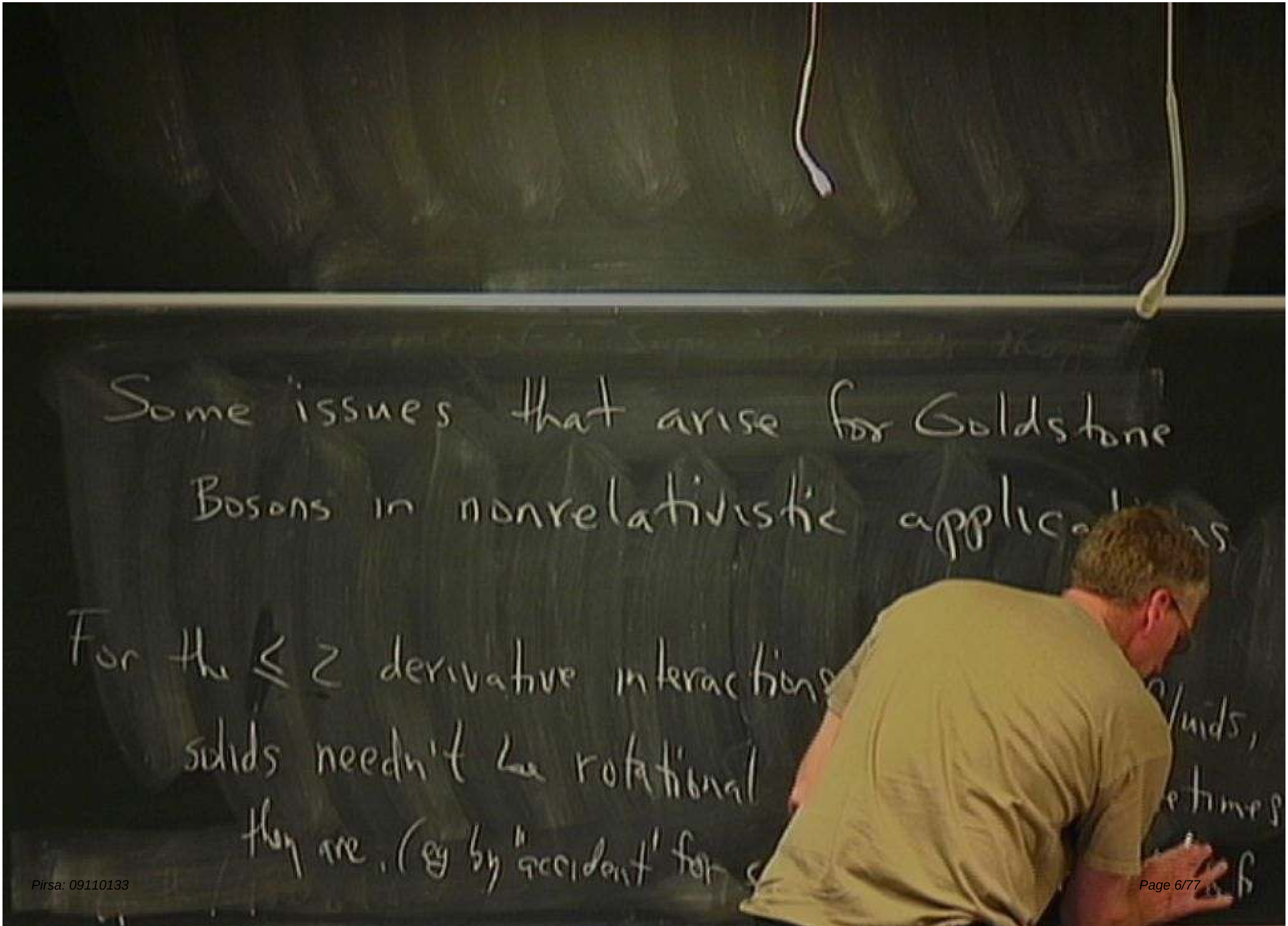
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Some issues that arise for Goldstone Bosons in nonrelativistic applications

For the ≤ 2 derivative interactions, systems like fluids, solids needn't be rotational invariant but sometimes they are. (eg by "accident" for some lattice groups, or explicitly for fluids)

But they all have a preferred frame, the rest frame of the fluid. Break Lorentz transformations.

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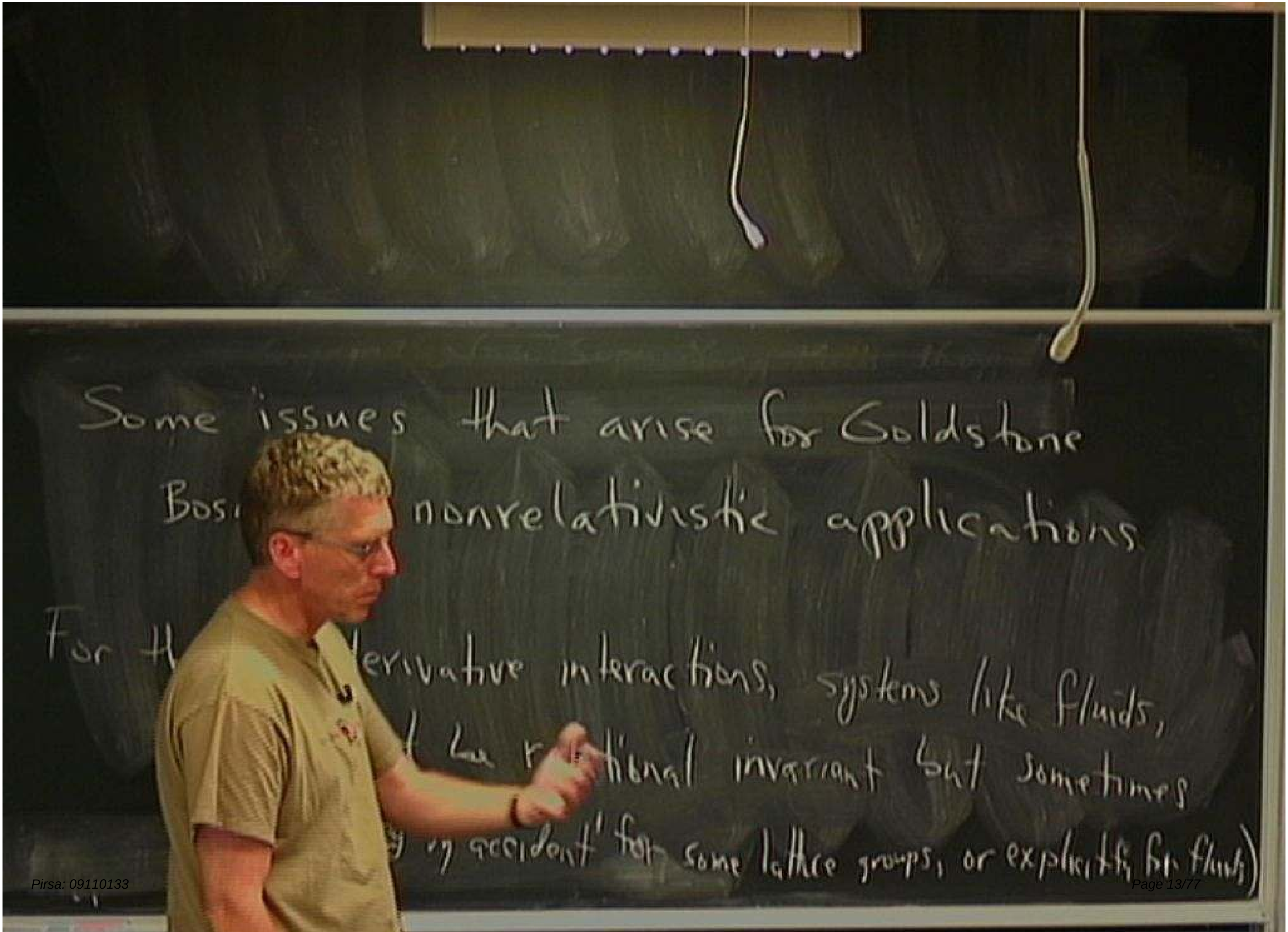
May or " " " T, P. eg ferromagnet breaks T ↑↑↑↑

anti " doesn't ↑↓↑↓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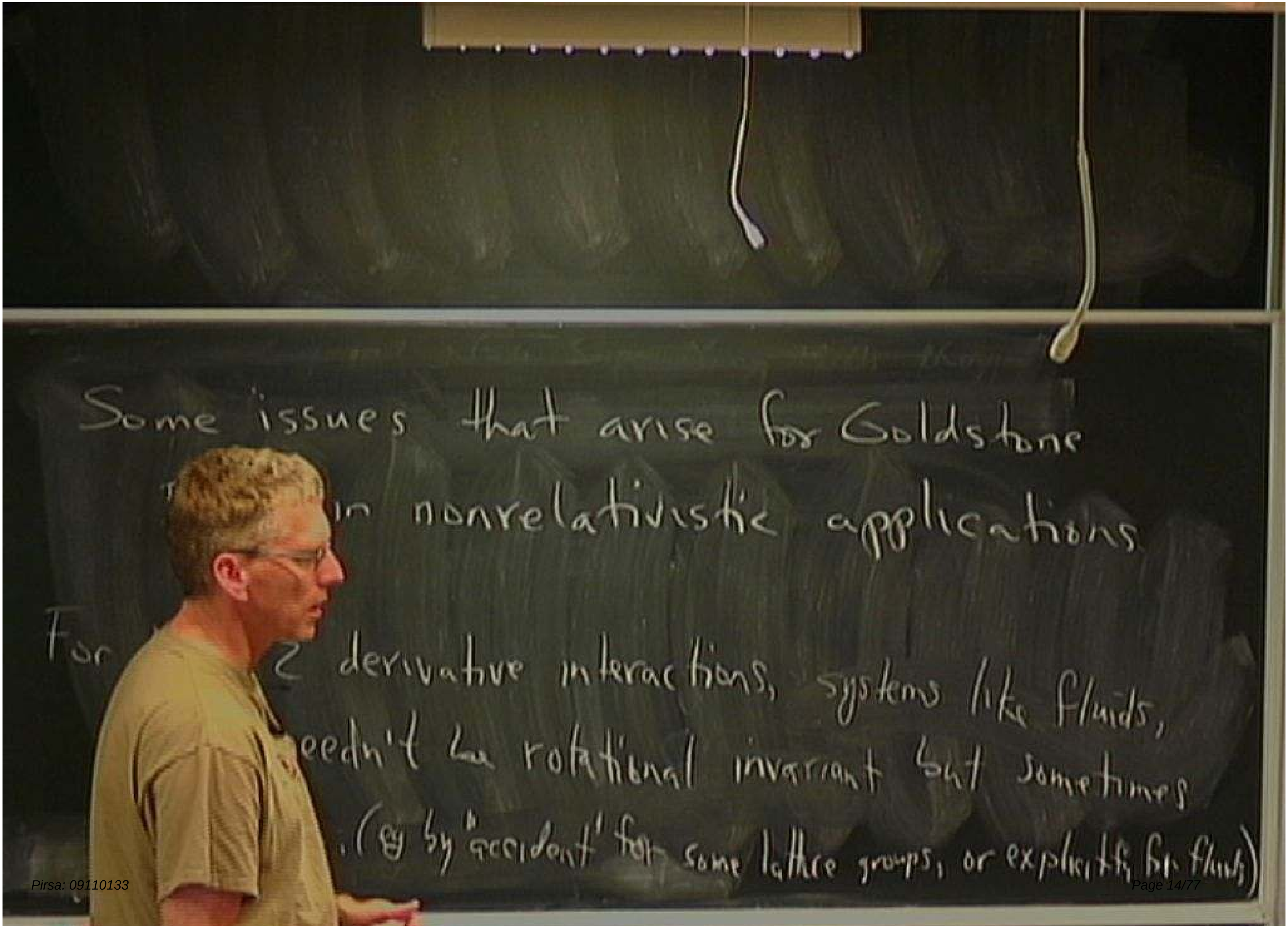
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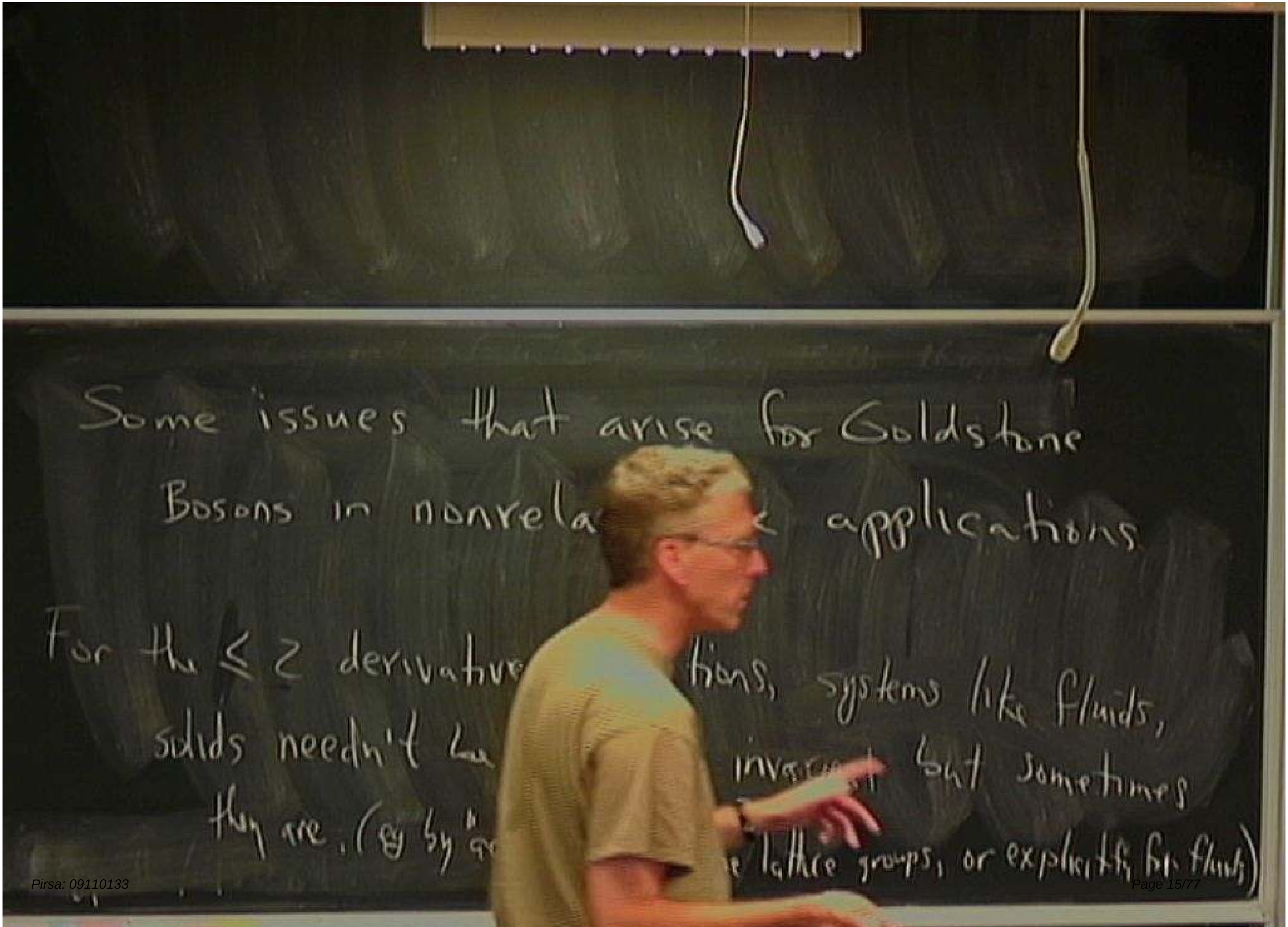
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eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \dots$

ST

X

G/H

$G_{\alpha\beta}$ metric on X

if $\theta^\alpha \to \tilde{\theta}^\alpha = \theta^\alpha + \xi^\alpha(\theta)$; $\mathcal{L}_{kin} \to -\frac{1}{2} \tilde{G}_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta$

where $\tilde{G}_{\alpha\beta} = G_{\alpha\beta} + \boxed{\xi^\gamma \partial_\gamma G_{\alpha\beta} + G_{\alpha\gamma}\partial_\beta \xi^\gamma + G_{\gamma\beta}\partial_\alpha \xi^\gamma}$

If T is unbroken (eg antiferromagnet) then eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \ldots$

$\boxed{ST} \to \boxed{X} \cong G/H$

$\boxed{G_{\alpha\beta} \text{ metric on } X}$

if $\theta^\alpha \to \tilde{\theta}^\alpha = \theta^\alpha + \xi^\alpha(\theta)\,\gamma$ $\quad \mathcal{L}_{kin} \to -\frac{1}{2} \tilde{G}_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta$

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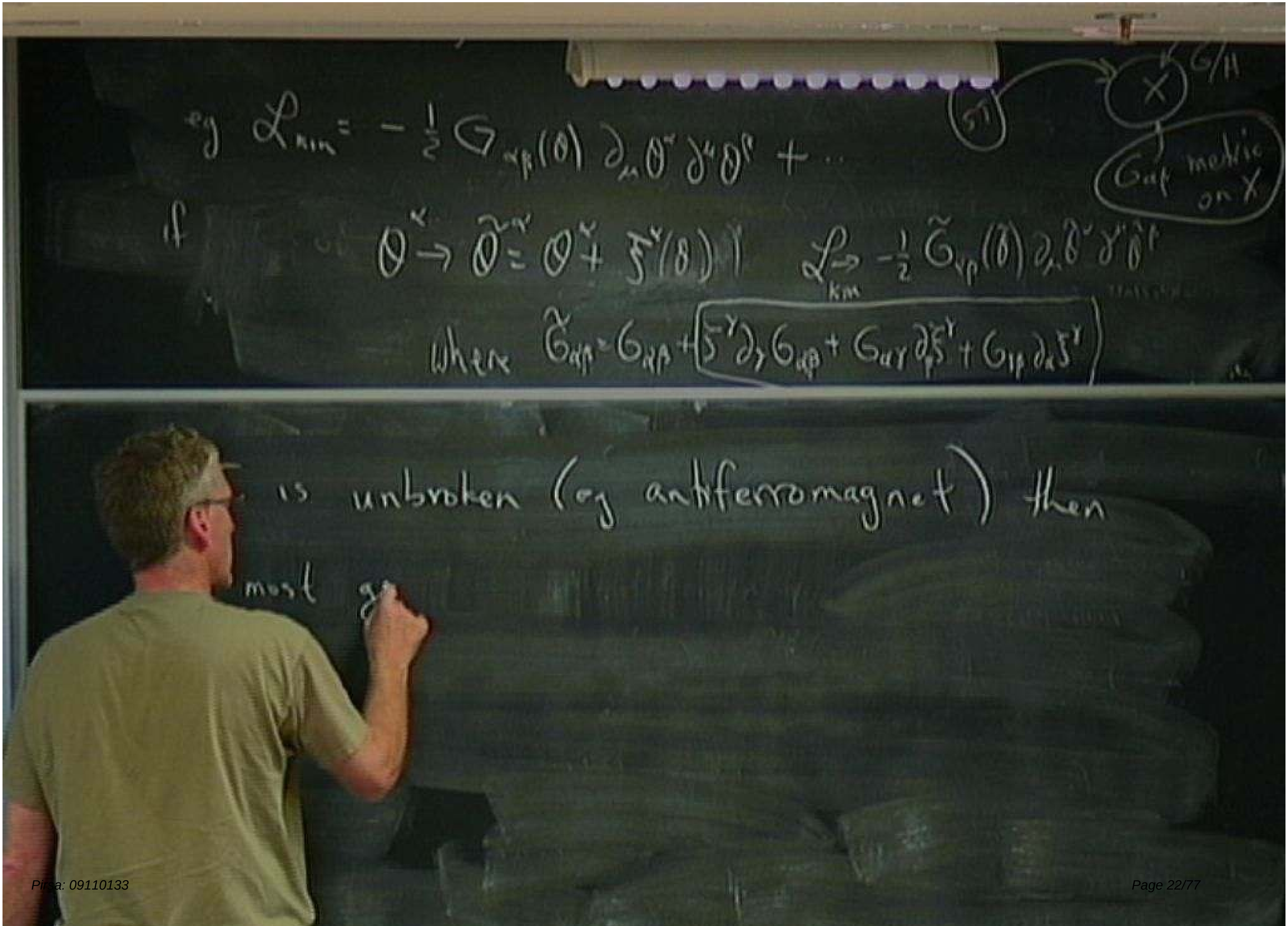
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ST
X
G/H
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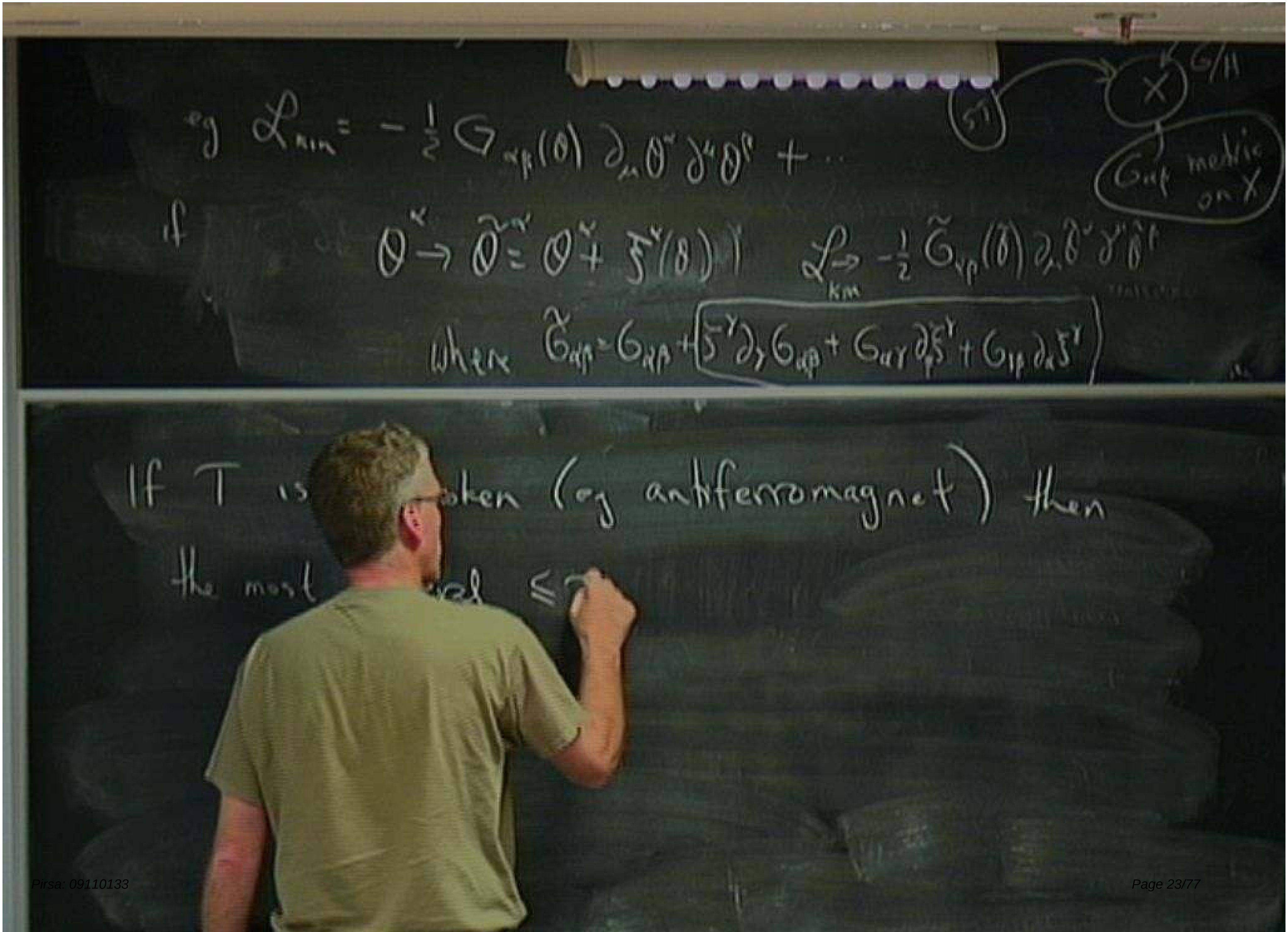
most g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G/H
X
$G_{\alpha\beta}$ metric on X
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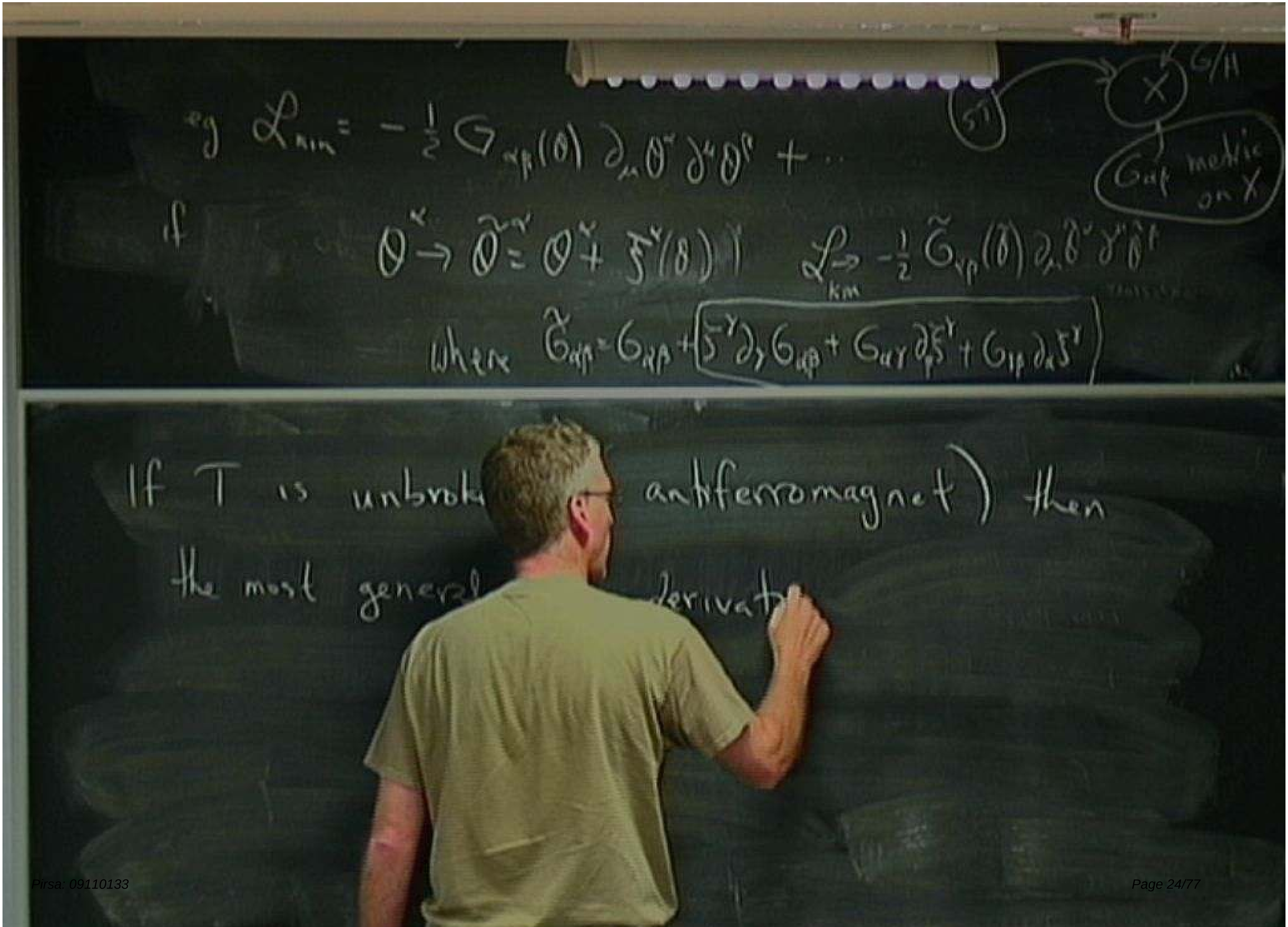
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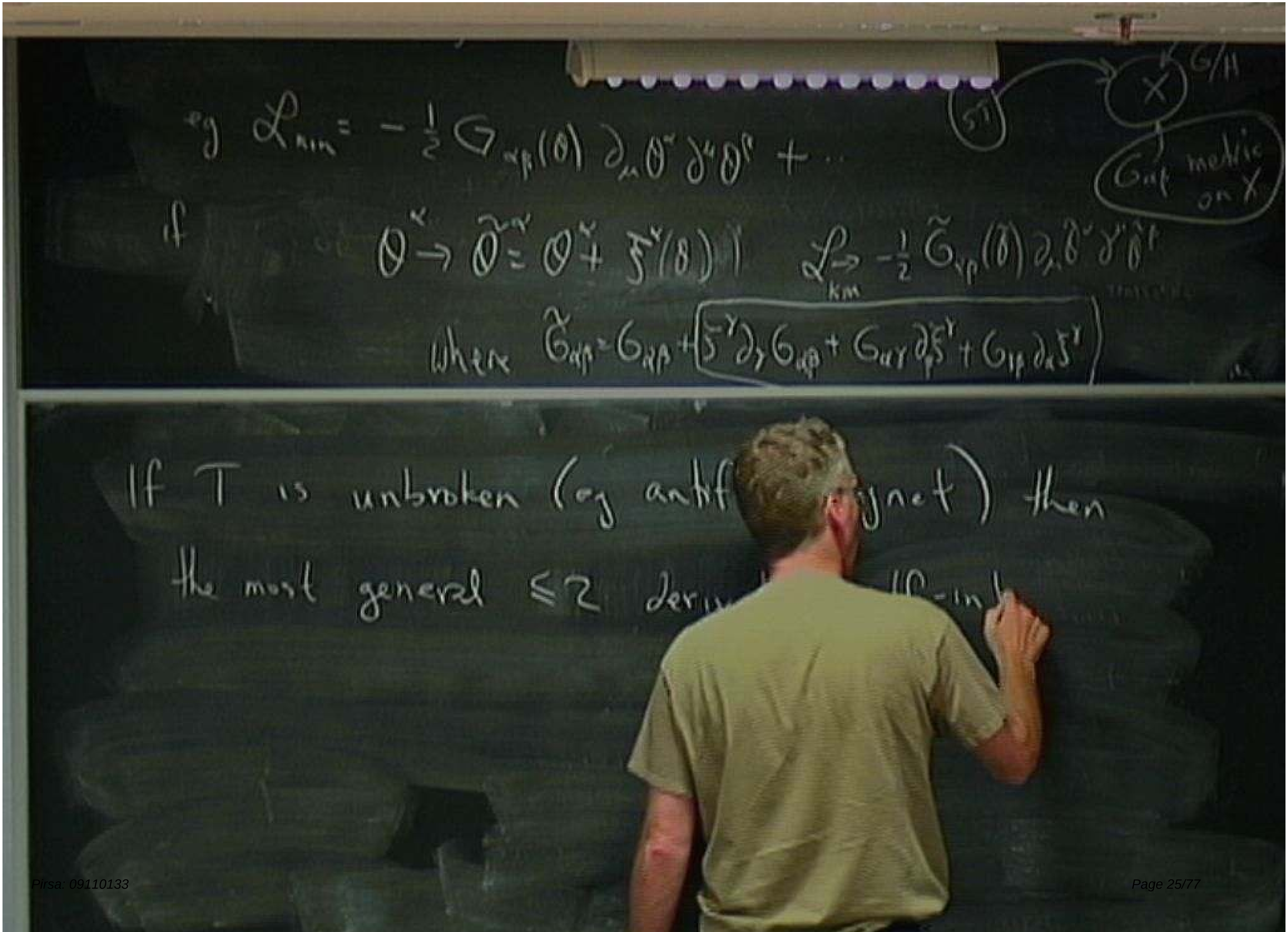
the most general derivat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if $\theta^\alpha \to \tilde{\theta}^\alpha = \theta^\alpha + \xi^\alpha(\theta)$
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ST
X
G/H
$G_{\alpha\beta}$ metric on X
If T is unbroken (eg antif
gnet) then
the most general ≤ 2 deriv
G-in

$ST \to X \leftarrow G/H$

$G_{\alpha\beta}$ metric on X

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If T is unbroken (eg antiferromagnet)

the most general ≤ 2 derivative self-in

ST → X ← G/H

$G_{\alpha\beta}$ metric on X

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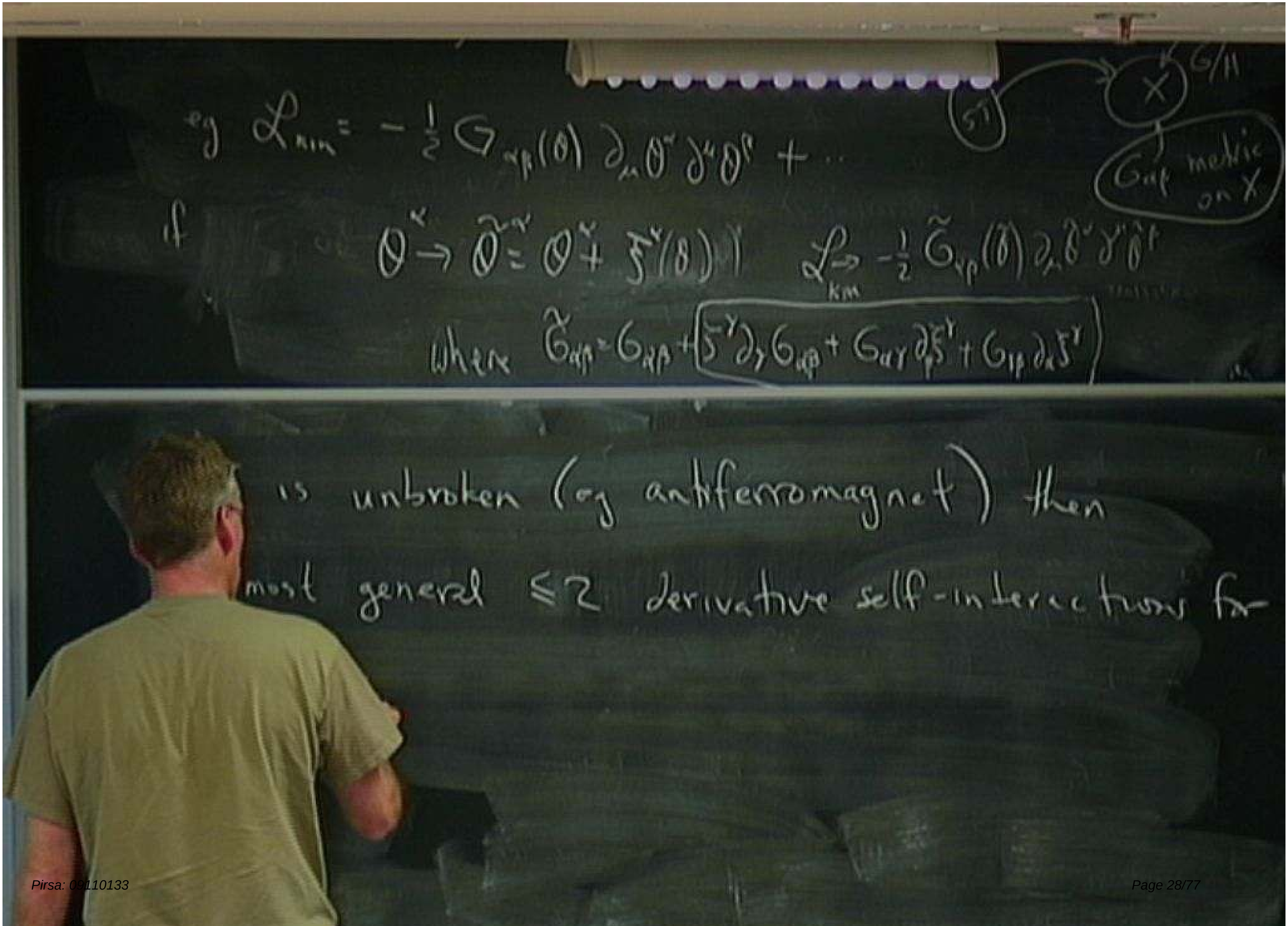
If T [is] unbroken (e.g. antiferromagnet) then the m[ost] general ≤ 2 derivative self-interactions for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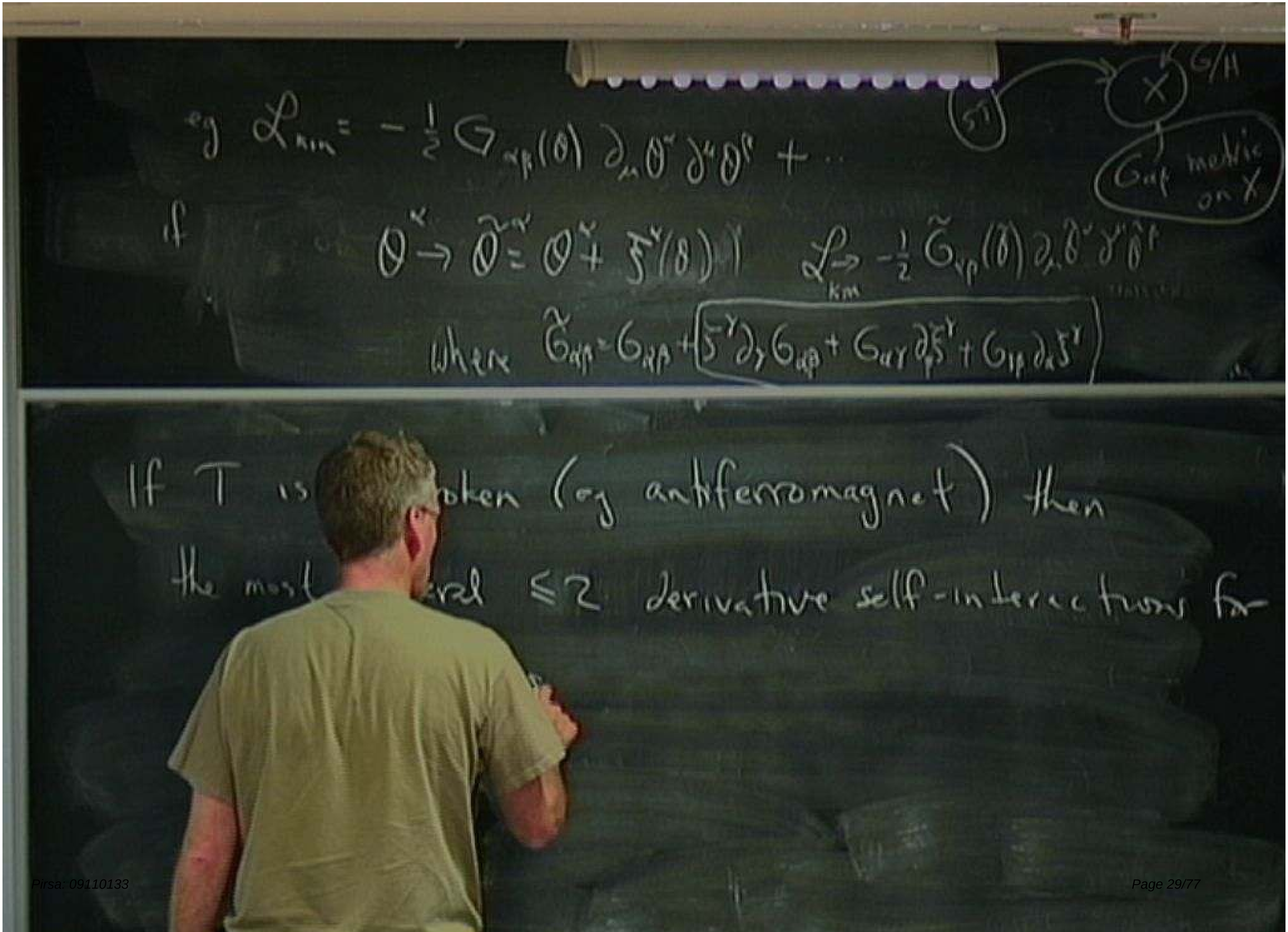
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If T is ... oken (eg antiferromagnet) then
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ST → X ← G/H

$G_{\alpha\beta}$ metric on X

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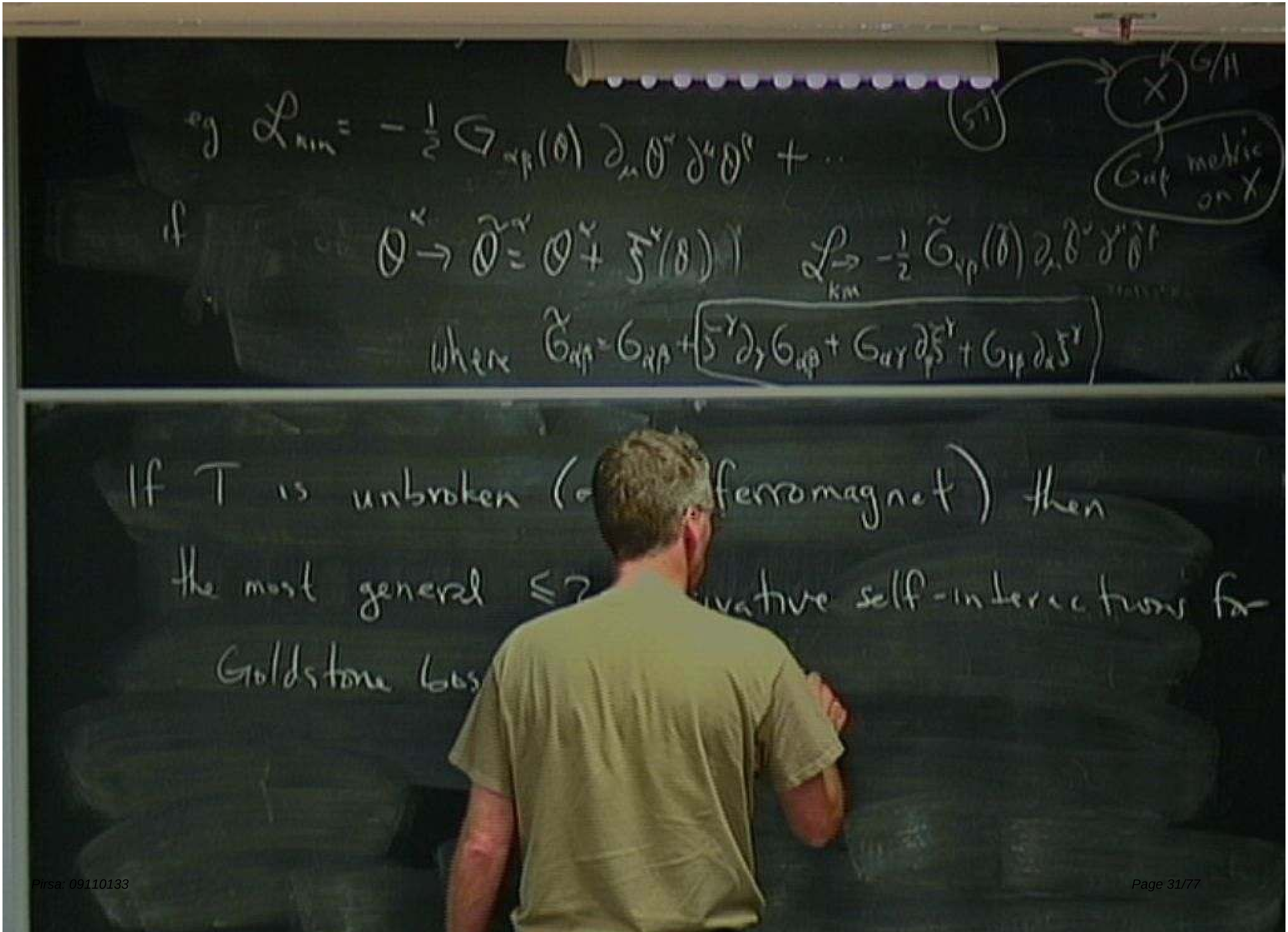
If T is unb… (eg antiferromagnet) then the most ge… ≤ 2 derivative self-interactions for Gol…



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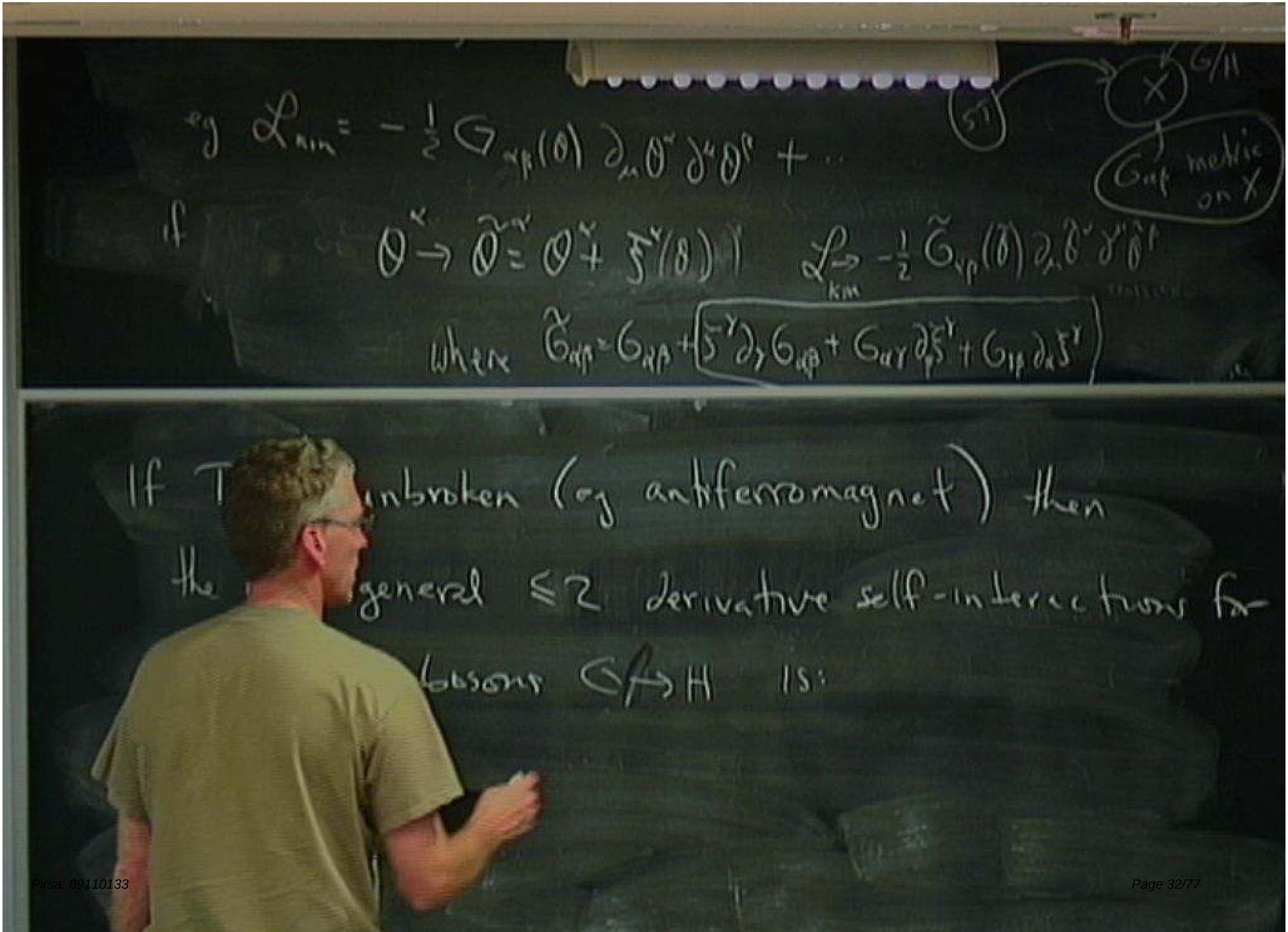
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If T ... unbroken (eg antiferromagnet) then
the ... general ≤ 2 derivative self-interactions for
... bosons G → H is:

eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \dots$

$G/H \to X$; ST; $G_{\alpha\beta}$ metric on X

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If T is unbroken (eg antiferromagnet) then the most general ≤ 2 derivative self-interactions for Goldstone bosons $G \to H$ are:

$\mathcal{L}_{\leq 2\,deriv} = -$

eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \ldots$

$\xrightarrow{\text{ST}} X \; G/H$

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$$\mathcal{L}_{\leq 2\,deriv} = -V_0 - \frac{F^2}{2} G_{\alpha\beta}(\theta) \nabla\theta^\alpha \cdot \nabla\theta^\beta + \frac{F_t^2}{2} G_{\alpha\beta}(\theta)\, \dot{\theta}^\alpha \dot{\theta}^\beta + \dots$$

const

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ST   X   G/H

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irrel

eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \dots$

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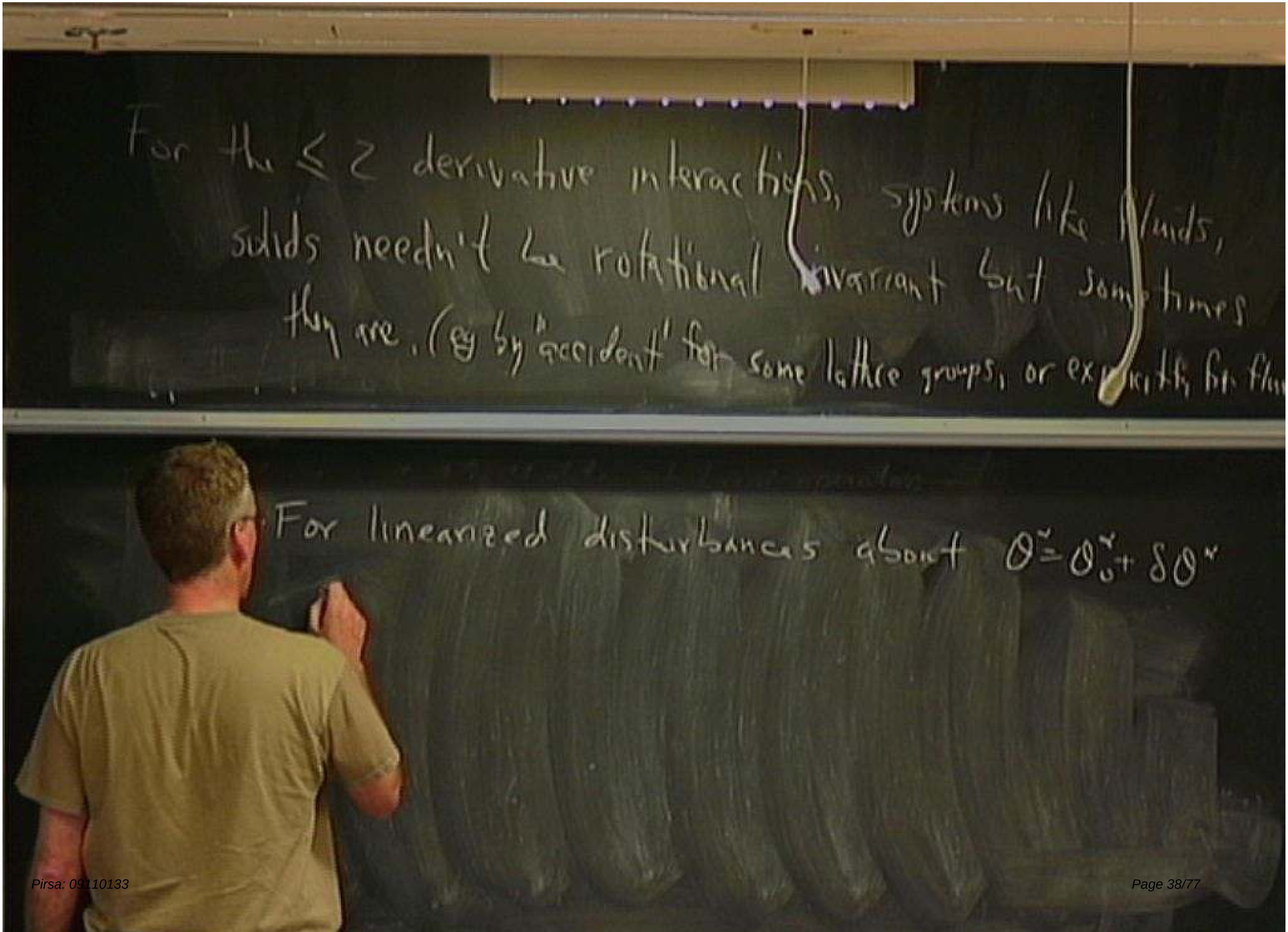
$\uparrow$ const


For the ≤ 2 derivative interactions, systems like fluids,
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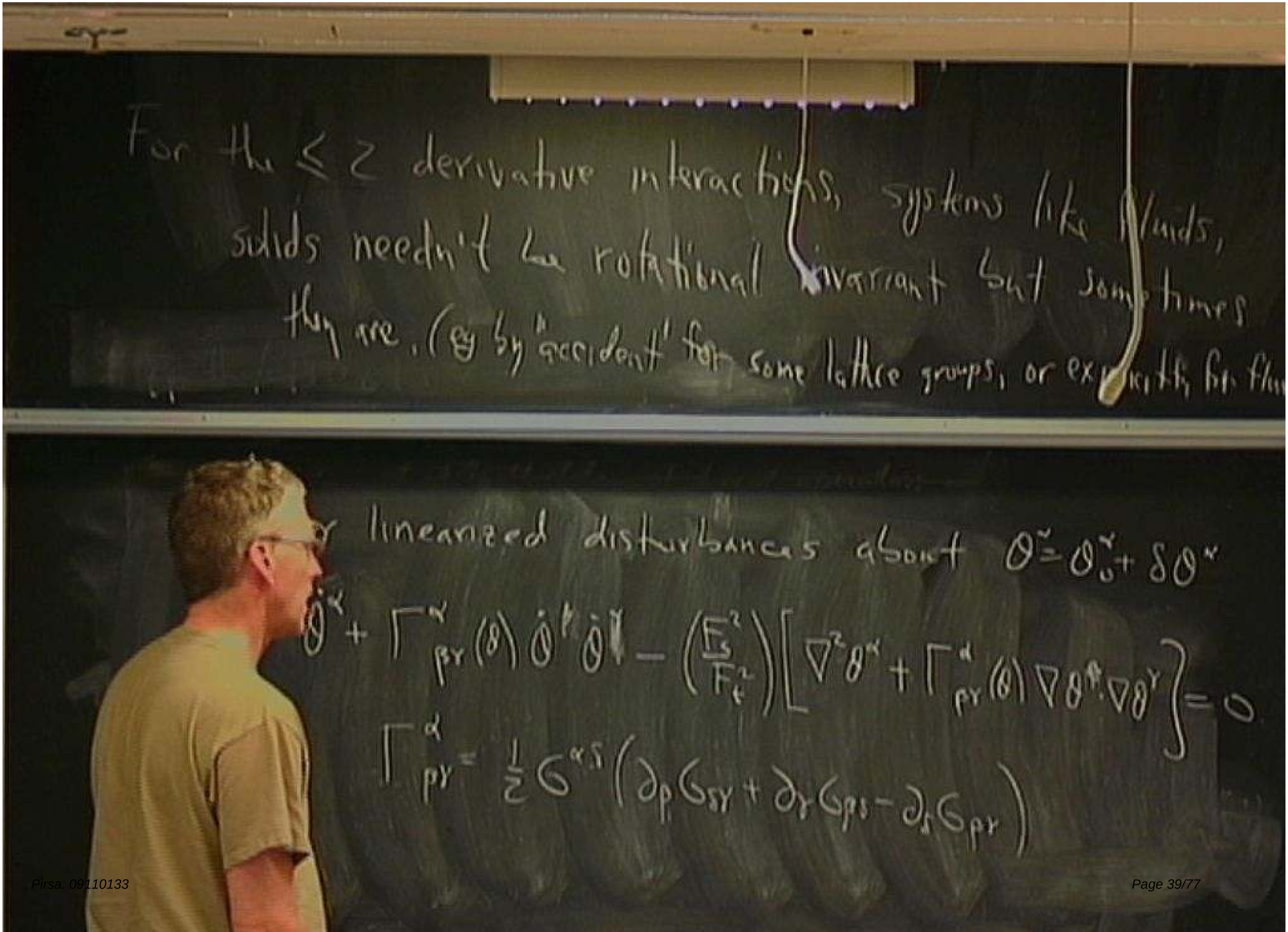
For linearized disturbances about $\theta^\alpha = \theta^\alpha_0 + \delta\theta^\alpha$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linearized disturbances about $\theta^\alpha = \theta^\alpha_0 + \delta\theta^\alpha$
$\ddot\theta^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\dot\theta^\beta\dot\theta^\gamma - \left(\frac{F_s^2}{F_t^2}\right)\left[\nabla^2\theta^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\nabla\theta^\beta\cdot\nabla\theta^\gamma\right\} = 0$
$\Gamma^\alpha_{\beta\gamma} = \frac{1}{2} G^{\alpha\delta}\left(\partial_\beta G_{\delta\gamma} + \partial_\gamma G_{\beta\delta} - \partial_\delta G_{\beta\gamma}\right)$

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For linearized disturbances about $\theta^\alpha = \theta^\alpha_0 + \delta\theta^\alpha$

$$\ddot{\theta}^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\dot{\theta}^\beta\dot{\theta}^\gamma - \left(\frac{F_s^2}{F_t^2}\right)\left[\nabla^2\theta^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\nabla\theta^\beta\cdot\nabla\theta^\gamma\right\} = 0$$

$$\Gamma^\alpha_{\beta\gamma} = \frac{1}{2} G^{\alpha\delta}\left(\partial_\beta G_{\delta\gamma} + \partial_\gamma G_{\beta\delta} - \partial_\delta G_{\beta\gamma}\right)$$

eg $\mathcal{L}_{kin} = -\frac{1}{2} G_{\alpha\beta}(\theta)\, \partial_\mu \theta^\alpha \partial^\mu \theta^\beta + \dots$

(ST) (X)

$G_{\alpha\beta}$ metric on X

if

$\theta^\alpha \to \tilde{\theta}^\alpha = \theta^\alpha + \xi^\alpha(\theta)$ $\mathcal{L}_{kin} \to -\frac{1}{2} \tilde{G}_{\gamma\rho}(\theta)\, \partial_\mu \theta^\gamma \partial^\mu \theta^\rho$

where $\tilde{G}_{\alpha\beta} = G_{\alpha\beta} + \boxed{\xi^\gamma \partial_\gamma G_{\alpha\beta} + G_{\alpha\gamma} \partial_\beta \xi^\gamma + G_{\gamma\beta} \partial_\alpha \xi^\gamma}$

If T is unbroken (eg antiferromagnet) then the most general ≤ 2 derivative self-interactions for Goldstone bosons $G \to H$ are: [assuming rot, transl, inv]

$$\mathcal{L}_{\leq 2\, deriv} = -V_0 - \frac{F_s^2}{2} G_{\alpha\beta}(\theta) \nabla\theta^\alpha \cdot \nabla\theta^\beta + \underbrace{\frac{F_t^2}{2} G_{\alpha\beta}(\theta)\, \dot{\theta}^\alpha \dot{\theta}^\beta + \dots}_{-\frac{1}{2} F^2 G_{\alpha\beta}(\theta) \partial_\mu\theta^\alpha \partial^\mu \theta^\beta \text{ if LI}}$$

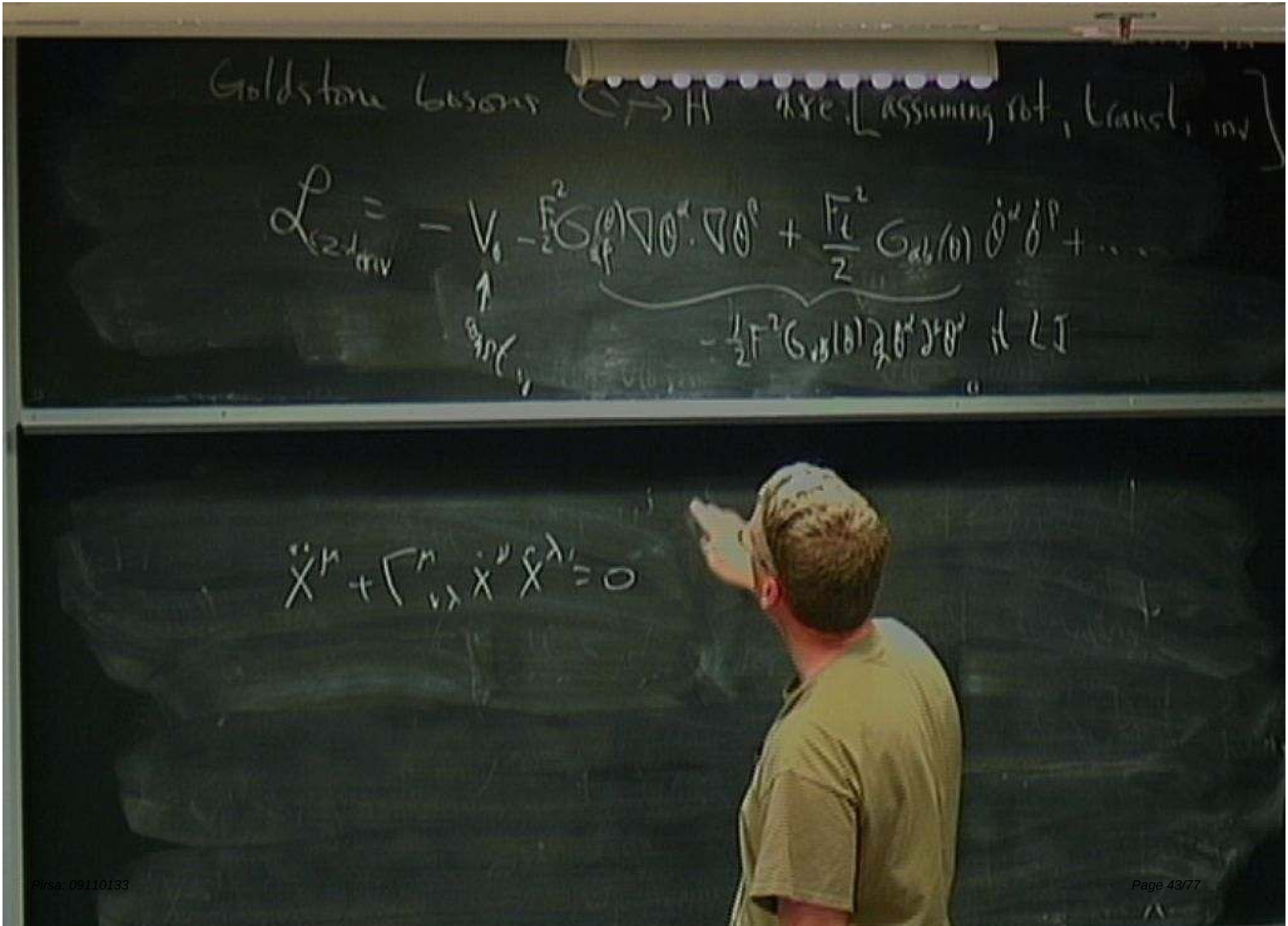
For the ≤ 2 derivative interactions, systems like fluids, solids needn't be rotational invariant but sometimes they are. (eg by 'accident' for some lattice groups, or explicitly for flu

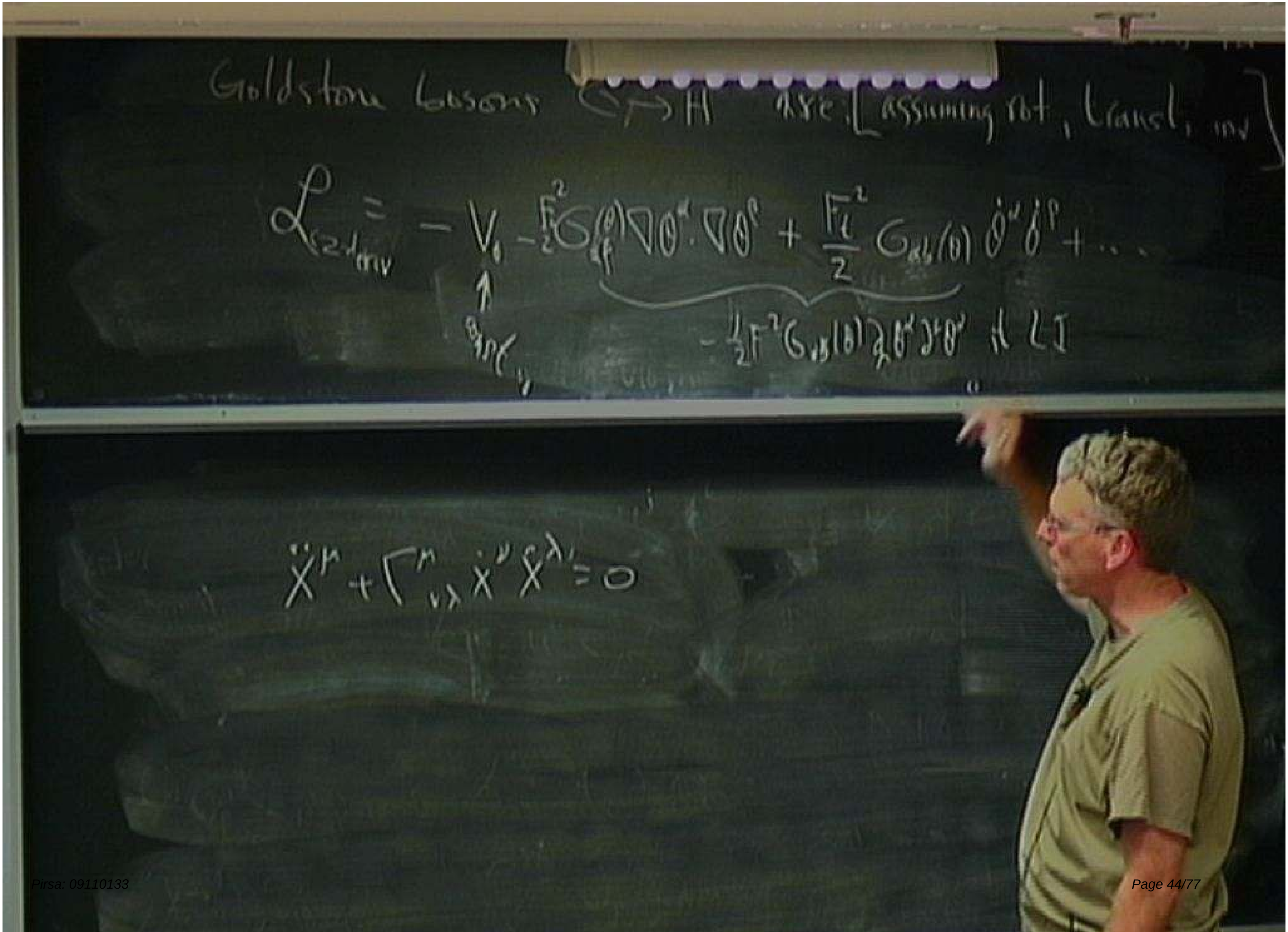
For linearized disturbances about $\theta^\alpha = \theta_0^\alpha + \delta\theta^\alpha$

$$\ddot{\theta}^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\underline{\dot{\theta}^\beta\dot{\theta}^\gamma} - \left(\frac{F_s^2}{F_t^2}\right)\left[\nabla^2\theta^\alpha + \Gamma^\alpha_{\beta\gamma}(\theta)\,\nabla\theta^\beta\cdot\nabla\theta^\gamma\right\} = 0.$$

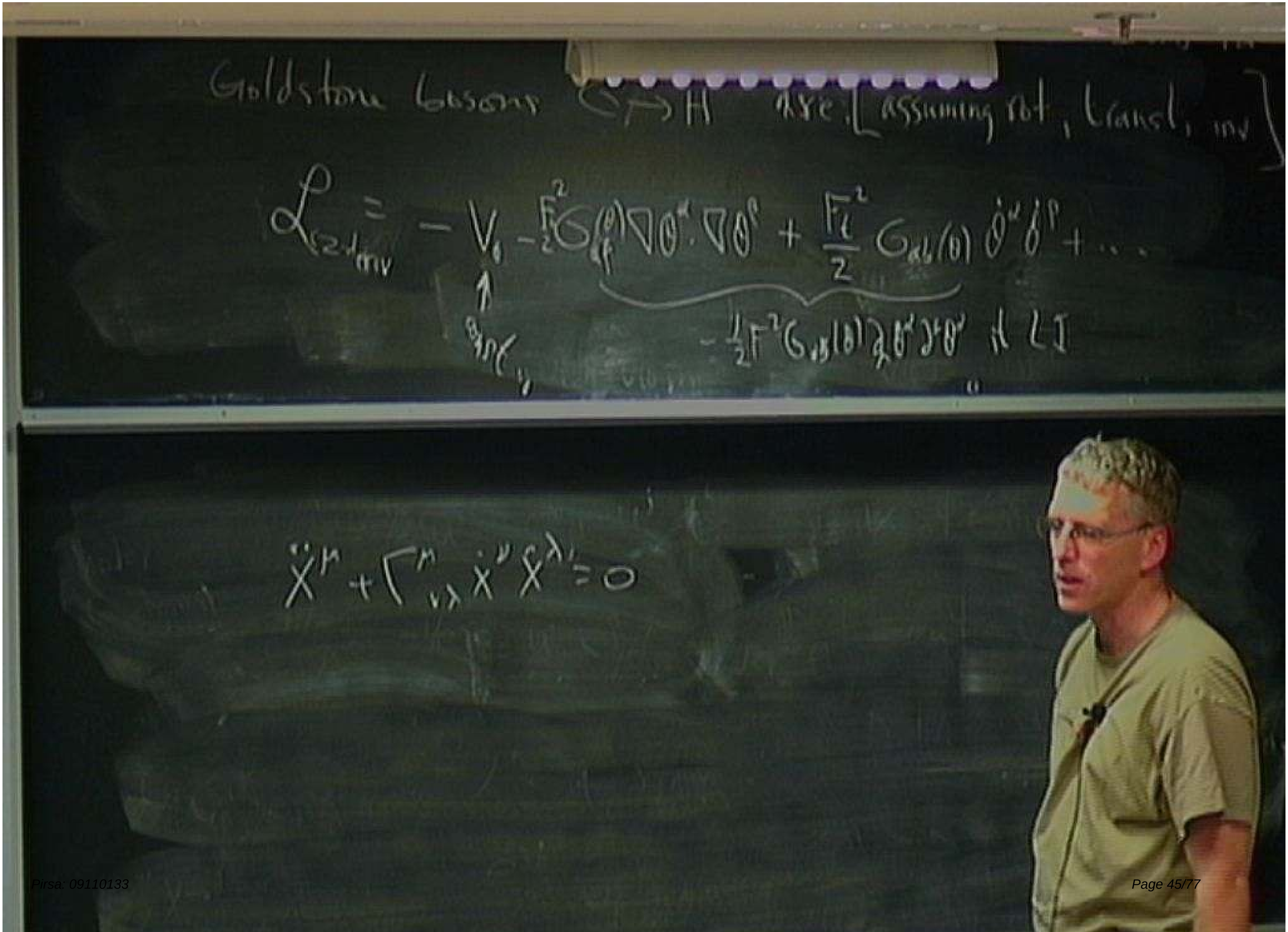
$$\Gamma^\alpha_{\beta\gamma} = \frac{1}{2}G^{\alpha\delta}\left(\partial_\beta G_{\delta\gamma} + \partial_\gamma G_{\beta\delta} - \partial_\delta G_{\beta\gamma}\right)$$

linearize: $\ddot{\theta}^\alpha - \left(\frac{F_s^2}{F_t^2}\right)\nabla^2\theta^\alpha = 0 \qquad \omega^2 = v_s^2\vec{p}^{\,2} \qquad v_s = \frac{F_s}{F_t}$


Goldstone bosons G → H
[assuming rot, transl, inv]
$\mathcal{L} = -V_0 - \frac{F_s^2}{2} G_{ab}(\theta)\nabla\theta^a\cdot\nabla\theta^b + \frac{F_t^2}{2} G_{ab}(\theta)\dot\theta^a\dot\theta^b + \dots$
$-\frac{1}{2}F^2 G_{ab}(\theta)\partial_\mu\theta^a\partial^\mu\theta^b$
$\ddot{x}^\mu + \Gamma^\mu_{\nu\lambda}\dot{x}^\nu\dot{x}^\lambda = 0$



Goldstone bosons G → H aka [assuming rot, transl, inv]
$\mathcal{L}_{2\,deriv} = -V_0 - \frac{F_r^2}{2} G_{\alpha\beta}(\theta) \nabla\theta^\alpha \cdot \nabla\theta^\beta + \frac{F_t^2}{2} G_{\alpha\beta}(\theta)\, \dot\theta^\alpha \dot\theta^\beta + \ldots$
$-\frac{1}{2} F^2 G_{\alpha\beta}(\theta)\, \partial_\mu\theta^\alpha \partial^\mu\theta^\beta$ if LI
$\ddot X^\mu + \Gamma^\mu_{\nu\lambda} \dot X^\nu \dot X^\lambda = 0$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Goldstone bosons $G \to H$ are, [assuming rot, transl, inv]

$$\mathcal{L}_{(2\,\mathrm{deriv})} = \underset{\substack{\uparrow \\ \text{const}}}{-V_1} \underbrace{- \frac{F_s^2}{2} G_{\alpha\beta}(\theta)\, \nabla\theta^\alpha \cdot \nabla\theta^\beta + \frac{F_t^2}{2} G_{\alpha\beta}(\theta)\, \dot\theta^\alpha \dot\theta^\beta}_{-\frac{1}{2} F^2 G_{\alpha\beta}(\theta)\, \partial_\mu\theta^\alpha \partial^\mu\theta^\beta \ \text{if LI}} + \dots$$

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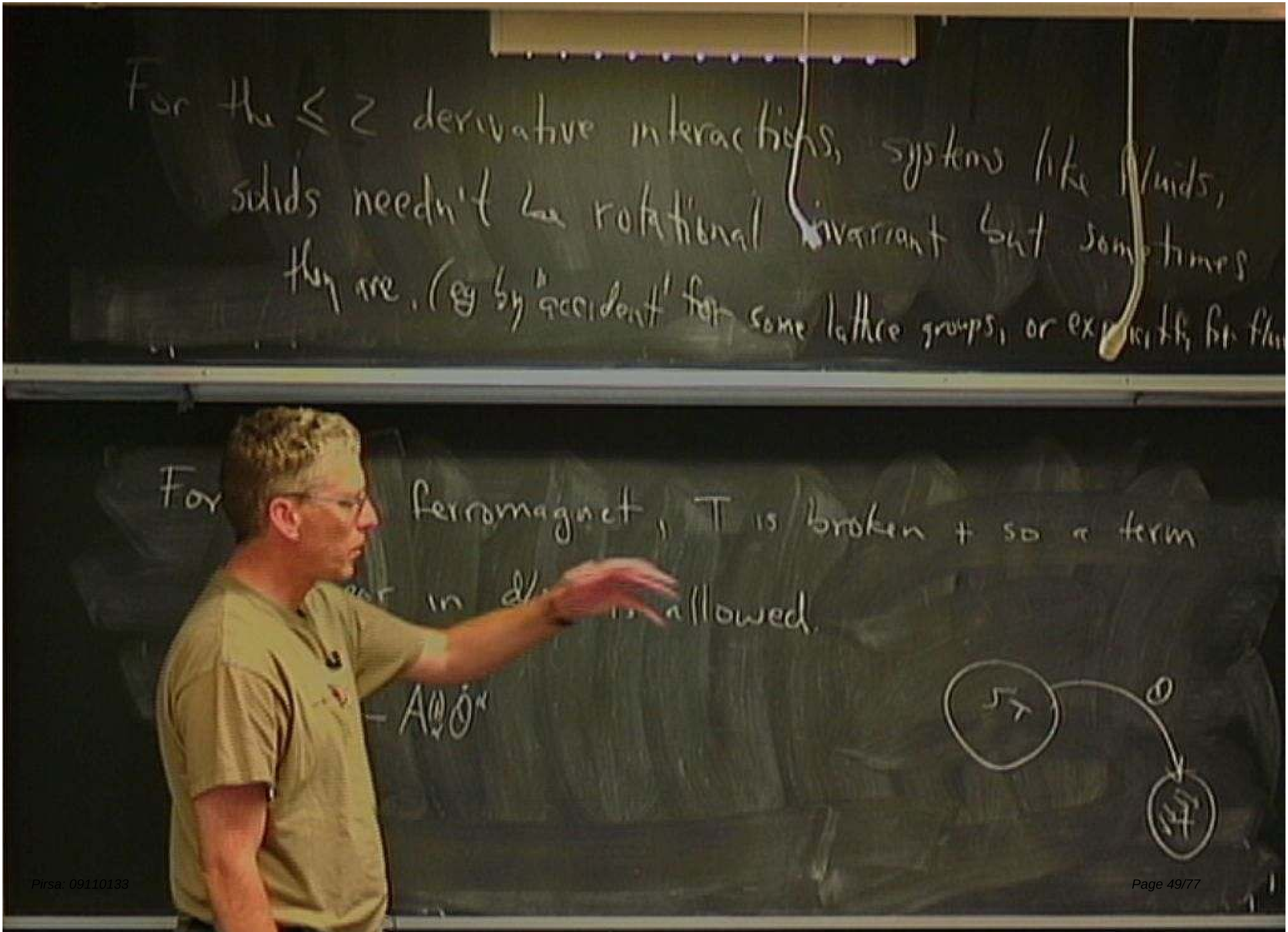
For an ferromagnet, T is broken + so a term linear in d/dt is allowed.

$$\mathcal{L}_{1\text{-der.}} = -A(\theta)\dot{\theta}^{\alpha}$$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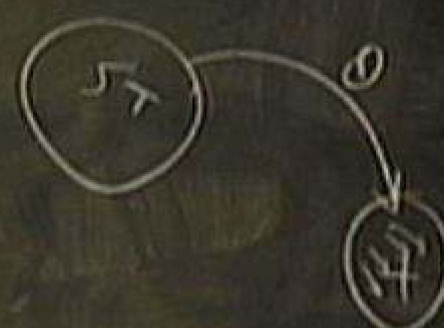

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– May or may not break translation inv. (assume not).
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anti " doesn't ↑↓↑↓

In some cases (eg $SO(3) \to SO(2)$) no invariant such
an $\mathcal{L}_{1\text{-}d}$ is possible, because there is no such
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<u>BUT</u> G being a symmetry only requires $S = \int dt\, d^3x\, \mathcal{L}$ to inv.

when is $\delta \mathcal{L}_{1\text{-}d\text{er}} = \frac{d}{dt}\Omega(\theta)$?

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$$-\frac{1}{2}F^2 G_{\alpha\beta}(\theta)\,\partial_\mu\theta^\alpha\,\partial^\mu\theta^\beta$$

$$\theta^\alpha \to \theta^\alpha + \delta\theta^\alpha$$

$$A_\alpha(\theta)\,\dot\theta^\alpha \to A_\alpha\,\delta\dot\theta^\alpha + \partial_\beta A_\alpha\,\delta\theta^\beta\,\dot\theta^\alpha$$

$$= \frac{d}{dt}\left[A_\alpha\,\delta\theta^\alpha\right] + \left(-\partial_\beta A_\alpha\,\dot\theta^\beta + \partial_\alpha A_\beta\,\dot\theta^\beta\right)$$

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$\uparrow$ Λ const

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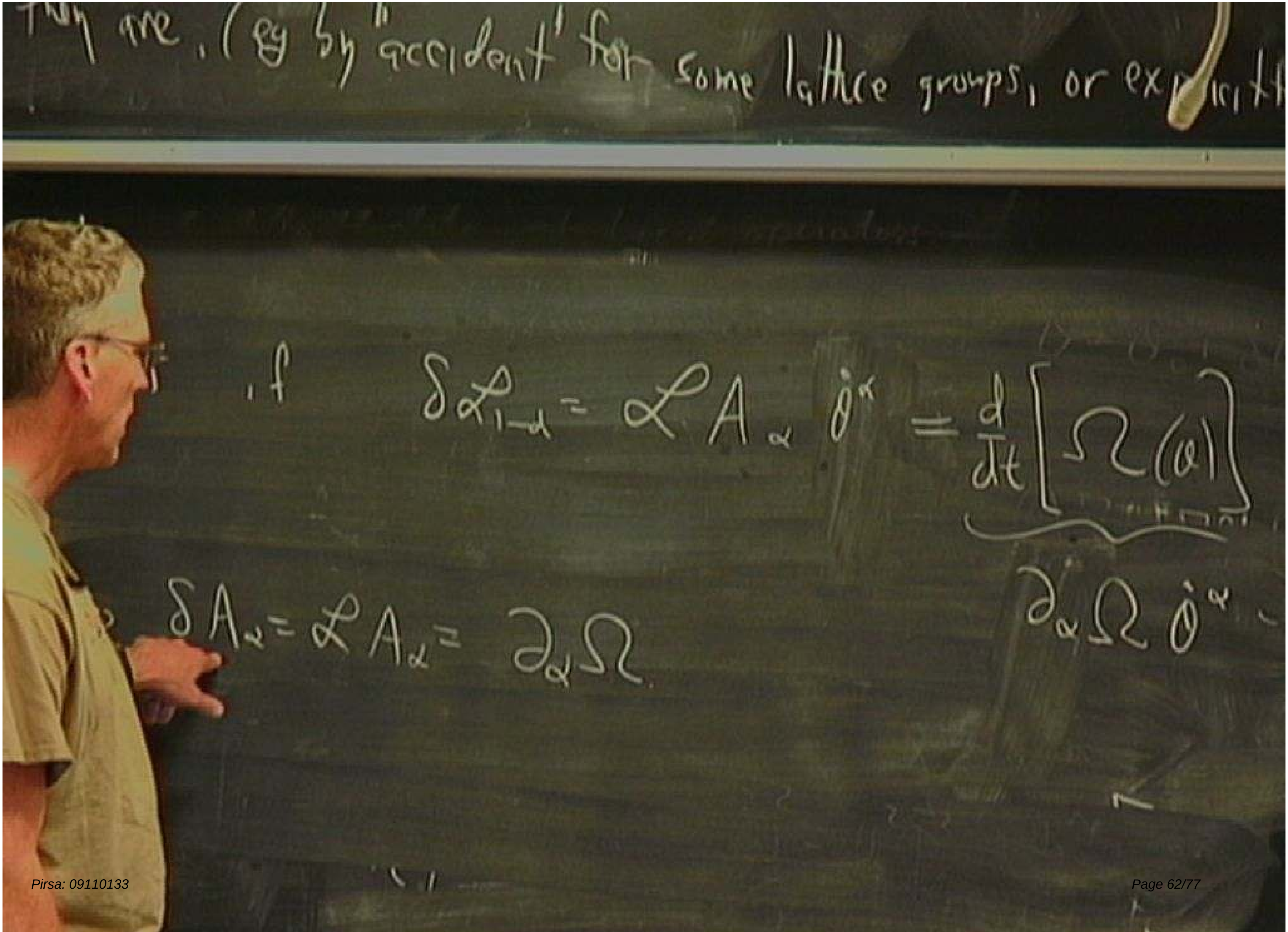
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$\delta A_\alpha = \mathcal{L} A_\alpha = \partial_\alpha \Omega$

$$\mathcal{L}_{2\text{-deriv}} = -V_0 - \tfrac{1}{2} G_{\alpha\beta}(\theta)\nabla\theta \cdot \nabla\theta + \frac{i\hbar}{2} G_{ab}(\theta)\, \dot\theta\, \dot\theta + \ldots$$

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so $\delta A_\alpha = \mathcal{L} A_\alpha = \partial_\alpha \Omega$

S Invariance only requires A_α to be inv. up to a gauge transf^n.

ie $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$ to be inv.

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So in the example of most interest

$SO(3) \to SO(2)$ where $SO(3)/SO(2) = S_2$

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$\mathcal{L}_{1-d} = c\cos\theta\,\dot{\theta}$

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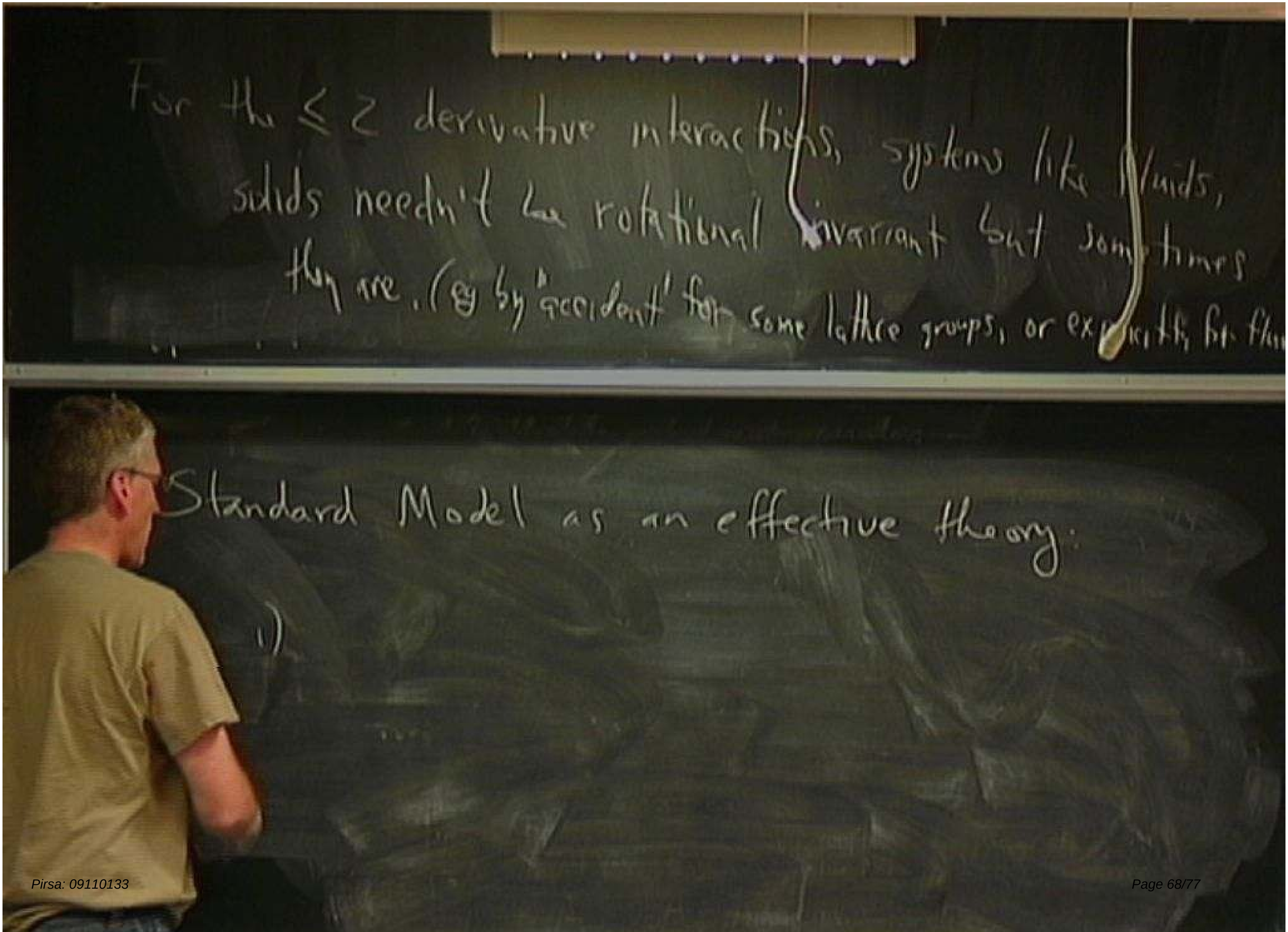
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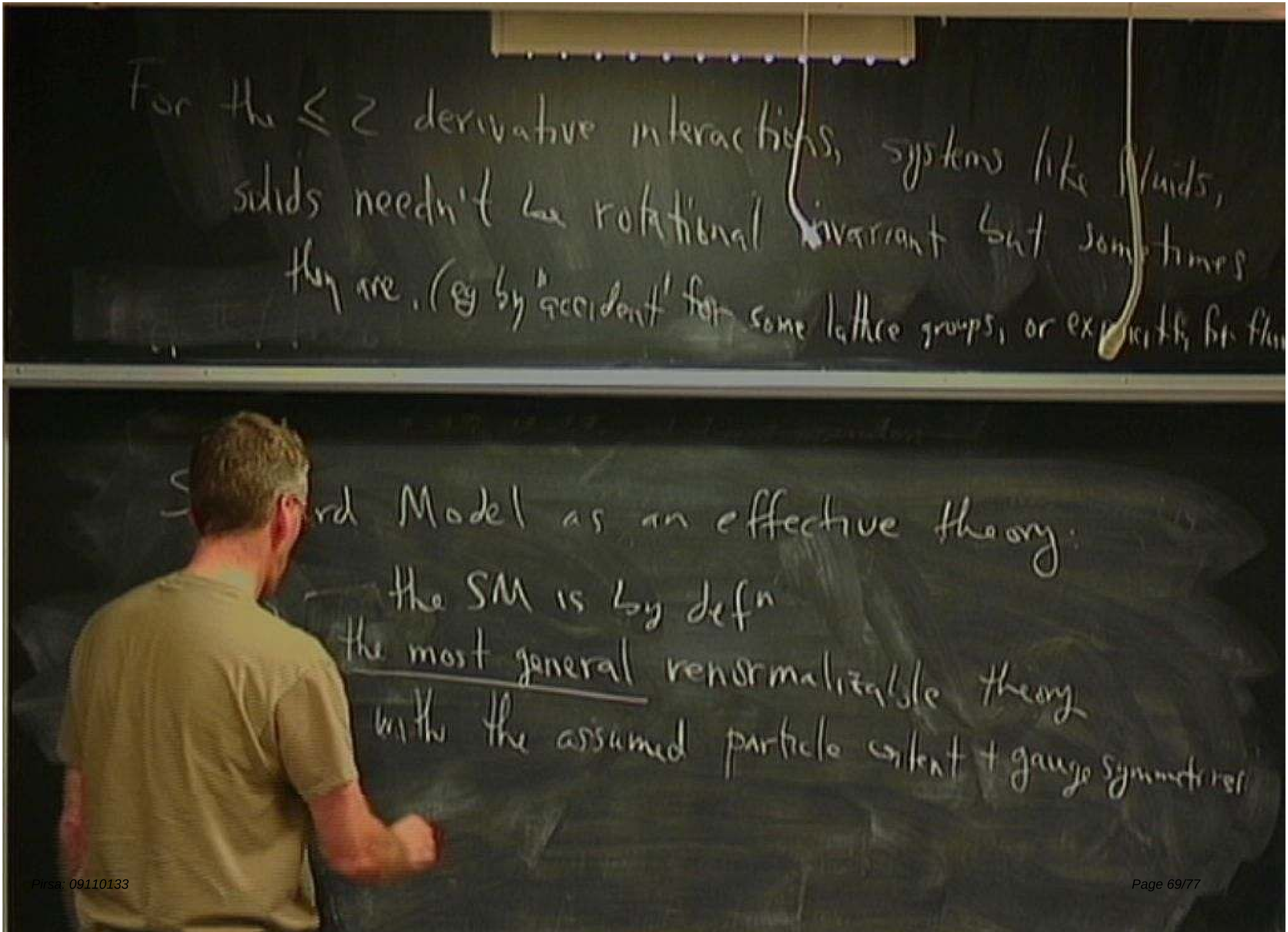
Standard Model as an effective theory:
i)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ν-masses, 10^{18} GeV $M_p \gg 10^2$ GeV (SM)

of the ... transformations

— May or may not break translation inv. (assume n...

May or " " " T, P. eg ferromagnet breaks T
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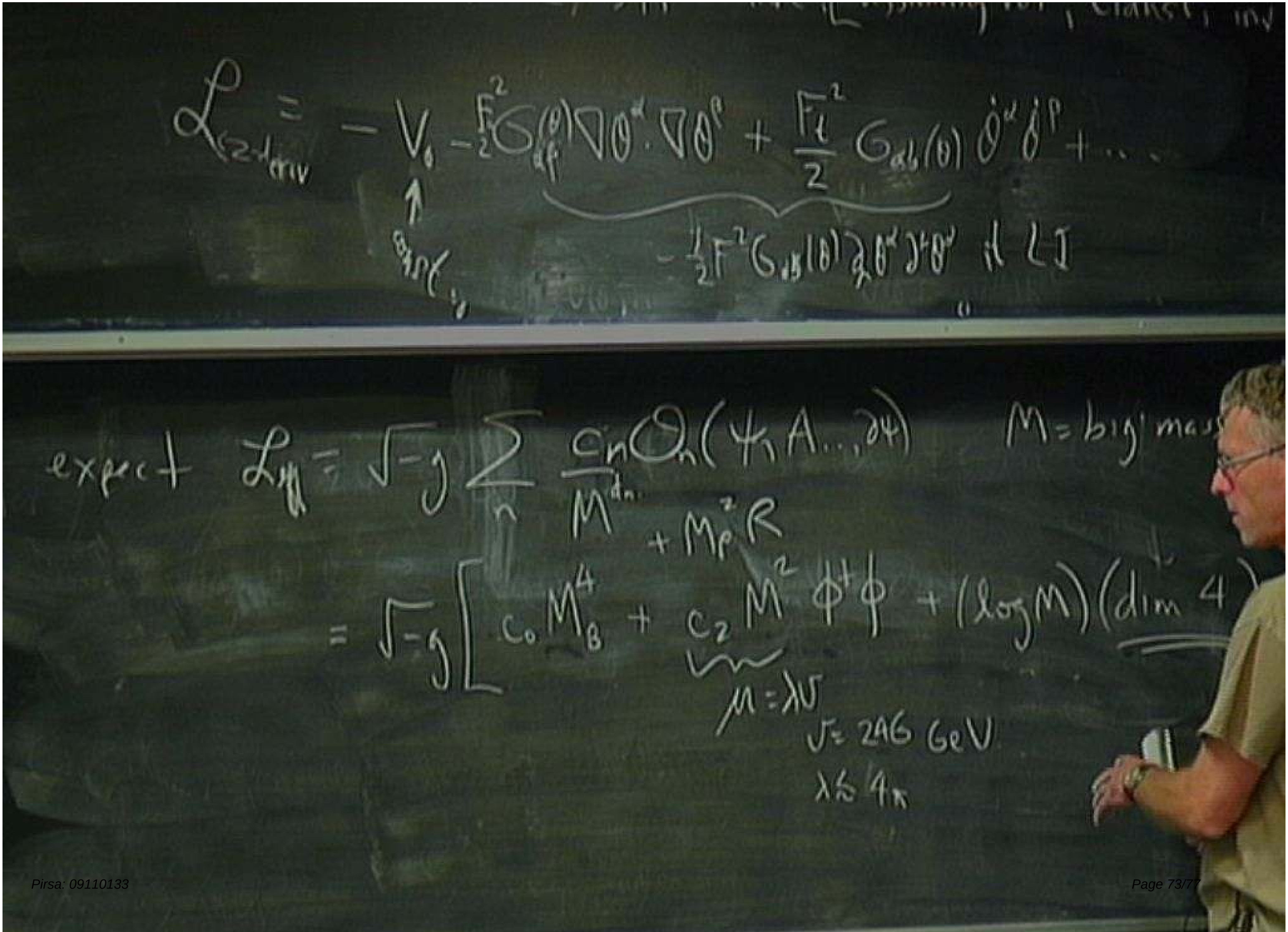
Field content: $SU_3 \times SU_2 \times U_1$

$G^a_\mu \quad W^a_\mu \quad B_\mu. \leftarrow \gamma, W^{\pm}, Z, \overset{8}{\text{gluons}}$

fermions: ψ $\underline{\text{3 colours}}$

$e_{L,R}, \nu_e, u_{L,R}, d_{L,R}$ + 3 generations

scalar: $\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \to$ 3 WBGB, 1 higgs.


$\mathcal{L}_{(2+1)\,\mathrm{triv}} = -V_0 - \frac{F_s^2}{2} G_{\alpha\beta}(\theta)\nabla\theta^\alpha\cdot\nabla\theta^\beta + \frac{F_t^2}{2} G_{\alpha\beta}(\theta)\dot\theta^\alpha\dot\theta^\beta + \dots$
const.
$-\frac{1}{2}F^2 G_{\alpha\beta}(\theta)\partial_\mu\theta^\alpha\partial^\mu\theta^\beta$ if LI
expect $\mathcal{L}_{\mathrm{eff}} = \sqrt{-g}\sum_n \frac{c_n O_n(\psi, A, \dots, \partial\psi)}{M^{d_n}} + M_p^2 R$
M = big mass
$= \sqrt{-g}\left[c_0 M_B^4 + c_2 M^2 \phi^\dagger\phi + (\log M)(\dim 4)\right.$
$\mu = \lambda v$
$v = 246$ GeV
$\lambda \lesssim 4\pi$

$$\mathcal{L}_{eff} = \sqrt{-g}\sum_n \frac{c_n \mathcal{O}_n(\psi, A, \ldots, \partial\psi)}{M^{d_n}} + M_P^2 R \qquad M = \text{big mass}$$

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$D_\mu \phi^\dagger D^\mu \phi$

$\phi \to U\phi$

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$$+ M_p^2 R \qquad (10^{18}\ \text{GeV})^2$$

$$\theta G^{\alpha}_{\mu\nu}\tilde{G}^{\alpha\mu\nu}$$

$$= \sqrt{-g}\left[c_0 M_B^4 + c_2 M^2 \boxed{\phi^\dagger\phi} + (\log M)(\text{dim } 4) \right]$$

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$$+ \frac{1}{M} LLHH + \text{dim } 6$$

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$$+ \underbrace{M_{Pl}^2}_{(10^{18}\,\text{GeV})^2} R \qquad \theta\, G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

$$= \sqrt{-g}\left[c_0 M_{B,?}^4 + ?\, c_2 \underbrace{M^2}_{M=\lambda v} \boxed{\phi^\dagger\phi} + (\log M)\,(\underline{\text{dim } 4}) \right]$$

VVV

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