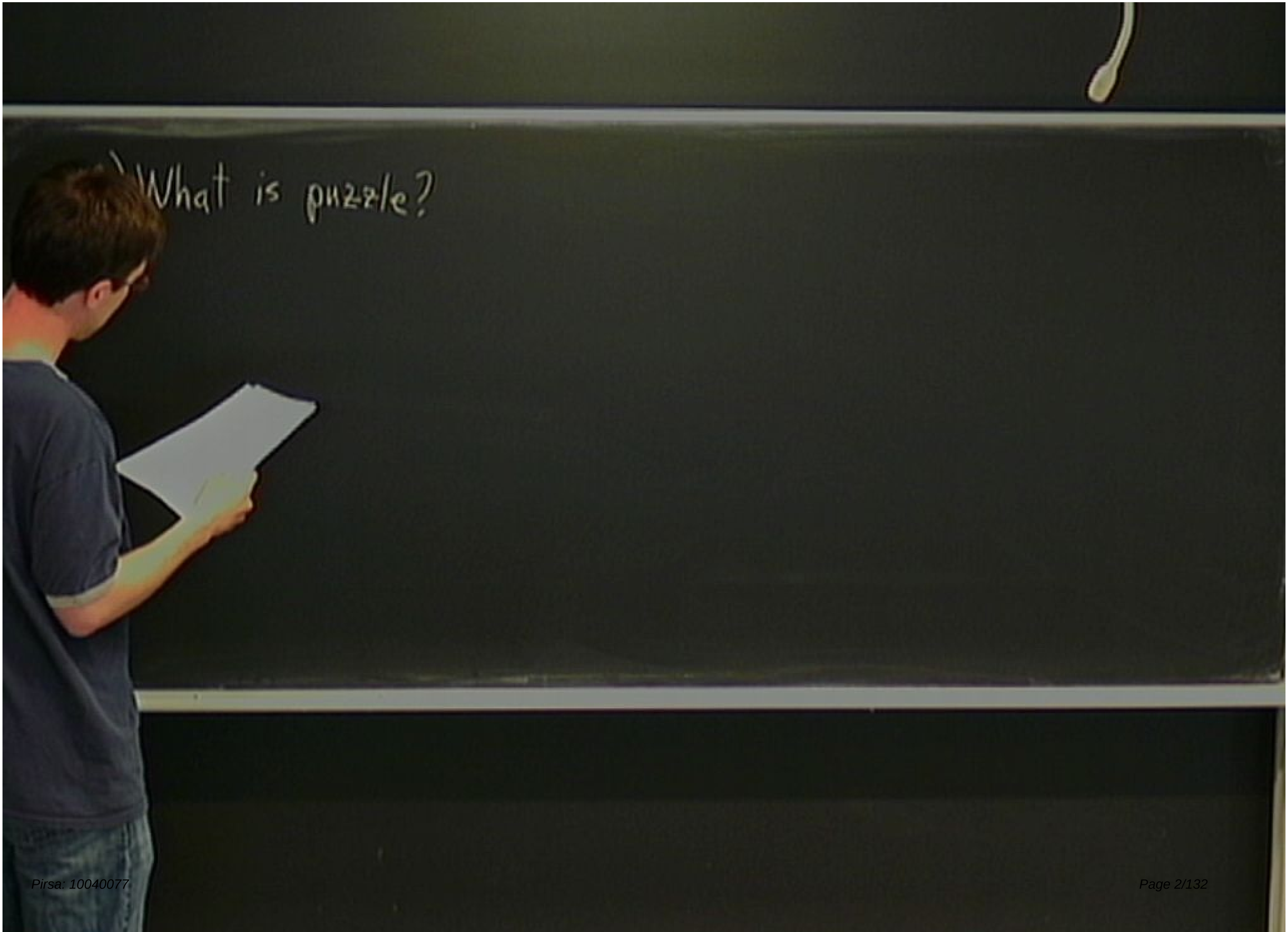
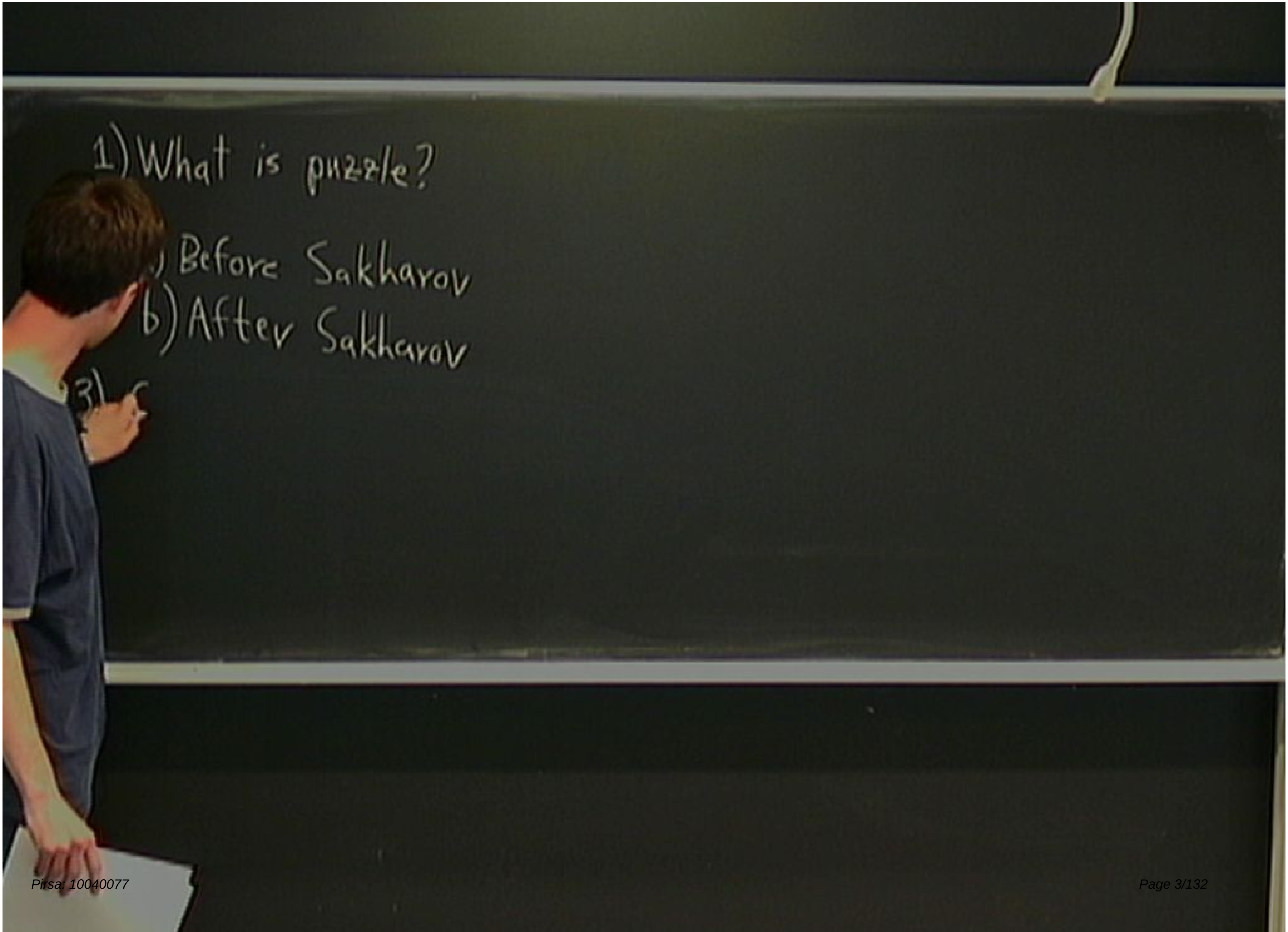
Title: Baryogenesis and Leptogenesis

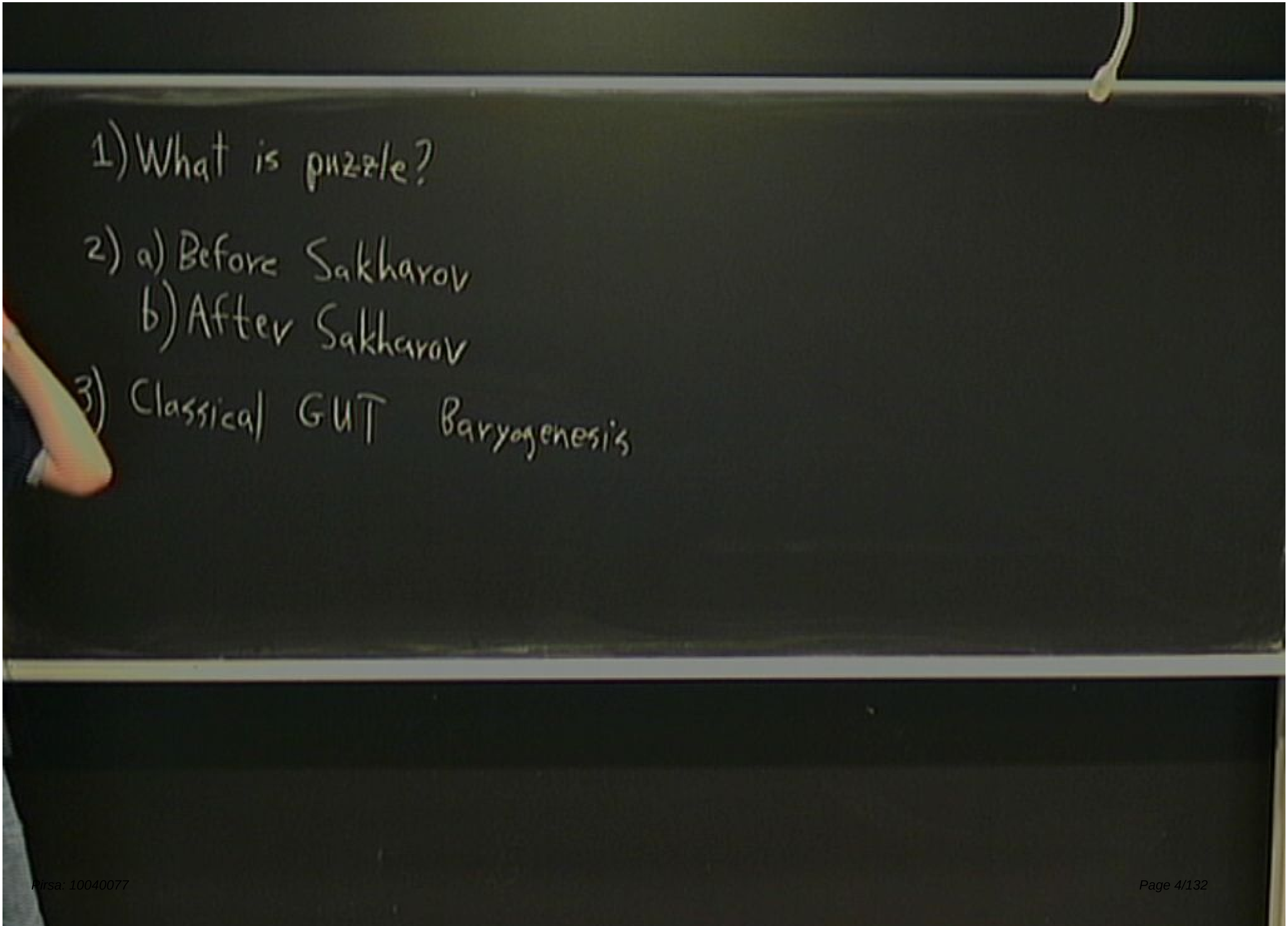
Date: Apr 19, 2010 02:00 PM

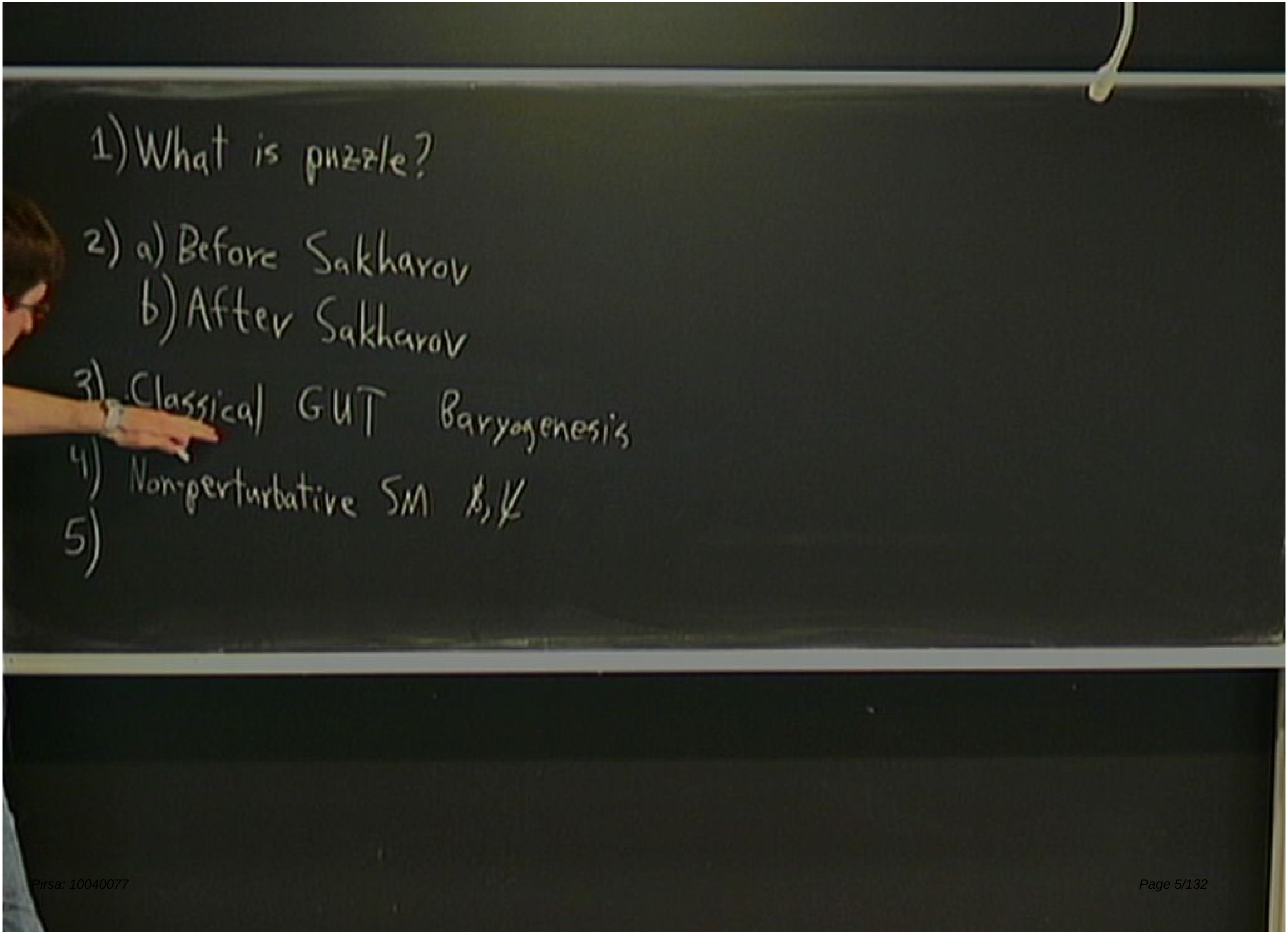
URL: http://pirsa.org/10040077

Abstract:


What is puzzle?


1) What is puzzle?
Before Sakharov
b) After Sakharov
3)


1) What is puzzle?
2) a) Before Sakharov
b) After Sakharov
3) Classical GUT Baryogenesis


1) What is puzzle?
2) a) Before Sakharov
b) After Sakharov
3) Classical GUT Baryogenesis
4) Non-perturbative SM B̸, L̸
5)

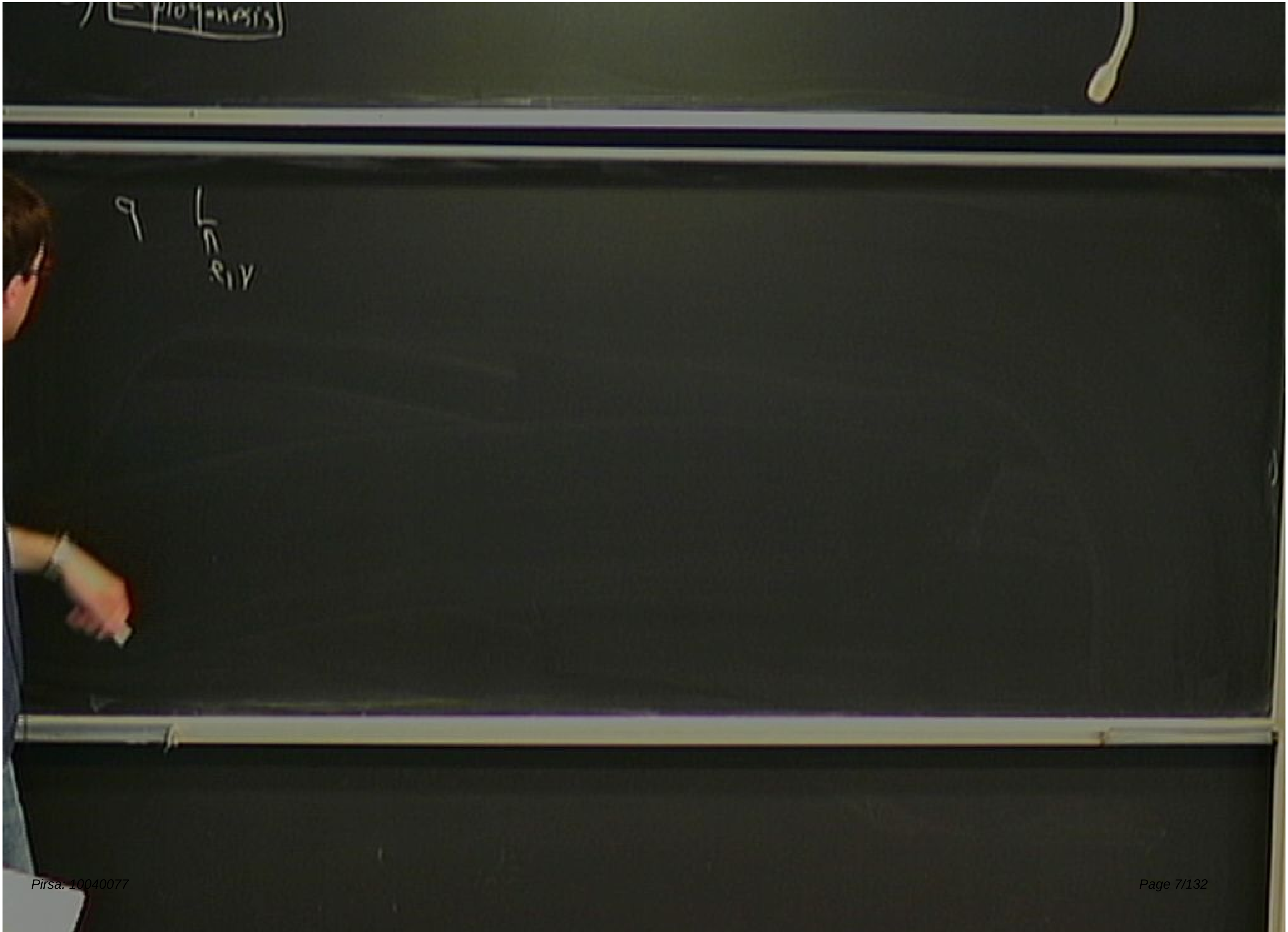
1) What is puzzle?

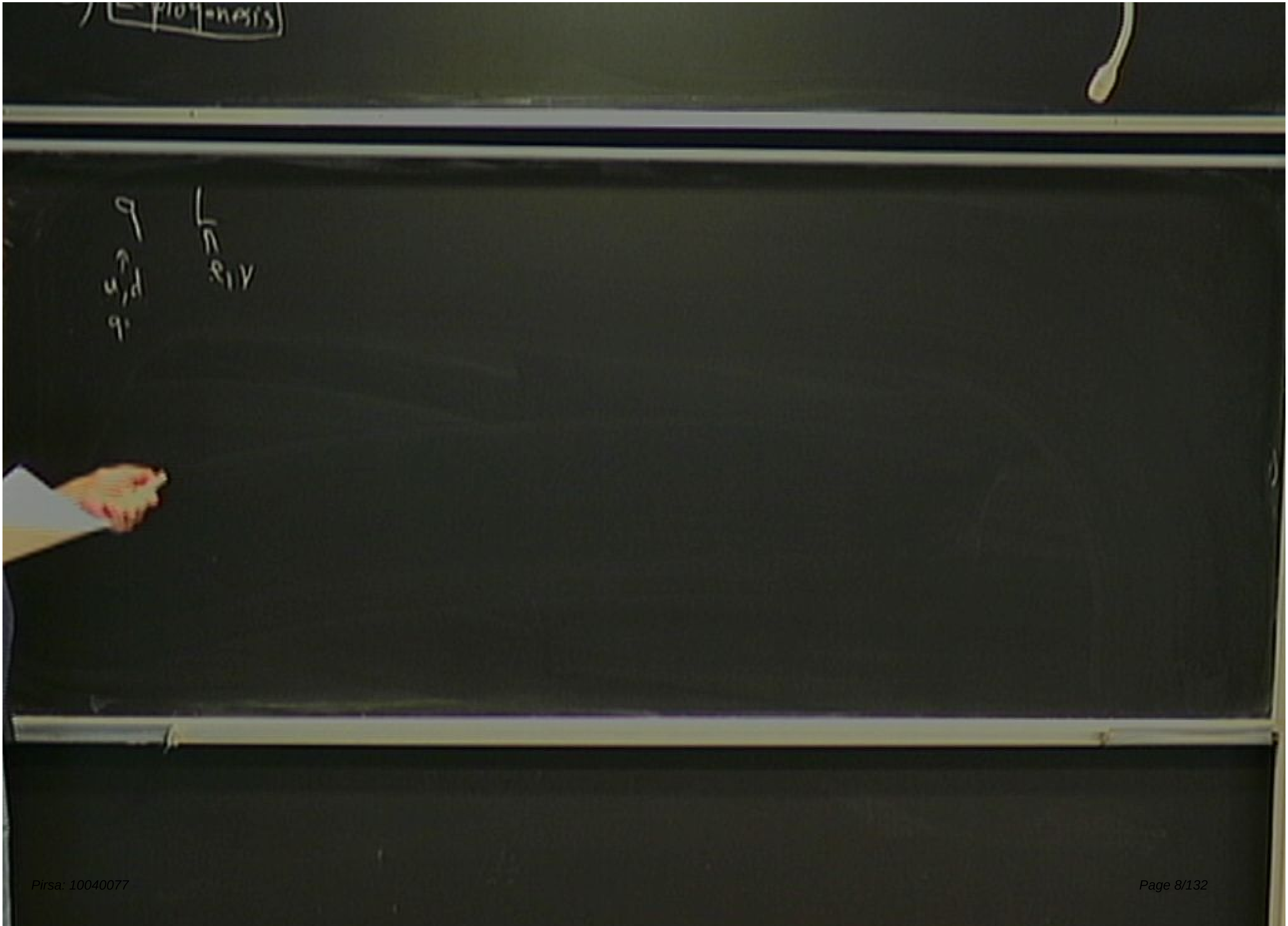
2) a) Before Sakharov
   b) After Sakharov

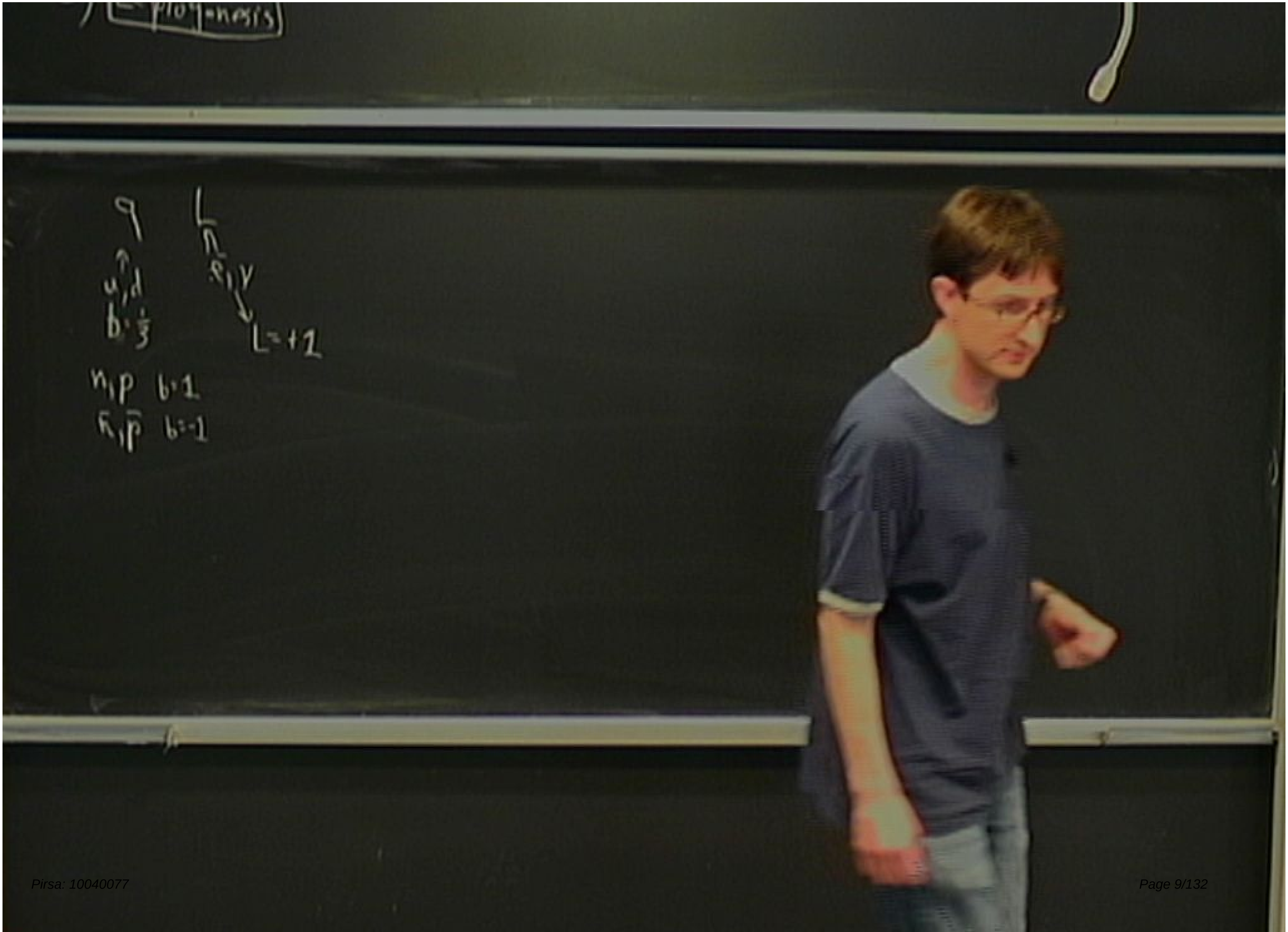
3) Classical GUT Baryogenesis

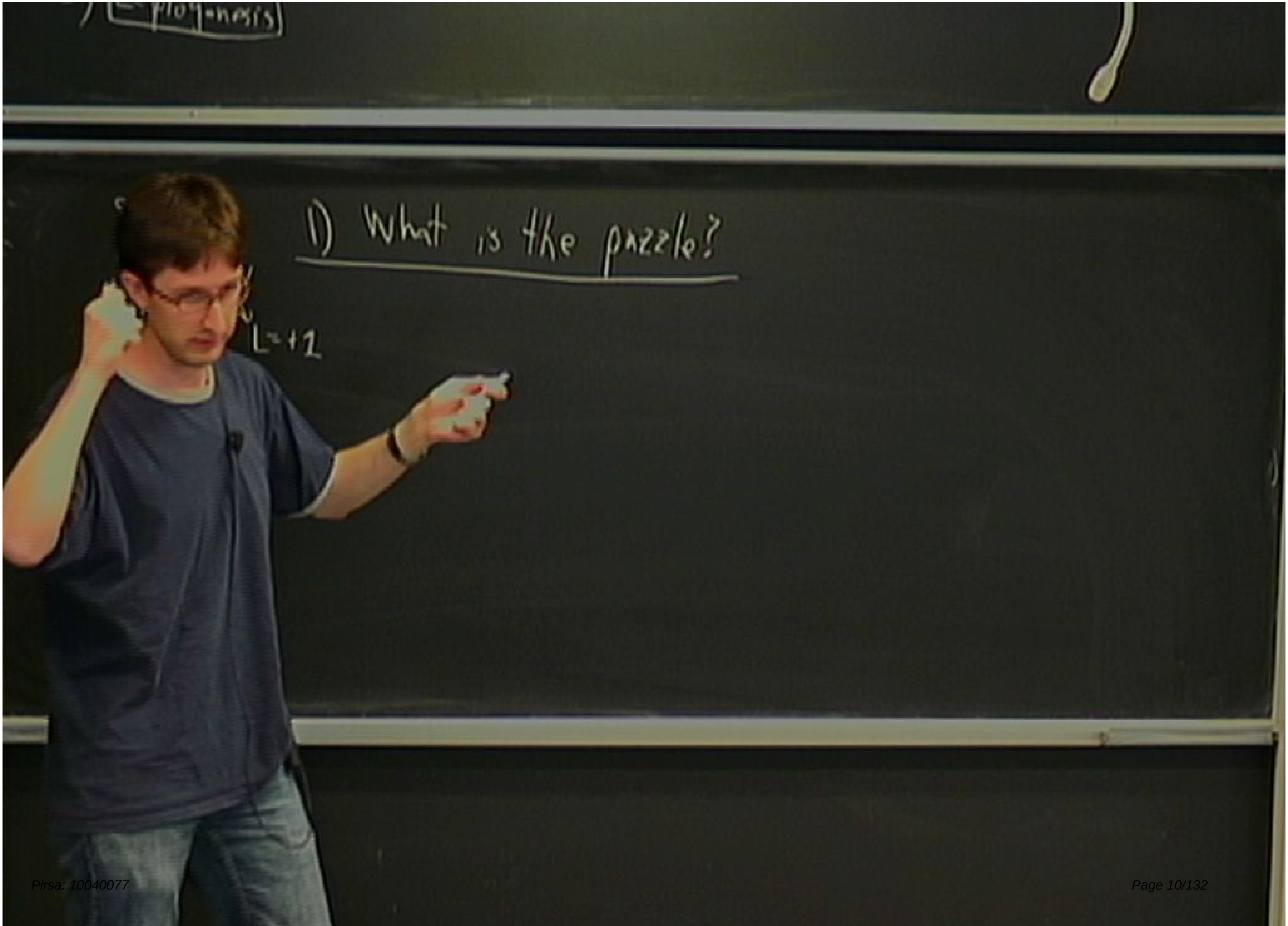
4) Non-perturbative SM $\not{B}, \not{L}$

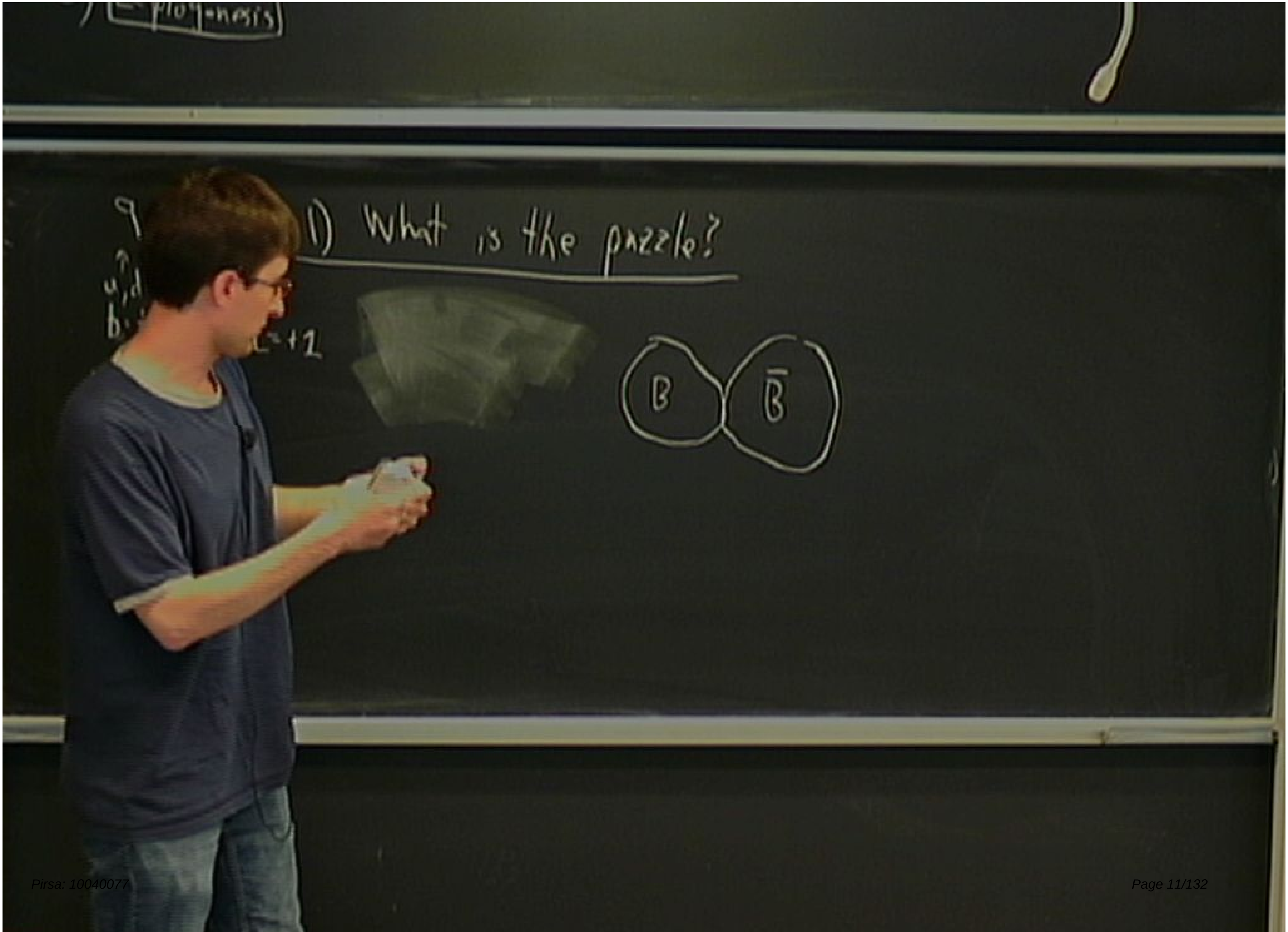
5) Leptogenesis

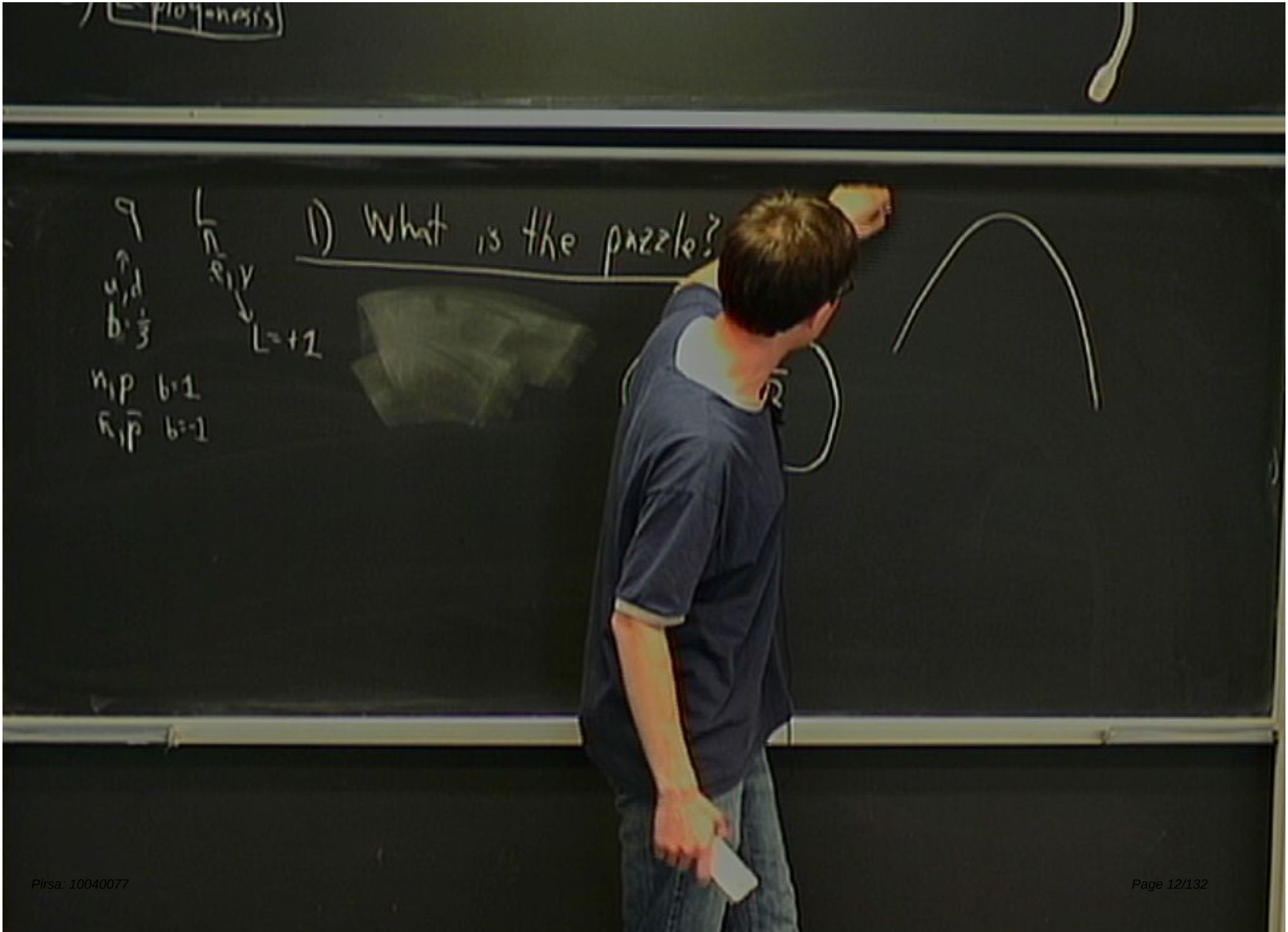



q
L
u,d
e,ν

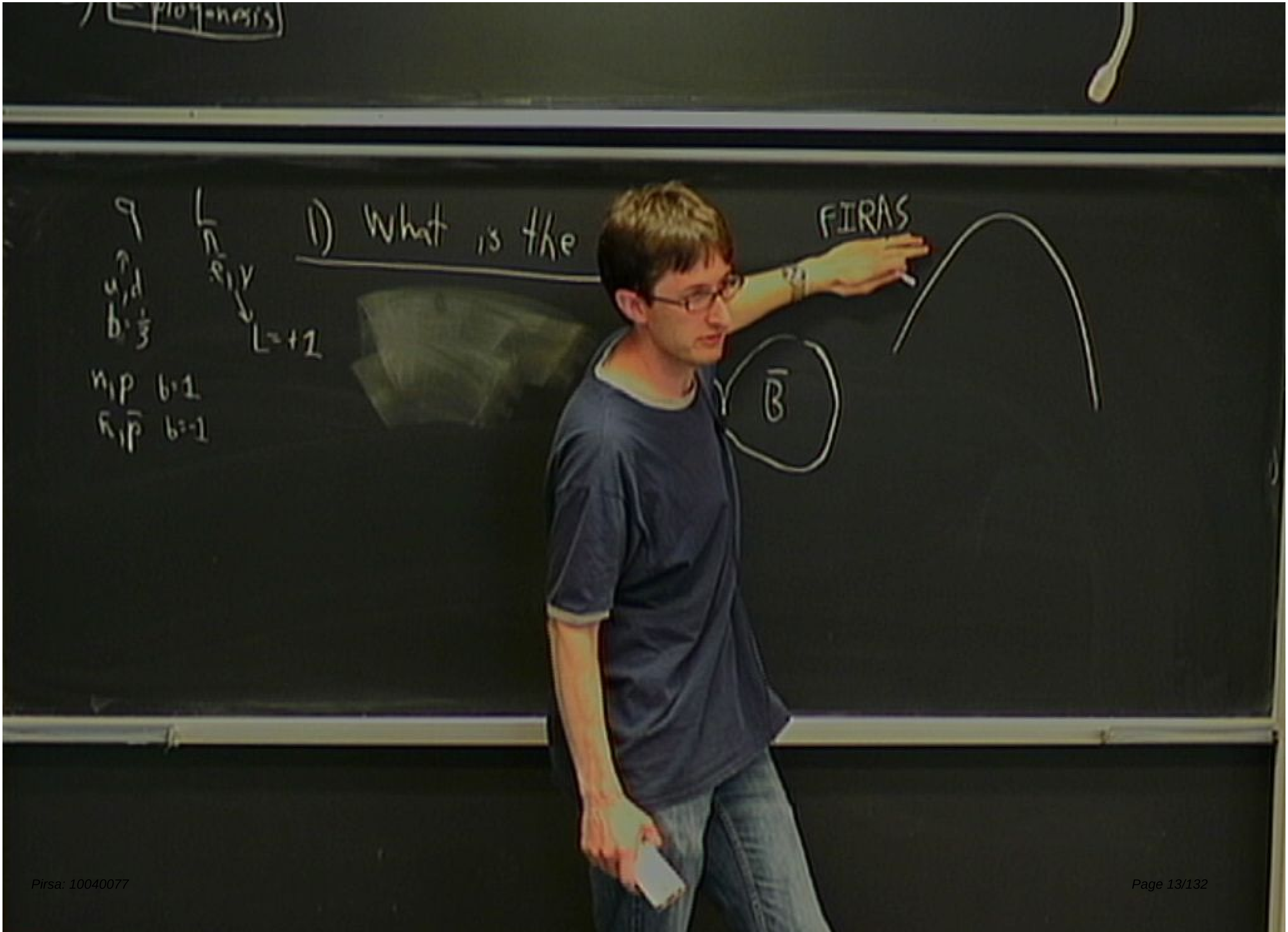

q
L
u, d
b = 1/3
e, ν
L = +1
n, p b = 1
n̄, p̄ b = -1

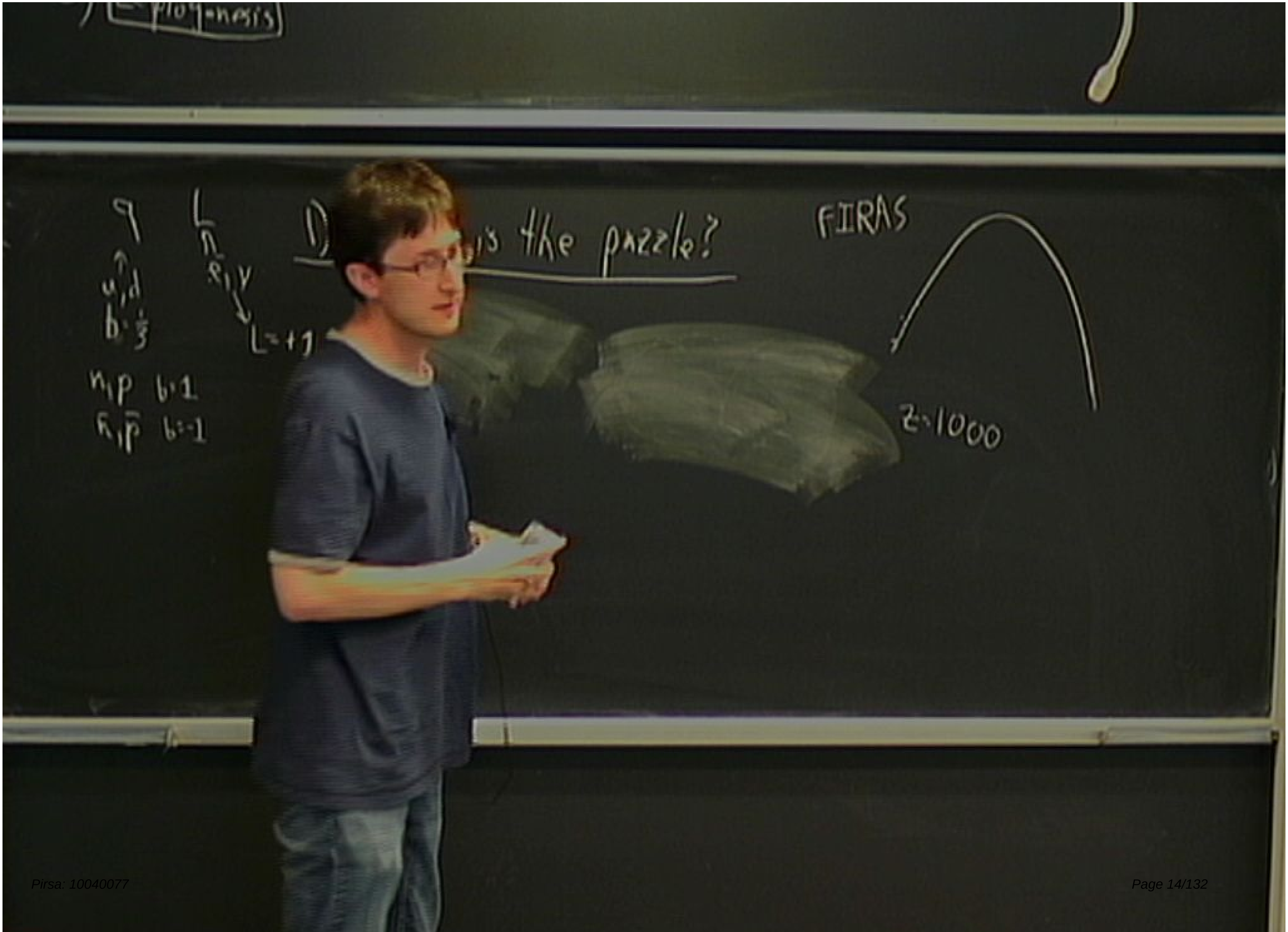

1) What is the puzzle?
L=+1

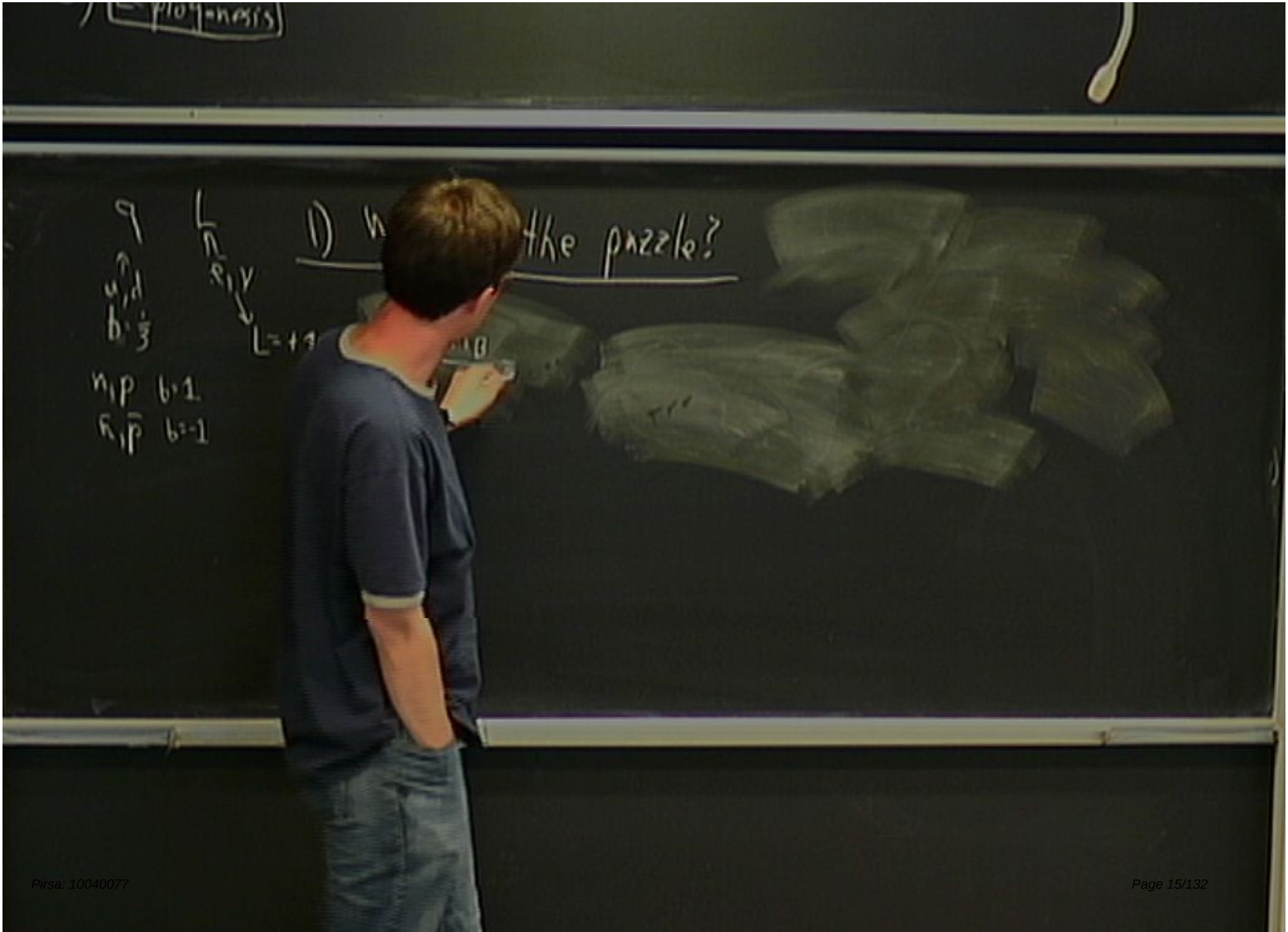

1) What is the puzzle?
B
B̄

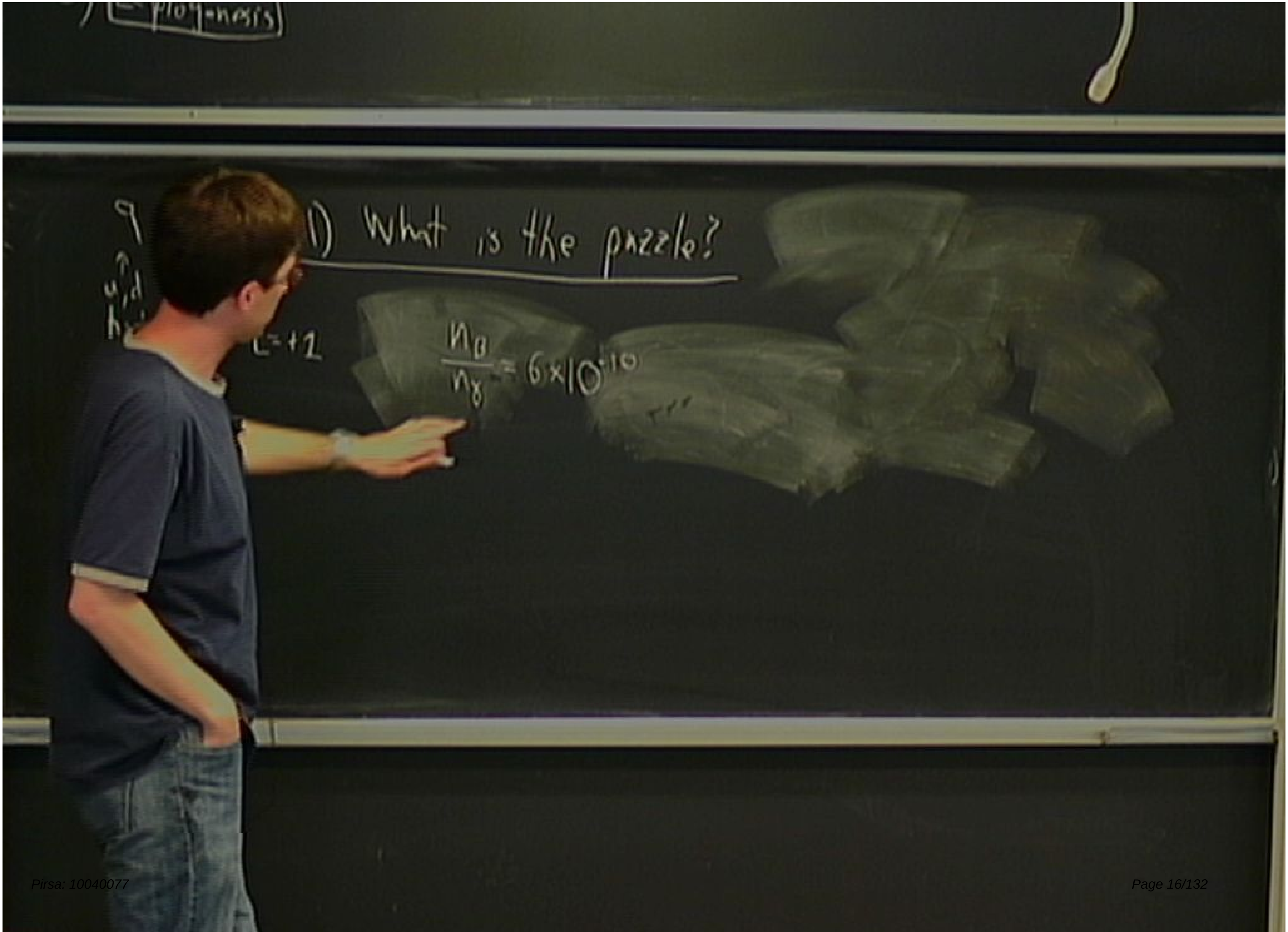


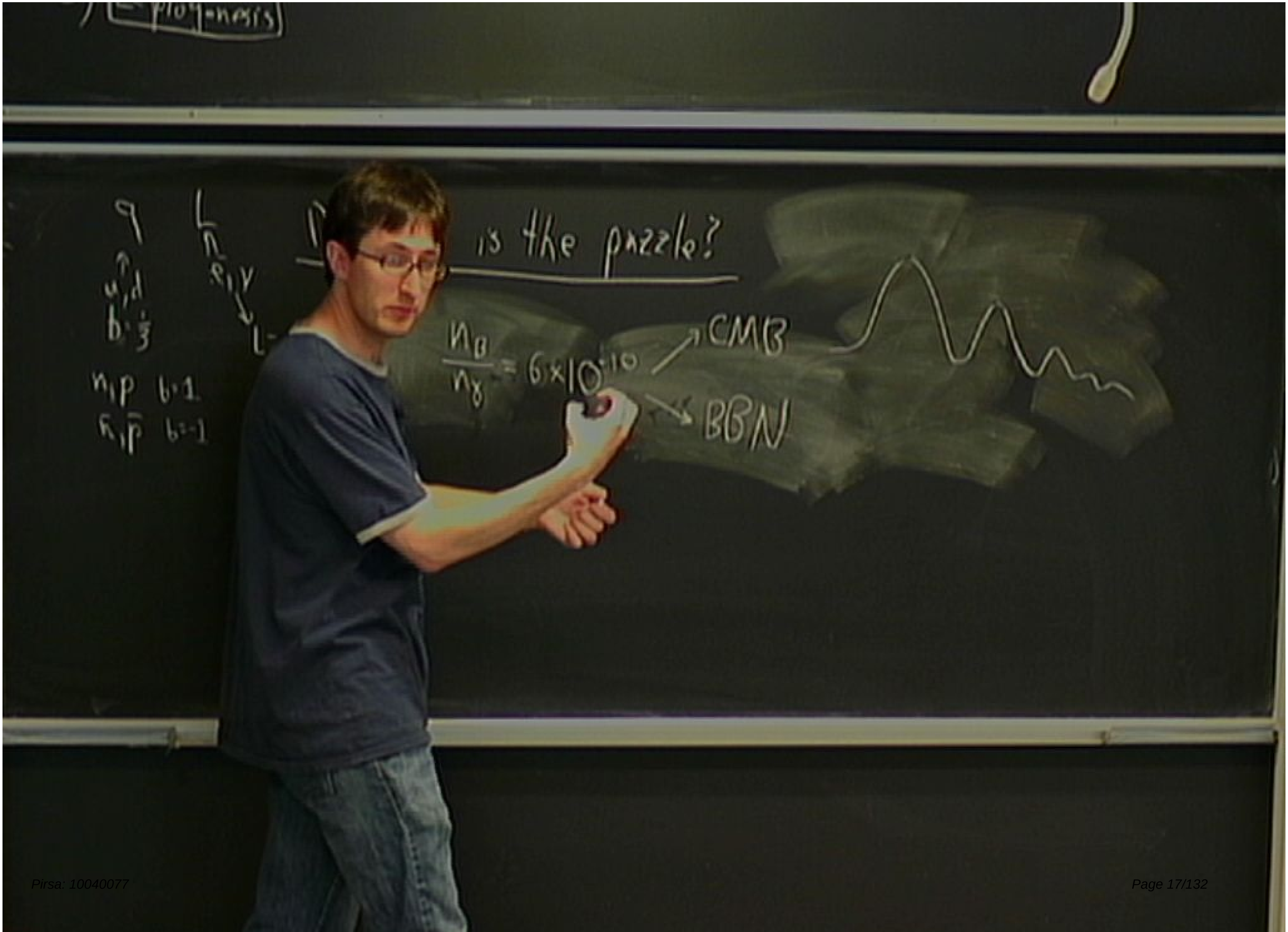
1) What is the puzzle?
q
L
u, d
b = 1/3
e, ν
L = +1
n, p b = 1
n̄, p̄ b = -1


1) What is the
FIRAS
L=+1

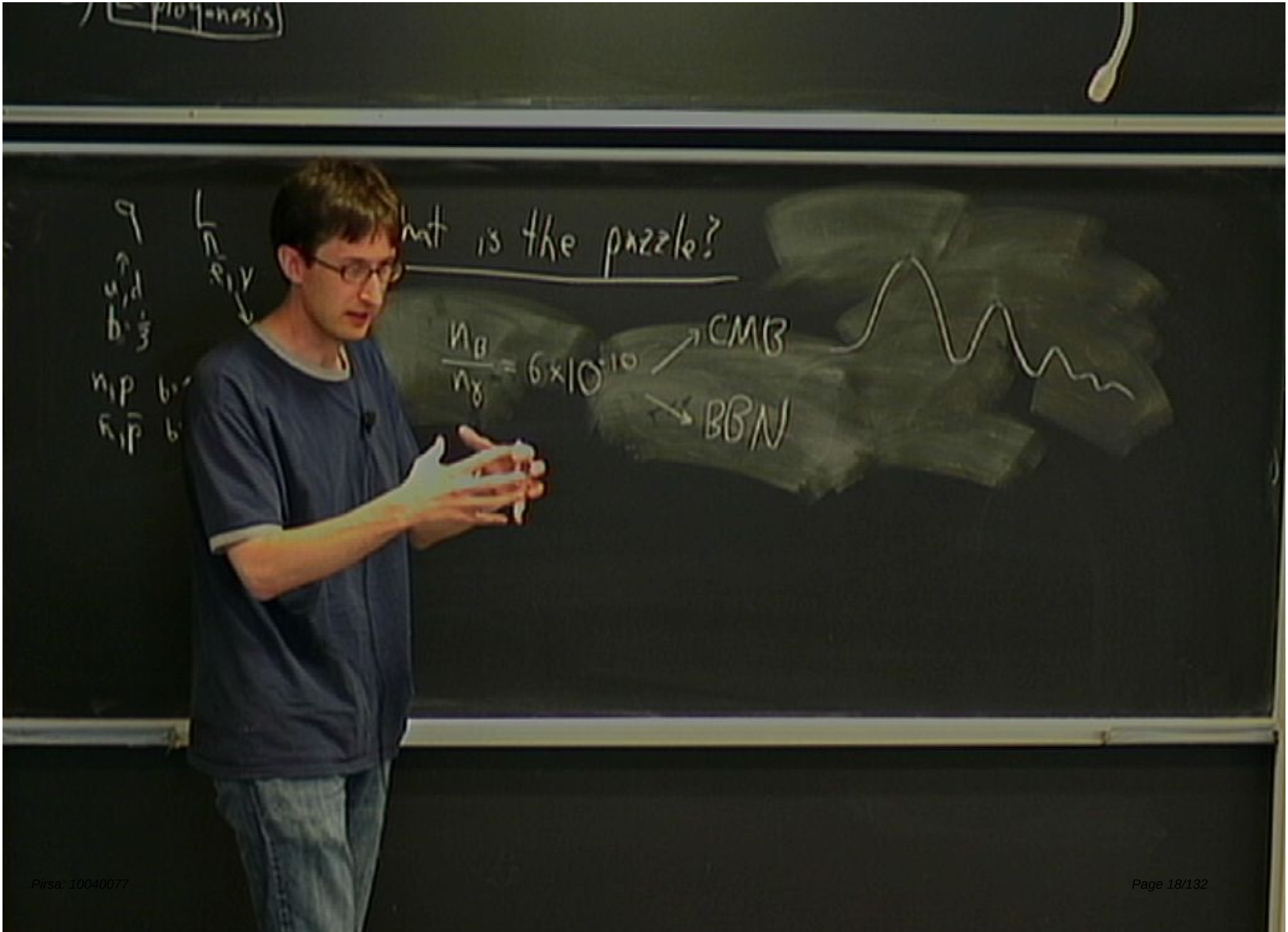

FIRAS
z~1000

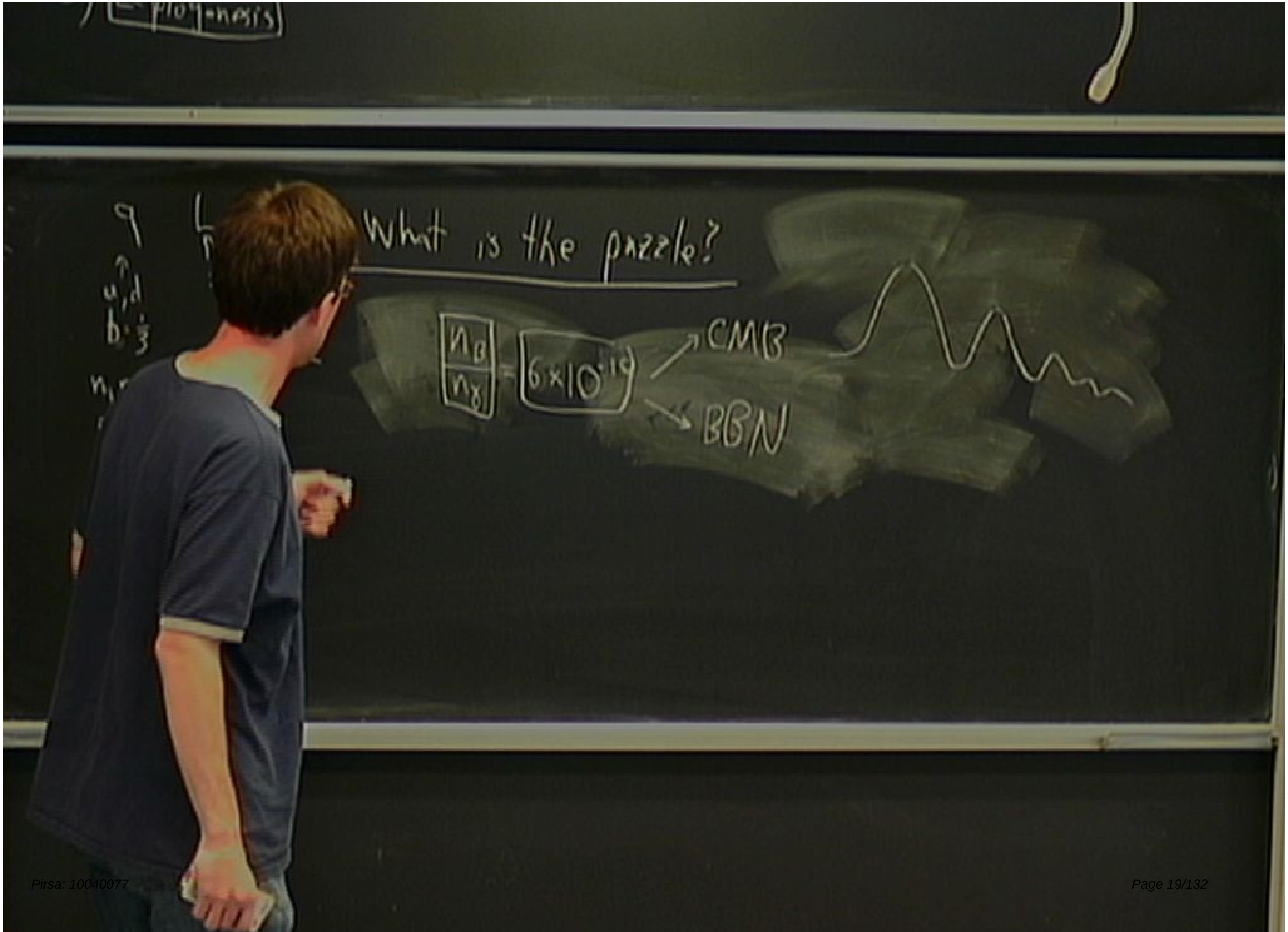

the puzzle?

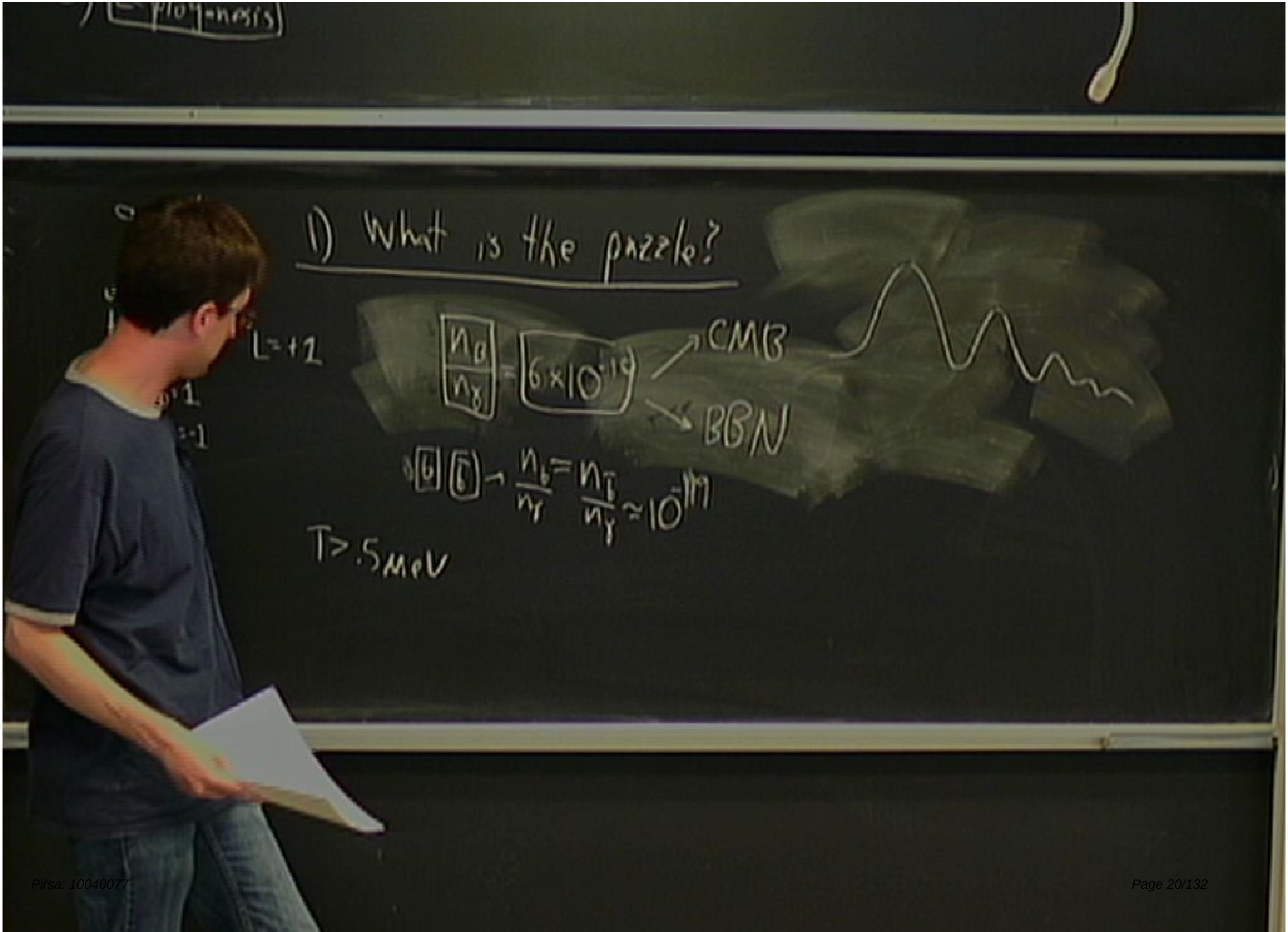

1) What is the puzzle?
L = +1
$\frac{n_B}{n_\gamma} = 6 \times 10^{-10}$

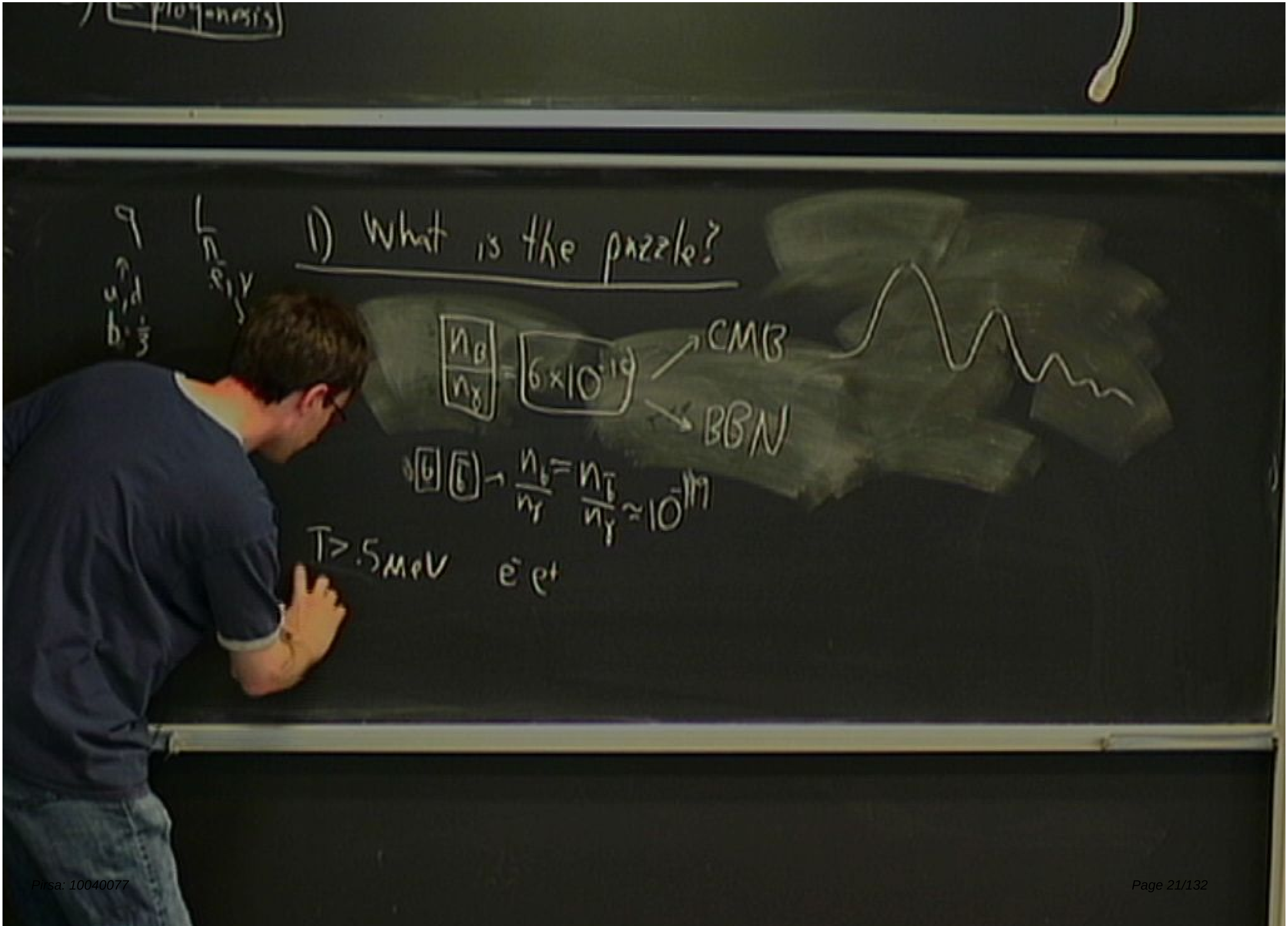


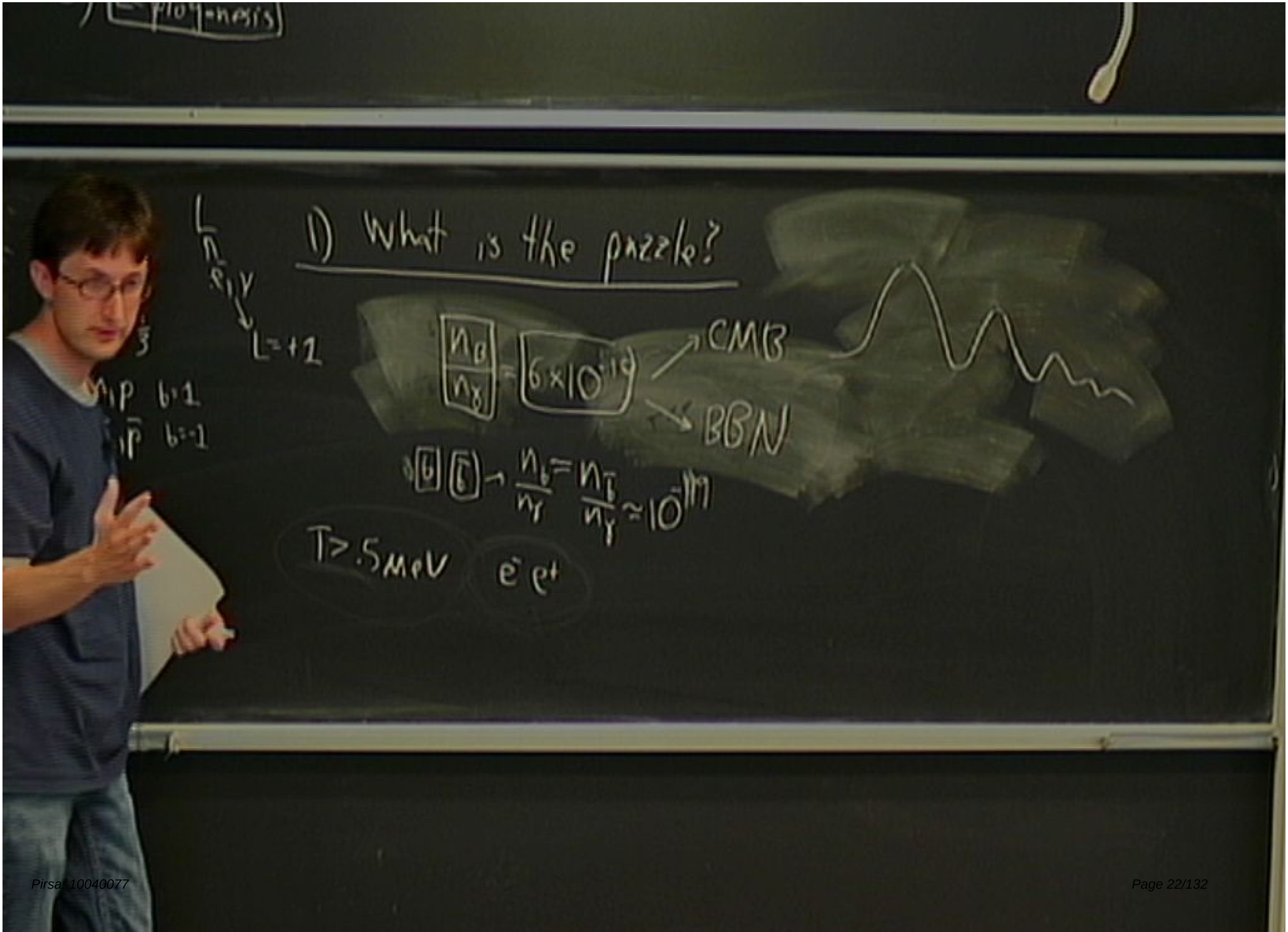
is the puzzle?
CMB
BBN
$\frac{n_B}{n_\gamma} = 6\times10^{-10}$

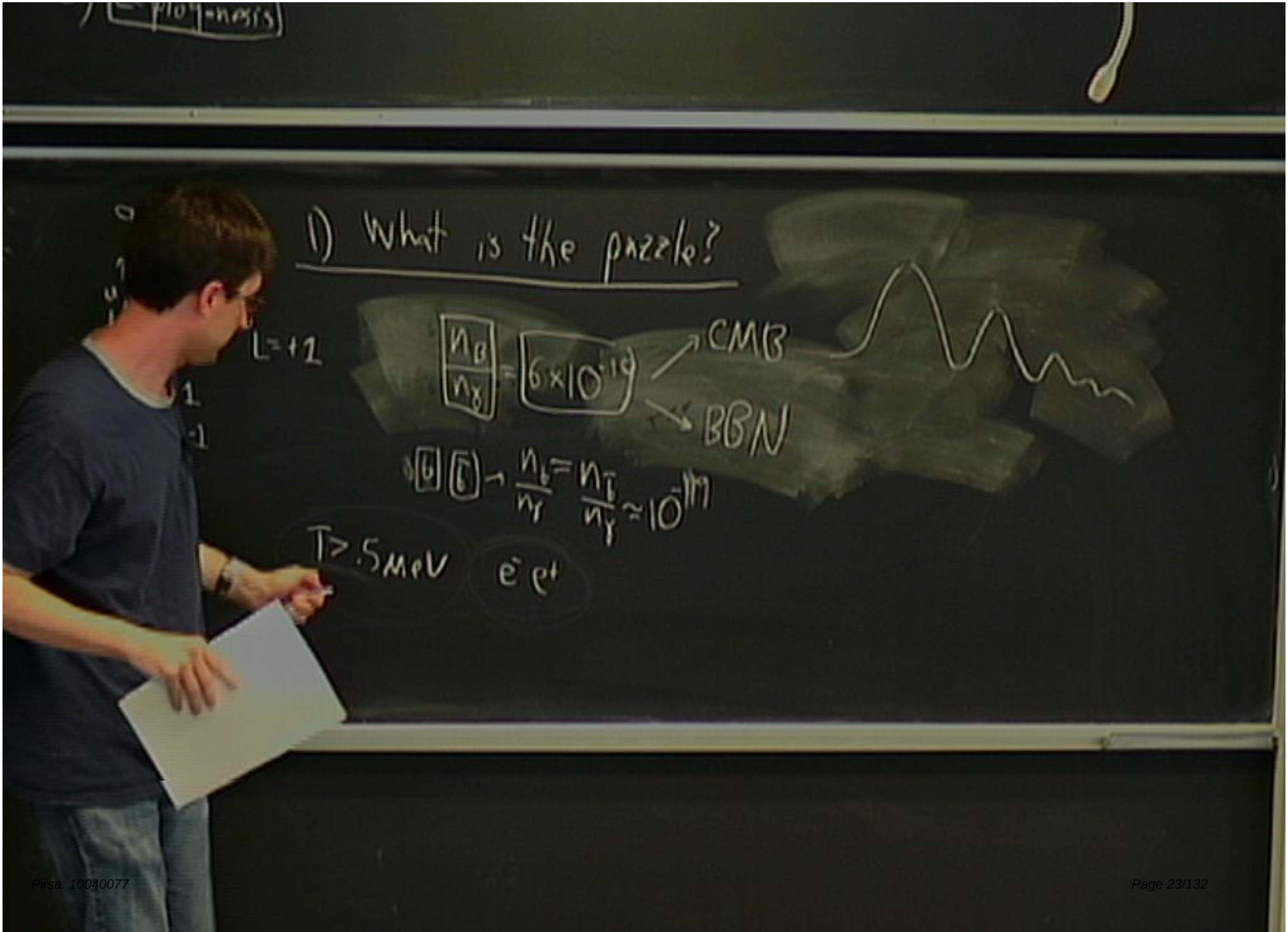

hat is the puzzle?
CMB
BBN

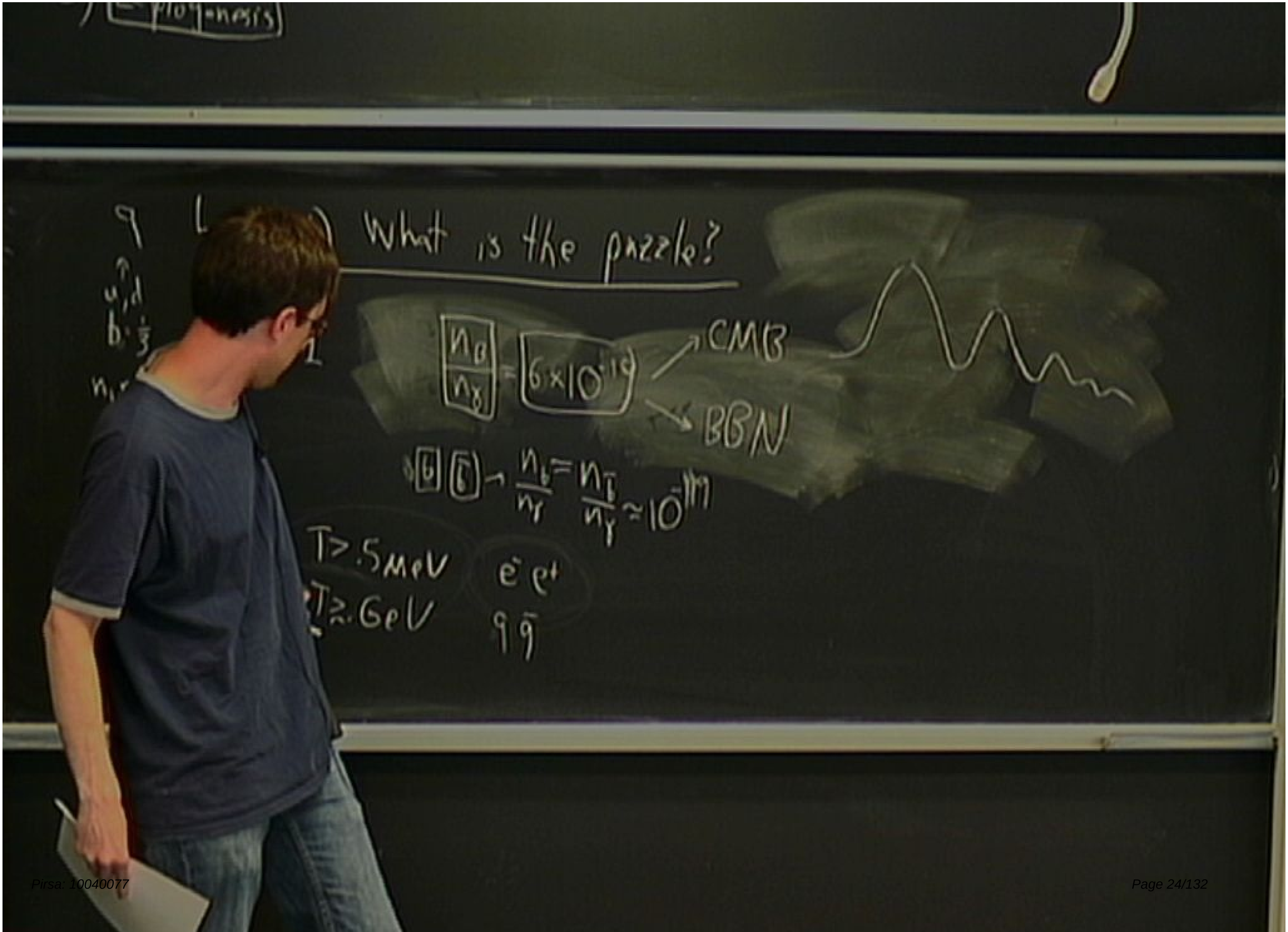

What is the puzzle?
nB
nγ
6×10-10
CMB
BBN


1) What is the puzzle?
L=+1
CMB
BBN
T>.5MeV

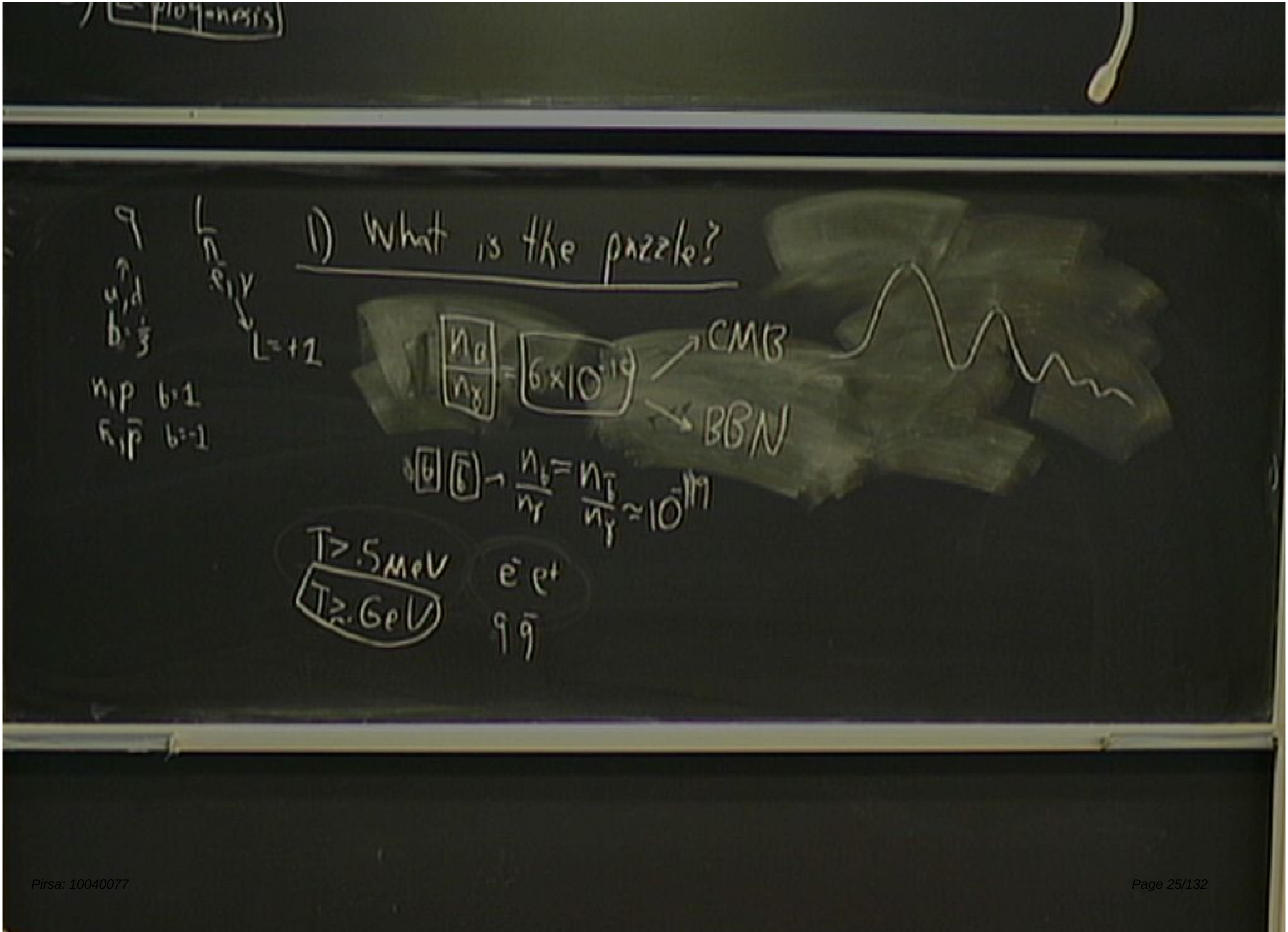

1) What is the puzzle?
CMB
BBN
T>.5MeV

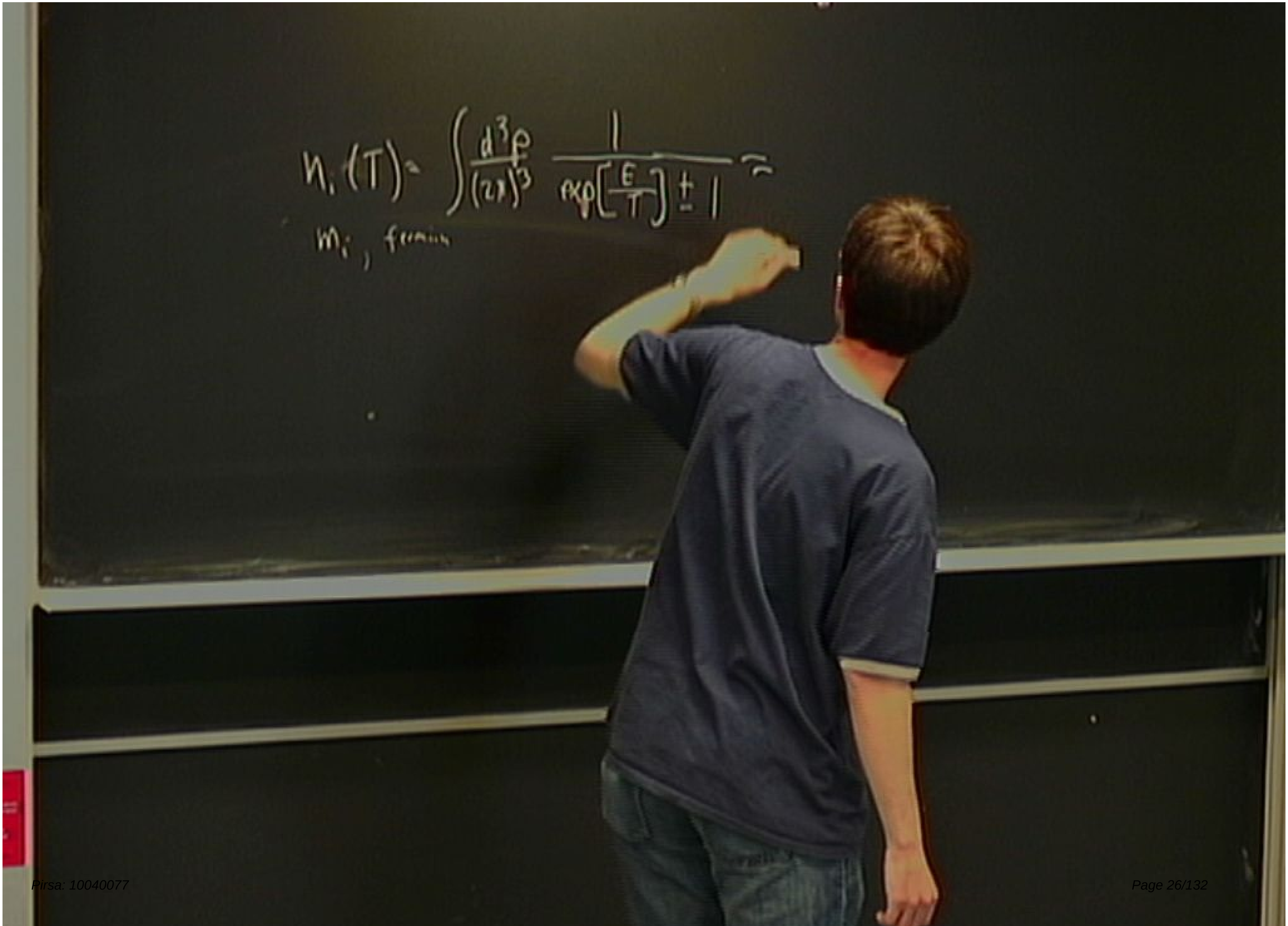

1) What is the puzzle?
CMB
BBN
L = +1
T > .5 MeV
e⁻ e⁺

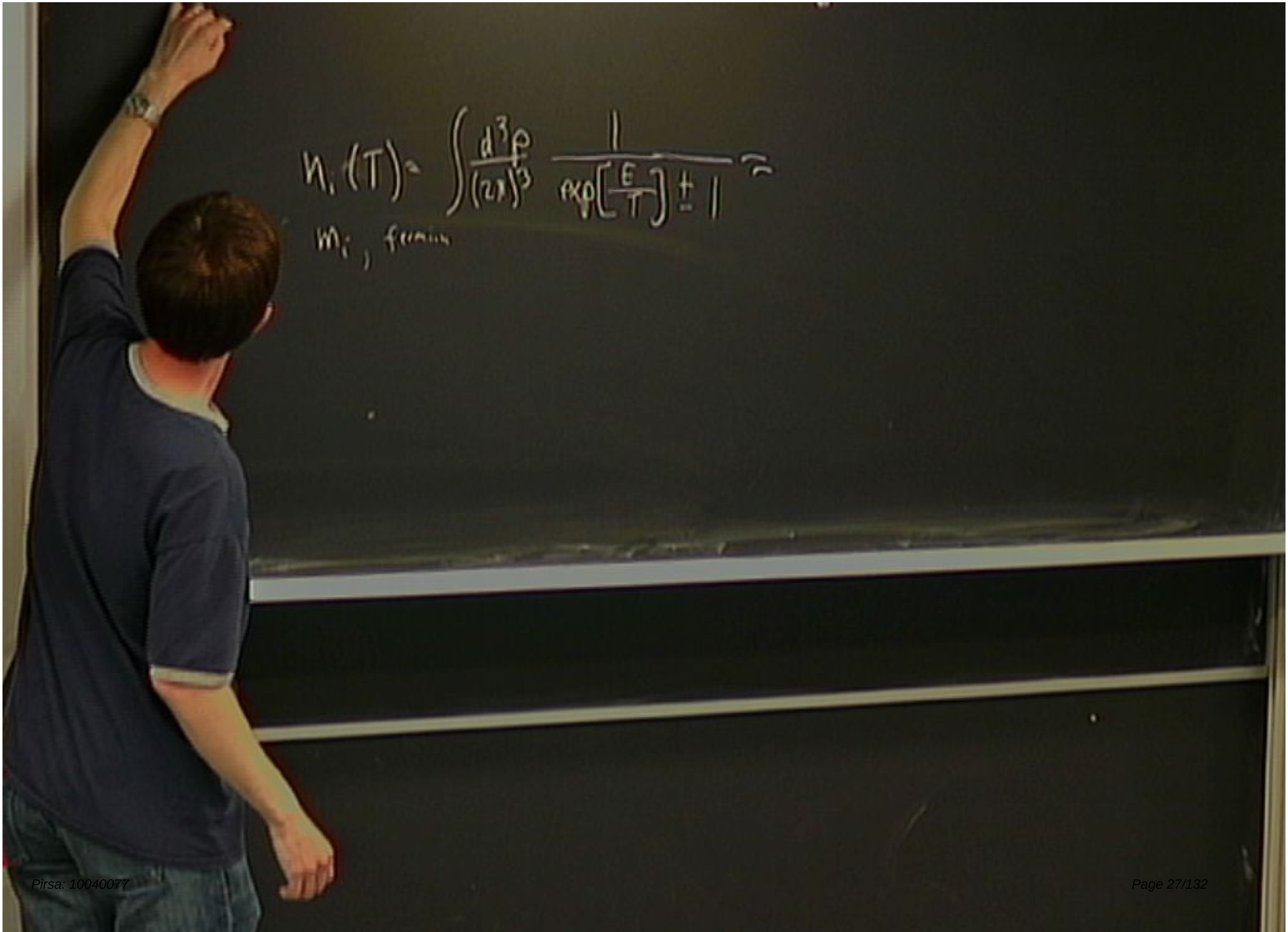

1) What is the puzzle?
L=+1
CMB
BBN
T>.5MeV
e- e+

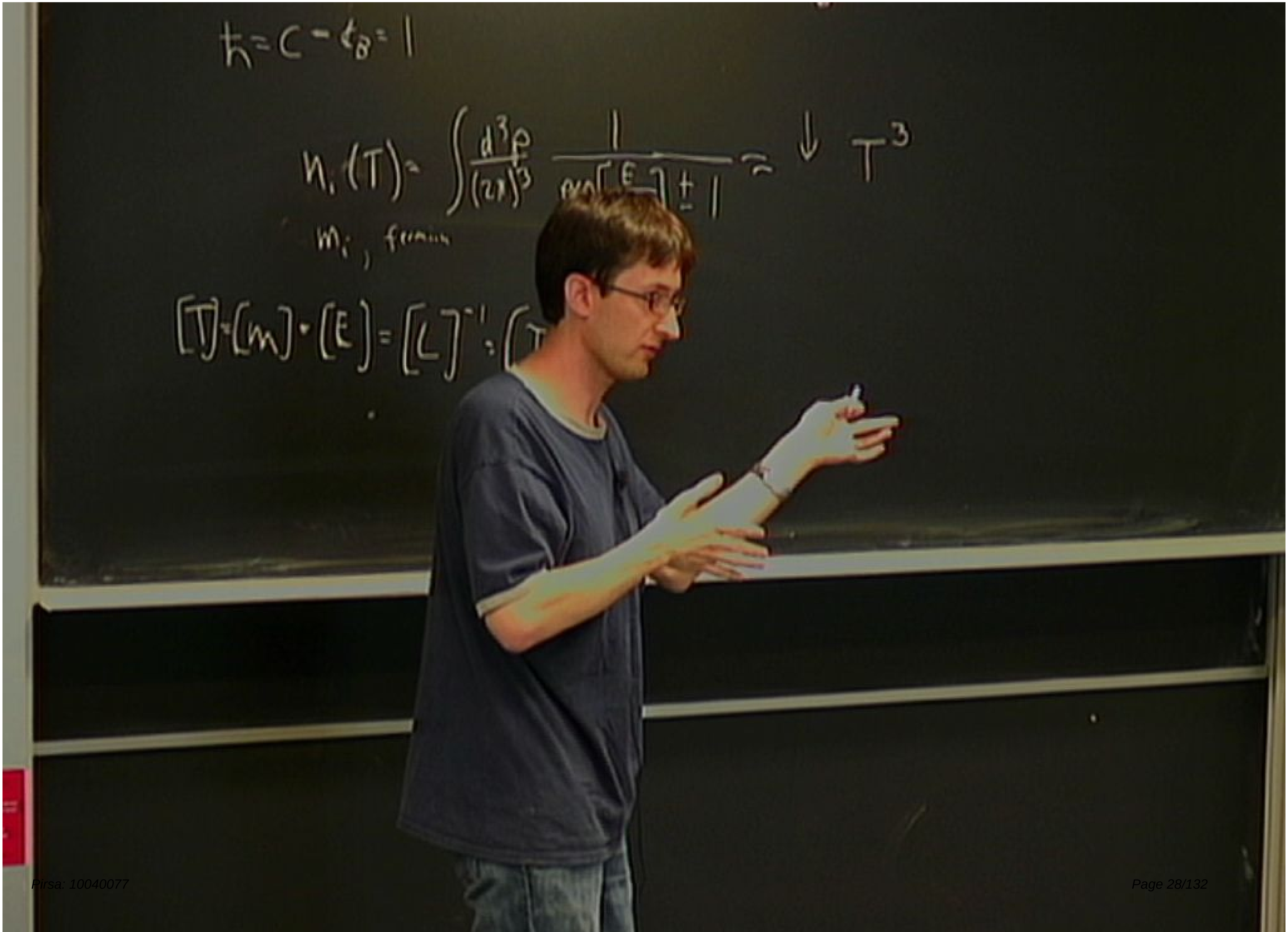


What is the puzzle?
CMB
BBN
T > .5 MeV
T ≳ GeV


1) What is the puzzle?
CMB
BBN
L = +1
n, p b=1
T > .5 MeV
T ≳ GeV
e⁻ e⁺
q q̄


$n_i(T) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left[\frac{E}{T}\right] \pm 1} \approx$
m_i, fermion


$n_i(T) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left[\frac{E}{T}\right] \pm 1} \simeq$
m_i , fermion

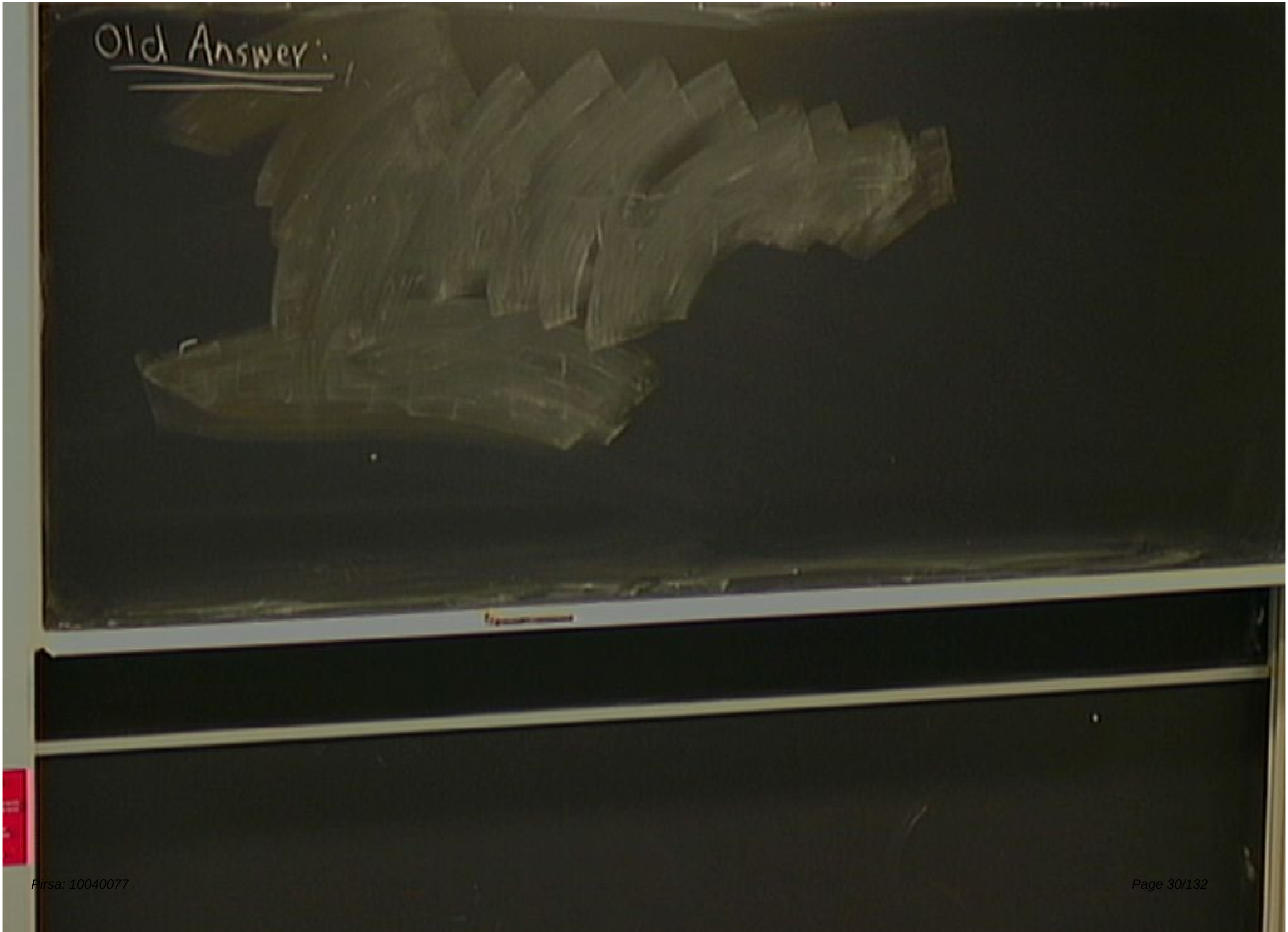

ħ = c = k_B = 1
n_i(T) = ∫ d³p/(2π)³ 1/(exp[E ...] ± 1) ≈ T³
m_i , fermion
[T] = [m] = [E] = [L]⁻¹ = [T

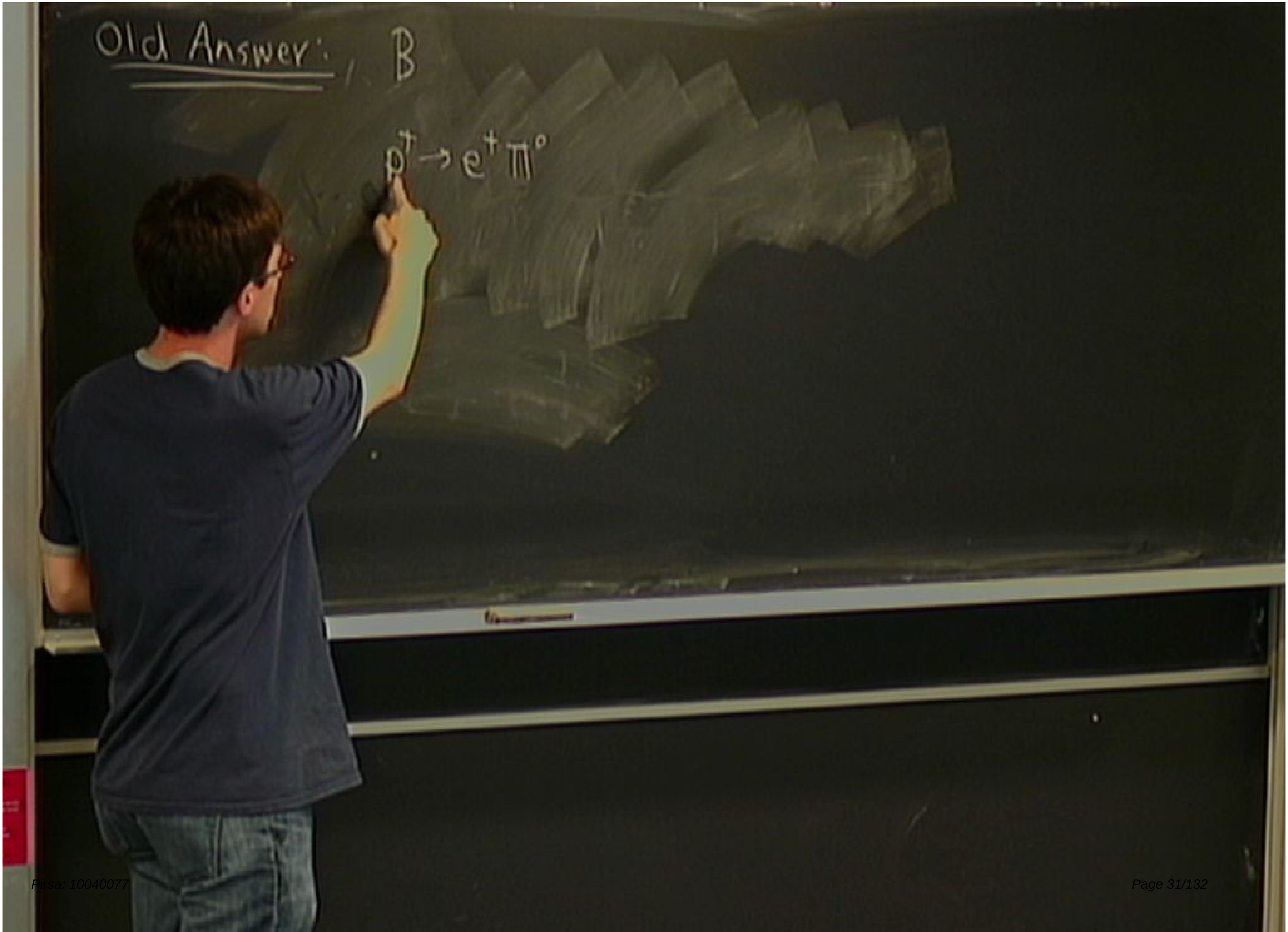
$\hbar = c = k_B = 1$

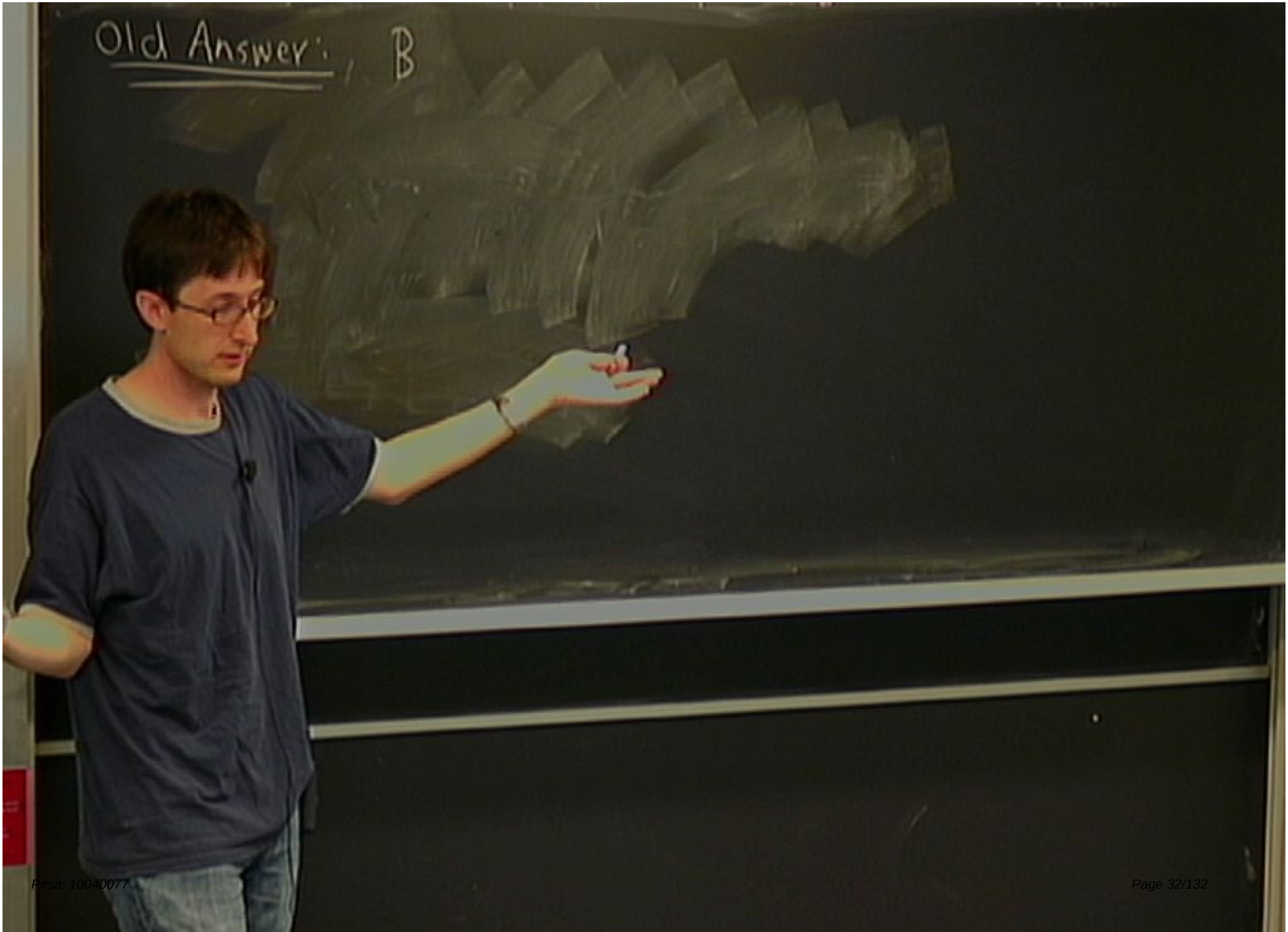
$$n_i(T) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left[\frac{E}{T}\right] \pm 1} \simeq \downarrow T^3$$

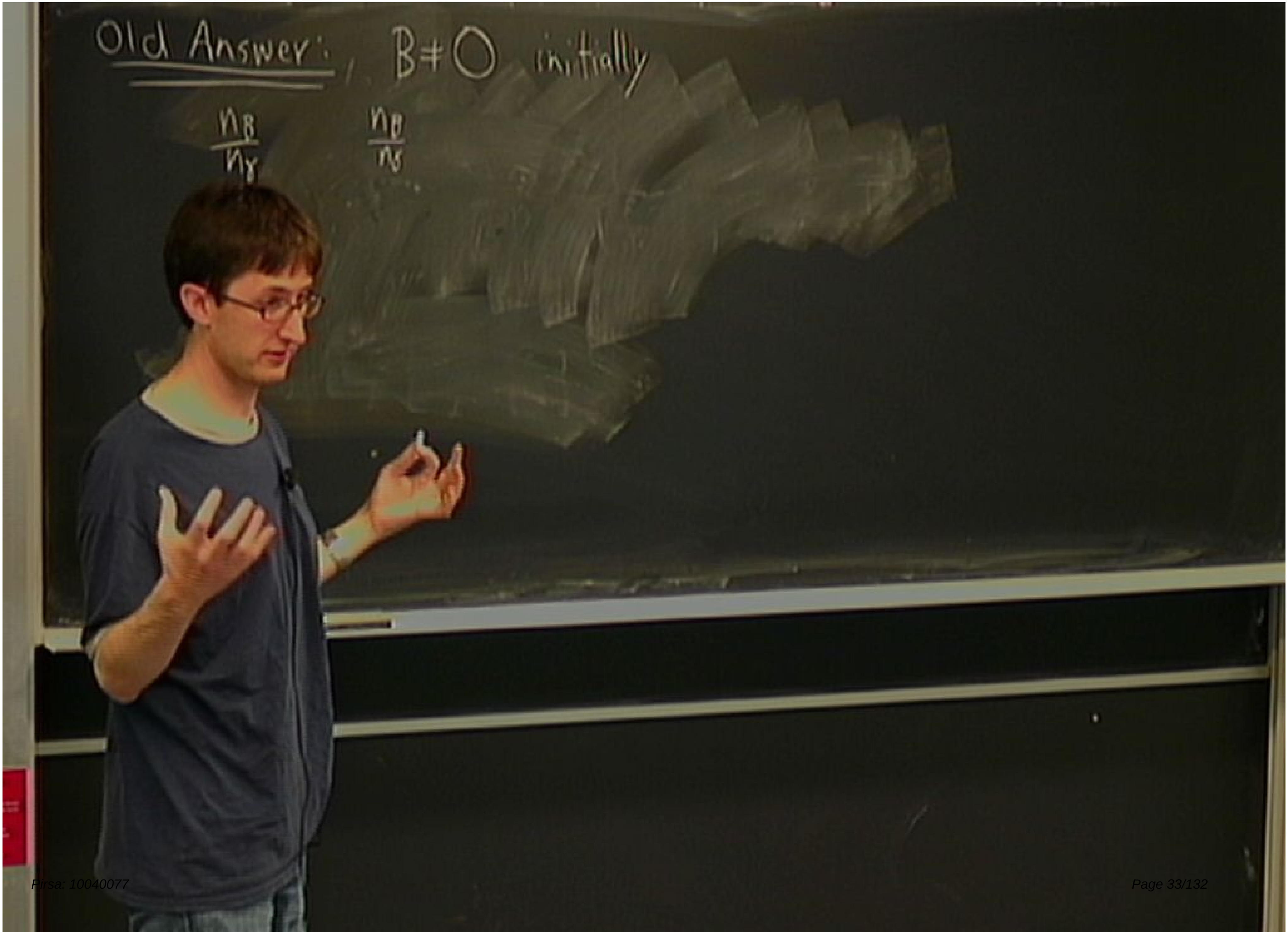
m_i, fermion

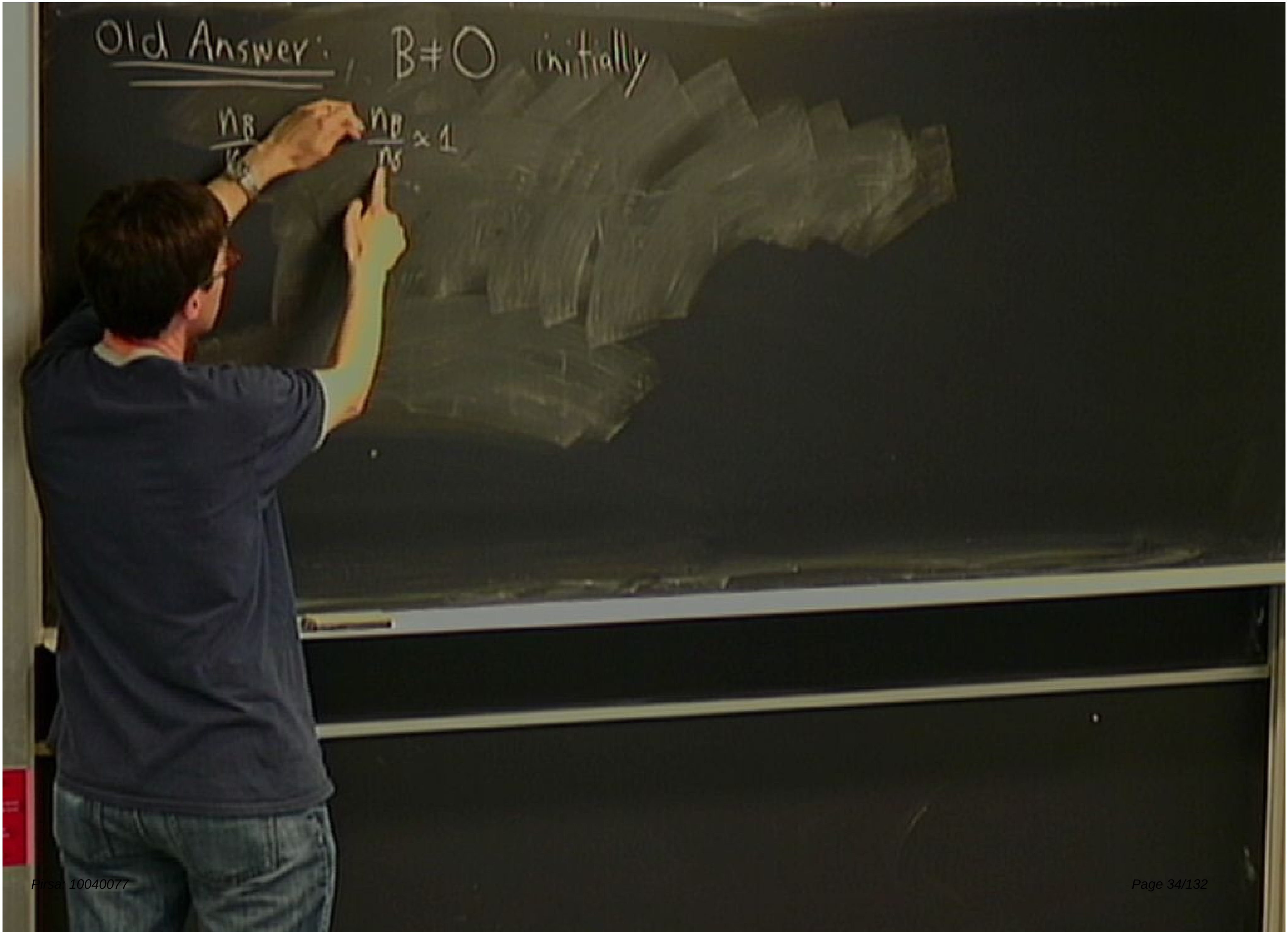
$$[T] = [m] = [E] = [L]^{-1} = (T)^{-1}$$

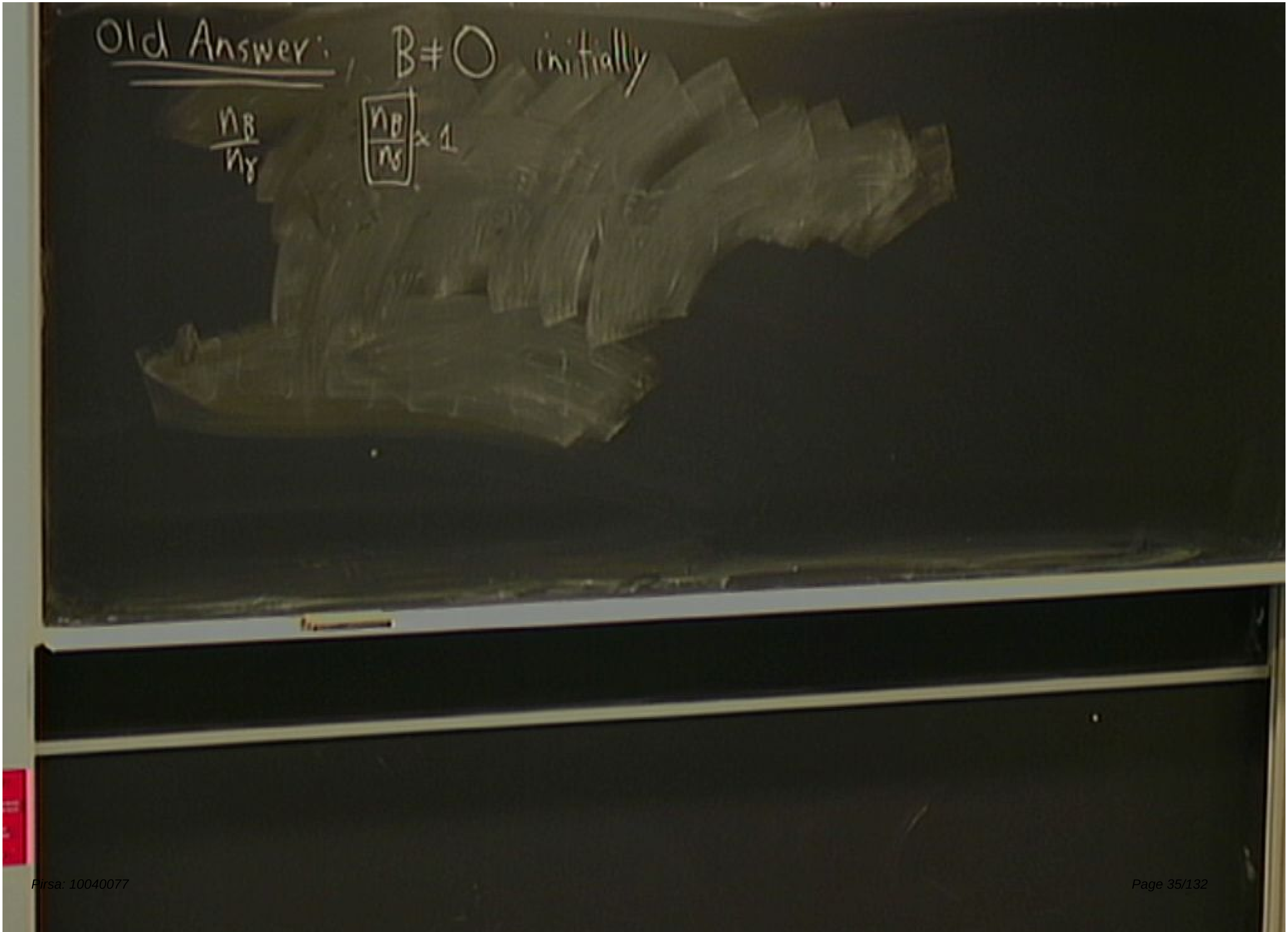

Old Answer:

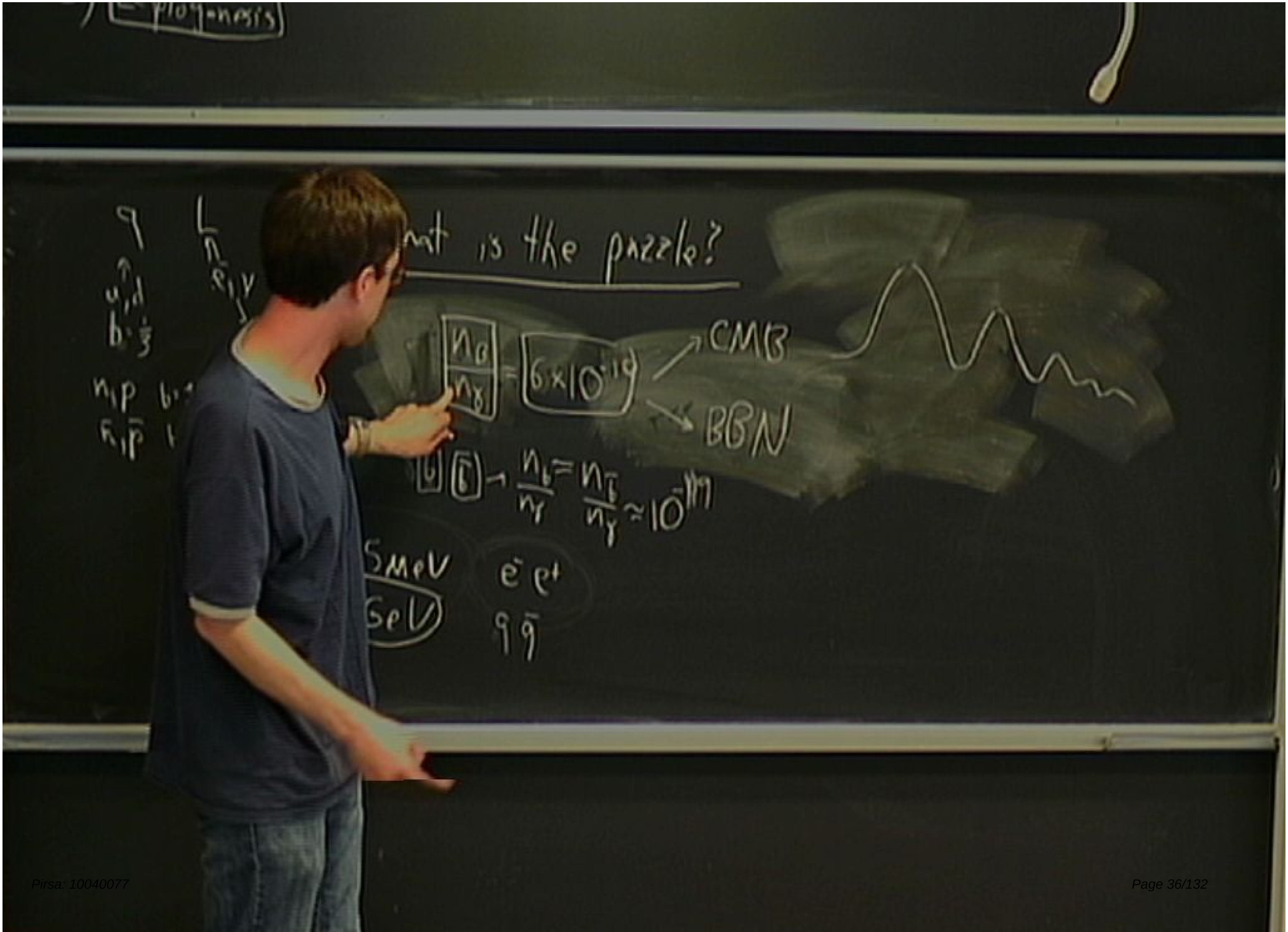

Old Answer: B
$p^+ \to e^+ \pi^0$

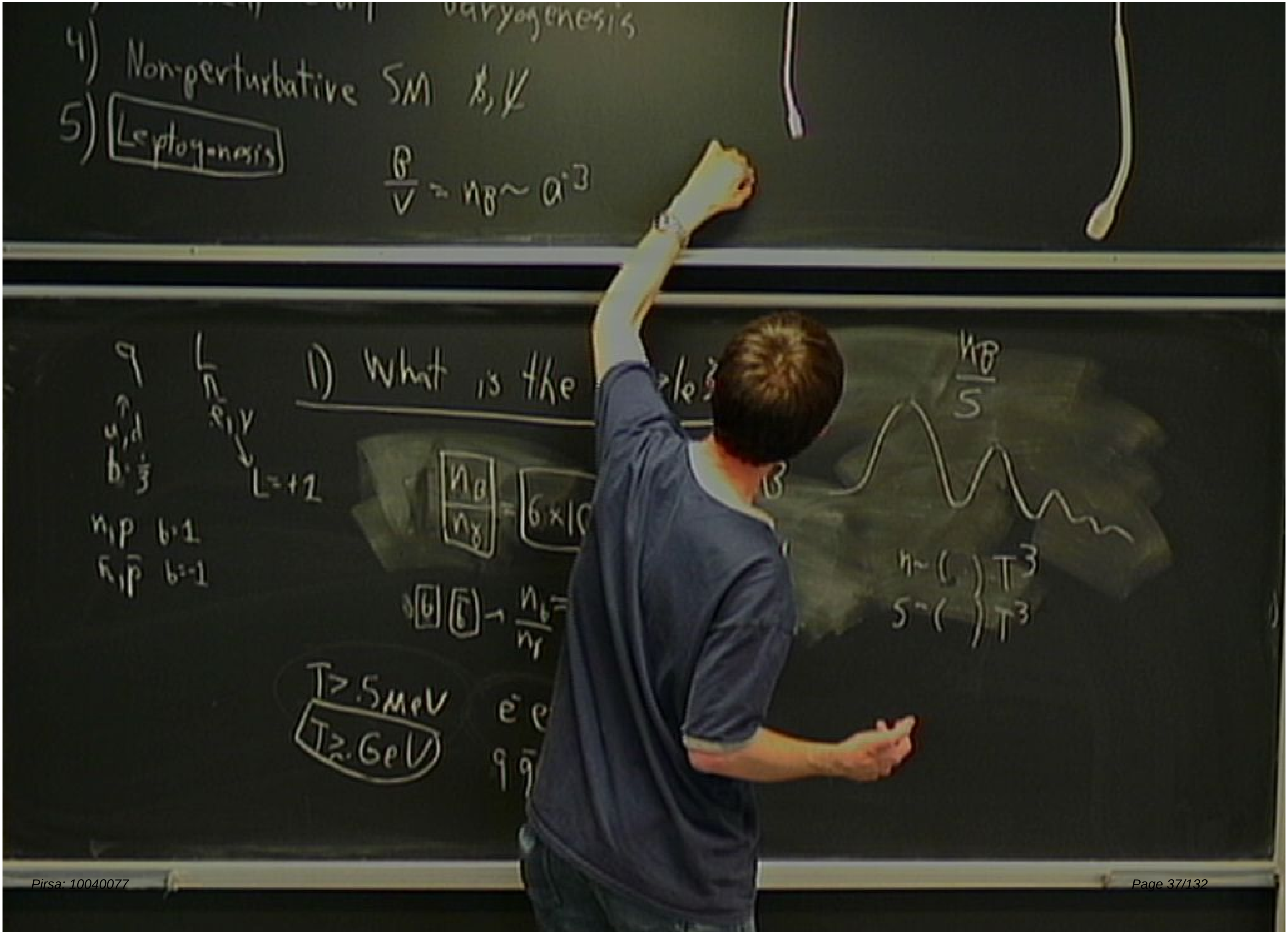

Old Answer: B


Old Answer: B≠0 initially
nB/nγ
nB/nγ

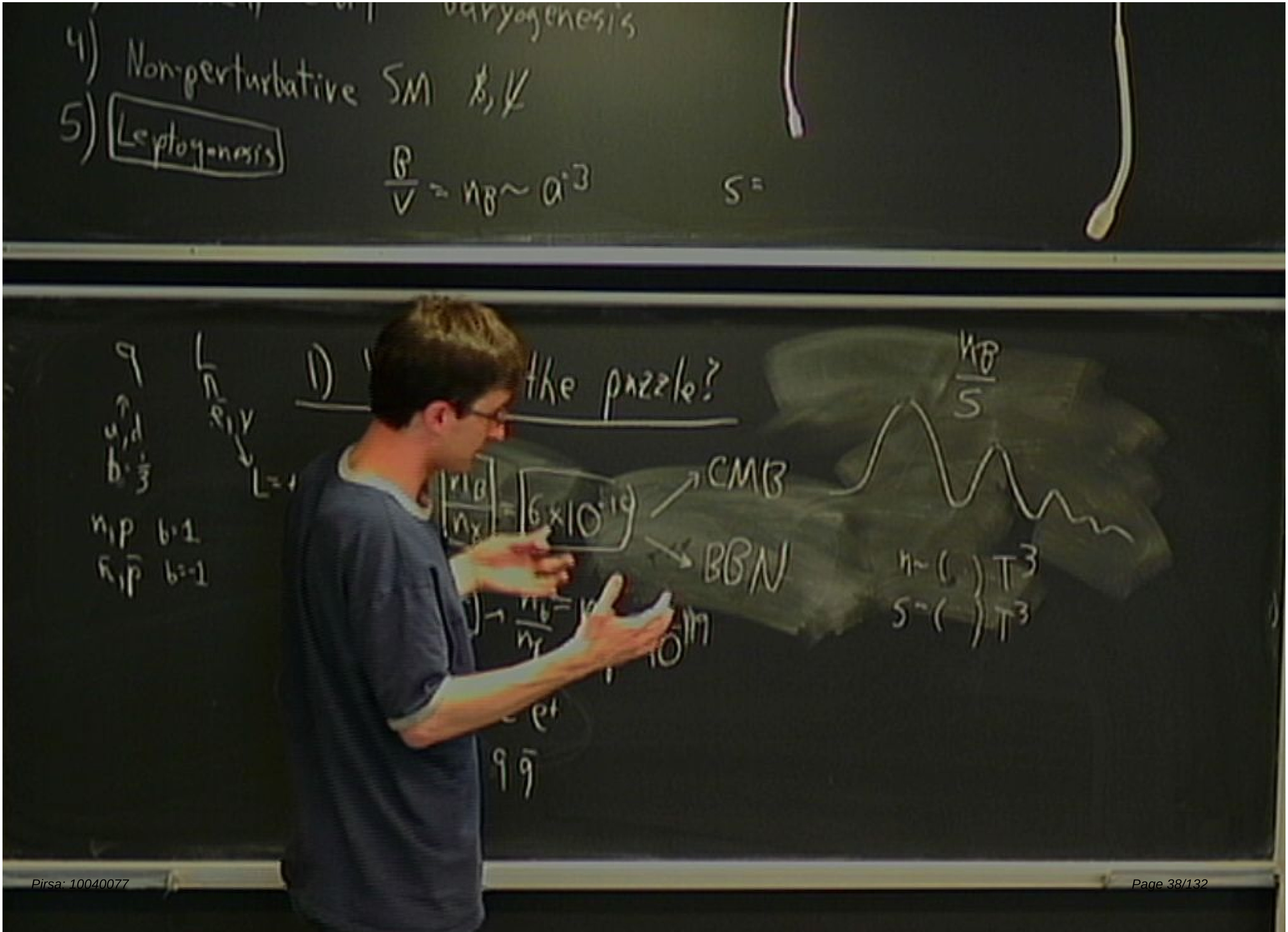

Old Answer: B≠0 initially

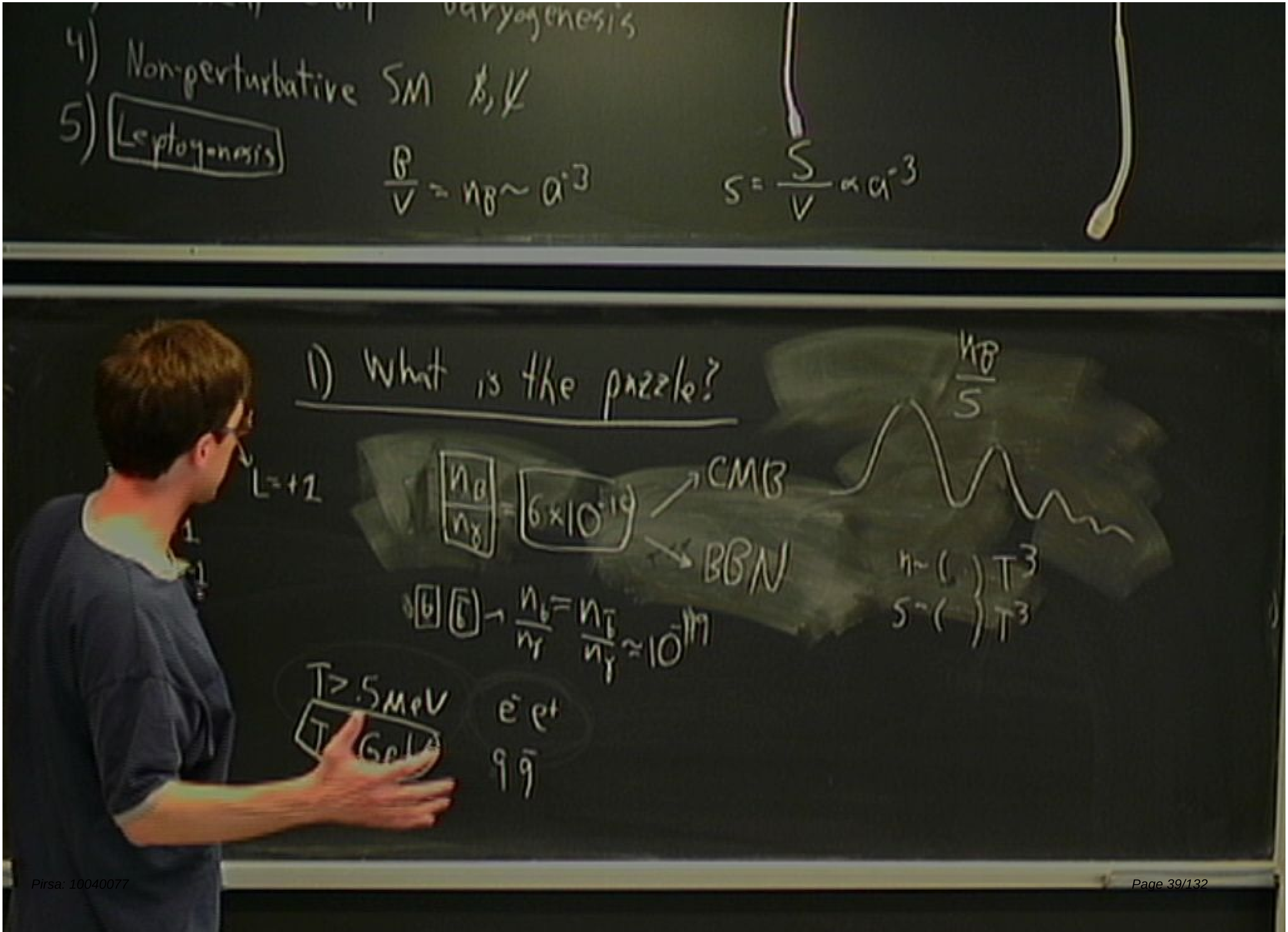

Old Answer: B ≠ 0 initially
$\frac{n_B}{n_\gamma}$
$\frac{n_B}{n_\gamma} \approx 1$

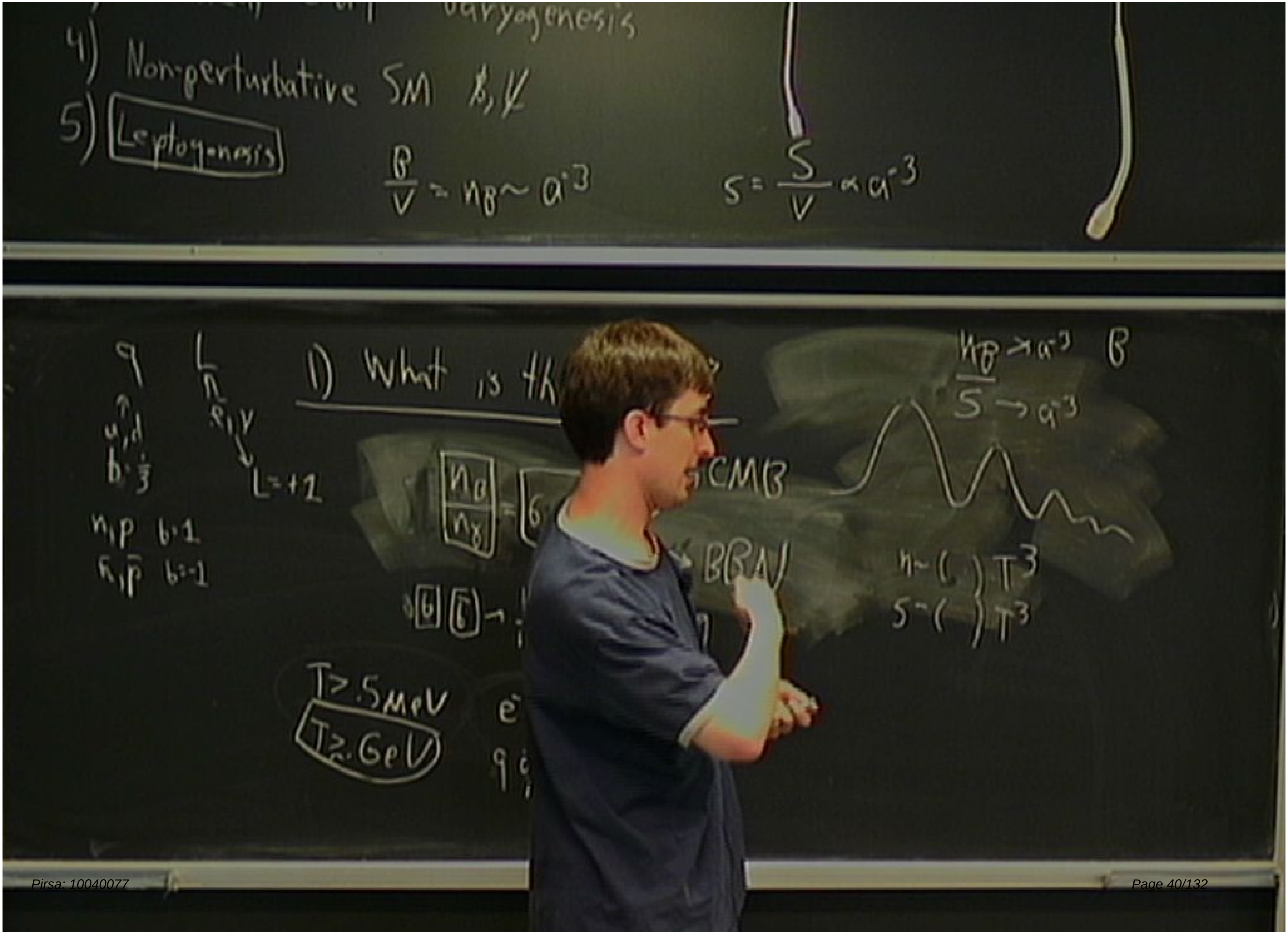

is the puzzle?
CMB
BBN
5MeV
GeV



Baryogenesis
4) Non-perturbative SM
5) Leptogenesis
1) What is the
L = +1
n, p b = 1
T ≳ .5 MeV
T ≳ GeV
n ~ ( ) T3
s ~ ( ) T3


baryogenesis
4) Non-perturbative SM
5) Leptogenesis
the puzzle?
CMB
BBN


4) Non-perturbative SM B, CP
5) Leptogenesis
B/V = n_B ~ a^-3
s = S/V ∝ a^-3
1) What is the puzzle?
n_B/n_γ = 6×10^-10
CMB
BBN
n_B/s
n ~ ( ) T^3
s ~ ( ) T^3
L = +1
T > .5 MeV
e^- e^+
q q̄


4) Non-perturbative SM
5) Leptogenesis
s =
1) What is th
CMB
BBN
T ≳ .5 MeV
T ≳ .GeV
L = +1
b = 1
b = -1

baryogenesis

4) Non-perturbative SM $\not{B}$, $\not{V}$

5) Leptogenesis

$$\frac{B}{V} = n_B \sim a^{-3} \qquad s = \frac{S}{V} \propto a^{-3}$$

q L

1) What is the puzzle?

u, d e, ν

$b = \frac{1}{3}$ $L = +1$

n, p $b = 1$

$\bar{n}, \bar{p}$ $b = -1$

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \rightarrow \text{CMB}, \ \text{BBN}$$

$$\frac{n_B}{S} \rightarrow \frac{a^{-3}}{a^{-3}} \quad B$$

$\tau_d < H^{-1}$

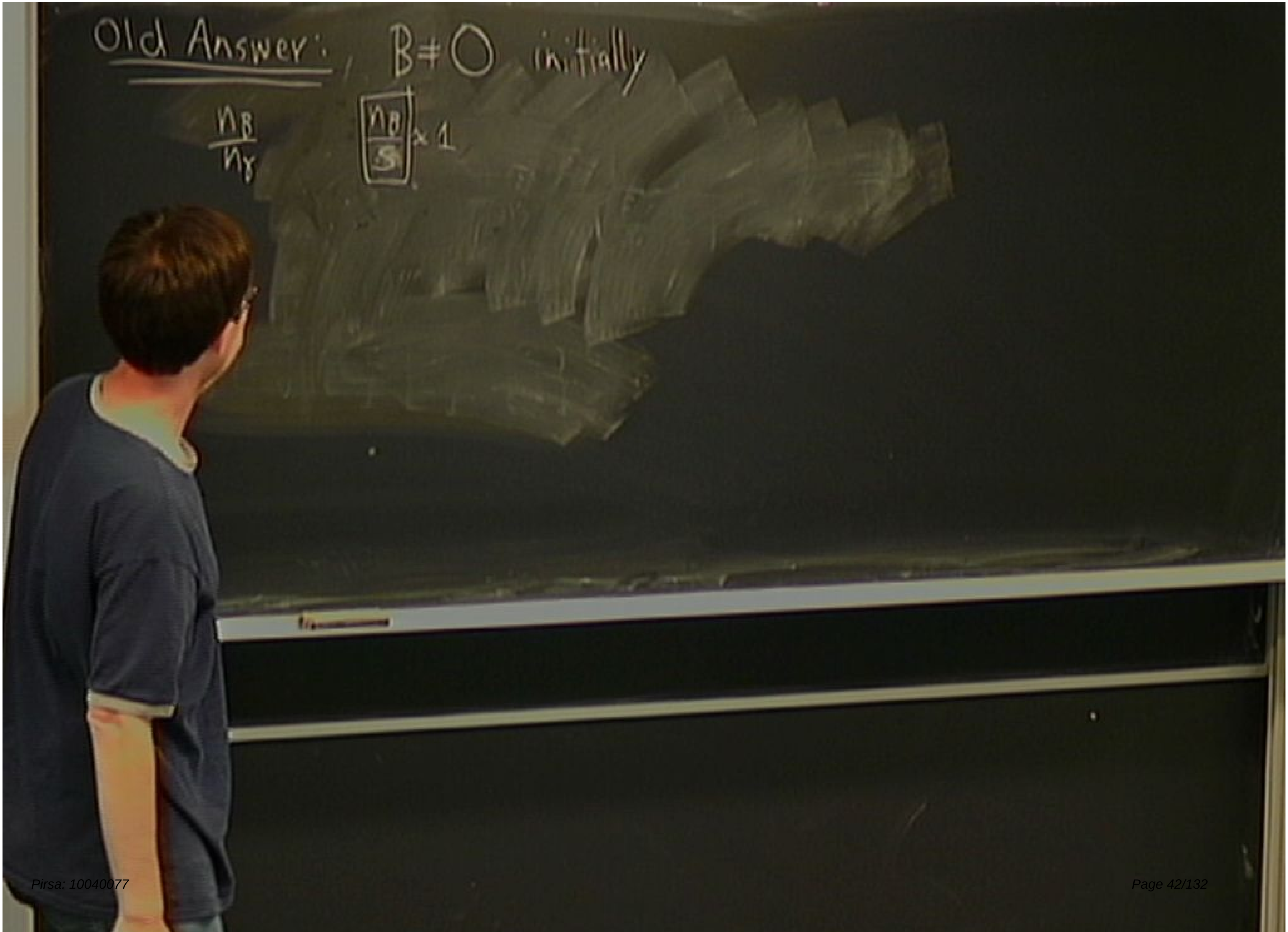
$n \sim (\ ) T^3$

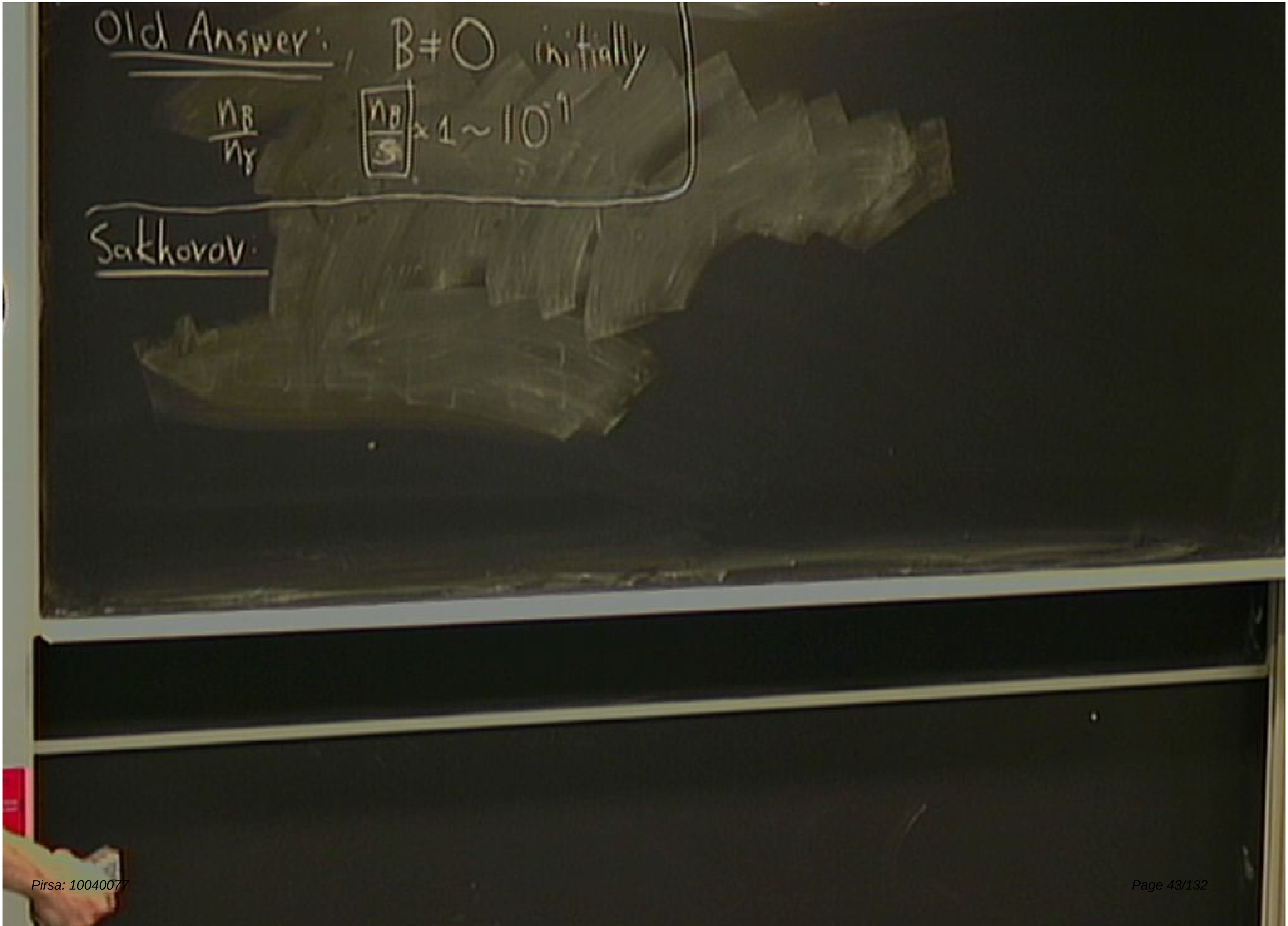
$s \sim (\ ) T^3$

$b \ \bar{b} \rightarrow \frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n_\gamma} \simeq 10^{-19}$

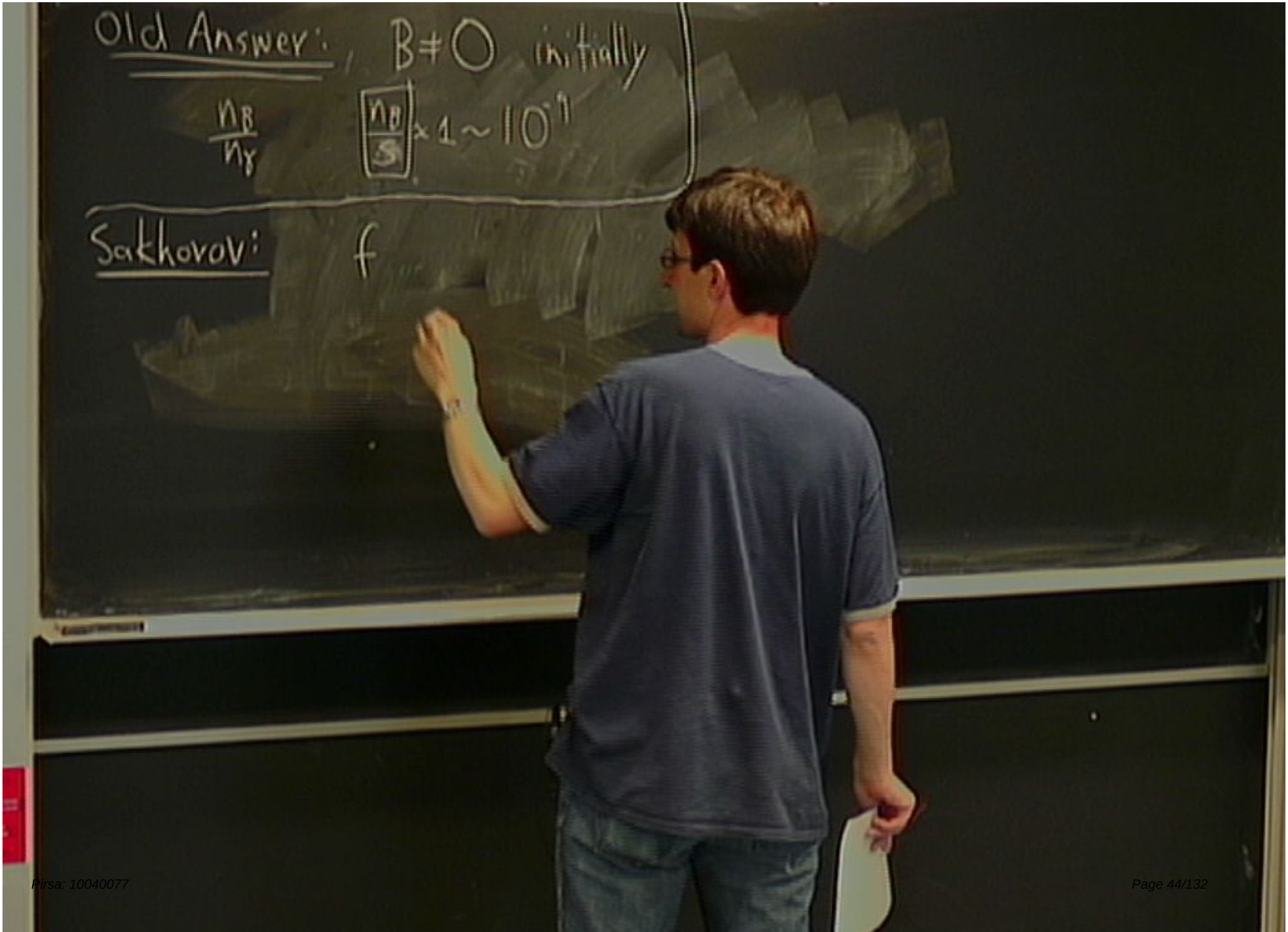
$T \gtrsim .5\,\text{MeV}$ $e^- e^+$

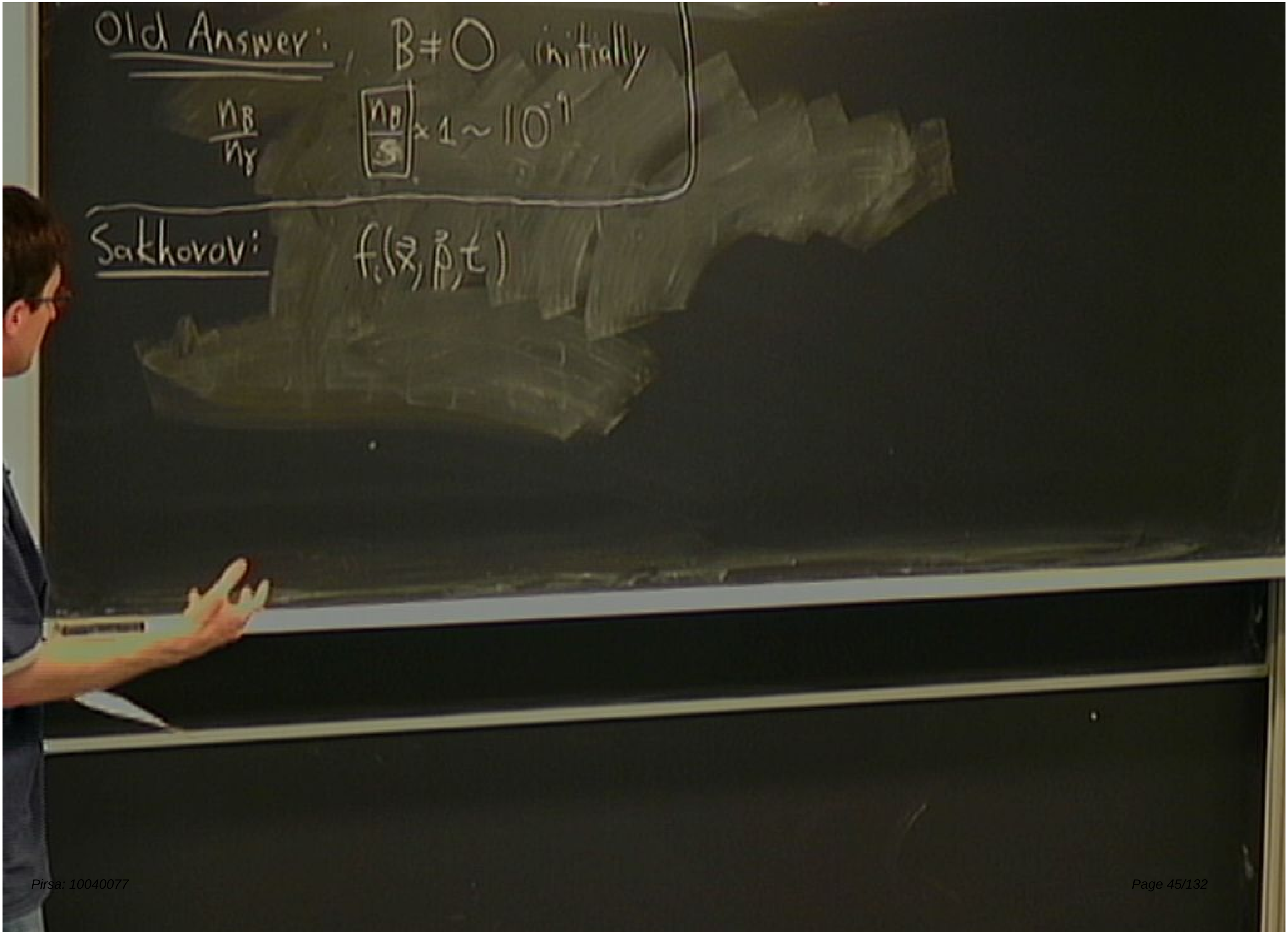
$T \gtrsim .\text{GeV}$ $q \bar{q}$

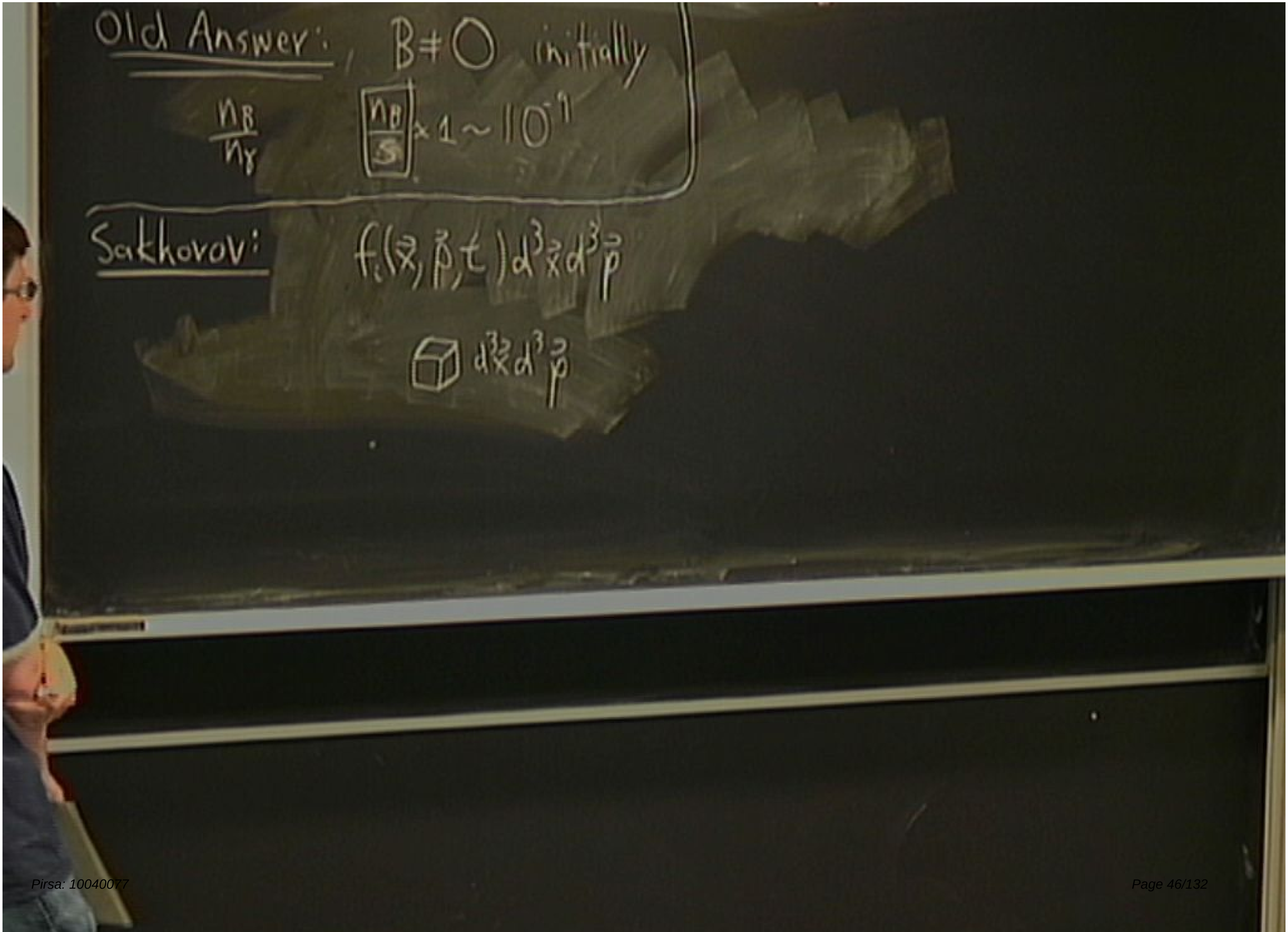

Old Answer: B ≠ 0 initially
$\frac{n_B}{n_\gamma}$
$\frac{n_B}{s} \times 1$

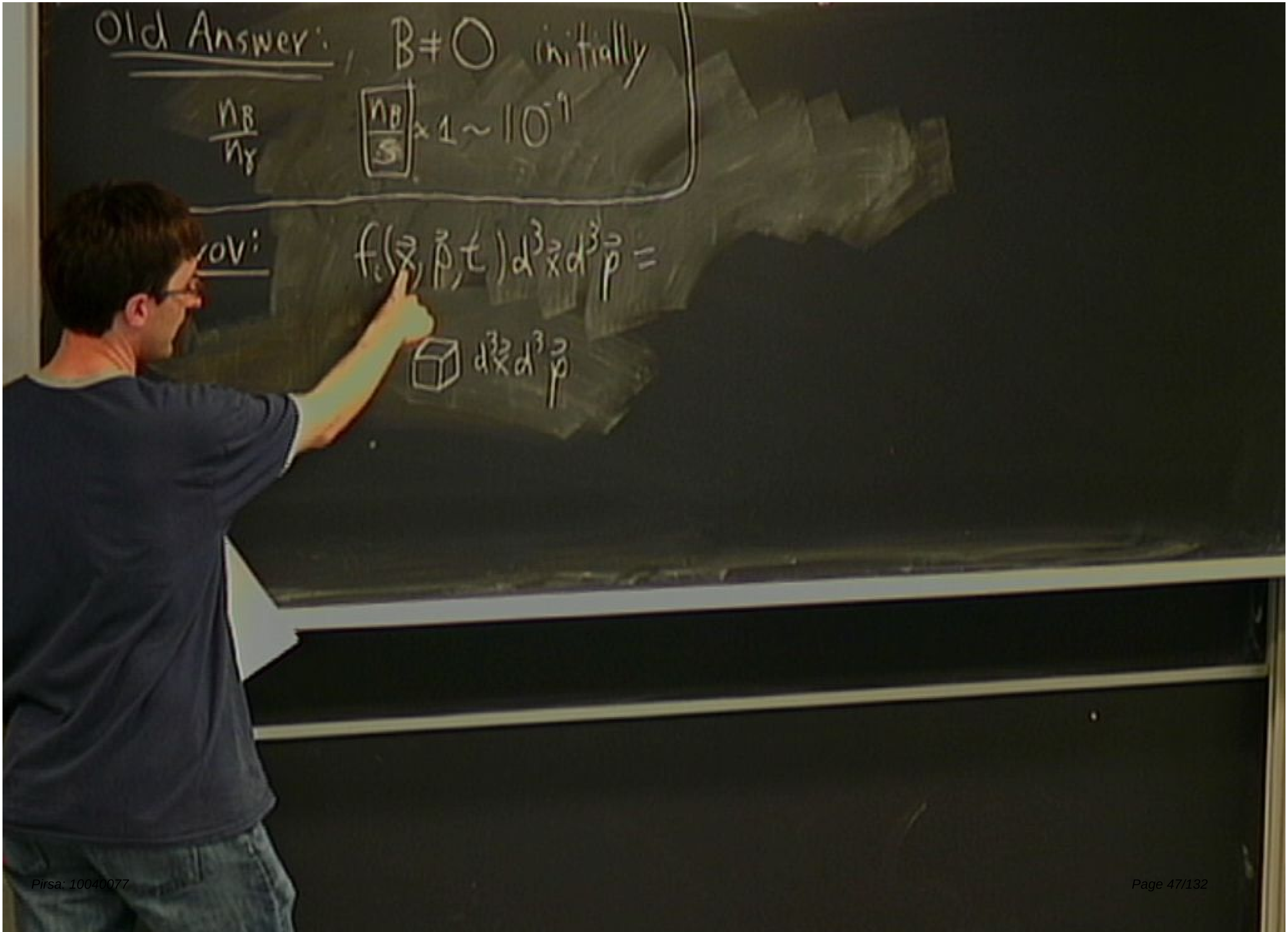


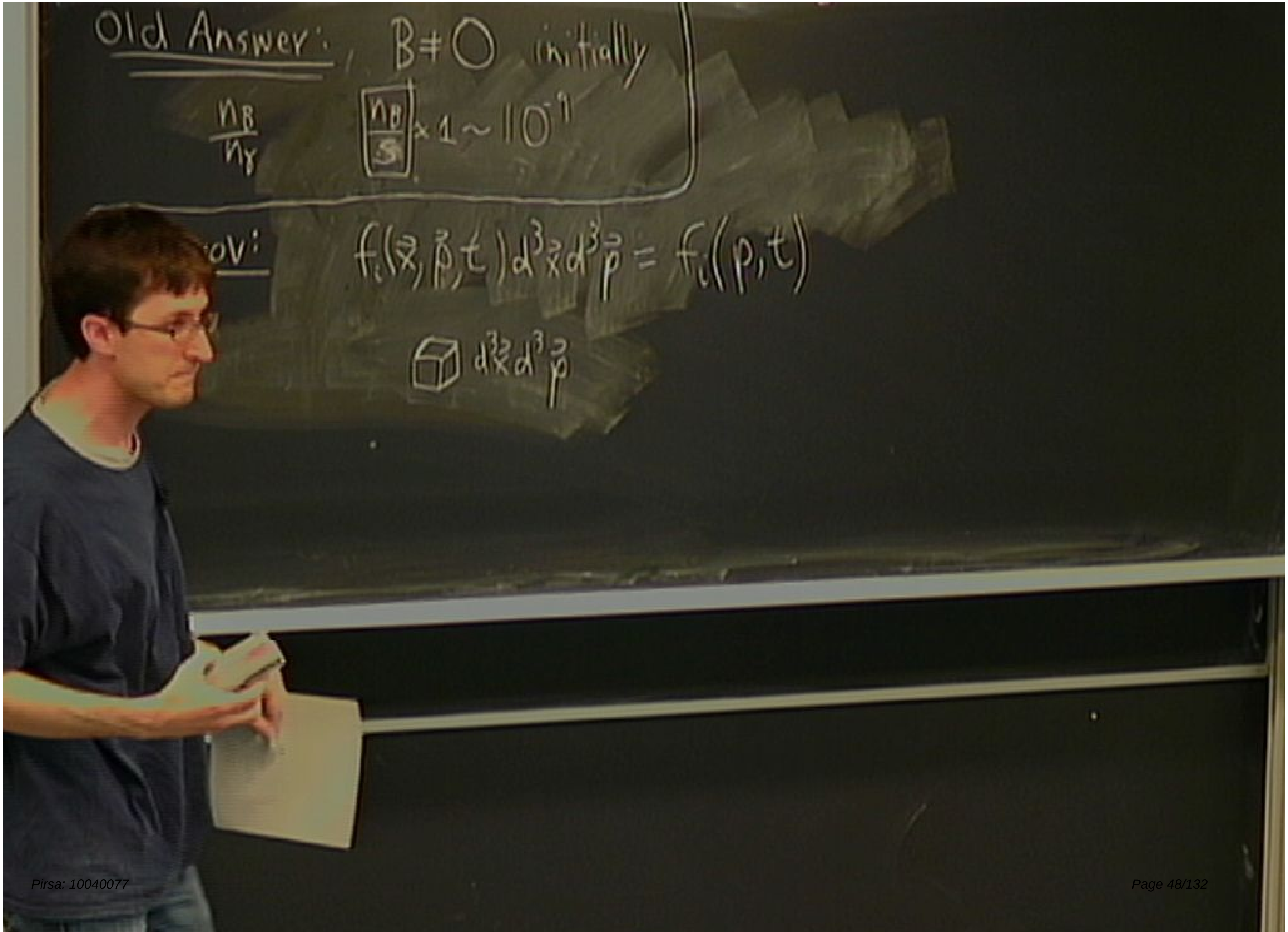
Old Answer:
B ≠ 0 initially
$\frac{n_B}{n_\gamma}$
$\frac{n_B}{s} \times 1 \sim 10^{-9}$
Sakhorov:

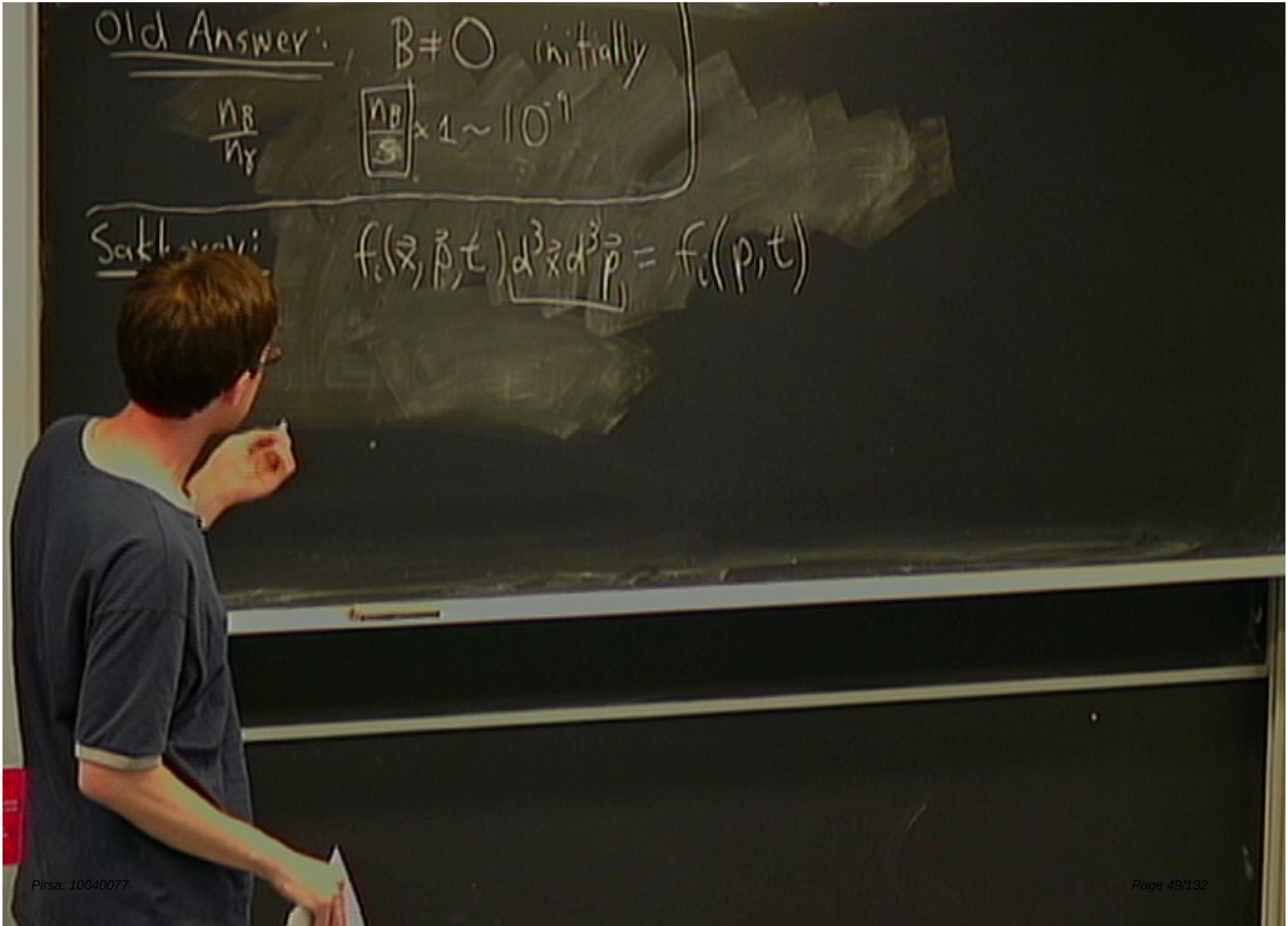

Old Answer:
B≠0 initially
n_B / n_γ
n_B / S × 1 ~ 10^-9
Sakhorov:
f

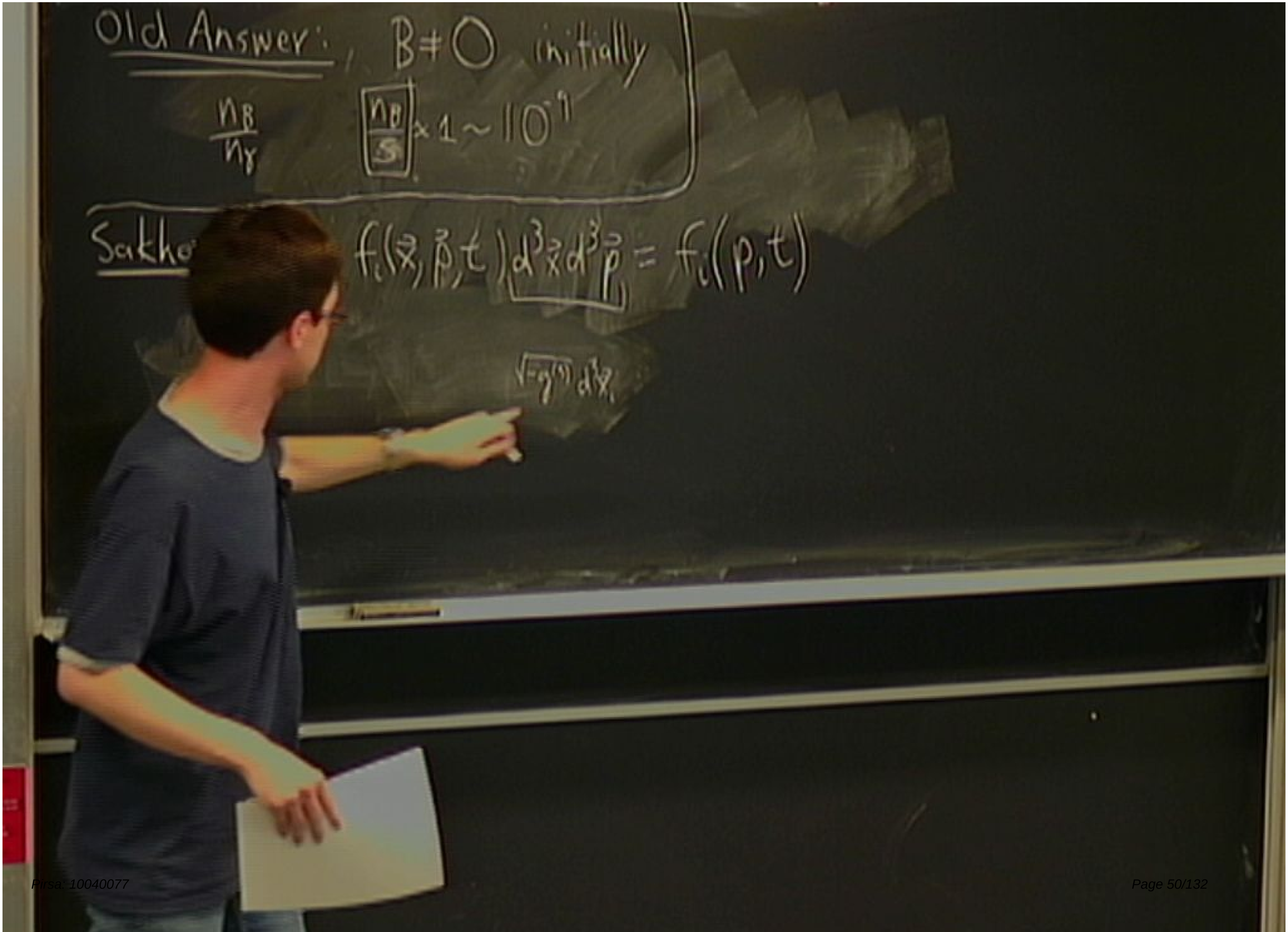

Old Answer: B ≠ 0 initially
$\frac{n_B}{n_\gamma}$
n_B × 1 ~ 10^{-9}
Sakhorov:
$f_i(\vec{x}, \vec{p}, t)$

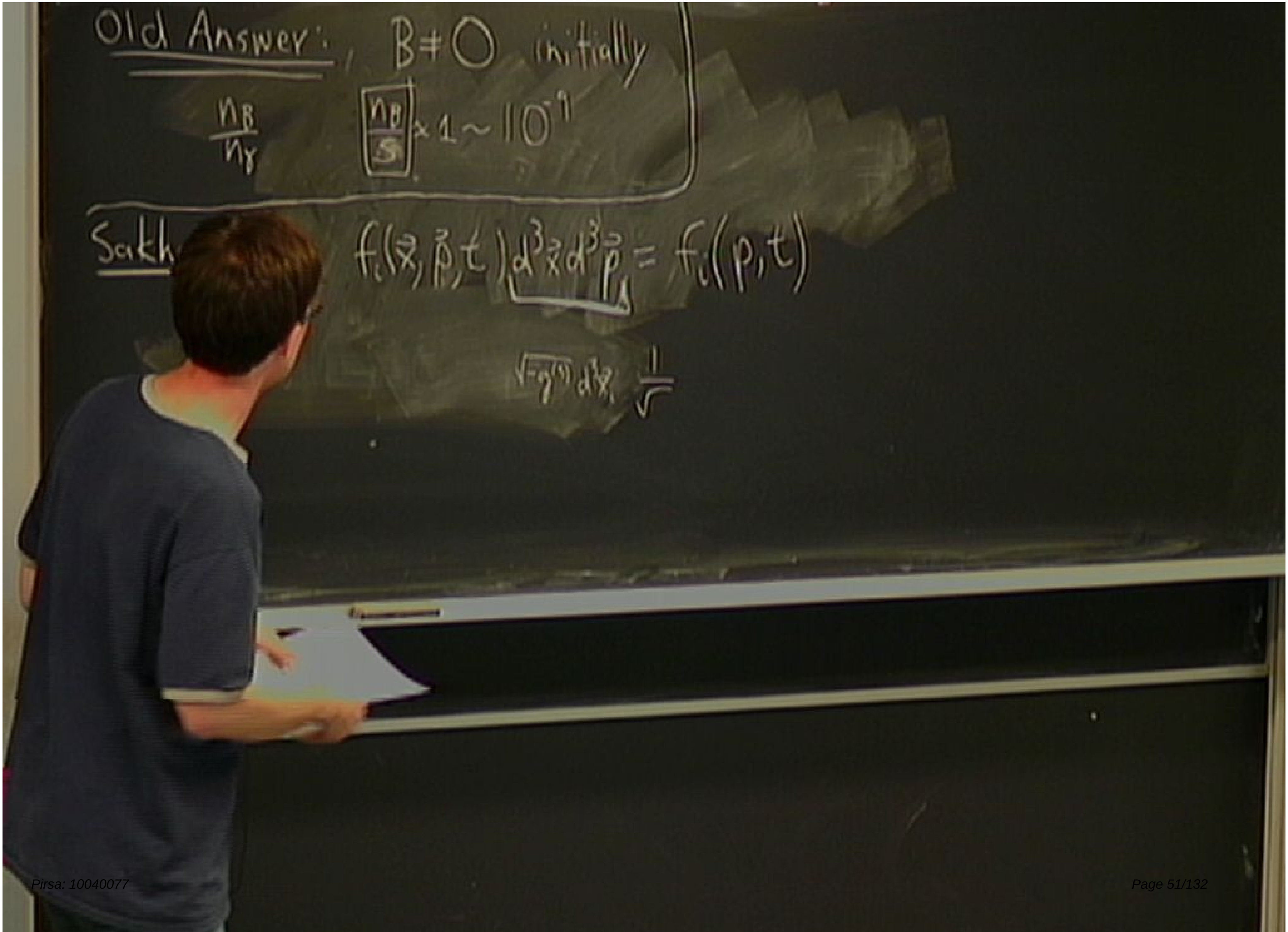

Old Answer:
B≠0 initially
nB/nγ
nB x 1 ~ 10^-9
Sakhorov:
fi(x, p, t) d3x d3p
d3x d3p

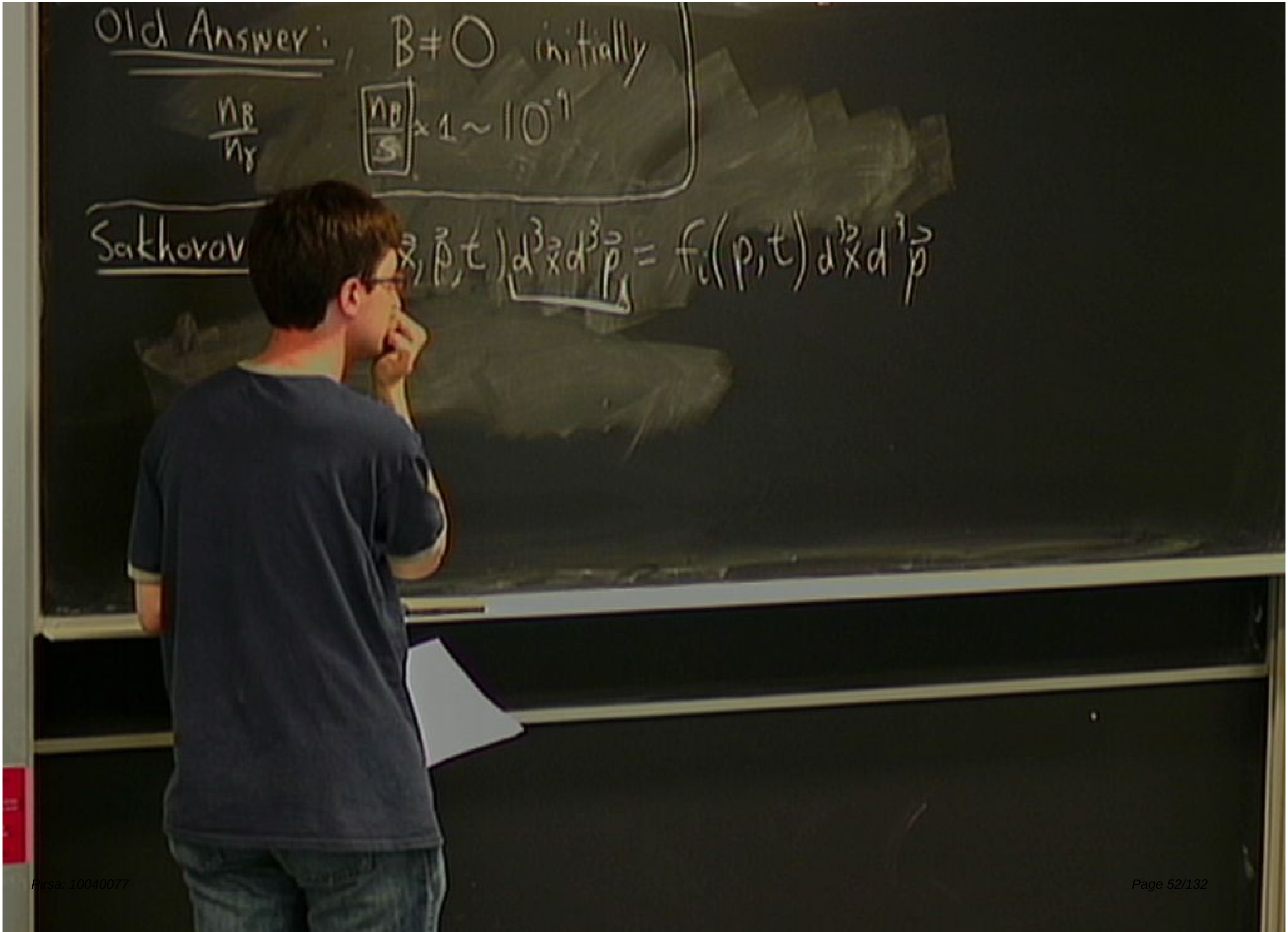

Old Answer:
B ≠ 0 initially
n_B / n_γ
× 1 ~ 10^-9
ov:
f_i(x, p, t) d^3x d^3p =
d^3x d^3p

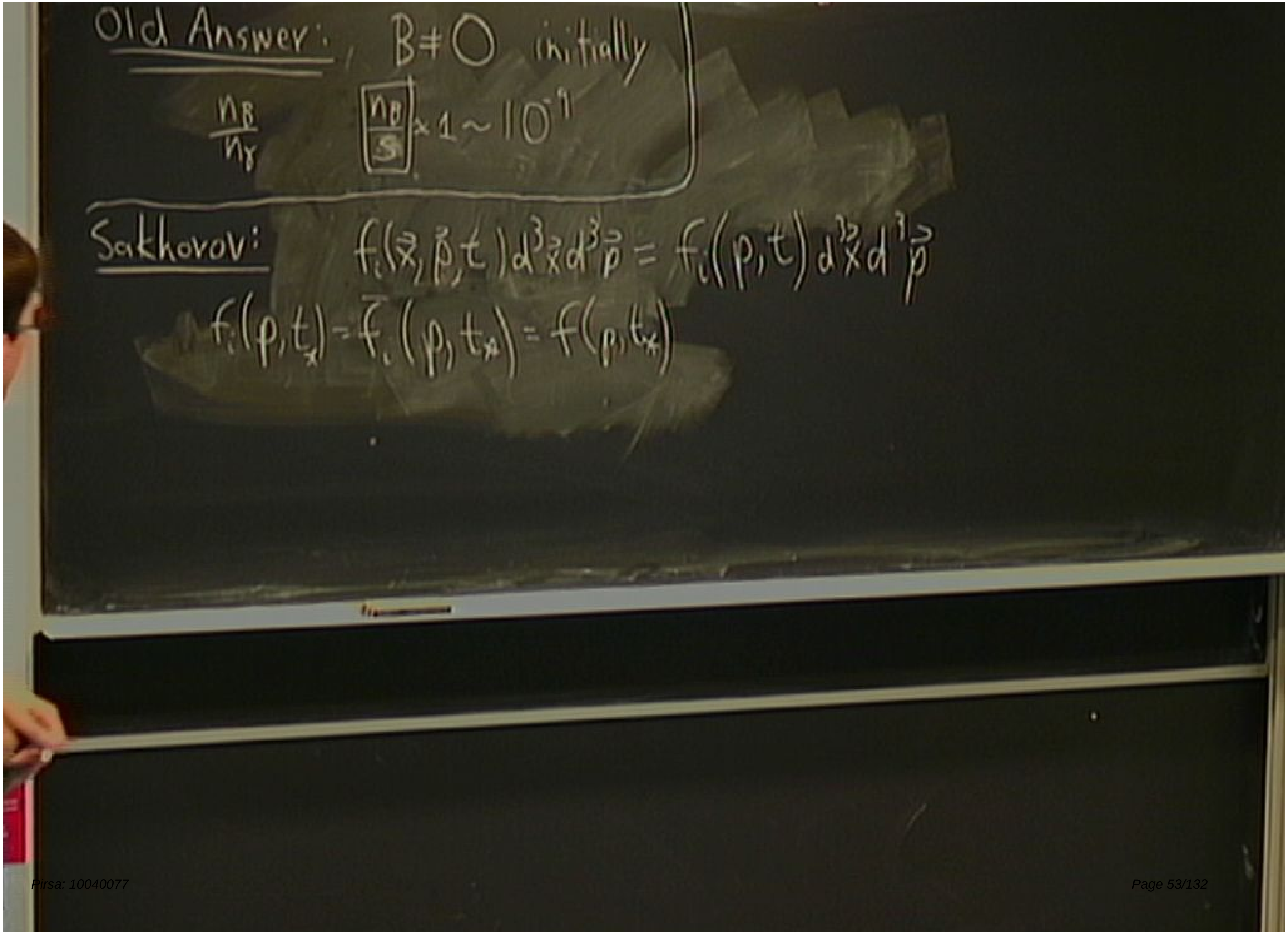

Old Answer: B ≠ 0 initially
n_B / n_γ
× 1 ~ 10^-9
ov:
f_i(x, p, t) d^3x d^3p = f_i(p, t)
d^3x d^3p

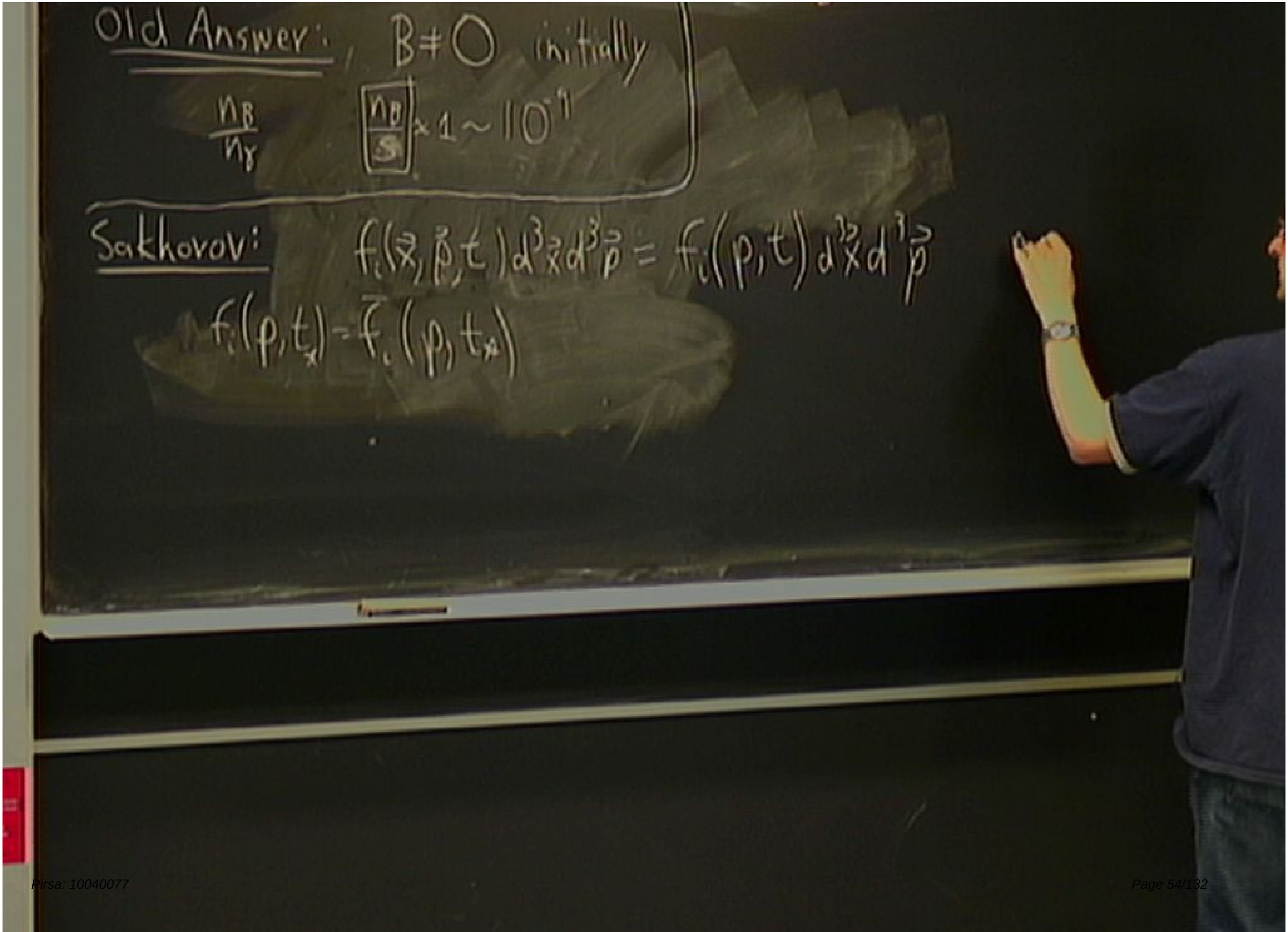

Old Answer:
B ≠ 0 initially
n_B / n_γ
n_B / s × 1 ~ 10^-9
f_i(x, p, t) d^3x d^3p = f_i(p, t)


Old Answer:
B ≠ 0 initially
n_B / n_γ
n_B / s × 1 ~ 10^-9
f_i(x, p, t) d^3x d^3p = f_i(p, t)
√-g^(4) d^3x


Old Answer:
B ≠ 0 initially
n_B / n_γ
n_B / s × 1 ~ 10^-9
f_i(x, p, t) d³x d³p = f_i(p, t)


Old Answer:
B≠0 initially
nB / nγ
nB / s × 1 ~ 10^-9
Sakhorov
= fi(p, t) d3x d3p


Old Answer: B≠0 initially
n_B / n_γ   n_B / s × 1 ~ 10^-9
Sakhorov: f_i(x⃗, p⃗, t) d³x⃗ d³p⃗ = f_i(p, t) d³x⃗ d³p⃗
f_i(p, t_*) = f̄_i(p, t_*) = f(p, t_*)

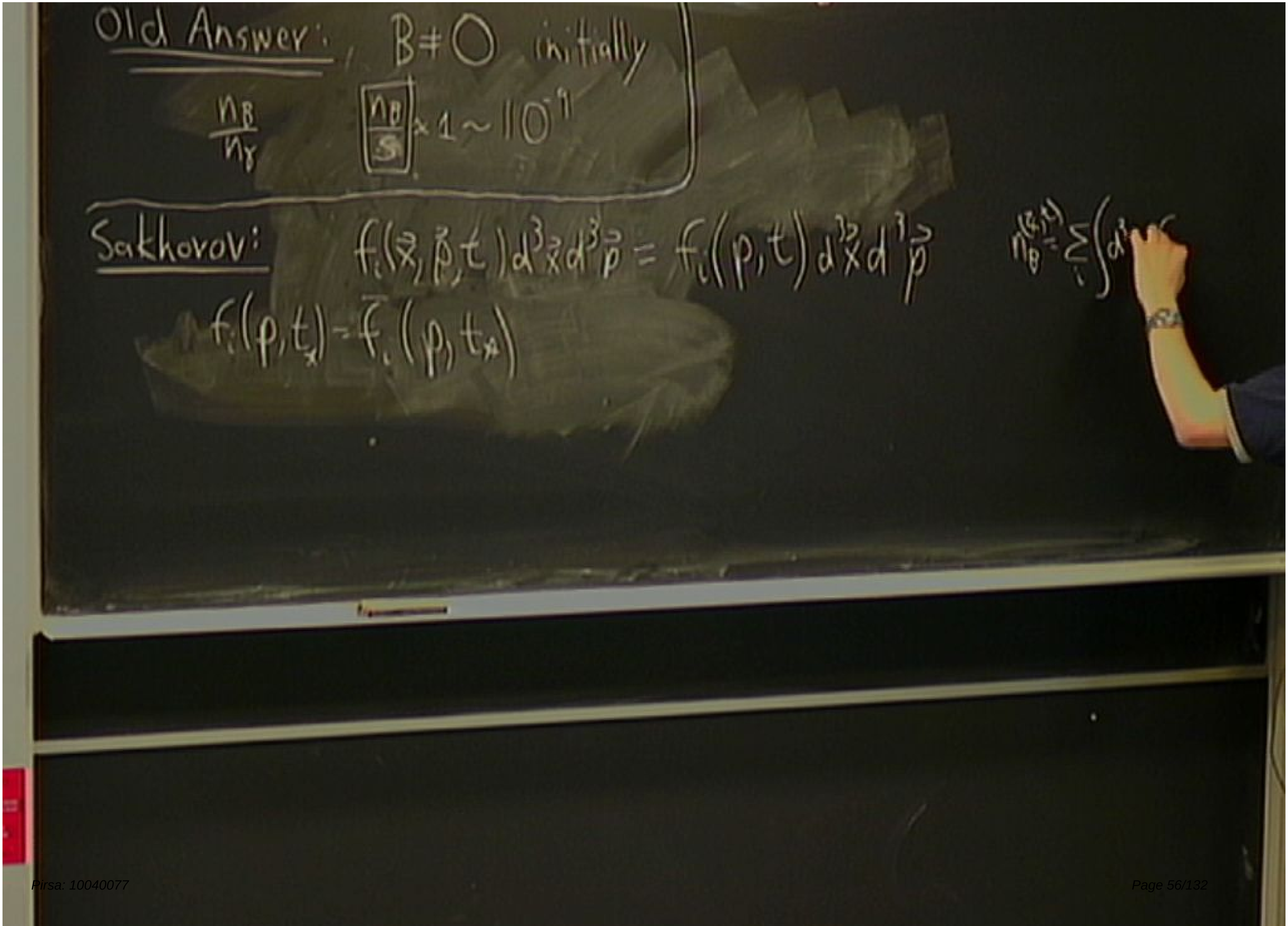

Old Answer: B≠O initially
Sakharov:
f_i(x,p,t) d³x d³p = f_i(p,t) d³x d³p
f_i(p,t_*) = f̄_i(p,t_*)

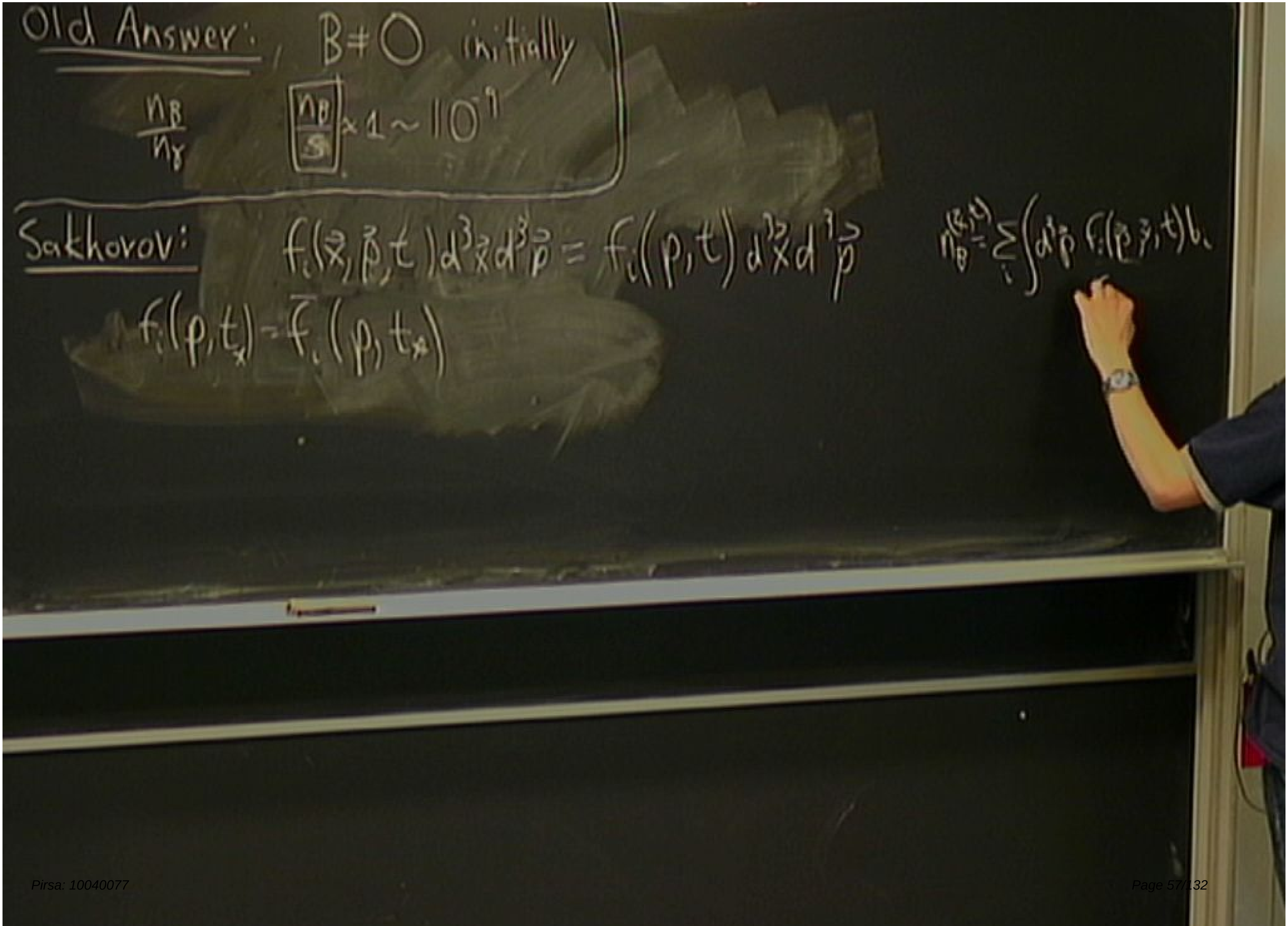
Old Answer: $B \neq 0$ initially

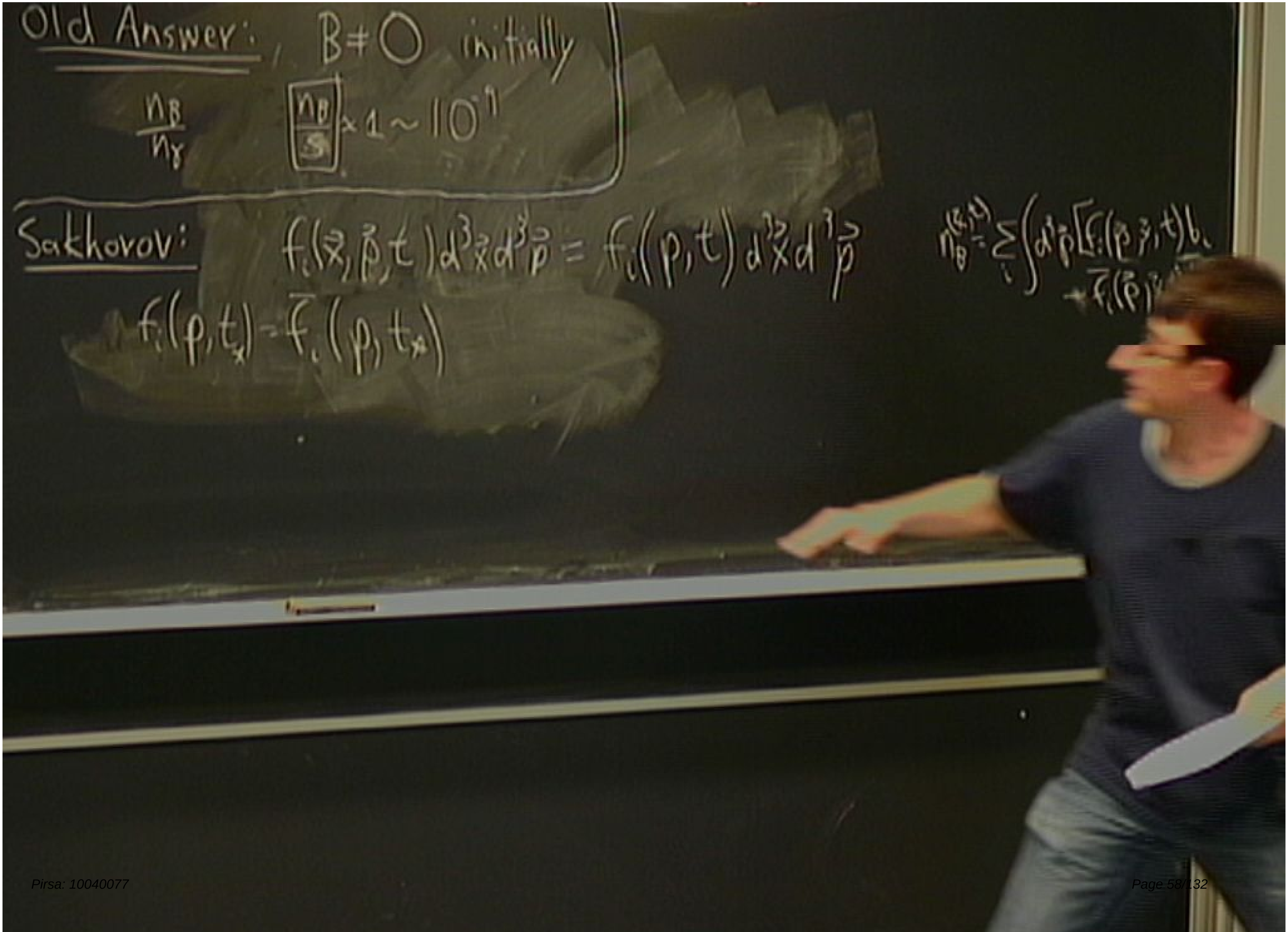
$$\frac{n_B}{n_\gamma} \qquad \boxed{\frac{n_B}{s}} \times 1 \sim 10^{-9}$$

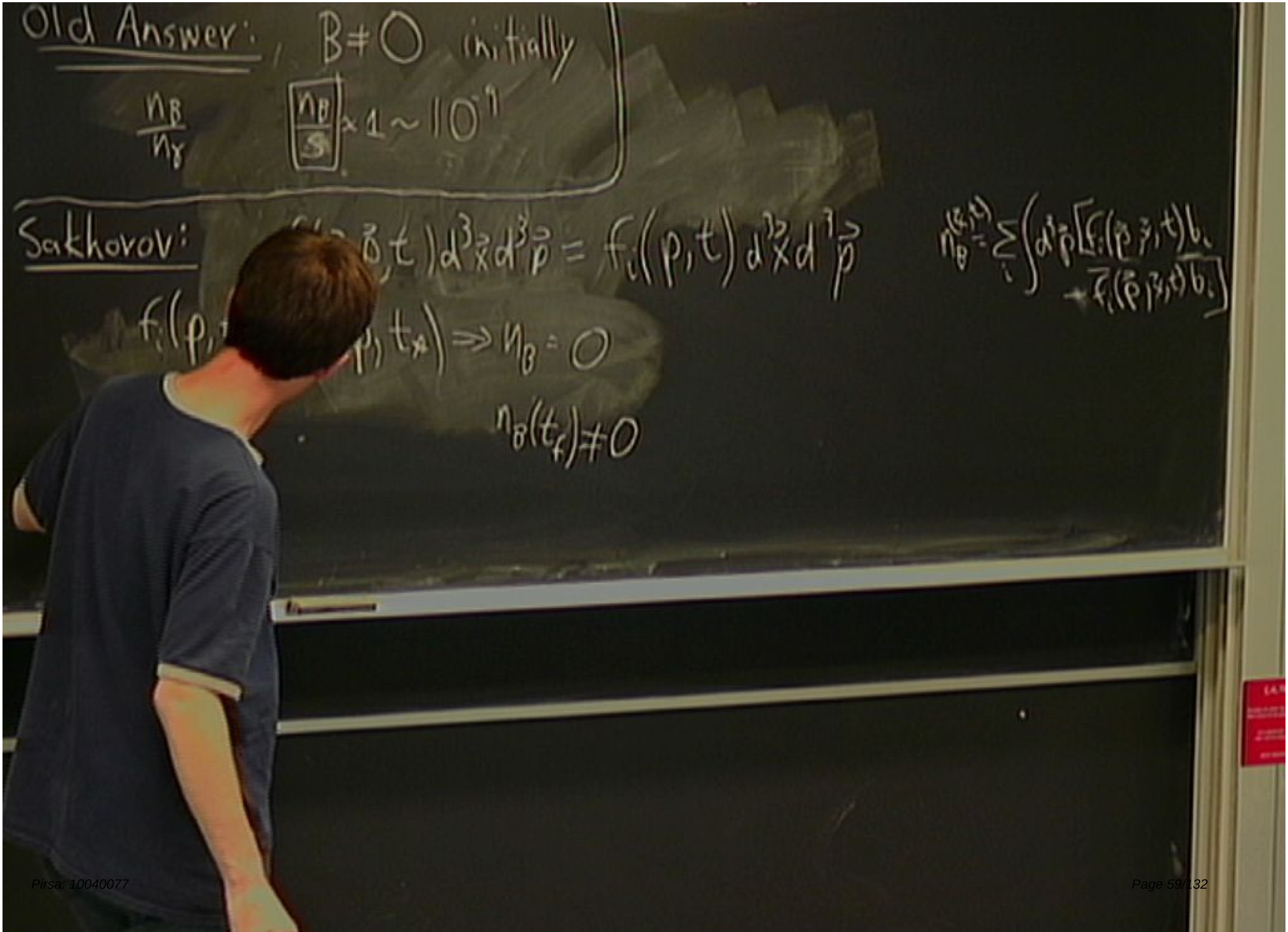
Sakhorov: $f_i(\vec{x}, \vec{p}, t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p, t)\, d^3\vec{x}\, d^3\vec{p}$ $\qquad n_B =$

$$f_i(p, t_*) = \bar{f}_i(p, t_*)$$


Old Answer: B ≠ 0 initially
nB/nγ nB/S × 1 ~ 10^-9
Sakharov: fi(x, p, t) d³x d³p = fi(p, t) d³x d³p
fi(p, t*) = f̄i(p, t*)
nB(x,t) = Σi ∫ d³


Old Answer:
B≠0 initially
$\frac{n_B}{n_\gamma}$
×1 ~ 10^{-9}
Sakhorov:
$f_i(\vec{x},\vec{p},t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p,t)\, d^3\vec{x}\, d^3\vec{p}$
$f_i(p,t_*) - \bar{f}_i(p,t_*)$


Old Answer: B≠0 initially
n_B / n_γ
× 1 ~ 10^-9
Sakhorov:
f_i(x, p, t) d³x d³p = f_i(p, t) d³x d³p
f_i(p, t_*) - f̄_i(p, t_*)


Old Answer: B≠0 initially
Sakhorov:
$n_B(t_f) \neq 0$

Old Answer: $B \neq 0$ initially

$$\frac{n_B}{n_\gamma} \qquad \boxed{\frac{n_B}{s}} \times 1 \sim 10^{-9}$$

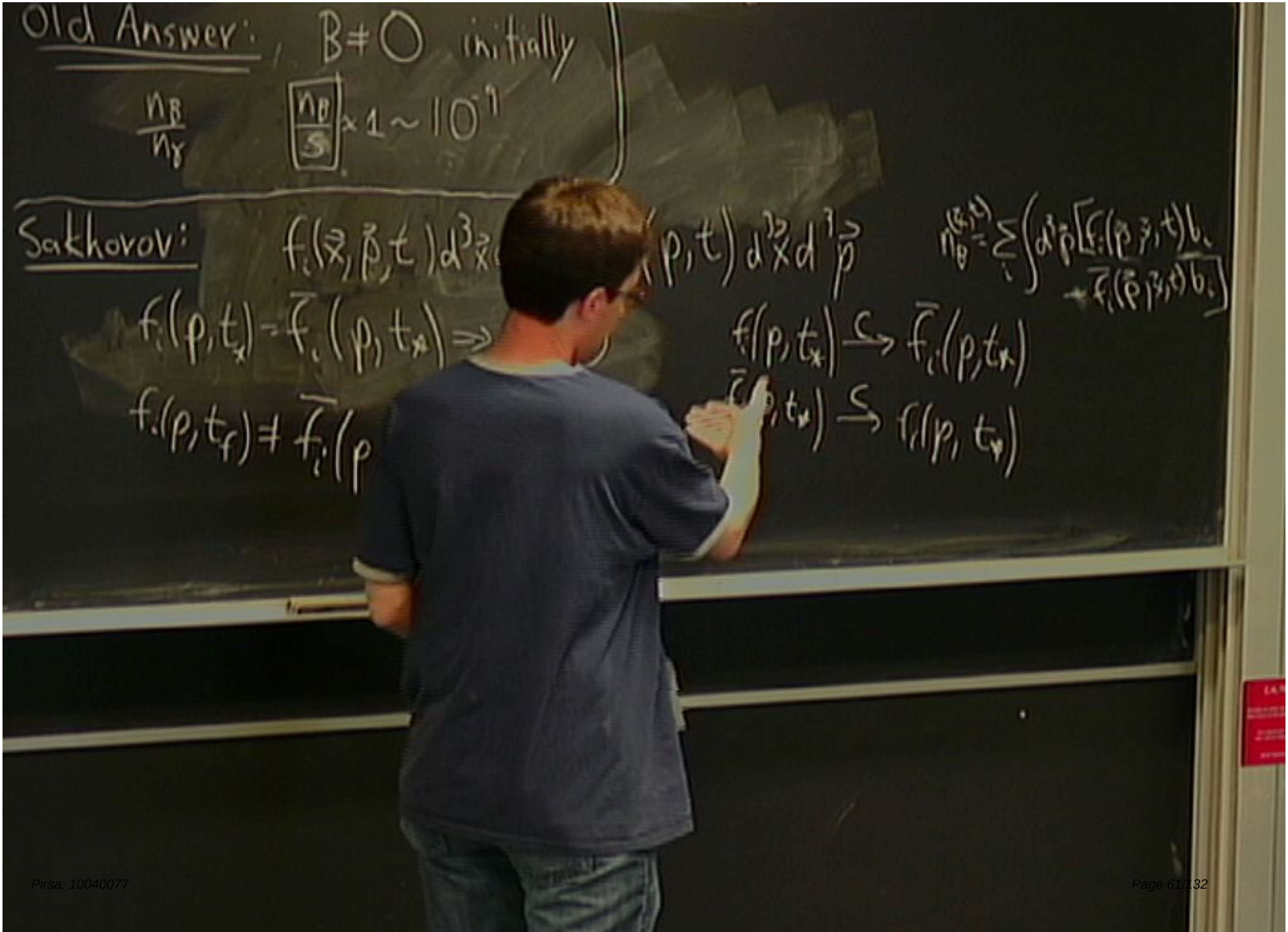
Sakharov:

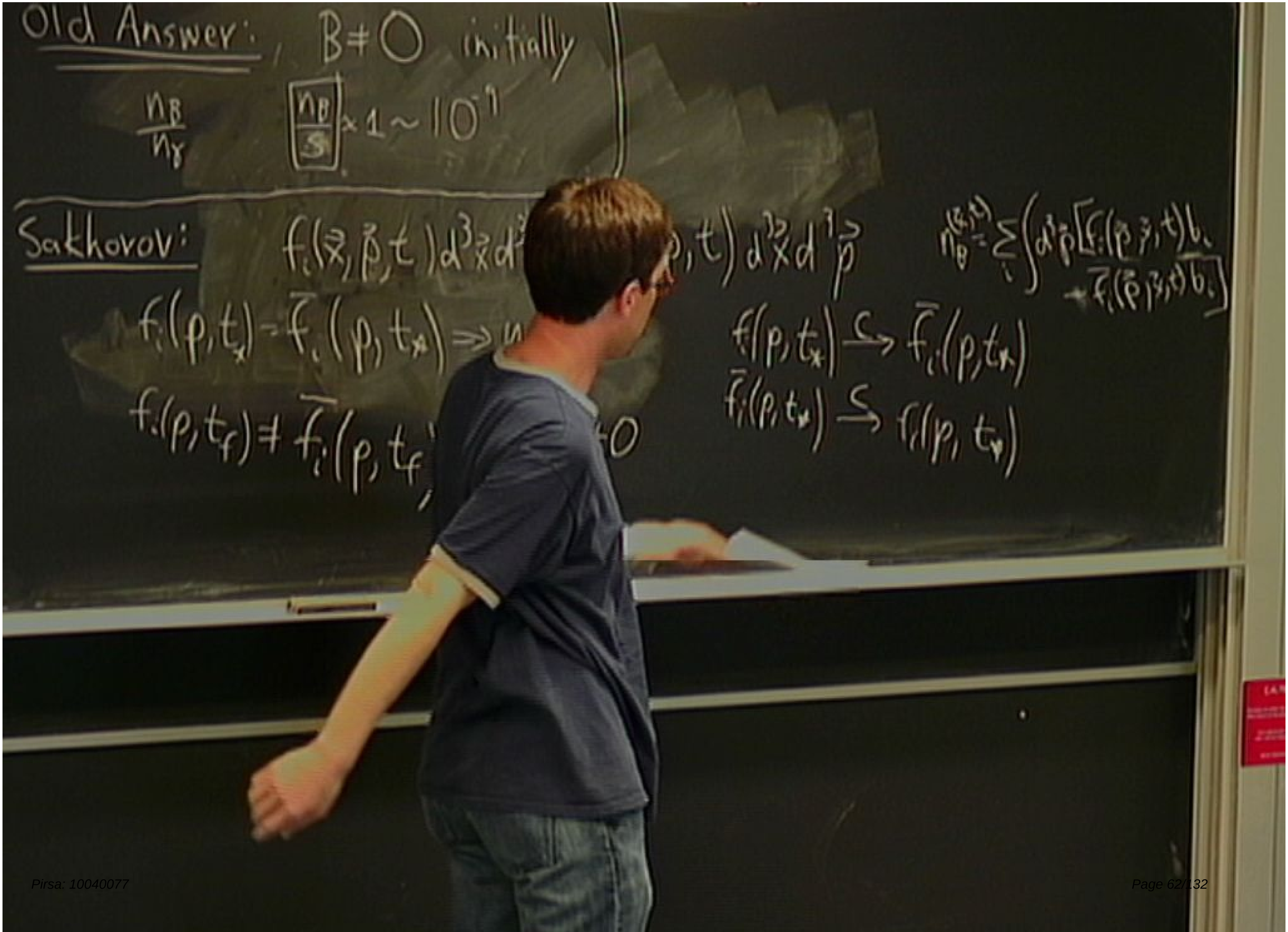
$$f_i(\vec{x}, \vec{p}, t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p, t)\, d^3\vec{x}\, d^3\vec{p}$$

$$n_B^{(\vec{x},t)} = \sum_i \int d^3\vec{p} \left[f_i(\vec{p}, \vec{x}, t)\, b_i + \bar{f}_i(\vec{p}, \vec{x}, t)\, \bar{b}_i \right]$$

$$f_i(p, t_*) = \bar{f}_i(p, t_*) \Rightarrow n_B = 0$$

$$f_i(p, t_f) \neq \bar{f}_i(p, t_f) \qquad n_B(t_f) \neq 0$$


Old Answer: B≠0 initially
nB/nγ
nB/s × 1 ~ 10^-9
Sakharov:
f(p, t) d³x d³p
f(p, tx) S→ f̄(p, tx)
f̄(p, tx) S→ f(p, tx)


Old Answer:
B ≠ 0 initially
Sakhorov:

Old Answer: $B \neq 0$ initially

$$\frac{n_B}{n_\gamma} \quad \boxed{\frac{n_B}{s}} \times 1 \sim 10^{-9}$$

Sakhorov:

$$f_i(\vec{x},\vec{p},t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p,t)\, d^3\vec{x}\, d^3\vec{p}$$

$$n_B(\vec{x},t) = \sum_i \int d^3p \left[f_i(\vec{p},\vec{x},t)\, b_i + \bar{f}_i(\vec{p},\vec{x},t)\, \bar{b}_i \right]$$

$$f_i(p,t_*) = \bar{f}_i(p,t_*) \Rightarrow n_B = 0$$

$$f_i(p,t_f) \neq \bar{f}_i(p,t_f) \qquad n_B(t_f) \neq 0$$

$$f_i(p,t_i) \xrightarrow{C} \bar{f}_i(p,t_f):$$

$$\bar{f}_i(p,t_i) \xrightarrow{C} f_i(p,t_f):$$

Old Answer: $B \neq 0$ initially

$\frac{n_B}{n_\gamma}$ $\qquad \frac{n_B}{s} \times 1 \sim 10^{-9}$

Sakhorov: $f_i(\vec{x},\vec{p},t)\,d^3\vec{x}\,d^3\vec{p} = f_i(p,t)\,d^3\vec{x}\,d^3\vec{p}$

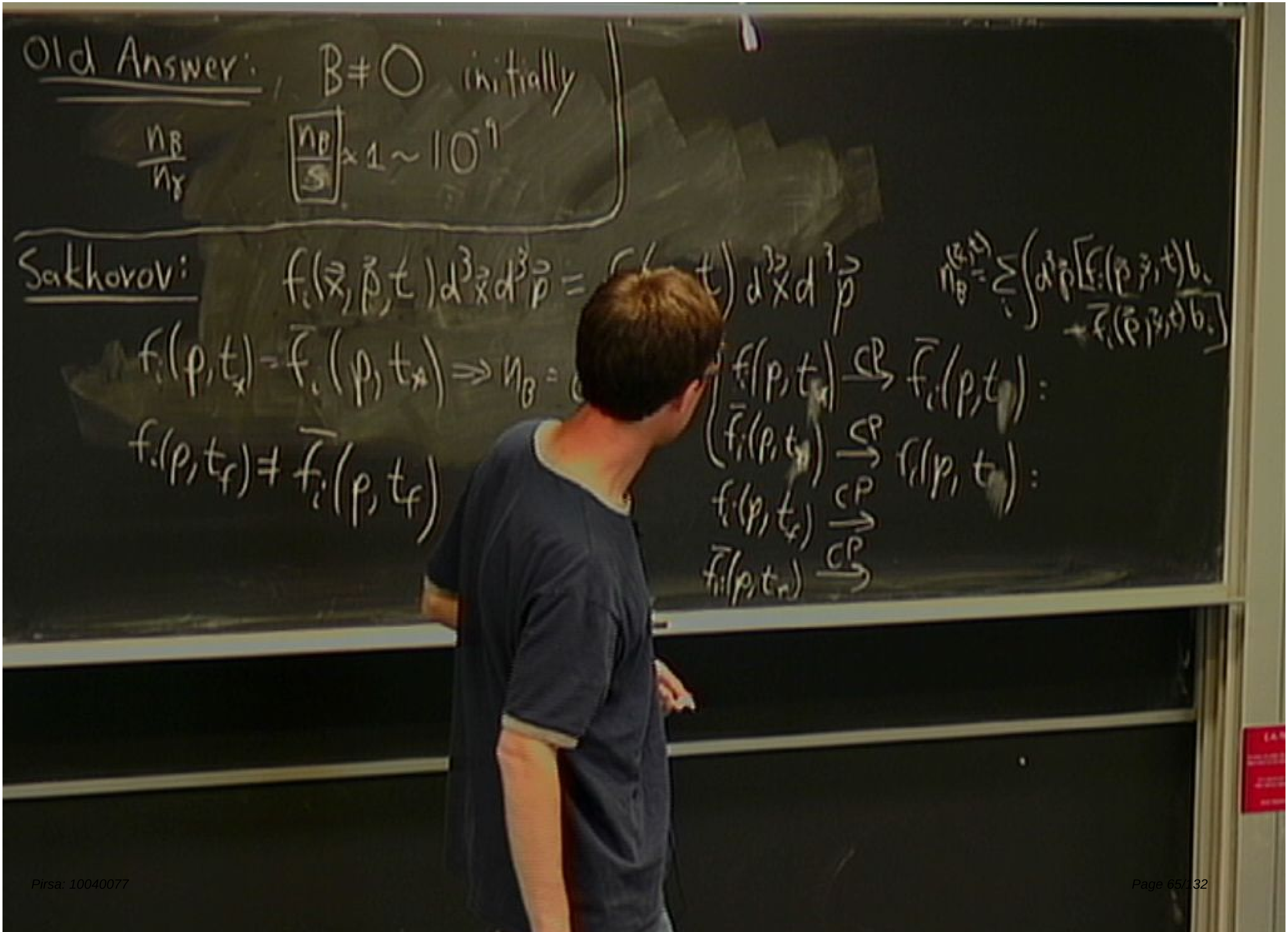
$n_B(\vec{x},t) = \sum_i \int d^3p \left[f_i(\vec{p},\vec{x},t)\, b_i + \bar{f}_i(\vec{p},\vec{x},t)\, \bar{b}_i \right]$

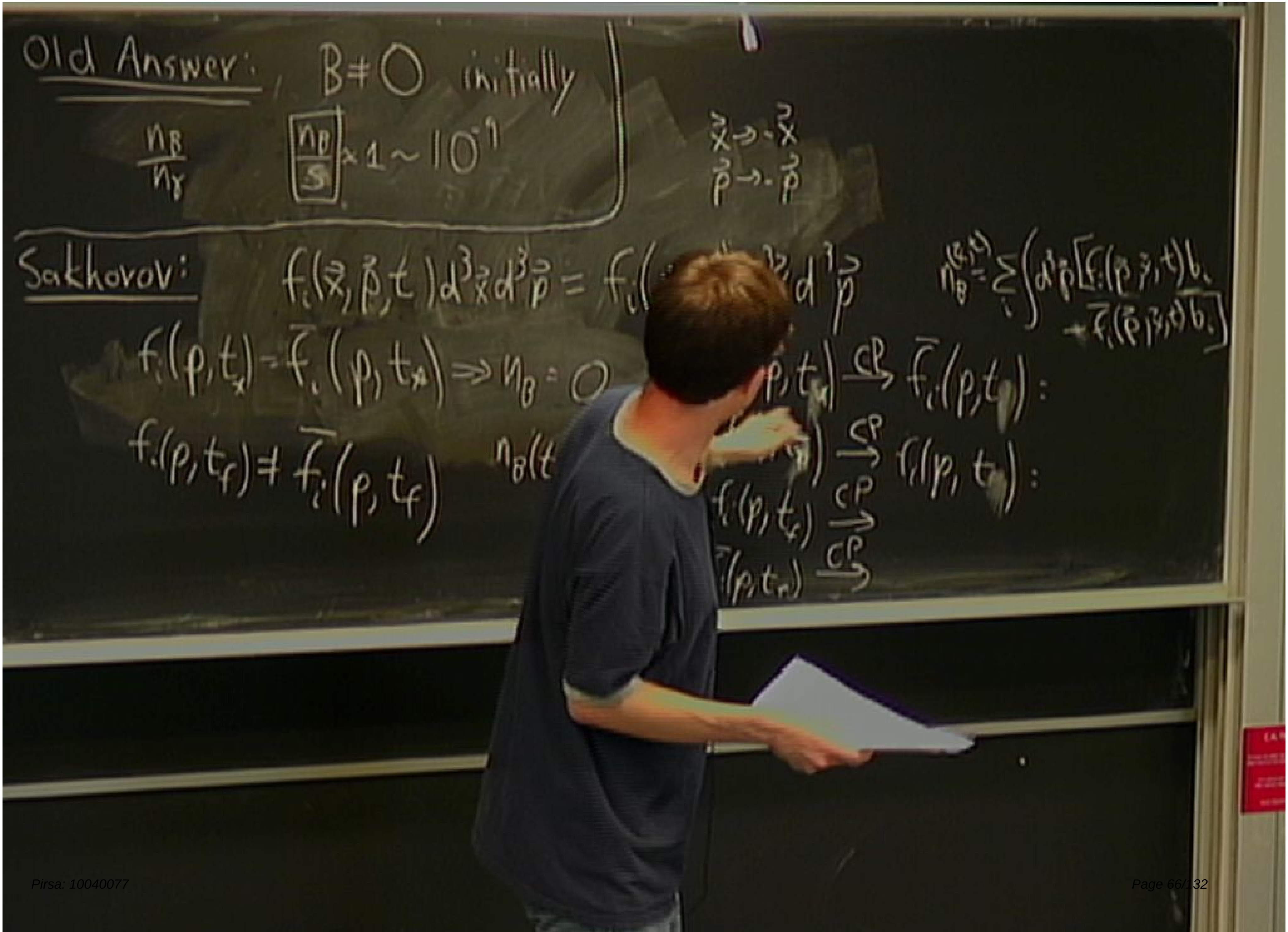
$f_i(p,t_*) = \bar{f}_i(p,t_*) \Rightarrow n_B = 0$

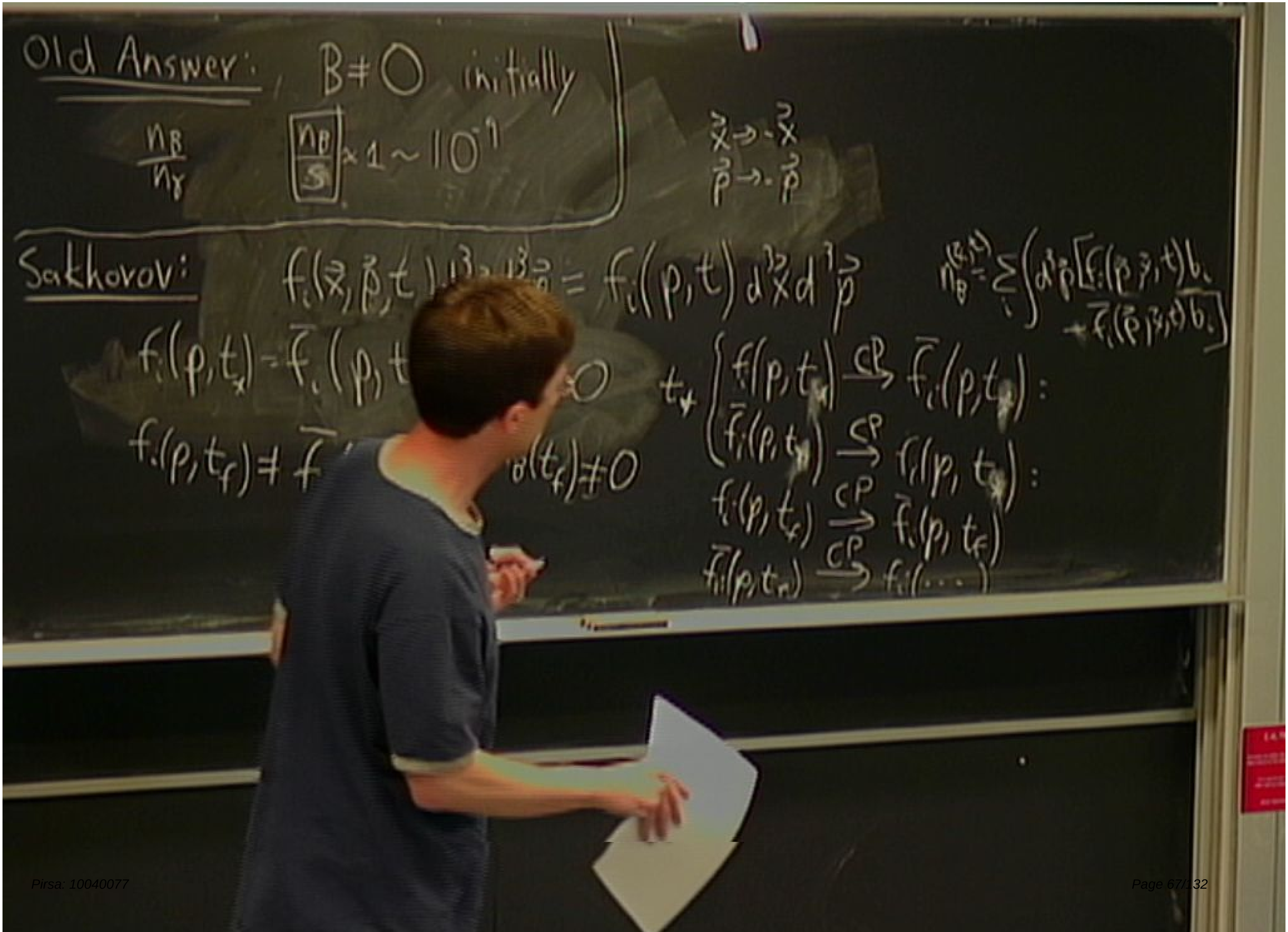
$f_i(p,t_f) \neq \bar{f}_i(p,t_f) \qquad n_B(t_f) \neq 0$

$f_i(p,t_*) \xrightarrow{S} \bar{f}_i(p,t_f)$:

$\bar{f}_i(p,t_*) \xrightarrow{S} f_i(p,t_f)$:


Old Answer:
B ≠ 0 initially
Sakhorov:


Old Answer: B ≠ 0 initially
nB/nγ
x → -x
p → -p
Sakharov:
CP
CP
CP
CP


Old Answer:
B≠0 initially
Sakhorov:

Old Answer: $B \neq 0$ initially

$$\frac{n_B}{n_\gamma} \quad \boxed{\frac{n_B}{s}} \times 1 \sim 10^{-9}$$

$$\vec{x} \to -\vec{x}$$
$$\vec{p} \to -\vec{p}$$

Sakharov:

$$f_i(\vec{x},\vec{p},t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p,t)\, d^3\vec{x}\, d^3\vec{p}$$

$$n_B(\vec{x},t) = \sum_i \int d^3\vec{p} \left[f_i(\vec{p},\vec{x},t)\, b_i + \bar{f}_i(\vec{p},\vec{x},t)\, \bar{b}_i \right]$$

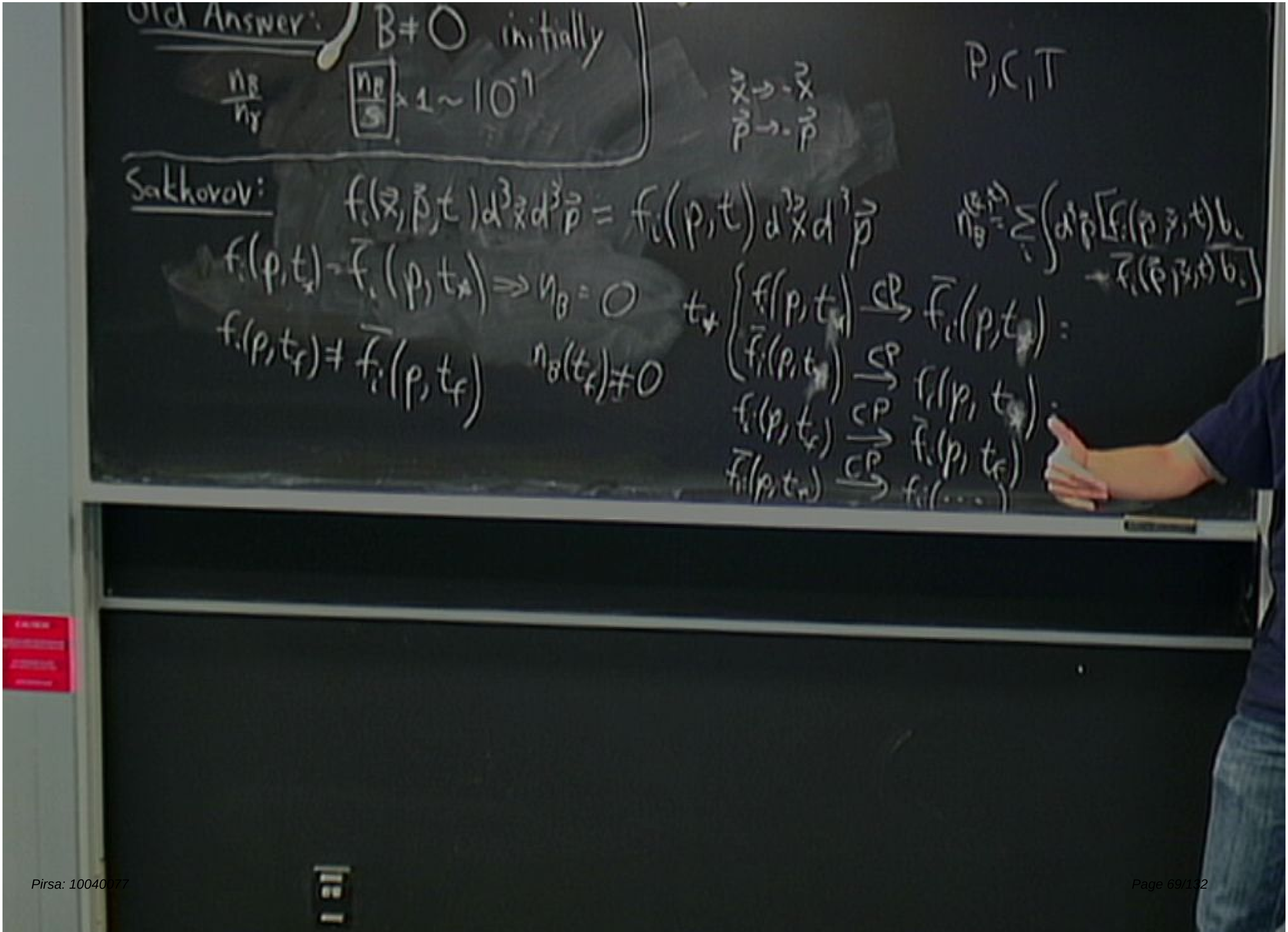
$$f_i(p,t_*) = \bar{f}_i(p,t_*) \Rightarrow n_B = 0$$

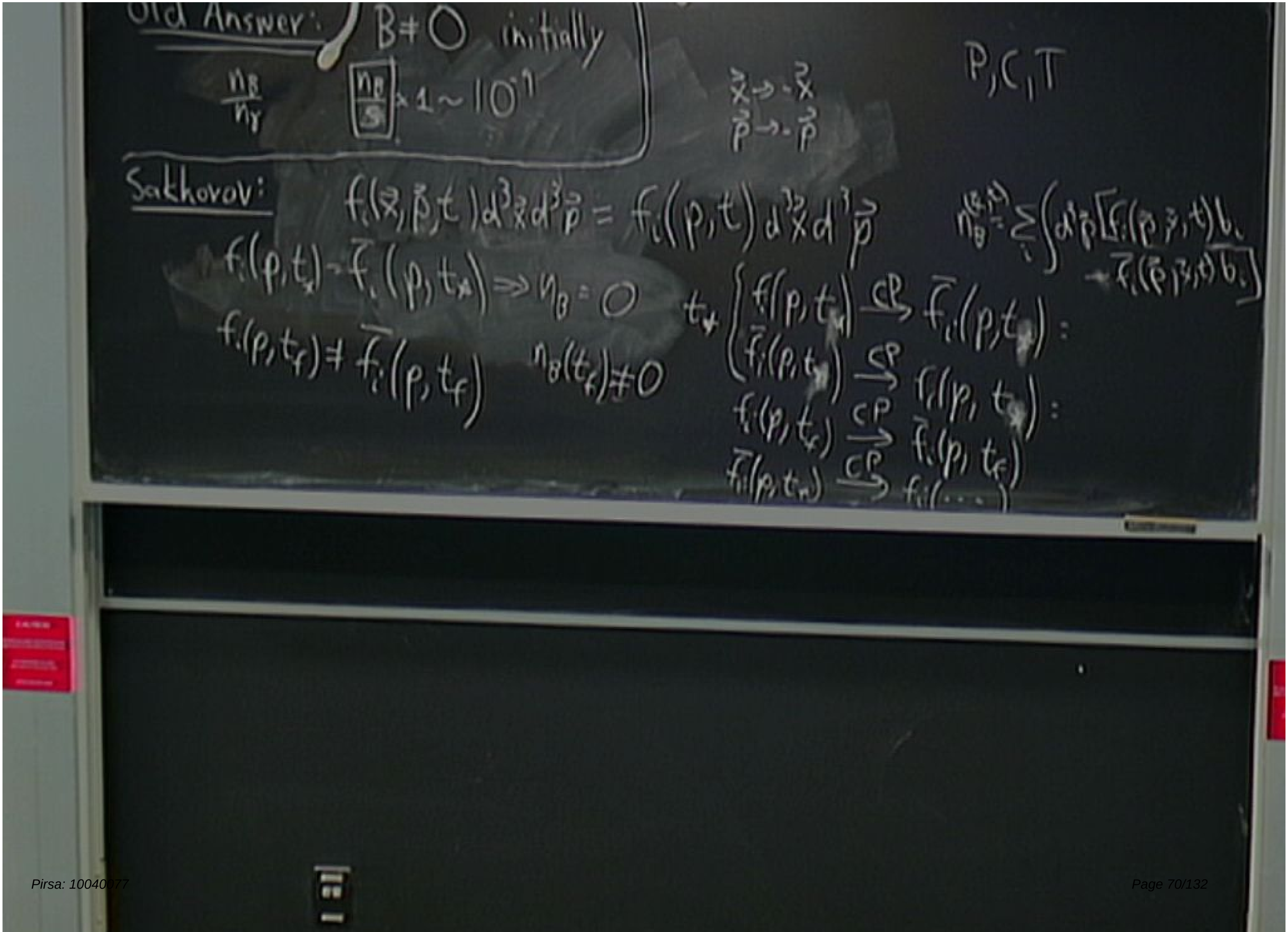
$$f_i(p,t_f) \neq \bar{f}_i(p,t_f) \qquad n_B(t_f) \neq 0$$

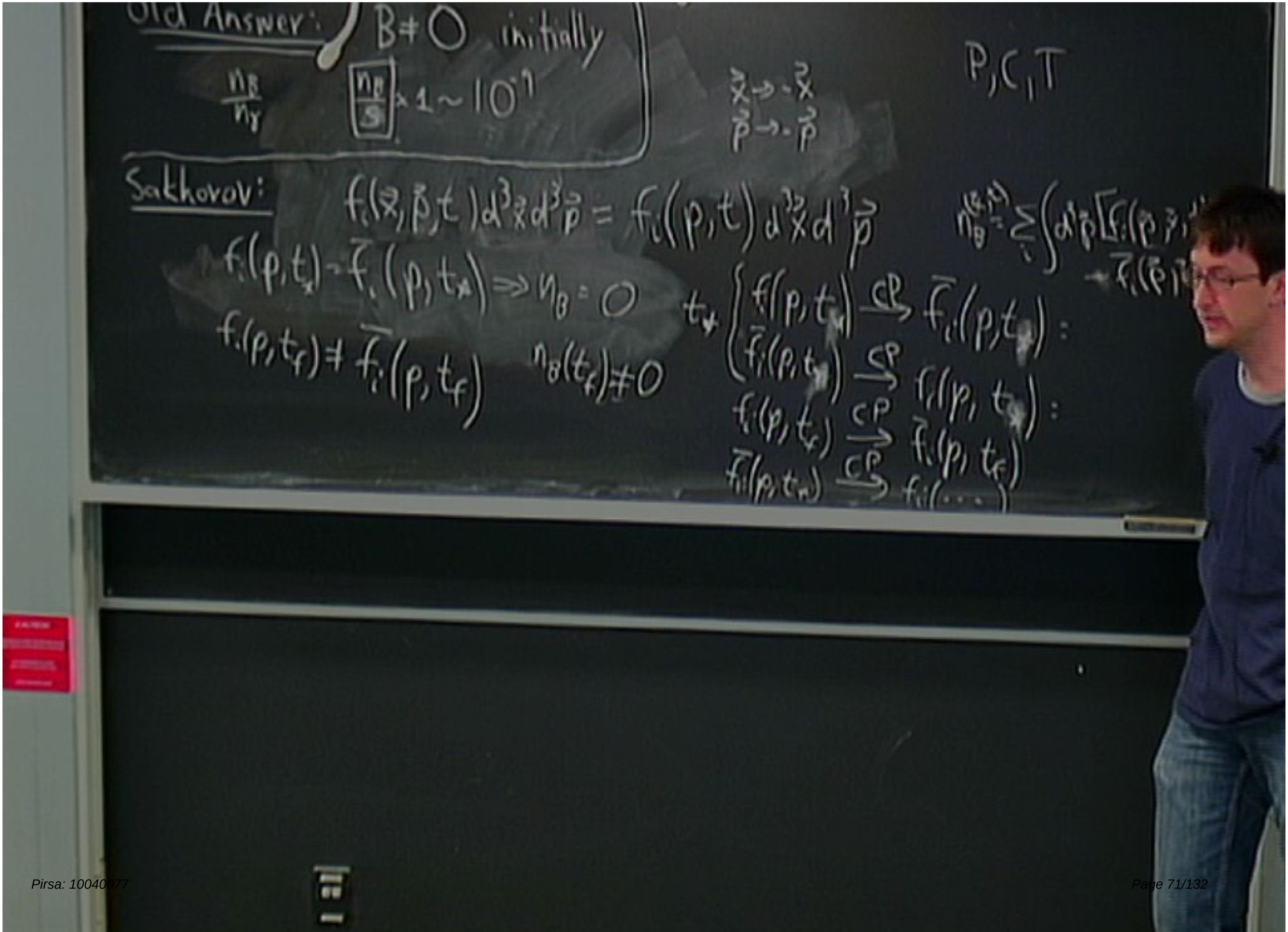
$$t_*: \begin{cases} f_i(p,t_*) \xrightarrow{CP} \bar{f}_i(p,t_*) : \\ \bar{f}_i(p,t_*) \xrightarrow{CP} f_i(p,t_*) : \end{cases}$$

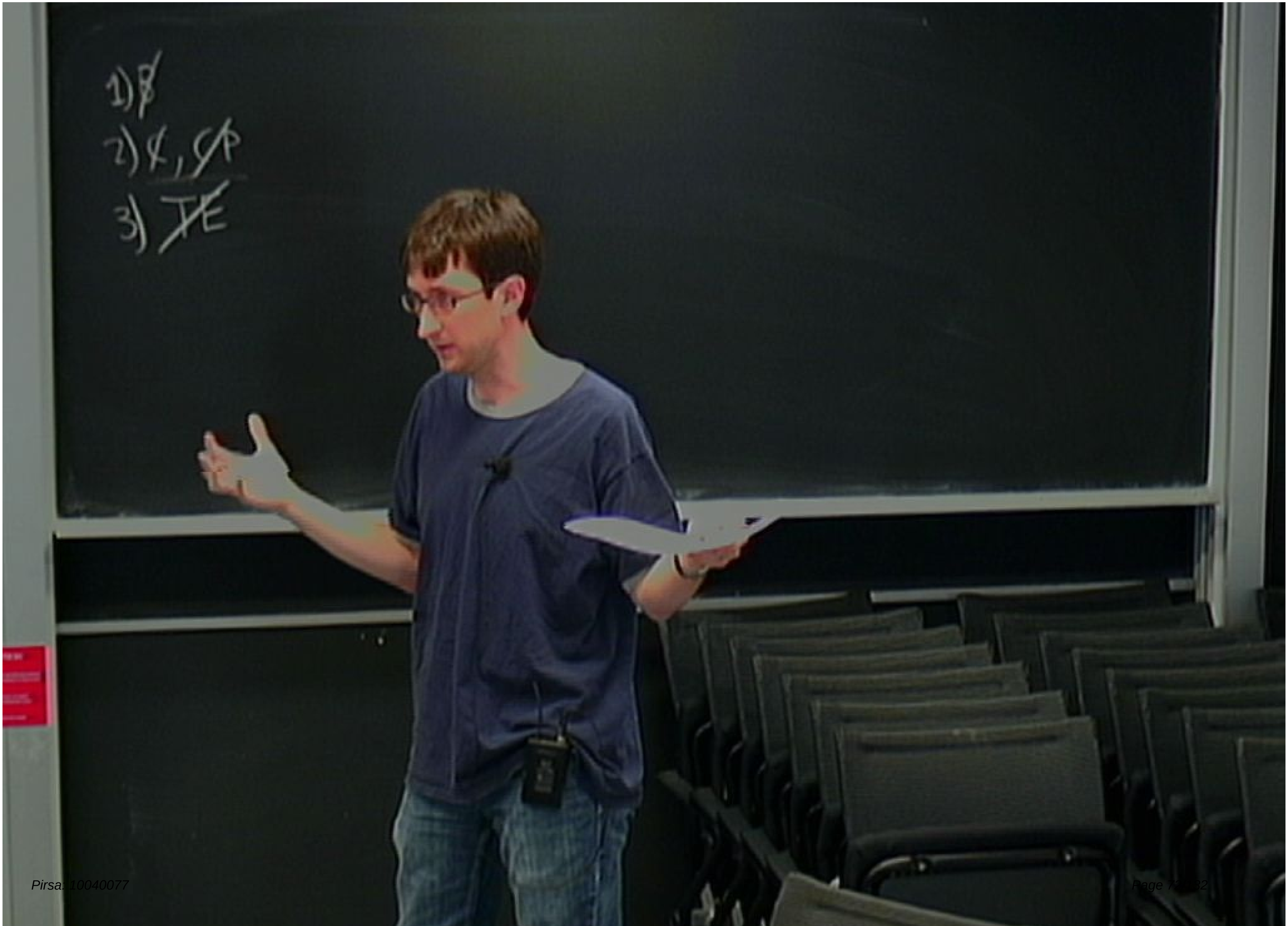
$$f_i(p,t_f) \xrightarrow{CP} \bar{f}_i(p,t_f)$$

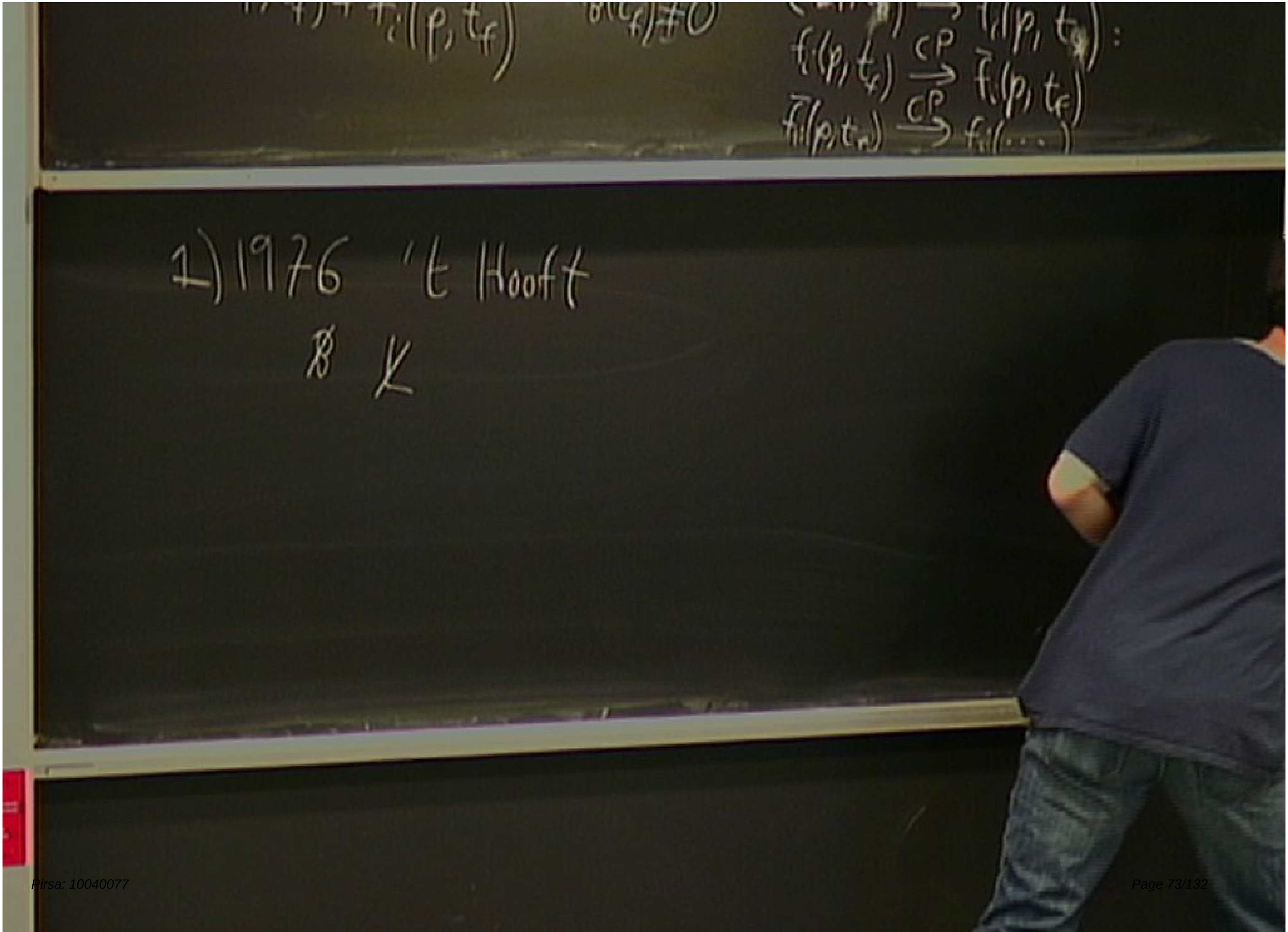
$$\bar{f}_i(p,t_f) \xrightarrow{CP} f_i(\ldots)$$

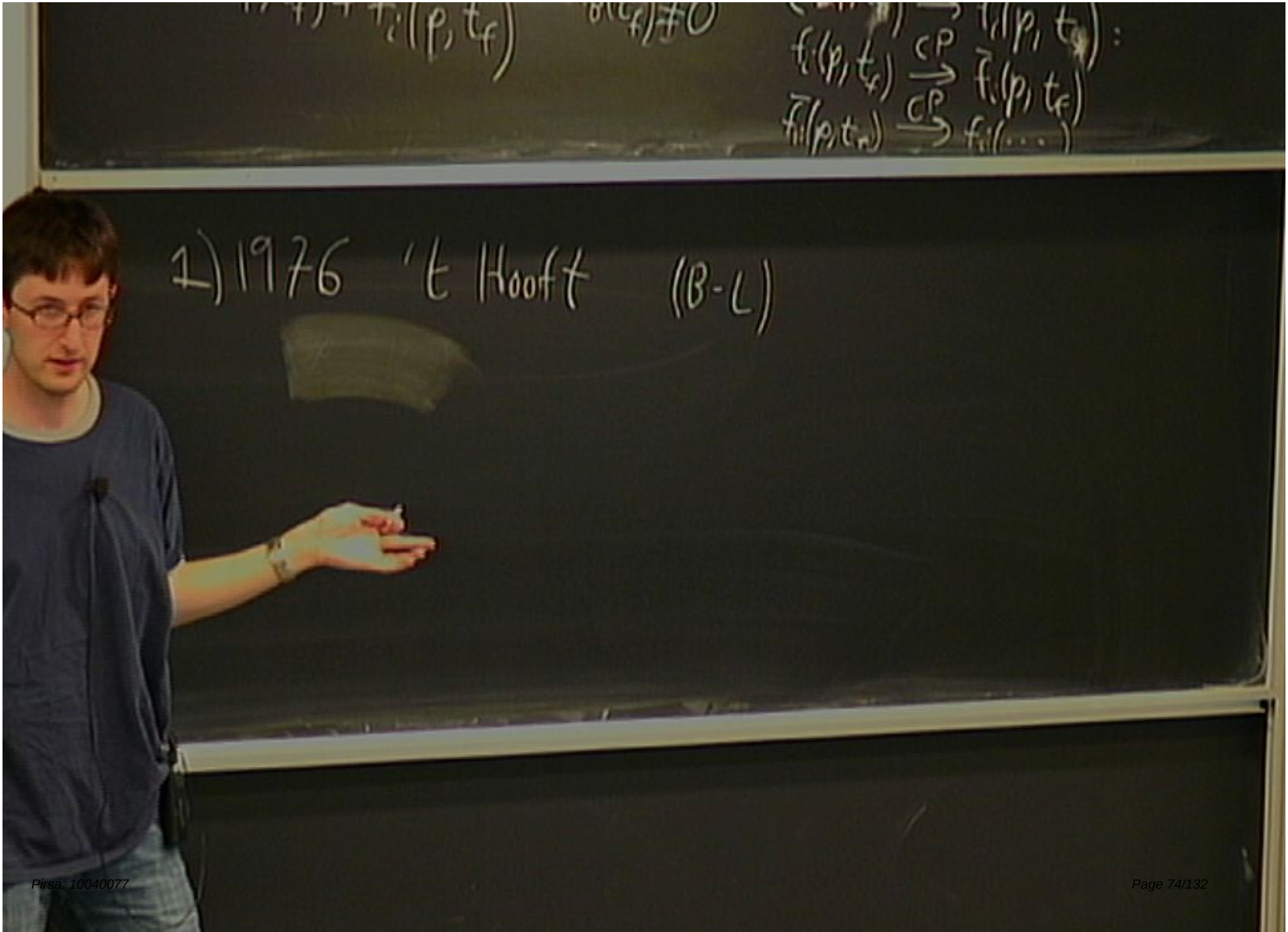

Old Answer:
B ≠ 0 initially
n_B / n_γ
n_B / s ~ 10^-9
x → -x
p → -p
P, C, T
Sakharov:
f_i(x, p, t) d^3x d^3p = f_i(p, t) d^3x d^3p
f_i(p, t_*) = f̄_i(p, t_*) ⇒ n_B = 0
f_i(p, t_f) ≠ f̄_i(p, t_f)
n_B(t_f) ≠ 0
CP

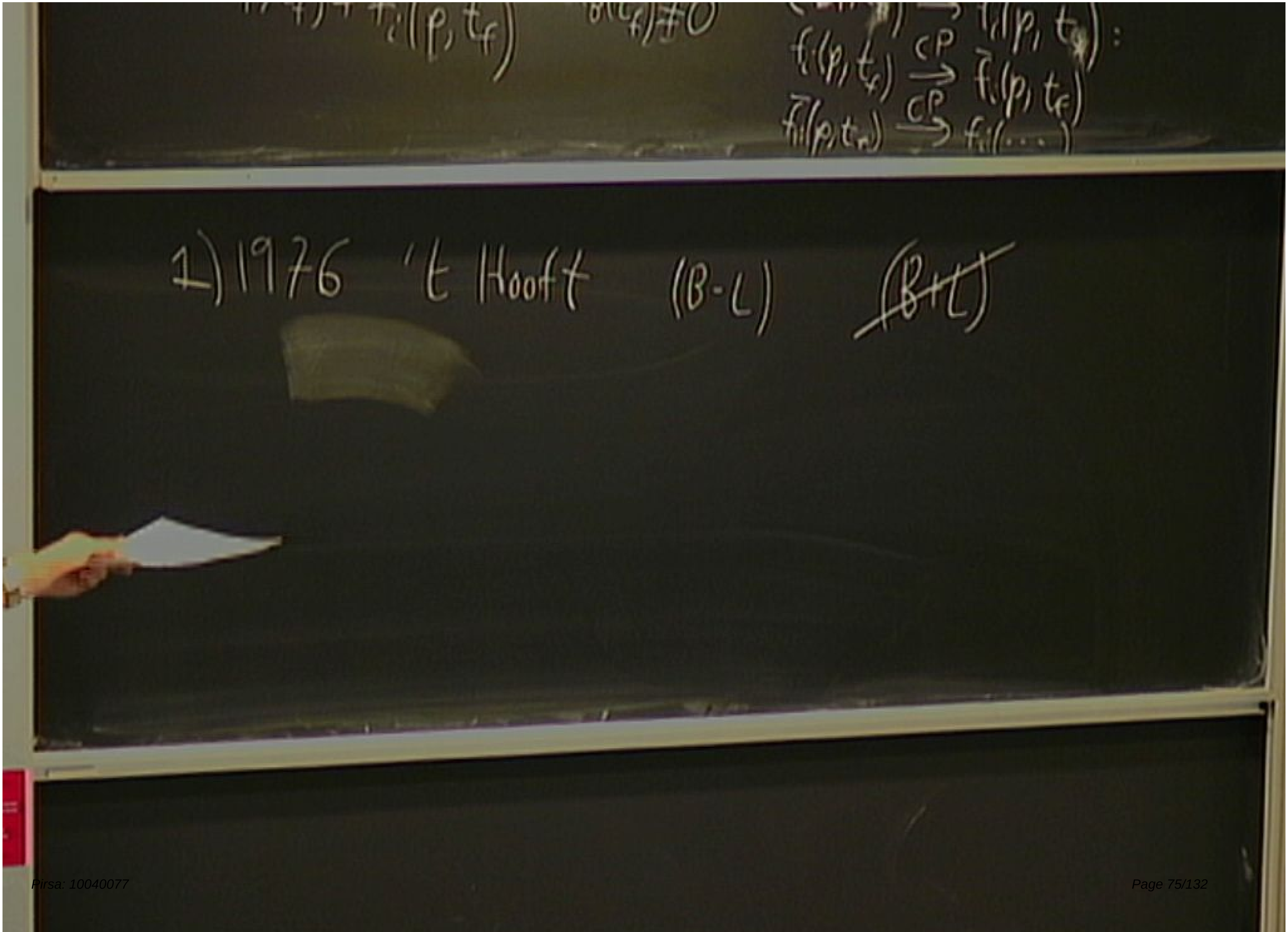

Old Answer:
B ≠ 0 initially
n_B / n_γ
n_B / s ≈ 1 ~ 10^-9
P, C, T
x → -x
p → -p
Sakharov:
f_i(x, p, t) d^3x d^3p = f_i(p, t) d^3x d^3p
f_i(p, t_*) = f̄_i(p, t_*) ⇒ n_B = 0
f_i(p, t_f) ≠ f̄_i(p, t_f)
n_B(t_f) ≠ 0
CP
CP
CP
CP

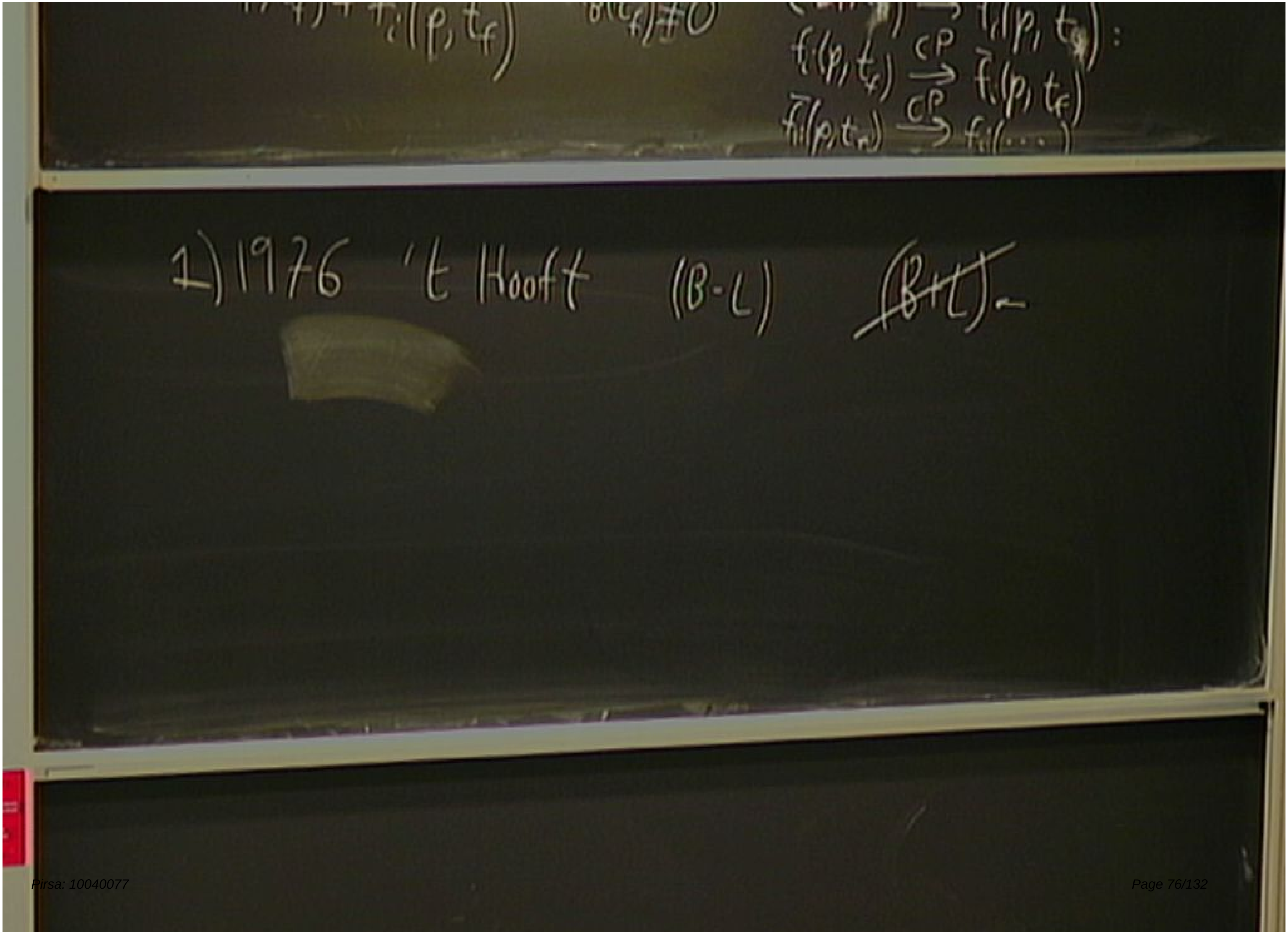

Old Answer:
B ≠ 0 initially
P, C, T
Sakharov:




1) 1976 't Hooft
B L


1) 1976 't Hooft (B-L)


1) 1976 't Hooft
(B-L)
(B+L)


1) 1976 't Hooft (B-L) (B+L)
CP
CP

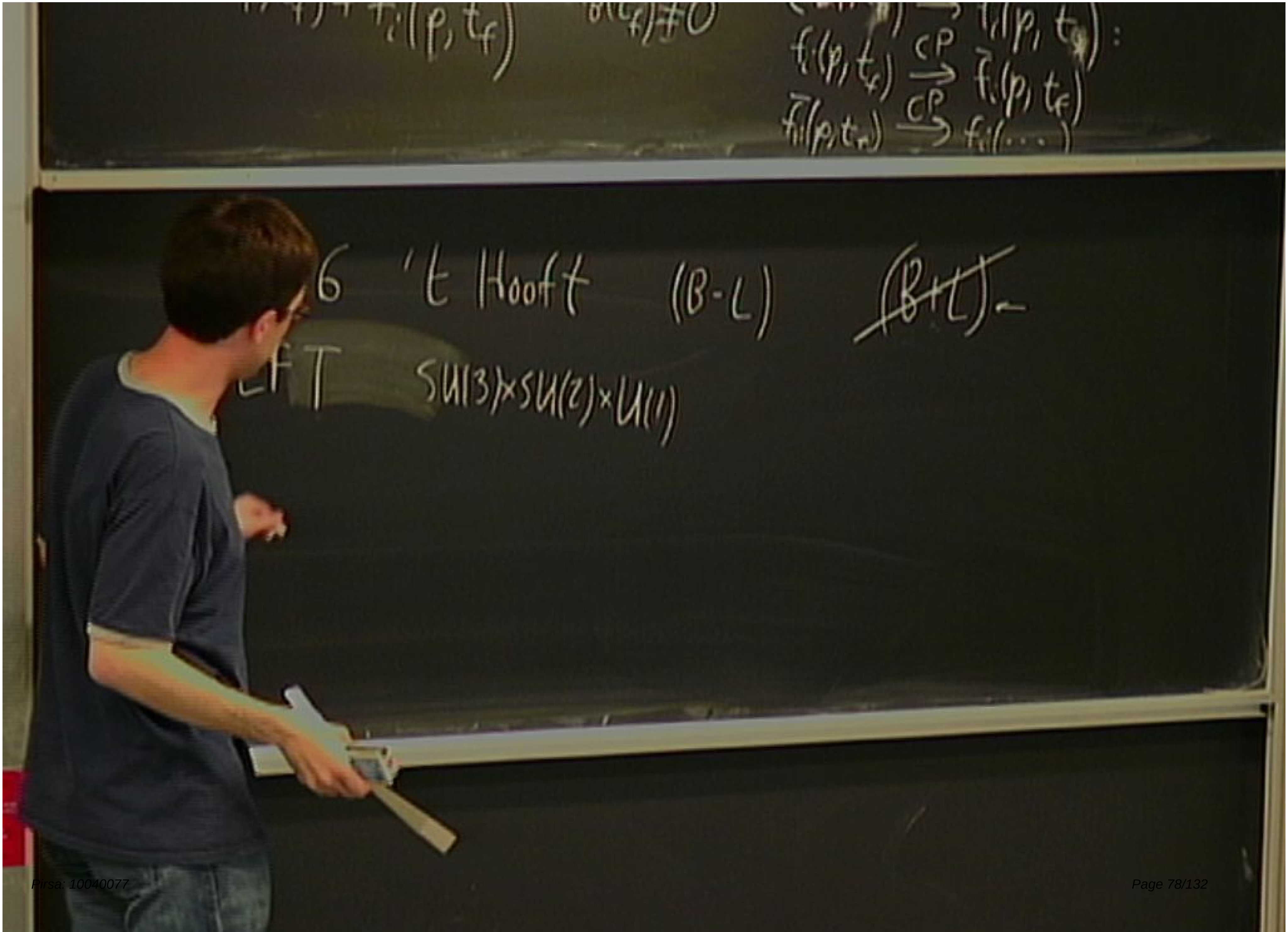
$f_i(p,t_f)$ $\quad \delta(t_f) \neq 0$ $\quad \to f_i(p,t_f)$:

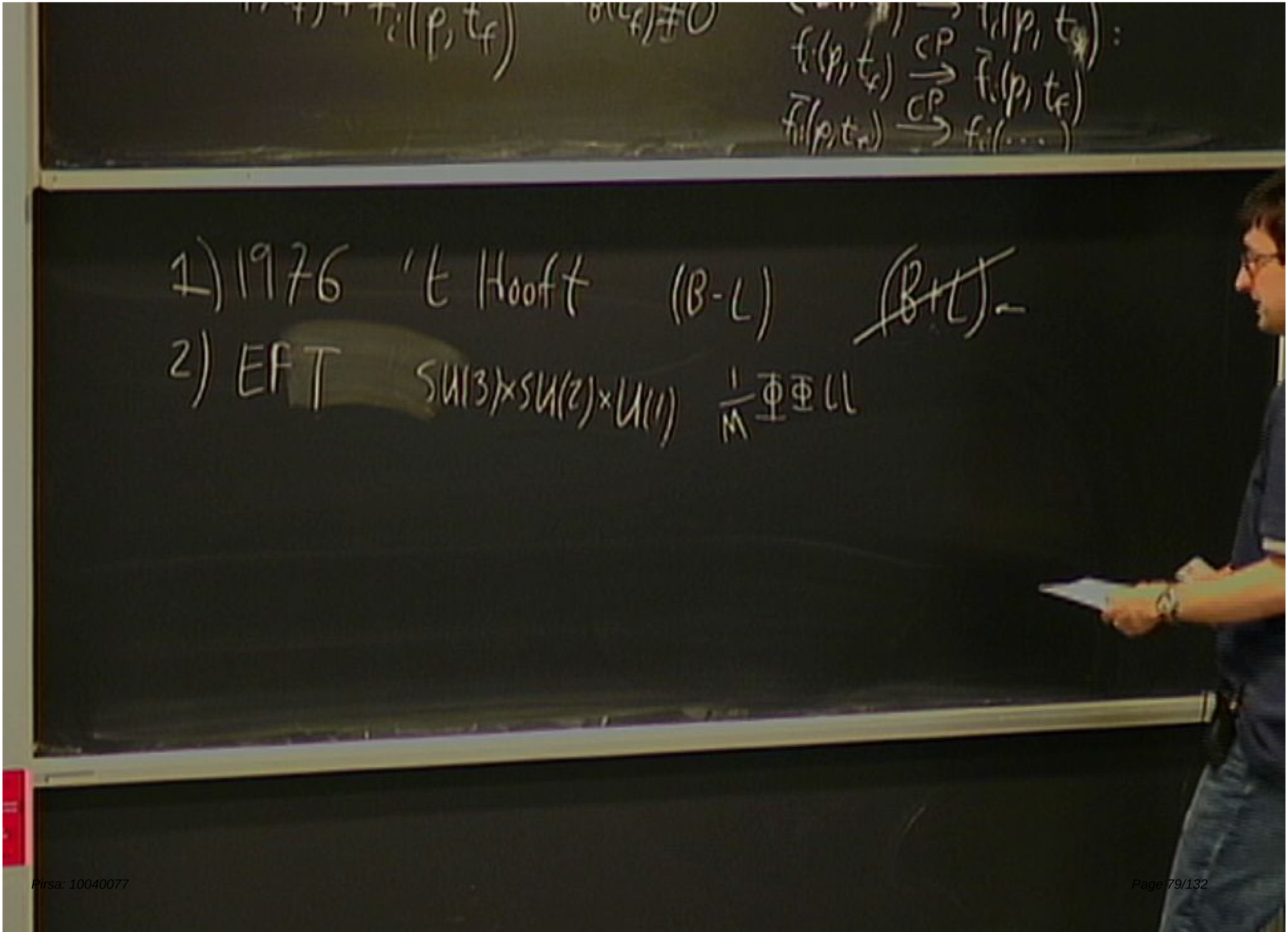
$f_i(p,t_f) \xrightarrow{CP} \bar{f}_i(p,t_f)$

$\bar{f}_i(p,t_f) \xrightarrow{CP} f_i(\ldots)$

1) 1976 't Hooft $(B-L)$ ~~$(B+L)$~~

2) EFT


't Hooft
(B-L)
(B+L)
SU(3)×SU(2)×U(1)


f_i(p, t_f) CP→ f̄_i(p, t_f)
f̄_i(p, t_f) CP→ f_i(...)
1) 1976 't Hooft (B-L) (B+L)
2) EFT SU(3)×SU(2)×U(1) 1/M ΦΦLL

$\dots + f_i(p, t_f)$ $\delta(t_f) \neq 0$ $\dots \to f_i(p, t_f)$:

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\dots)$

1) 1976 't Hooft $(B-L)$ ~~$(B+L)$~~

2) EFT $SU(3) \times SU(2) \times U(1)$ $\frac{1}{M} \Phi \Phi L L$, $\frac{1}{M^2} QQQL$

$f_i(p, t_f)$ $\quad \delta(t_f) \neq 0$ $\quad \to f_i(p, t_f)$:

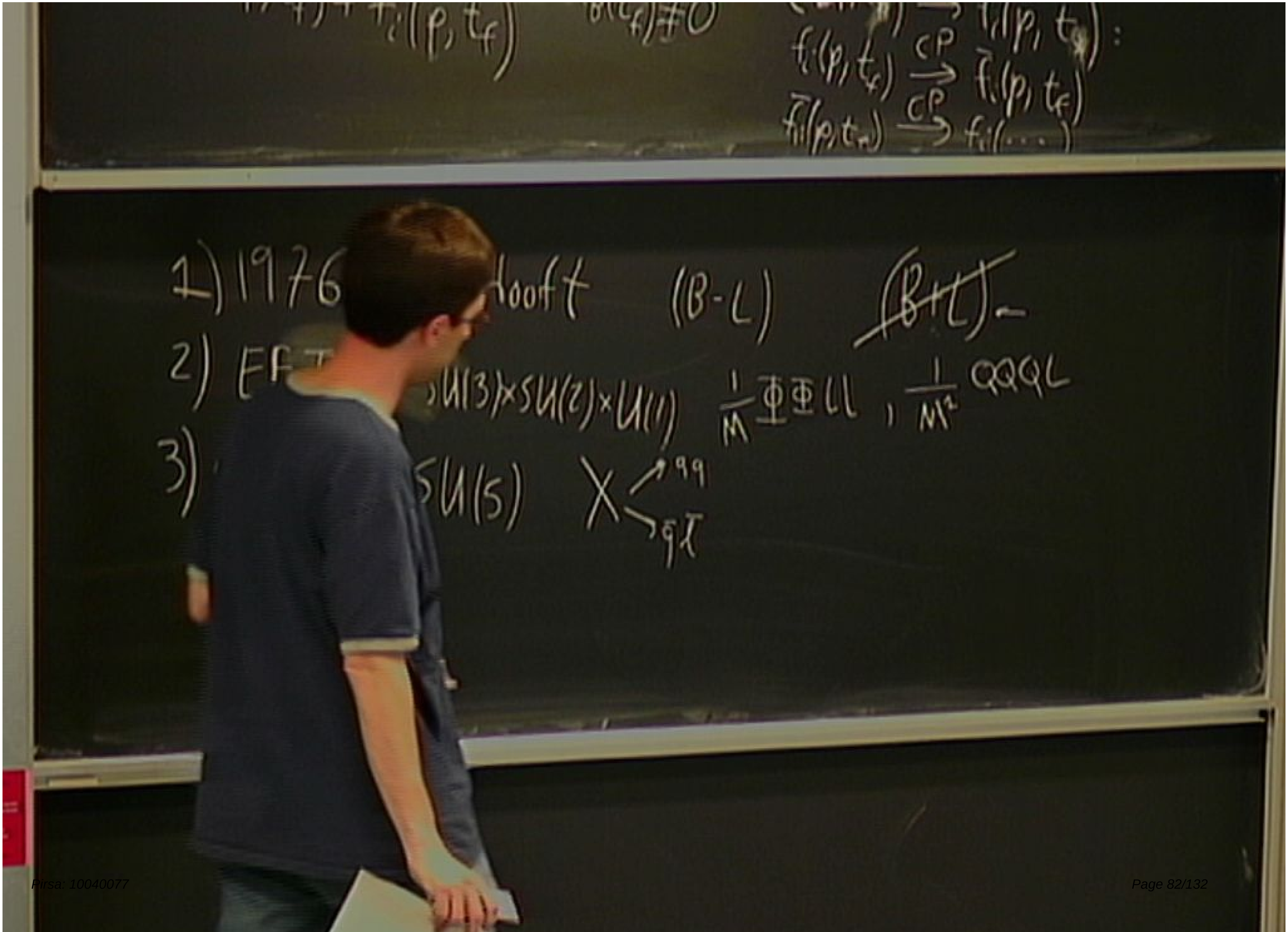
$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\ldots)$

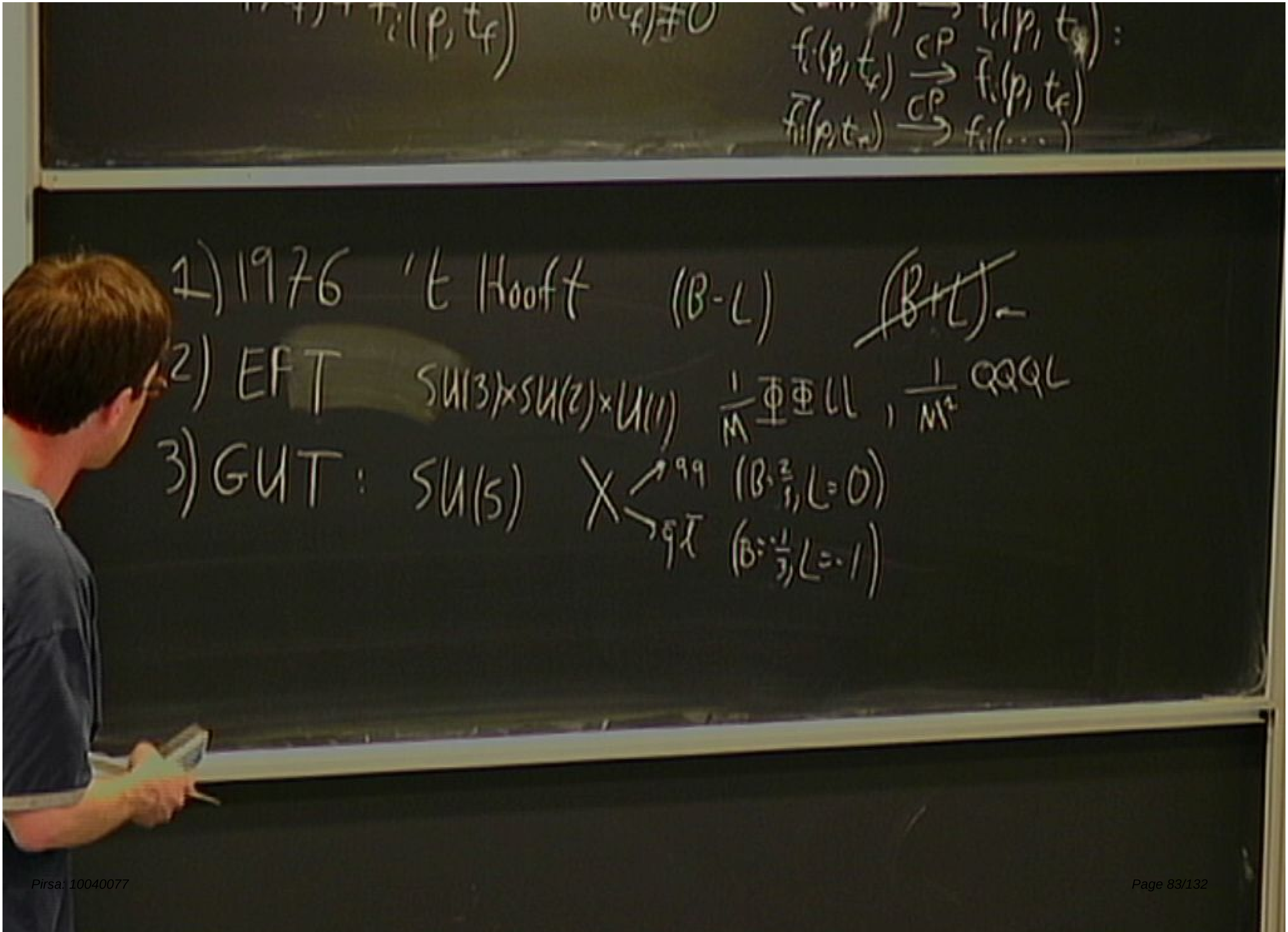
1) 1976 't Hooft $\quad (B-L) \quad$ ~~$(B+L)$~~ ←

2) EFT $\quad SU(3) \times SU(2) \times U(1) \quad \frac{1}{M} \Phi \Phi L L \, , \; \frac{1}{M^2} QQQL$

3) GUT



1) 1976
(B-L)
(B+L)
2)
SU(3)×SU(2)×U(1)
1/M ΦΦLL , 1/M² QQQL
3)
SU(5)
X → qq
q l̄


1) 1976 't Hooft (B-L) (B+L)
2) EFT SU(3)×SU(2)×U(1) 1/M ΦΦLL , 1/M² QQQL
3) GUT: SU(5) X → qq (B=2/3, L=0)
X → q̄l̄ (B=-1/3, L=-1)

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

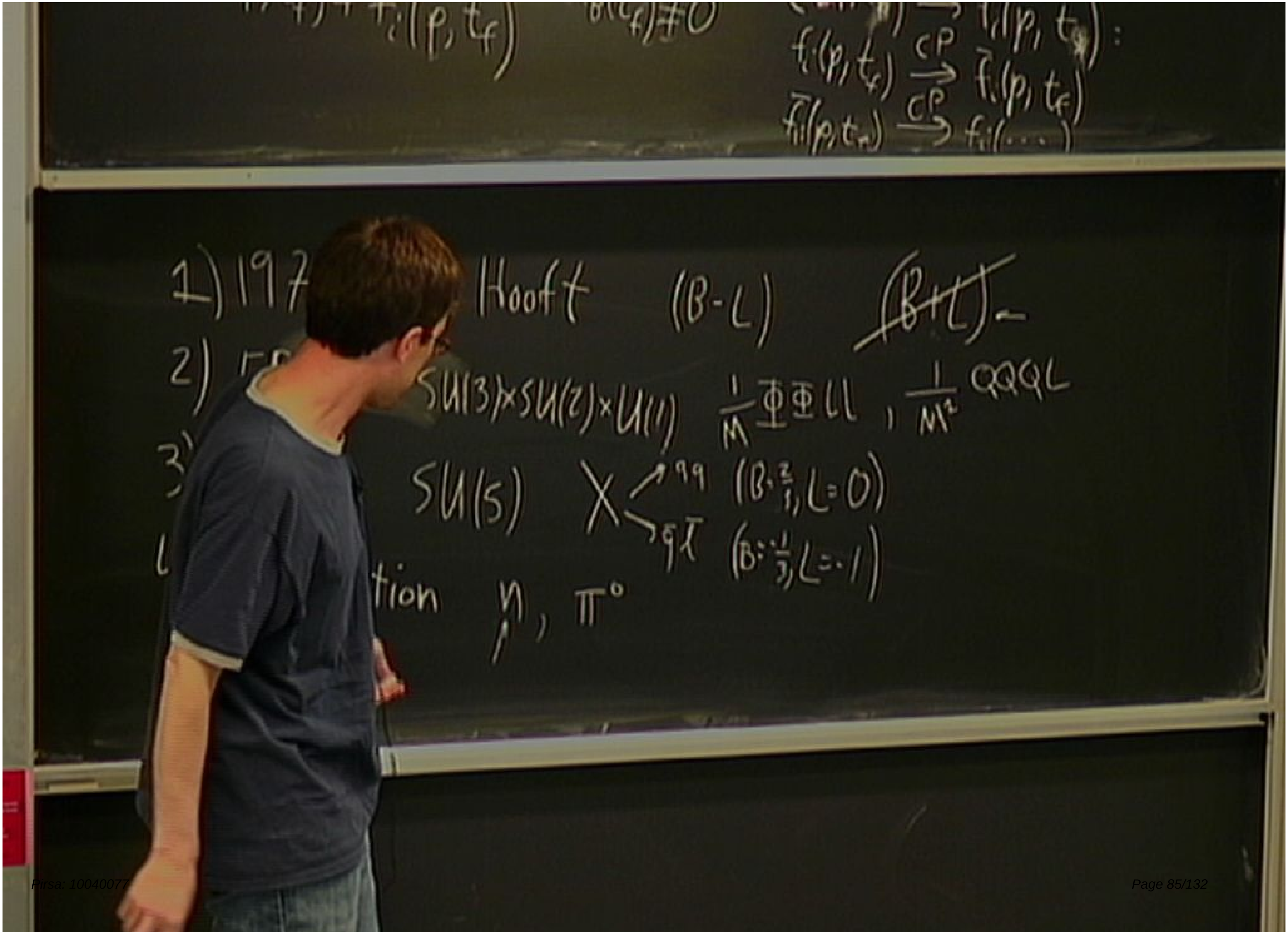
$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\ldots)$

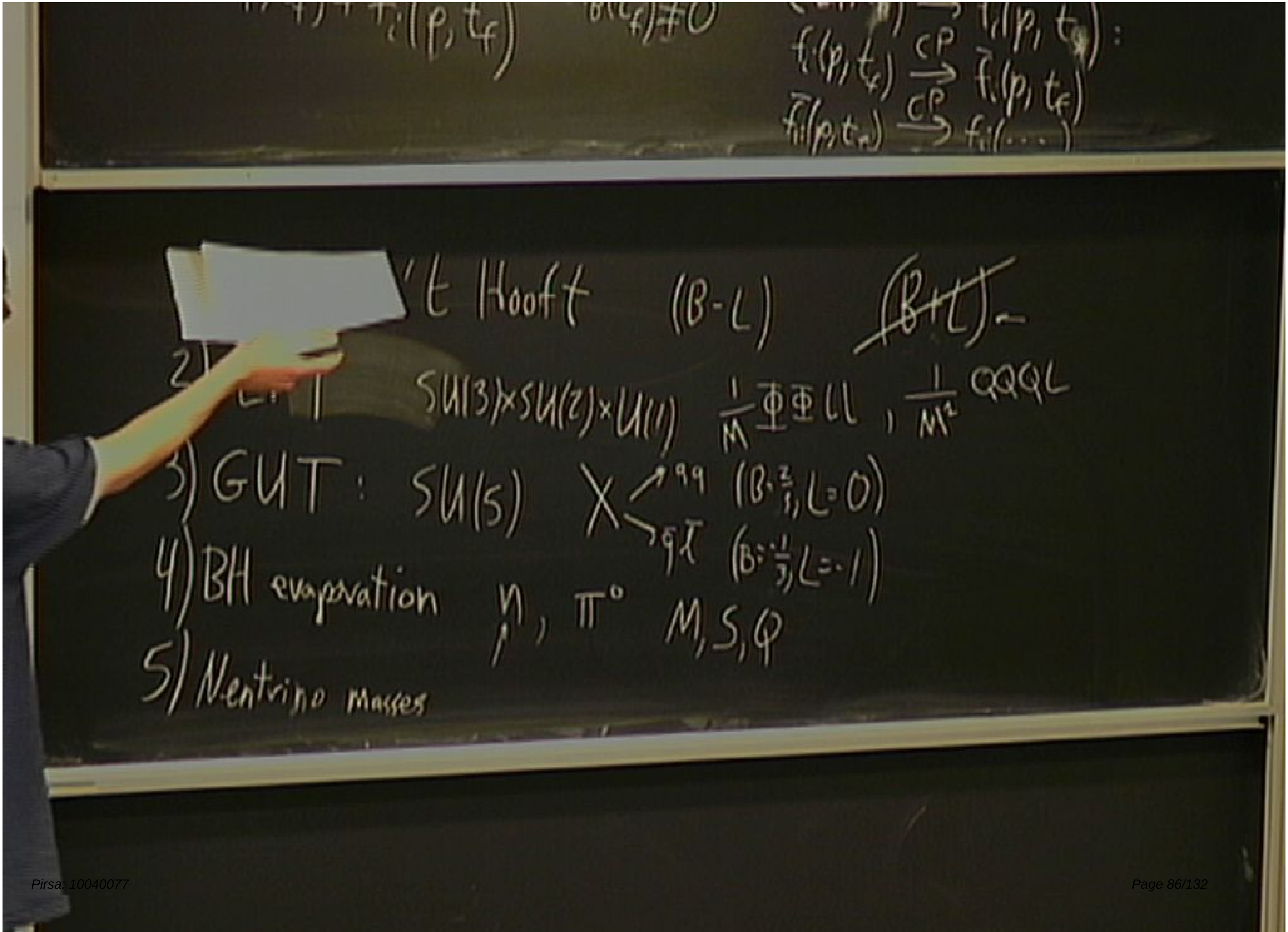
1) 1976 't Hooft $(B-L)$ ~~$(B+L)$~~

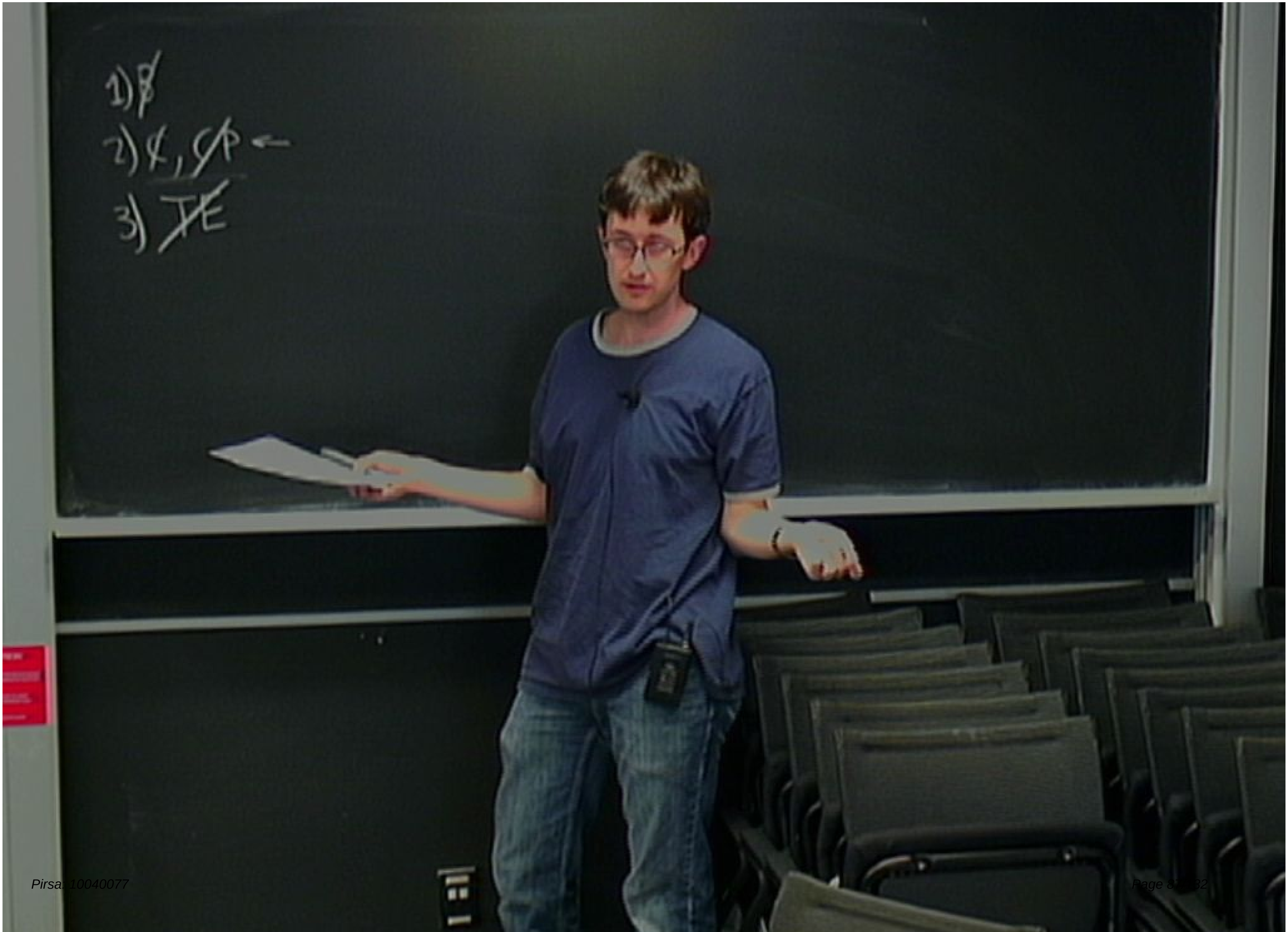
2) EFT $SU(3)\times SU(2)\times U(1)$ $\frac{1}{M}\Phi\Phi LL$, $\frac{1}{M^2} QQQL$

3) GUT : $SU(5)$ $X \to qq$ $(B=\frac{2}{3}, L=0)$; $X \to q\bar{l}$ $(B=-\frac{1}{3}, L=-1)$

4) BH evaporation


1) 197
Hooft
(B-L)
(B+L)
2)
SU(3)×SU(2)×U(1)
QQQL
3)
SU(5)
X
qq
(B=2/3, L=0)
(B=-1/3, L=-1)
tion
π°


f_i(p, t_f) CP→ f̄_i(p, t_f)
f̄_i(p, t_f) CP→ f_i(...)
't Hooft (B-L) (B+L)
2) SU(3)×SU(2)×U(1) 1/M ΦΦLL , 1/M² QQQL
3) GUT: SU(5) X → qq (B=2/3, L=0)
q̄l̄ (B=-1/3, L=-1)
4) BH evaporation η, π⁰ M, S, Q
5) Neutrino masses



$\ldots f_i(p, t_f)$ $\quad \delta(t_f) \neq 0$ $\quad \ldots \rightarrow \bar{f}_i(p, t_f)$:

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\ldots)$

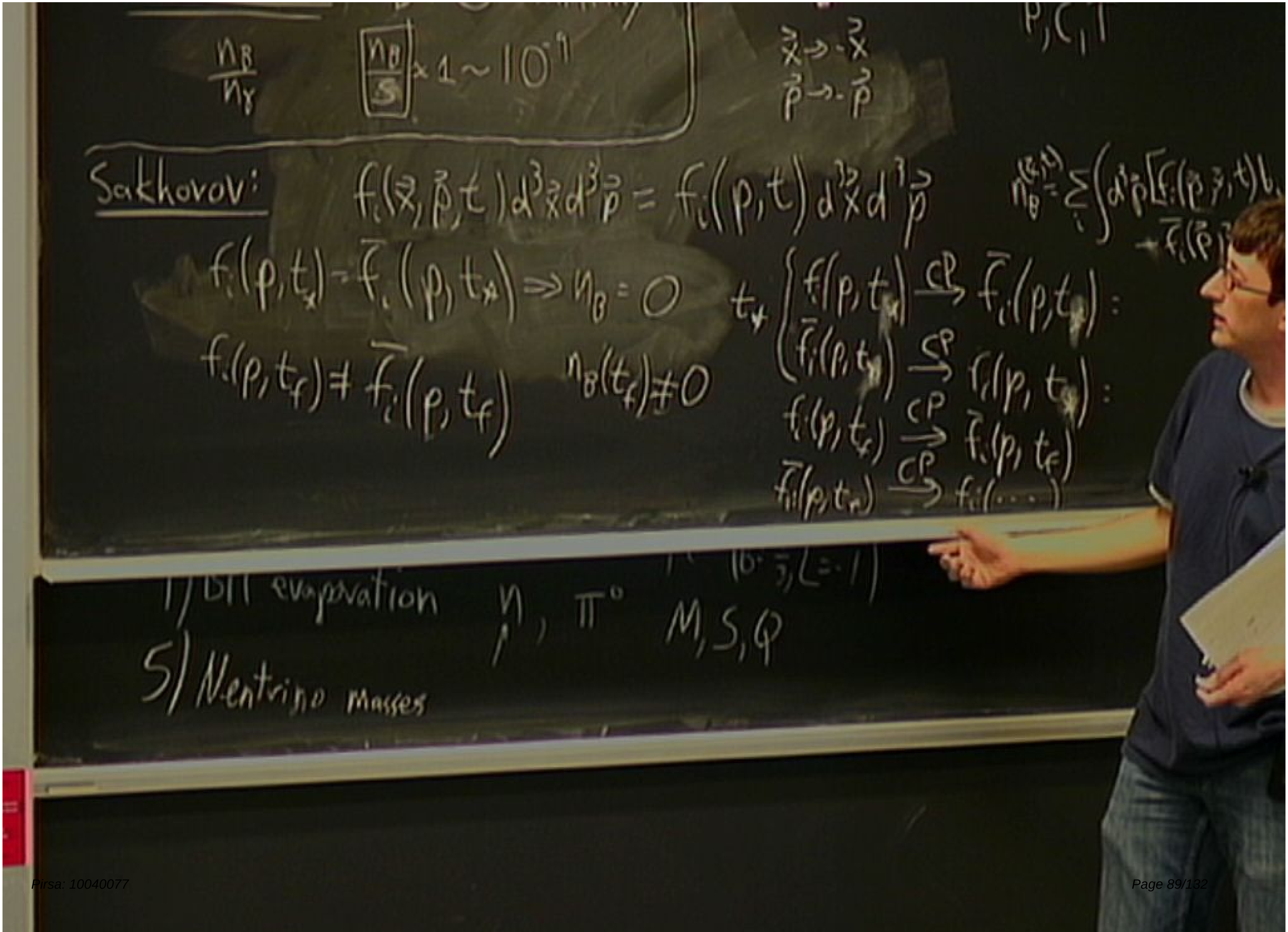
1) 1976 't Hooft $(B-L)$ $\cancel{(B+L)}$

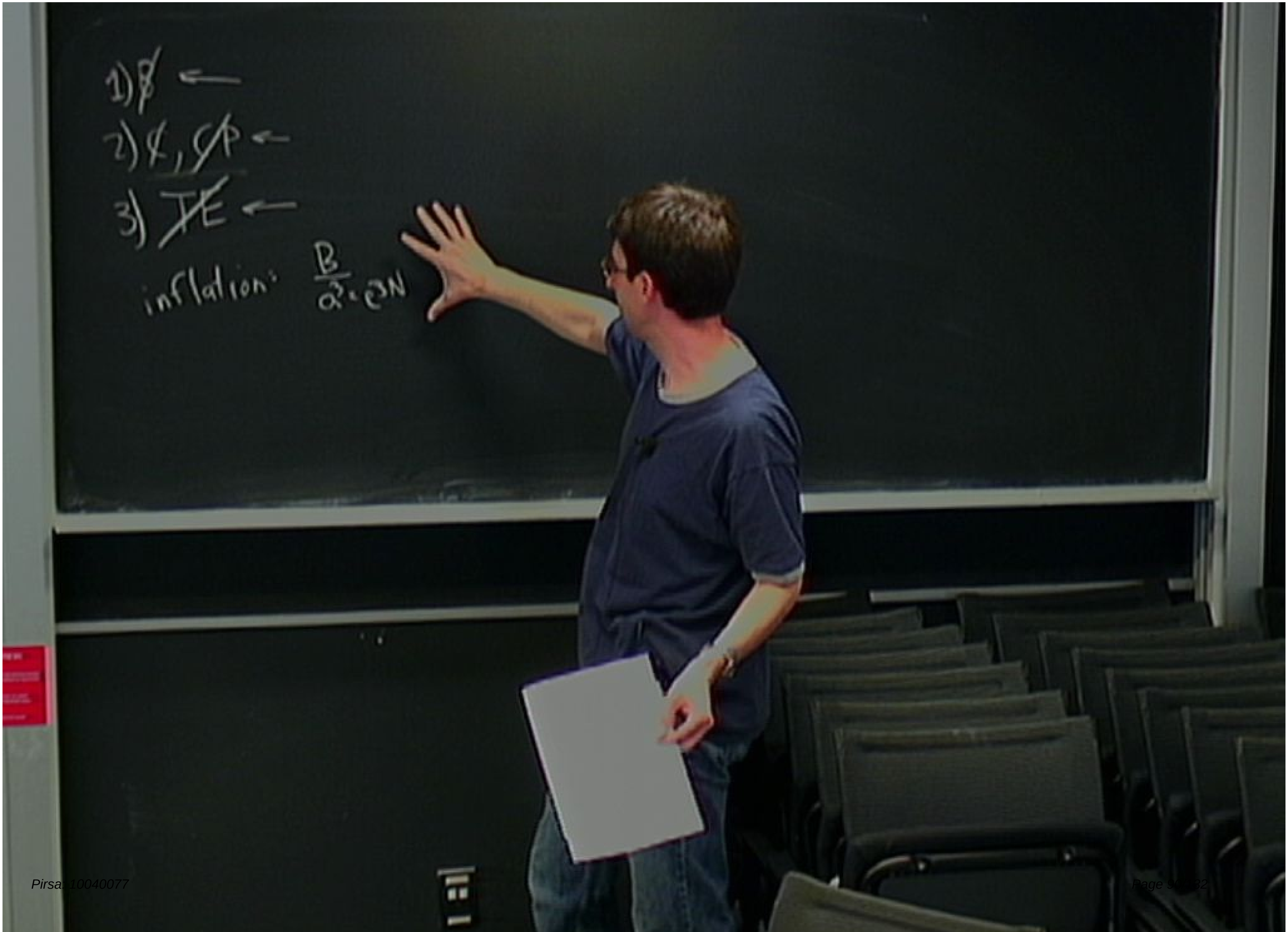
2) EFT $SU(3) \times SU(2) \times U(1)$ $\frac{1}{M} \Phi \Phi L L$, $\frac{1}{M^2} QQQL$

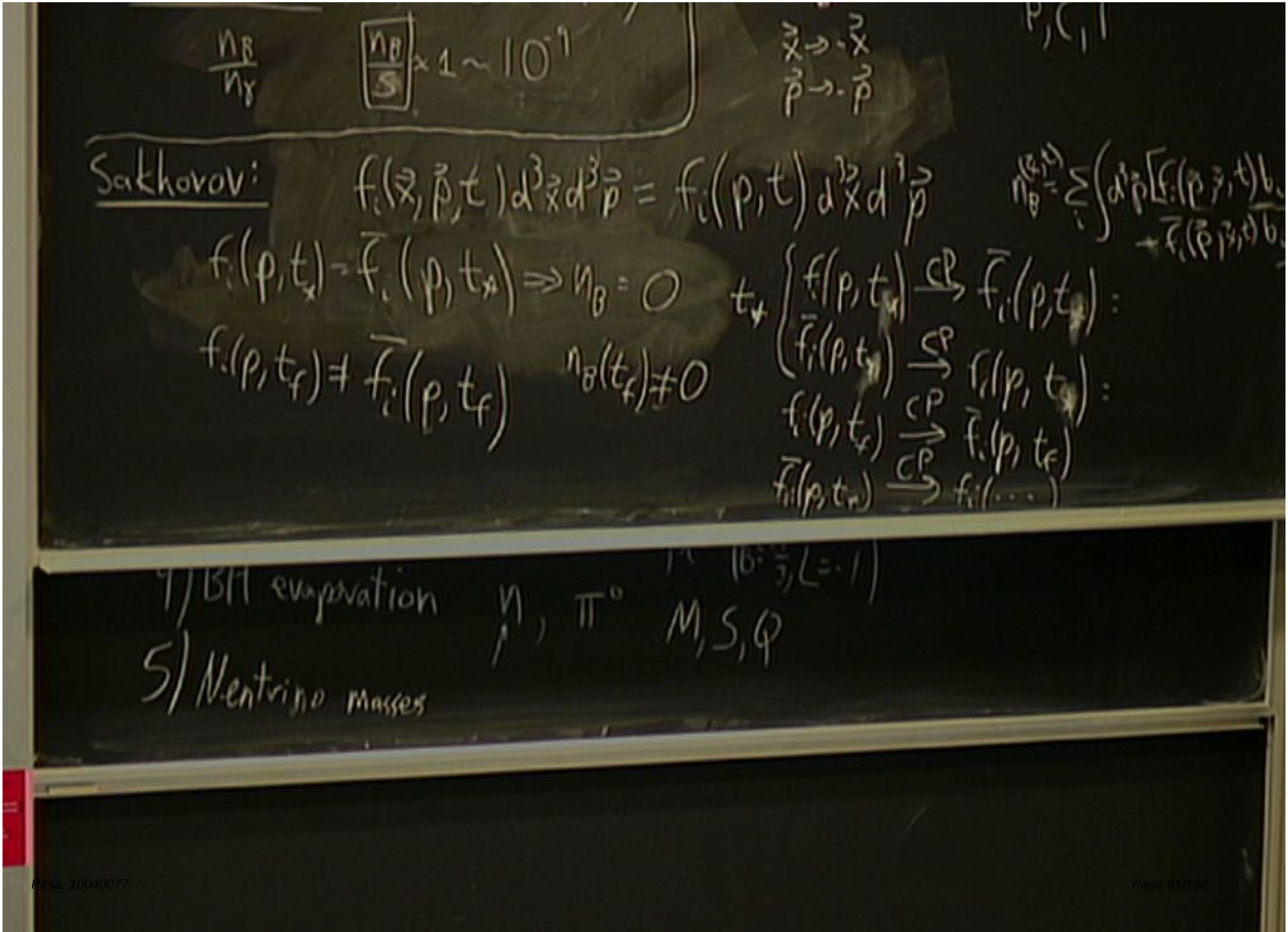
3) GUT : $SU(5)$ $X \rightarrow qq$ $(B = \frac{2}{3}, L = 0)$; $X \rightarrow q\bar{\ell}$ $(B = -\frac{1}{3}, L = -1)$

4) BH evaporation γ, π^0 M, S, Q

5) Neutrino masses


Sakharov:
f_i(x, p, t) d^3x d^3p = f_i(p, t) d^3x d^3p
f_i(p,t_*) = f̄_i(p,t_*) ⇒ n_B = 0
f_i(p,t_f) ≠ f̄_i(p,t_f)
n_B(t_f) ≠ 0
CP
4) BH evaporation
M, S, Q
5) Neutrino masses


1) B̸ ←
2) C̸, C̸P ←
3) T̸E ←
inflation: B / a³ ~ e^{3N}



$\frac{n_B}{n_\gamma}$ $\frac{n_B}{s} \times 1 \sim 10^{-9}$
$\vec{x} \to -\vec{x}$
$\vec{p} \to -\vec{p}$
P, C, T
Sakharov:
$f_i(\vec{x}, \vec{p}, t)\, d^3\vec{x}\, d^3\vec{p} = f_i(p, t)\, d^3\vec{x}\, d^3\vec{p}$
$f_i(p, t_*) = \bar{f}_i(p, t_*) \Rightarrow n_B = 0$
$f_i(p, t_f) \neq \bar{f}_i(p, t_f)$ $n_B(t_f) \neq 0$
$f_i(p, t_*) \xrightarrow{CP} \bar{f}_i(p, t_*)$
$\bar{f}_i(p, t_*) \xrightarrow{CP} f_i(p, t_*)$
$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$
4) BH evaporation η, π^0 M, S, Q
5) Neutrino masses

$f_i(p, t_f)$ $\quad \neq 0$ $\quad f_i(p, t_f)$:

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_n) \xrightarrow{CP} f_i(\ldots)$

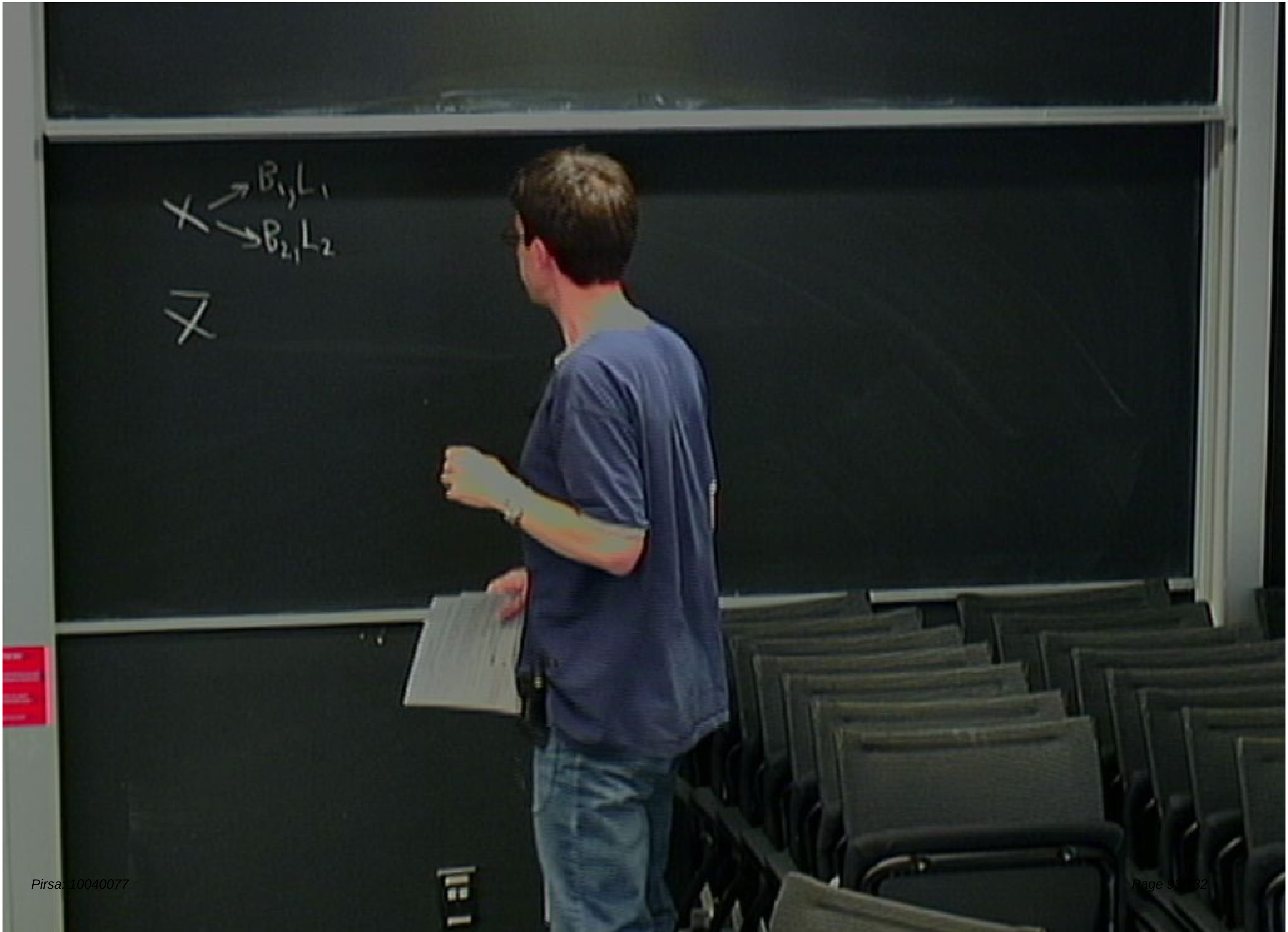
1) 1976 't Hooft $(B-L)$ ~~$(B+L)$~~

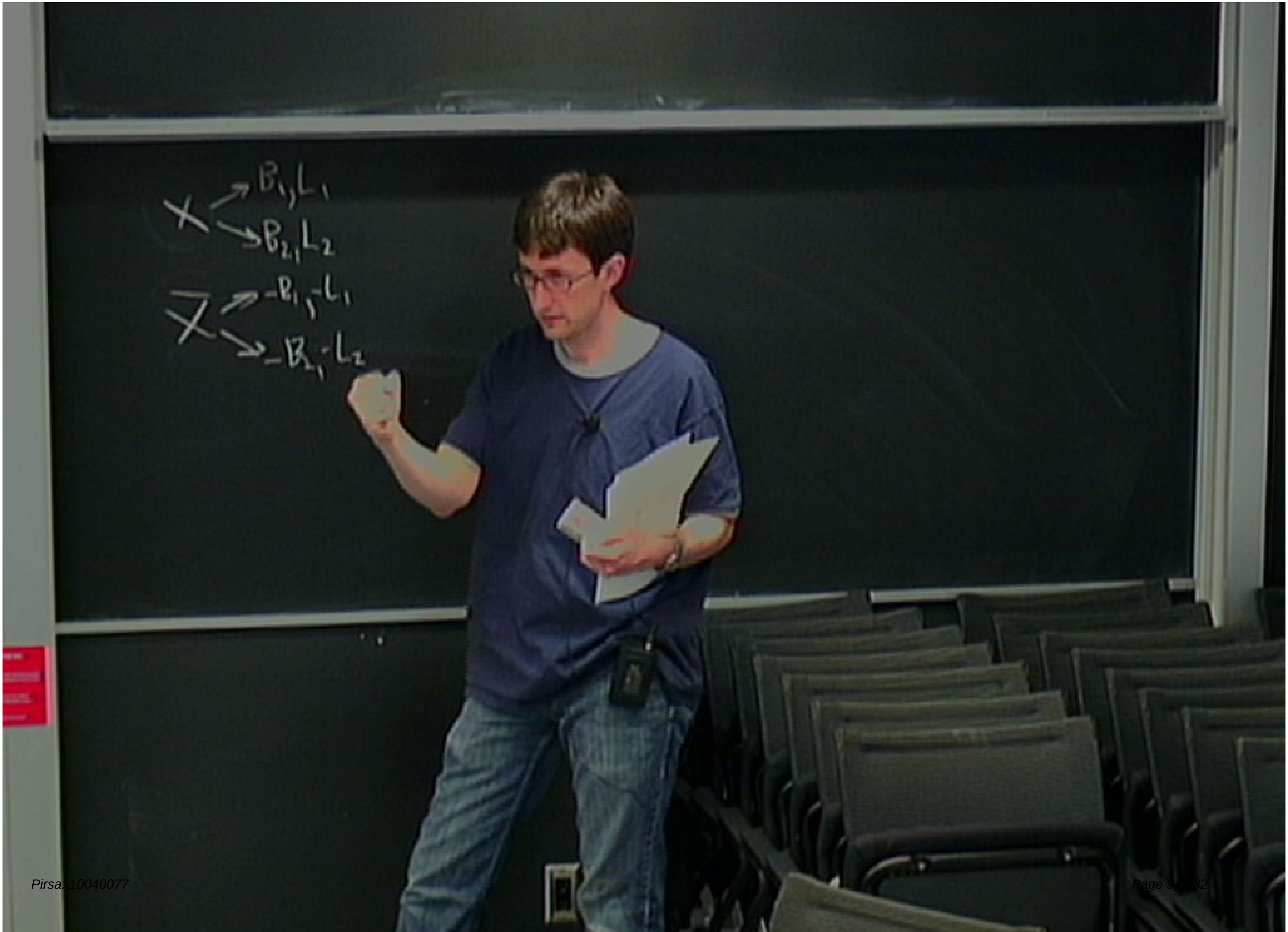
2) EFT $SU(3)\times SU(2)\times U(1)$ $\frac{1}{M}\Phi\Phi LL$, $\frac{1}{M^2}QQQL$

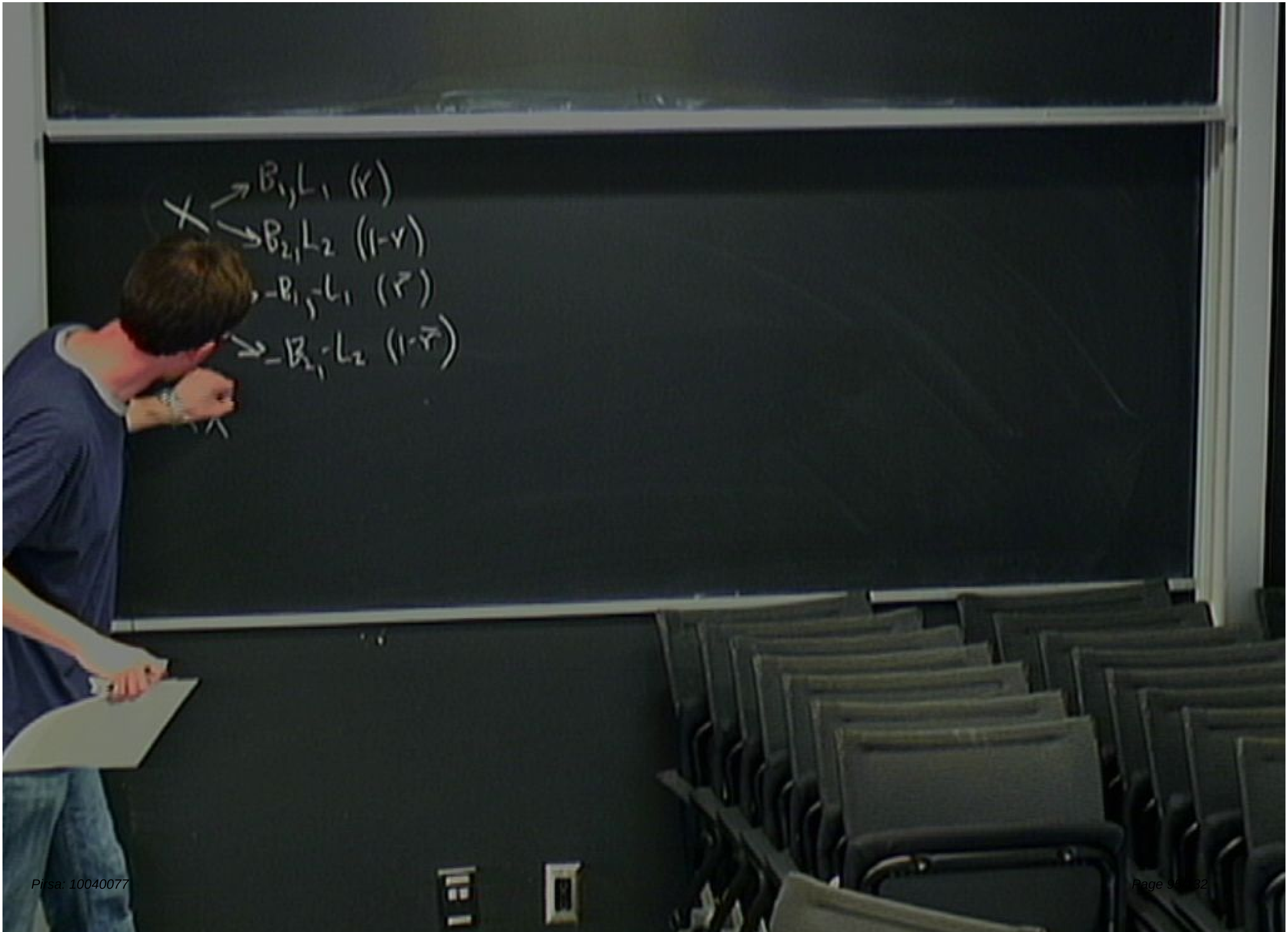
3) GUT: $SU(5)$ $X \to qq$ $(B=\frac{2}{3}, L=0)$; $X \to q\bar{l}$ $(B=-\frac{1}{3}, L=-1)$

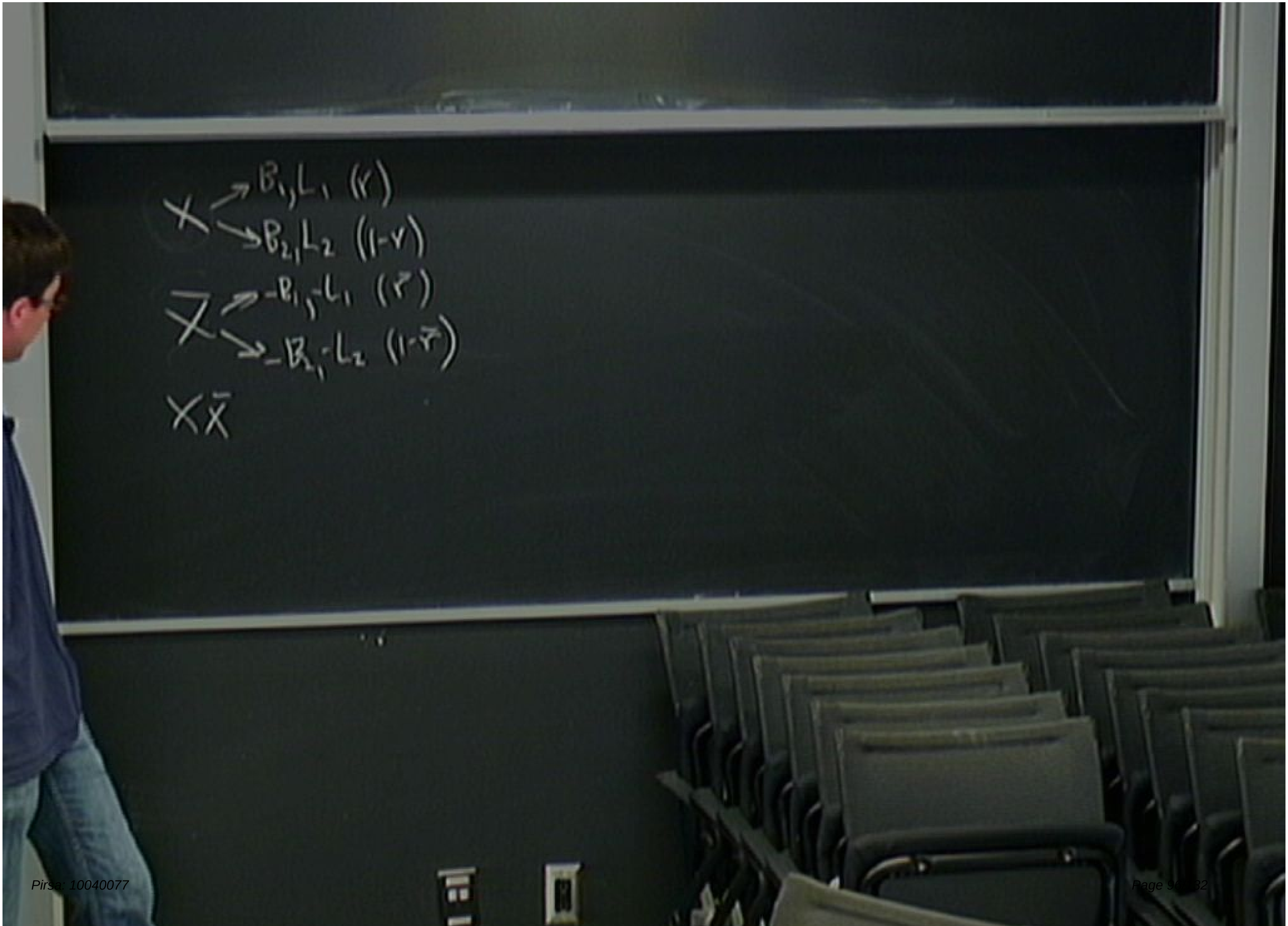
4) BH evaporation n, π^0 M, S, Q

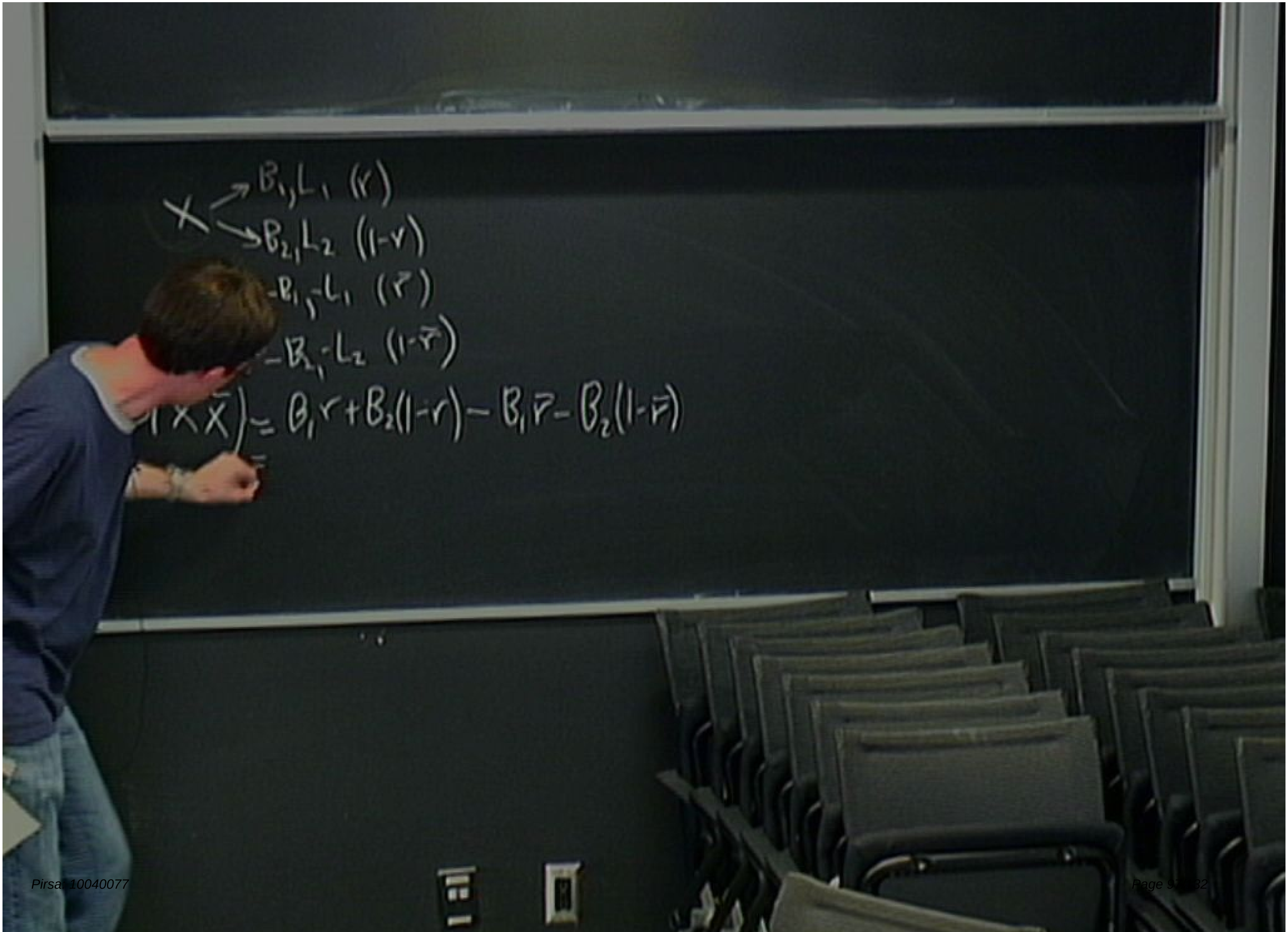
5) Neutrino masses


X → B1, L1
→ B2, L2
X̄

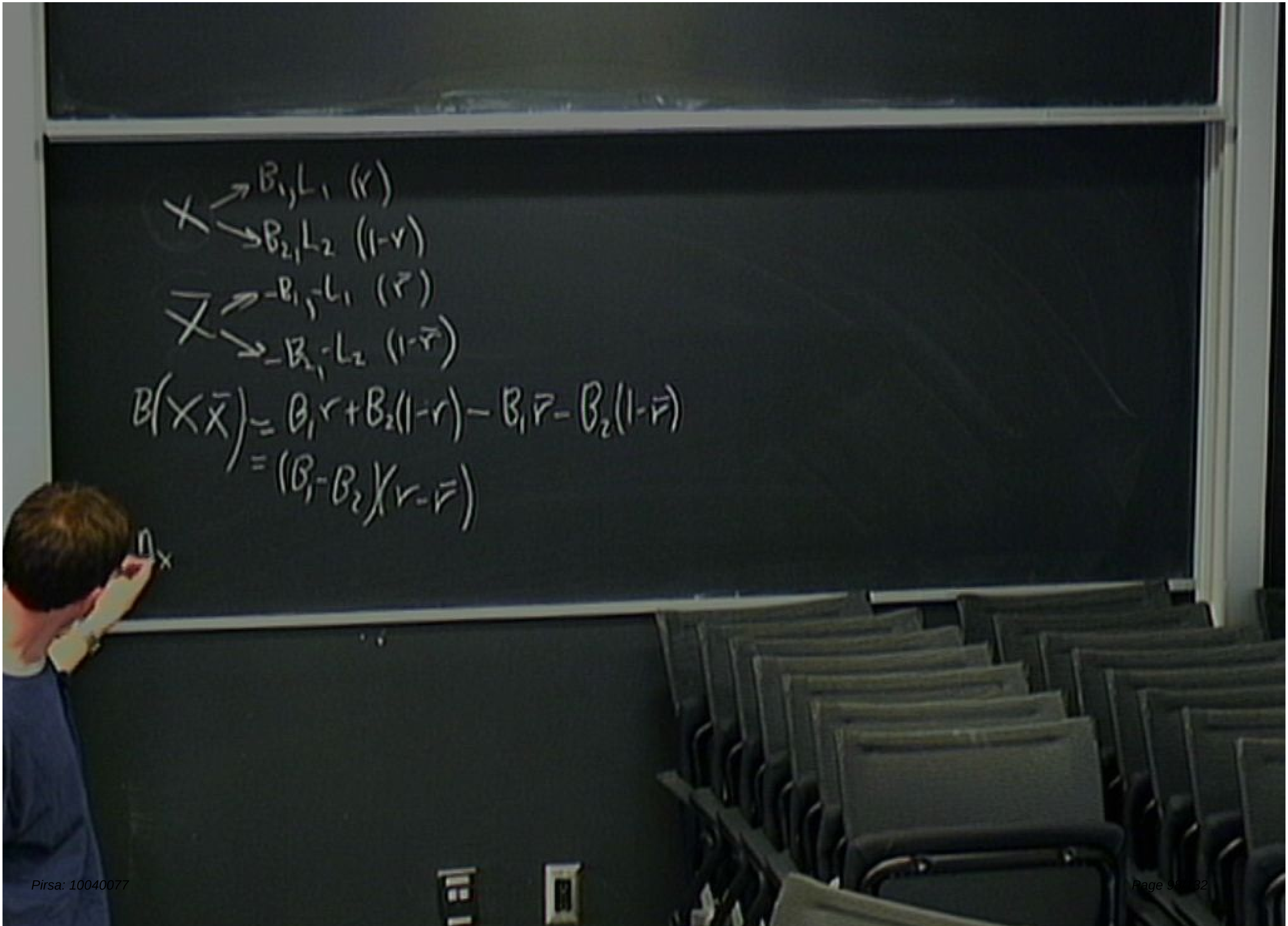

X → B1, L1
X → B2, L2
X̄ → -B1, -L1
X̄ → -B2, -L2

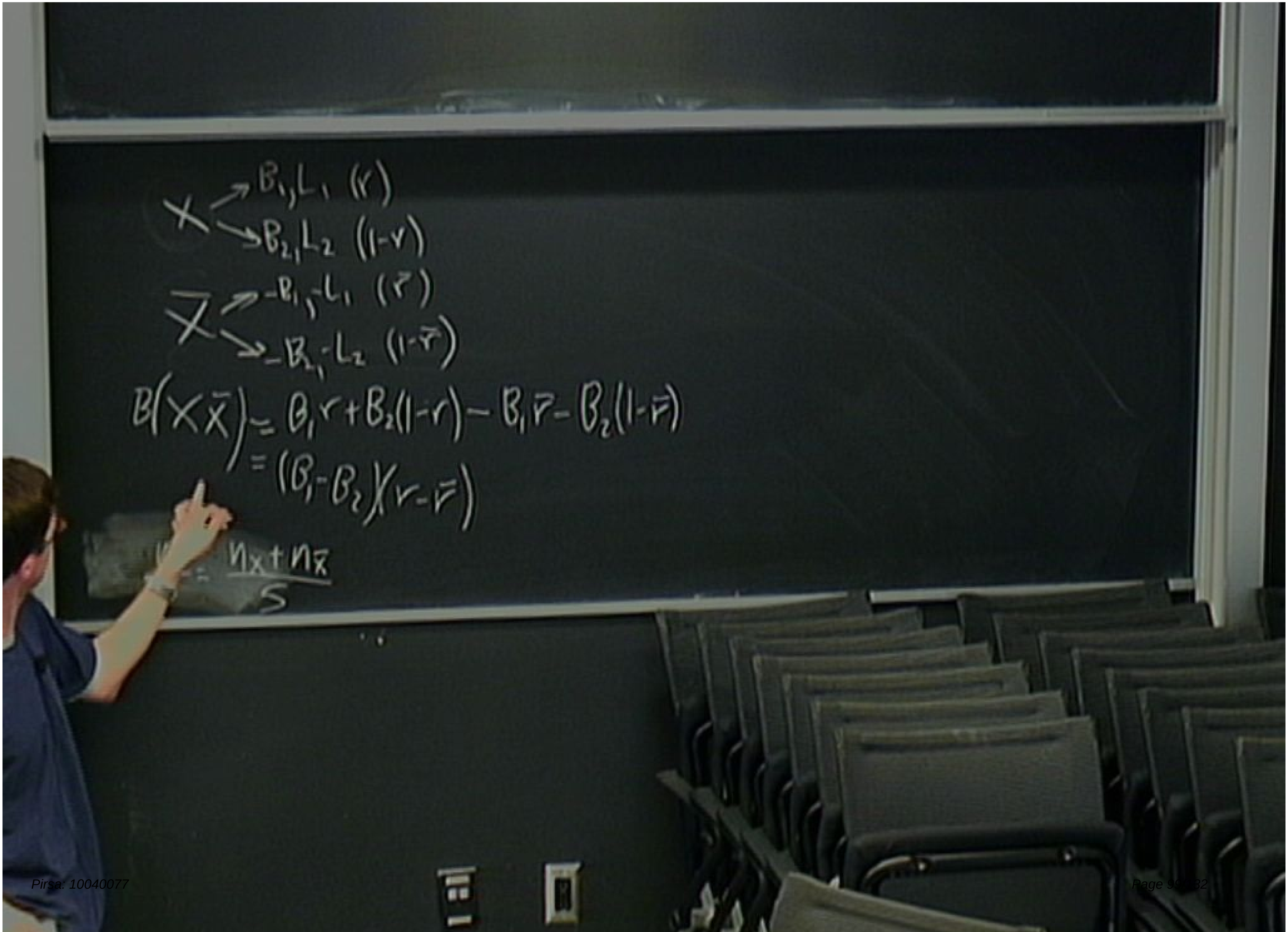

X → B1, L1 (r)
→ B2, L2 (1-r)
→ -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)

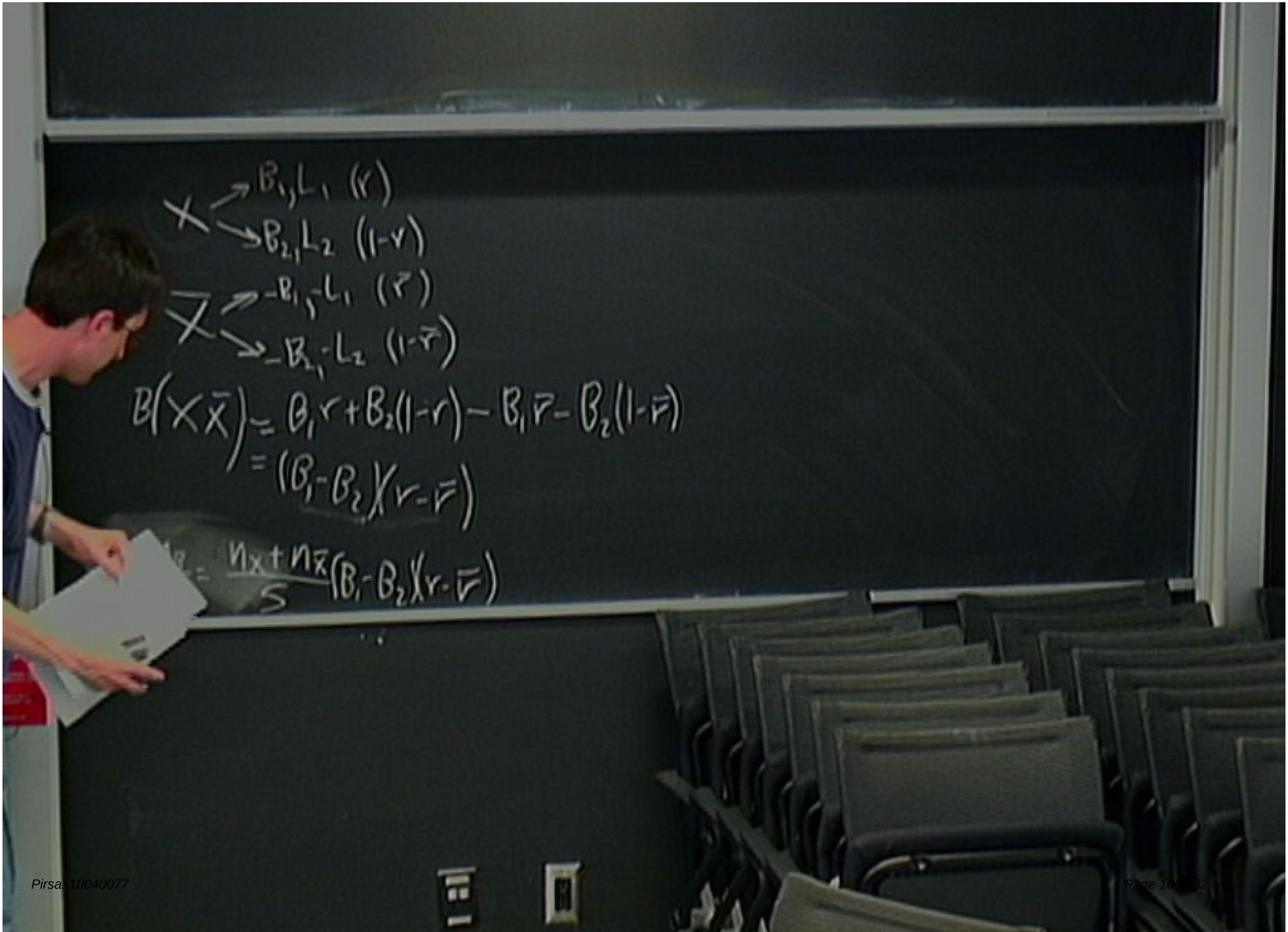

$X \to B_1, L_1 \quad (r)$
$X \to B_2, L_2 \quad (1-r)$
$\bar{X} \to -B_1, -L_1 \quad (\bar{r})$
$\bar{X} \to -B_2, -L_2 \quad (1-\bar{r})$
$X\bar{X}$



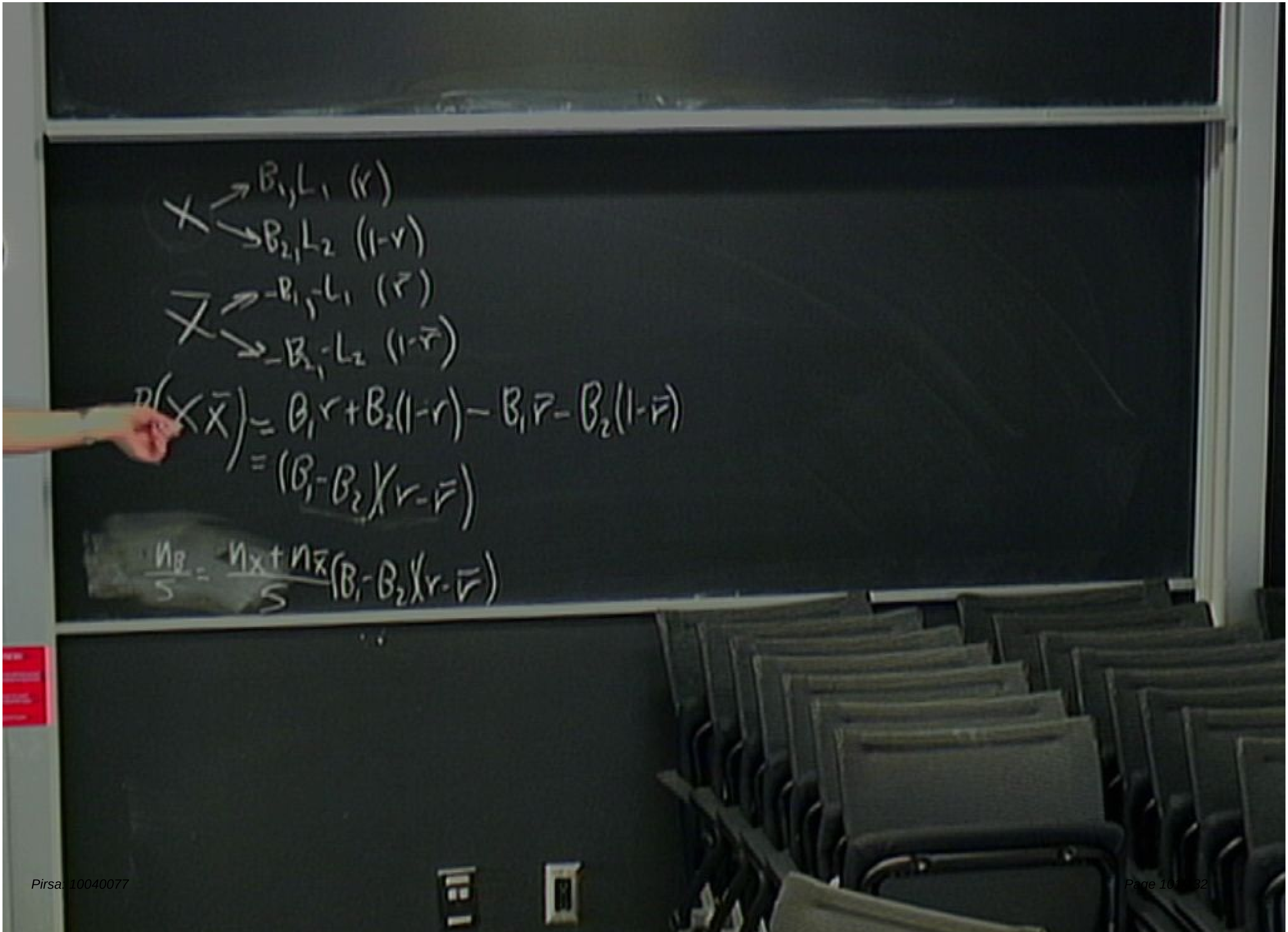
X → B1, L1 (r)
→ B2, L2 (1-r)
B1, L1 (r̄)
B2, L2 (1-r̄)
= B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)

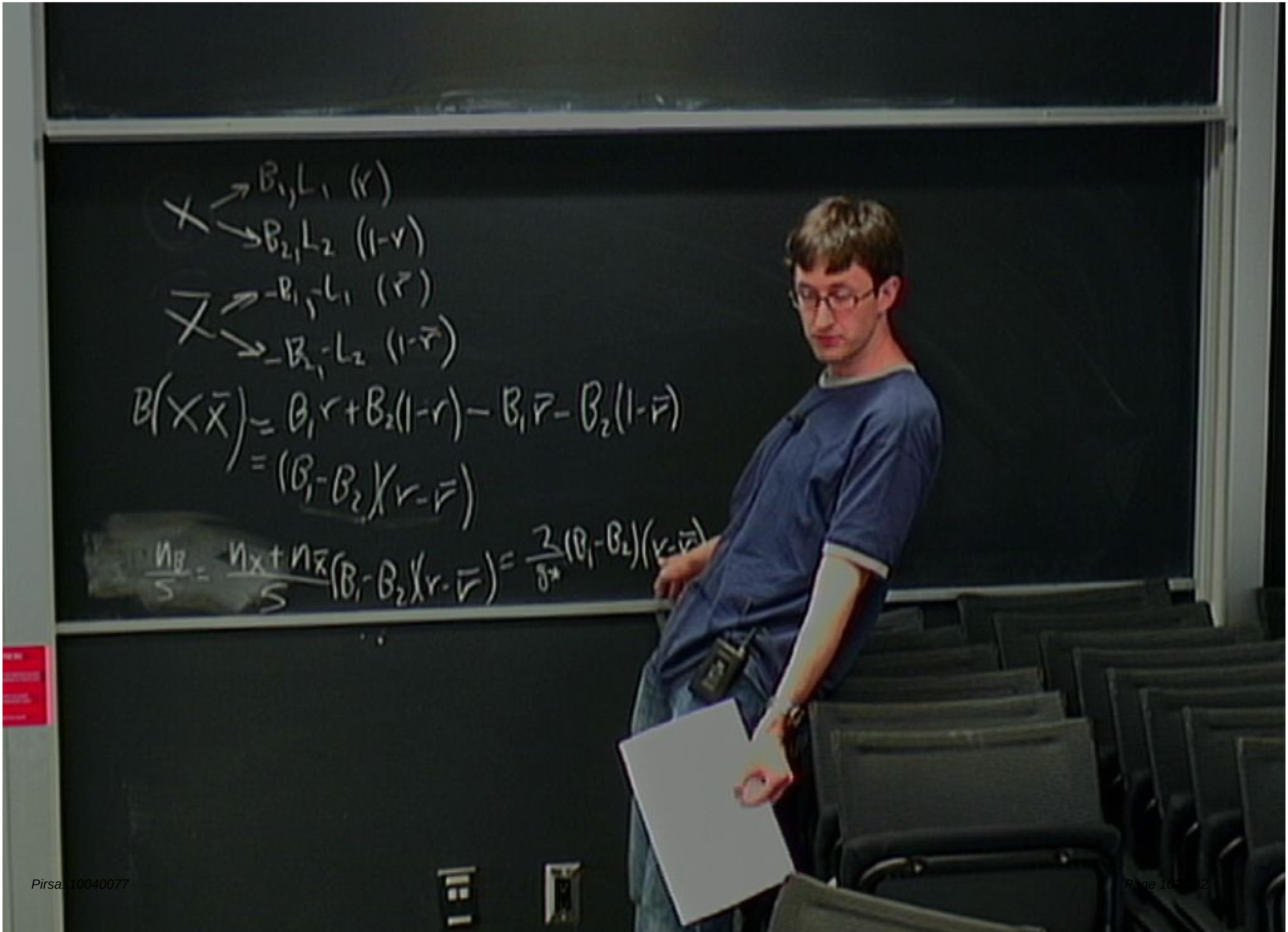

X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nX

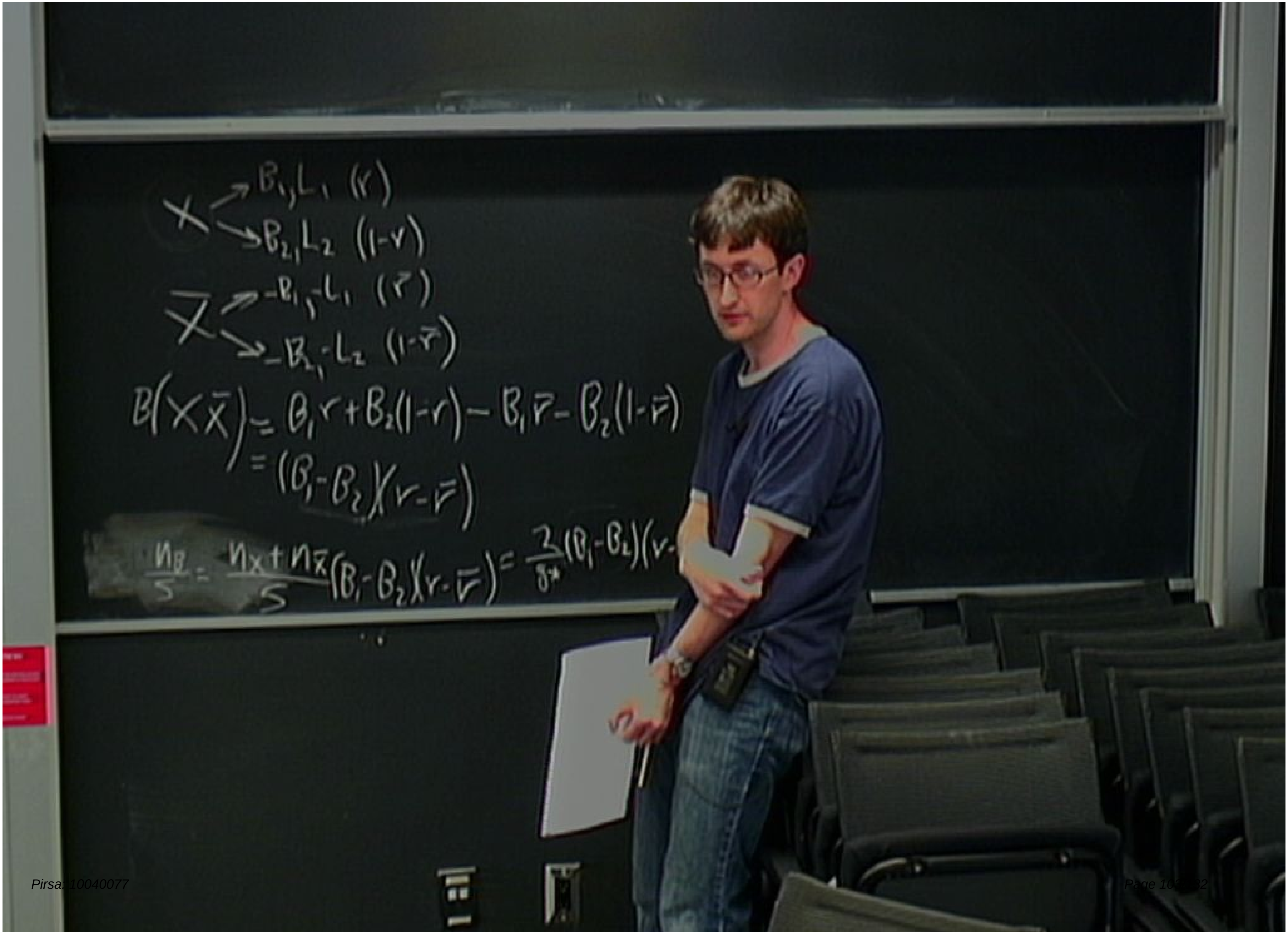

X → B1, L1 (r)
X → B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
X̄ → -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
(nX + nX̄)/S

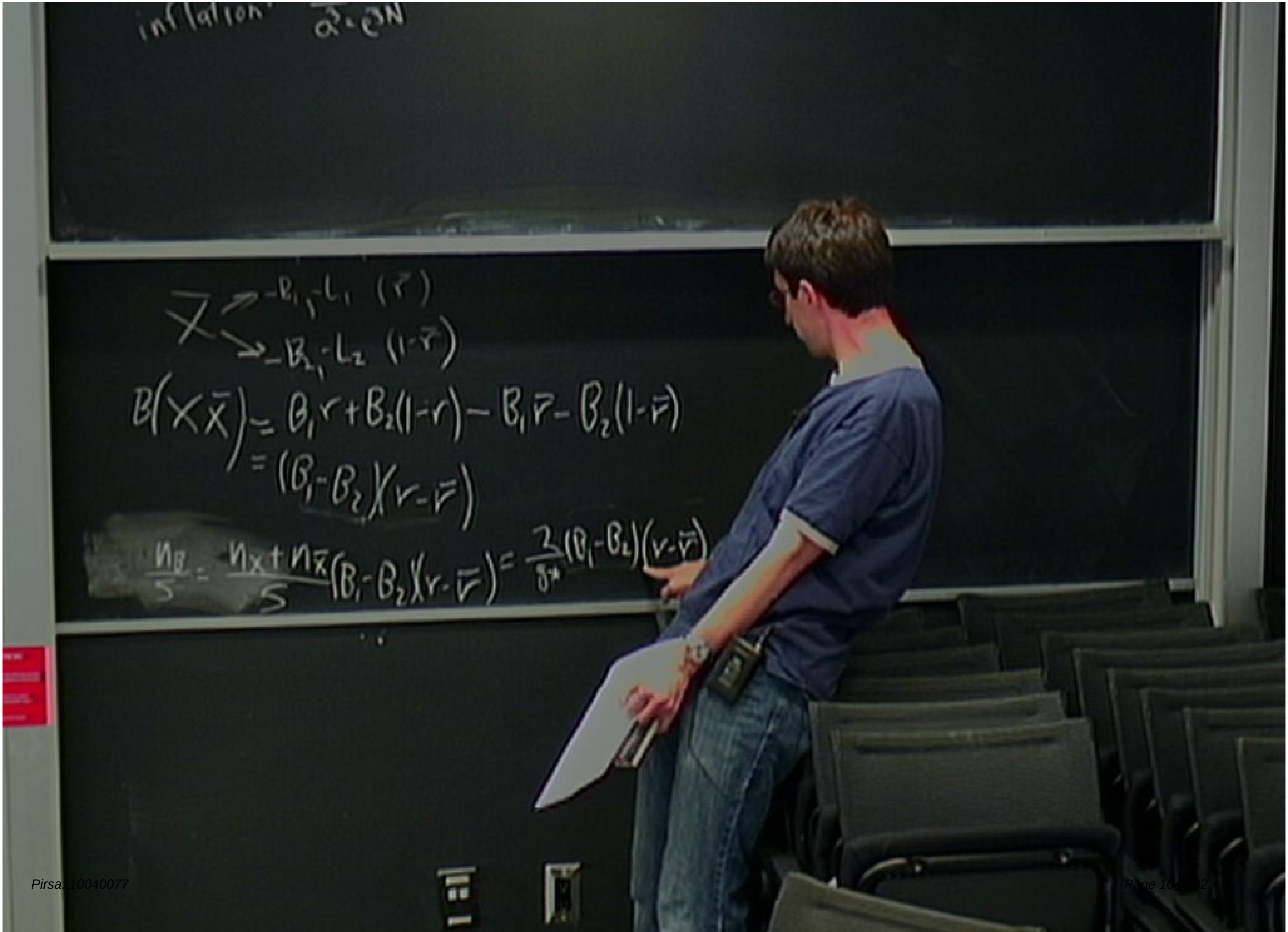


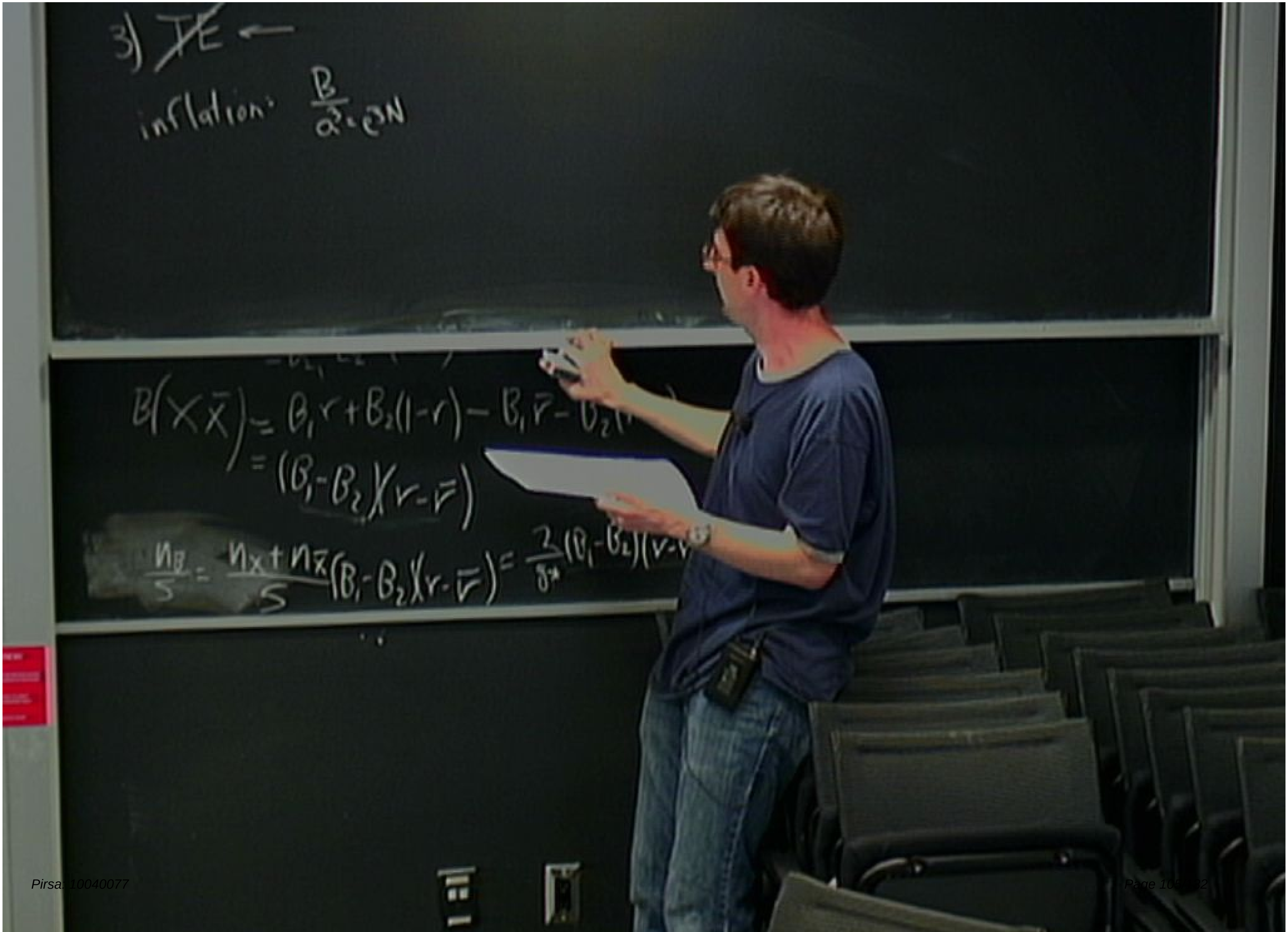
X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(XX̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
= (nX + nX̄)/S (B1-B2)(r-r̄)

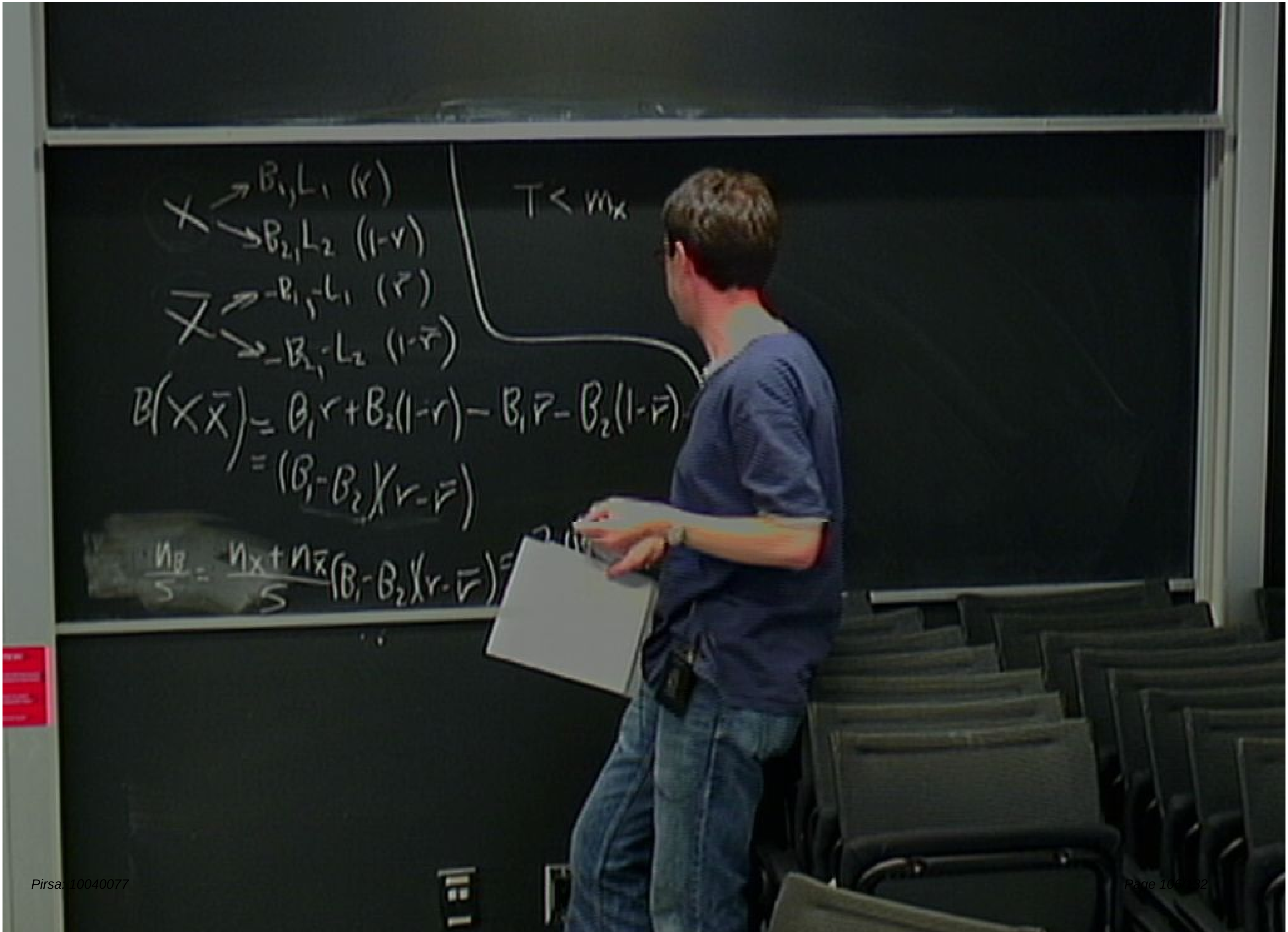

X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
D(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/S = (nX + nX̄)/S (B1-B2)(r-r̄)

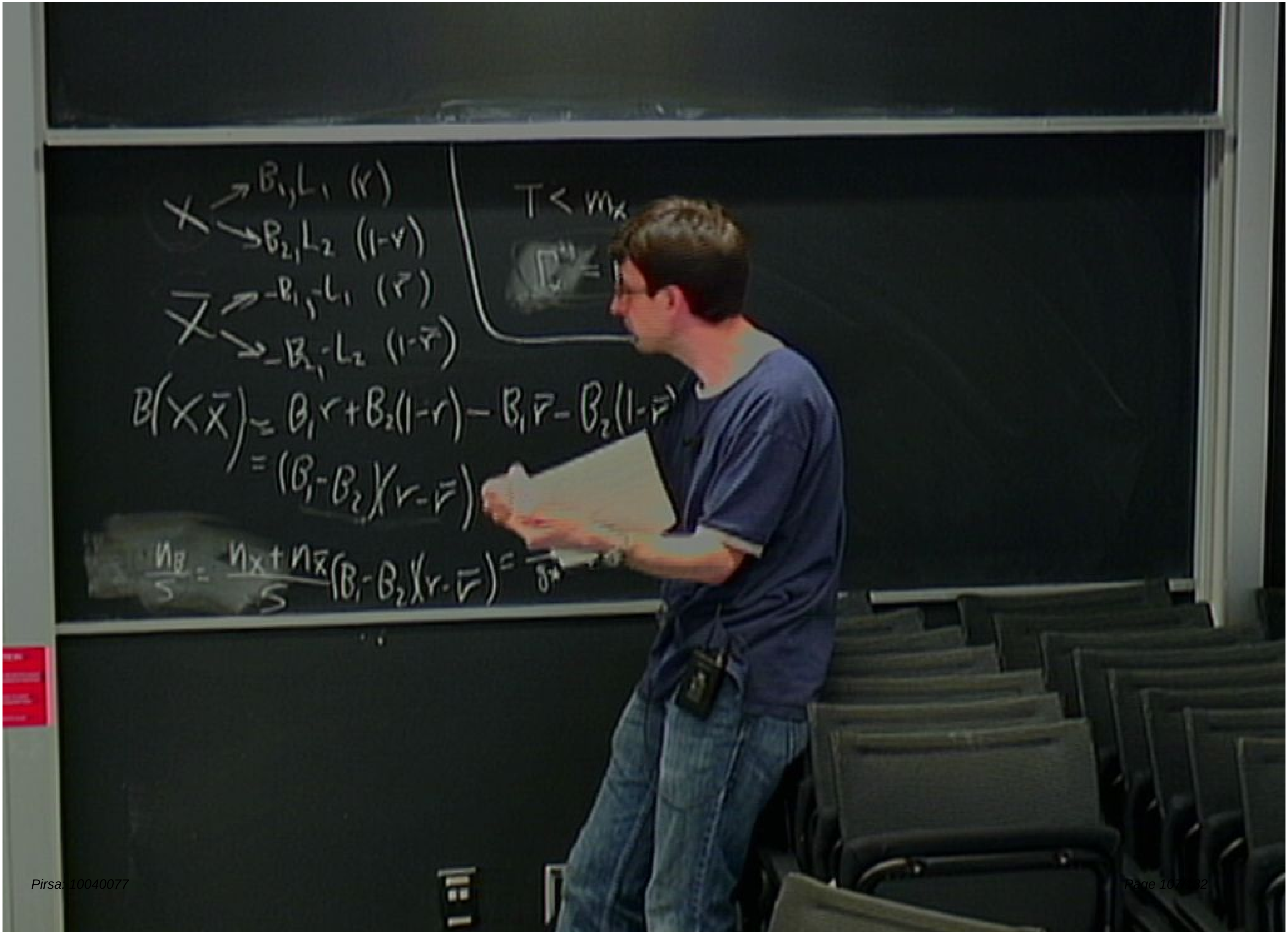

X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) − B1 r̄ − B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄) = 3/g* (B1-B2)(r-r̄)

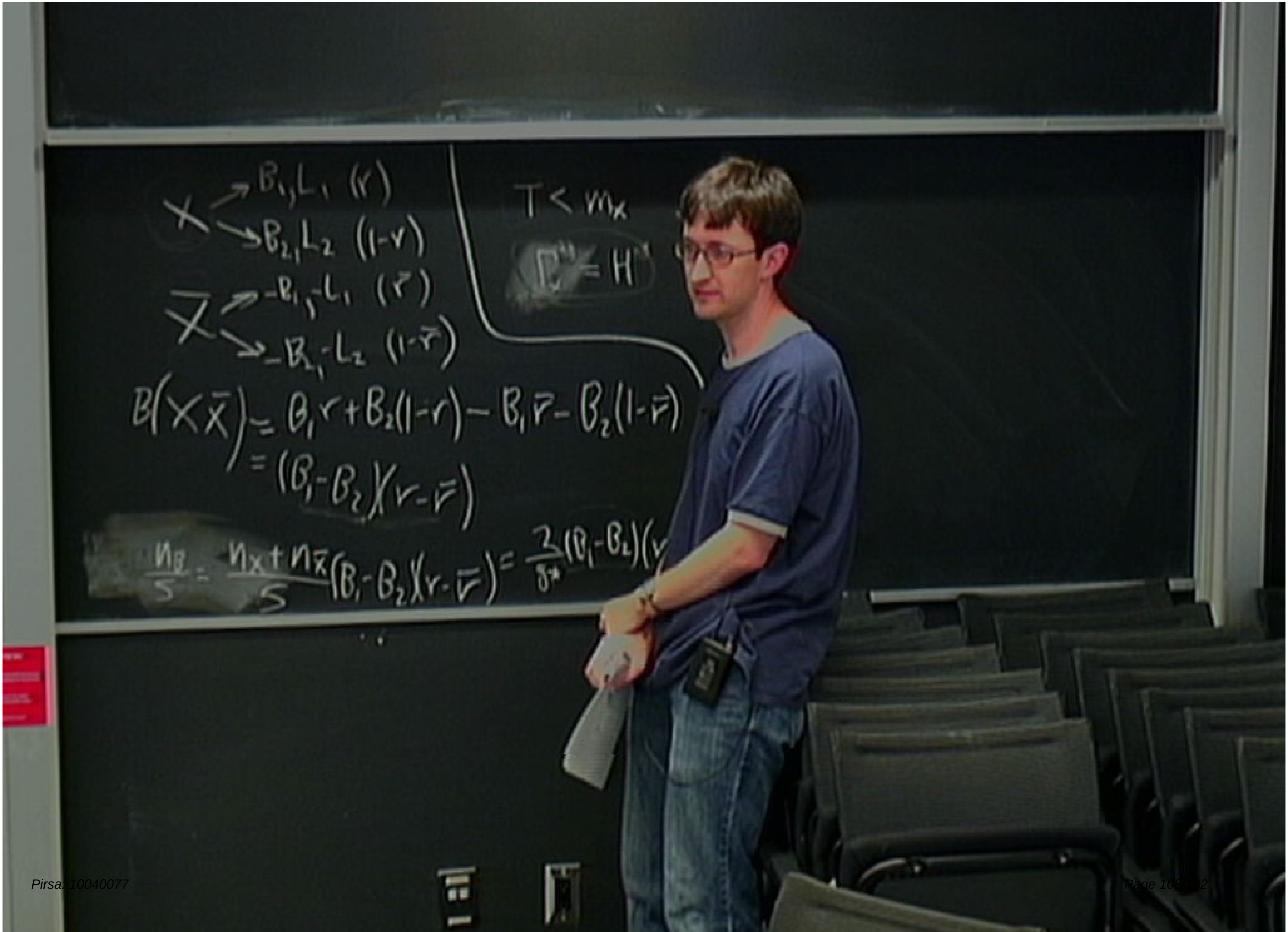

X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/S = (nX + nX̄)/S (B1-B2)(r-r̄)

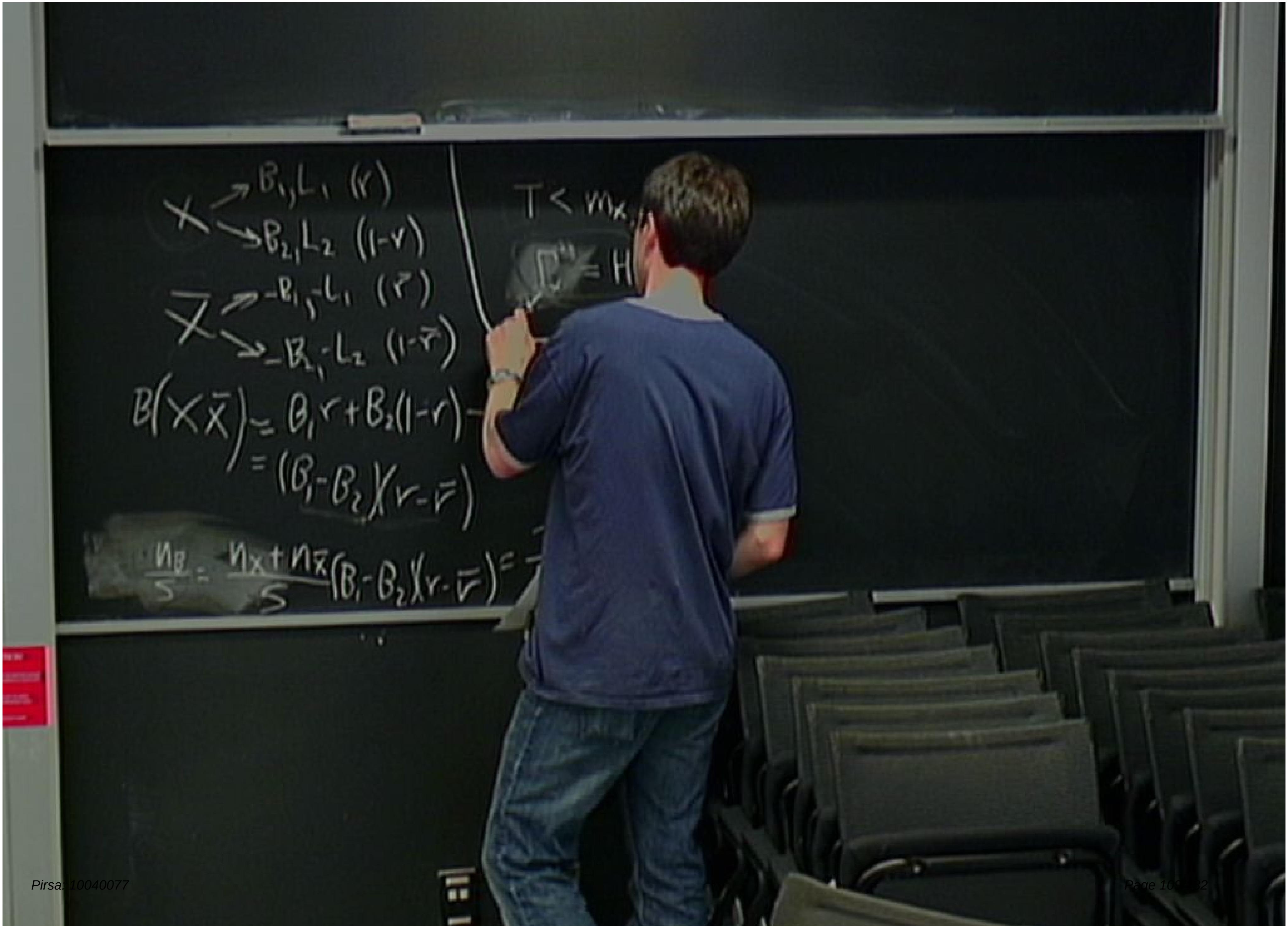

inflation
a³ = e³ᴺ
X̄ → −B₁ − L₁ (r̄)
→ −B₂ − L₂ (1−r̄)
B(X X̄) = B₁r + B₂(1−r) − B₁r̄ − B₂(1−r̄)
= (B₁−B₂)(r−r̄)
n_B/s = (n_X + n_X̄)/s (B₁−B₂)(r−r̄)

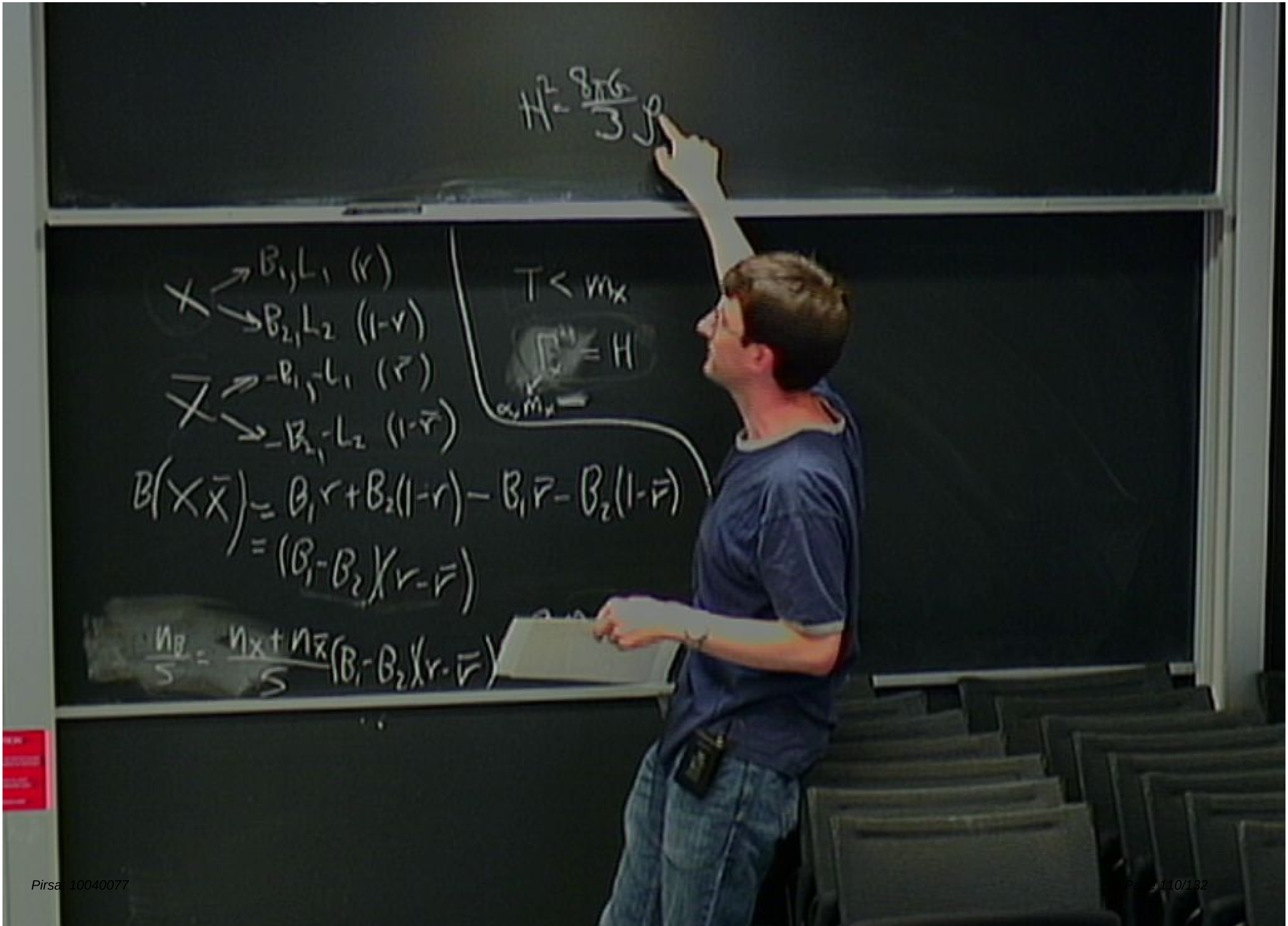

inflation:
B(X X̄) = B₁r + B₂(1-r) - B₁r̄ - B₂(
= (B₁-B₂)(r-r̄)
n_B/s = (n_X + n_X̄)/s (B₁-B₂)(r-r̄) = (B₁-B₂)(r-r̄)

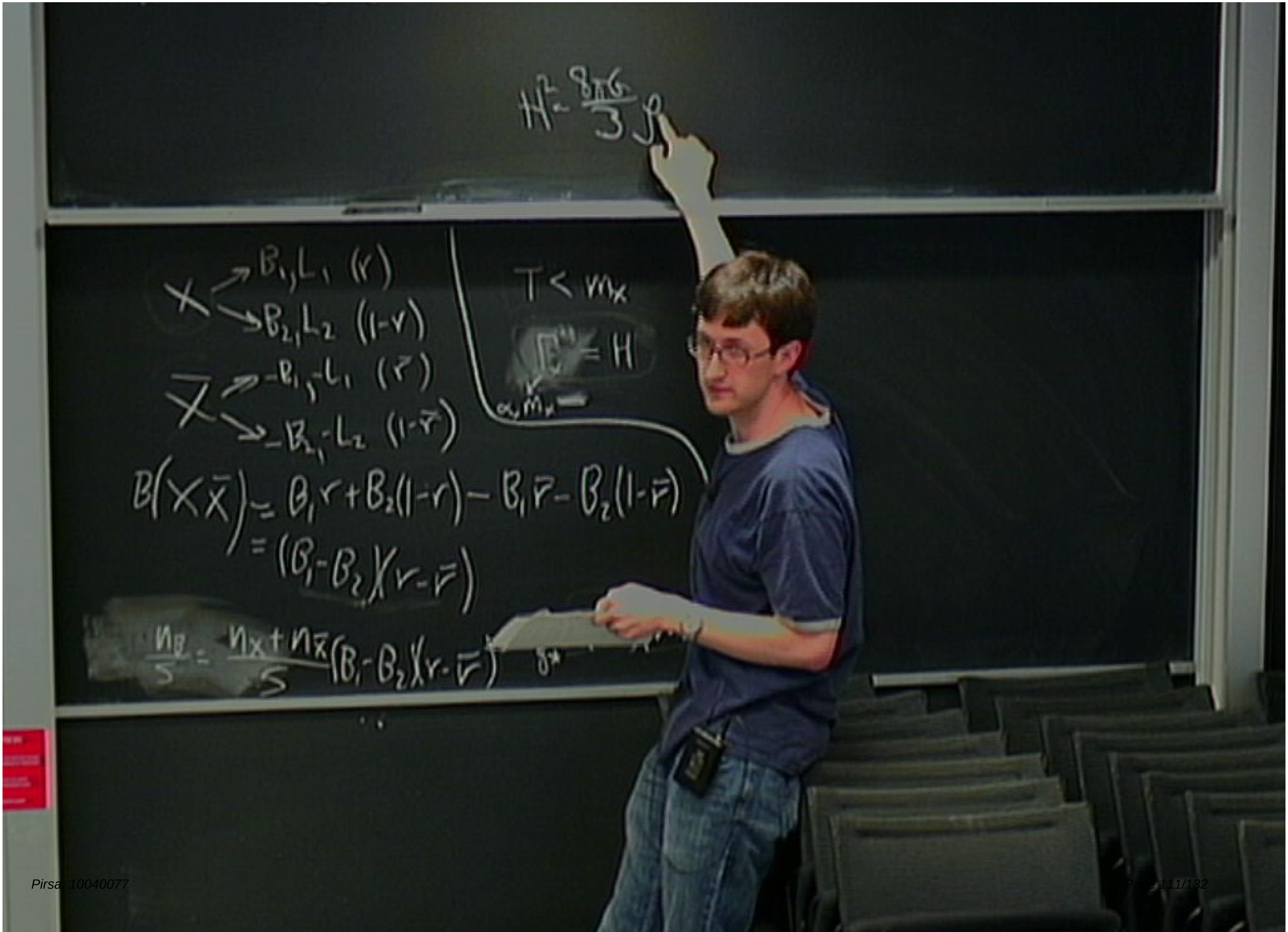

X → B1, L1 (r)
X → B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
X̄ → -B2, -L2 (1-r̄)
T < mX
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄)


X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
T < mX
B(XX̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄)

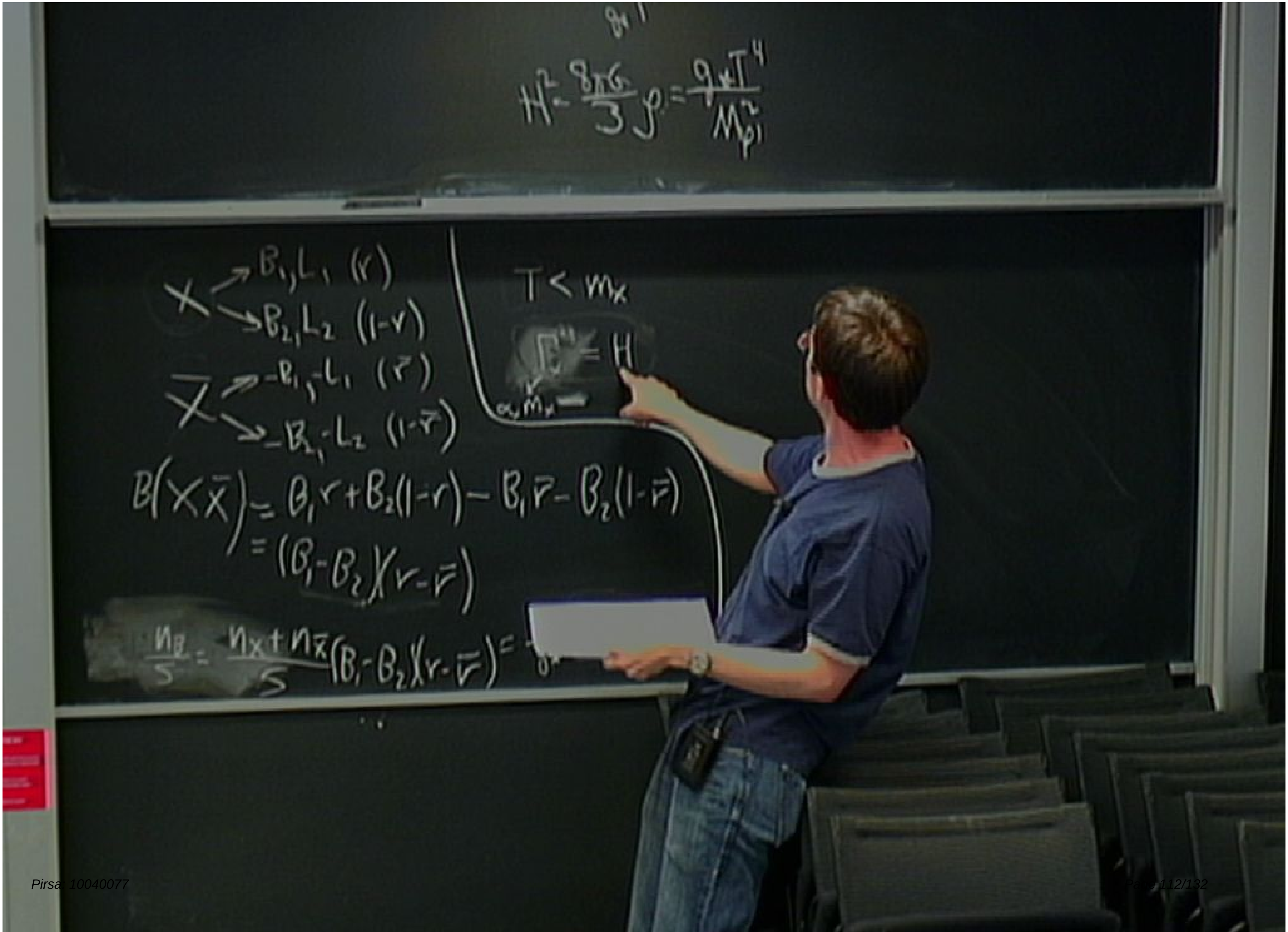

X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX+nX̄)/s (B1-B2)(r-r̄) = 3/g* (B1-B2)(r
T < mX
= H


X → B1, L1 (r)
→ B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
→ -B2, -L2 (1-r̄)
B(XX̄) = B1 r + B2(1-r) -
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄) =
T < mX

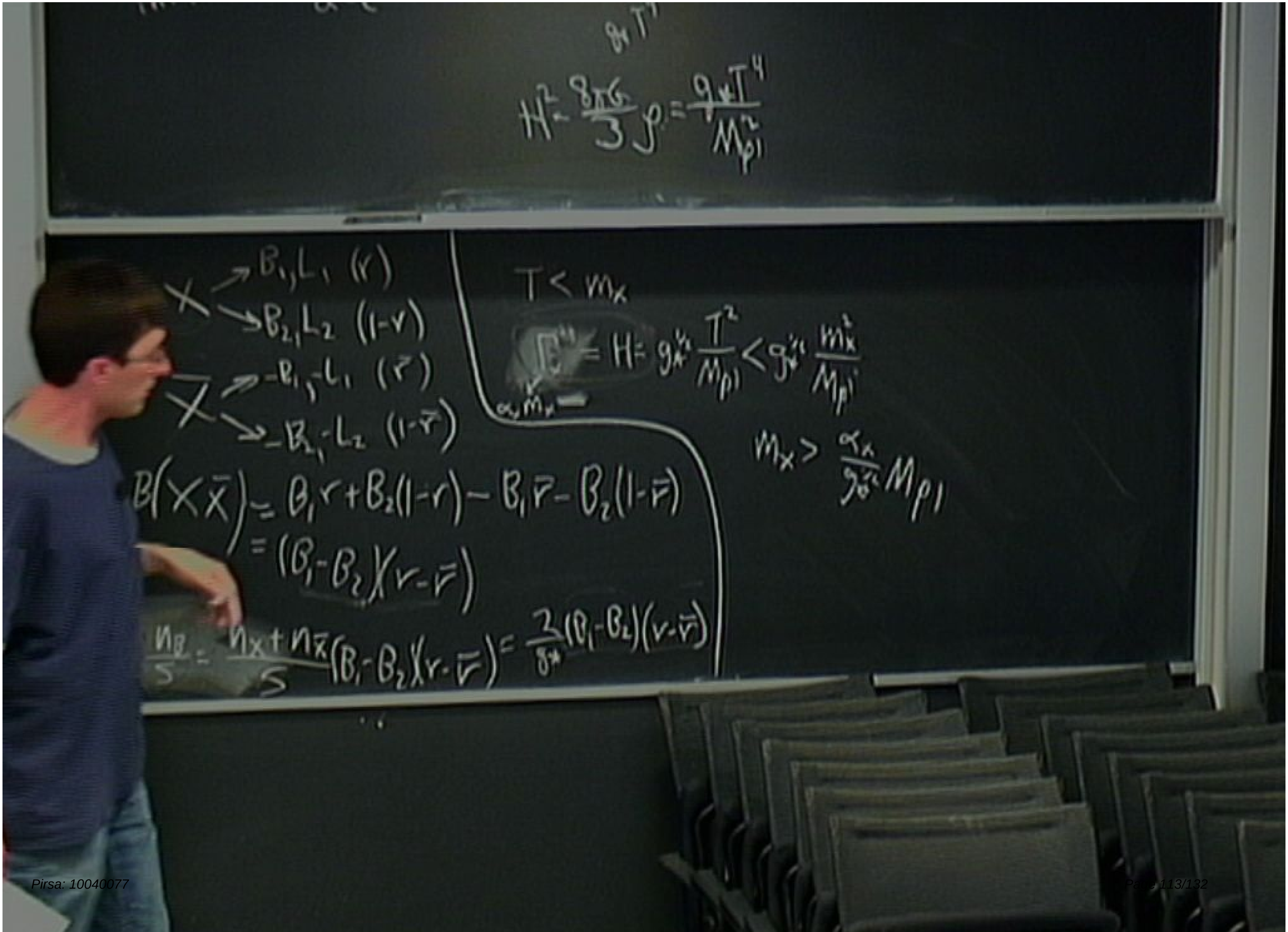

H² = 8πG/3 ρ
T < mx
Γ = H
B(XX̄) = B1r + B2(1-r) - B1r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄)

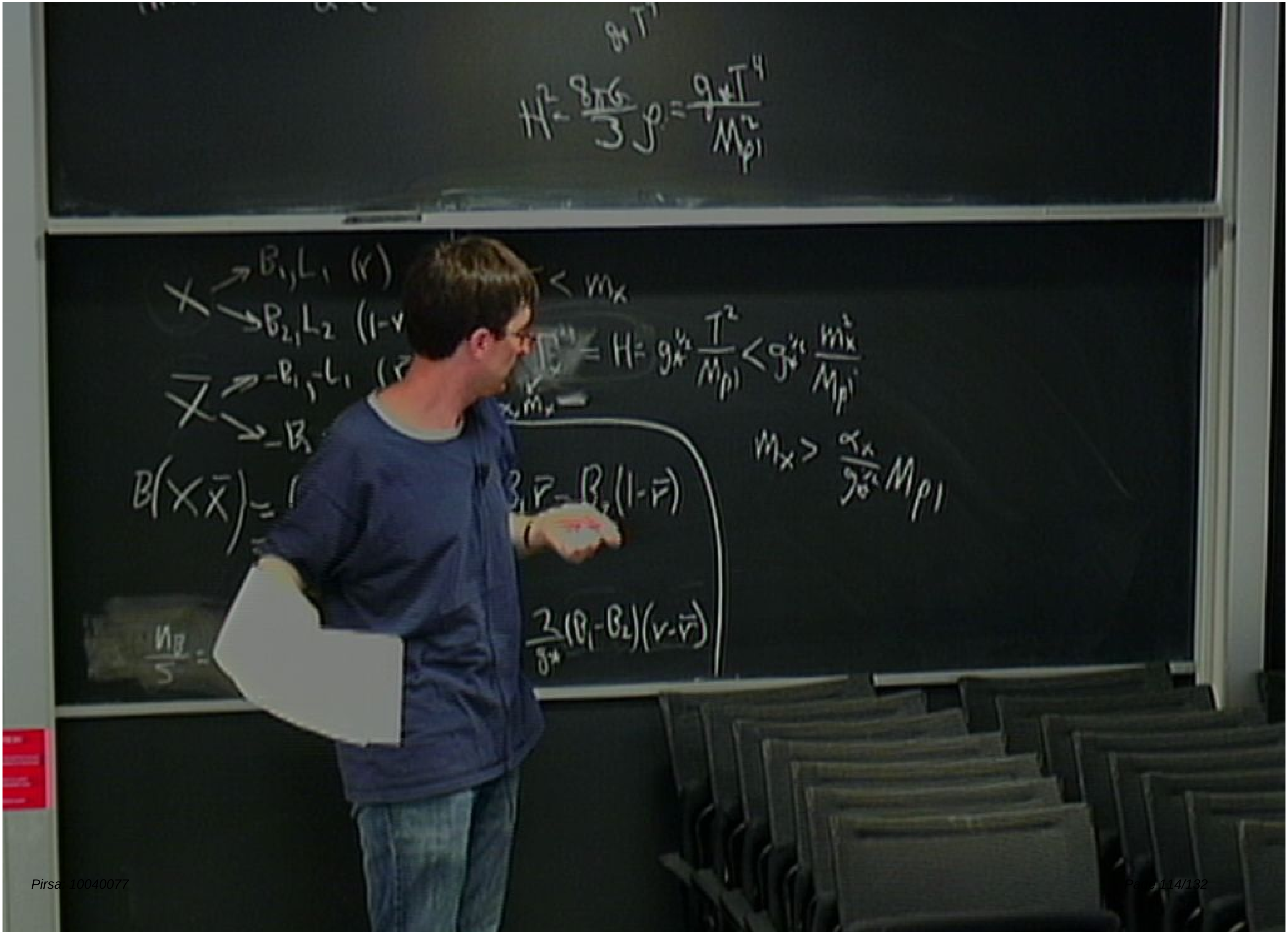


H² = 8πG/3 ρ
X → B₁,L₁ (r)
X → B₂,L₂ (1-r)
X̄ → -B₁,-L₁ (r̄)
X̄ → -B₂,-L₂ (1-r̄)
T < mₓ
Γ = H
B(XX̄) = B₁r + B₂(1-r) − B₁r̄ − B₂(1-r̄)
= (B₁-B₂)(r-r̄)
n_B/s = (nₓ + n_X̄)/s (B₁-B₂)(r-r̄)

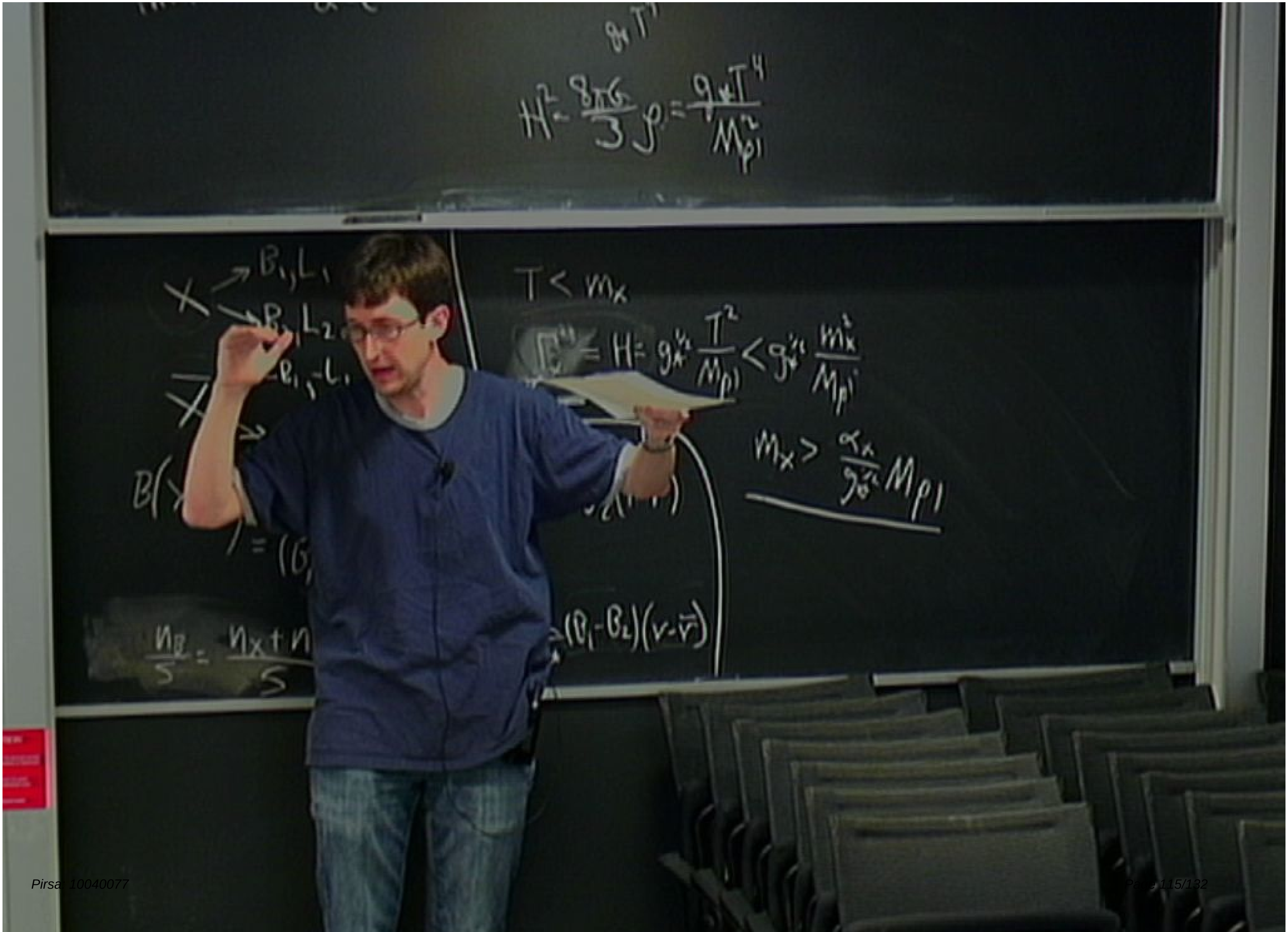


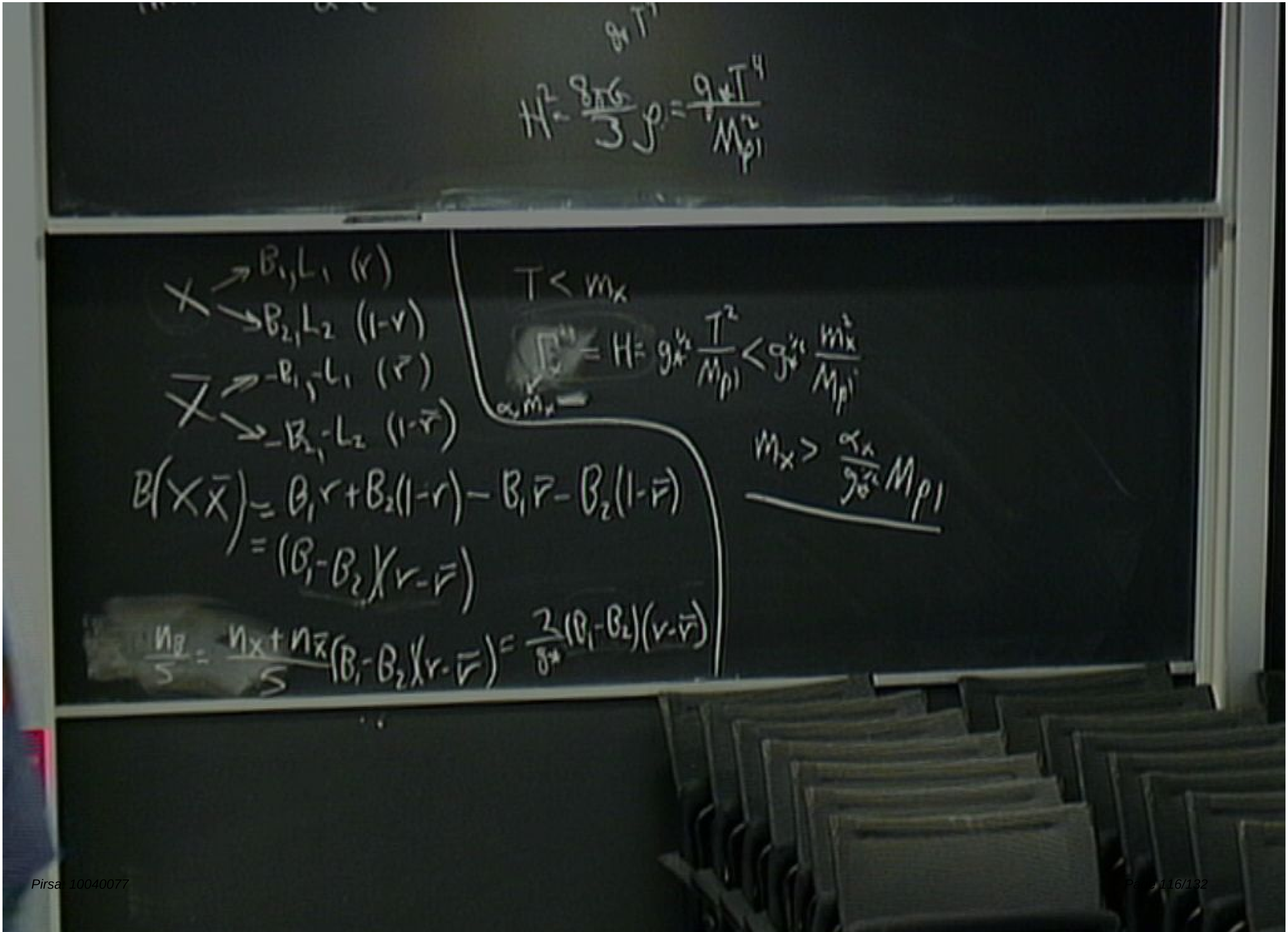
$H^2 = \frac{8\pi G}{3}\rho = \frac{g_* T^4}{M_{Pl}^2}$
$X \to B_1, L_1 \quad (r)$
$X \to B_2, L_2 \quad (1-r)$
$\bar{X} \to -B_1, -L_1 \quad (\bar{r})$
$\bar{X} \to -B_2, -L_2 \quad (1-\bar{r})$
$B(X\bar{X}) = B_1 r + B_2(1-r) - B_1\bar{r} - B_2(1-\bar{r})$
$= (B_1 - B_2)(r - \bar{r})$
$\frac{n_B}{s} = \frac{n_X + n_{\bar{X}}}{s}(B_1 - B_2)(r - \bar{r})$
$T < m_X$
$\Gamma = H$

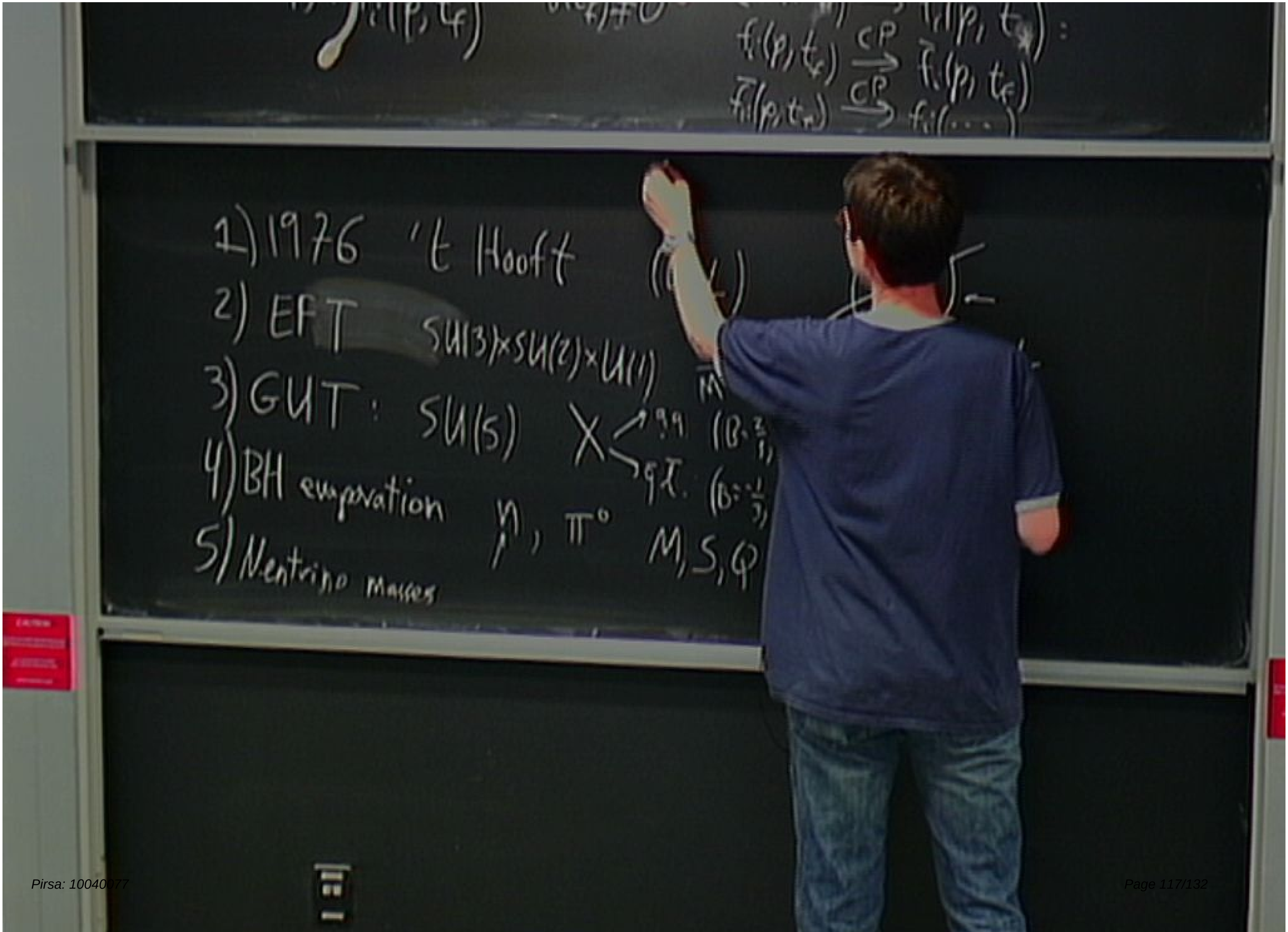

$H^2 = \frac{8\pi G}{3}\rho = \frac{g_* T^4}{M_{pl}^2}$
$X \to B_1, L_1 \; (r)$
$\to B_2, L_2 \; (1-r)$
$\bar{X} \to -B_1, -L_1 \; (\bar{r})$
$\to -B_2, -L_2 \; (1-\bar{r})$
$B(X\bar{X}) = B_1 r + B_2(1-r) - B_1\bar{r} - B_2(1-\bar{r})$
$= (B_1 - B_2)(r - \bar{r})$
$\frac{n_B}{s} = \frac{n_X + n_{\bar{X}}}{s}(B_1 - B_2)(r - \bar{r}) = \frac{3}{g_*}(B_1 - B_2)(r - \bar{r})$
$T < m_X$
$\Gamma = H = g_*^{1/2}\frac{T^2}{M_{pl}} < g_*^{1/2}\frac{m_X^2}{M_{pl}}$
$\alpha_X m_X$
$m_X > \frac{\alpha_X}{g_*^{1/2}} M_{pl}$



H² = 8πG/3 ρ = g*T⁴/Mpl²
mx > αx/g*½ Mpl


$H^2 = \frac{8\pi G}{3}\rho = \frac{g_* T^4}{M_{pl}^2}$
$T < m_X$
$m_X > \frac{\alpha_X}{g_*^{1/2}} M_{pl}$
$(B_1 - B_2)(r - \bar{r})$


H² = 8πG/3 ρ = g* T⁴ / Mpl²
X → B1, L1 (r)
X → B2, L2 (1-r)
X̄ → -B1, -L1 (r̄)
X̄ → -B2, -L2 (1-r̄)
B(X X̄) = B1 r + B2(1-r) - B1 r̄ - B2(1-r̄)
= (B1-B2)(r-r̄)
nB/s = (nX + nX̄)/s (B1-B2)(r-r̄) = 3/g* (B1-B2)(r-r̄)
T < mX
= H = g*^½ T²/Mpl < g*^½ mX²/Mpl
αX mX
mX > αX/g*^½ Mpl


1) 1976 't Hooft
2) EFT SU(3)×SU(2)×U(1)
3) GUT: SU(5)
4) BH evaporation
5) Neutrino masses
CP
CP

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\ldots)$

$\Gamma \sim T$

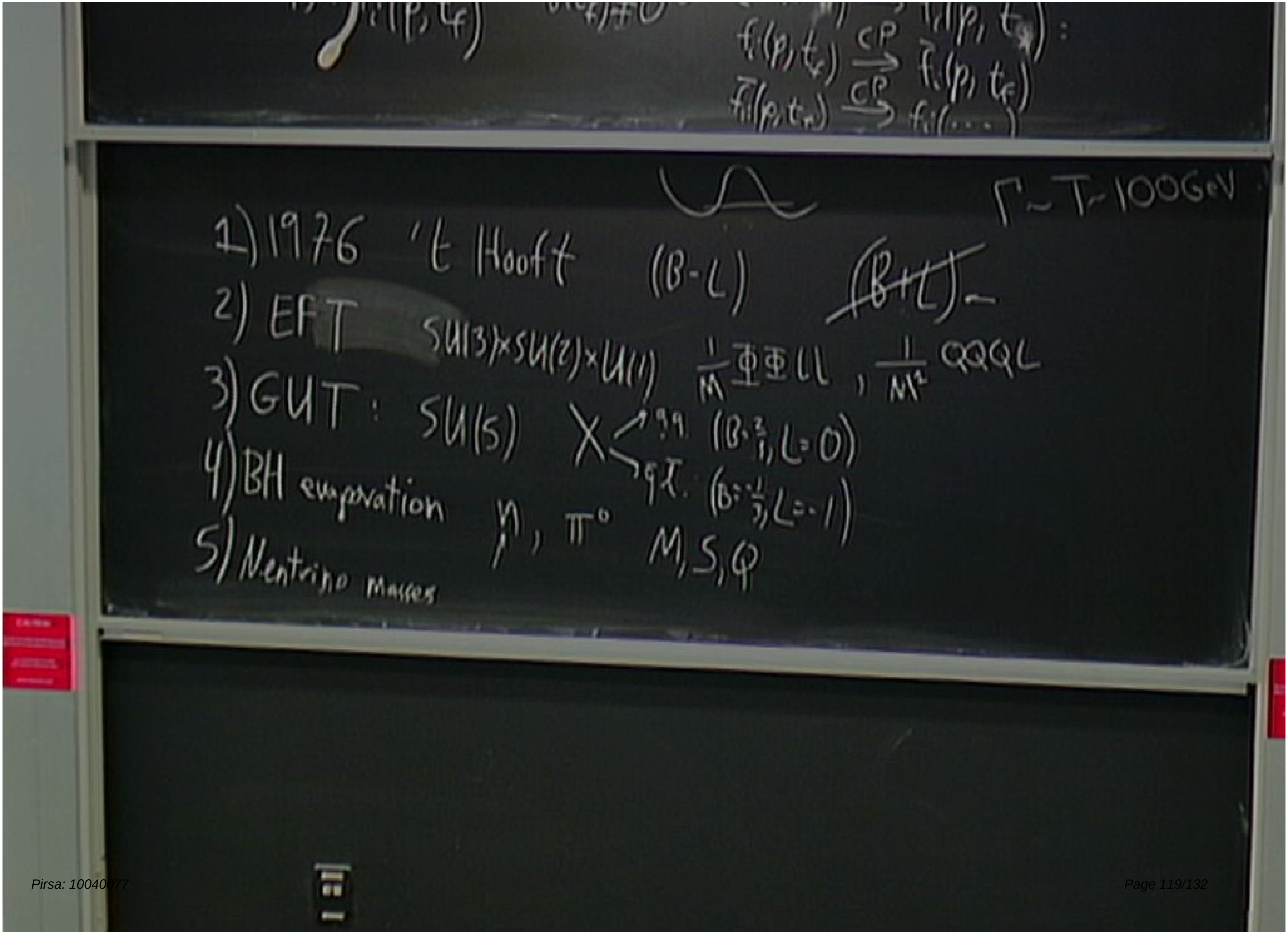
1) 1976 't Hooft $(B-L)$ ~~$(B+L)$~~

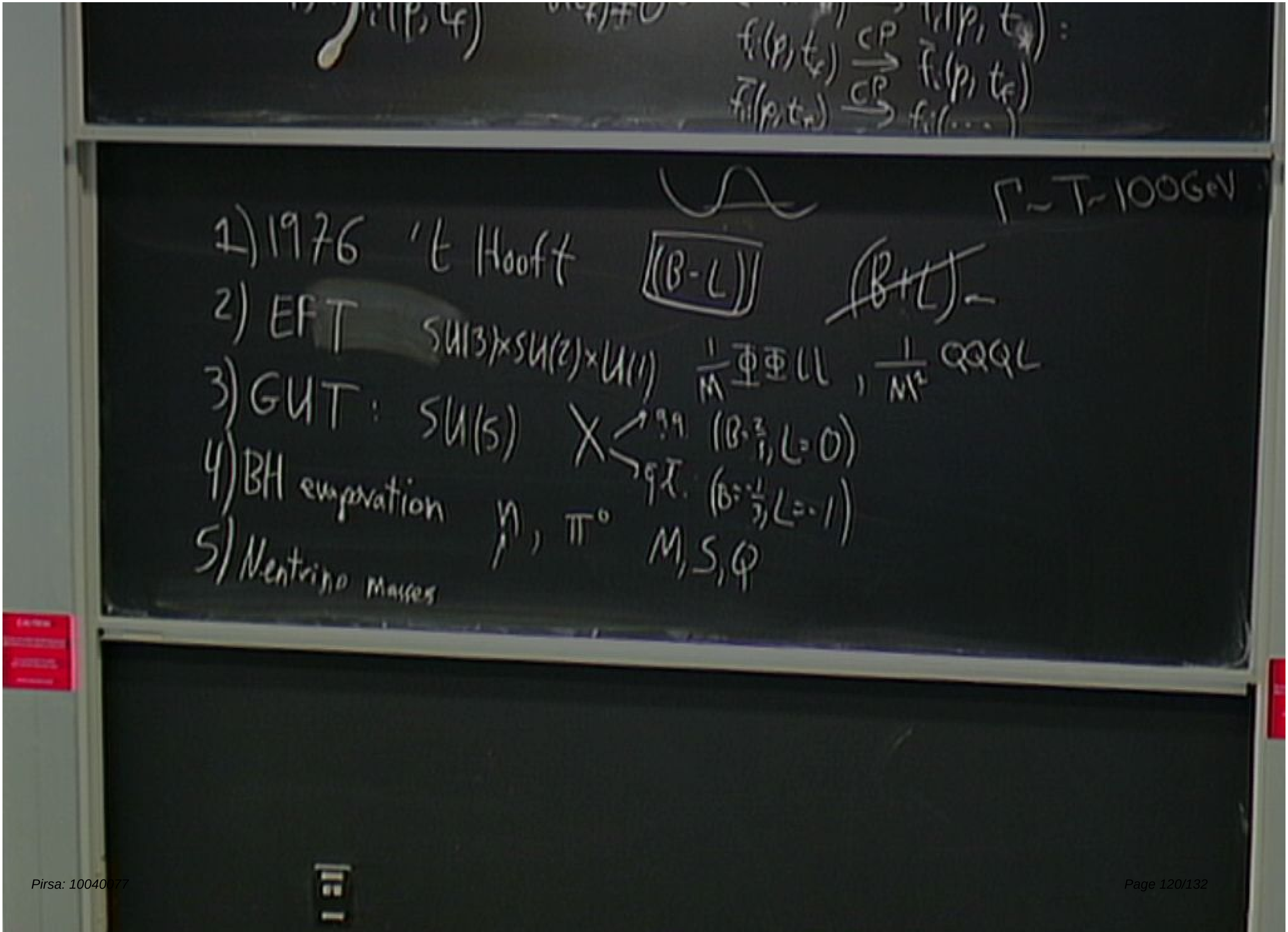
2) EFT $SU(3) \times SU(2) \times U(1)$ $\frac{1}{M} \Phi \Phi L L$, $\frac{1}{M^2} QQQL$

3) GUT: $SU(5)$ $X \to qq$ $(B = \frac{2}{3}, L = 0)$; $X \to \bar{q}\bar{\ell}$ $(B = -\frac{1}{3}, L = -1)$

4) BH evaporation n, π^0 M, S, Q

5) Neutrino masses


$f_i(p,t_f) \xrightarrow{CP} \bar{f}_i(p,t_f)$
$\bar{f}_i(p,t_f) \xrightarrow{CP} f_i(\ldots)$
$\Gamma \sim T \sim 100\,GeV$
1) 1976 't Hooft (B-L) (B+L)
2) EFT SU(3)×SU(2)×U(1) $\frac{1}{M}\Phi\Phi LL$, $\frac{1}{M^2}QQQL$
3) GUT : SU(5) X → qq (B=2/3, L=0) ; q$\bar{l}$ (B=-1/3, L=-1)
4) BH evaporation n, π°
5) Neutrino masses M, S, φ


Γ ~ T ~ 100 GeV
1) 1976 't Hooft (B-L) (B+L)
2) EFT SU(3)×SU(2)×U(1) 1/M ΦΦLL , 1/M² QQQL
3) GUT : SU(5) X qq (B=2/3, L=0) q̄l̄ (B=-1/3, L=-1)
4) BH evaporation n, π⁰ M, S, Q
5) Neutrino masses

$f_i(p, t_f)$

$f_i(p, t_f) \xrightarrow{CP} \bar{f}_i(p, t_f)$

$\bar{f}_i(p, t_f) \xrightarrow{CP} f_i(\dots)$

$\Gamma \sim T \sim 100\,\text{GeV}$

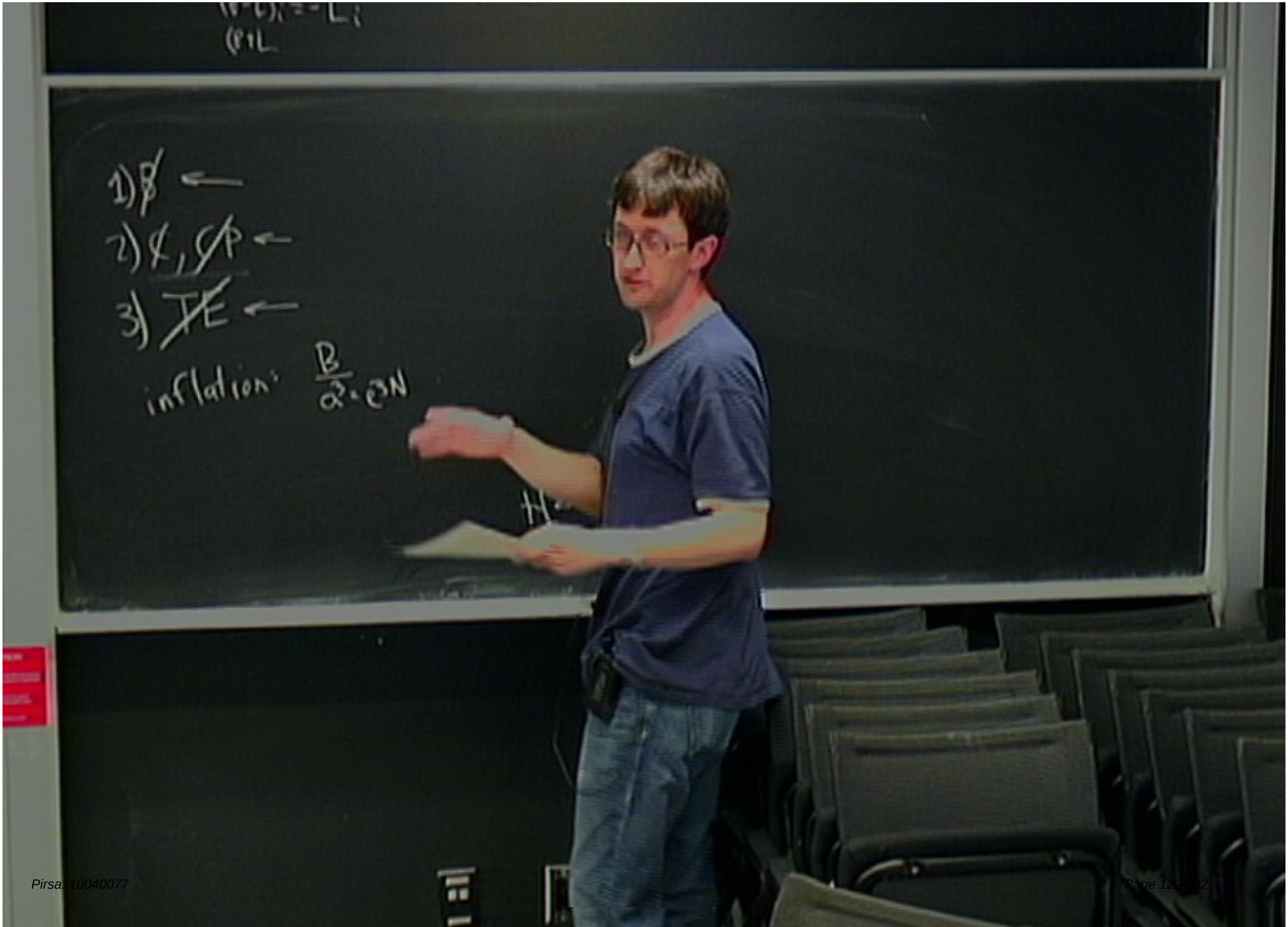
1) 1976 't Hooft $\boxed{(B-L)}$ ~~$(B+L)$~~

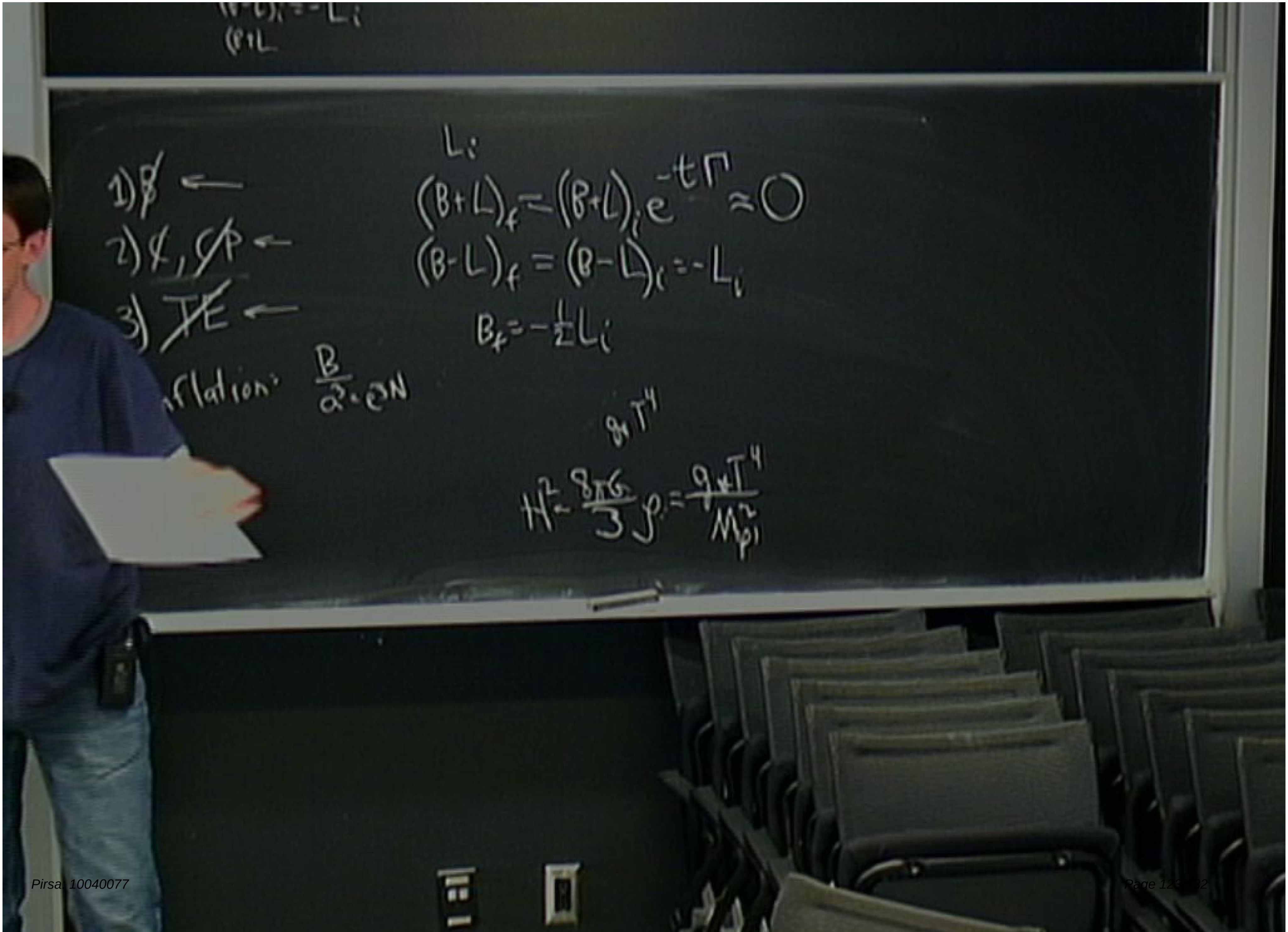
2) EFT $SU(3) \times SU(2) \times U(1)$ $\frac{1}{M} \Phi \Phi l l$, $\frac{1}{M^2} QQQL$

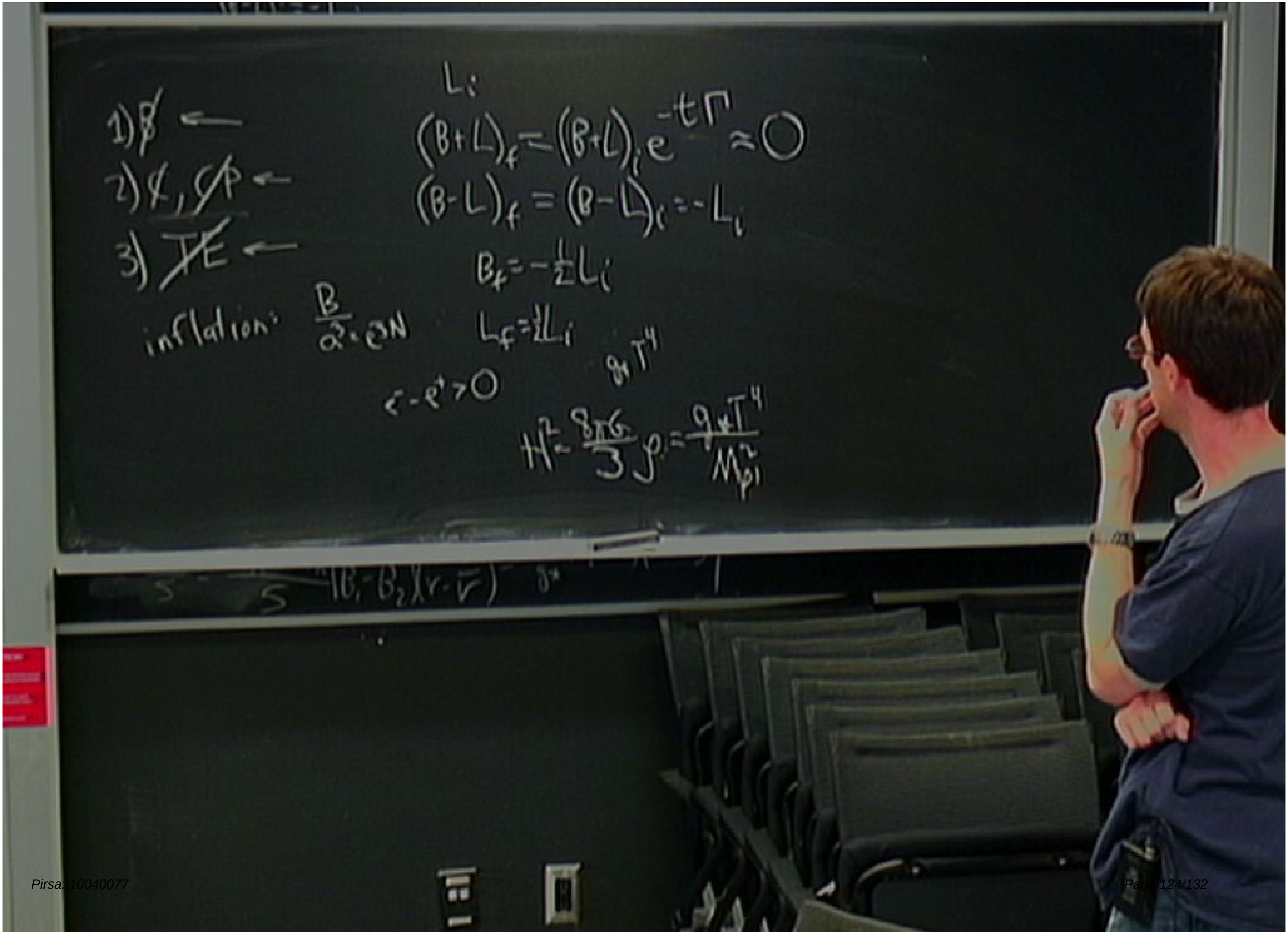
3) GUT : $SU(5)$ $X \to qq \; (B = \frac{2}{3}, L = 0)$, $X \to q\bar{l} \; (B = -\frac{1}{3}, L = -1)$

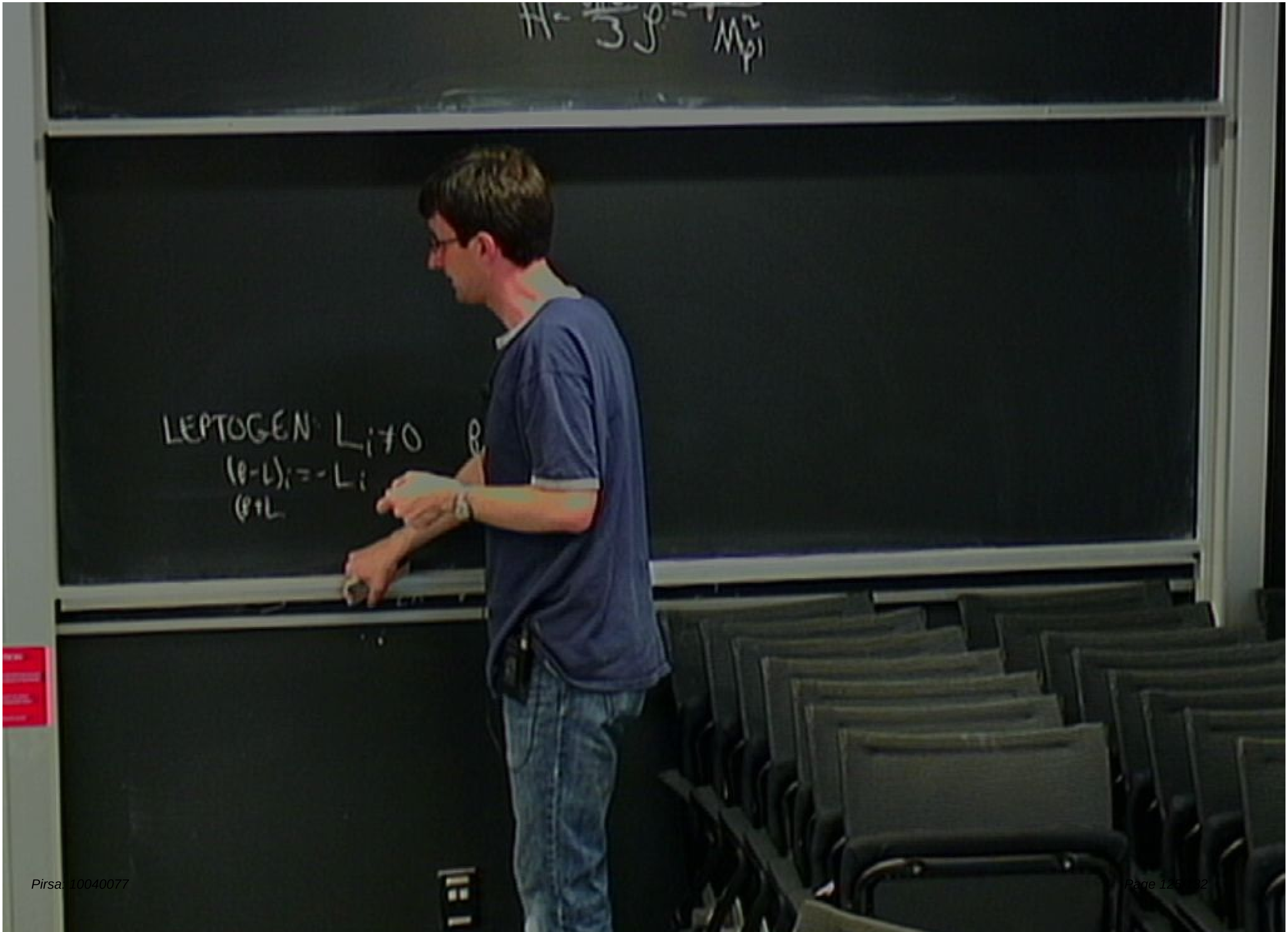
4) BH evaporation n, π^0

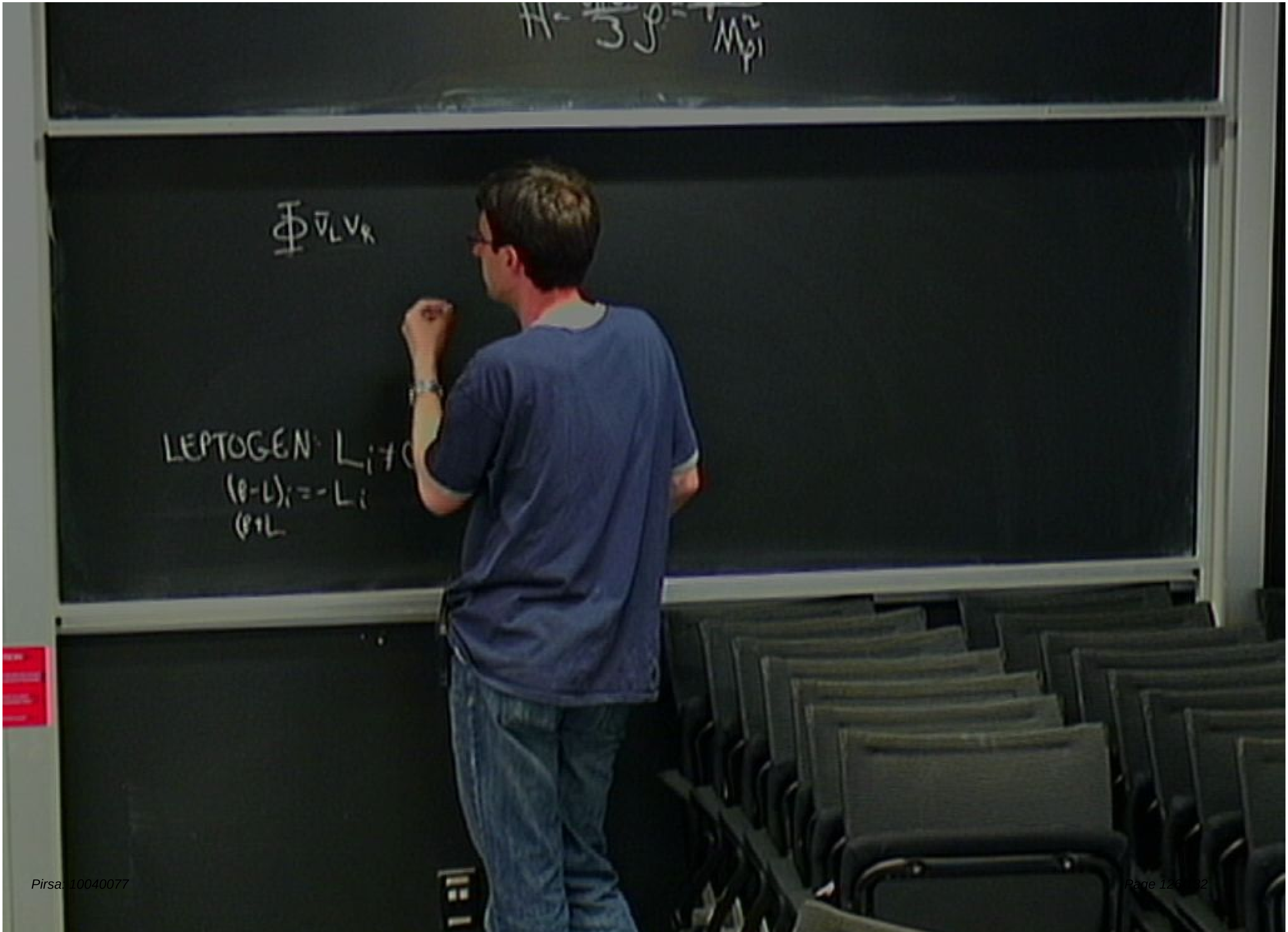
5) Neutrino masses M, S, φ

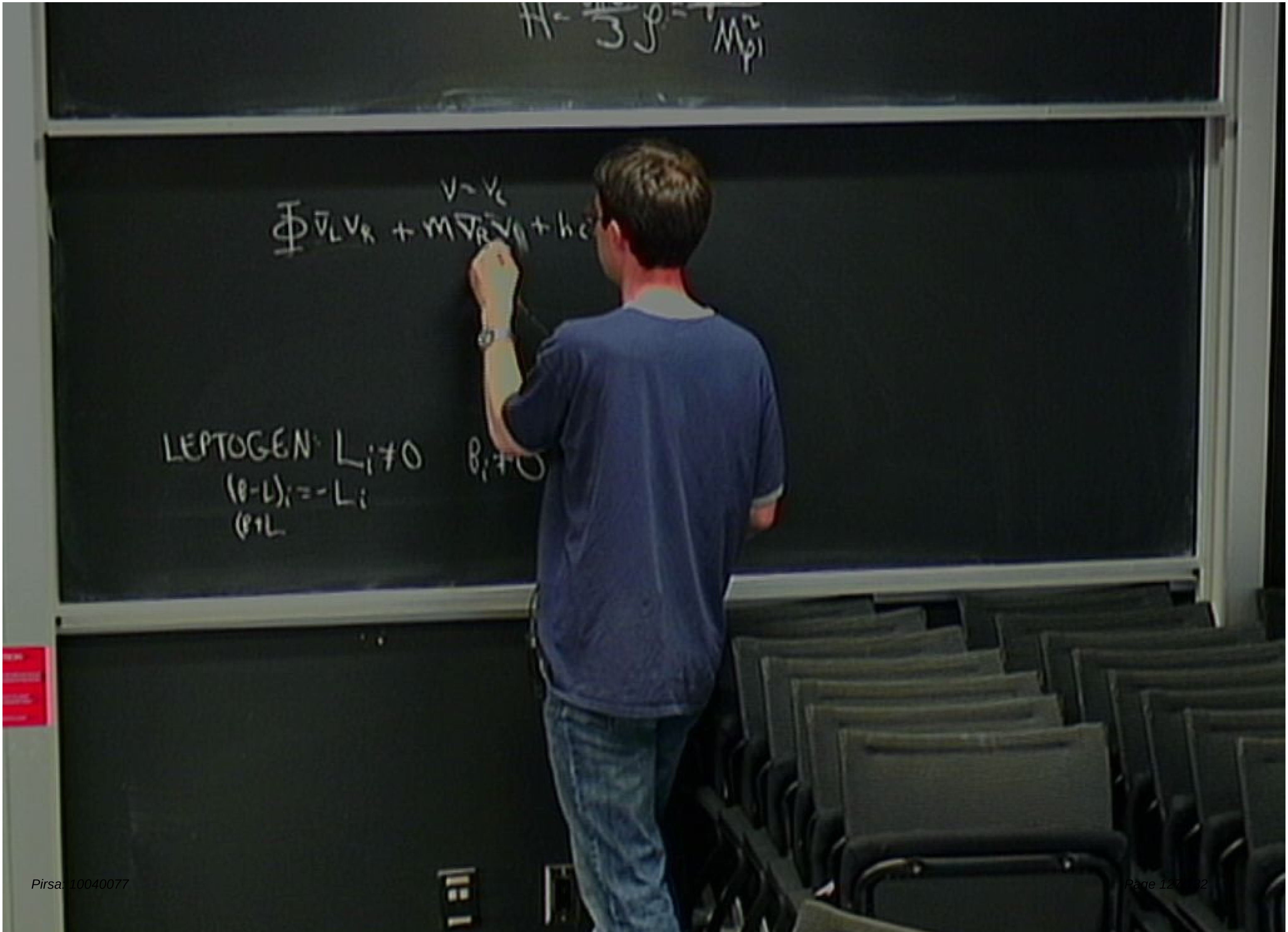

inflation:

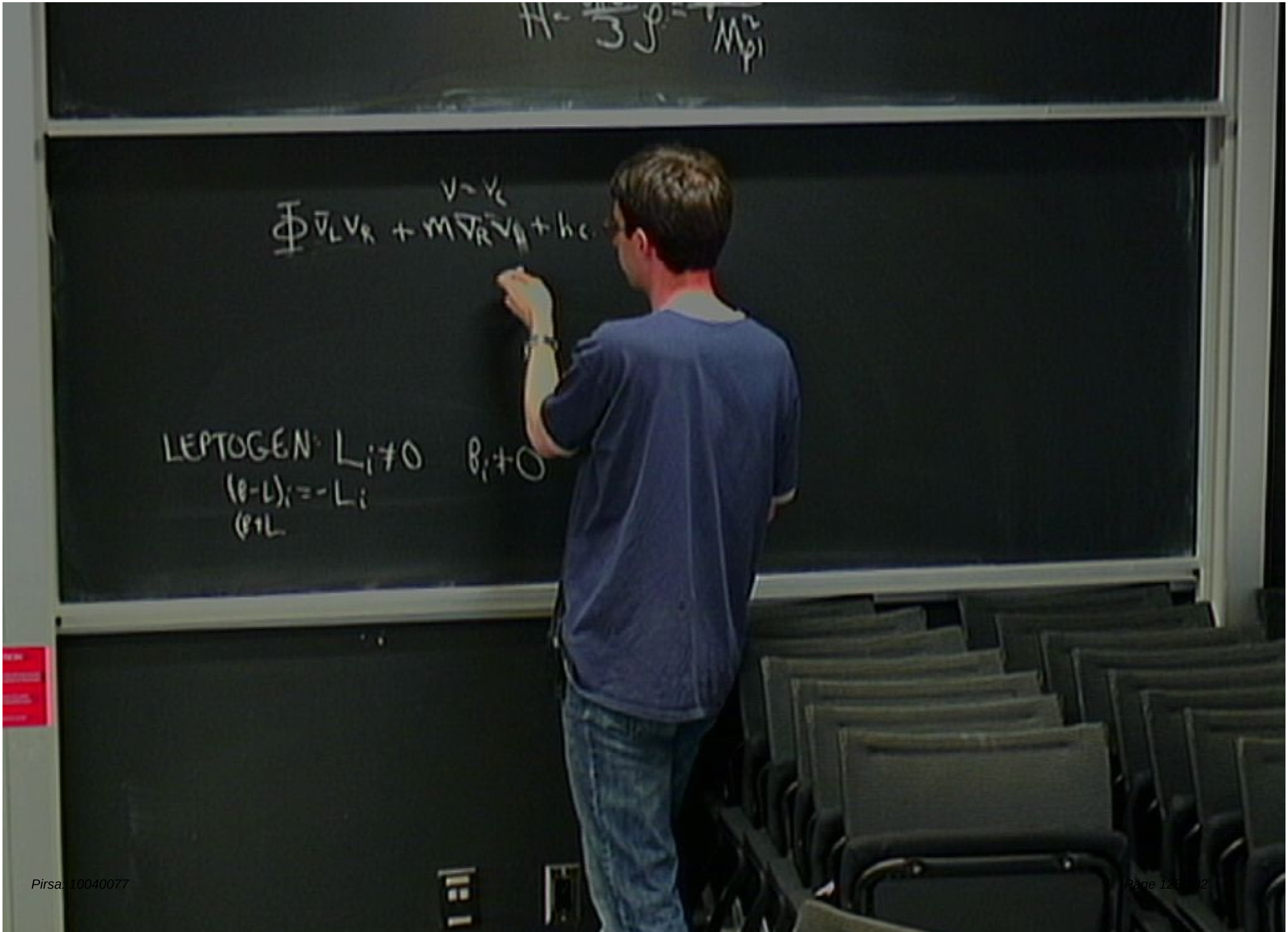

Lᵢ
(B+L)f = (B+L)ᵢ e^-tΓ ≈ 0
(B-L)f = (B-L)ᵢ = -Lᵢ
Bf = -½Lᵢ
1) B ←
2) C, CP ←
3) TE ←
nflation: B/a³ ~ e³N
H² = 8πG/3 ρ = g*T⁴/M²pl


1) B ←
2) C, CP ←
3) TE ←
inflation:
L_i
(B+L)_f = (B+L)_i e^{-tΓ} ≈ 0
(B-L)_f = (B-L)_i = -L_i
B_f = -1/2 L_i
L_f = 1/2 L_i
H^2 = 8πG/3 ρ = g_* T^4 / M_pl^2

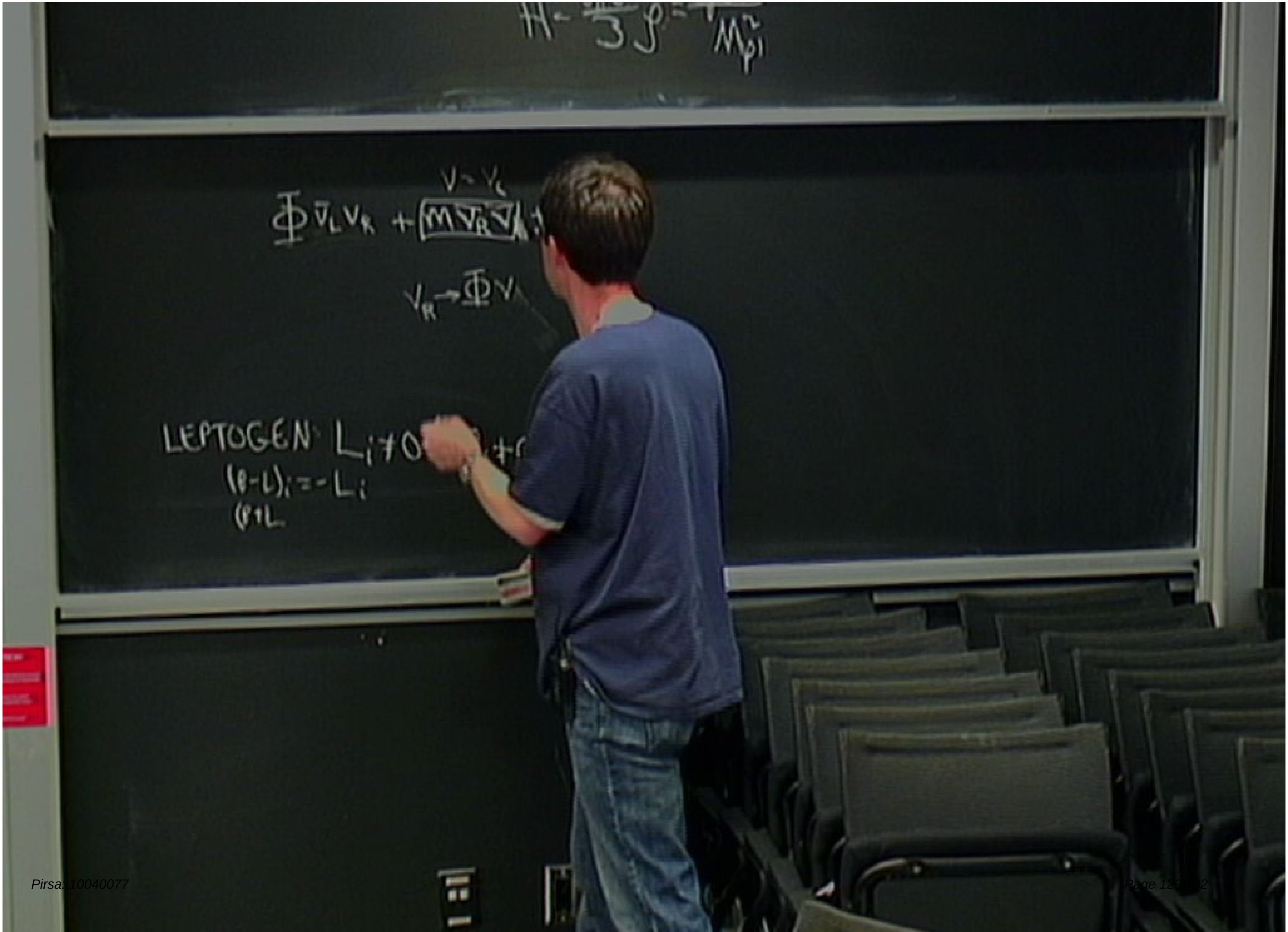

LEPTOGEN: L_i ≠ 0
(B-L)_i = -L_i
(B+L

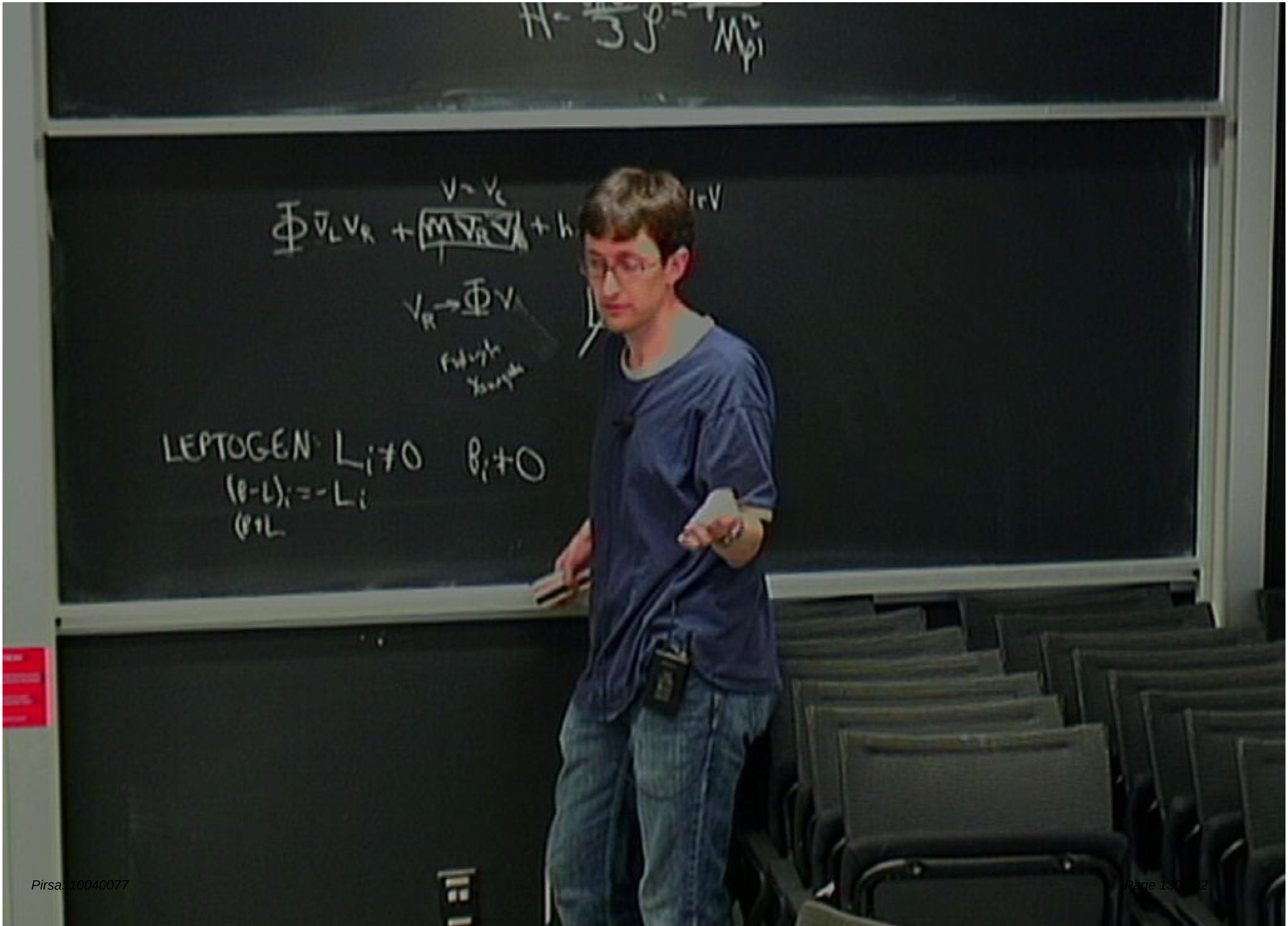

LEPTOGEN

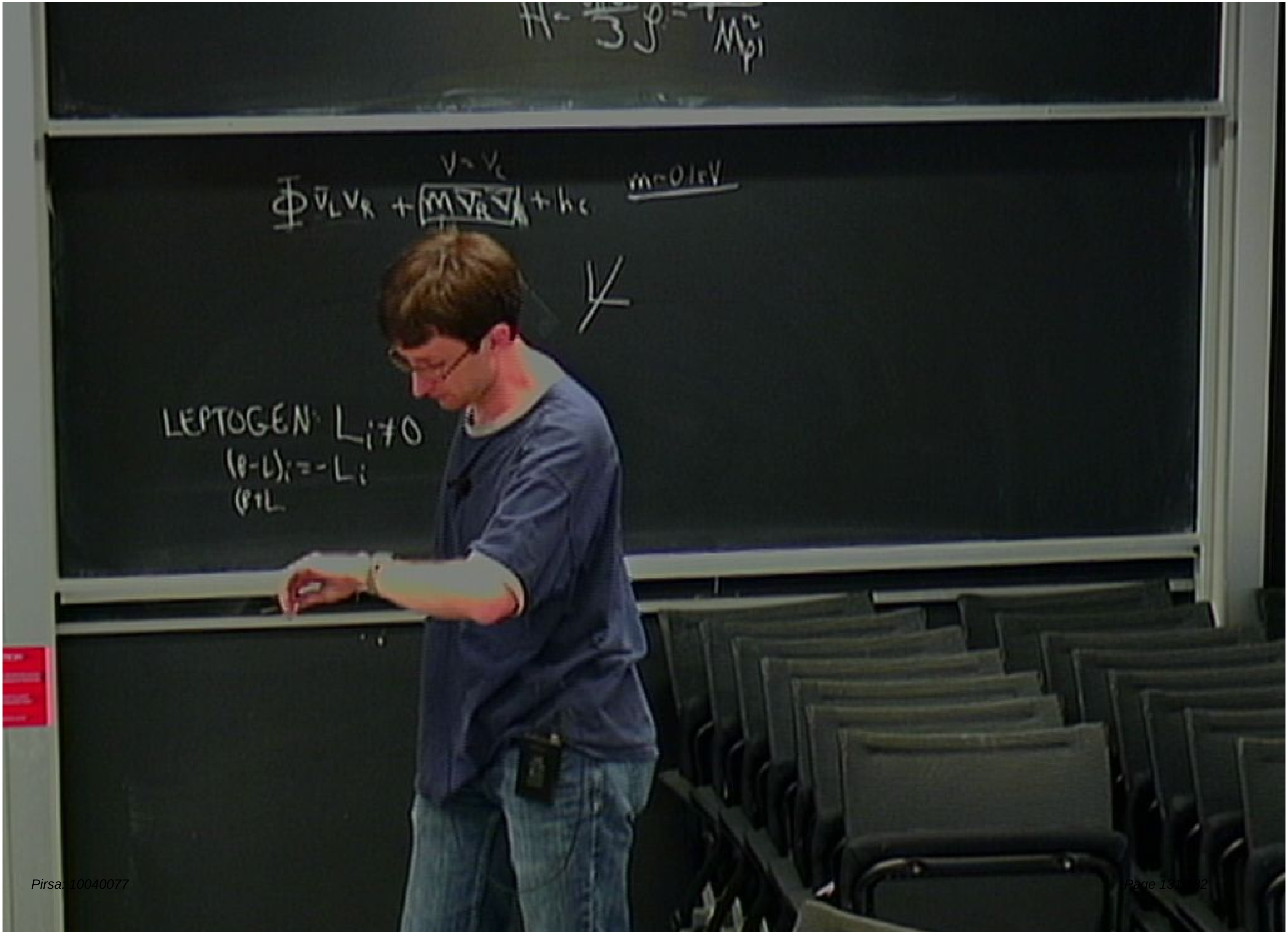

LEPTOGEN

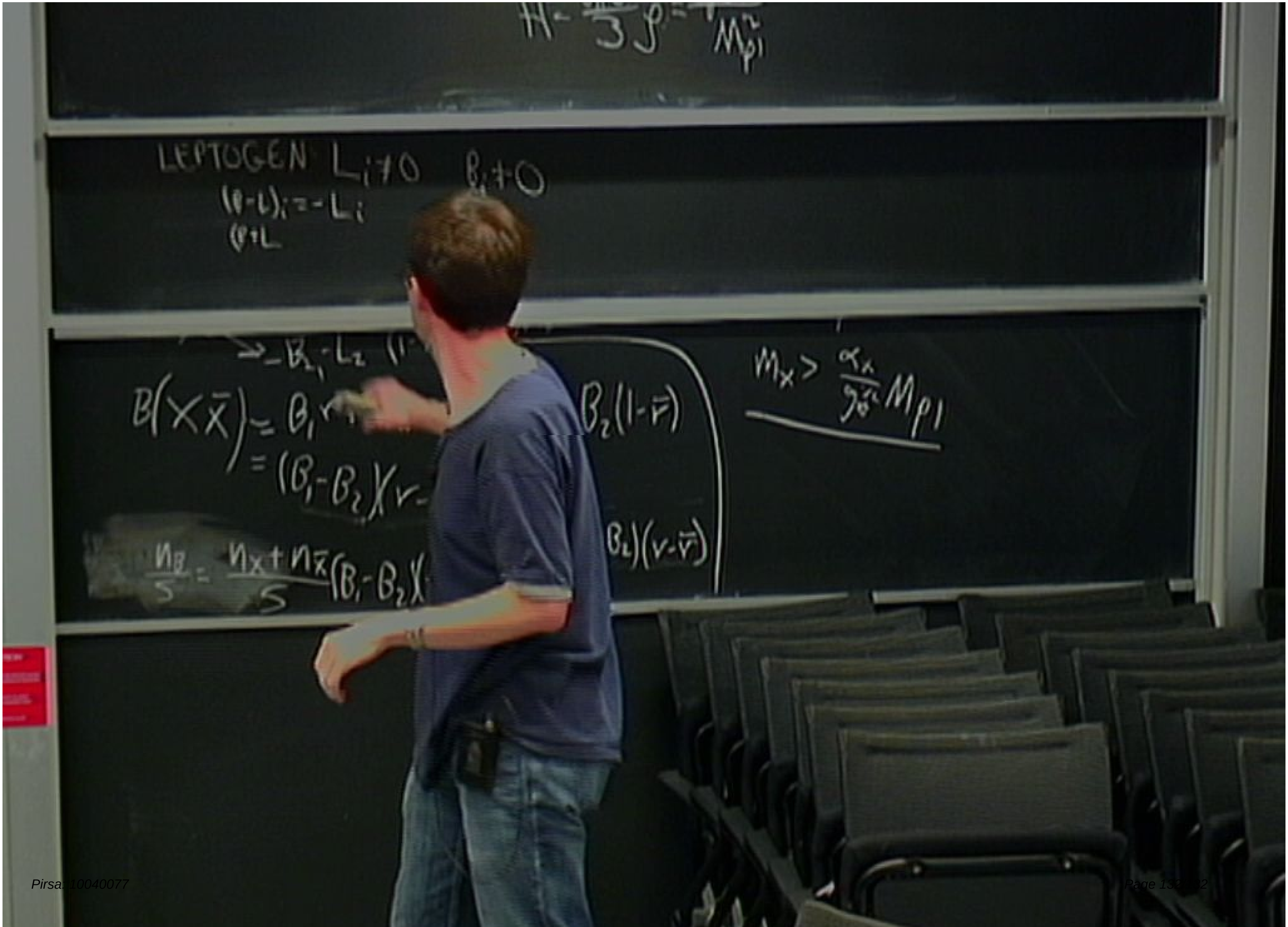


LEPTOGEN:


LEPTOGEN


LEPTOGEN


m~0.1eV
LEPTOGEN: L_i≠0
(B-L)_i = -L_i


LEPTOGEN
$m_X > \frac{\alpha_X}{g_*^{1/2}} M_{pl}$