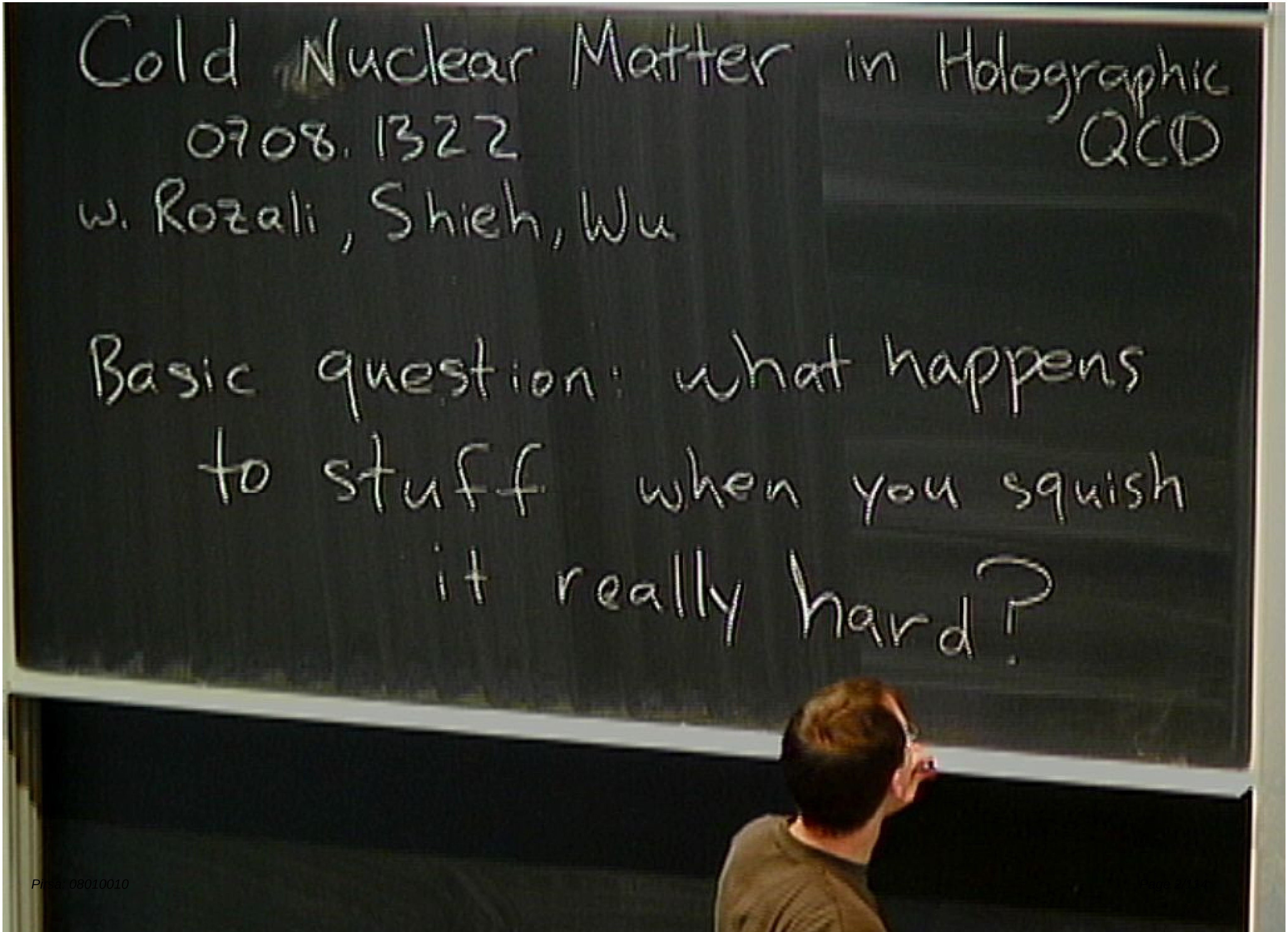
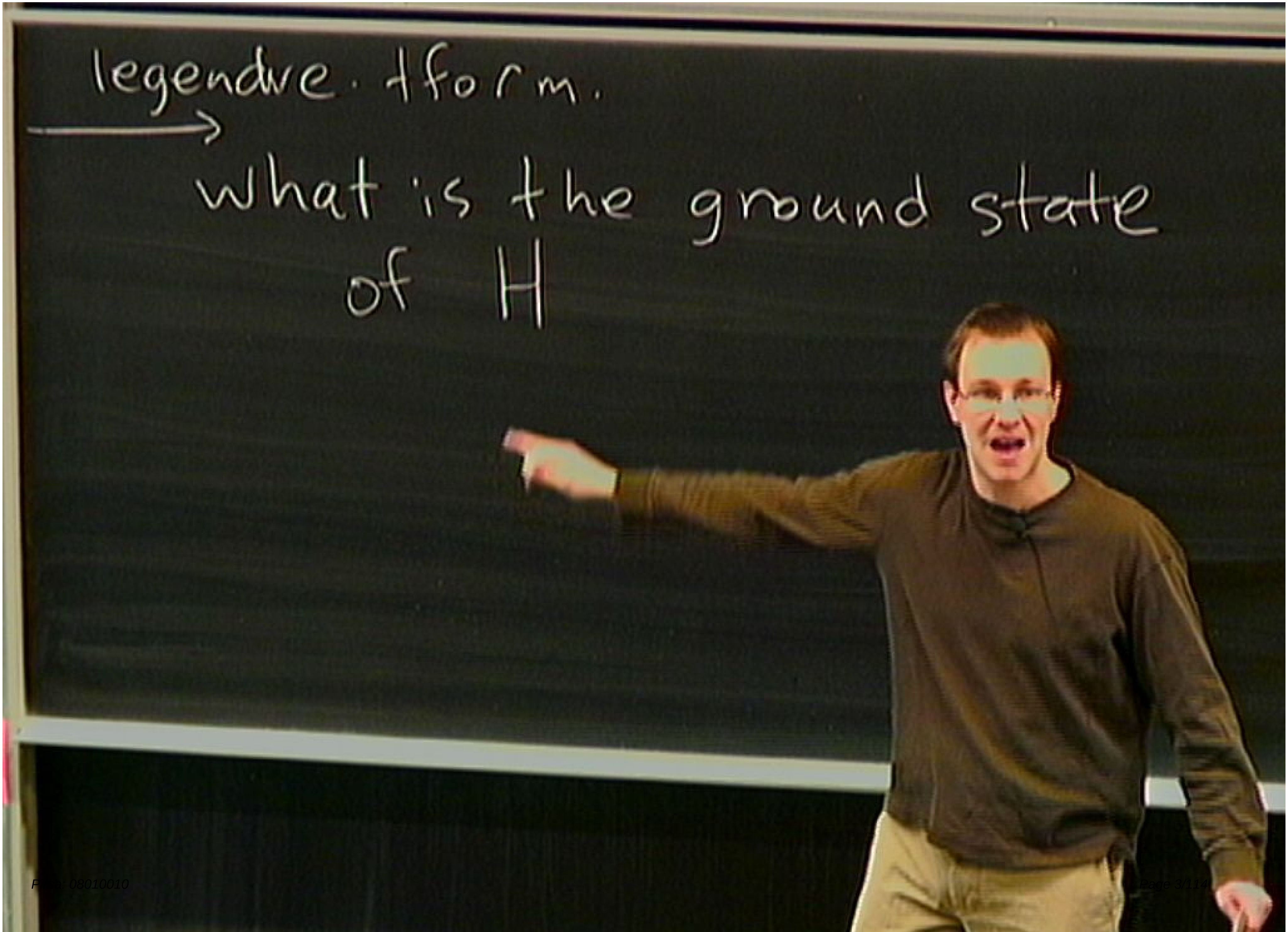
Title: Cold Nuclear Matter in Holographic QCD

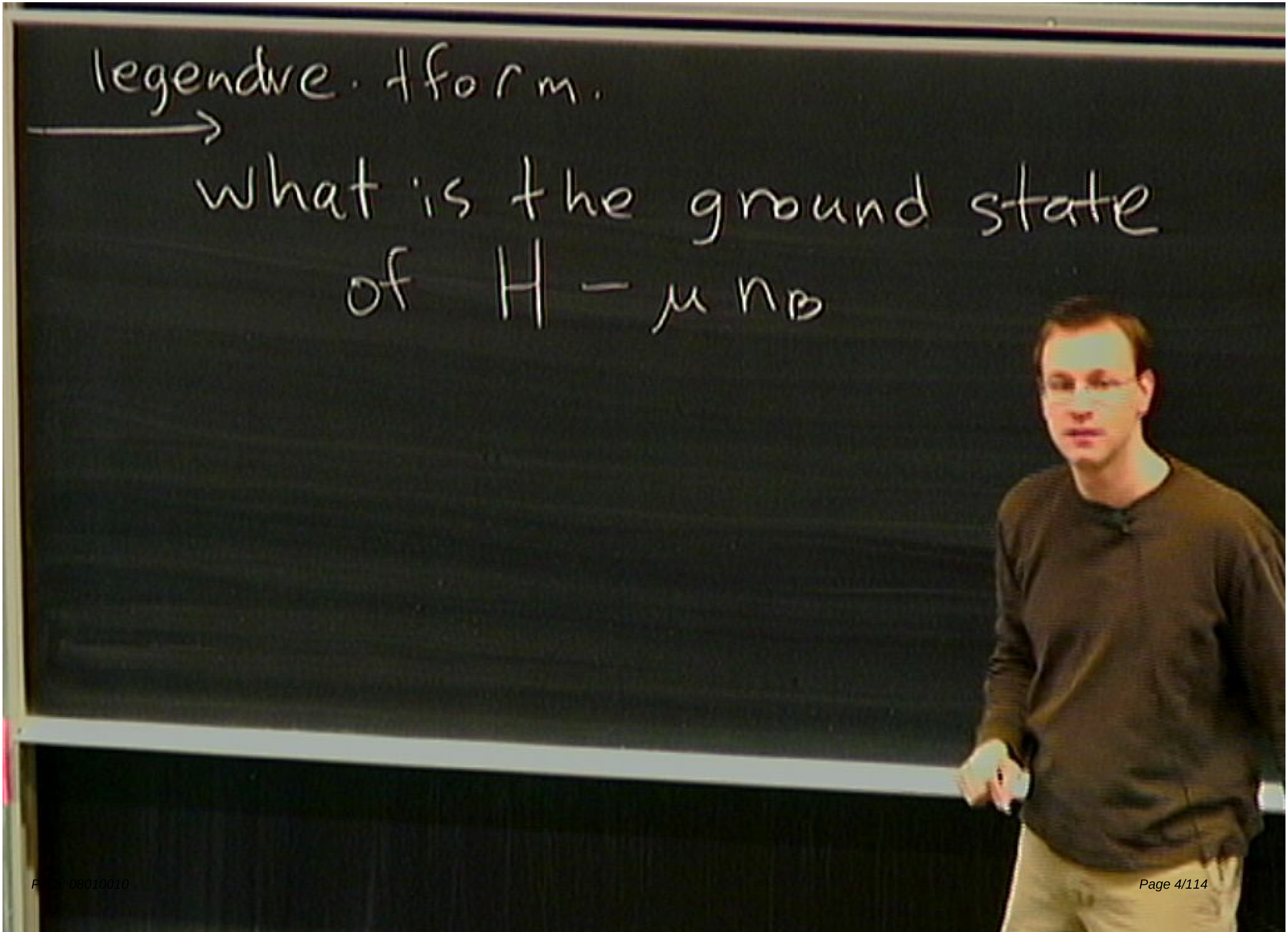
Date: Jan 15, 2008 11:00 AM

URL: http://pirsa.org/08010010

Abstract: TBA


Cold Nuclear Matter in Holographic QCD
0708.1322
w. Rozali, Shieh, Wu
Basic question: what happens to stuff when you squish it really hard?


legendre tform.
what is the ground state
of H


legendre tform.
what is the ground state
of H − μ n_B

legendre tform.

what is the ground state of $H - \mu n_B$

Baryon density

chemical potential.

legendre tform.

this talk: $T=0$

what is the ground state

of $H - \mu n_B$

Baryon densit

chemical potential

legendre tform.

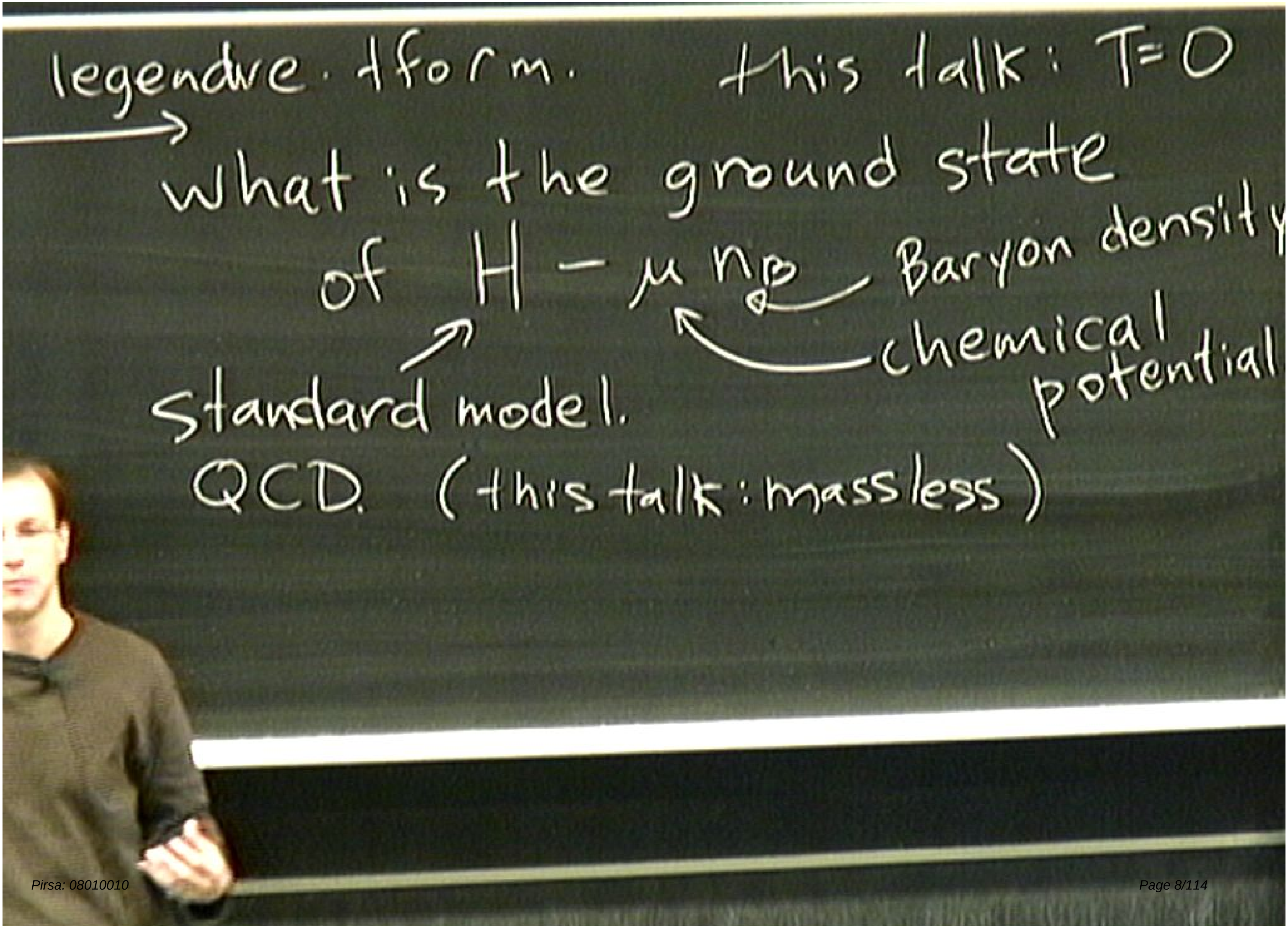
this talk: $T = 0$

$\longrightarrow$ what is the ground state of $H - \mu n_B$

Baryon density

chemical potential.

standard model.


legendre. tform.
this talk: T=0
what is the ground state
of H − μ nB
Baryon density
chemical potential
standard model.
QCD. (this talk: massless)

legendre tform. this talk: $T=0$

what is the ground state

of $H - \mu\, n_B$

n_B: Baryon density

μ: chemical potential.

H: standard model.

- QCD. (this talk: massless)
- large N_c QCD.

legendre. tform.

this talk: $T=0$

what is the ground state

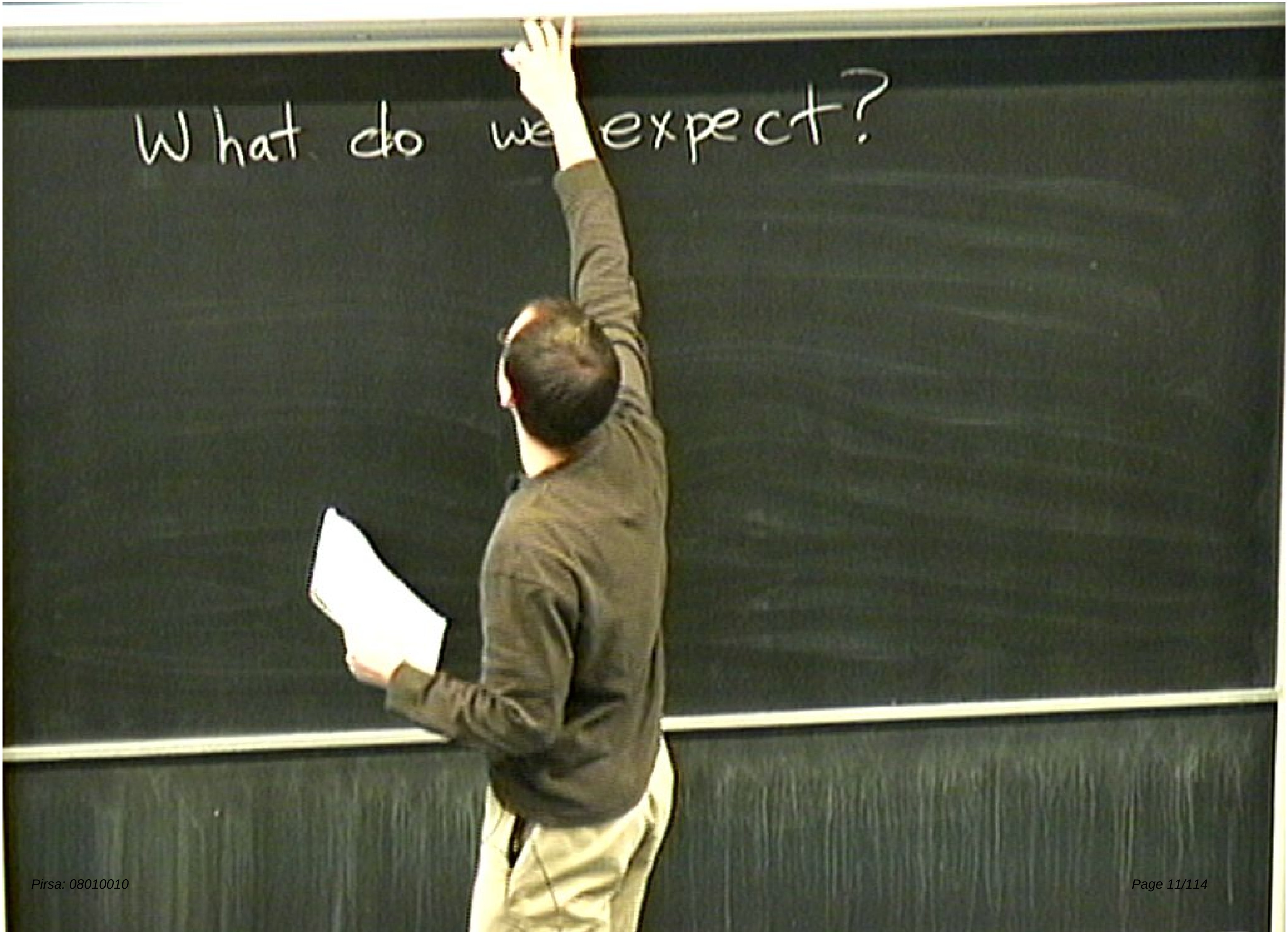
of $H - \mu\, n_B$

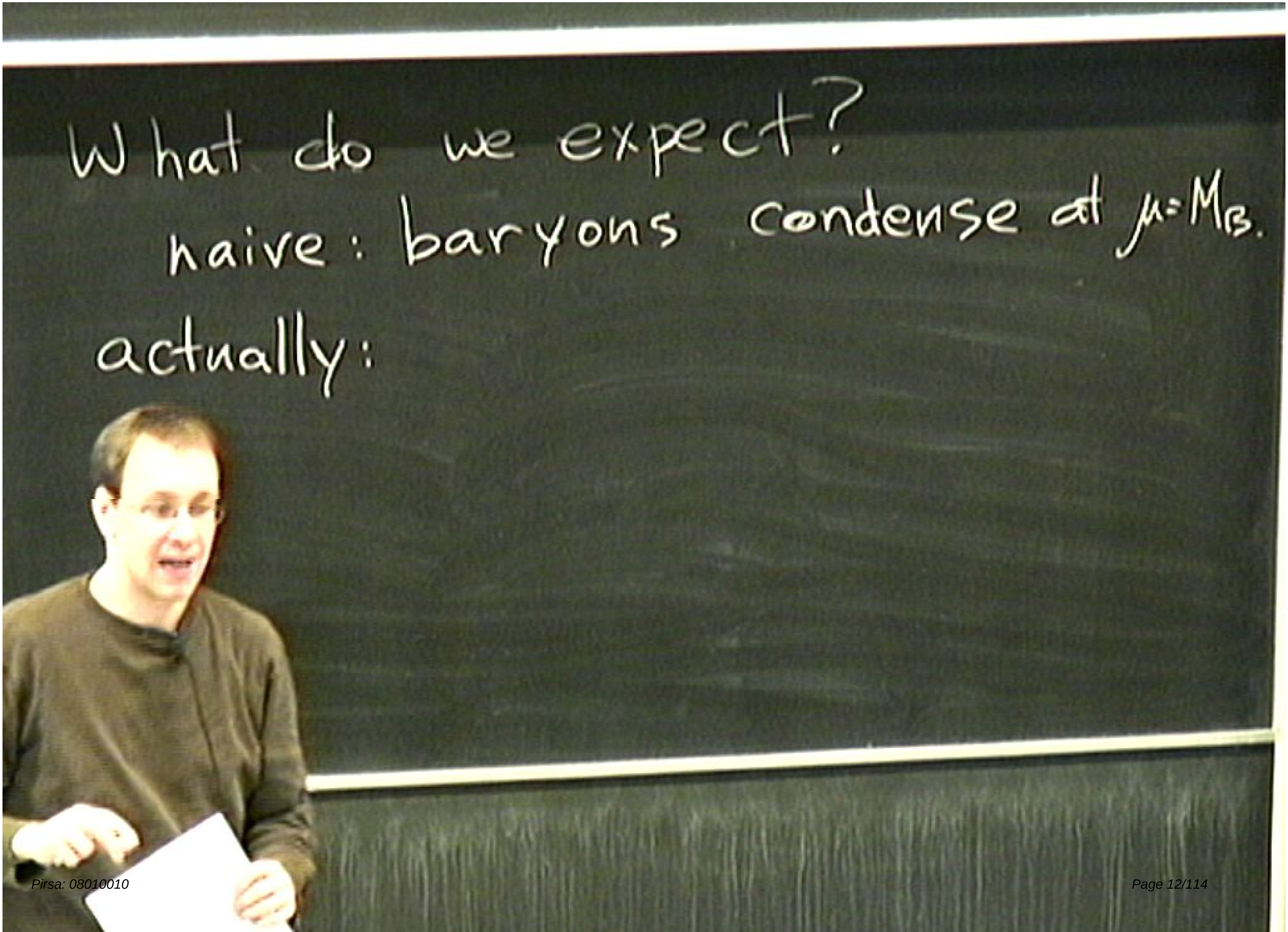
Baryon density

chemical potential.

standard model.

- QCD. (this talk: massless)
- large N_c QCD.
- large N_c holographic QCD (Witten, Sakai, Sugimoto)


What do we expect?


What do we expect?
naive: baryons condense at $\mu = M_B$.
actually:

What do we expect?

naive: baryons condense at $\mu = M_B$.

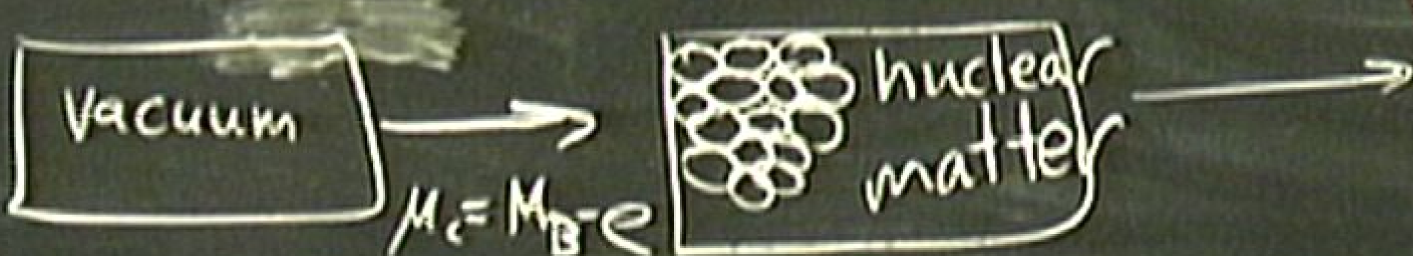
actually: $M_B - e$

$\boxed{\text{vacuum}} \longrightarrow$

What do we expect?

naive: baryons condense at $\mu = M_B$.

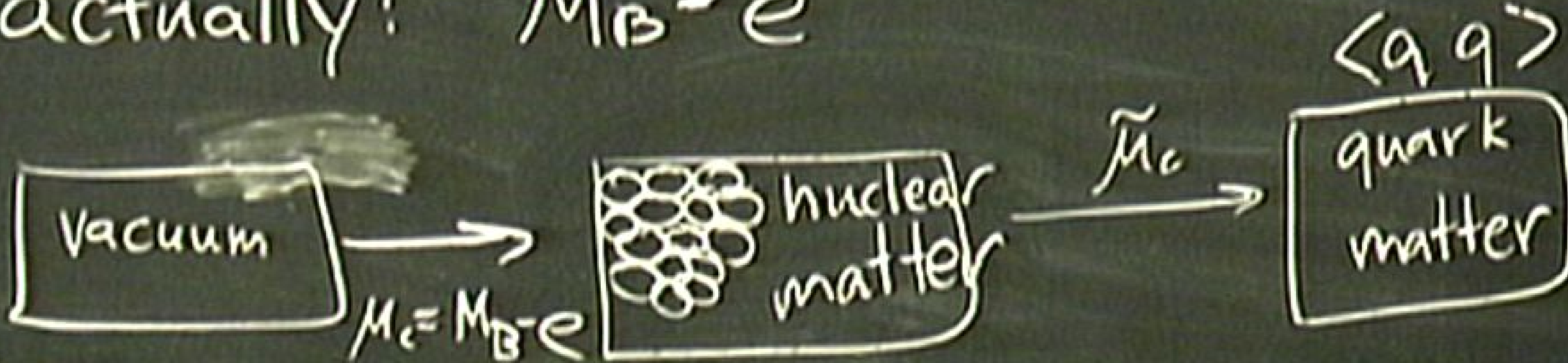
actually: $M_B - e$



What do we expect?

naive: baryons condense at $\mu = M_B$.

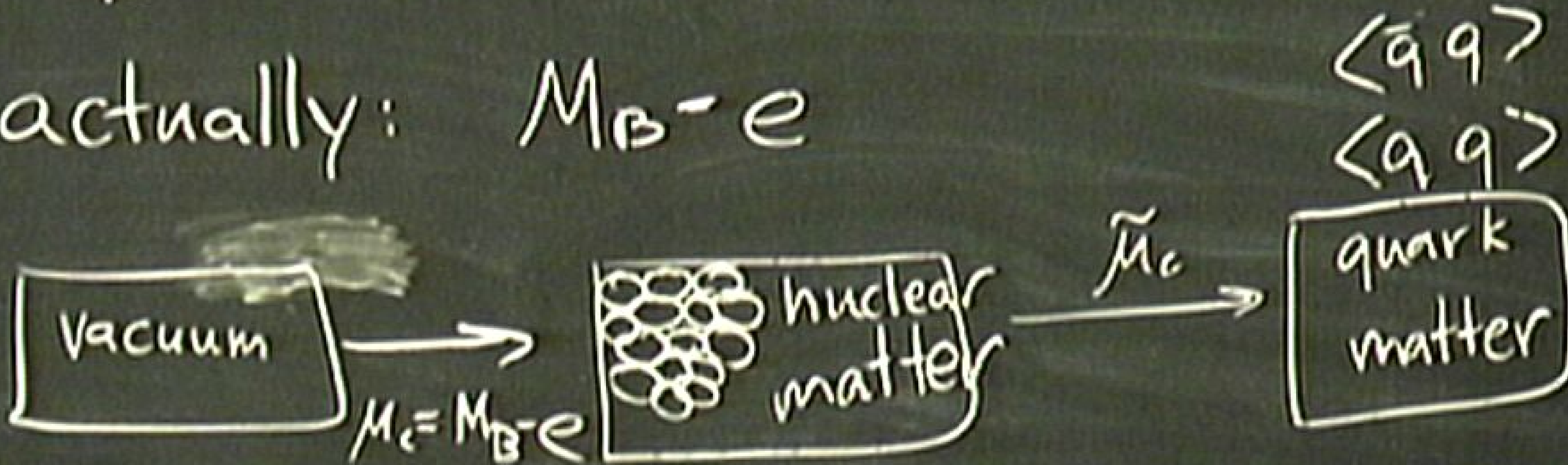
actually: $M_B - e$

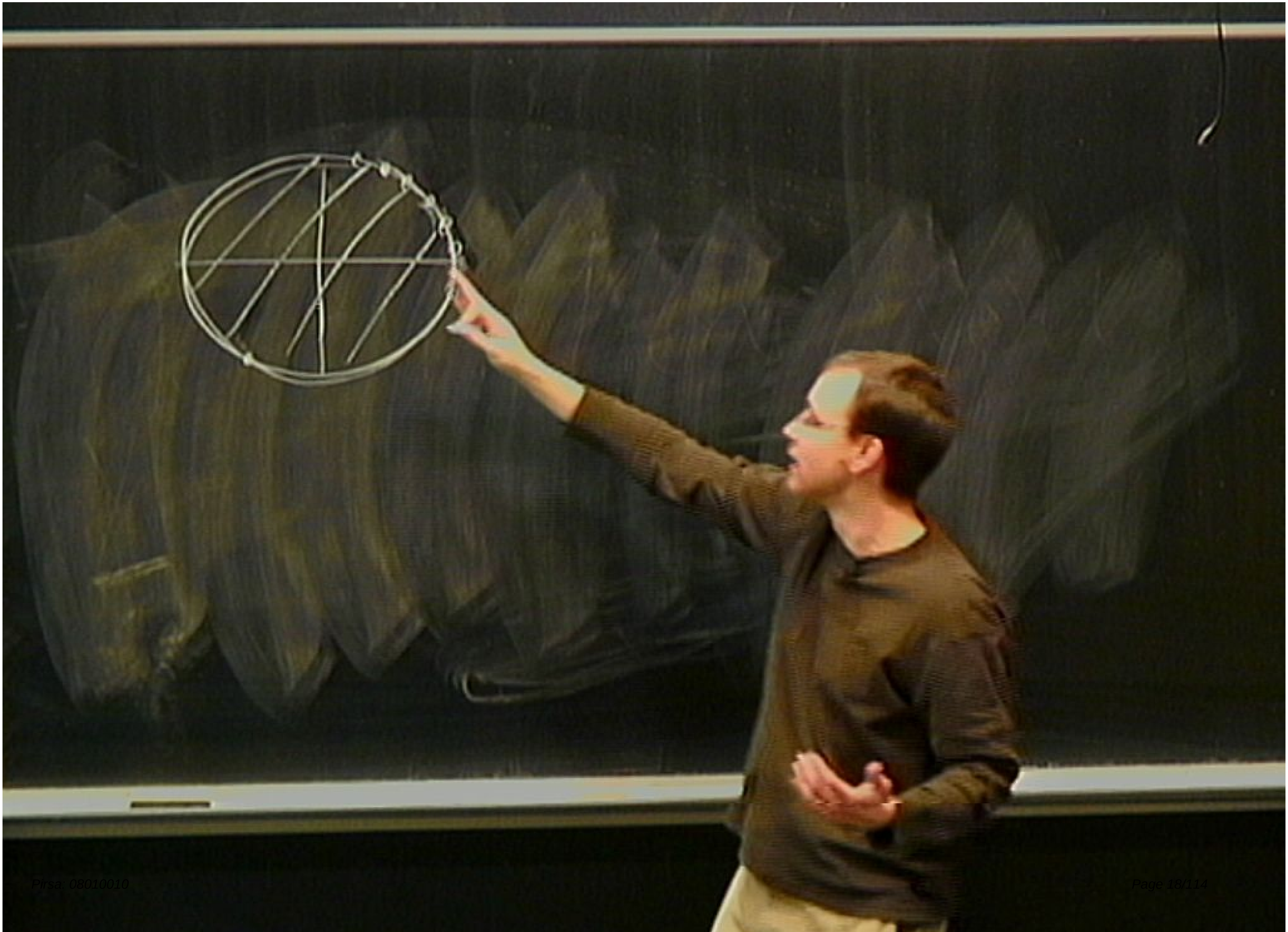


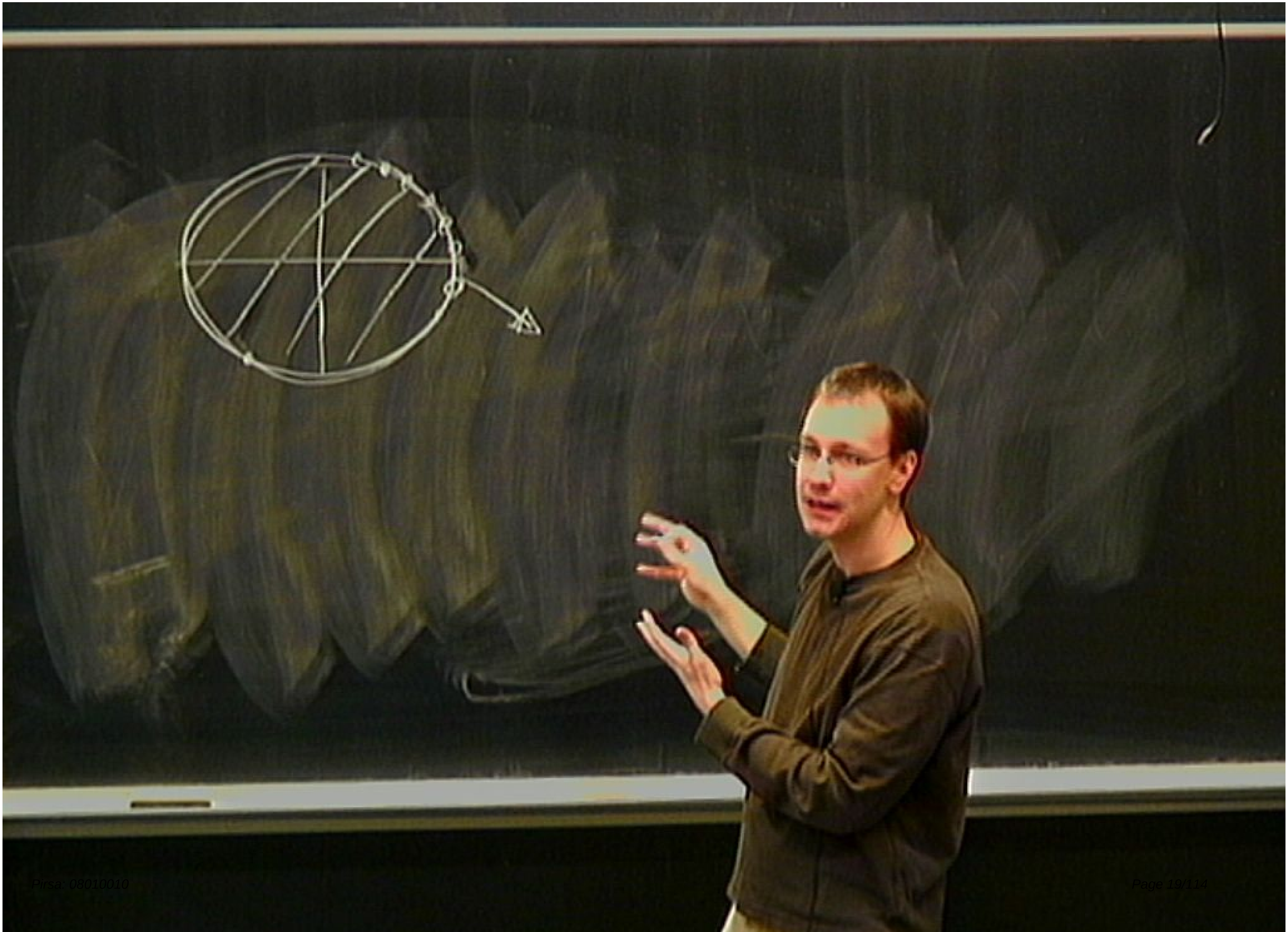
What do we expect?

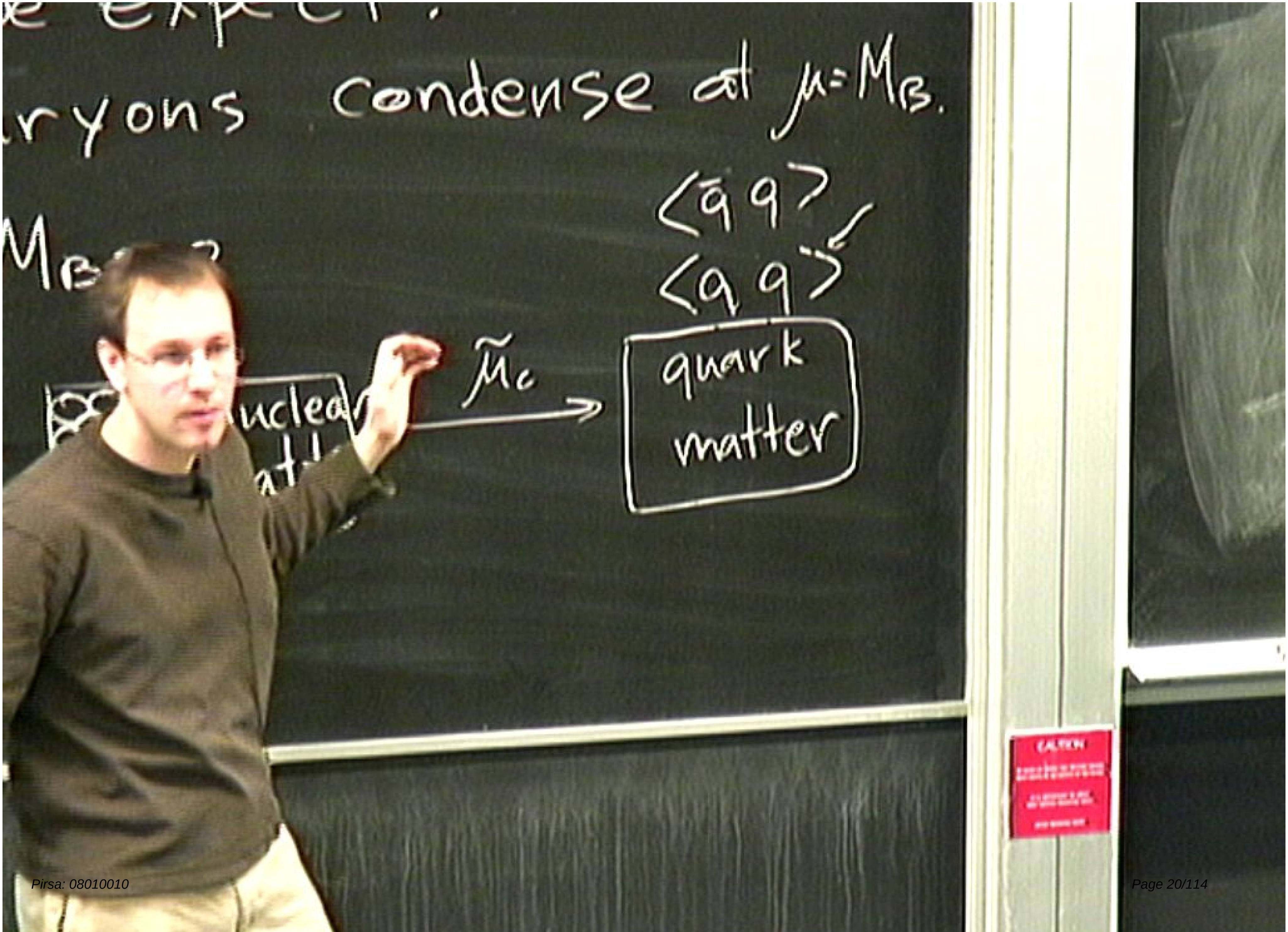
naive: baryons condense at $\mu = M_B$.

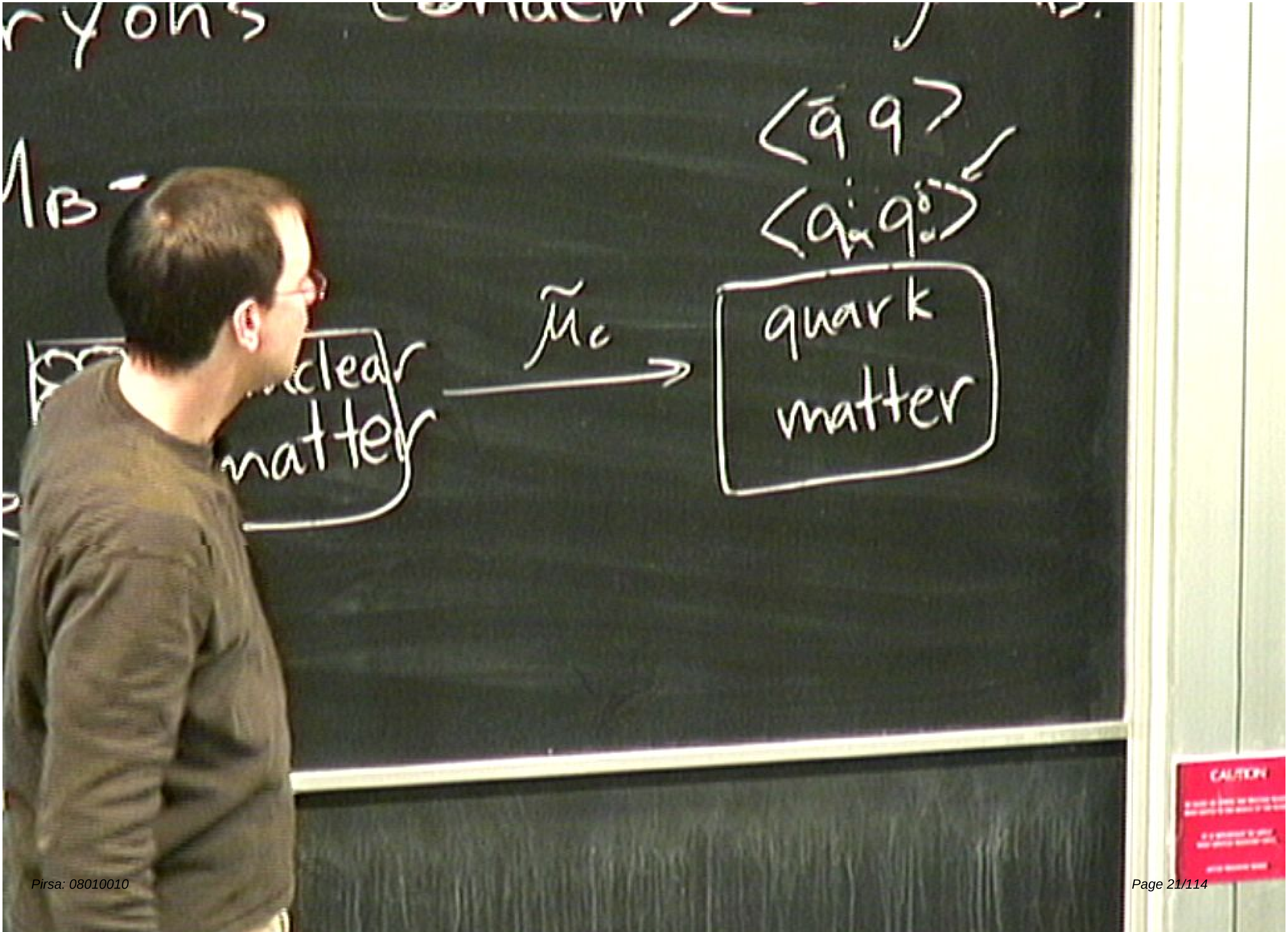
actually: $M_B - e$

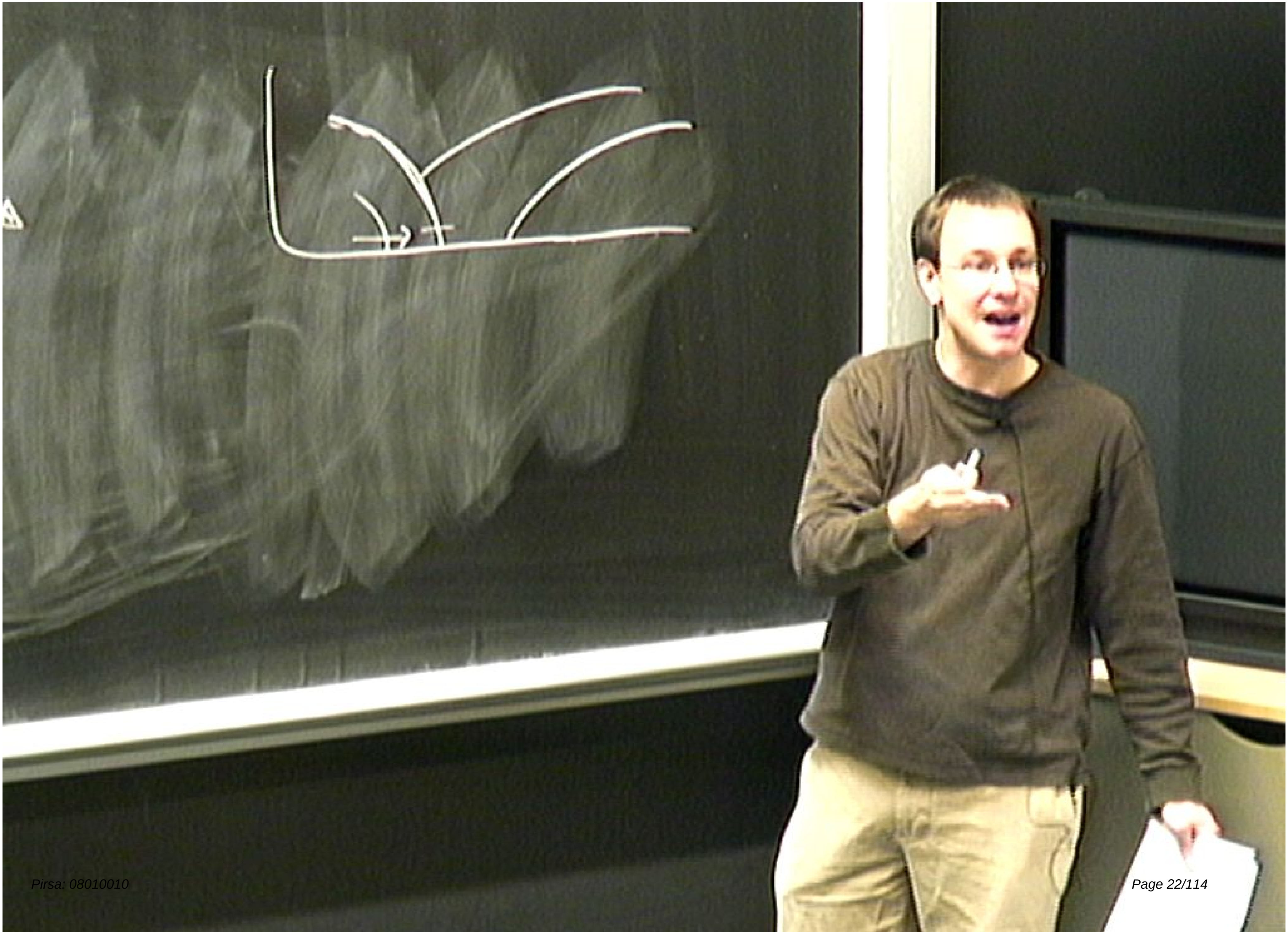


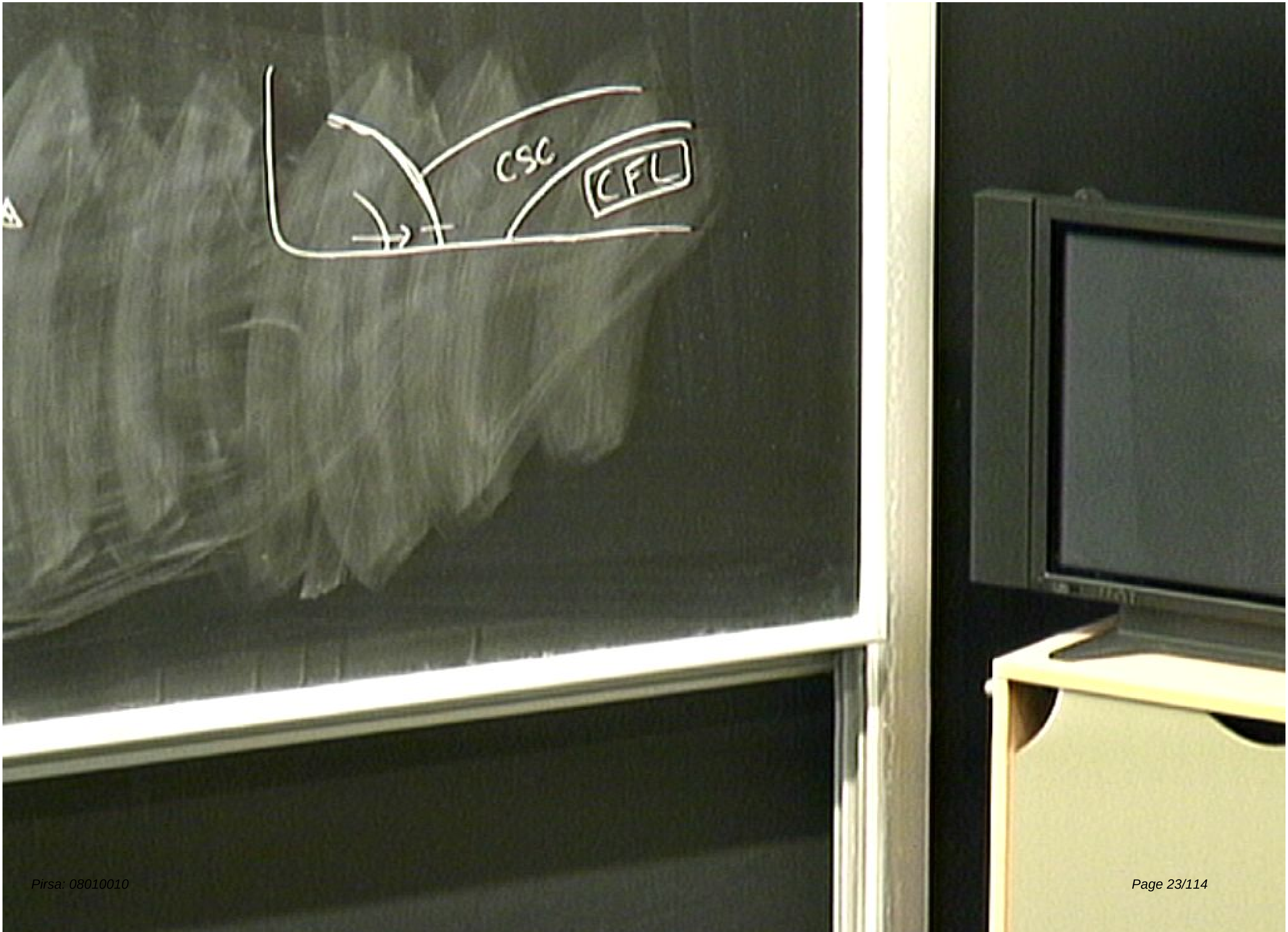


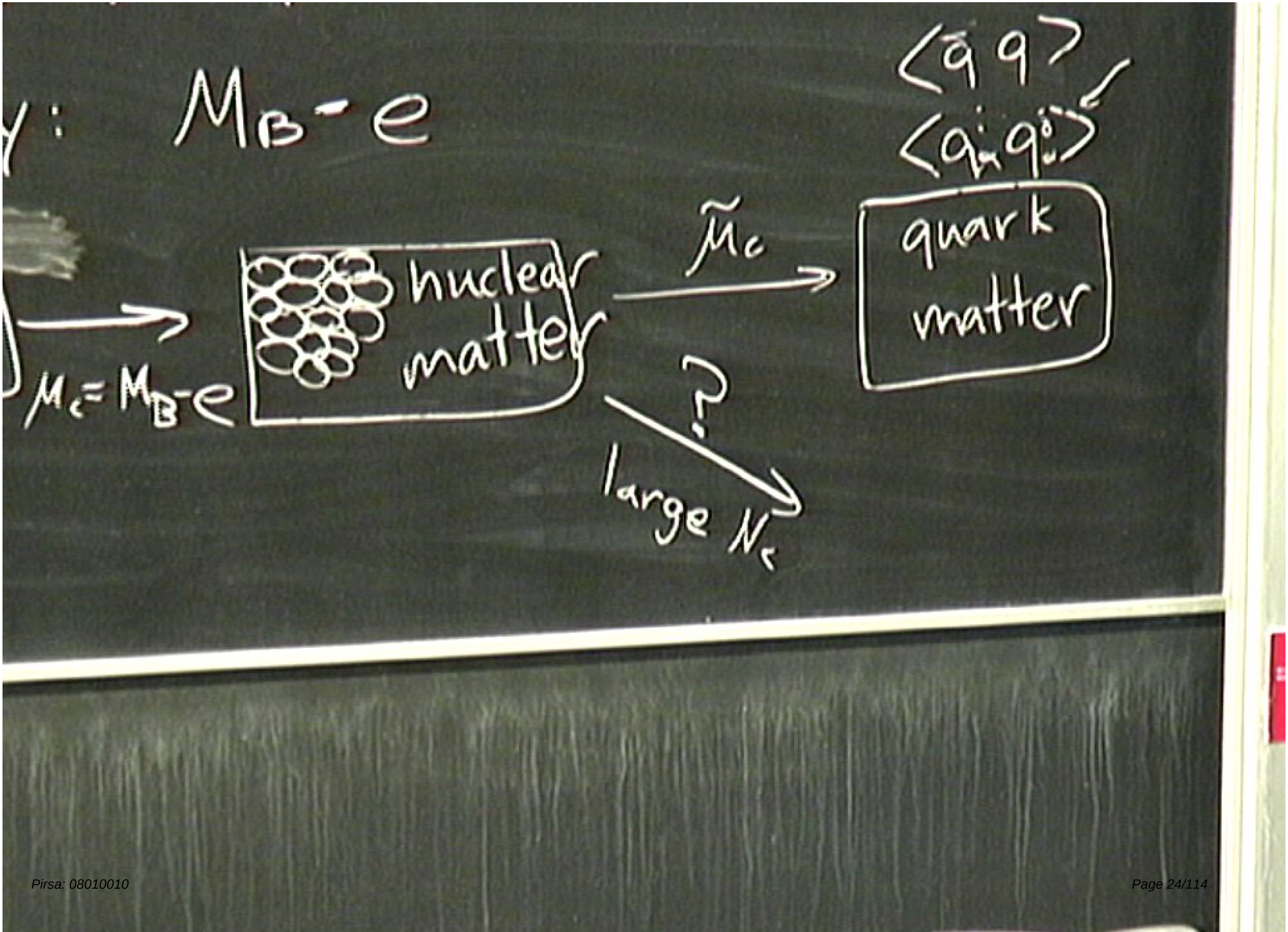


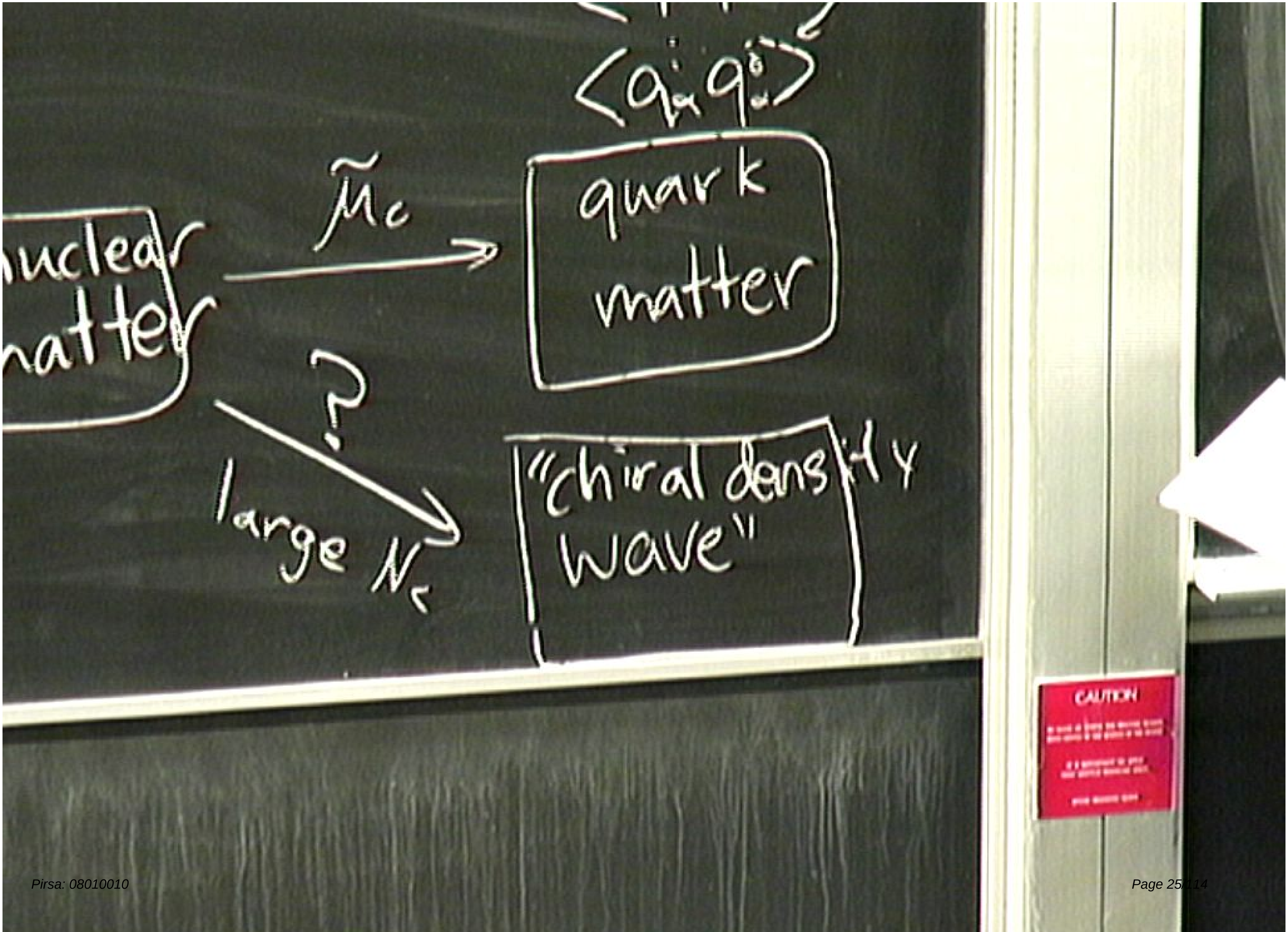

ryons condense at μ=M_B.
⟨q̄q⟩
⟨qq⟩
μ̃_c
quark matter


$\langle \bar{q} q \rangle$
$\tilde{\mu}_c$
quark
matter
matter
CAUTION



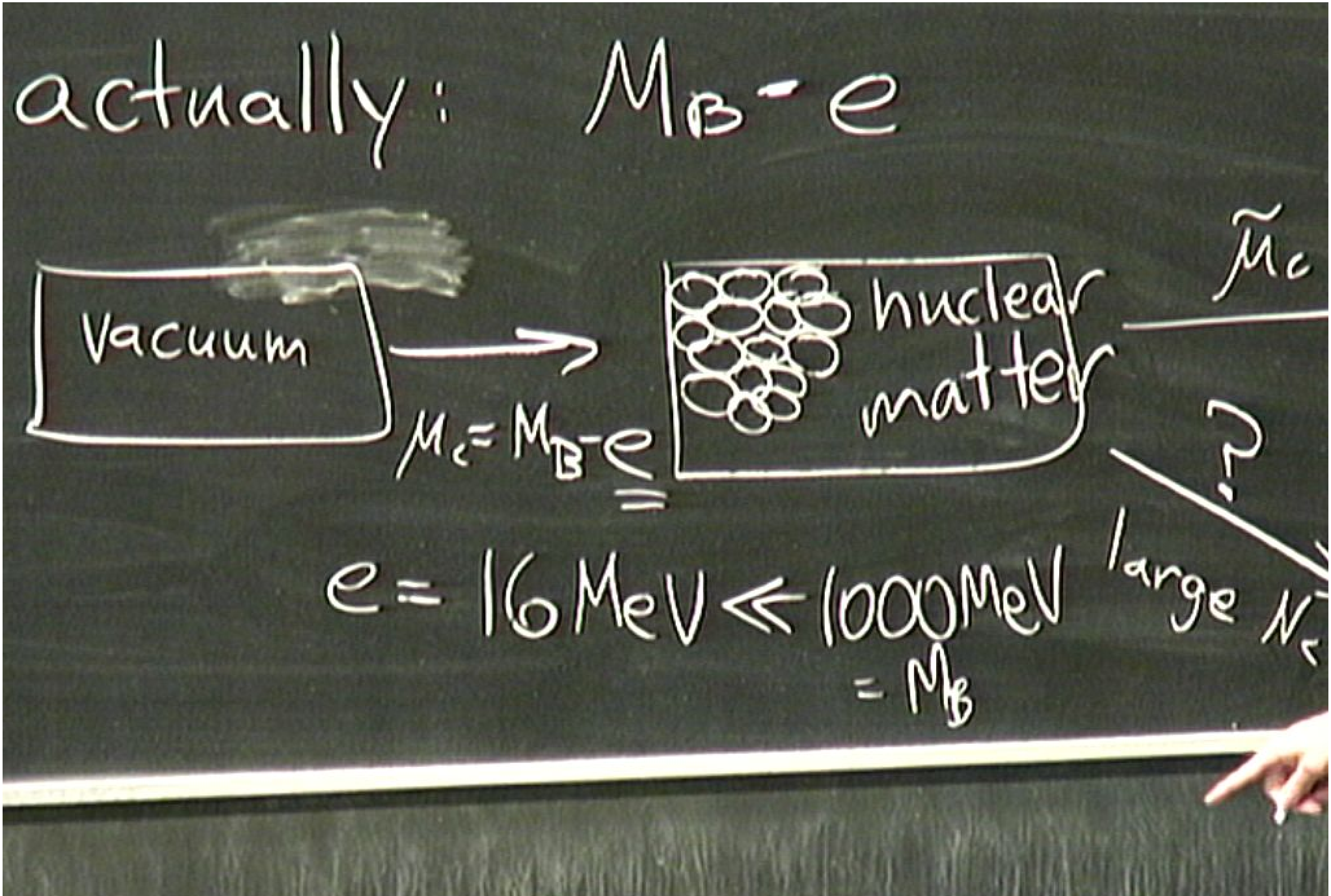

CSC
CFL

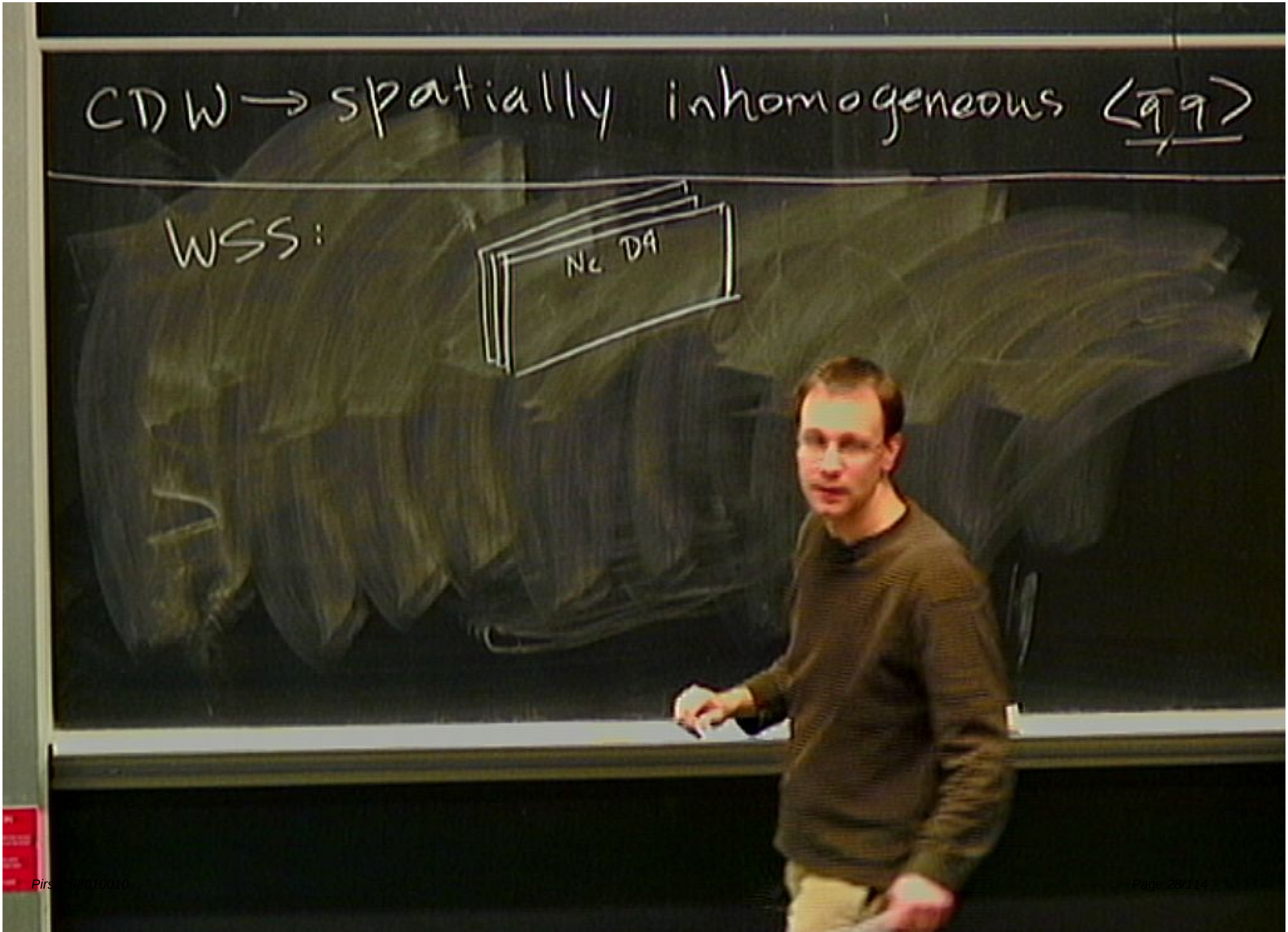

y : $M_B - e$
$\langle \bar{q} q \rangle$
$\langle q q \rangle$
$\tilde{\mu}_c$
quark matter
nuclear matter
$\mu_c = M_B - e$
?
large N_c

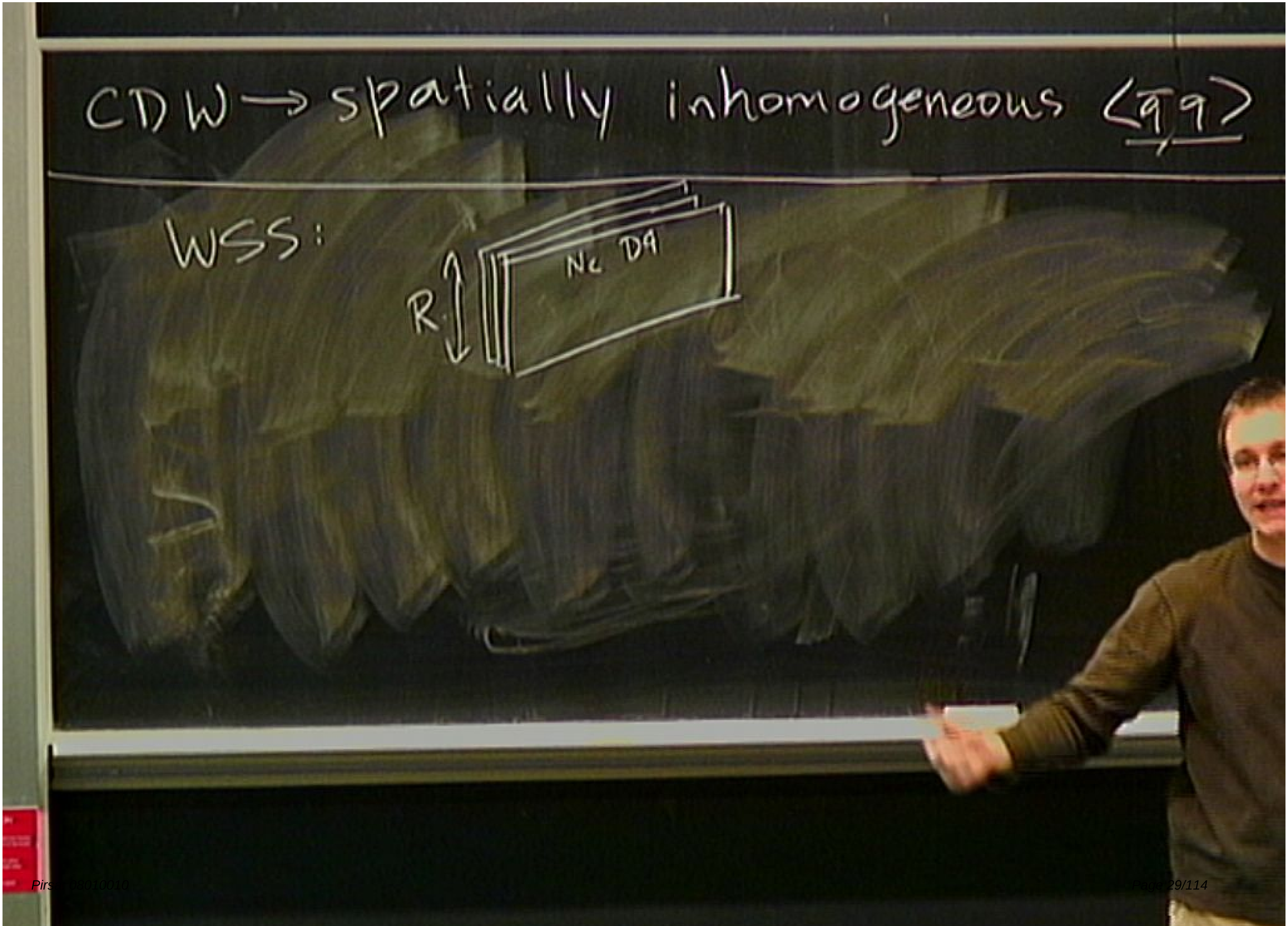


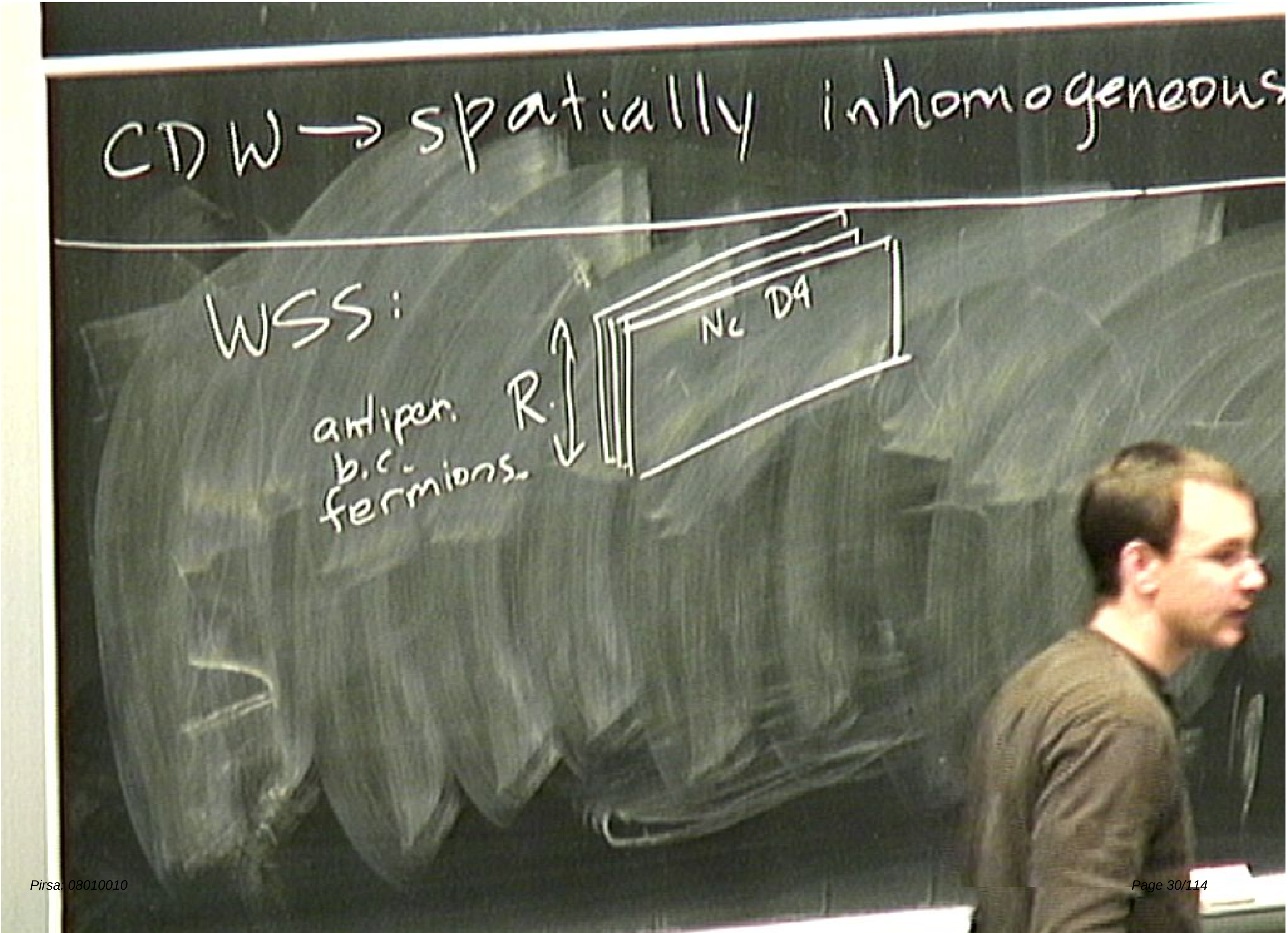
⟨qq⟩
$\tilde{\mu}_c$
nuclear matter
quark matter
?
large N_c
"chiral density wave"

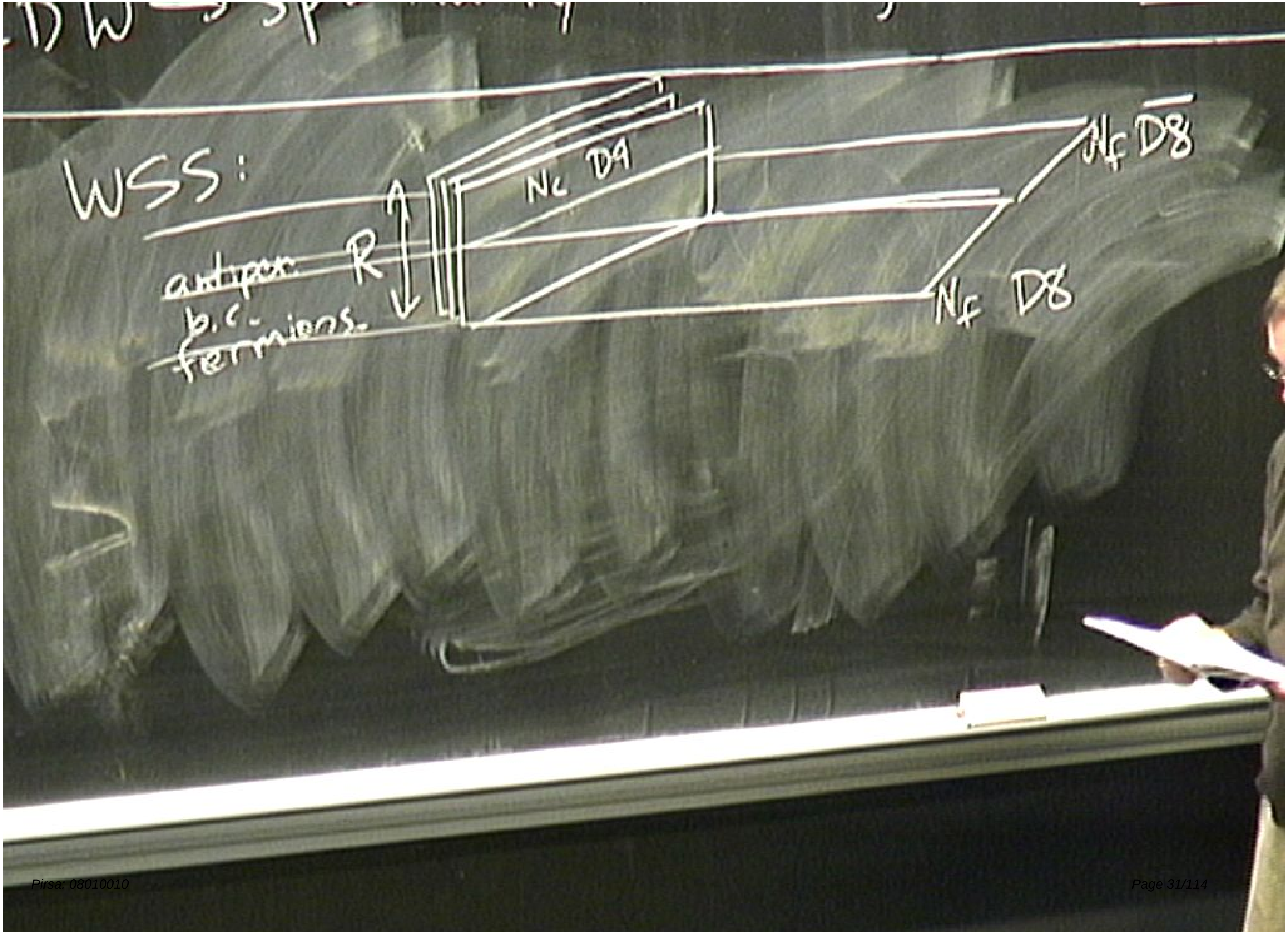
CDW $\rightarrow$ spatially inhomogeneous $\langle \bar{q} q \rangle$


actually: $M_B - e$
vacuum
nuclear matter
$\mu_c = M_B - e$
$\tilde{\mu}_c$
?
$e = 16\,\text{MeV} \ll 1000\,\text{MeV} = M_B$
large N_c


CDW → spatially inhomogeneous ⟨q̄q⟩
WSS:
Nc D4

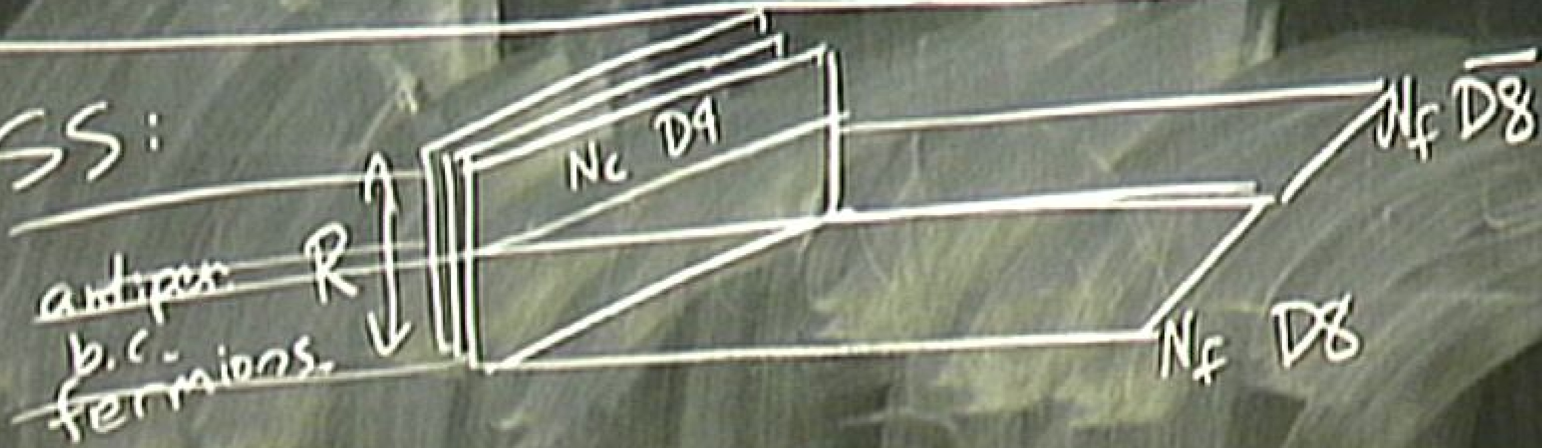

CDW → spatially inhomogeneous ⟨q̄q⟩
WSS:
R
Nc D4


CDW → spatially inhomogeneous
WSS:
Nc D4
R.
antiper.
b.c.
fermions.


WSS:
antiper.
b.c.
fermions.
R
Nc D4
Nf D8
Nf D8

CDW → spatially inhomogeneous $\langle \underline{\bar{q} q} \rangle$

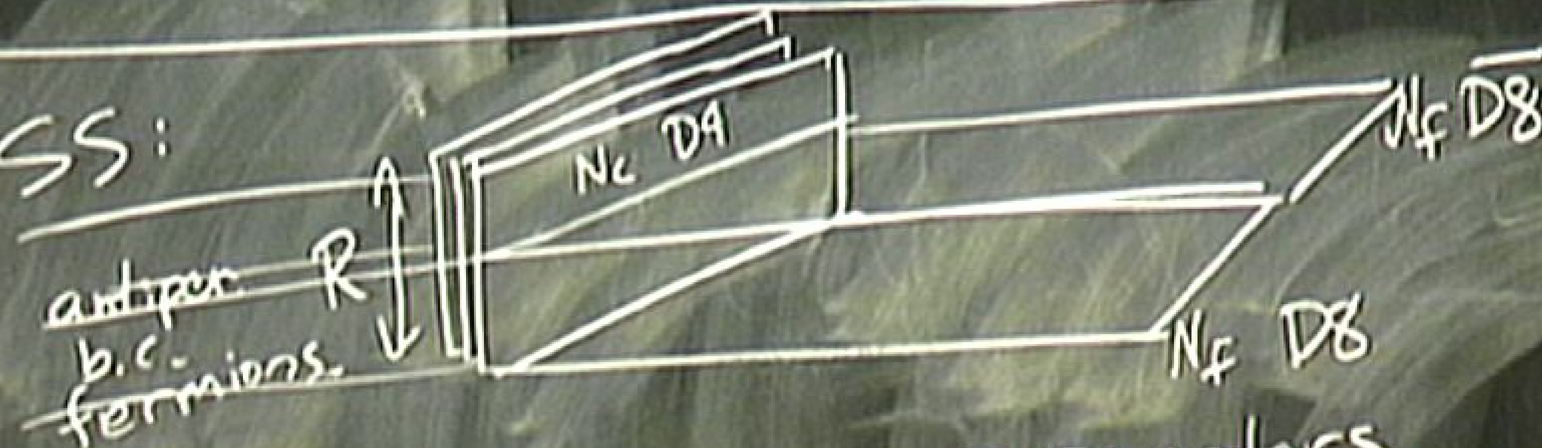
WSS:



$$M_{KK} \sim \frac{1}{R}$$

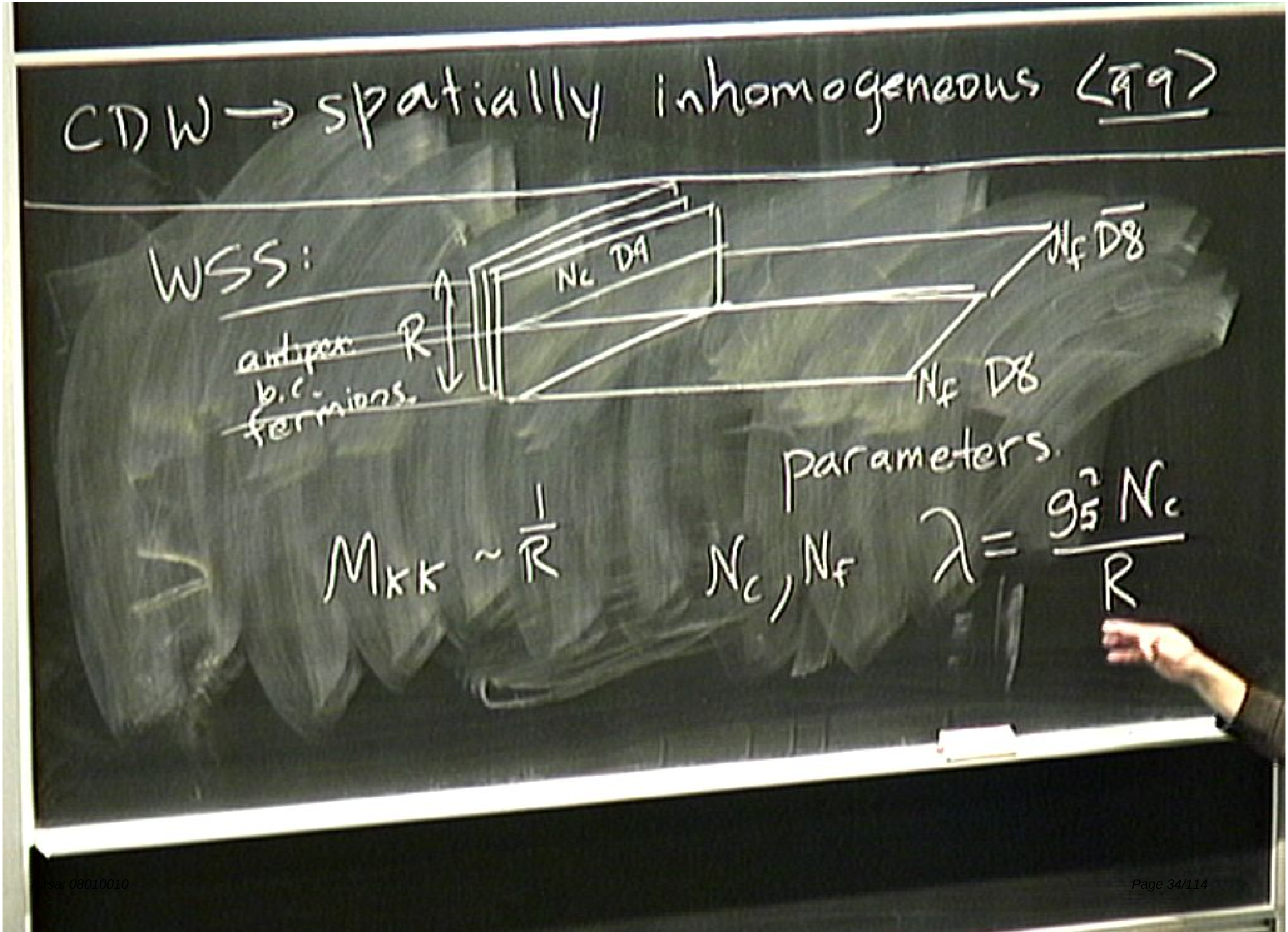
CDW → spatially inhomogeneous $\langle \bar{q} q \rangle$

WSS:



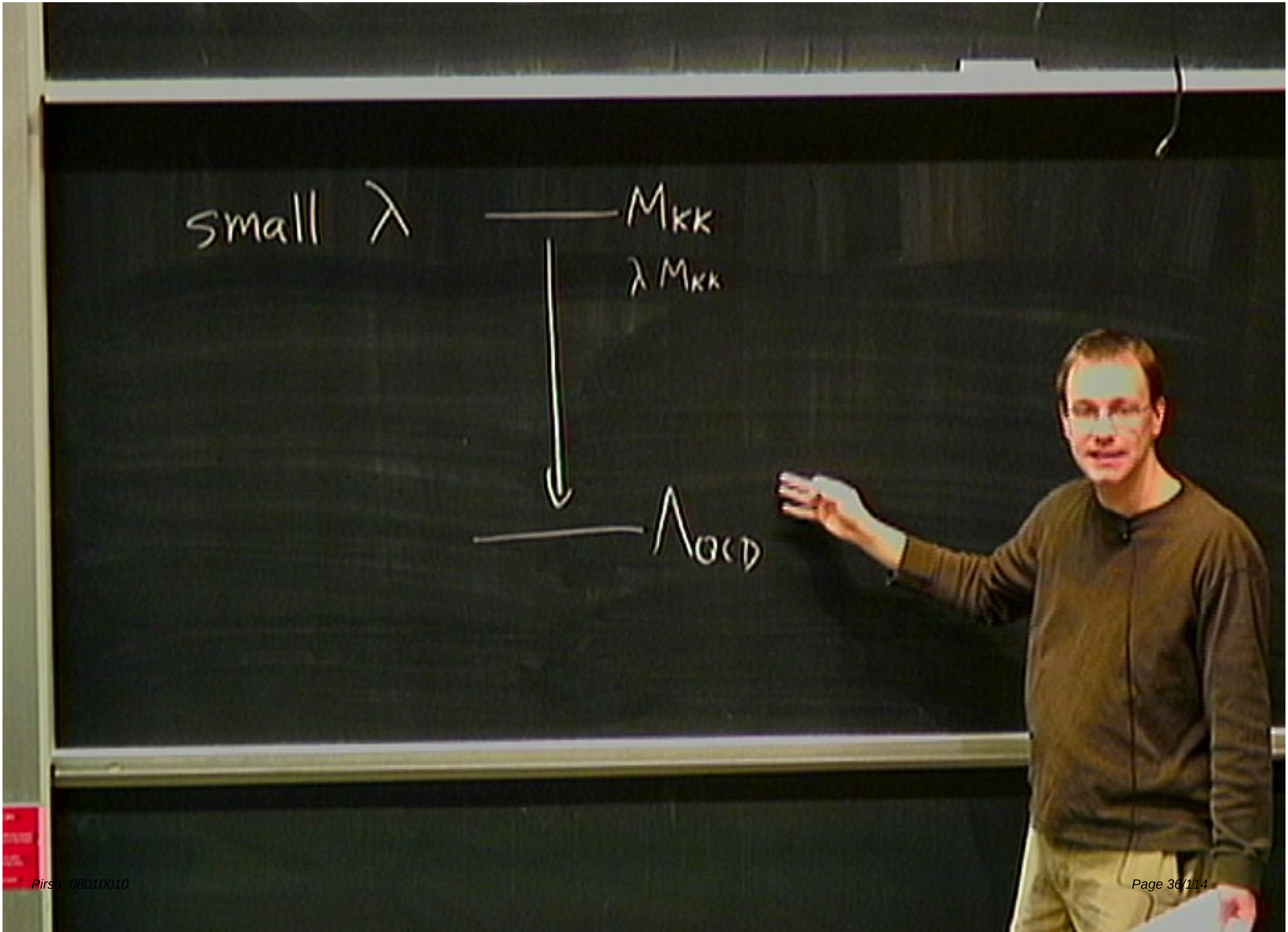
parameters.

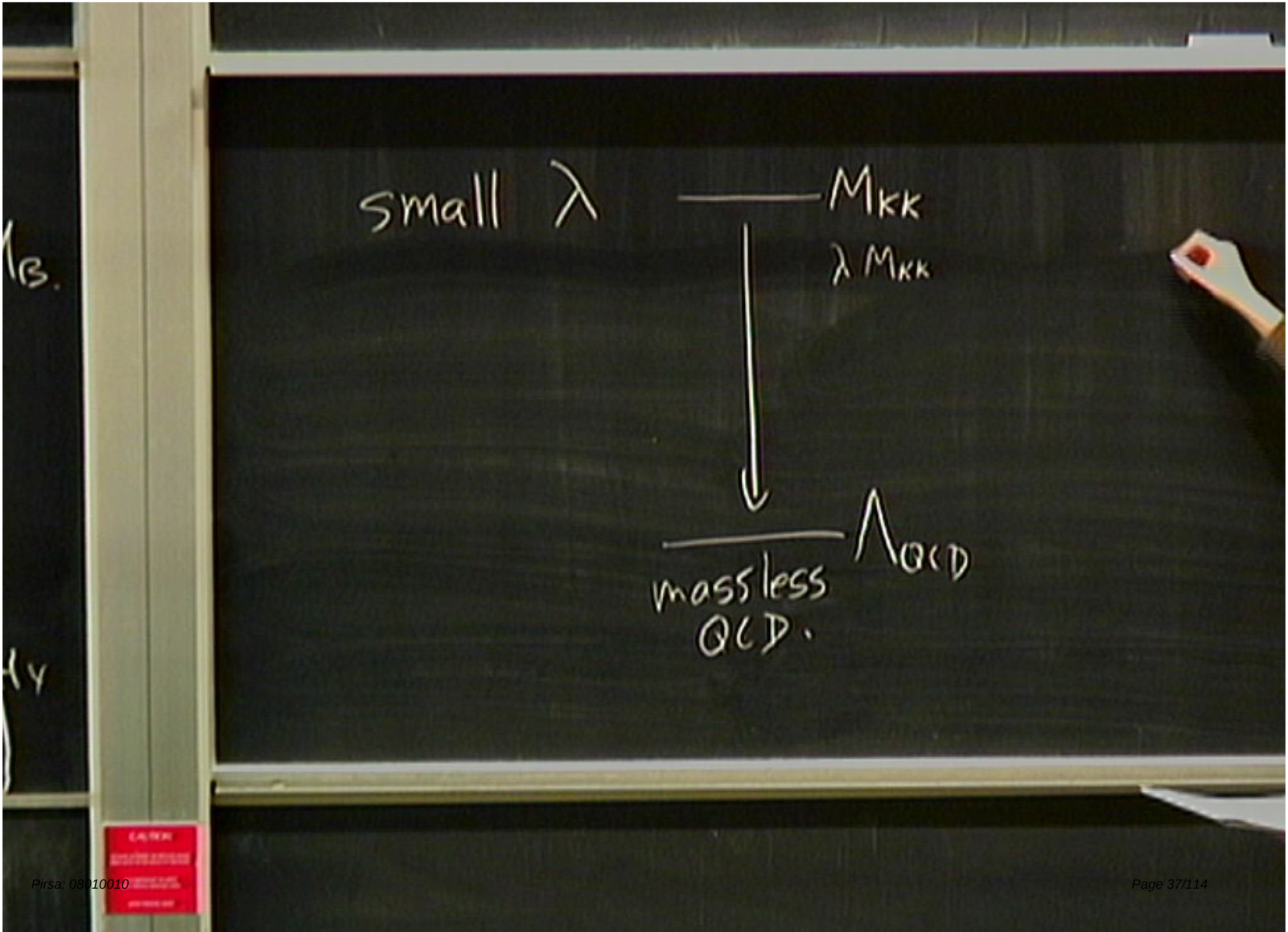
$$M_{KK} \sim \frac{1}{R} \qquad N_c, N_f$$

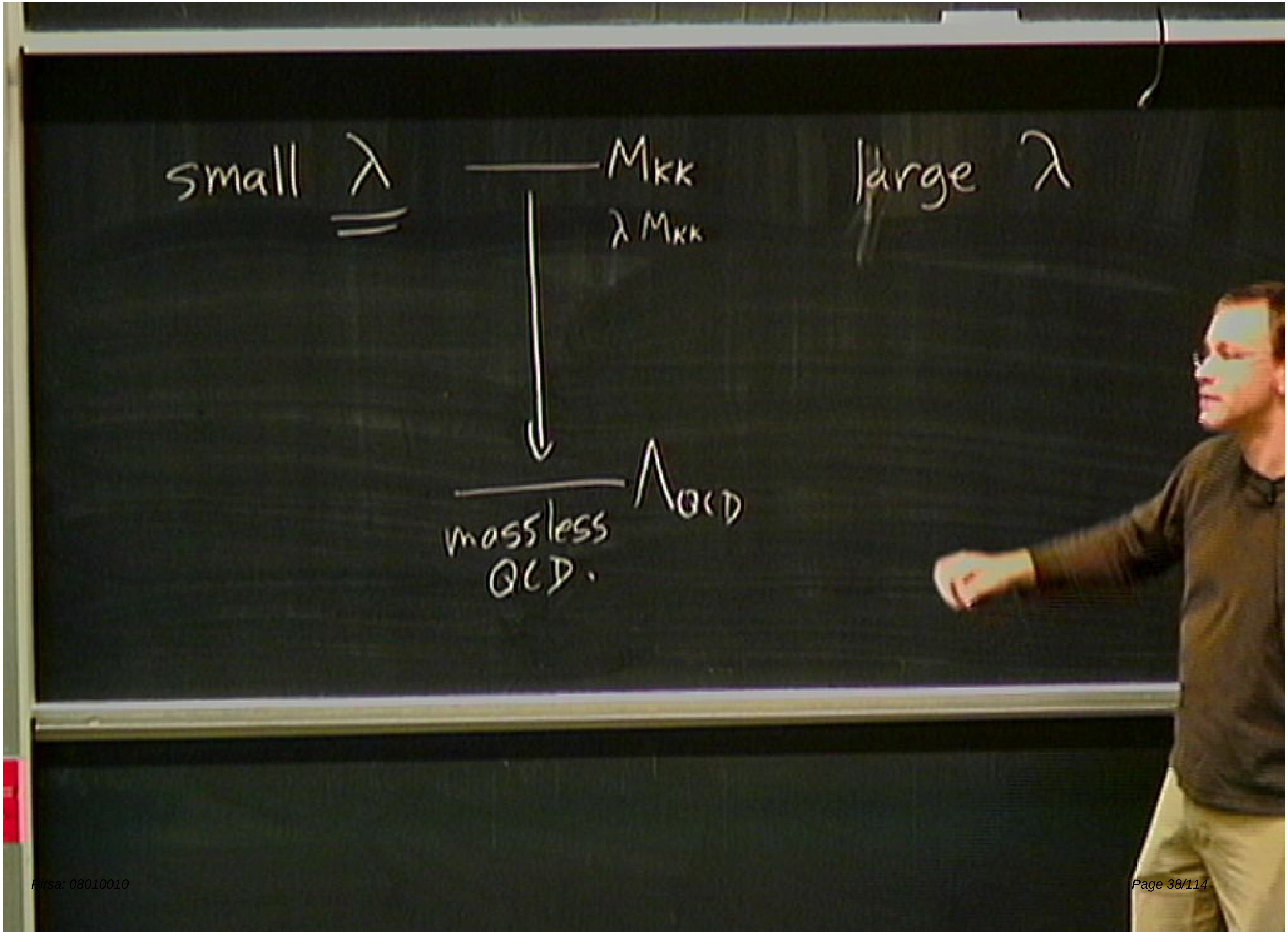


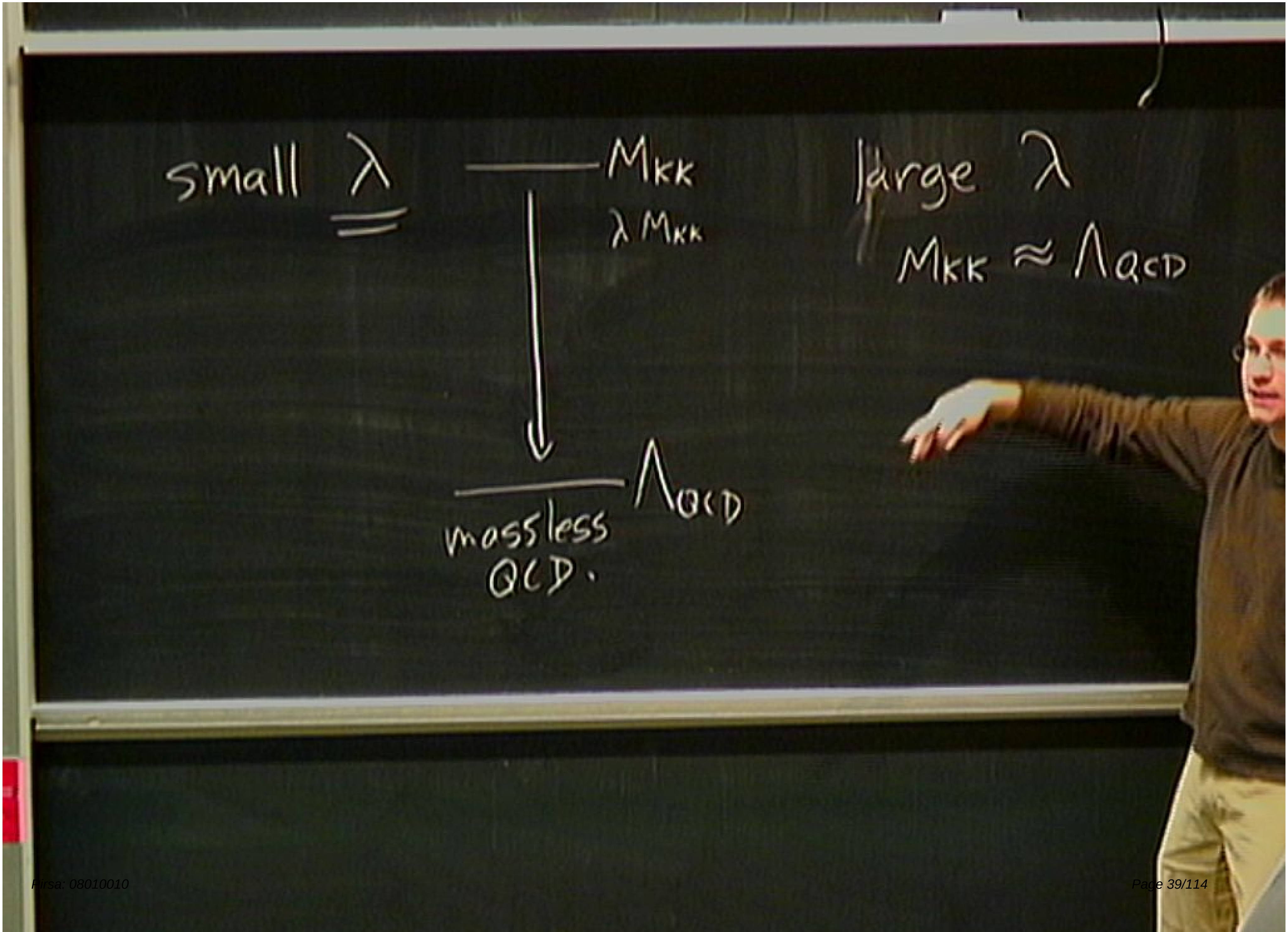
CDW → spatially inhomogeneous $\langle \bar{q} q \rangle$
WSS:
N_c D4
N_f $\overline{D8}$
N_f D8
antiper. b.c. fermions
R
parameters.
$M_{KK} \sim \frac{1}{R}$
N_c, N_f
$\lambda = \frac{g_5^2 N_c}{R}$

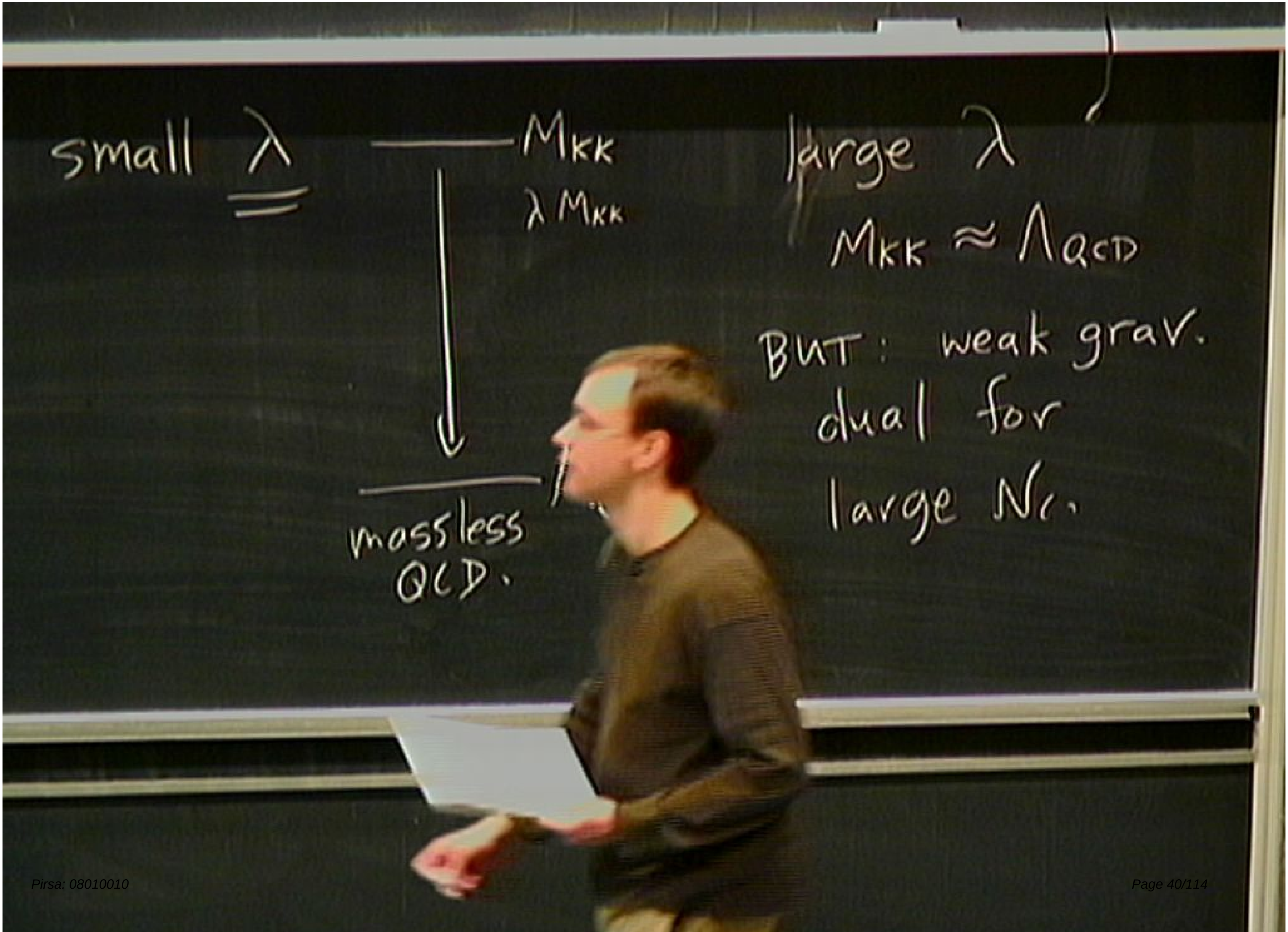
small λ —— M_{KK}


small λ
M_{KK}
λM_{KK}
Λ_{QCD}


small λ
M_KK
λ M_KK
Λ_QCD
massless QCD.


small λ
Mkk
λ Mkk
large λ
ΛQCD
massless
QCD.


small λ
M_{KK}
λM_{KK}
Λ_{QCD}
massless QCD.
large λ
$M_{KK} \approx \Lambda_{QCD}$


small λ
M_{KK}
λM_{KK}
massless QCD.
large λ
$M_{KK} \approx \Lambda_{QCD}$
BUT: weak grav. dual for large N_c.

small λ

M_{KK}

λM_{KK}

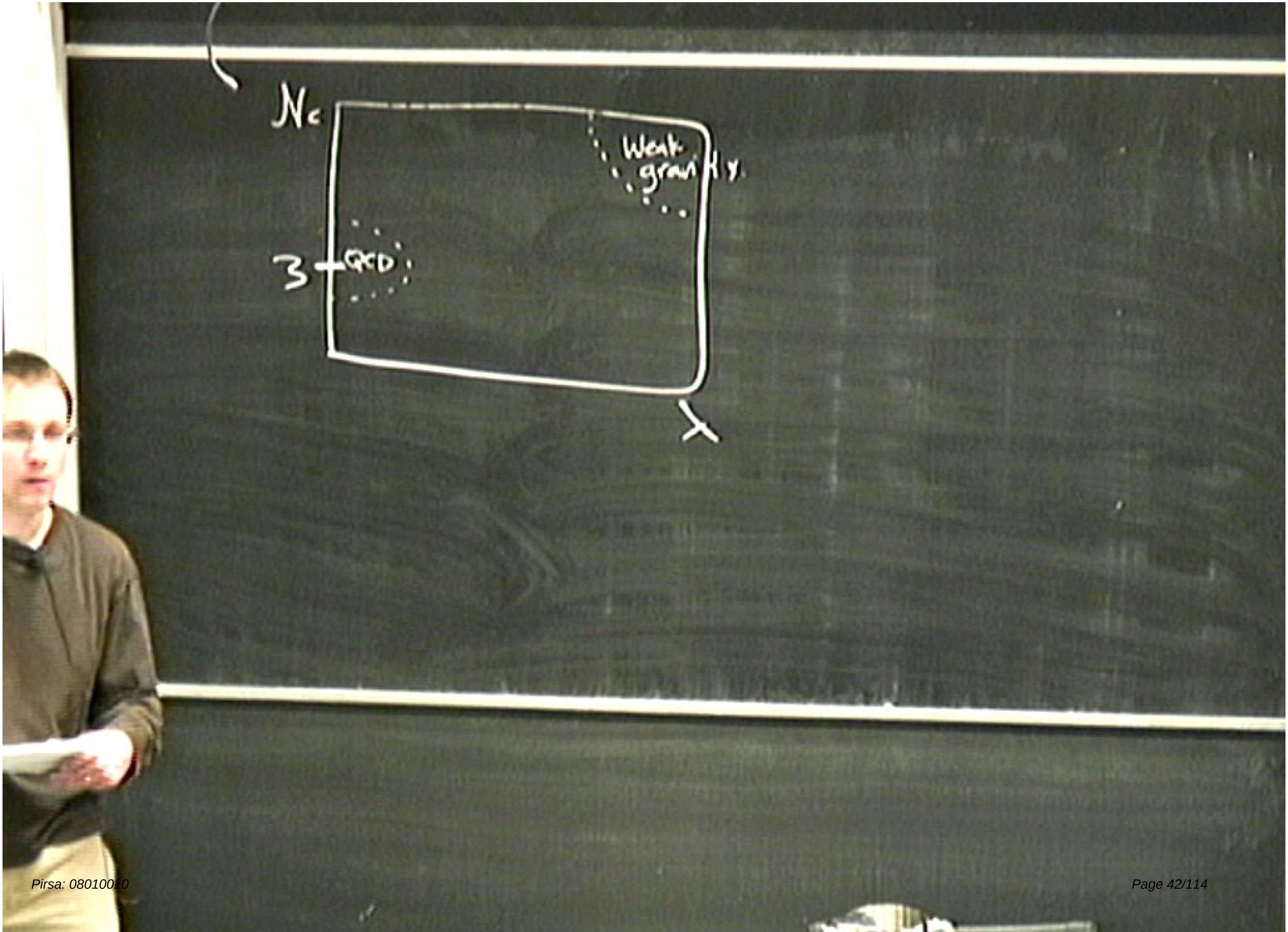
Λ_{QCD}

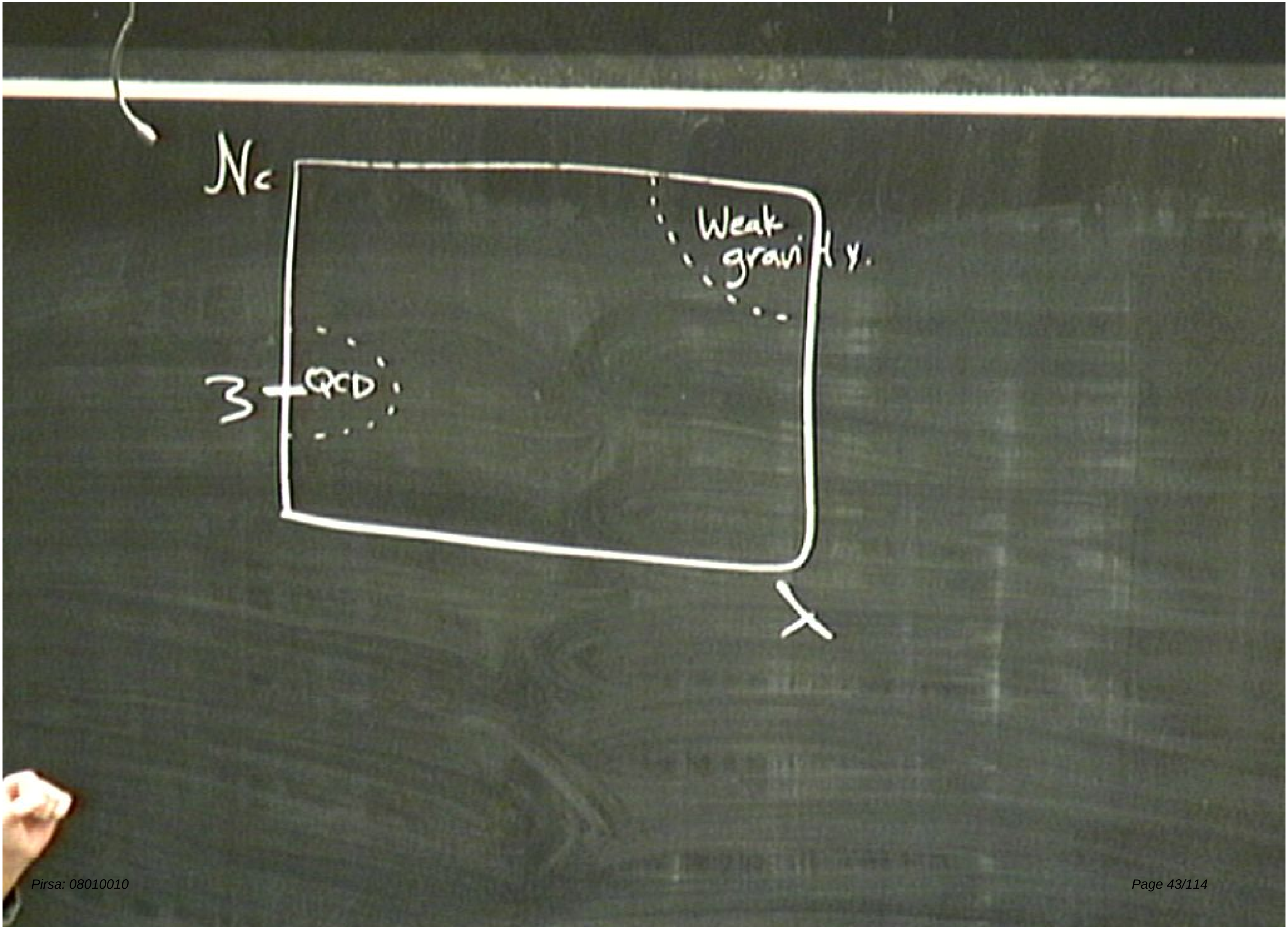
massless QCD.

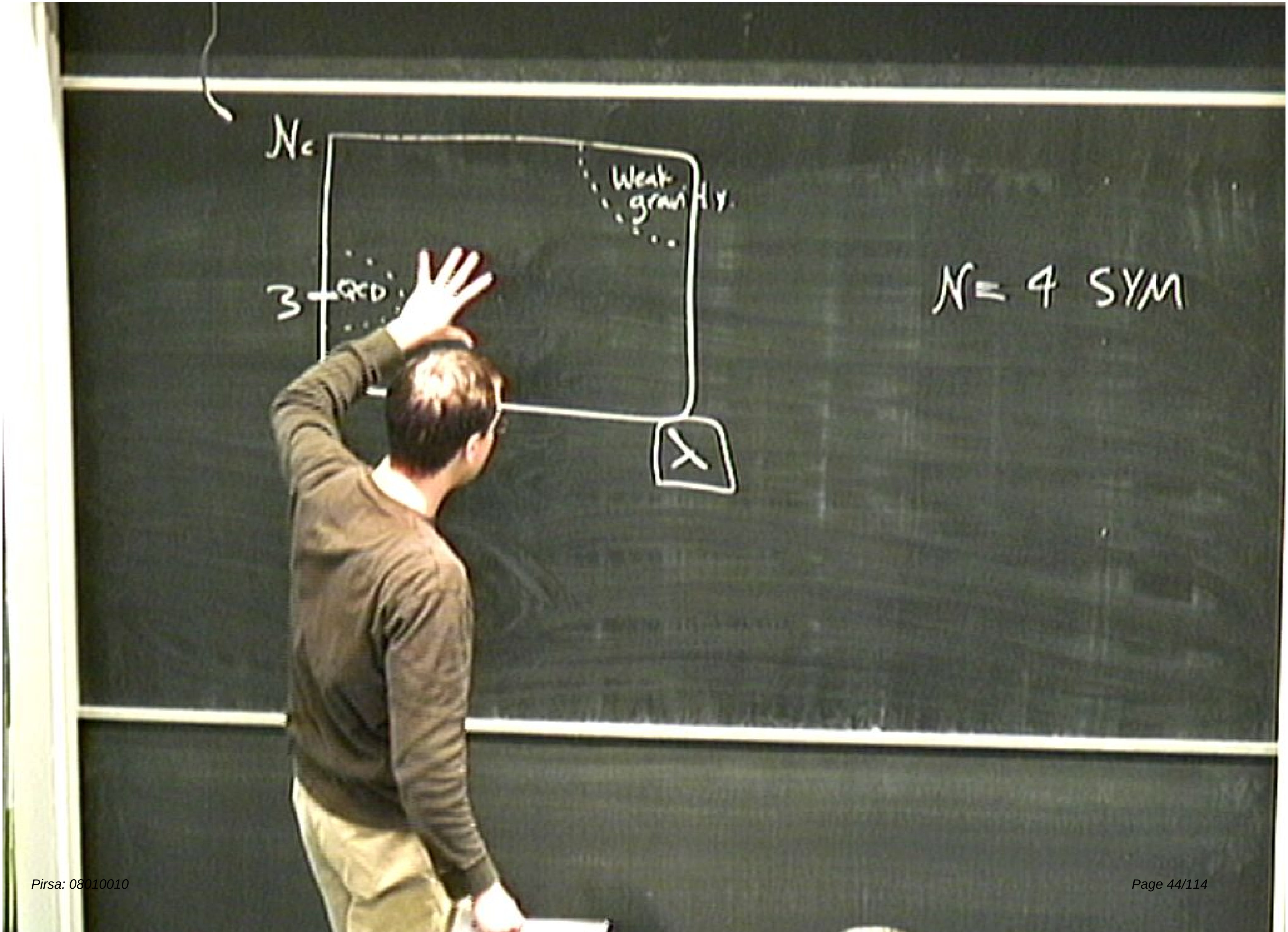
large λ

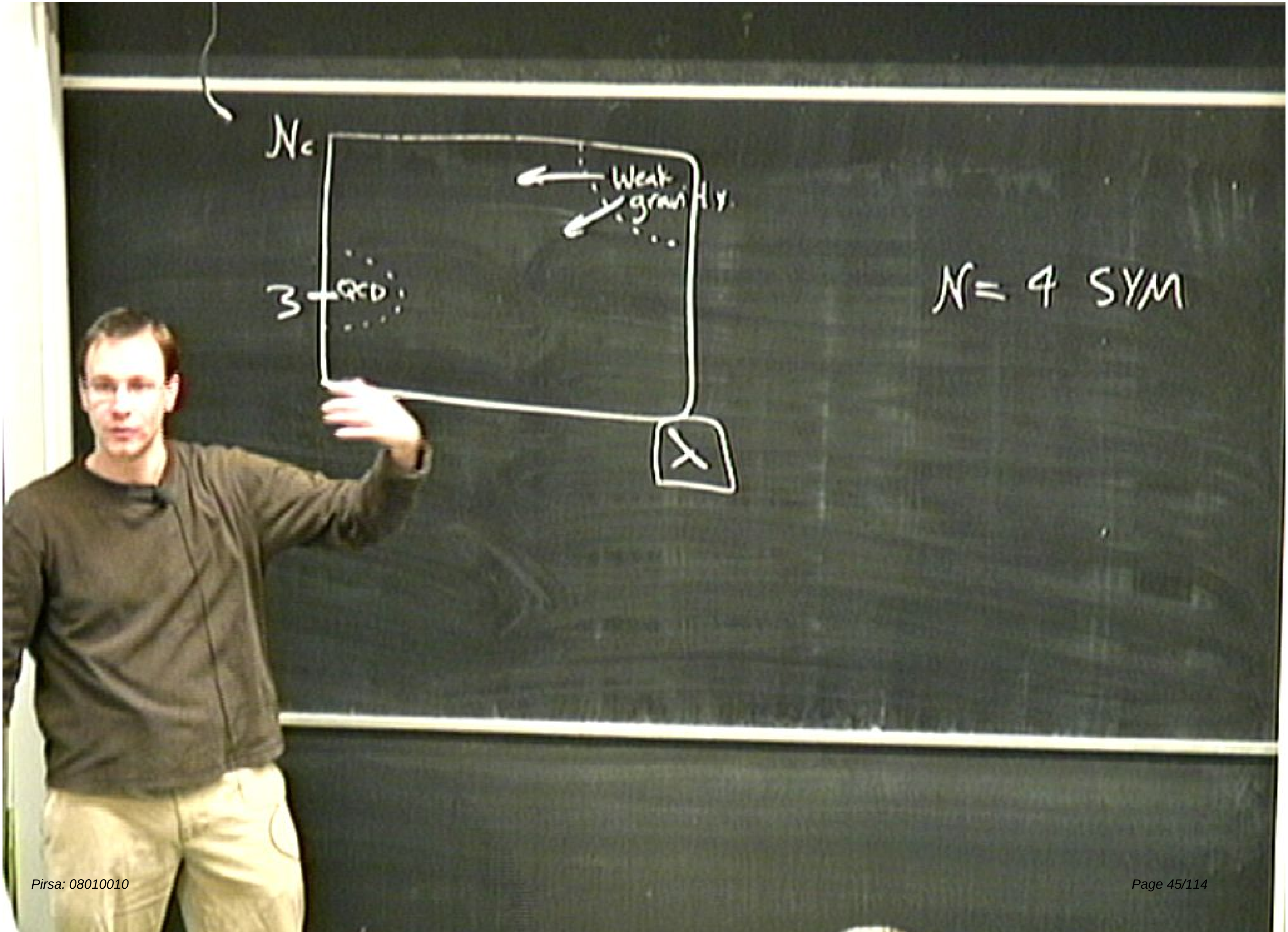
$M_{KK} \approx \Lambda_{QCD}$

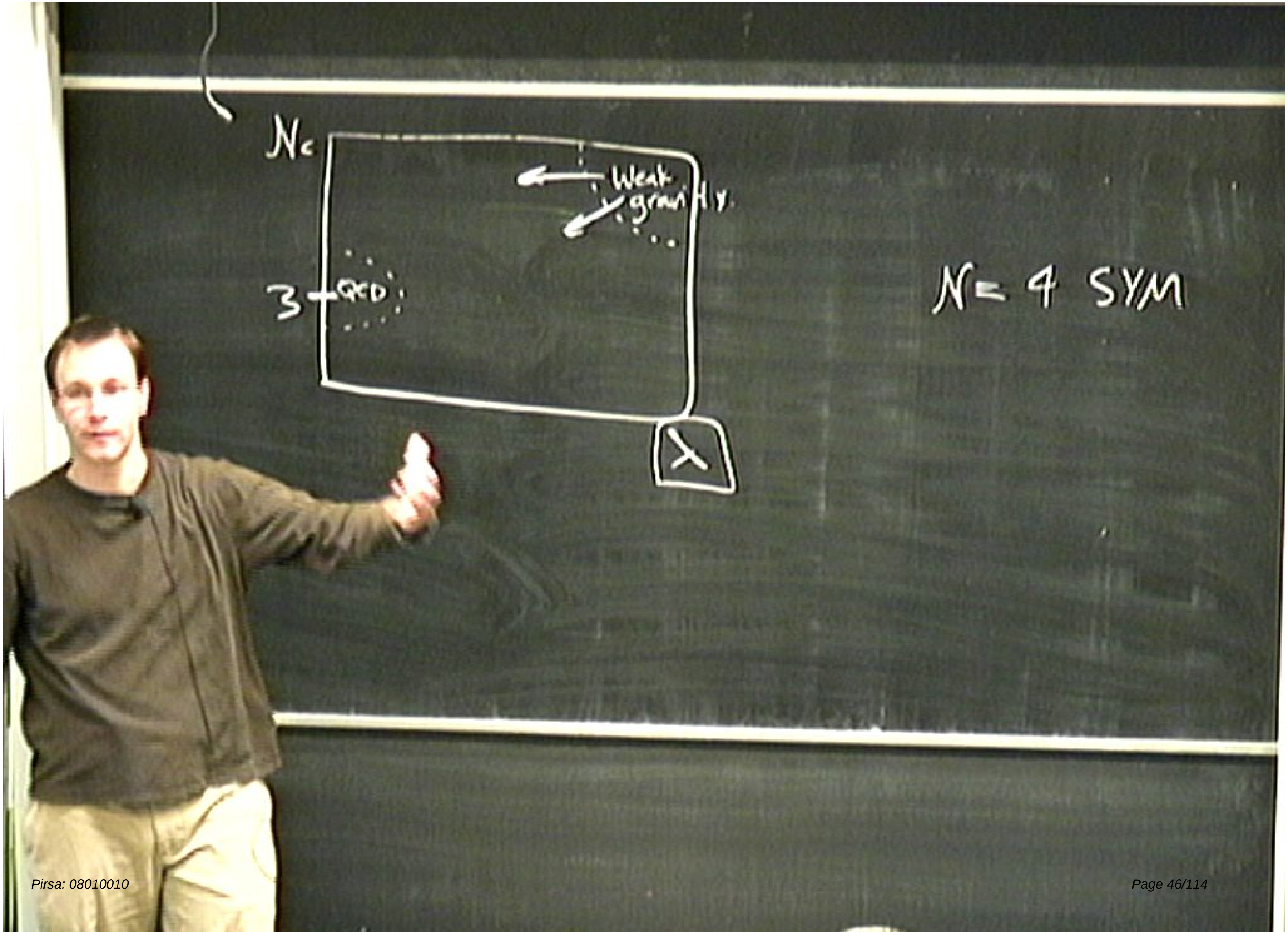
BUT: weak grav. dual for large N_c.


N_c
Weak gravity
3
QCD
λ

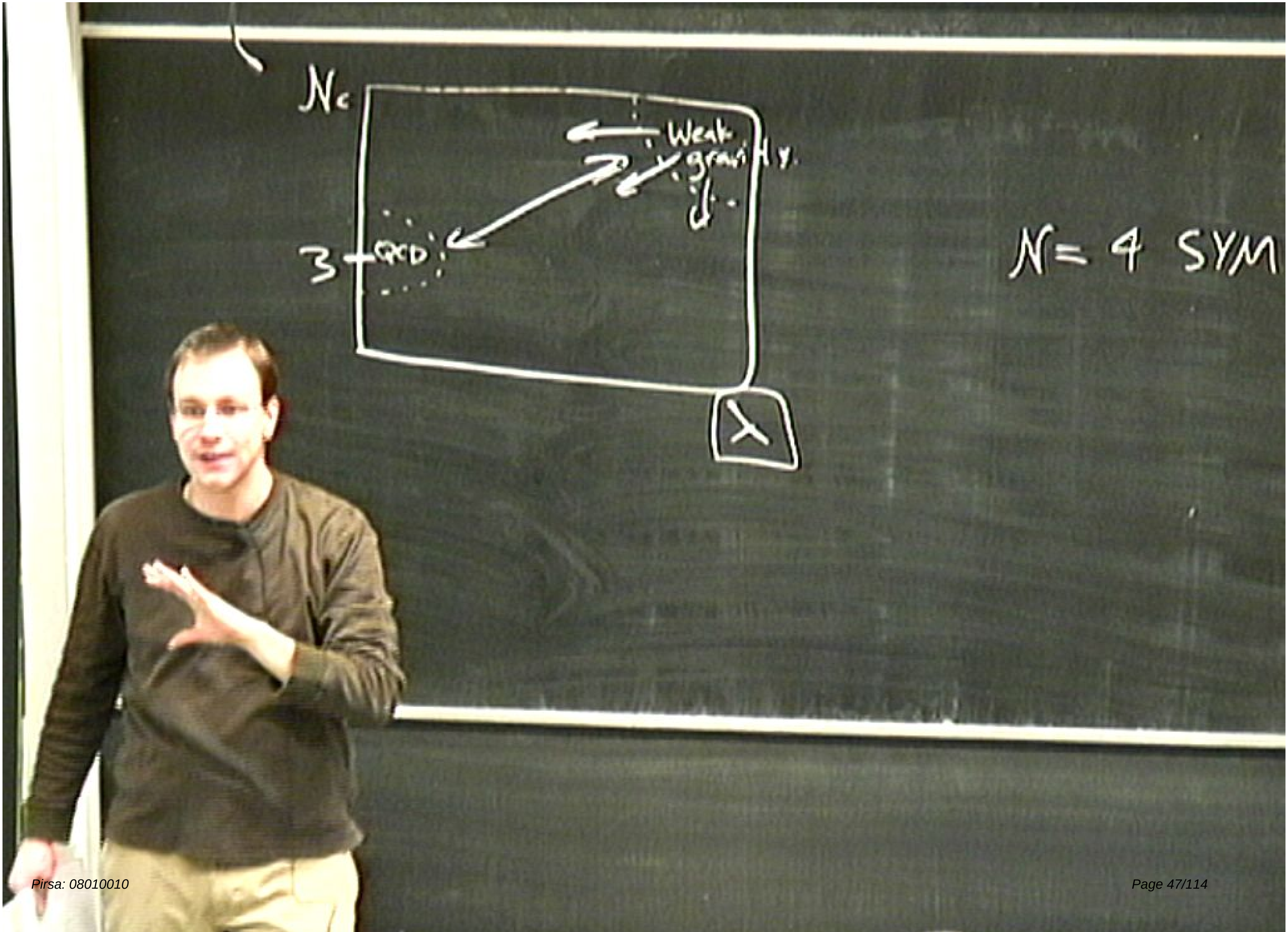

N_c
Weak gravity.
3
QCD
λ

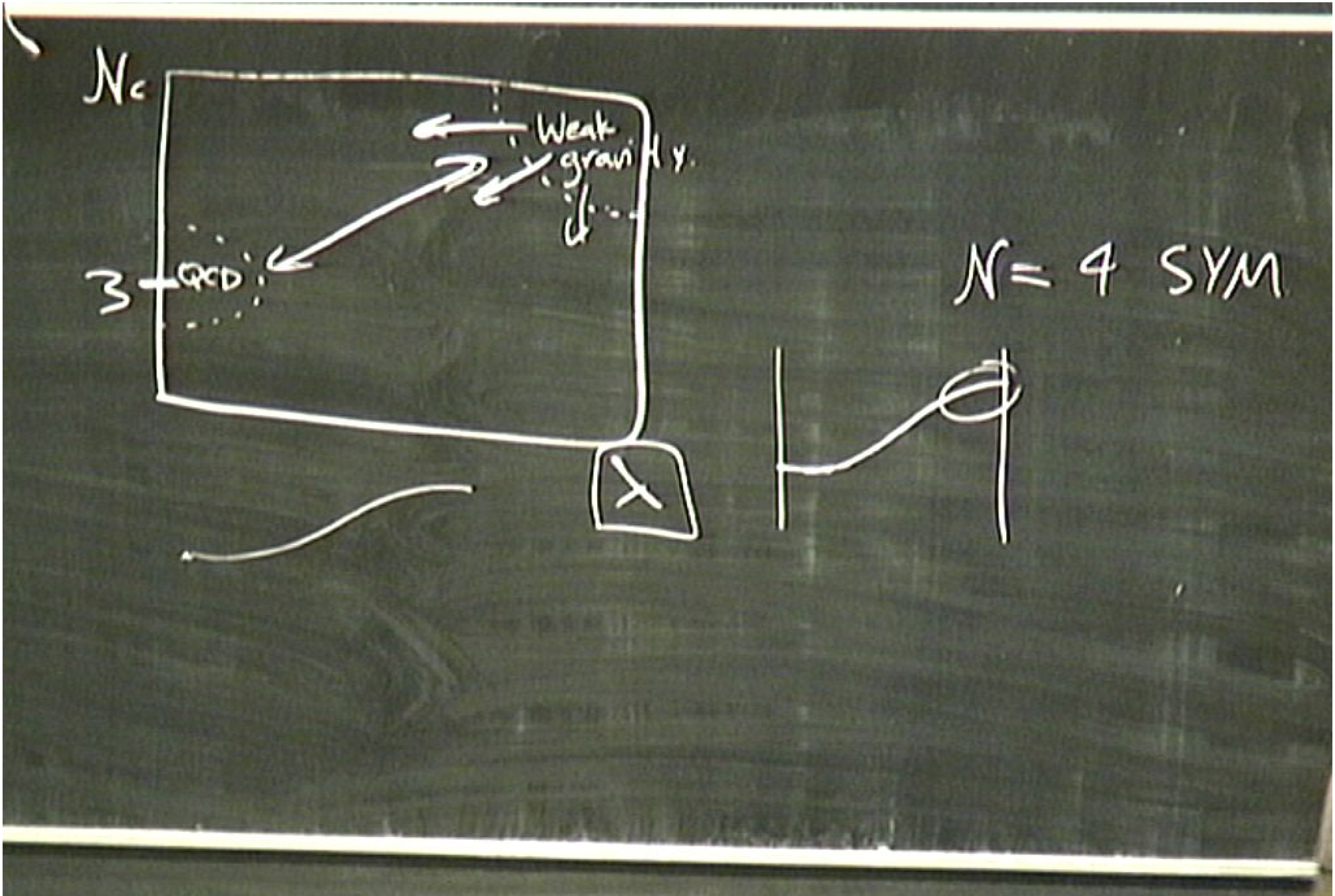

Nc
Weak
gravity
3
QCD
λ
N = 4 SYM

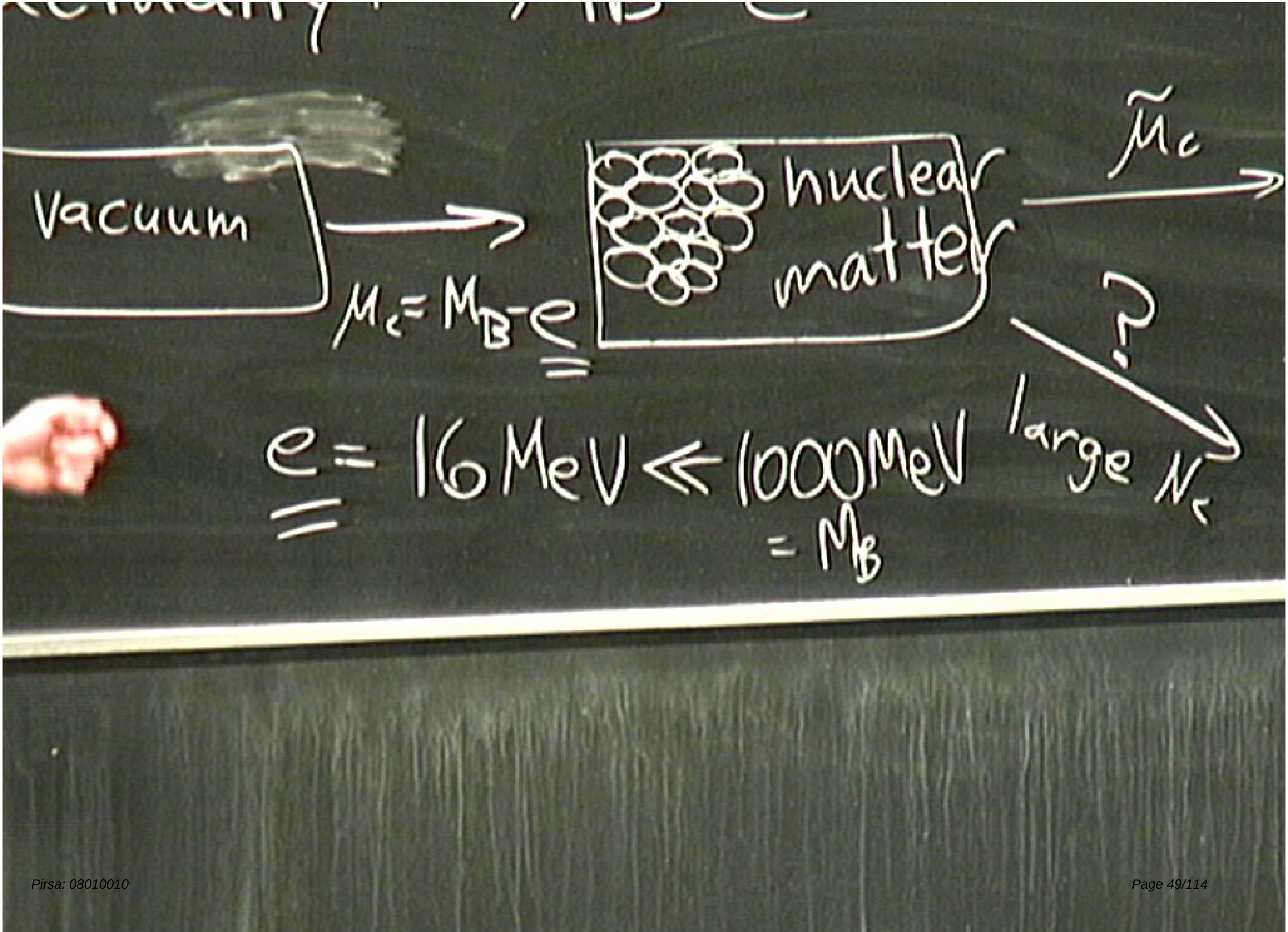

Nc
Weak
gravity
3
QCD
N = 4 SYM

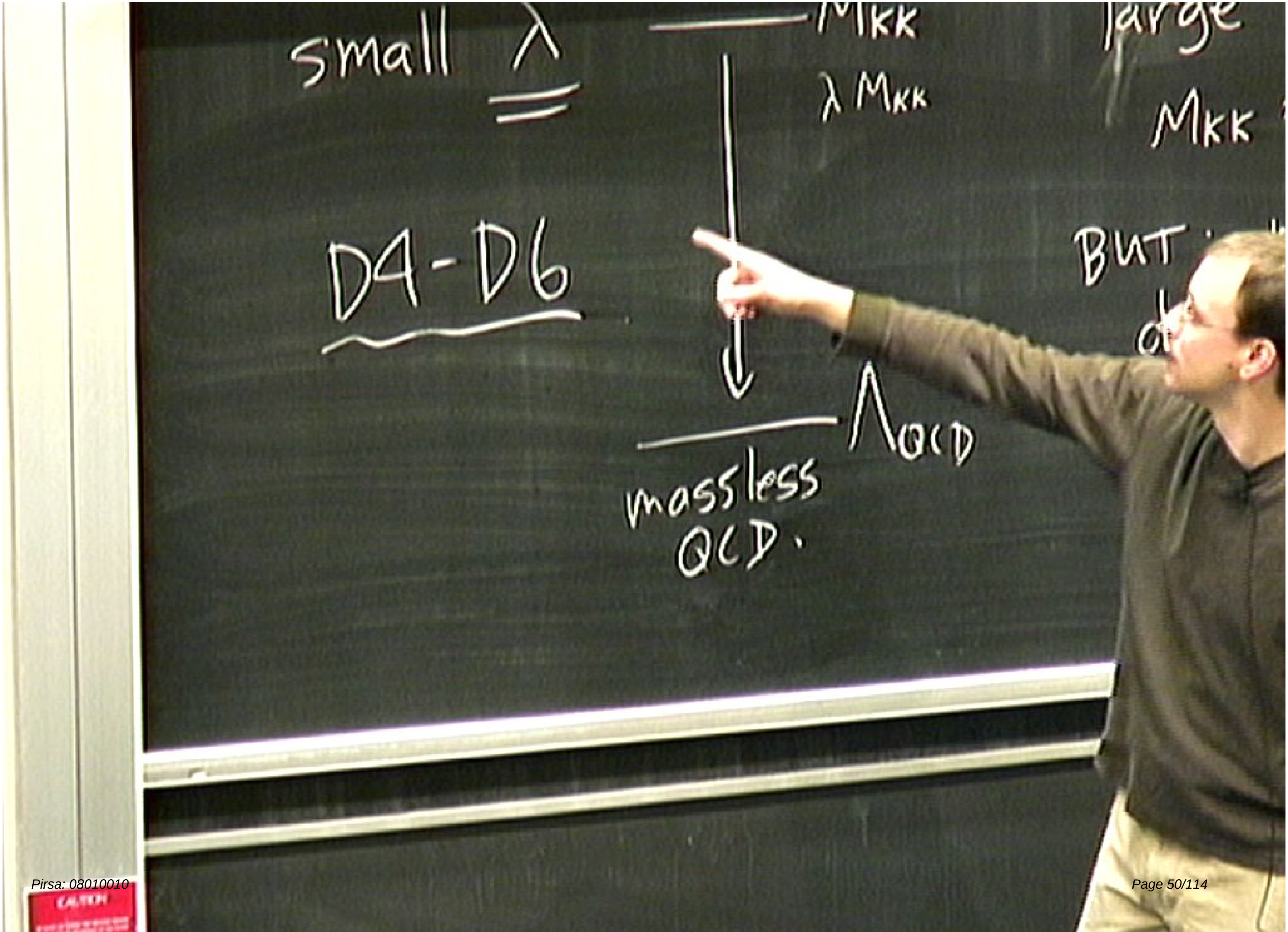


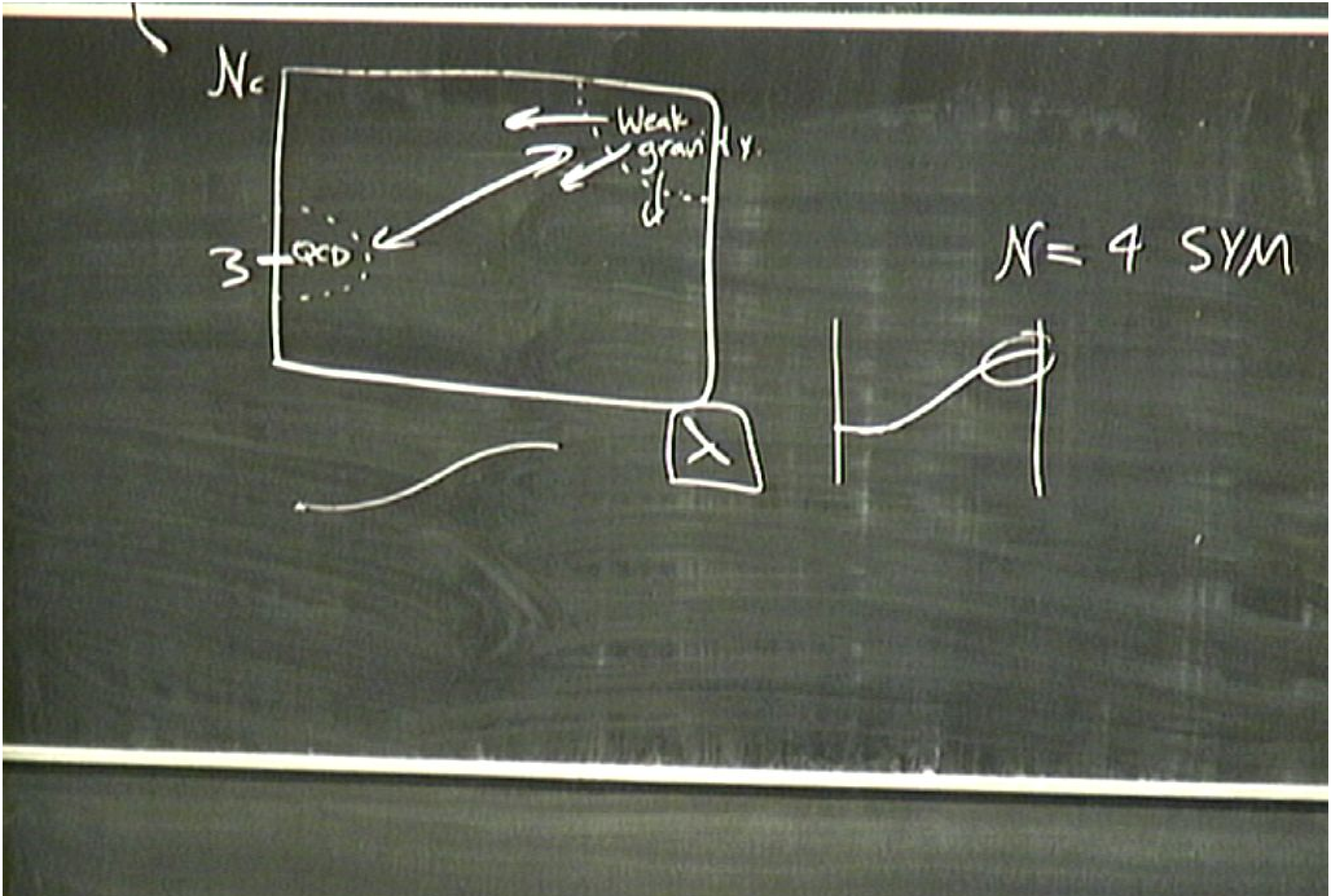
N_c
Weak
3
QCD
λ
N = 4 SYM

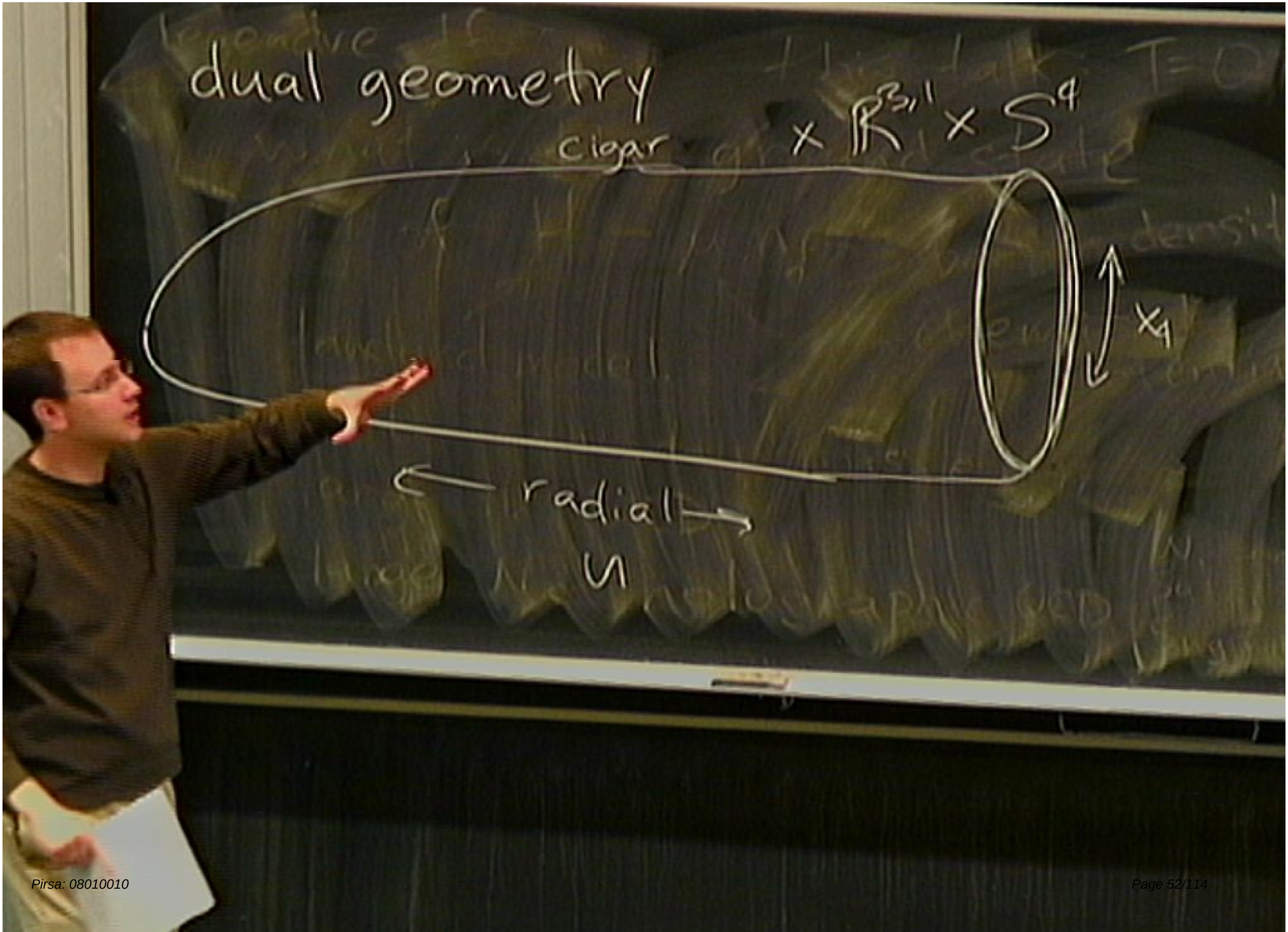

Nc
Weak
gravity
3
QCD
λ
N = 4 SYM

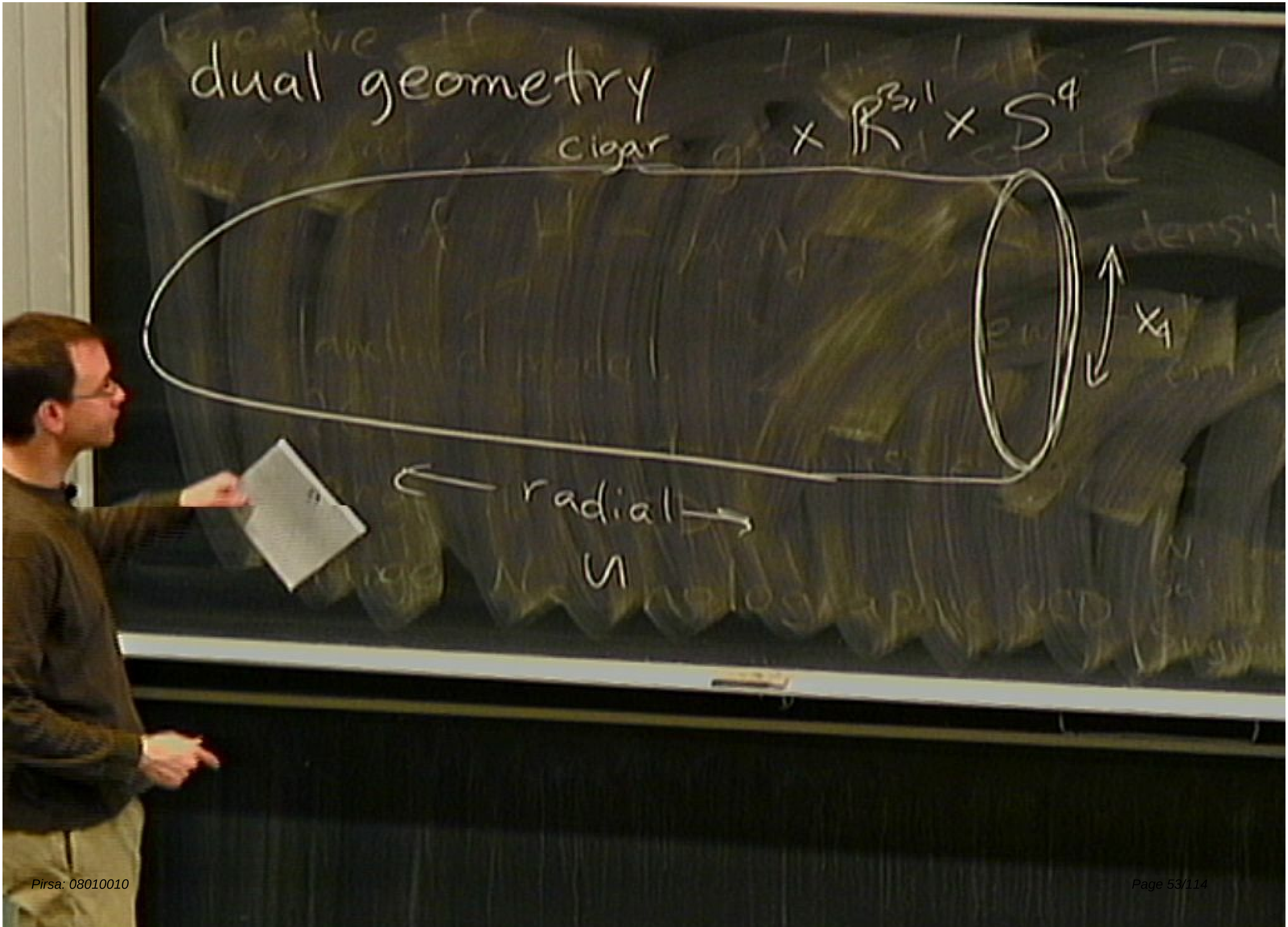

N_c
Weak
gravity
3
QCD
λ
$\mathcal{N}=4$ SYM

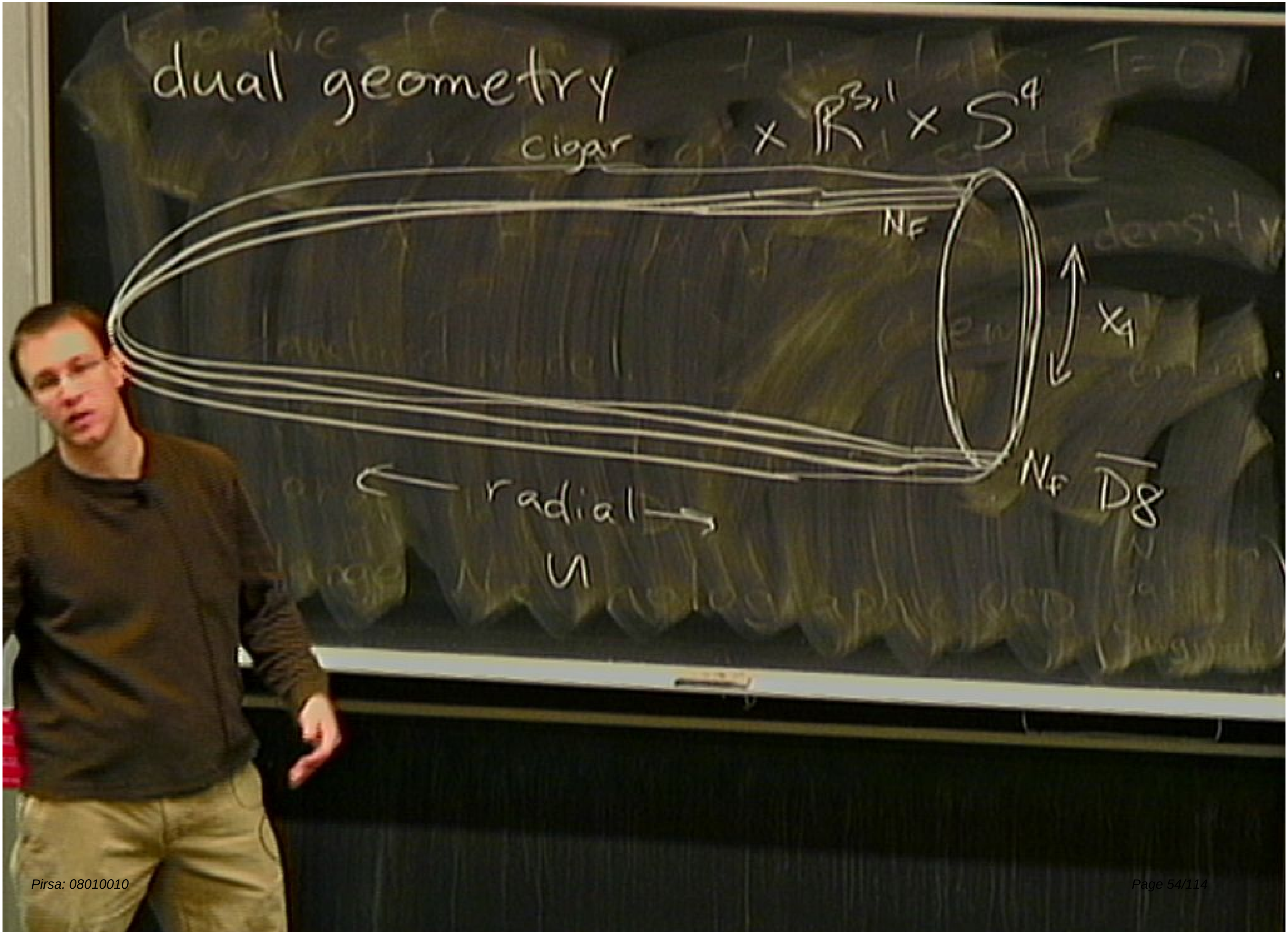

vacuum
μc = MB − e
nuclear matter
μ̃c
?
large Nc
e = 16 MeV ≪ 1000 MeV
= MB

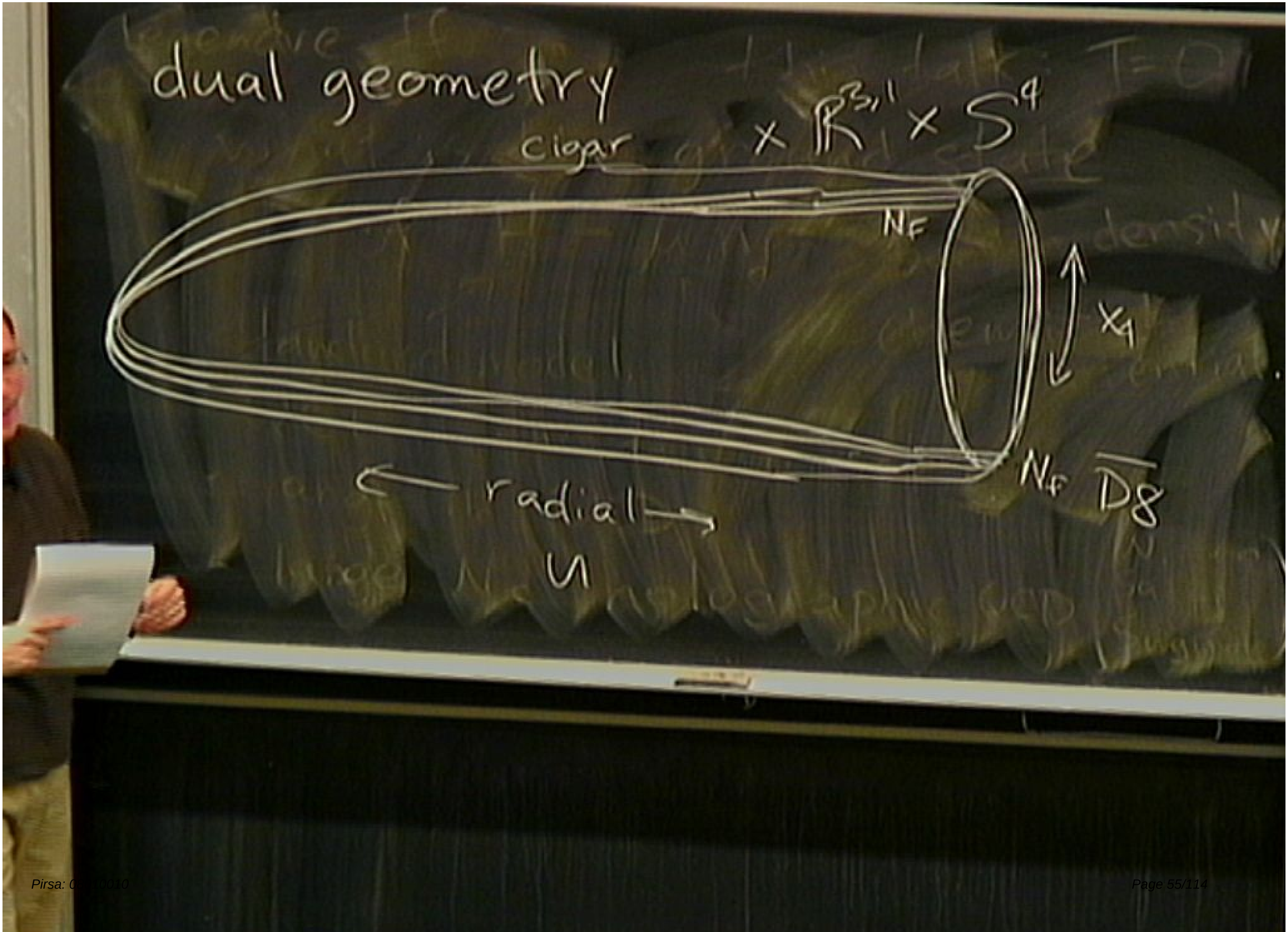

small λ
Mkk
large
λ Mkk
Mkk
D4-D6
But
ΛQCD
massless
QCD.


Nc
Weak
gravity
3
QCD
N = 4 SYM

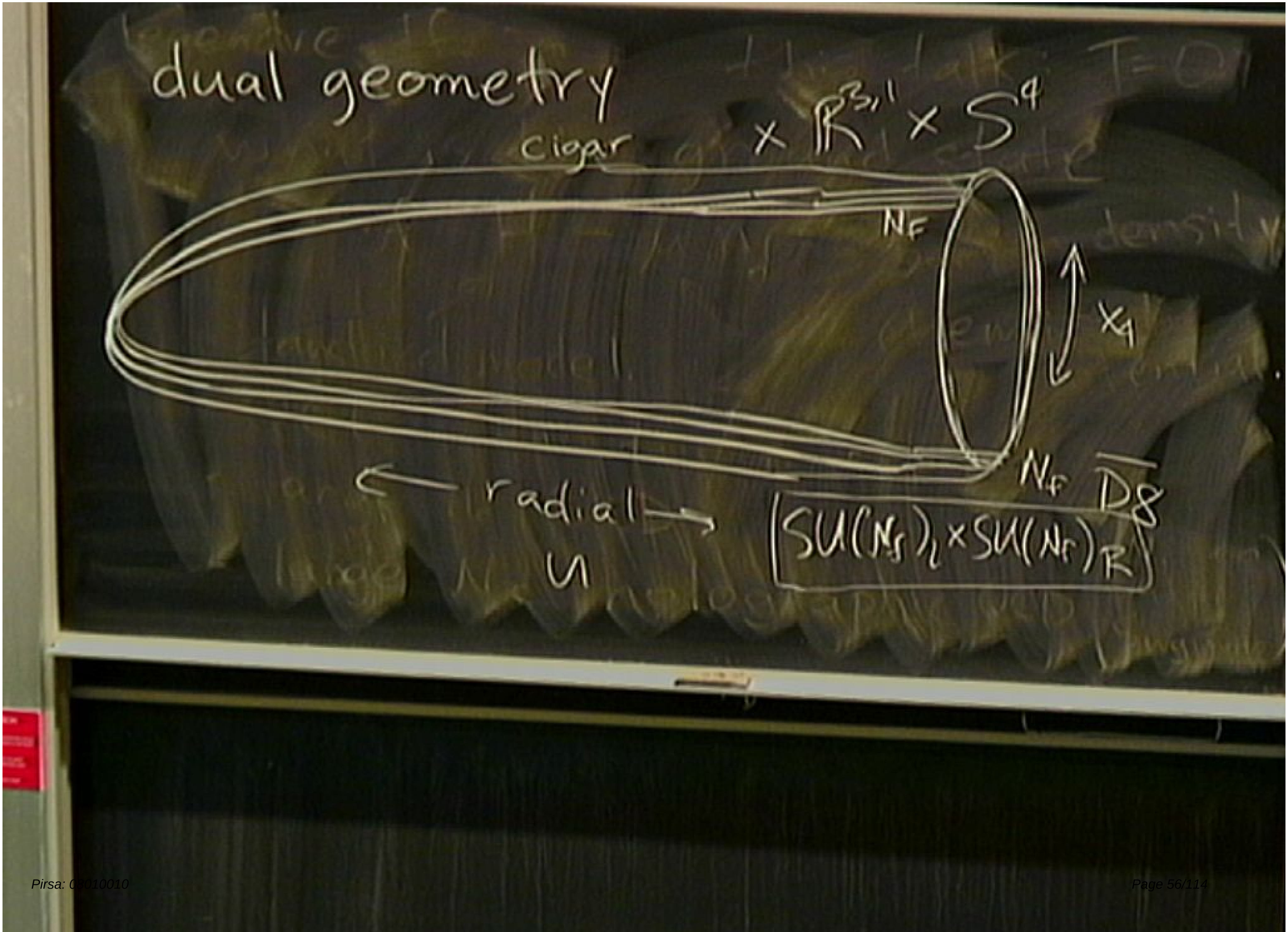

dual geometry
cigar
$\times \mathbb{R}^{3,1} \times S^4$
x_4
radial
u

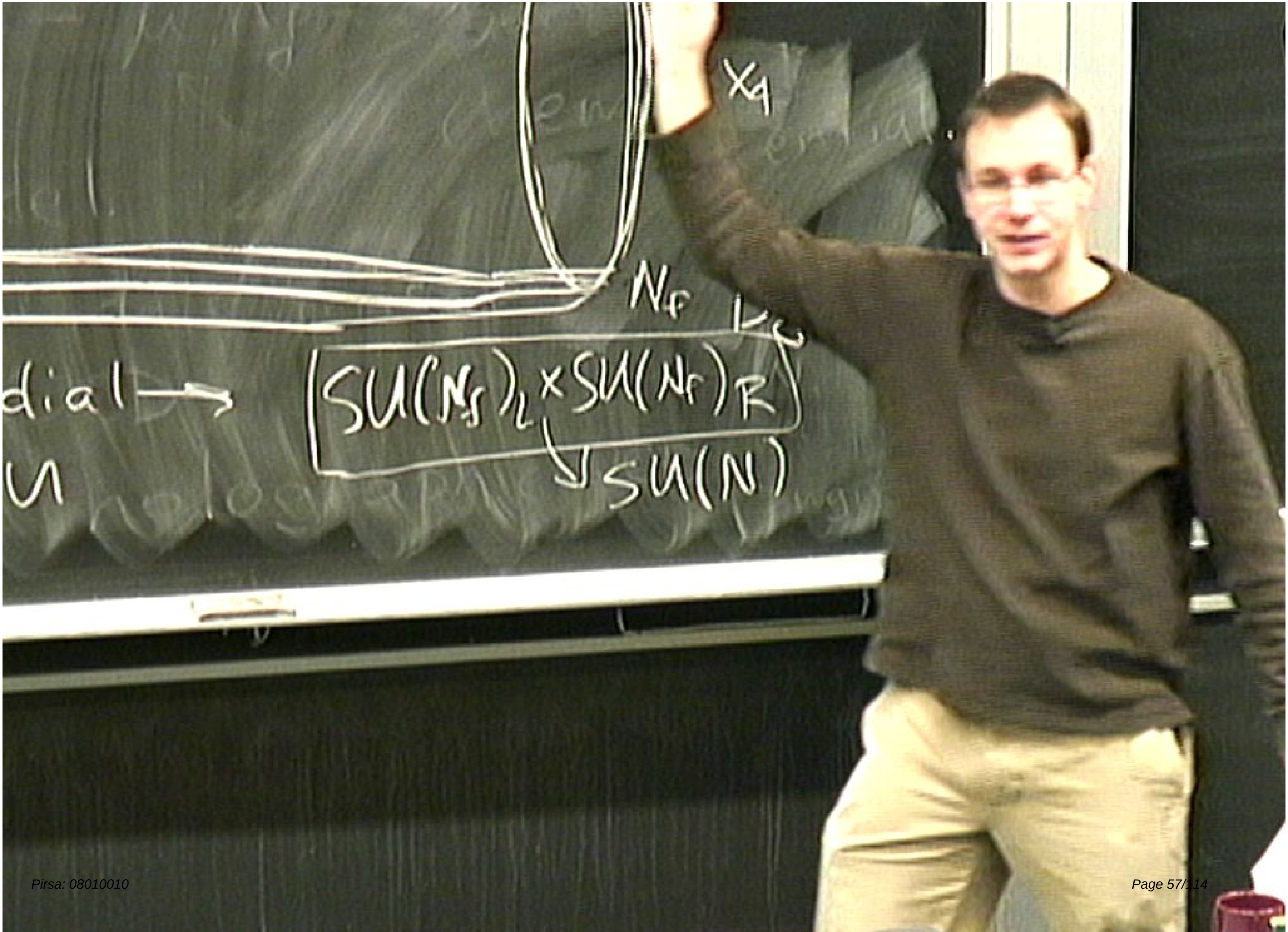

dual geometry
cigar $\times \mathbb{R}^{3,1} \times S^4$
x_4
radial
u

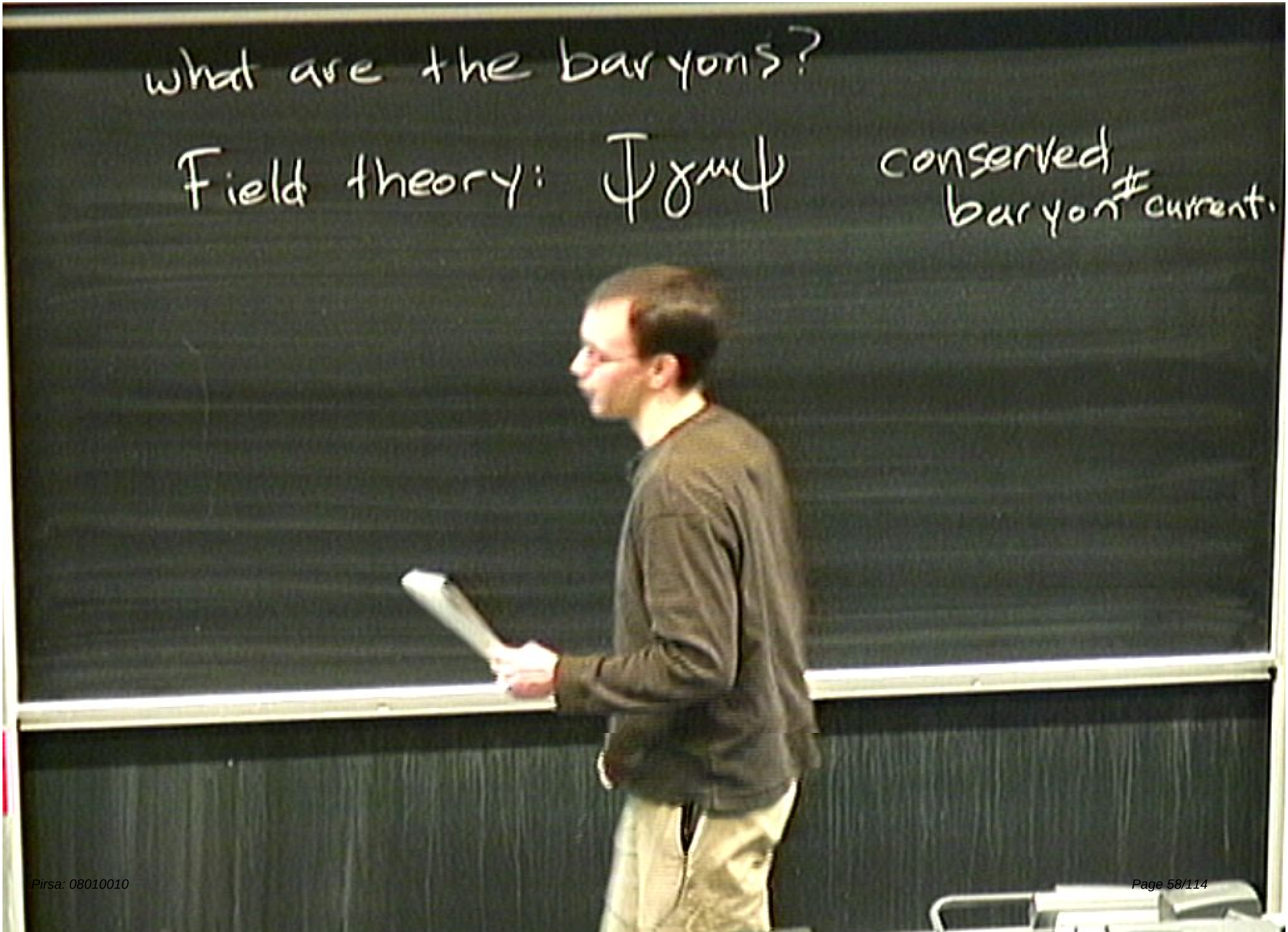

dual geometry
cigar $\times \mathbb{R}^{3,1} \times S^4$
N_f
x_4
N_f $\overline{D8}$
radial
u

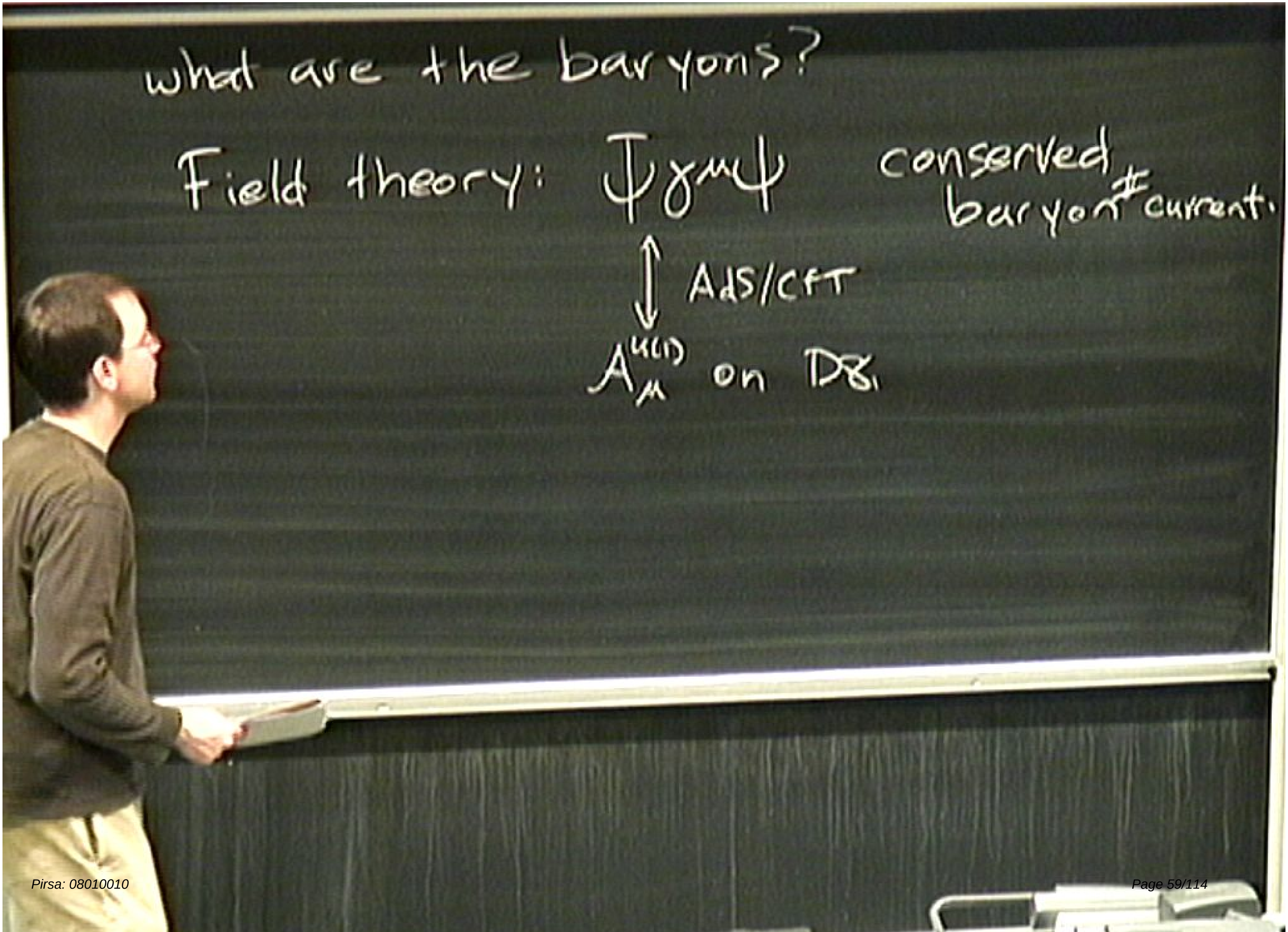


dual geometry
cigar × $\mathbb{R}^{3,1}$ × S^4
N_f
x_4
N_f $\overline{D8}$
radial
u


dual geometry
cigar × $\mathbb{R}^{3,1}$ × S^4
N_F
x_4
N_F
D8
radial
u
$SU(N_f)_L \times SU(N_f)_R$


X_4
N_f
dial →
$SU(N_f)_L \times SU(N_f)_R$
$SU(N)$


what are the baryons?
Field theory: $\bar{\psi}\gamma^\mu\psi$
conserved baryon # current.


what are the baryons?
Field theory: $\bar{\psi}\gamma^\mu\psi$
conserved baryon # current.
AdS/CFT
$A_\mu^{U(1)}$ on D8.

what are the baryons?

Field theory: $\bar{\psi}\gamma^\mu\psi$ conserved baryon # current.

$$\Big\updownarrow \text{ AdS/CFT}$$

$A_\mu^{U(1)}$ on D8.

$$A_\mu^{U(1)} \sim \mu + c\,\frac{n_B}{u^{3/2}} + \dots$$

what are the baryons?

Field theory: $\bar{\psi}\gamma^\mu\psi$ conserved baryon # current.

$$\Big\updownarrow \text{ AdS/CFT}$$

$A_\mu^{U(1)}$ on D8.

$$A_\mu^{U(1)} \sim \underline{\underline{\mu}} + c\,\frac{n_B}{u^{3/2}} + \dots$$

Field theory: $\bar{\psi}\gamma^{\mu}\psi$ c

$$\Updownarrow \text{AdS/CFT}$$

$A^{U(1)}_{\mu}$ on D8

$$A^{U(1)}_{0} \sim \mu + c\,\frac{n_B}{u^{3/2}} + \dots$$

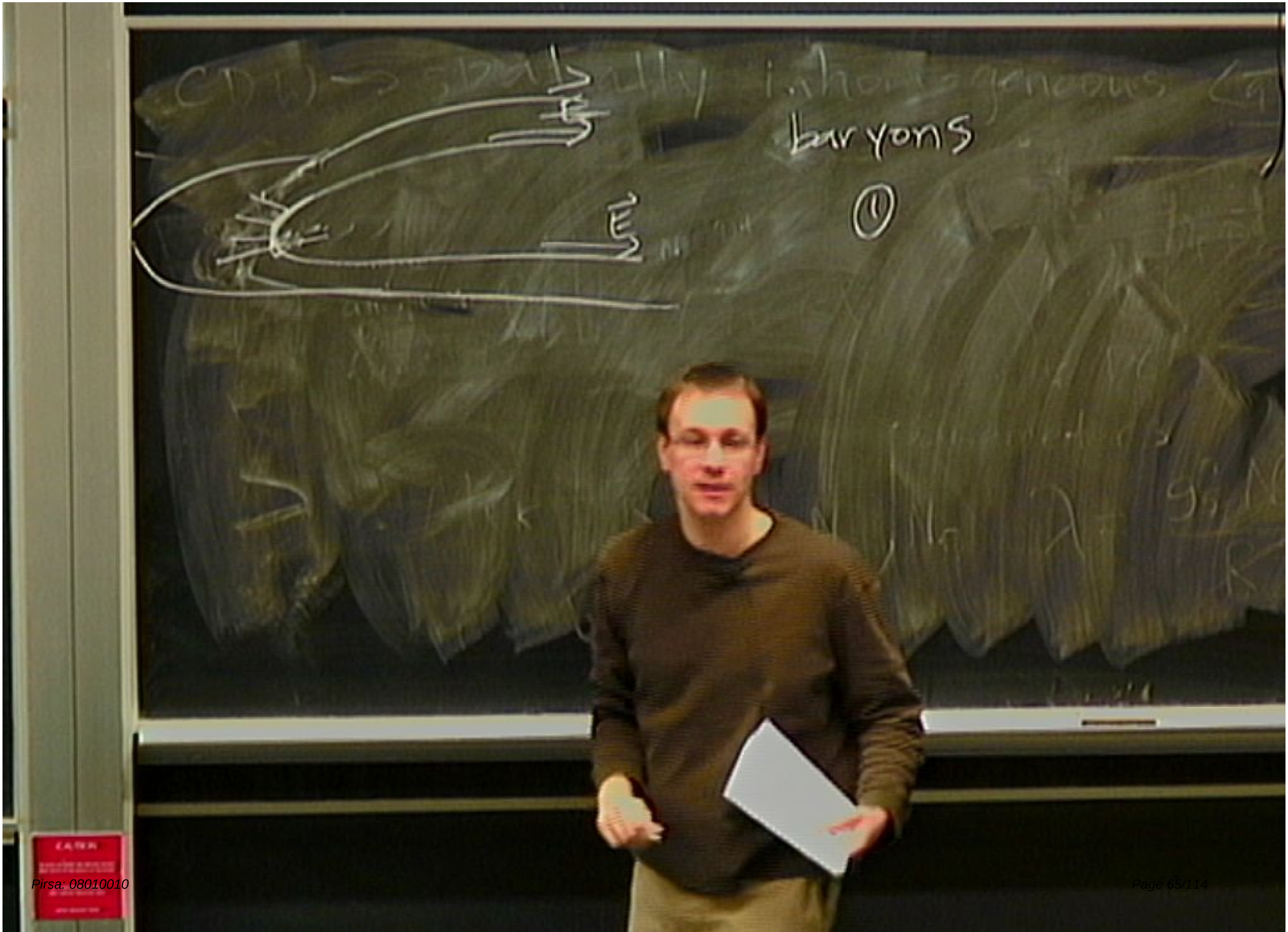
what are the baryons?

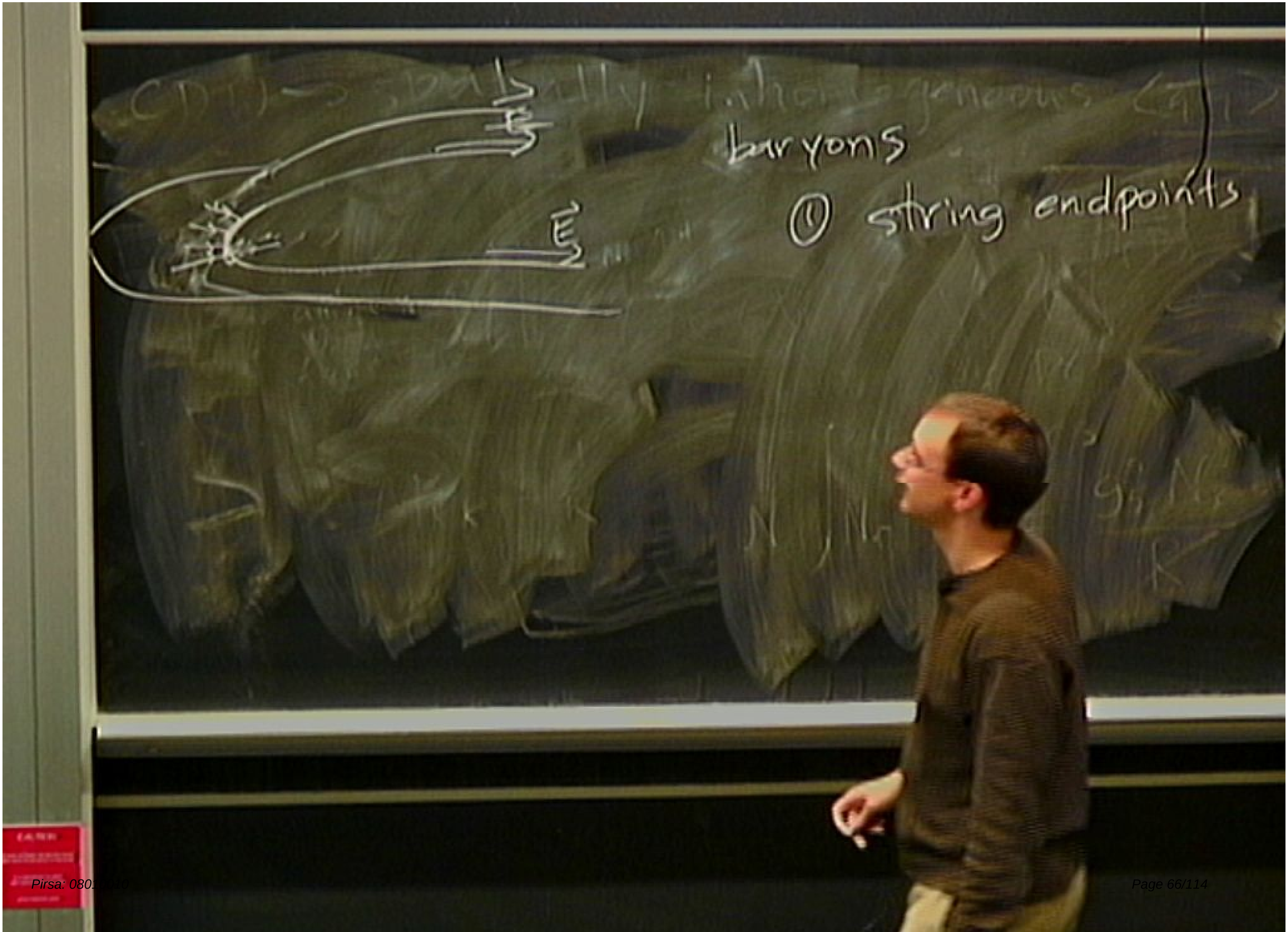
Field theory: $\bar{\psi}\gamma^{\mu}\psi$ conserved baryon # current.

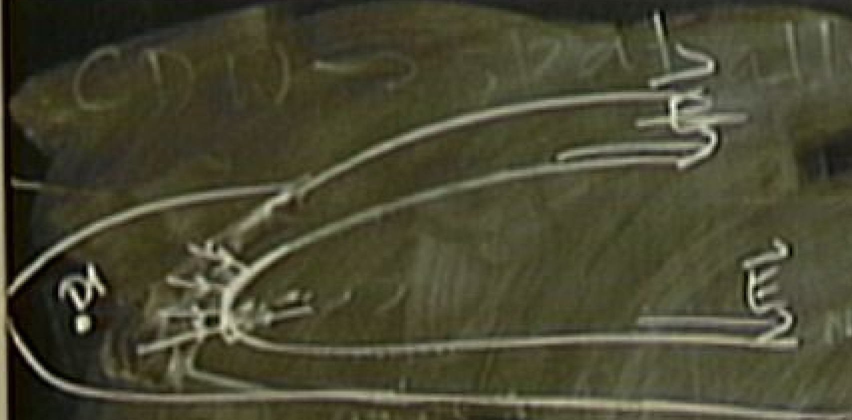
$$\Big\updownarrow \text{ AdS/CFT}$$

$A^{U(1)}_{\mu}$ on D8.

$$A^{U(1)}_{0} \sim \mu + c\,\frac{n_B}{u^{3/2}} + \dots$$

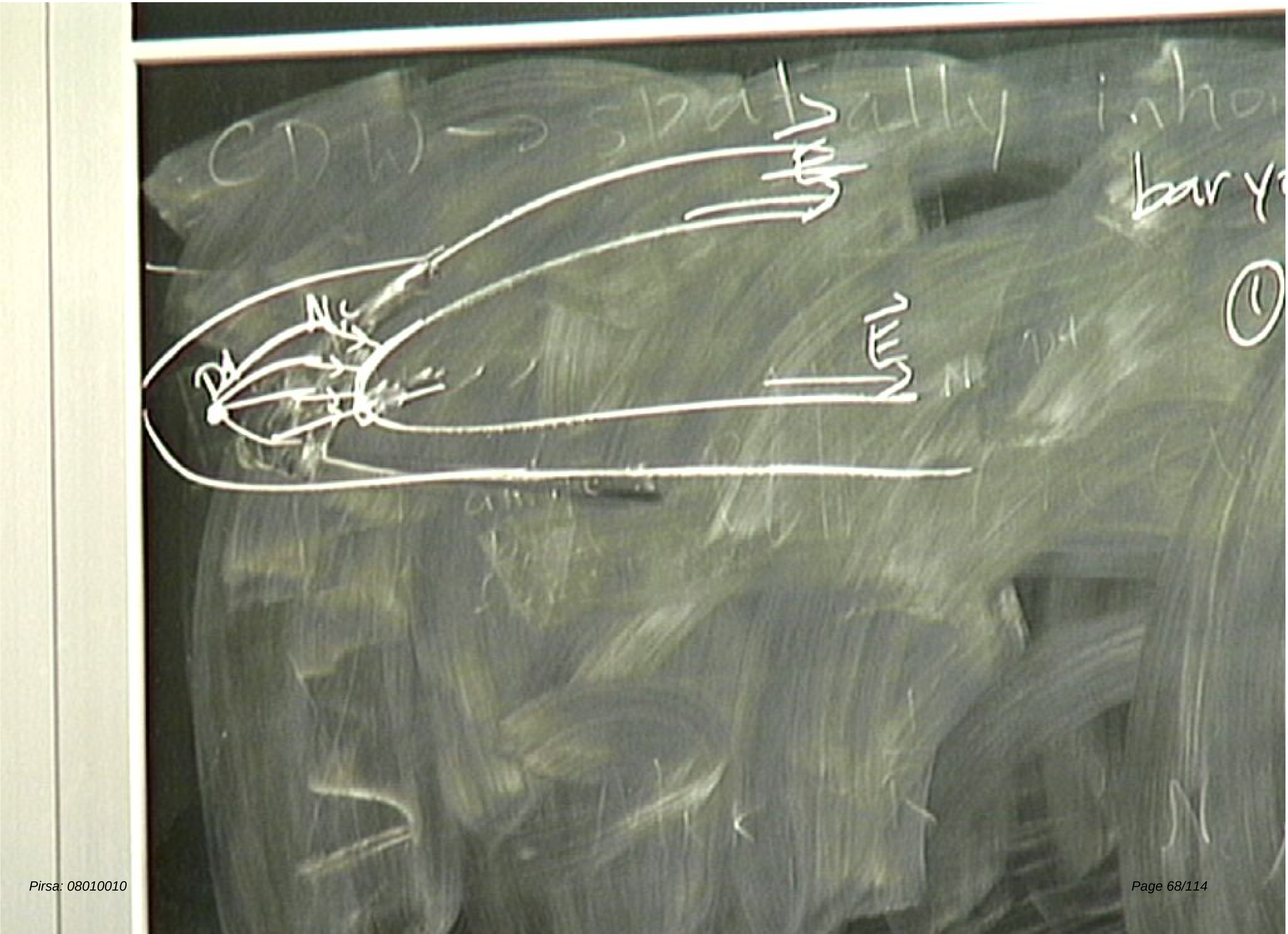

baryons

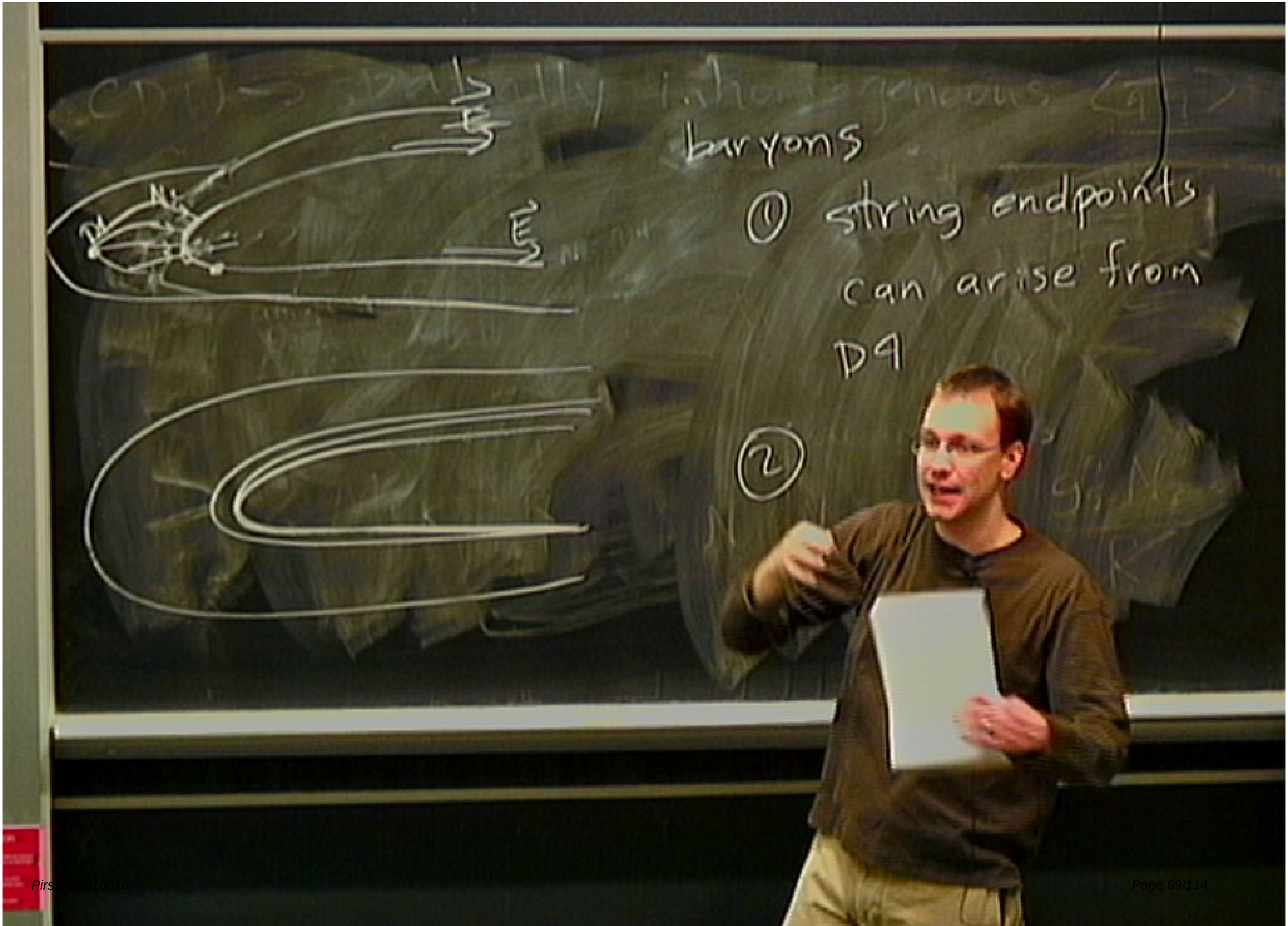

baryons
① string endpoints



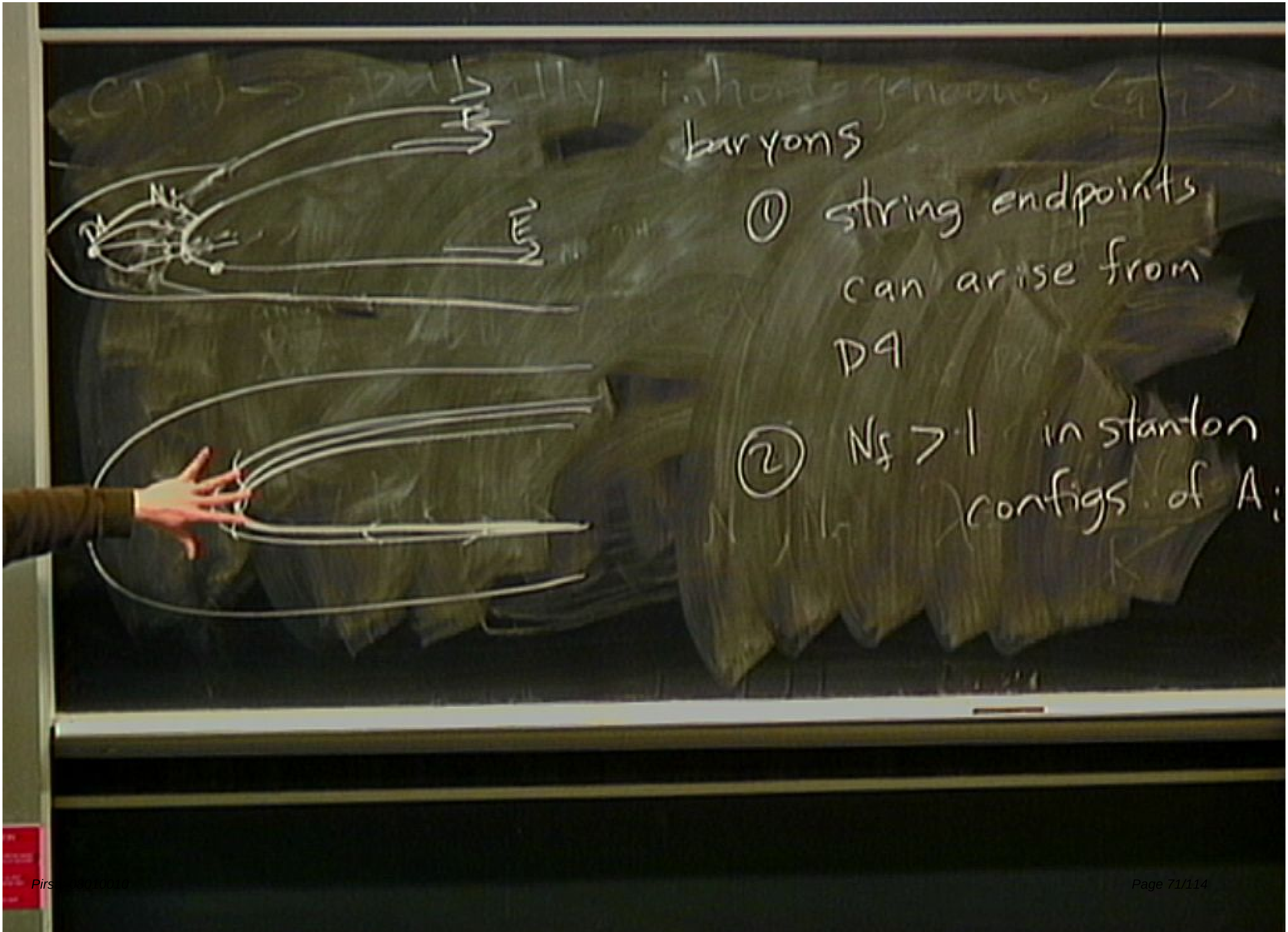
baryons

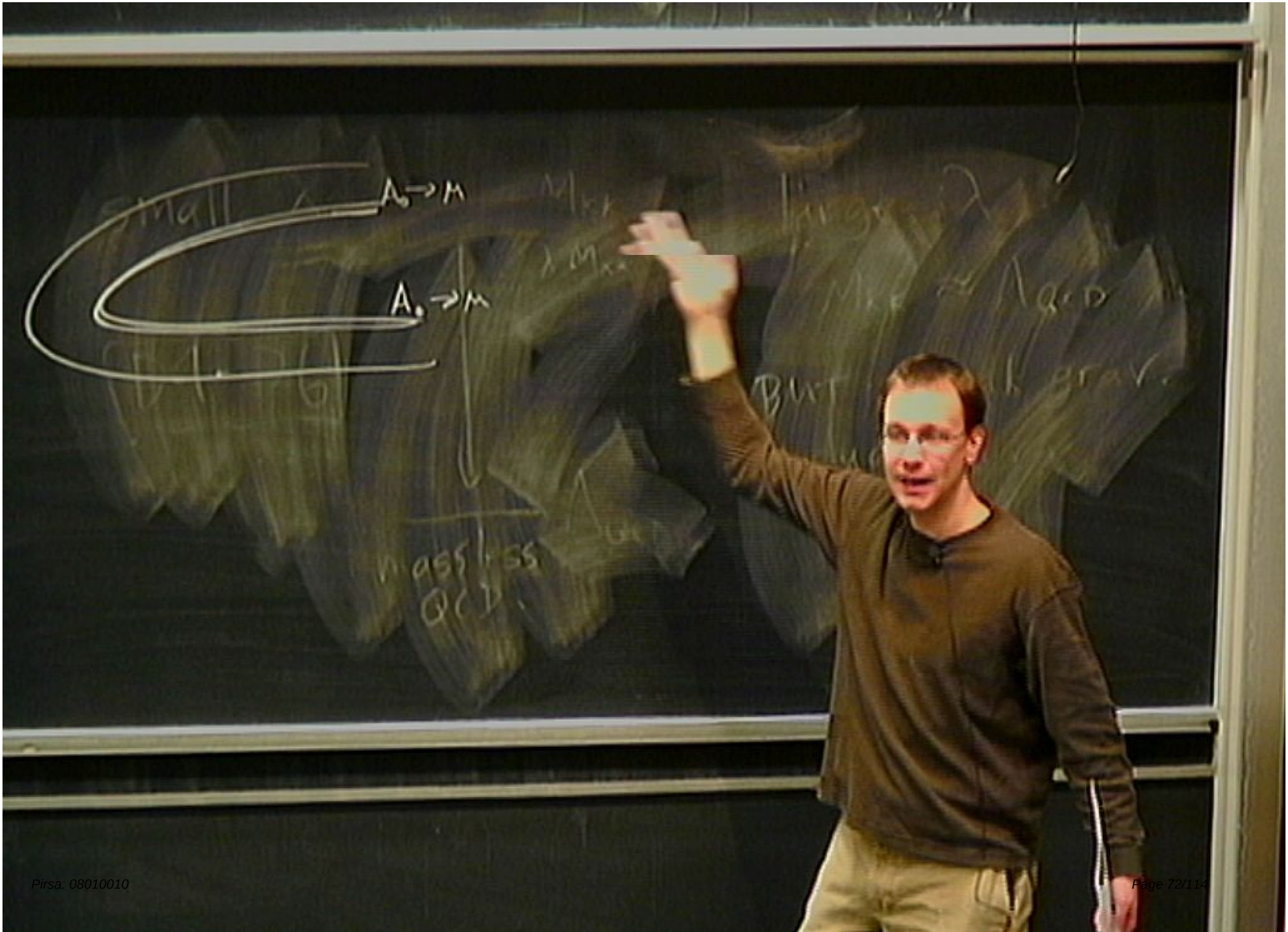
① string endpoints can arise from D9

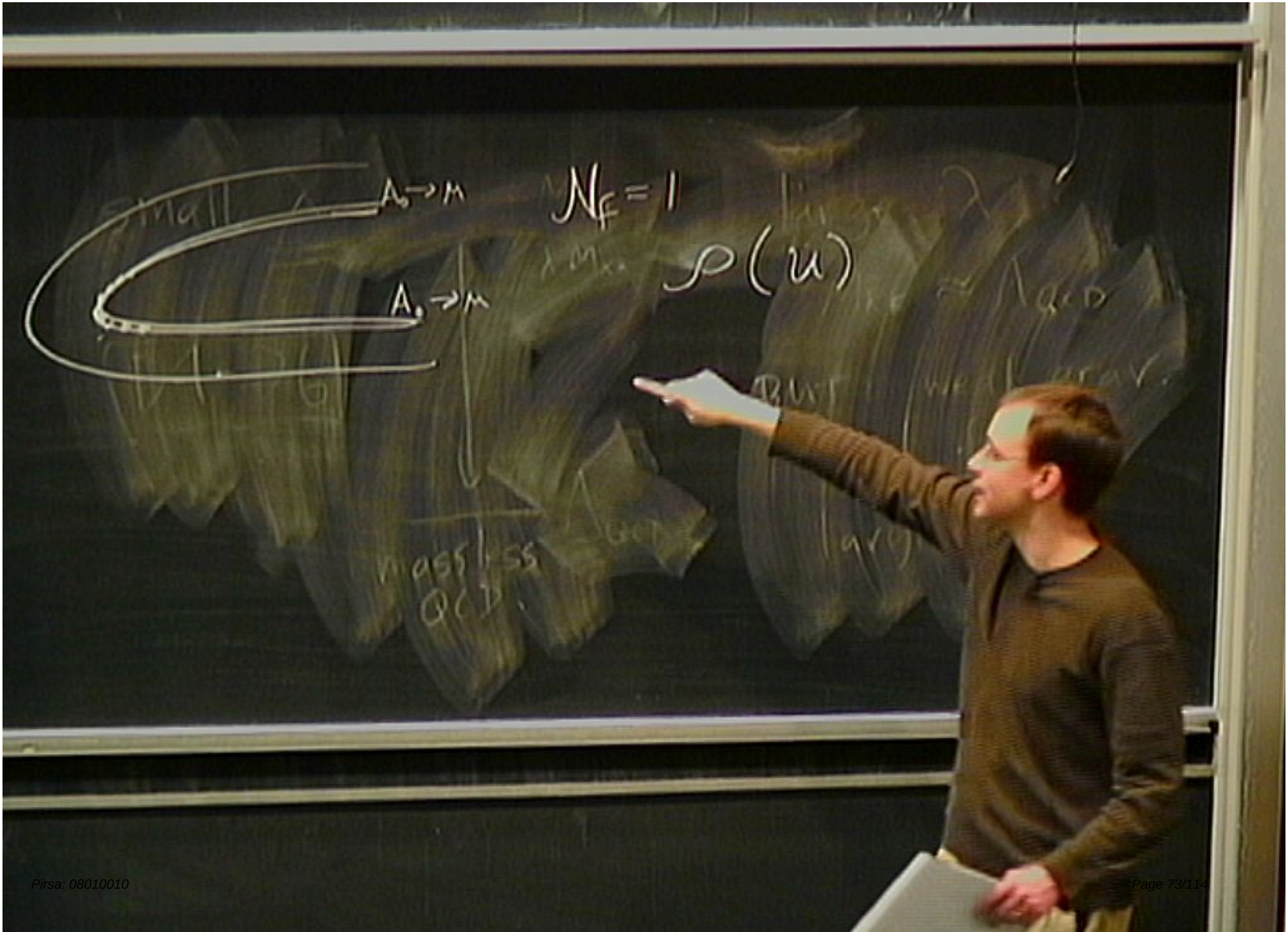

CDW
N
D
$\vec{E}$


baryons
① string endpoints
can arise from
D9
②

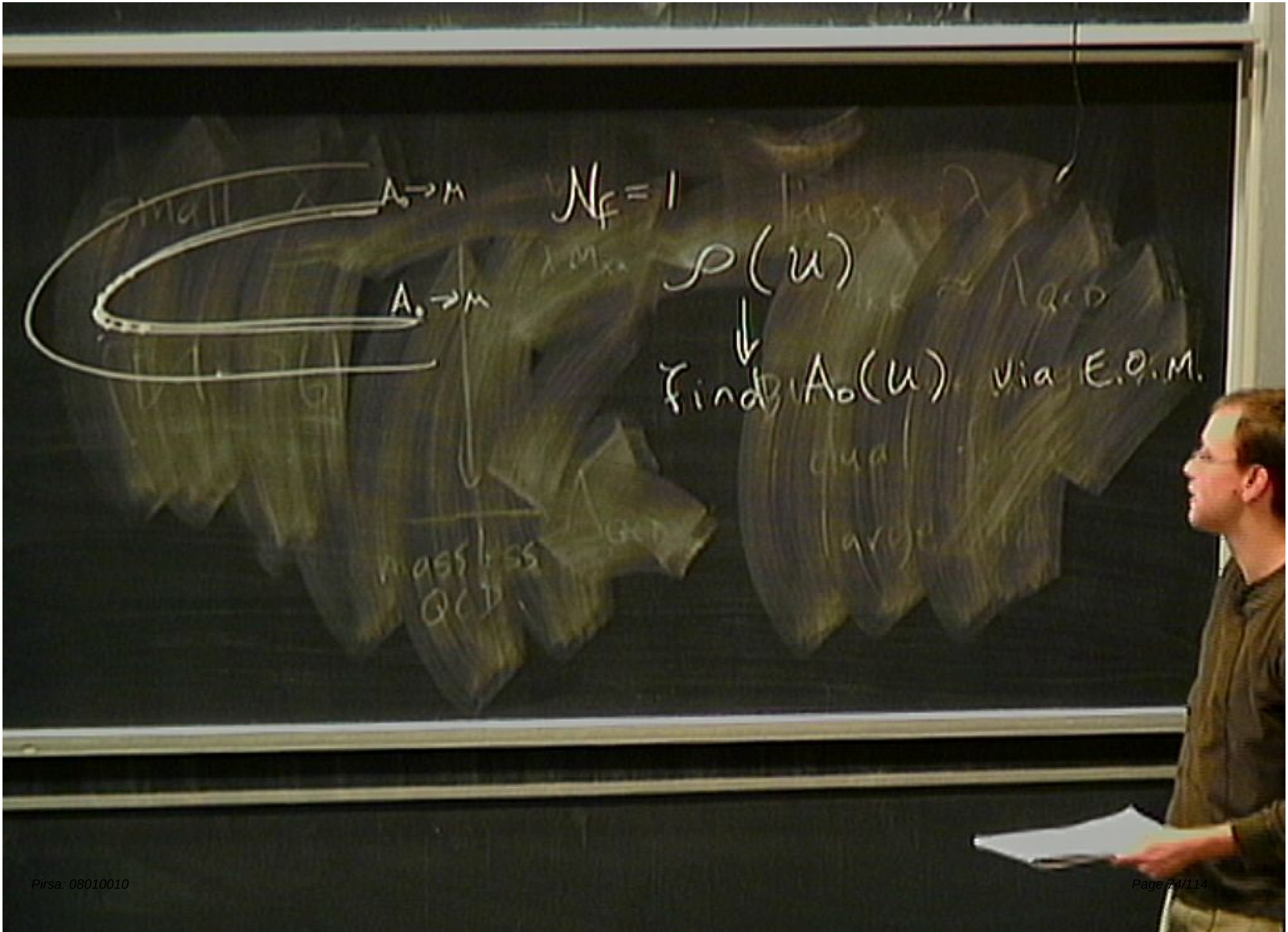

baryons
① string endpoints
can arise from
D9
②


baryons
① string endpoints
can arise from
D9
② $N_f > 1$ instanton
configs of A;

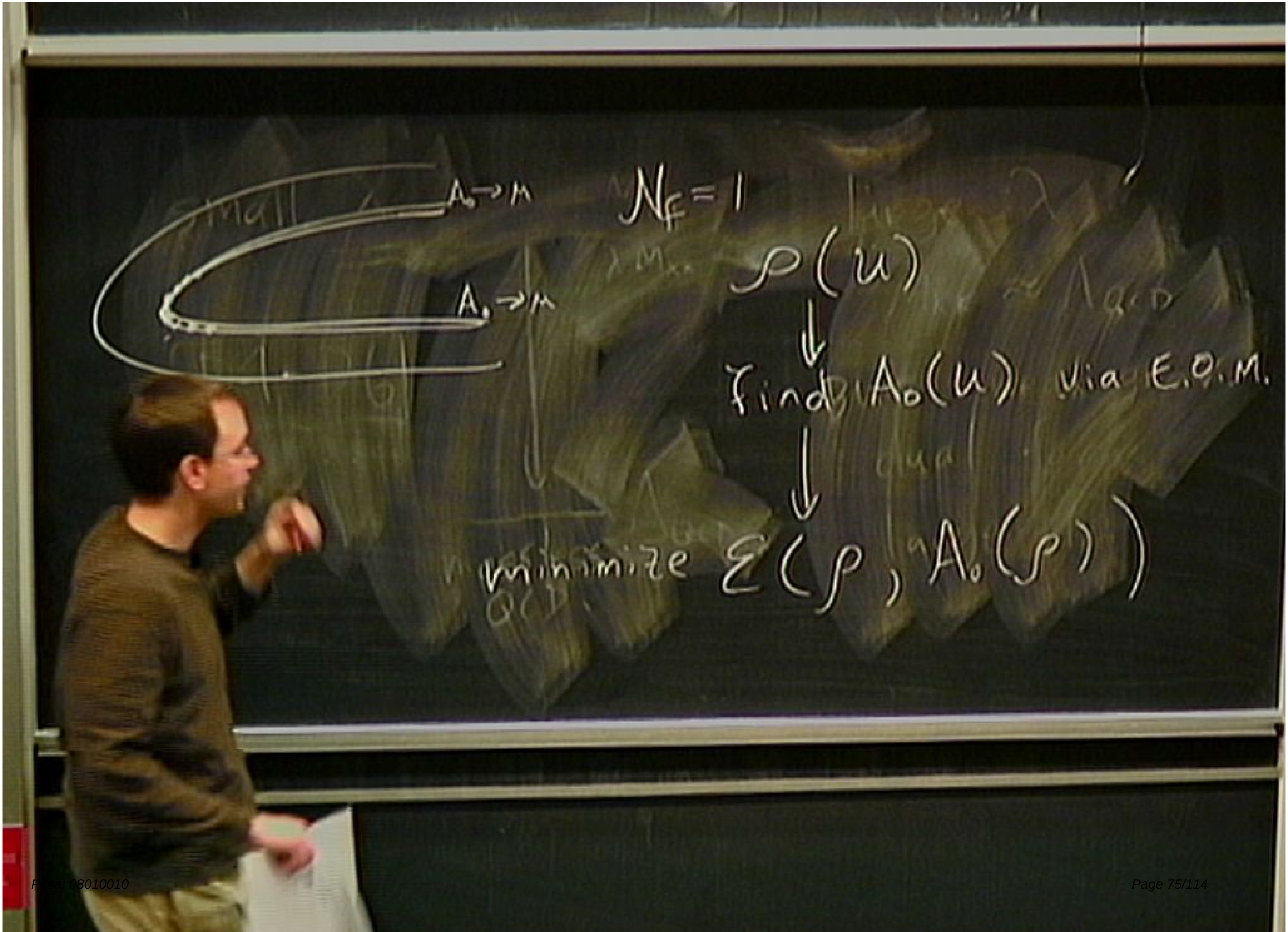

small
Λ₀→μ
M_KK
λM_KK
massless
QCD

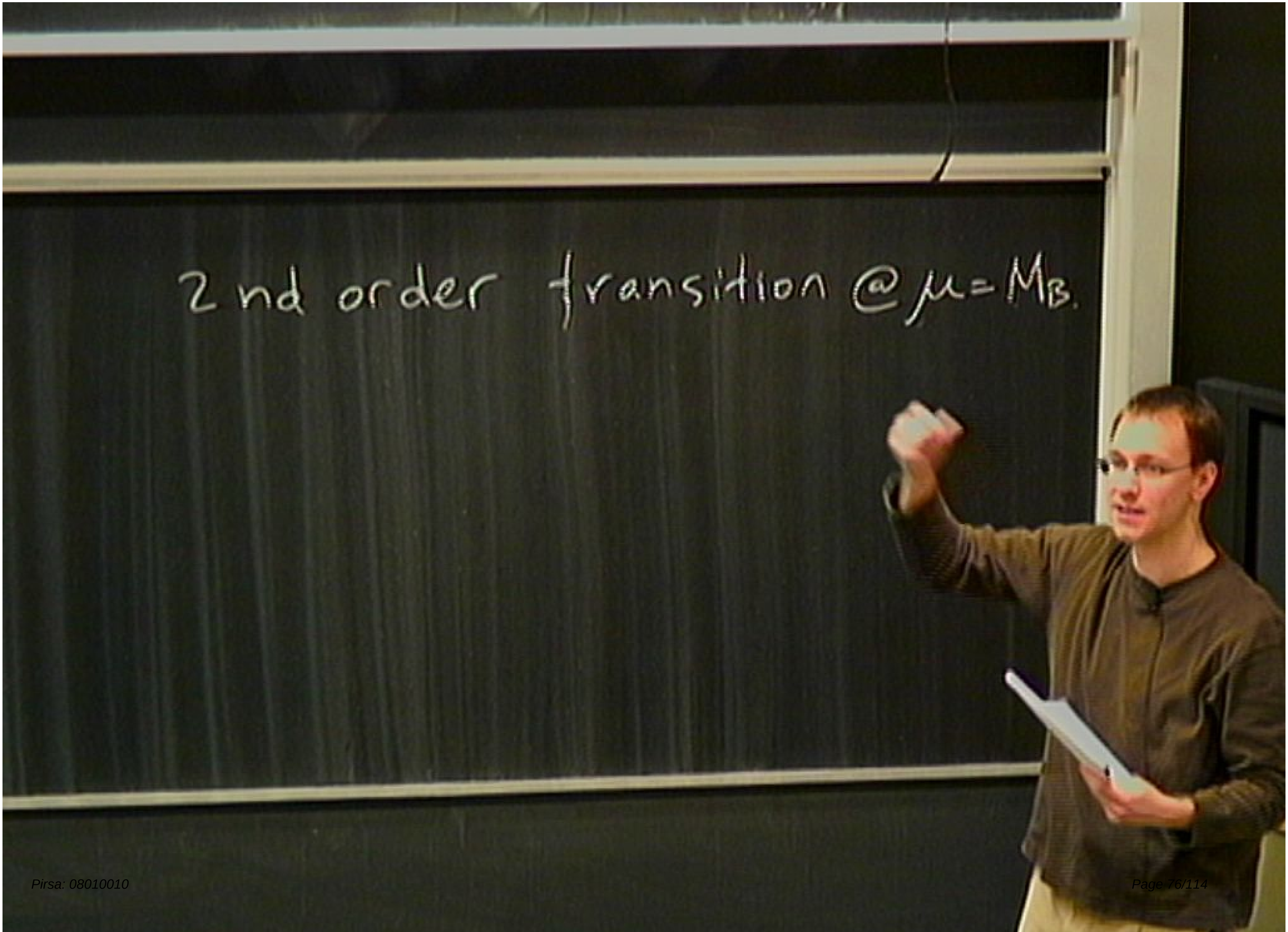


$N_F = 1$
$\rho(u)$

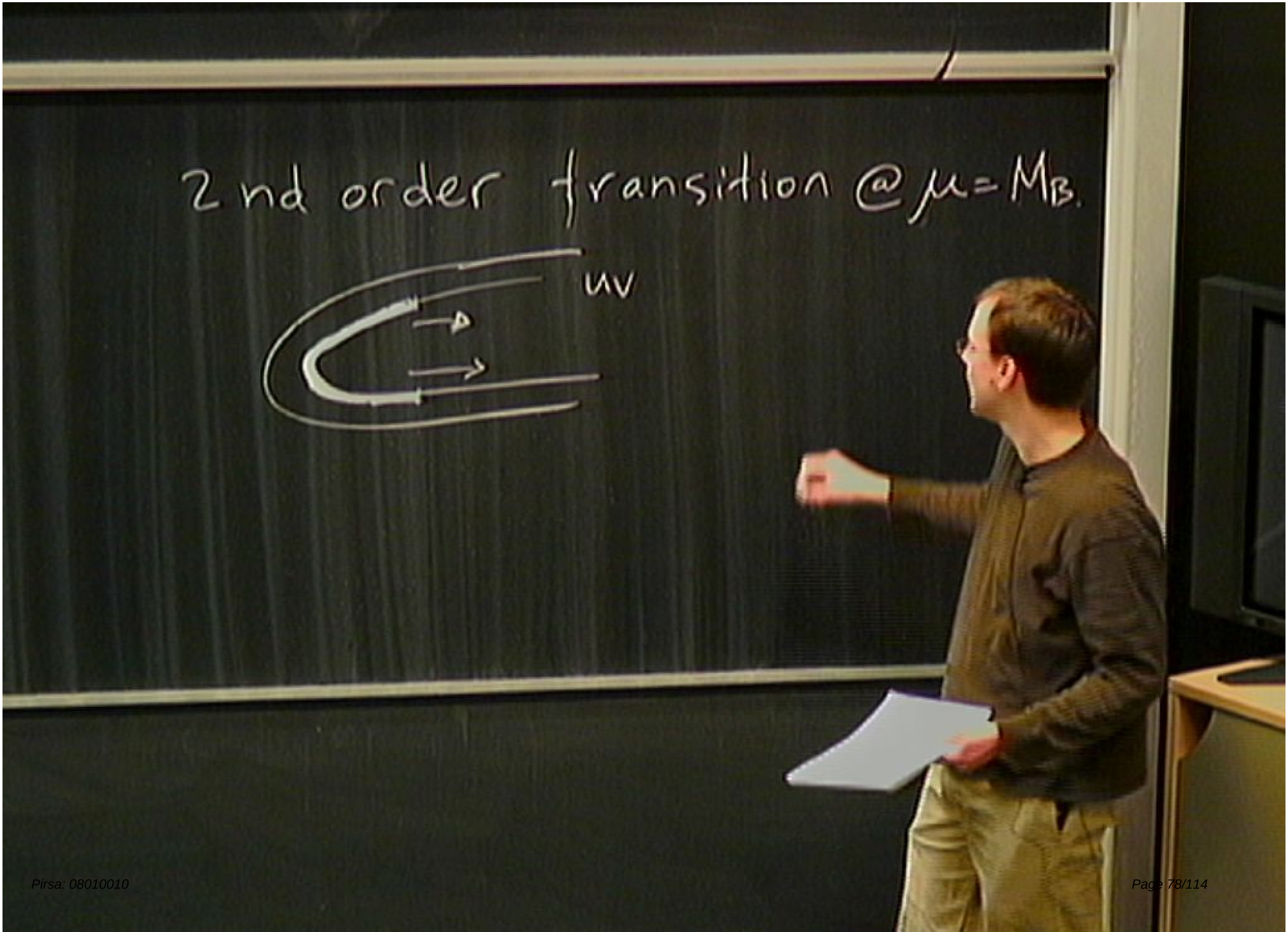


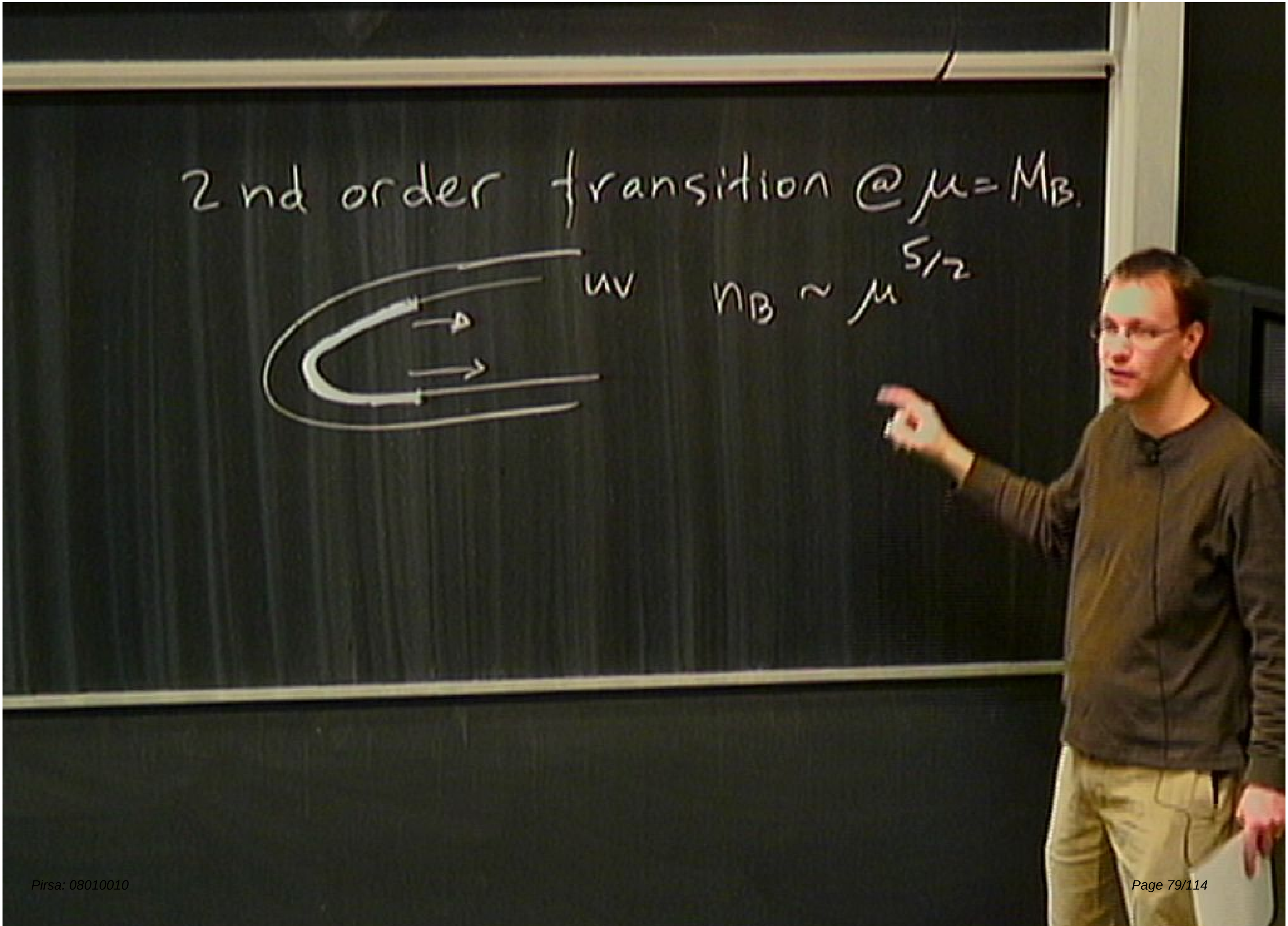
Λ₀→m
N_F = 1
Λ₀→m
ρ(u)
find A₀(u) via E.O.M.

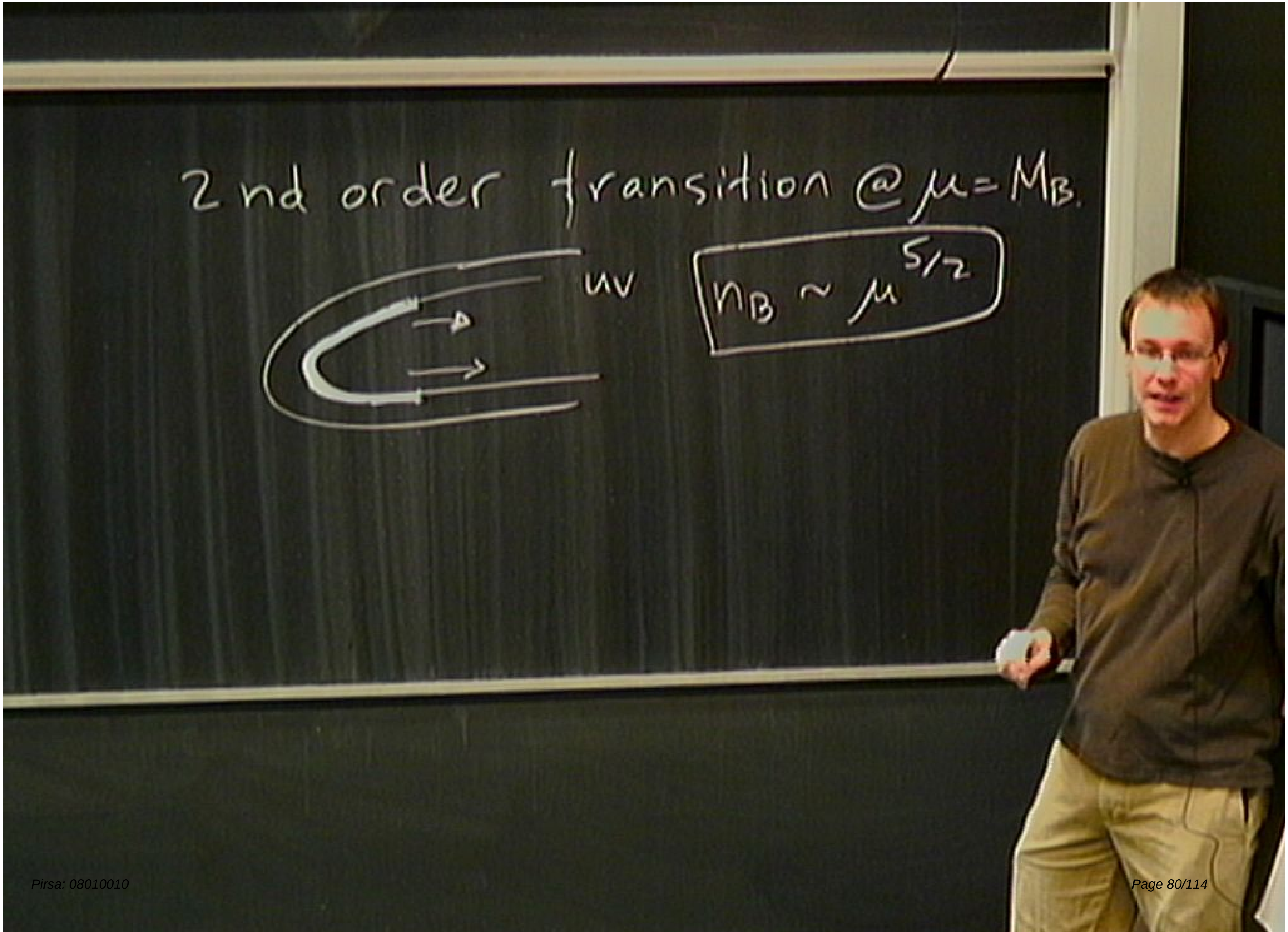

Λ₀ → μ
N_f = 1
ρ(u)
A₀ → μ
find A₀(u) via E.O.M.
minimize E(ρ, A₀(ρ))

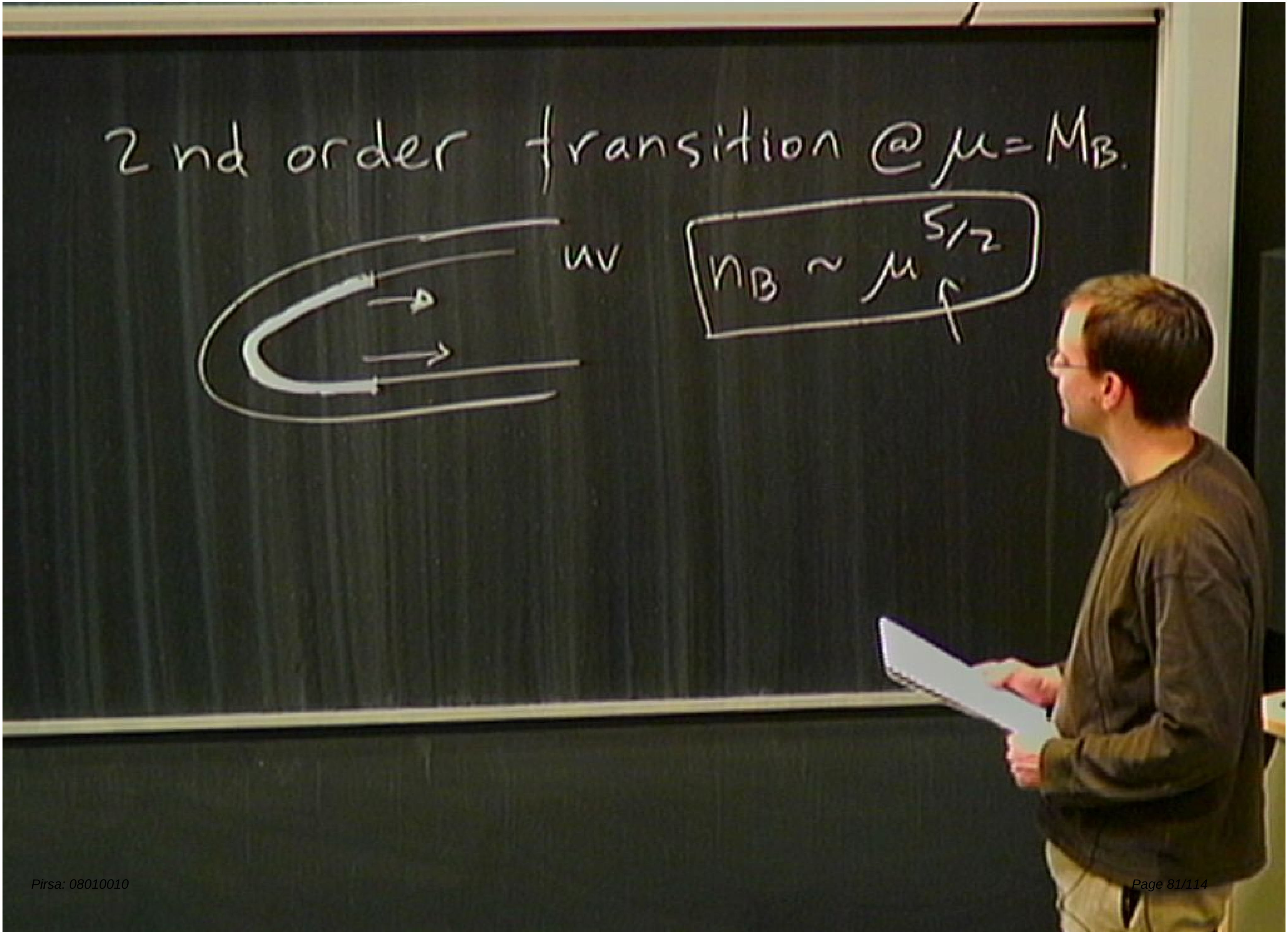

2nd order transition @ $\mu = M_B$.

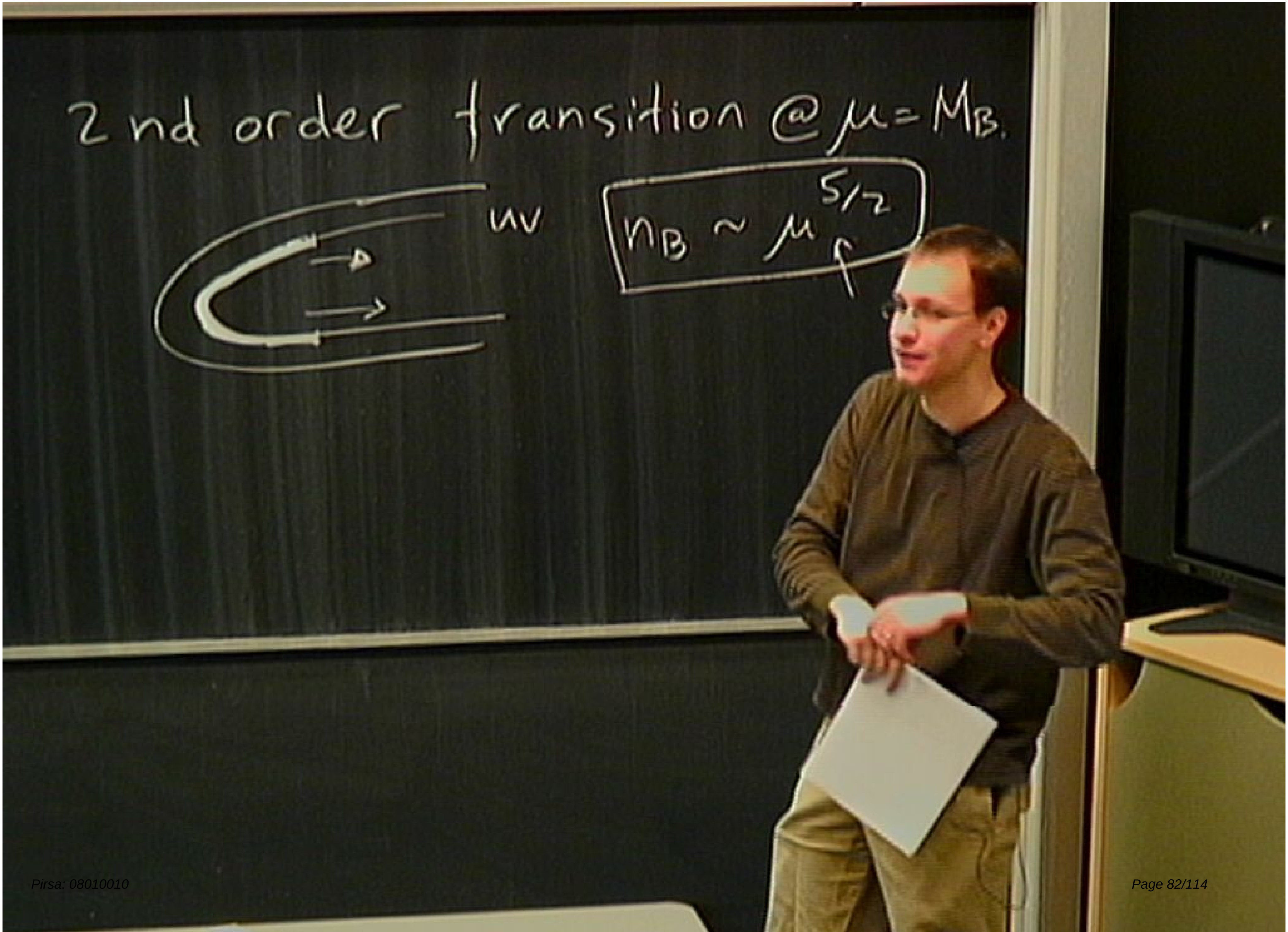

2nd order transition @ μ = M_B

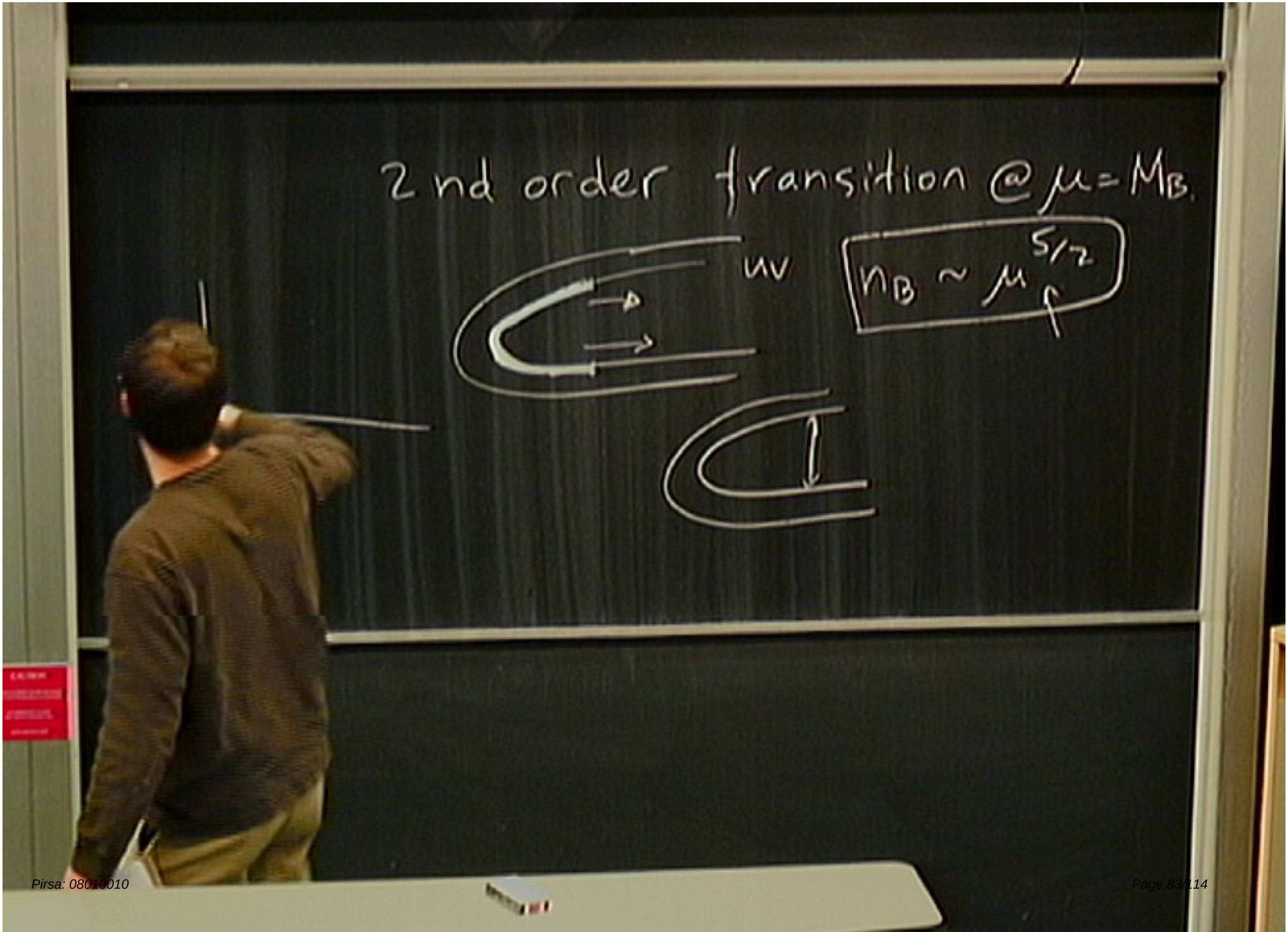

2nd order transition @ $\mu = M_B$.
UV

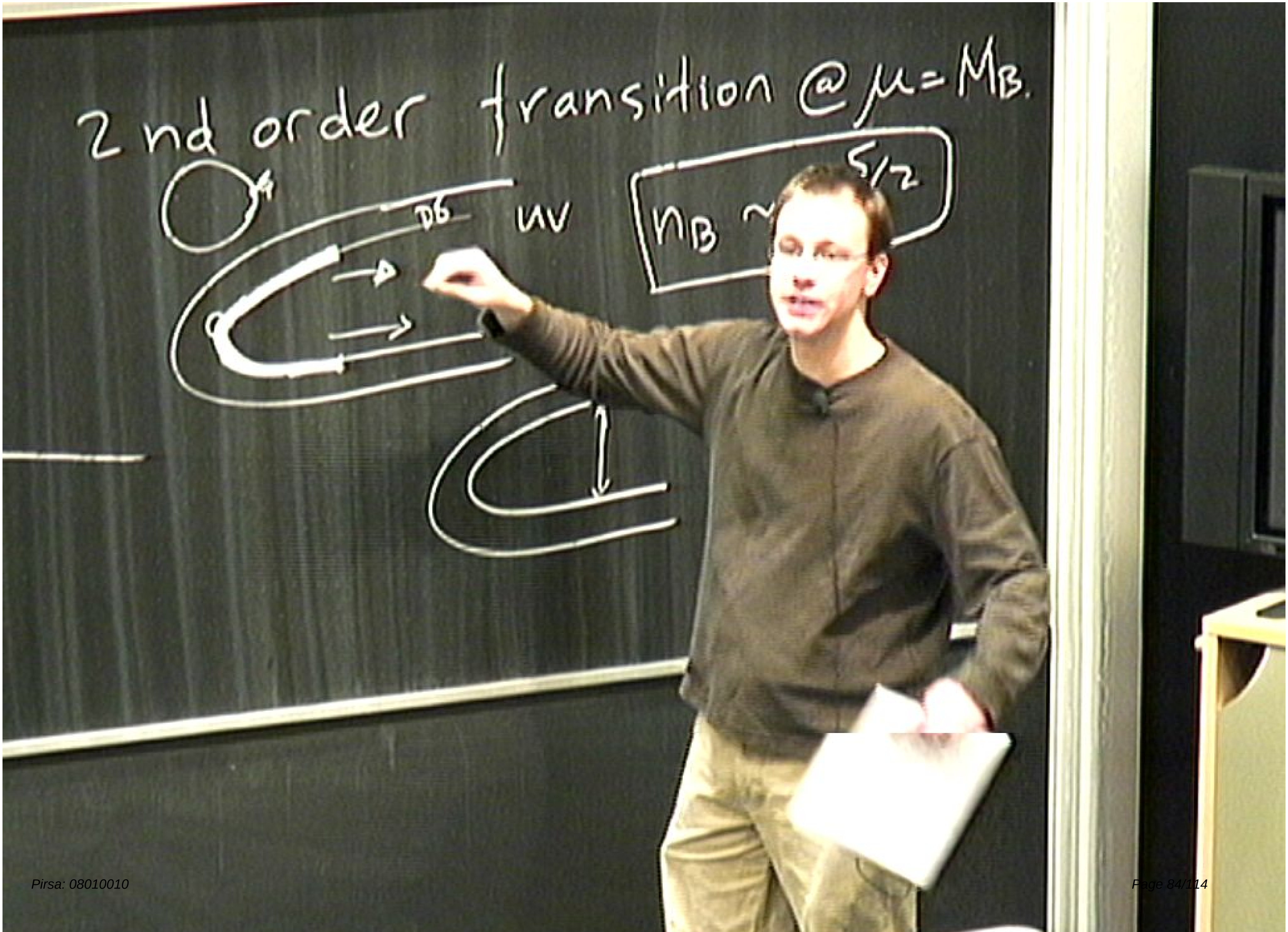

2nd order transition @ $\mu = M_B$
uv
$n_B \sim \mu^{5/2}$

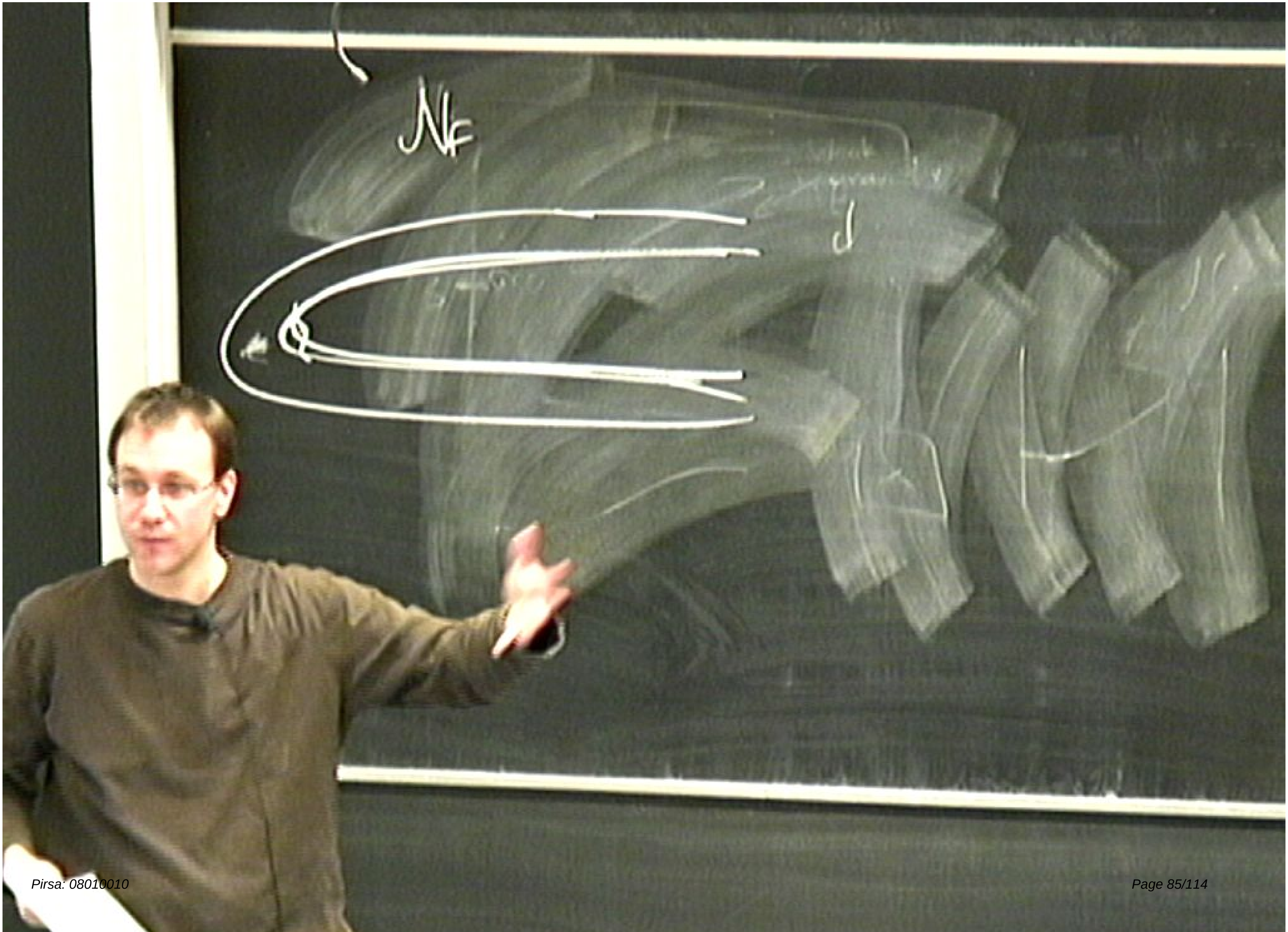

2nd order transition @ $\mu = M_B$
UV
$n_B \sim \mu^{5/2}$

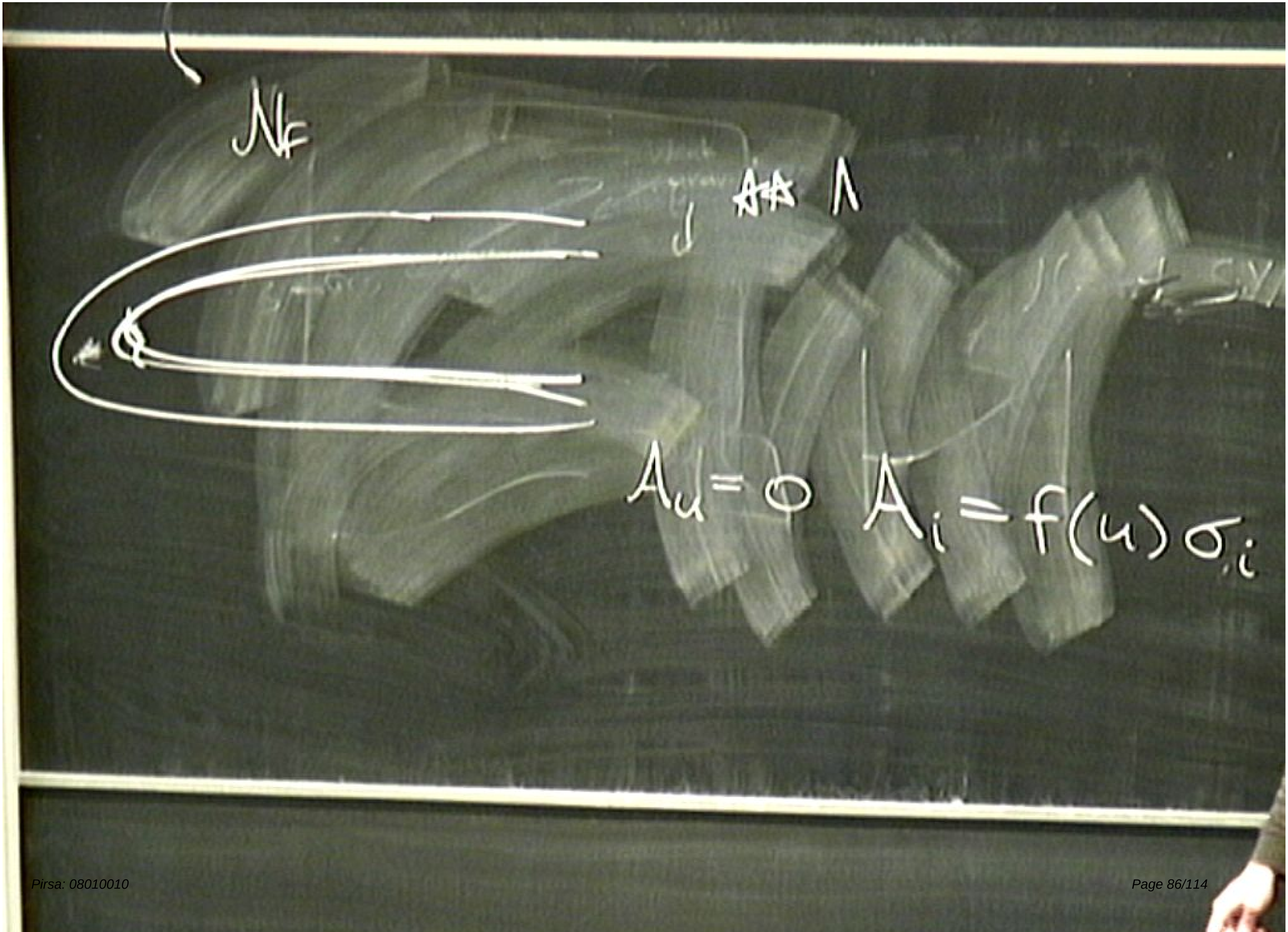

2nd order transition @ μ=M_B.
uv
n_B ~ μ^5/2


2nd order transition @ μ = M_B.
UV
n_B ~ μ^{5/2}

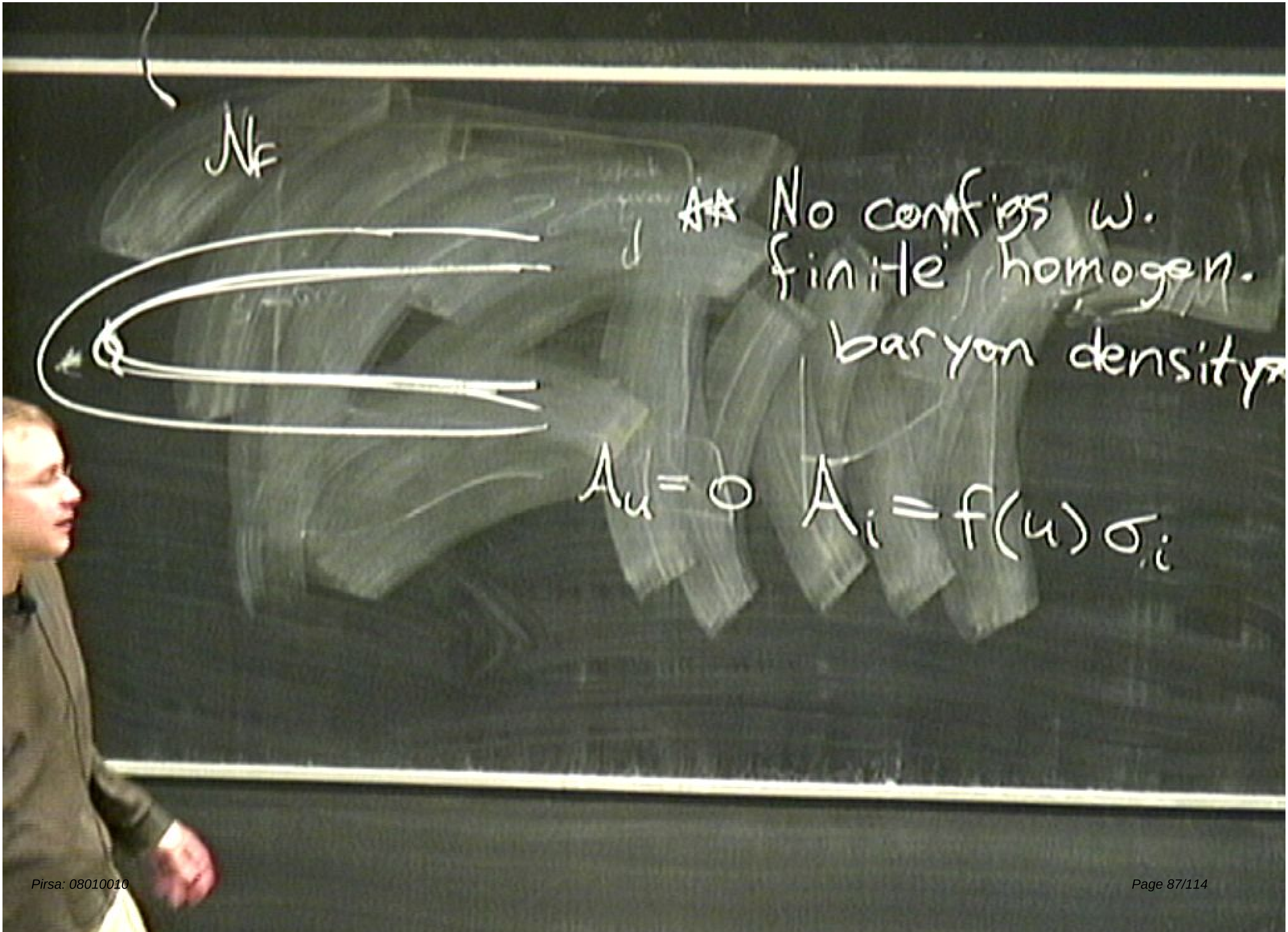

2nd order transition @ $\mu = M_B$
uv
$n_B \sim \mu_f^{5/2}$

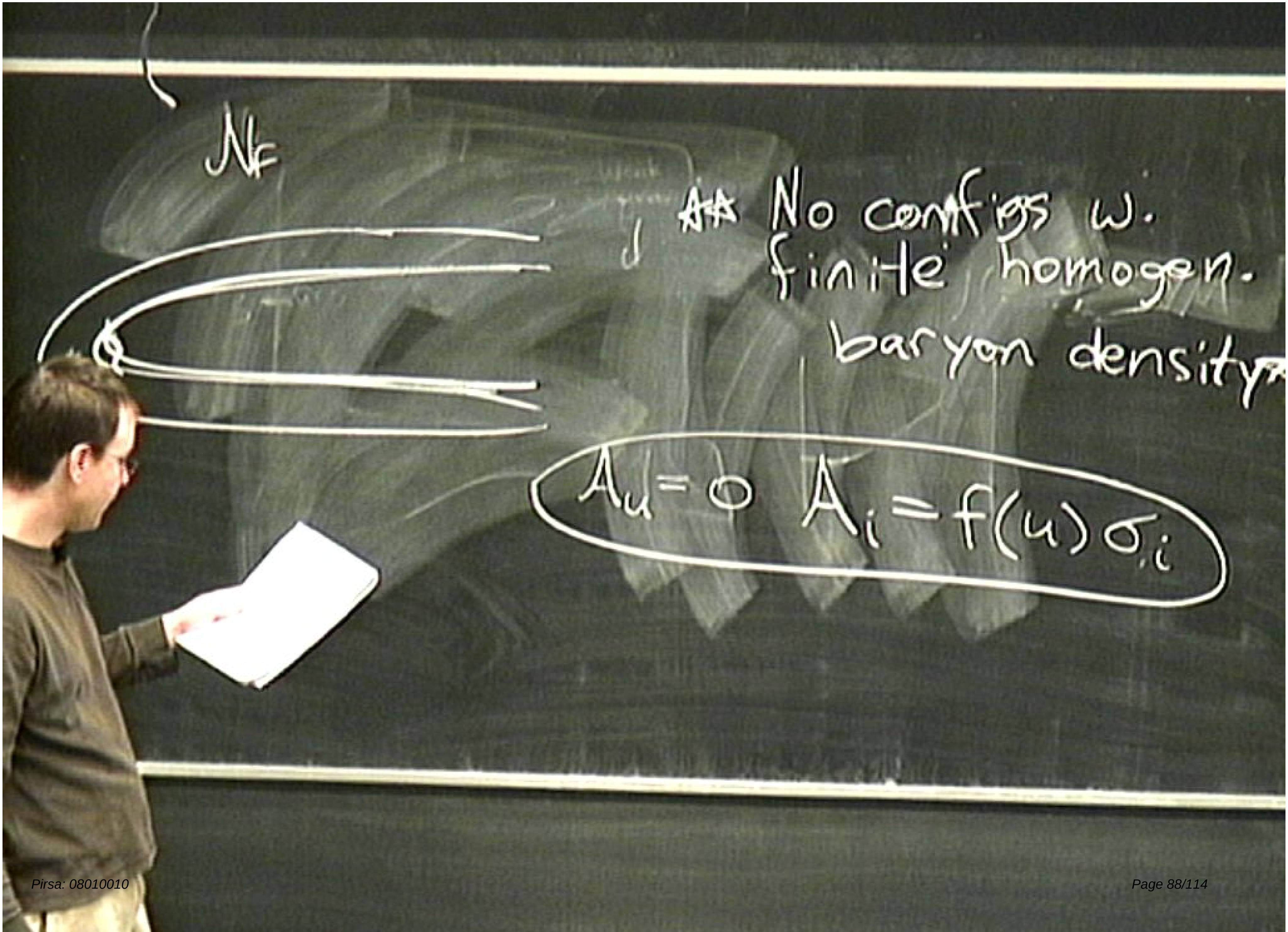

2nd order transition @ μ = M_B.
D6
UV


N_F



N_F
Λ
$A_u = 0 \quad A_i = f(u)\sigma_i$


N_c
No configs w.
finite homogen.
baryon density
$A_u = 0 \quad A_i = f(u)\sigma_i$

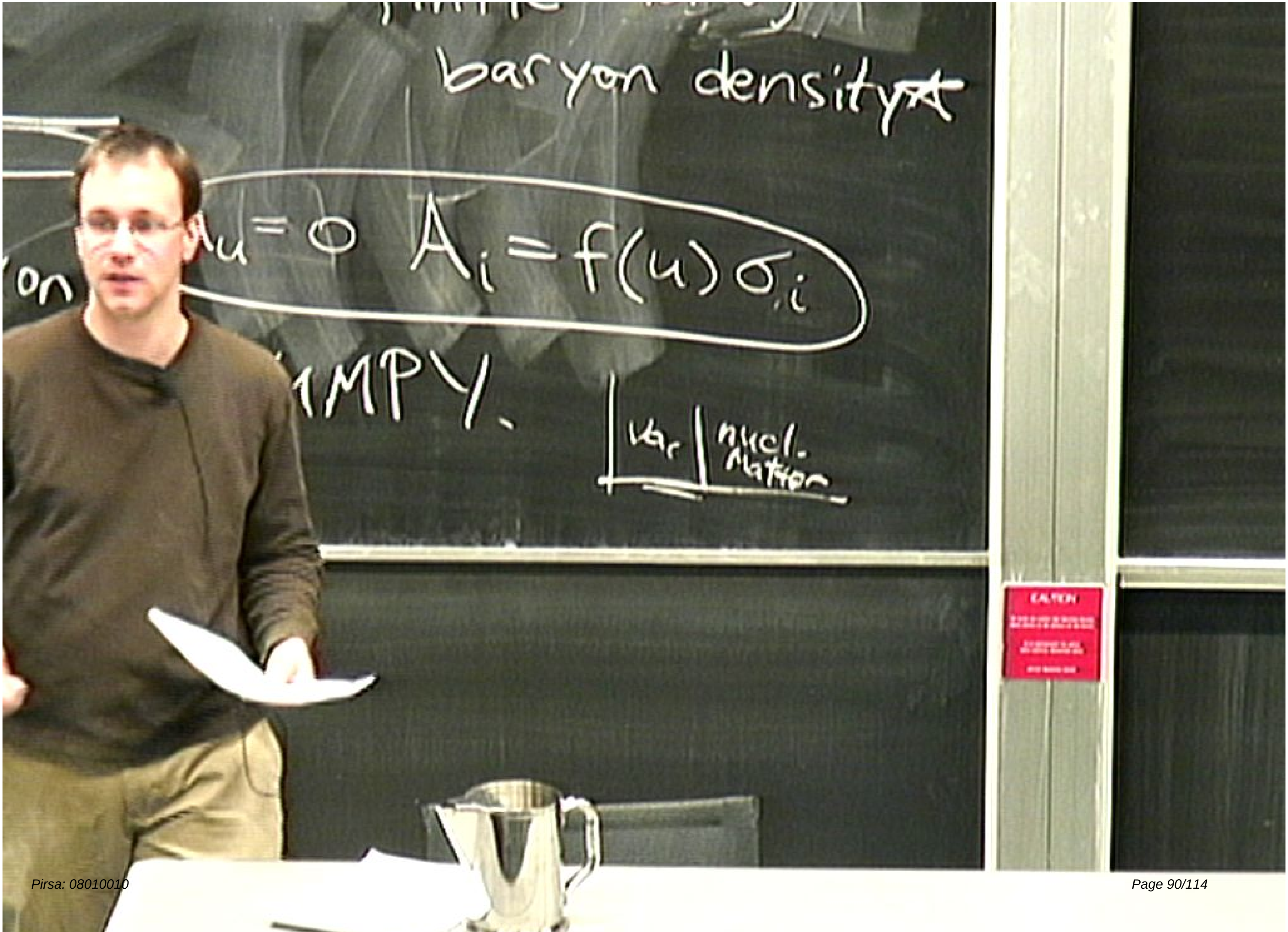

Nf
No configs w. finite homogen. baryon density
$A_u = 0$ $A_i = f(u)\sigma_i$

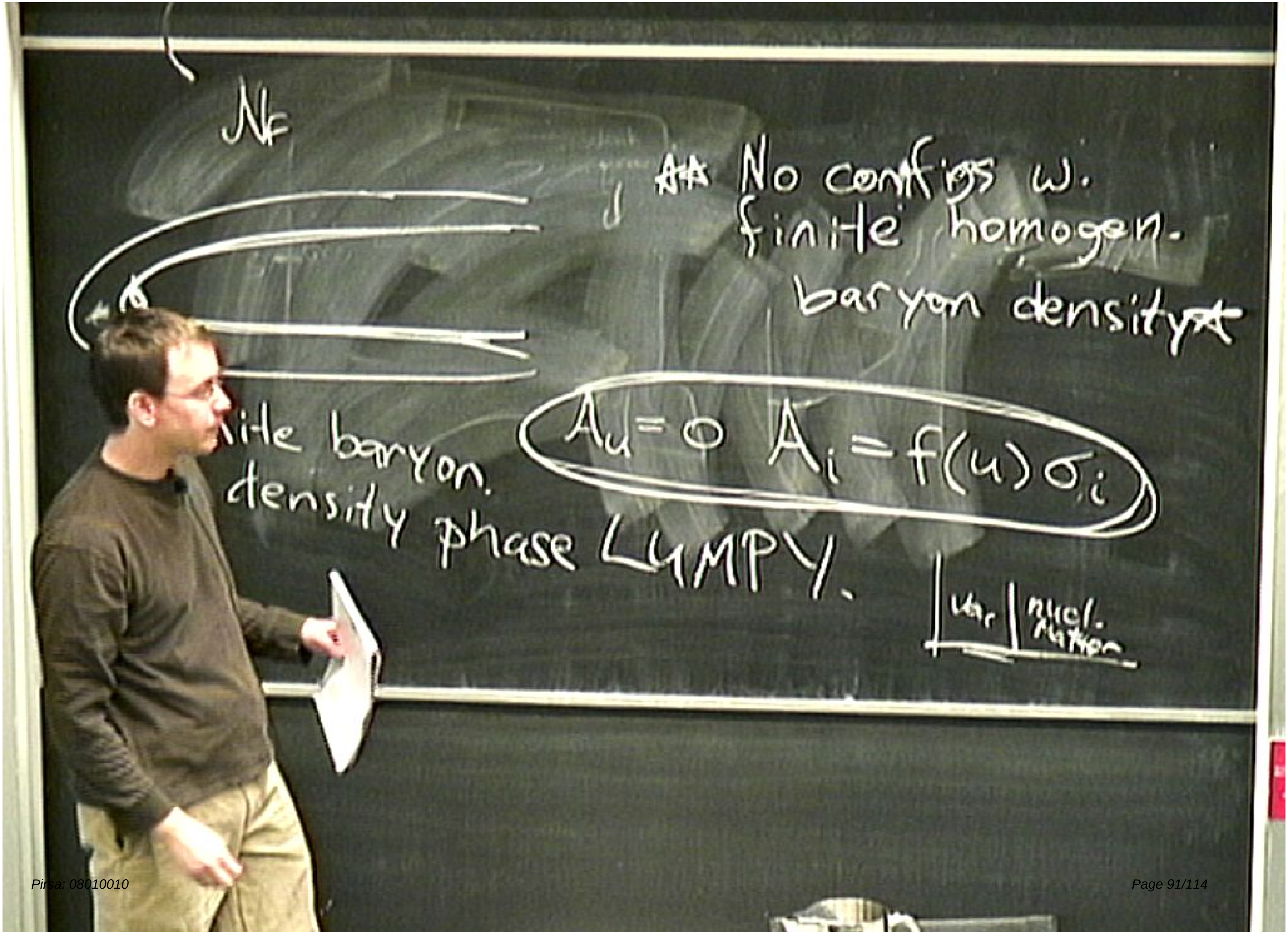
N_f

No configs w.
finite homogen.
baryon density

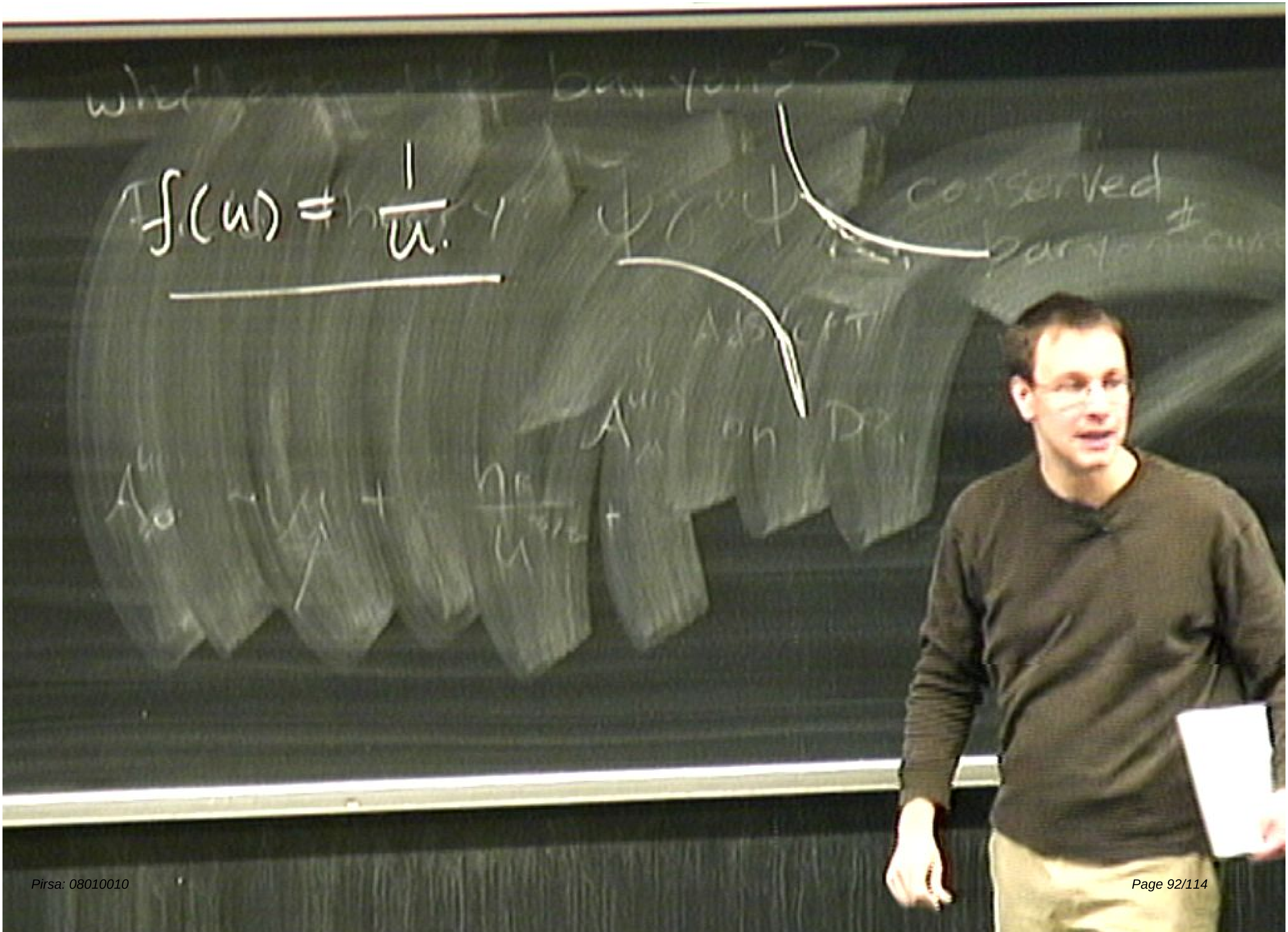
finite baryon
density phase LUMPY.

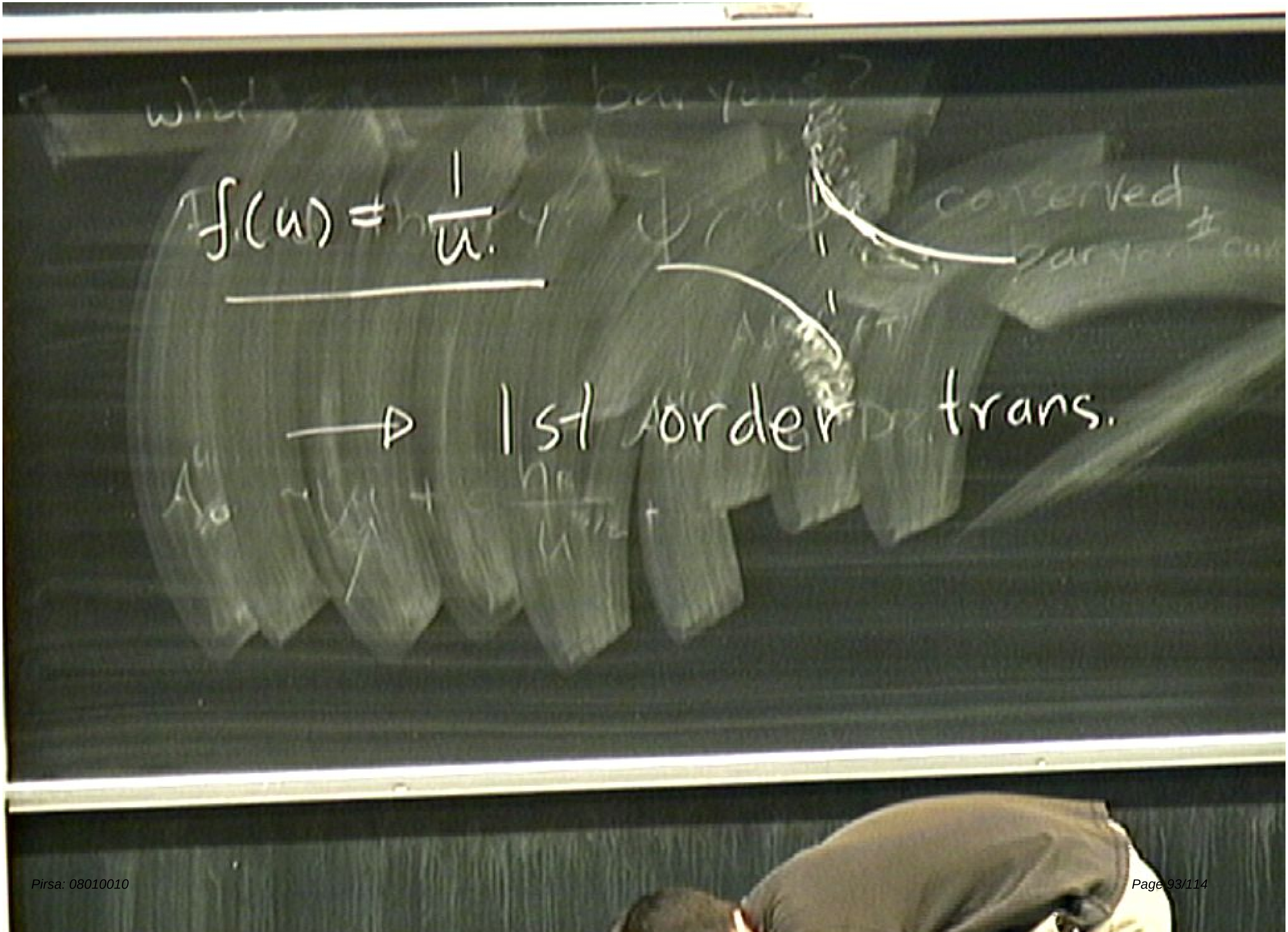
$A_u = 0 \quad A_i = f(u)\,\sigma_i$

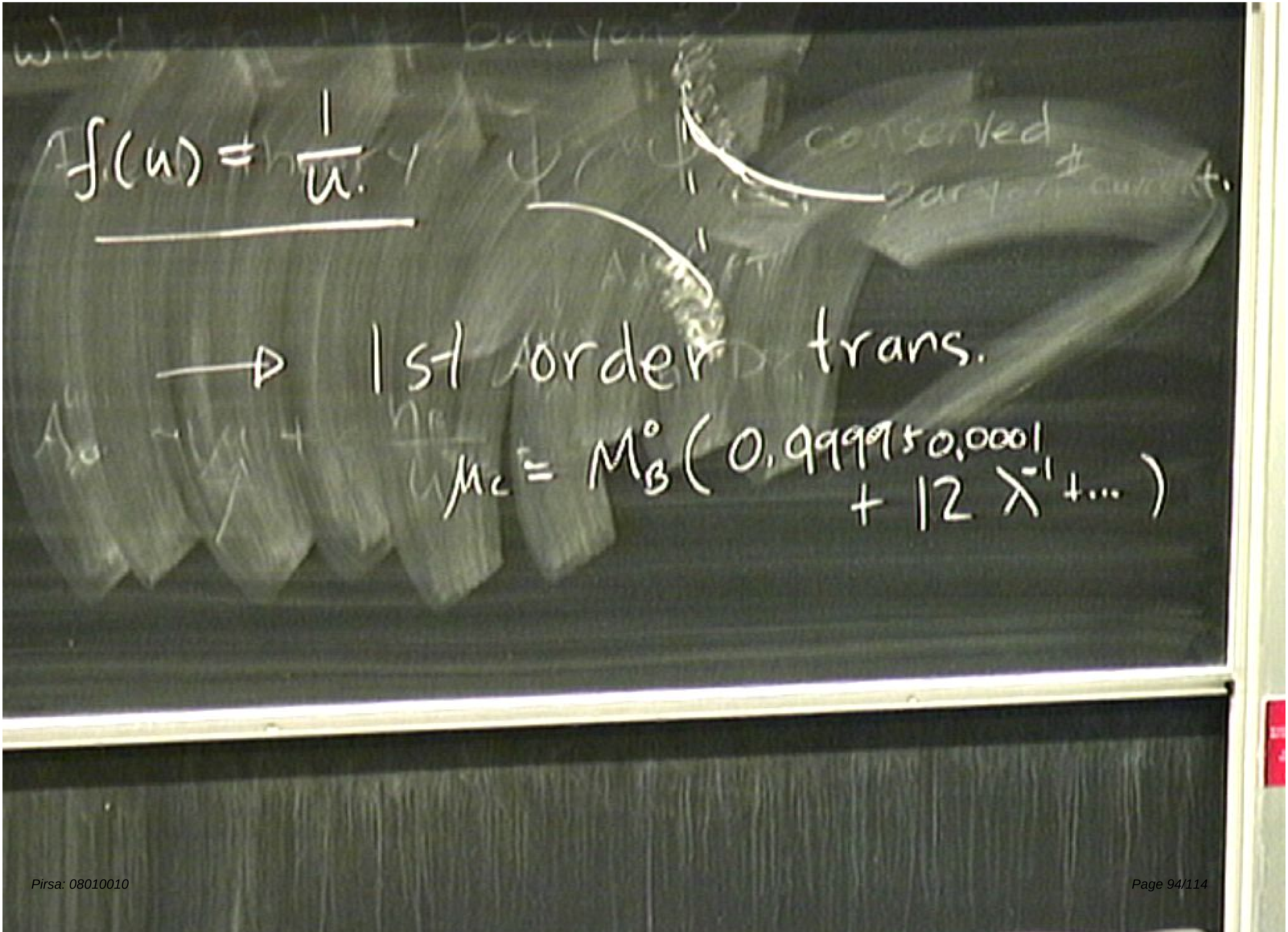

baryon density
$A_i = f(u)\sigma_i$
var
nucl. Matter

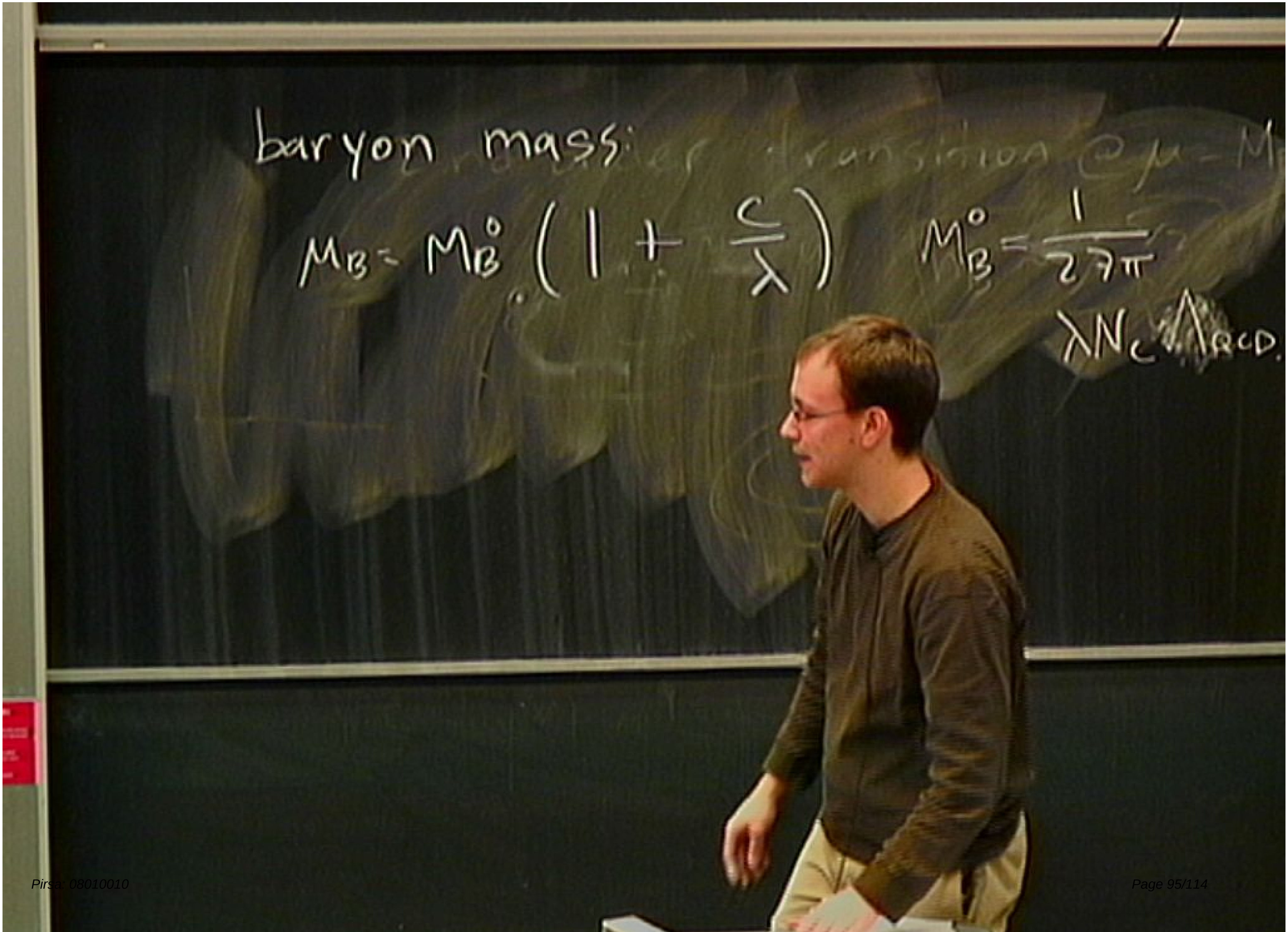


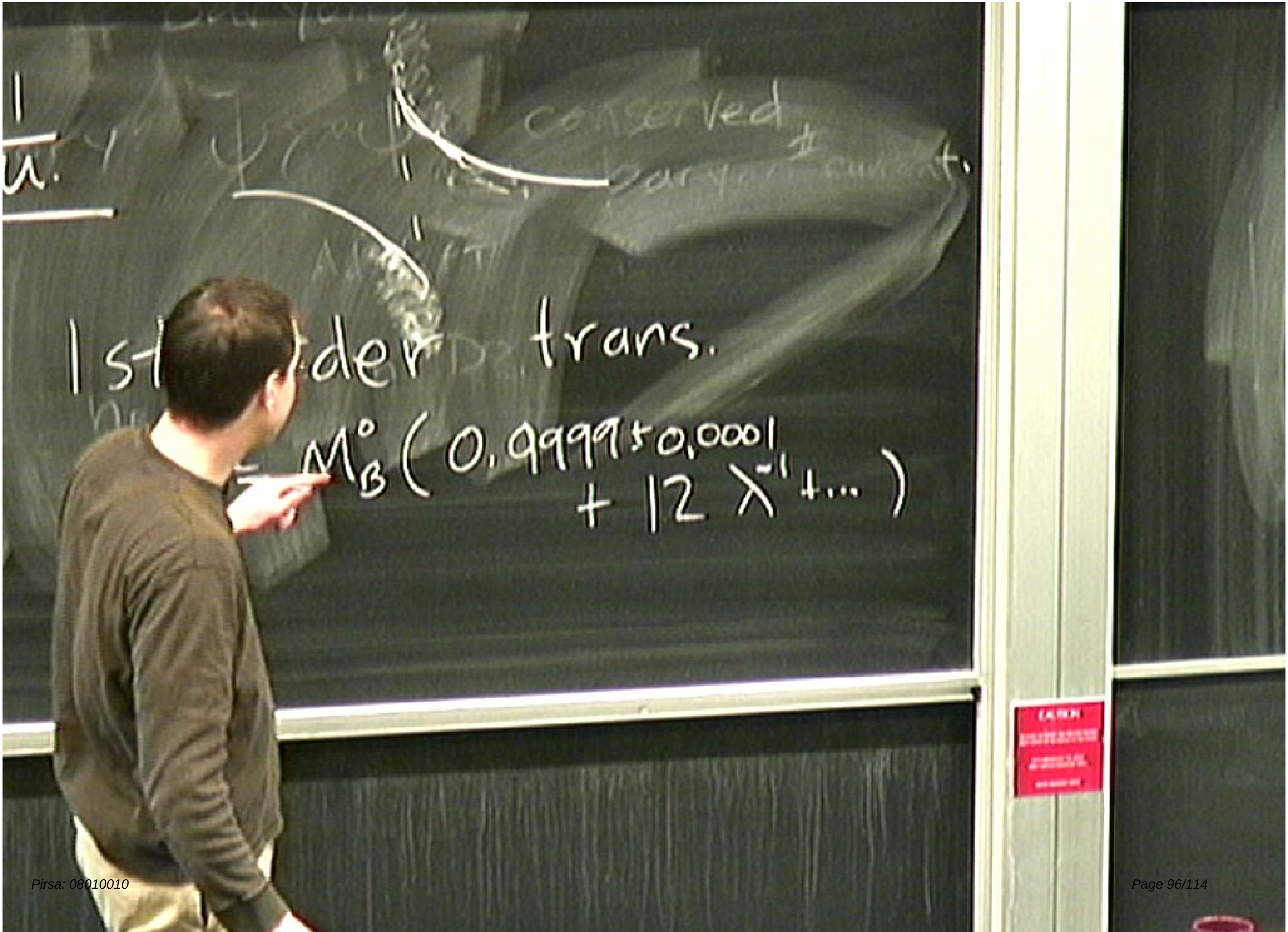
Nf
No configs w.
finite homogen.
baryon density
ite baryon.
density phase LUMPY.
Au=0 Ai=f(u)σi
nucl.
matter

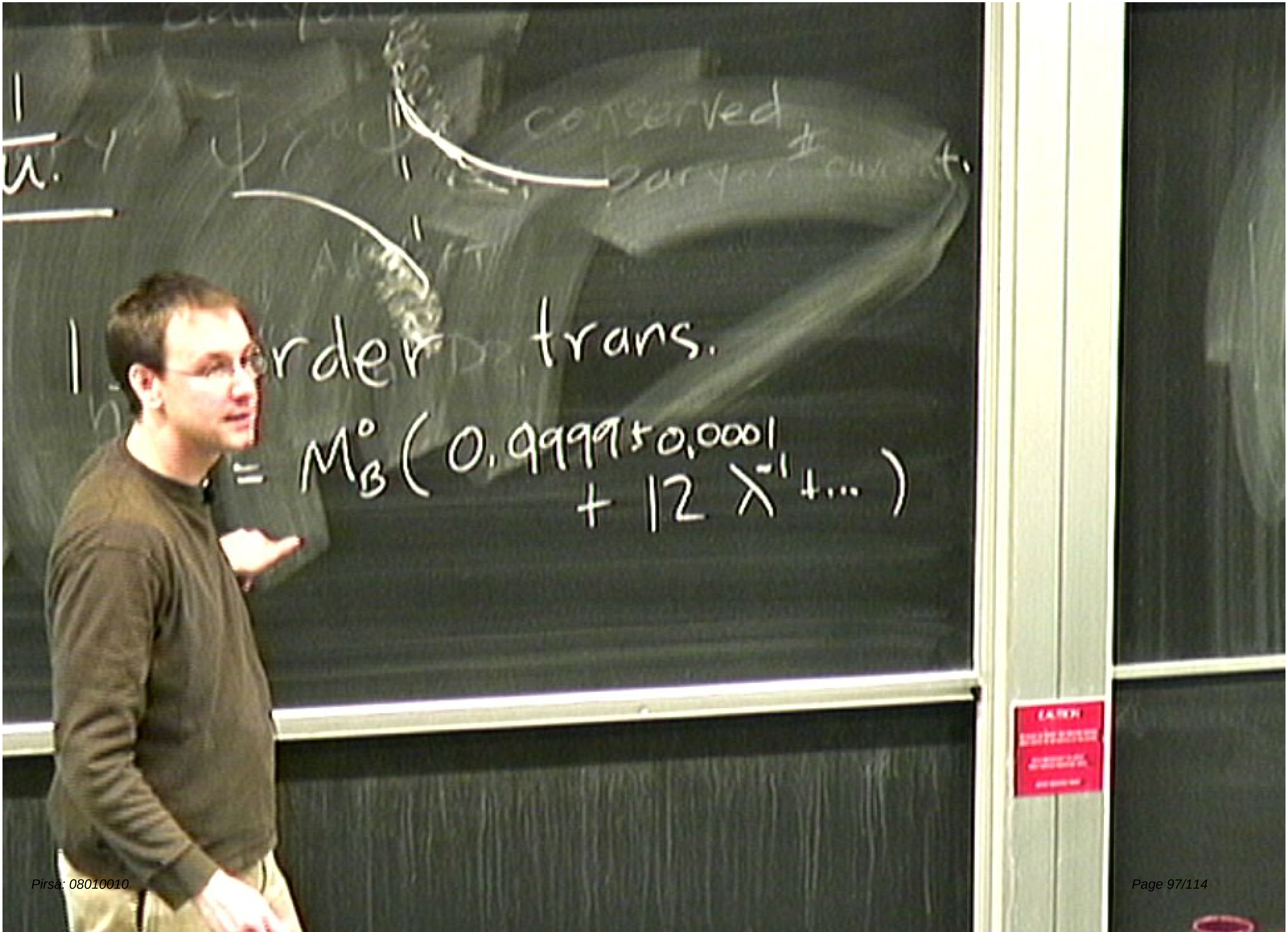

f(u) = 1/u
conserved
#


f(u) = 1/u
→ 1st order trans.
conserved


$f(u) = \frac{1}{u}$
conserved # baryon current.
→ 1st order trans.
$M_c = M_B^0 (0.9999 \pm 0.0001 + 12 \lambda^{-1} + \dots)$


baryon mass:
$M_B = M_B^0 \left(1 + \frac{c}{\lambda}\right)$
$M_B^0 = \frac{1}{27\pi} \lambda N_c \Lambda_{QCD}$


conserved
trans.
$M_B^0 (0.9999 \pm 0.0001 + 12 \lambda^{-1} + \dots)$


conserved
baryon current.
trans.
= M°B (0.9999 ± 0.0001
+ 12 λ⁻¹ + ...)

baryon mass:

$$M_B = M_B^0 \left(1 + \frac{c}{\lambda}\right) \qquad M_B^0 = \frac{1}{27\pi} \lambda N_c \Lambda_{QCD}$$

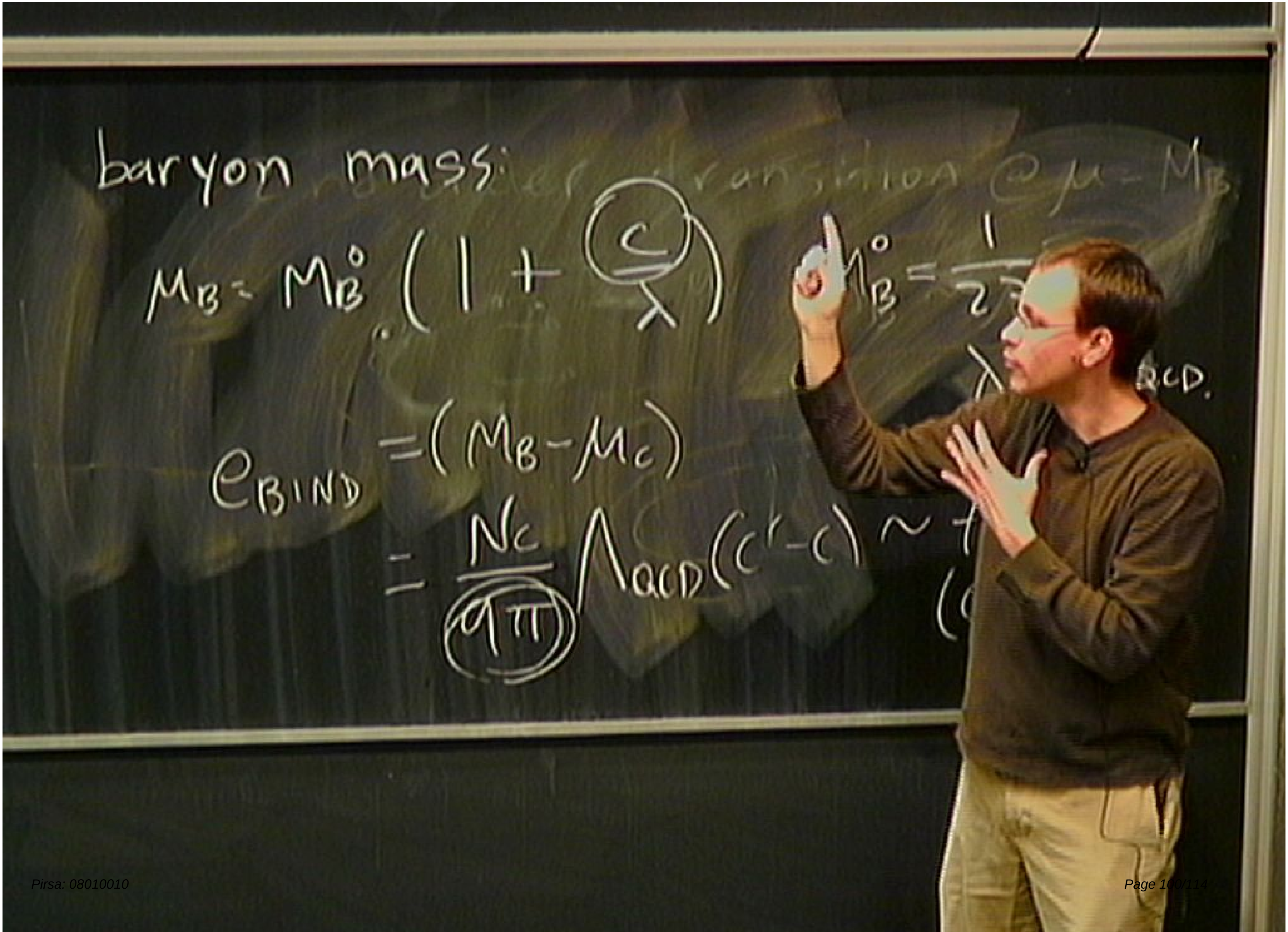
$$e_{BIND} = (M_B - \mu_c) = \frac{N_c}{9\pi} \Lambda_{QCD} (c' - c)$$

baryon mass:

$$M_B = M_B^0\left(1 + \frac{c}{\lambda}\right) \qquad M_B^0 = \frac{1}{27\pi}\lambda N_c \Lambda_{QCD}.$$

$$e_{BIND} = (M_B - \mu_c)$$

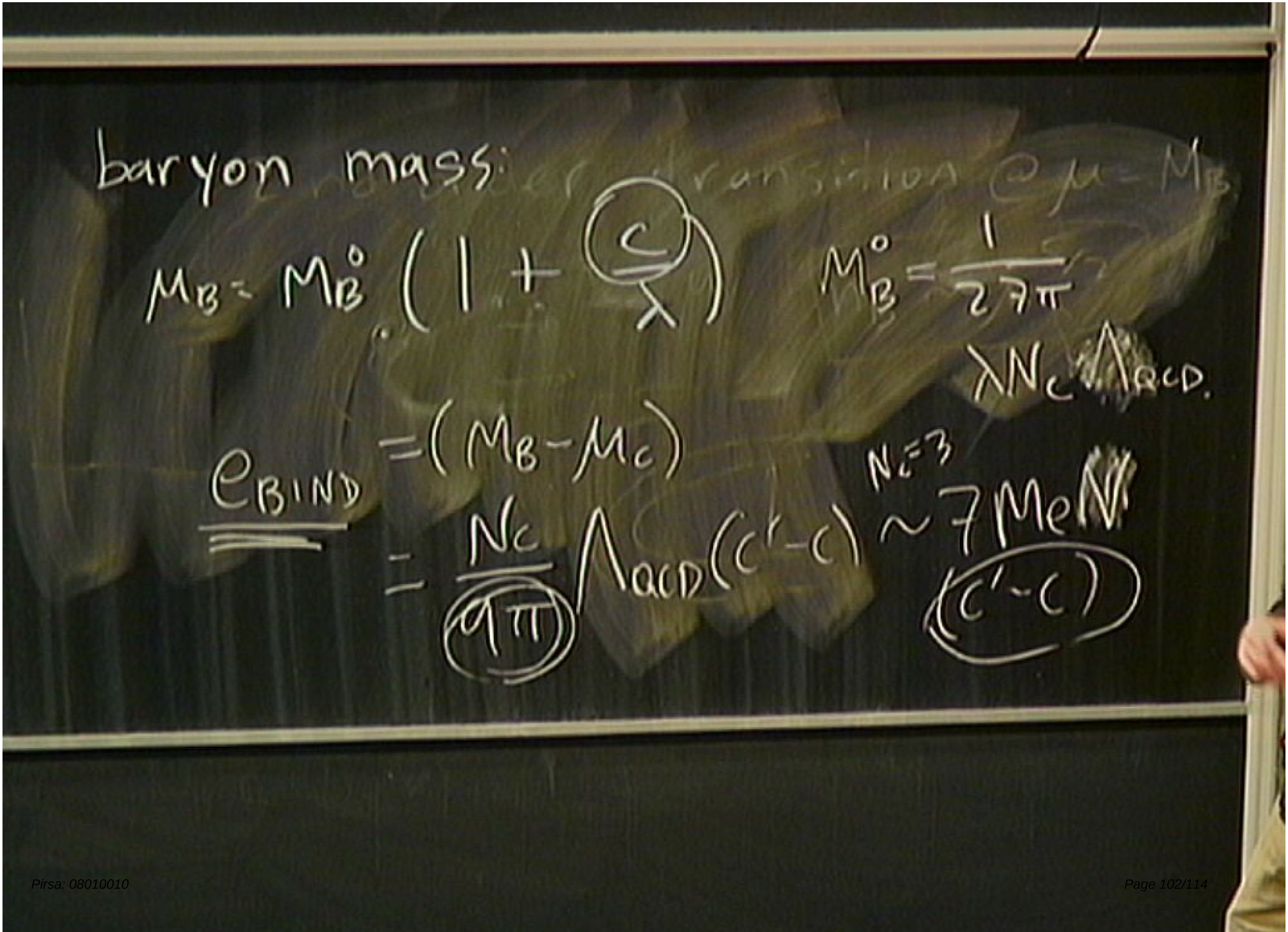
$$= \frac{N_c}{9\pi}\Lambda_{QCD}(c'-c) \overset{N_c=3}{\sim} 7\,\mathrm{MeV}\,(c'-c)$$

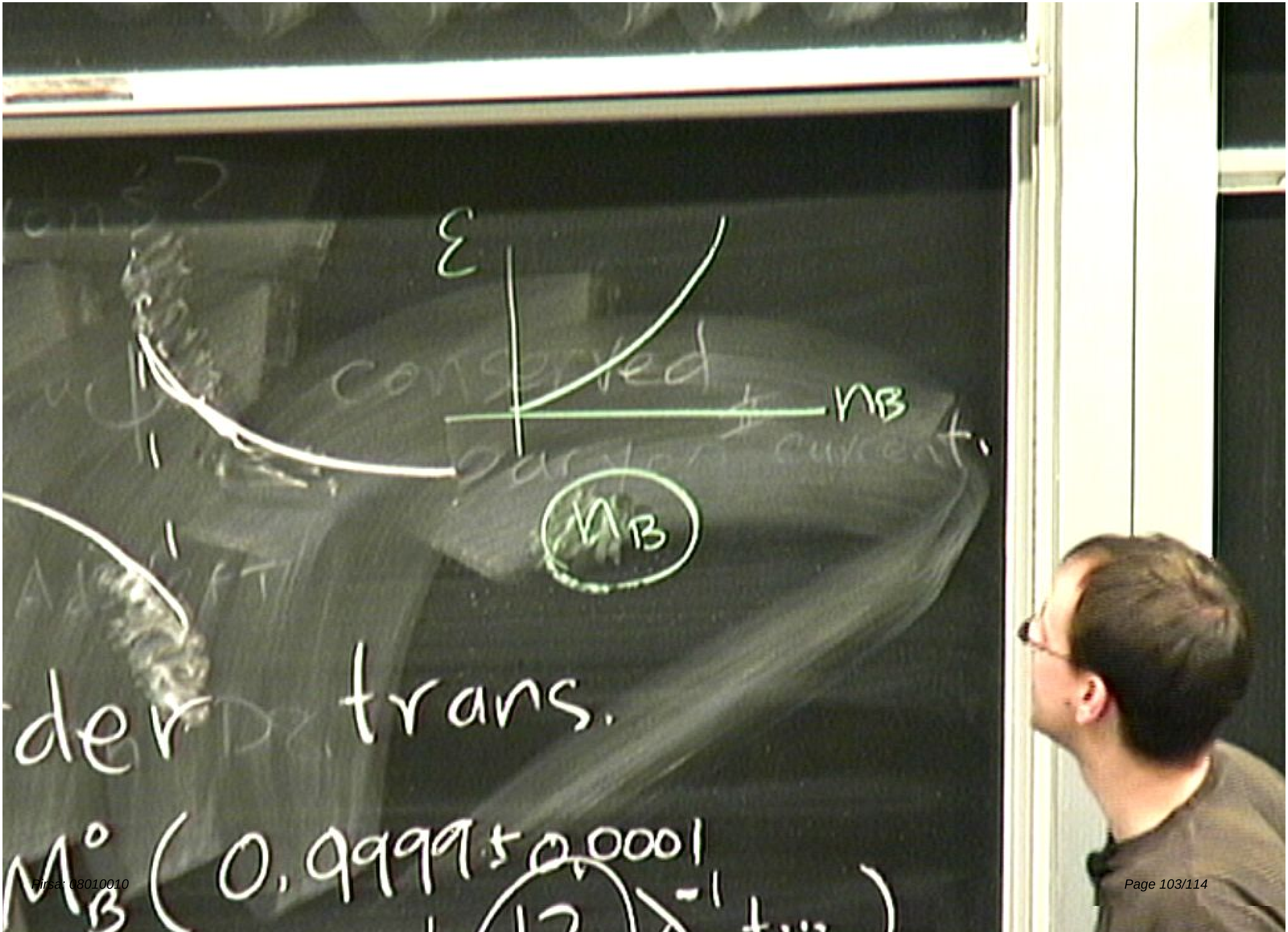

baryon mass:
M_B = M_B^0 (1 + c/λ)
M_B^0 = 1/2
QCD.
e_BIND = (M_B - M_c)
= N_c/4π Λ_QCD (c' - c) ~

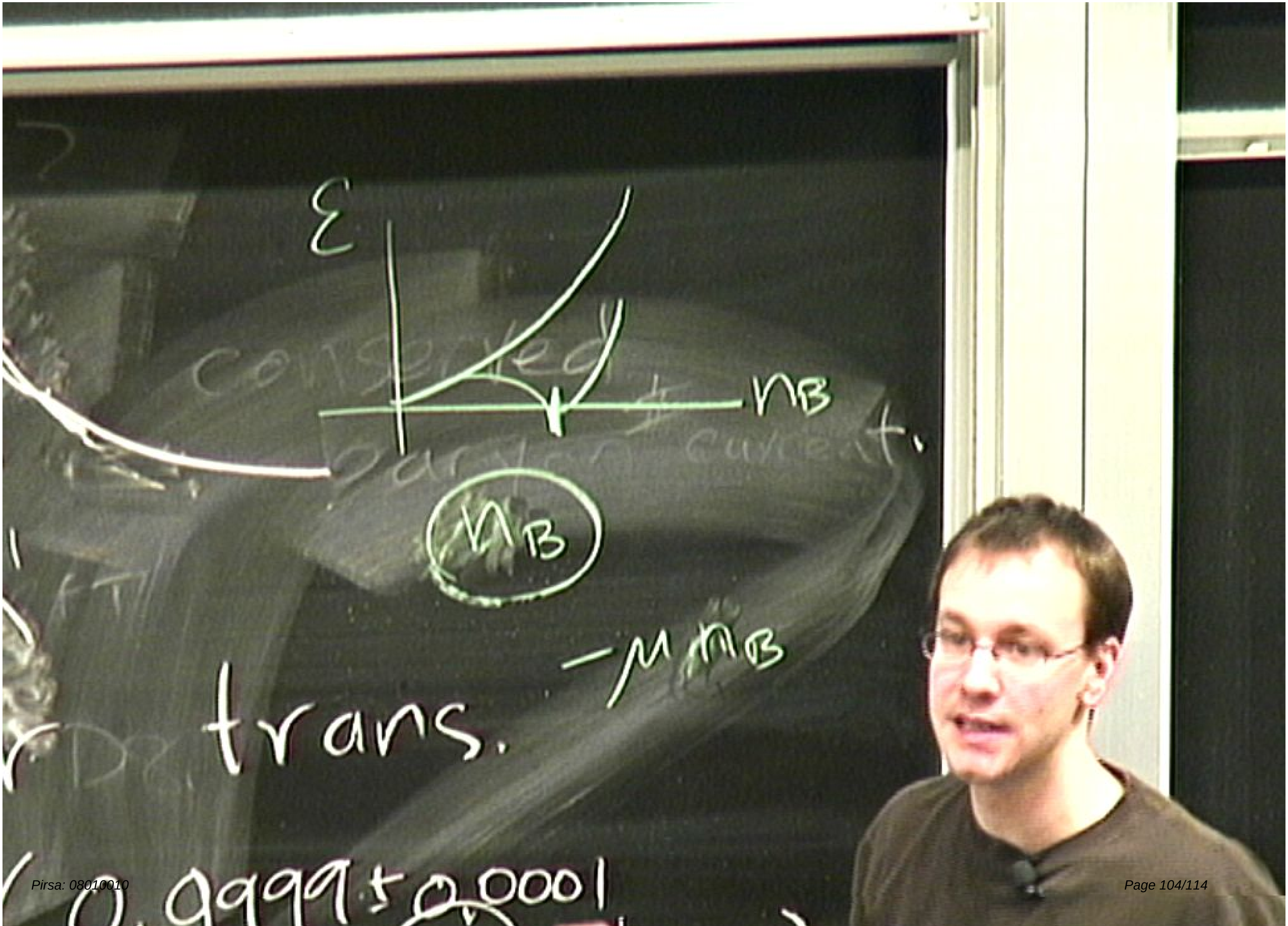
baryon mass:

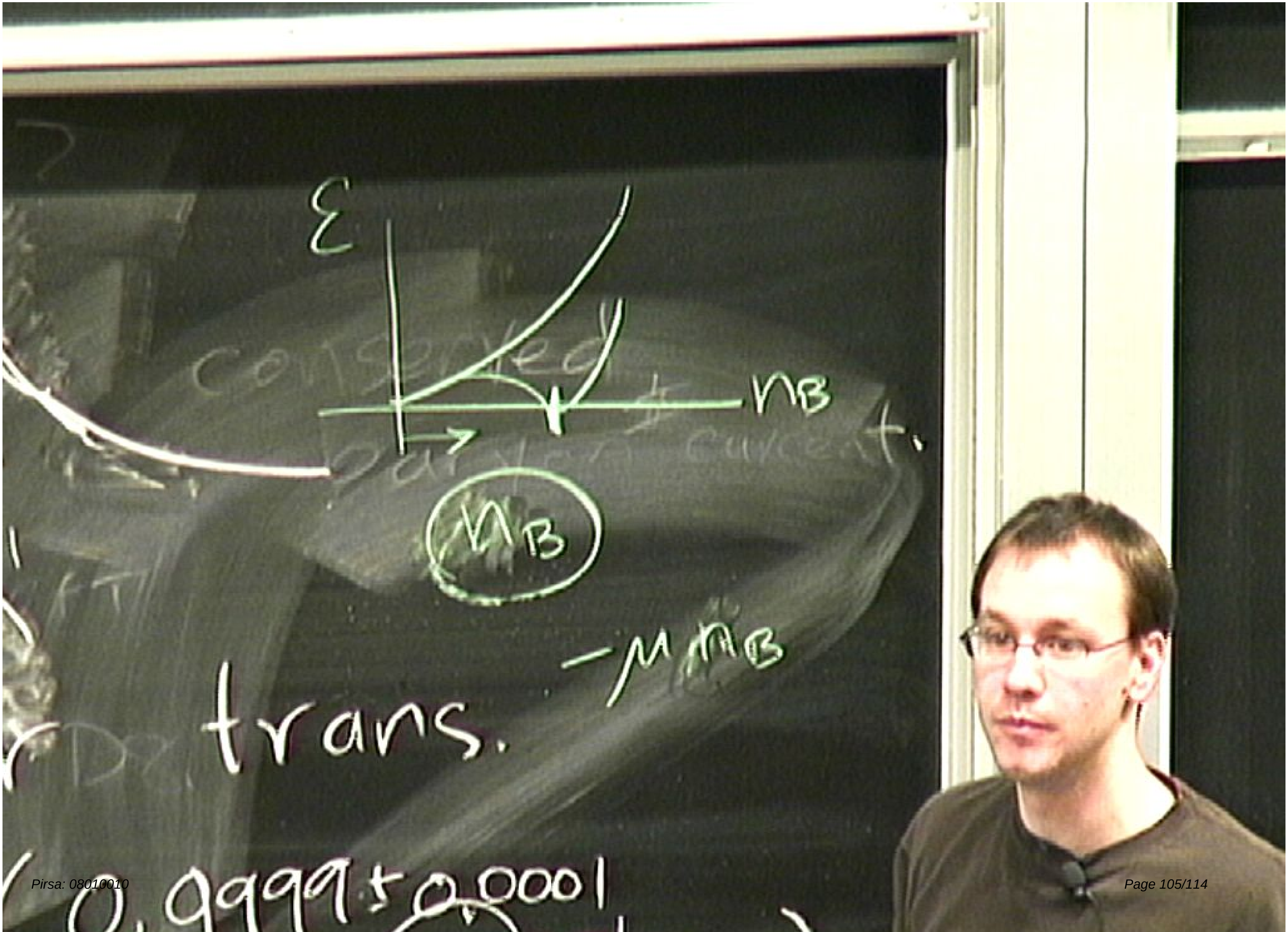
$$M_B = M_B^0 \left(1 + \frac{c}{\lambda}\right) \qquad M_B^0 = \frac{1}{27\pi}\lambda N_c \Lambda_{QCD}$$

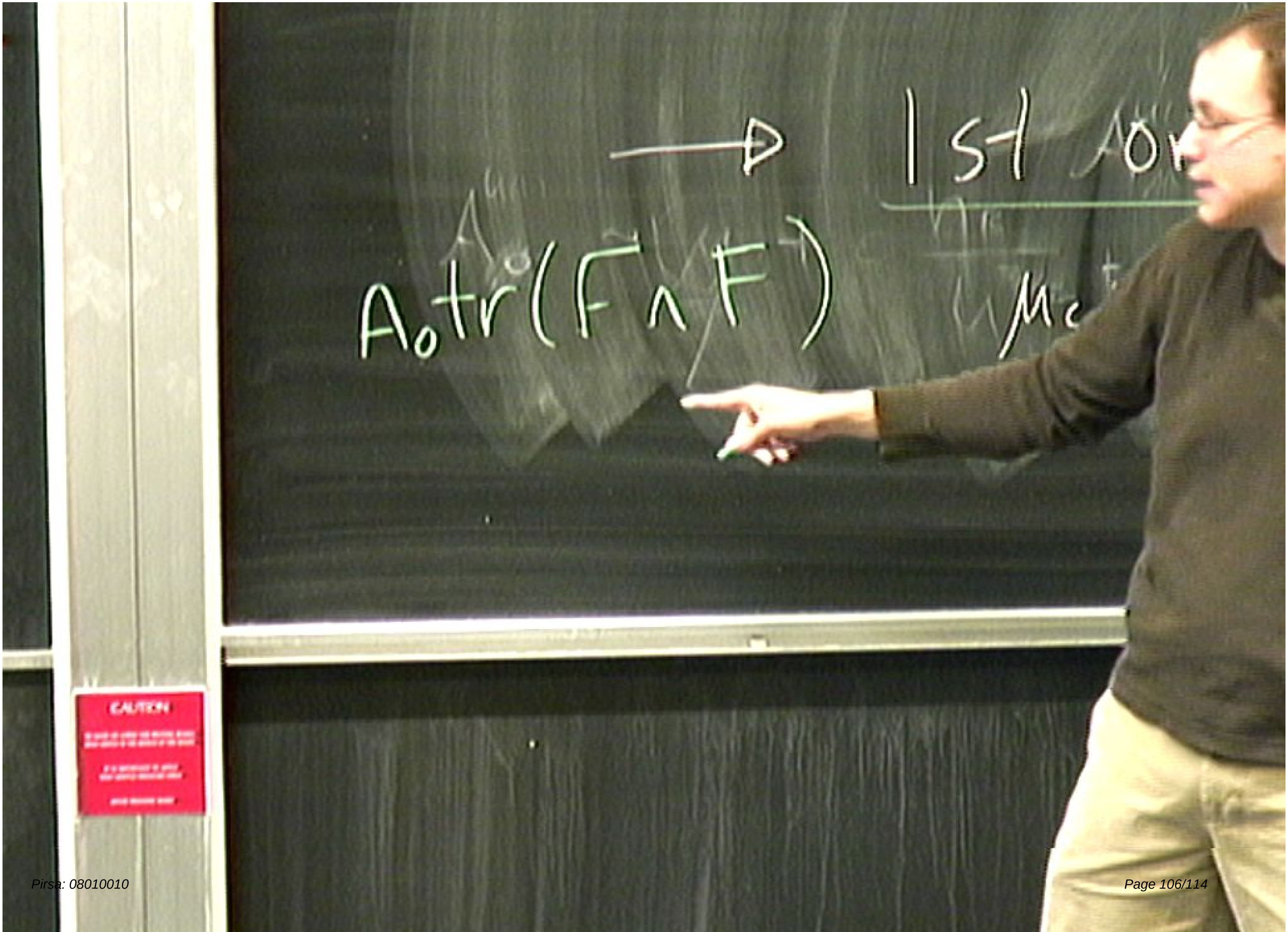
$$e_{BIND} = (M_B - M_c) = \frac{N_c}{9\pi}\Lambda_{QCD}(c'-c) \overset{N_c=3}{\sim} 7\,\mathrm{MeV}\,(c'-c)$$

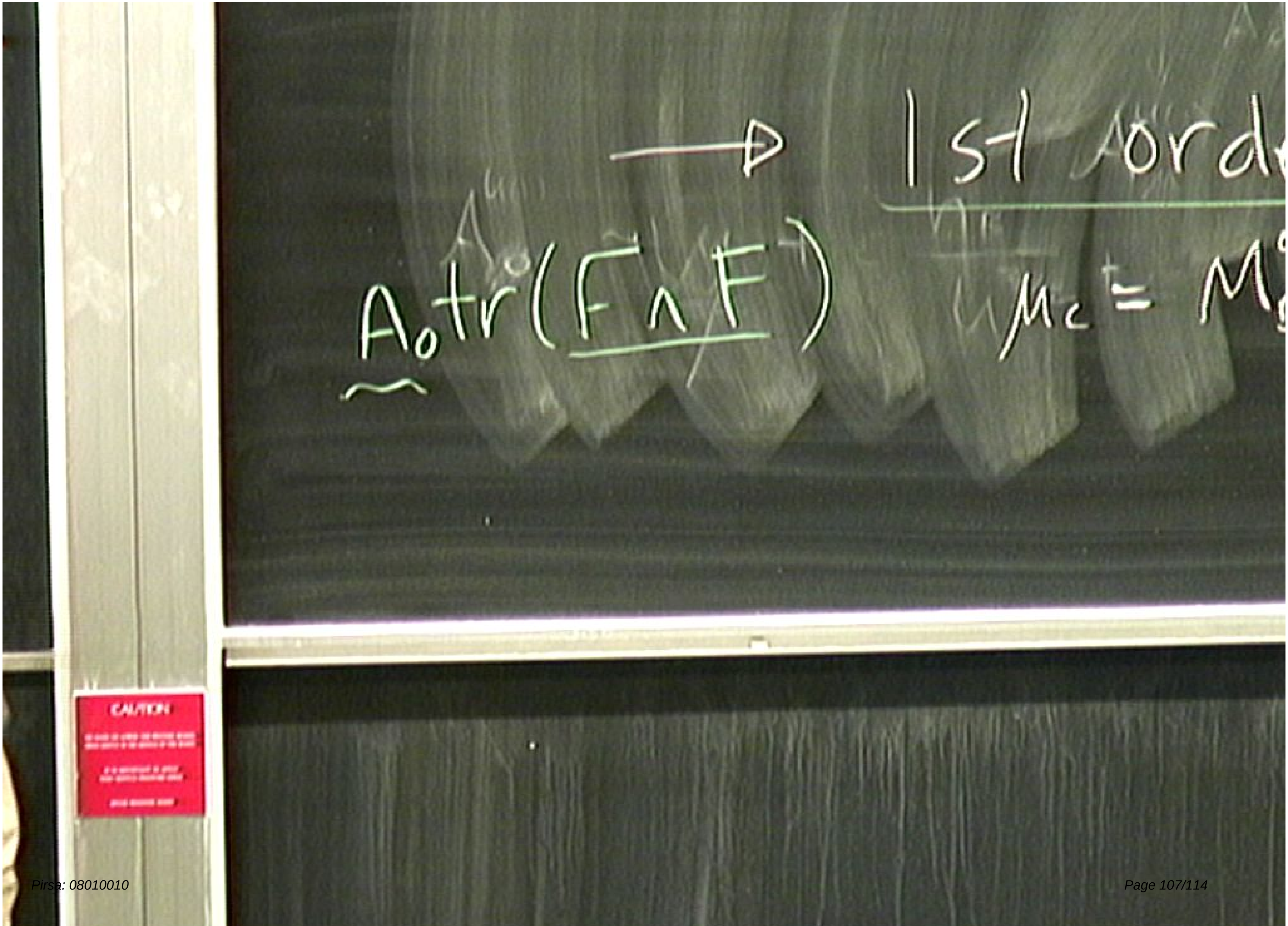

baryon mass:
$M_B = M_B^0 \left(1 + \frac{c}{\lambda}\right)$
$M_B^0 = \frac{1}{27\pi} \lambda N_c \Lambda_{QCD}$
$e_{BIND} = (M_B - M_c)$
$= \frac{N_c}{9\pi} \Lambda_{QCD} (c' - c) \sim 7\,\mathrm{MeV}\,(c'-c)$
$N_c = 3$

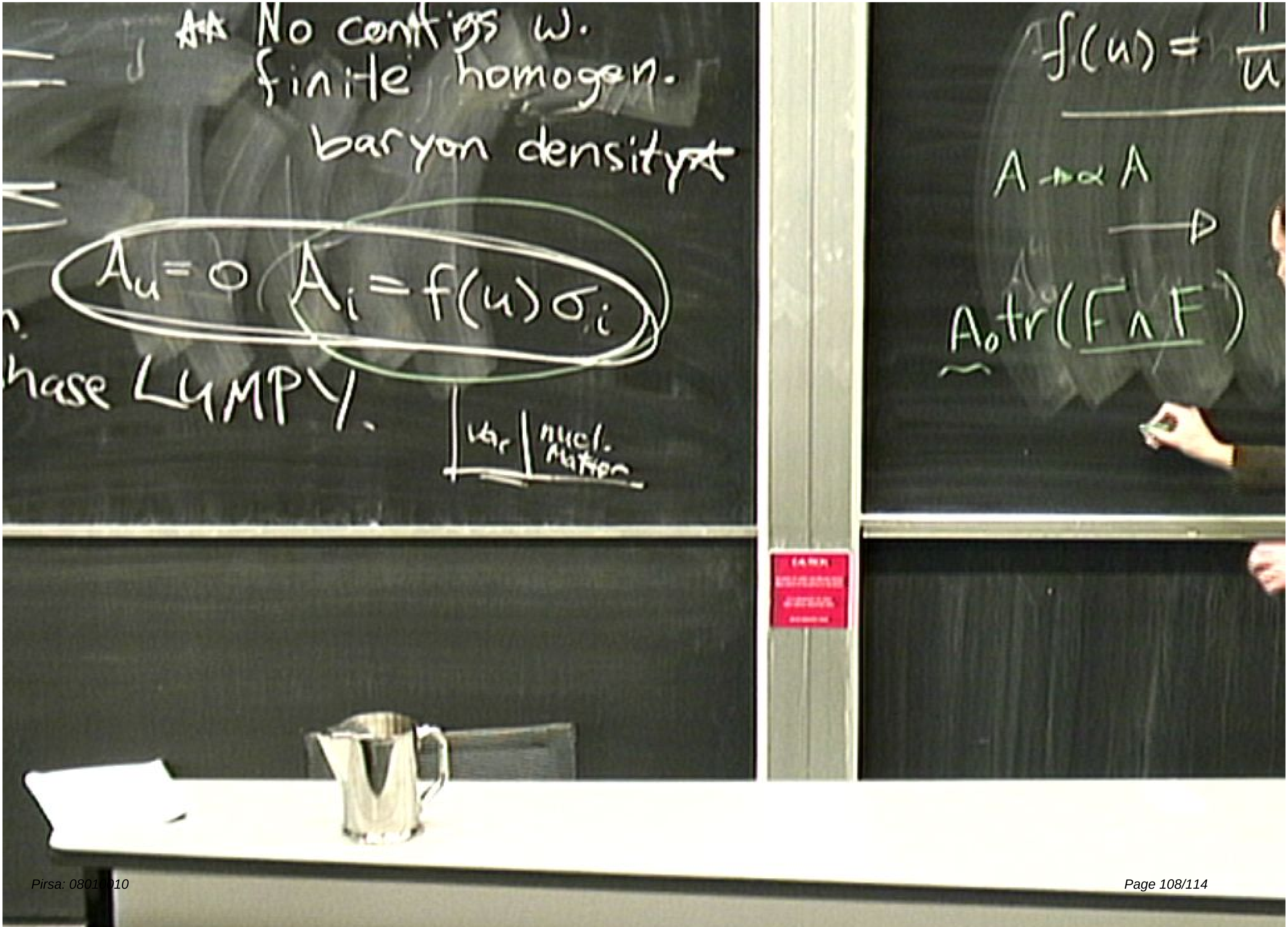

ε
nB
nB
der trans.
0.9999 ± 0.0001

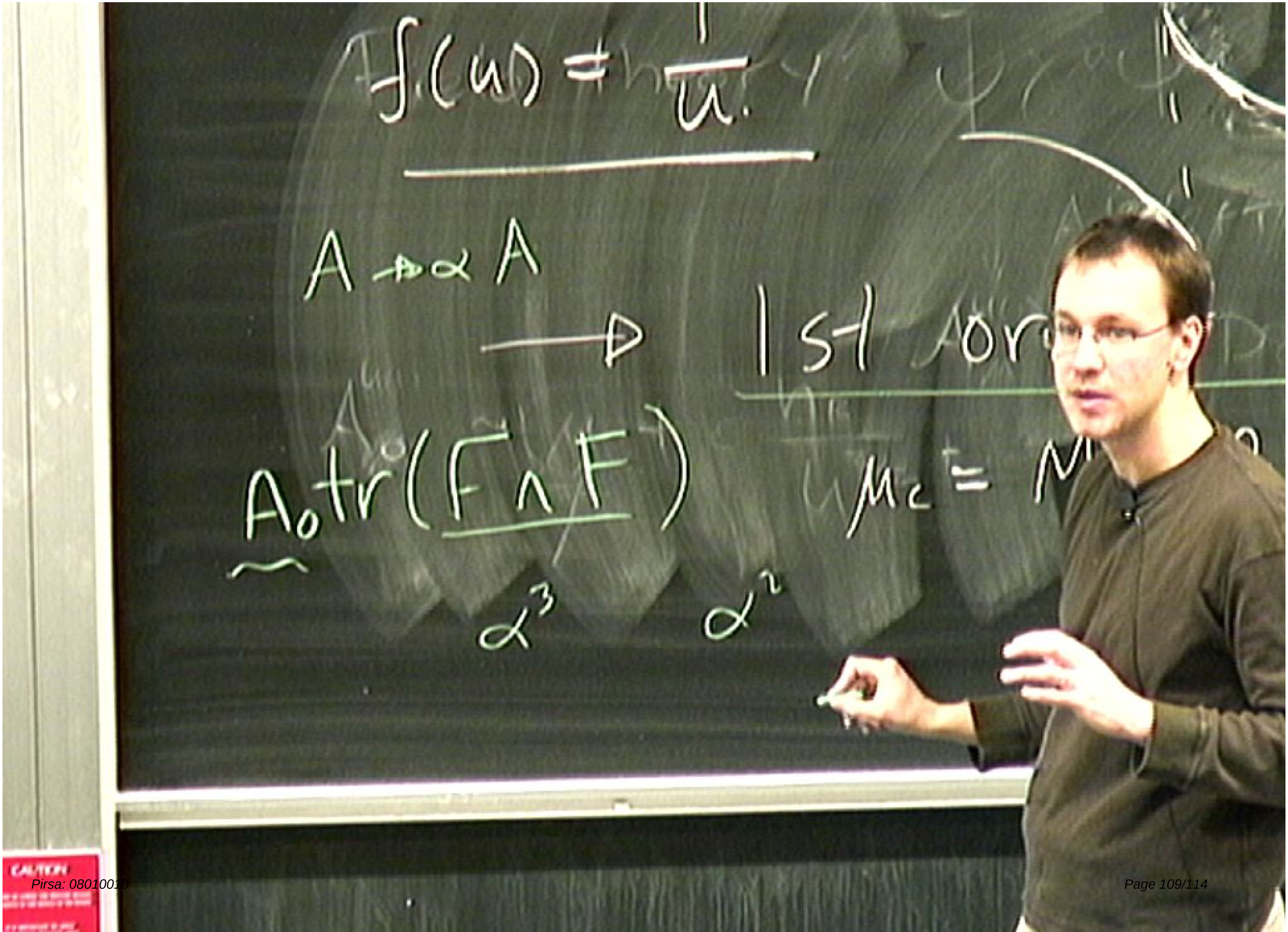

ε
n_B
conserved
baryon current.
n_B
−μ n_B
trans.
0.9999±0.0001

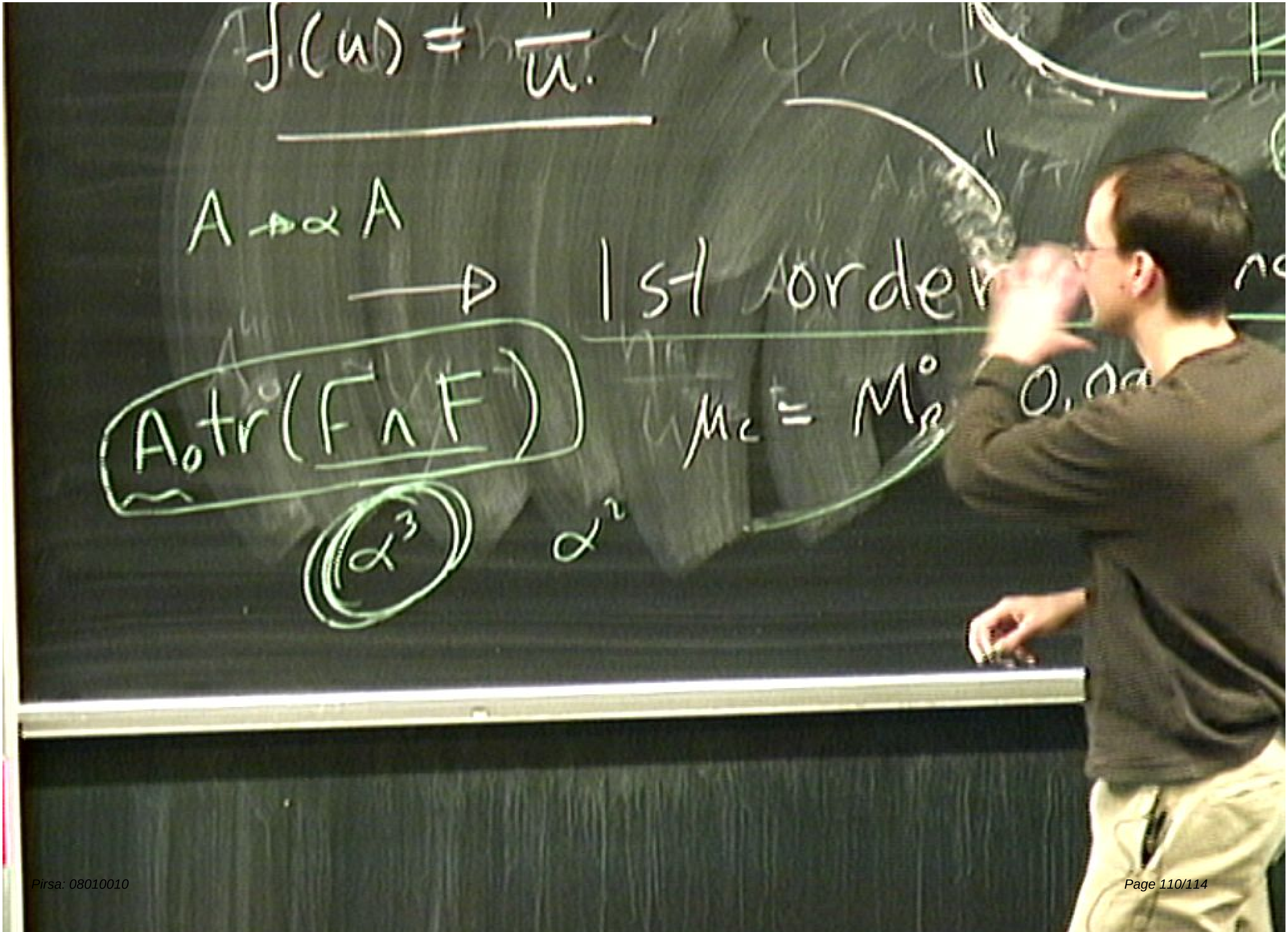

E
nB
nB
-μ nB
trans.
0.9999 + 0.0001

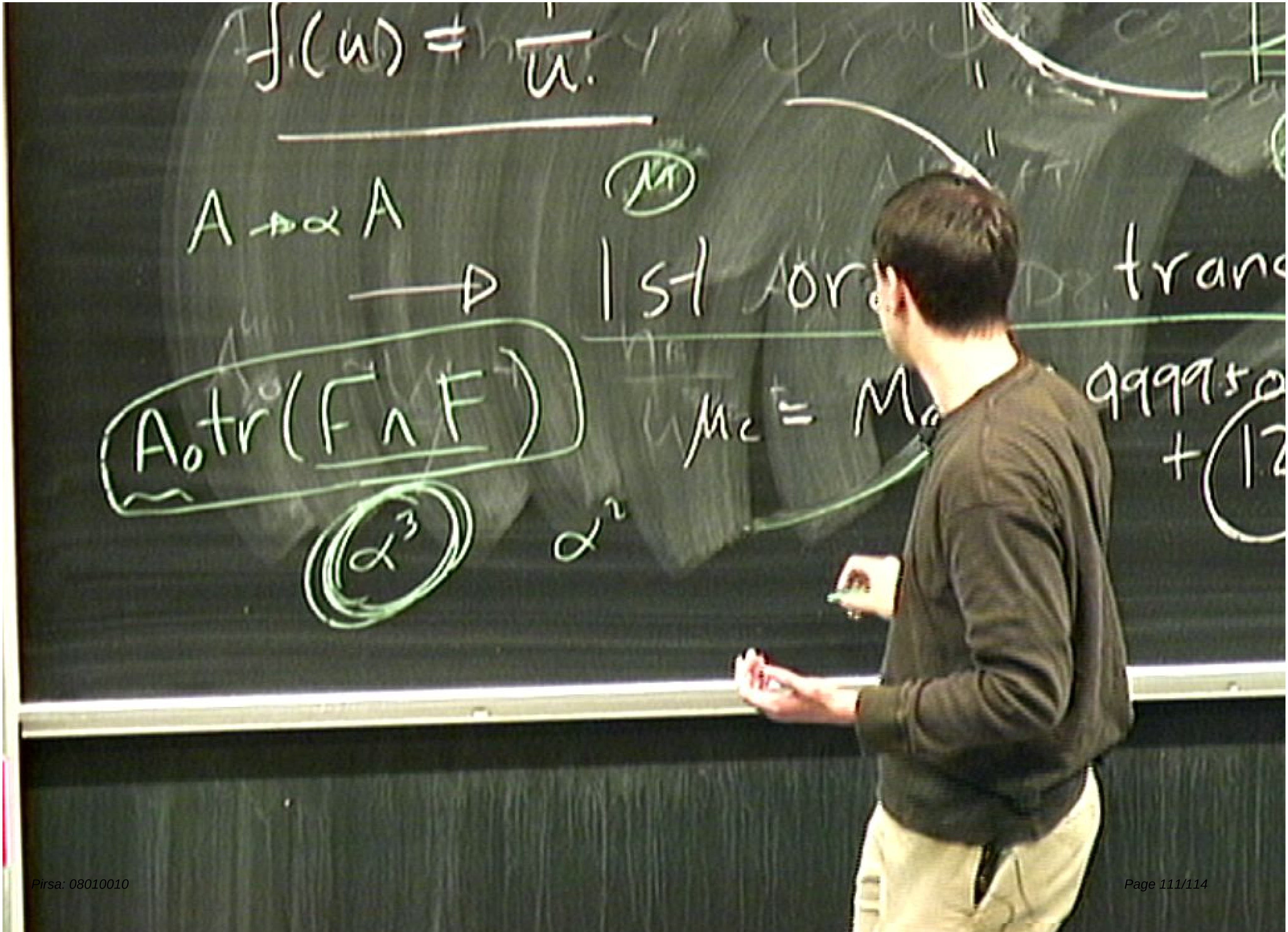

$A_0 \mathrm{tr}(F \wedge F)$
1st
CAUTION

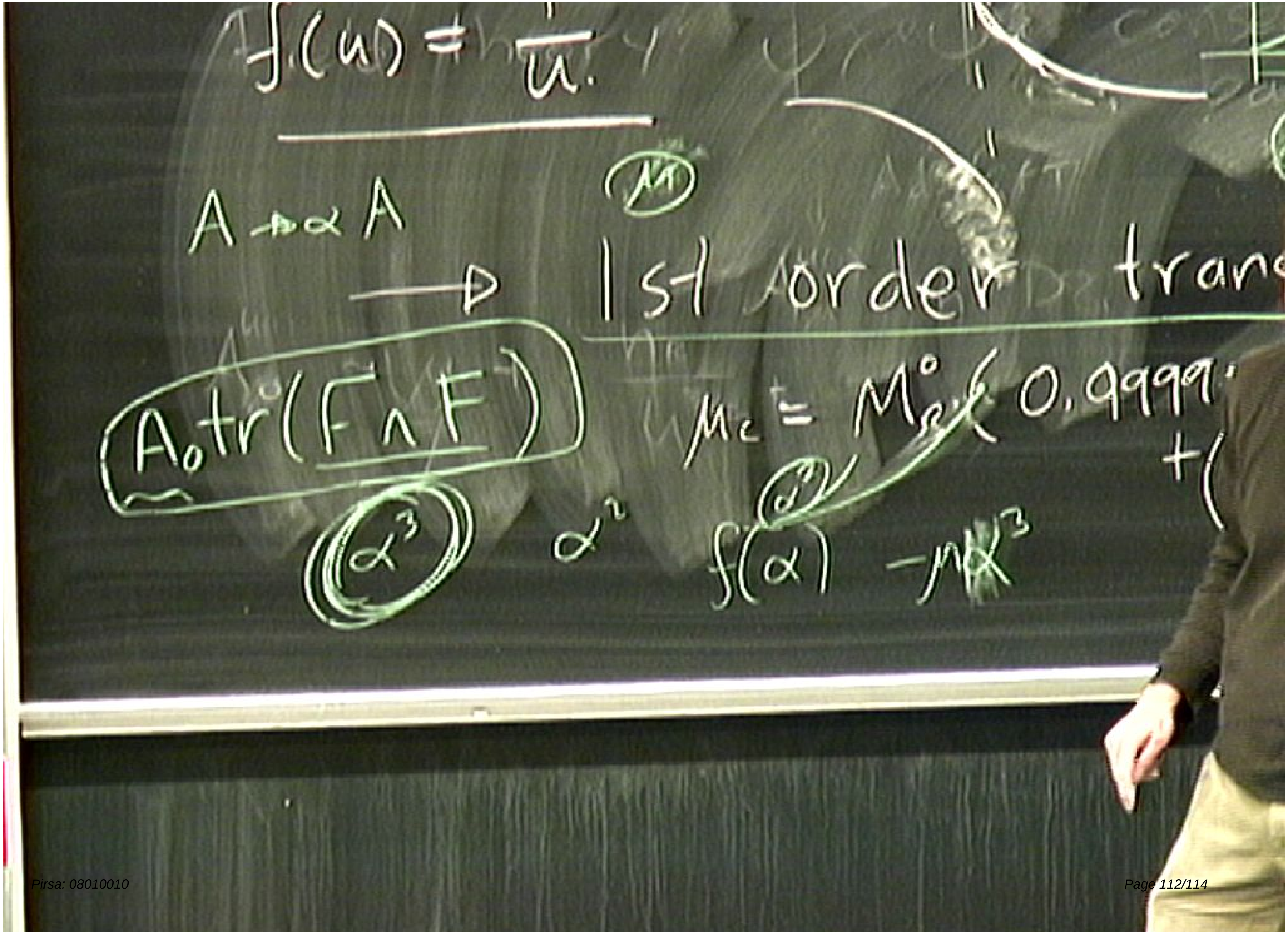

1st ord
$A_0 \, tr(F \wedge F)$
$\mu_c = M$
CAUTION

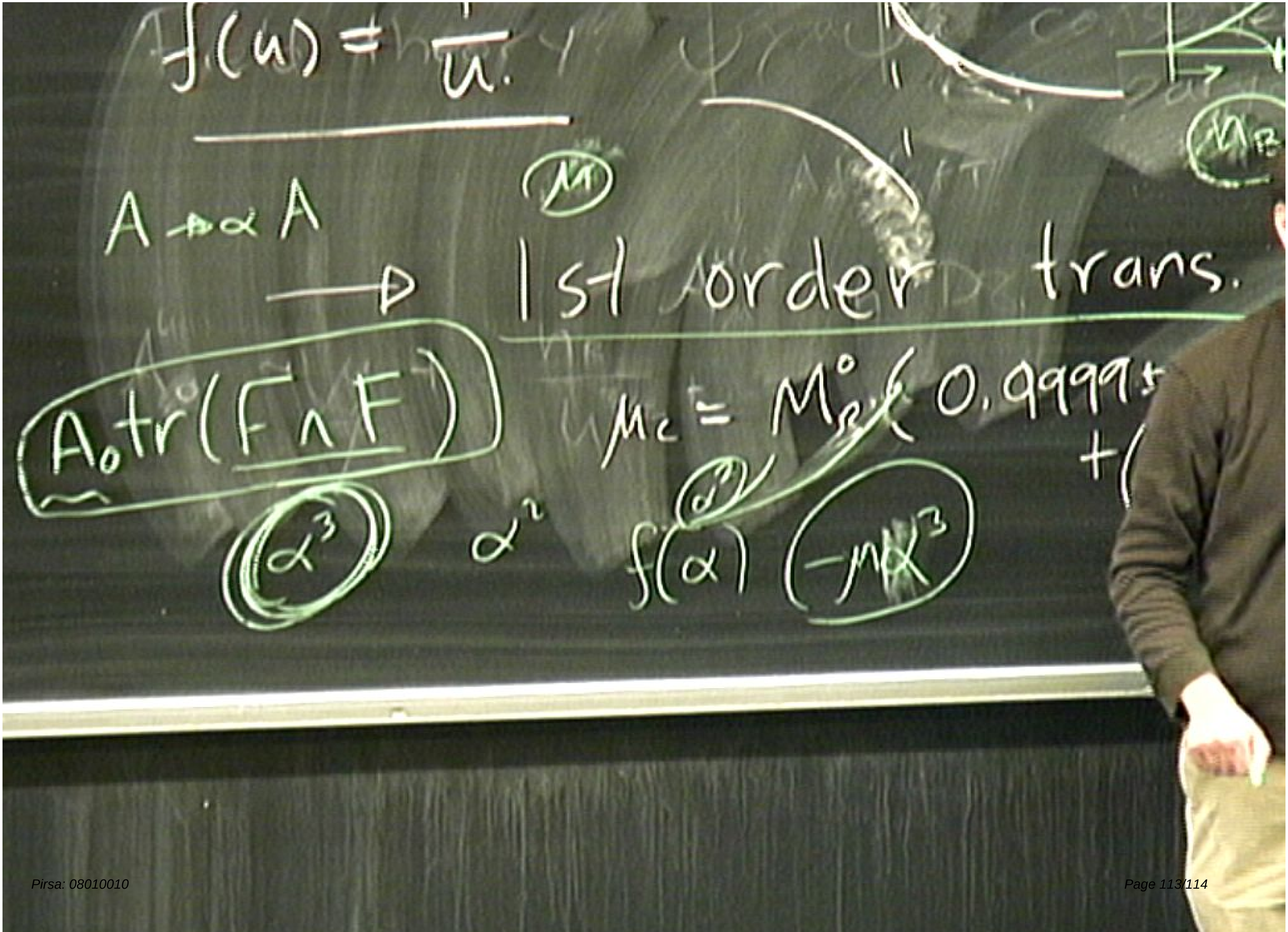

No configs w.
finite homogen.
baryon density
$A_u = 0$ $A_i = f(u)\sigma_i$
hase LUMPY.
nucl. matter
$f(u) =$
$A \to \alpha A$
$A_0 \,\mathrm{tr}(F \wedge F)$

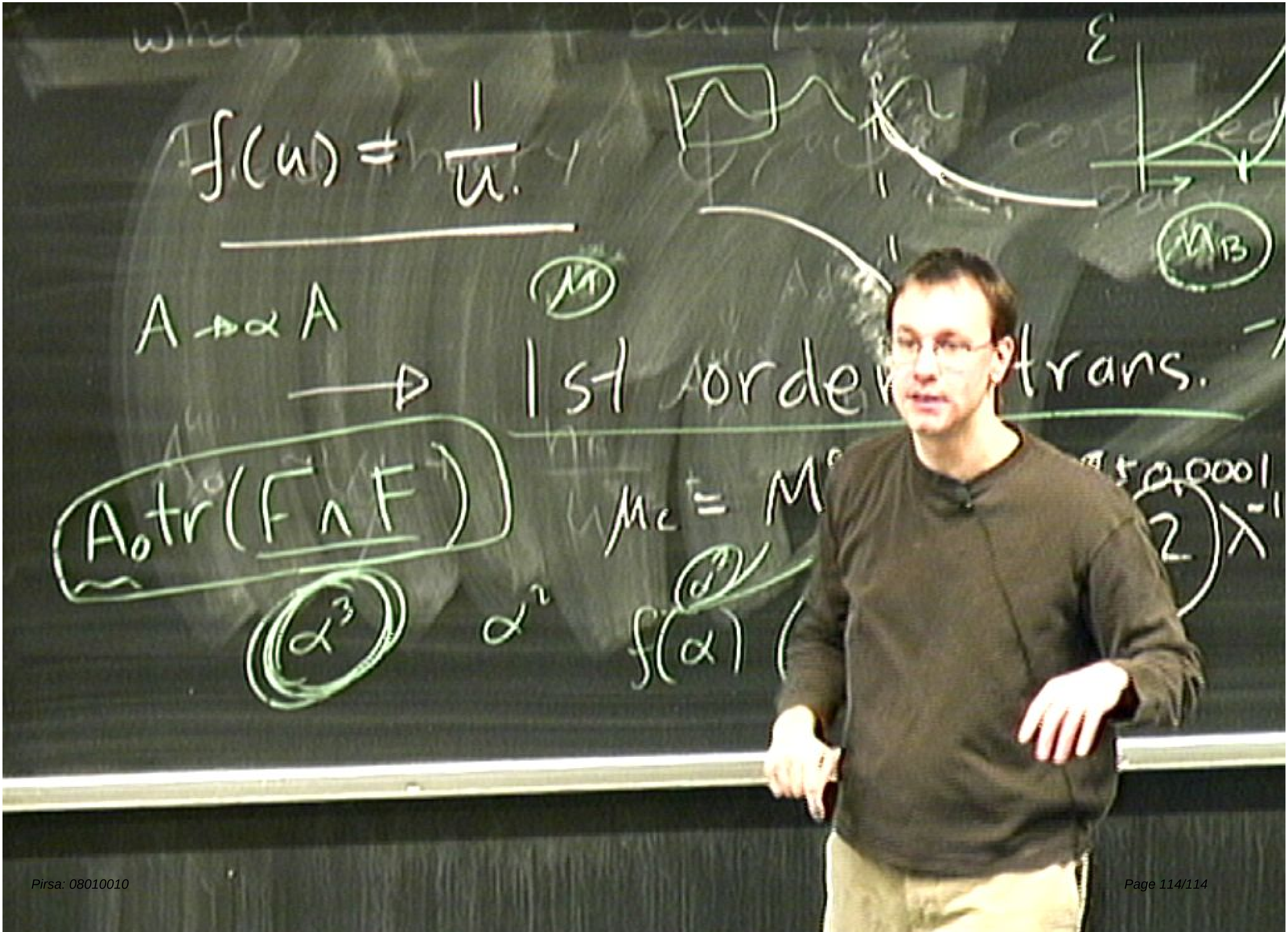

$f(u) = \frac{1}{u}$
$A \to \alpha A$
1st Or
$A_0 \mathrm{tr}(F \wedge F)$
α^3
α^2
$M_c = M$


f(u) = 1/u
A → α A
→ 1st order
A₀ tr(F ∧ F)
α³
α²
μc = M°c 0.0


f(u) = 1/u.
A → α A
1st
A₀ tr(F ∧ F)
α³
α²
M_c =
+


f(u) = 1/u
A → α A
1st order tran
A₀ tr(F ∧ F)
α³
α²
f(α)
M_c = M_c° (0.9999
+(


f(u) = 1/u.
A → α A
→ 1st order trans.
A₀ tr(F ∧ F)
α³
α²
f(α)
−Mα³
M_c = M_c° (0.9999
+(
M_B


f(u) = 1/u.
A → α A
→ 1st order trans.
A₀tr(F∧F)
α³
α²
0.0001