Title: Theories of Dark Matter - Lecture 2

Date: Jun 25, 2009 09:00 AM

URL: http://pirsa.org/09060067

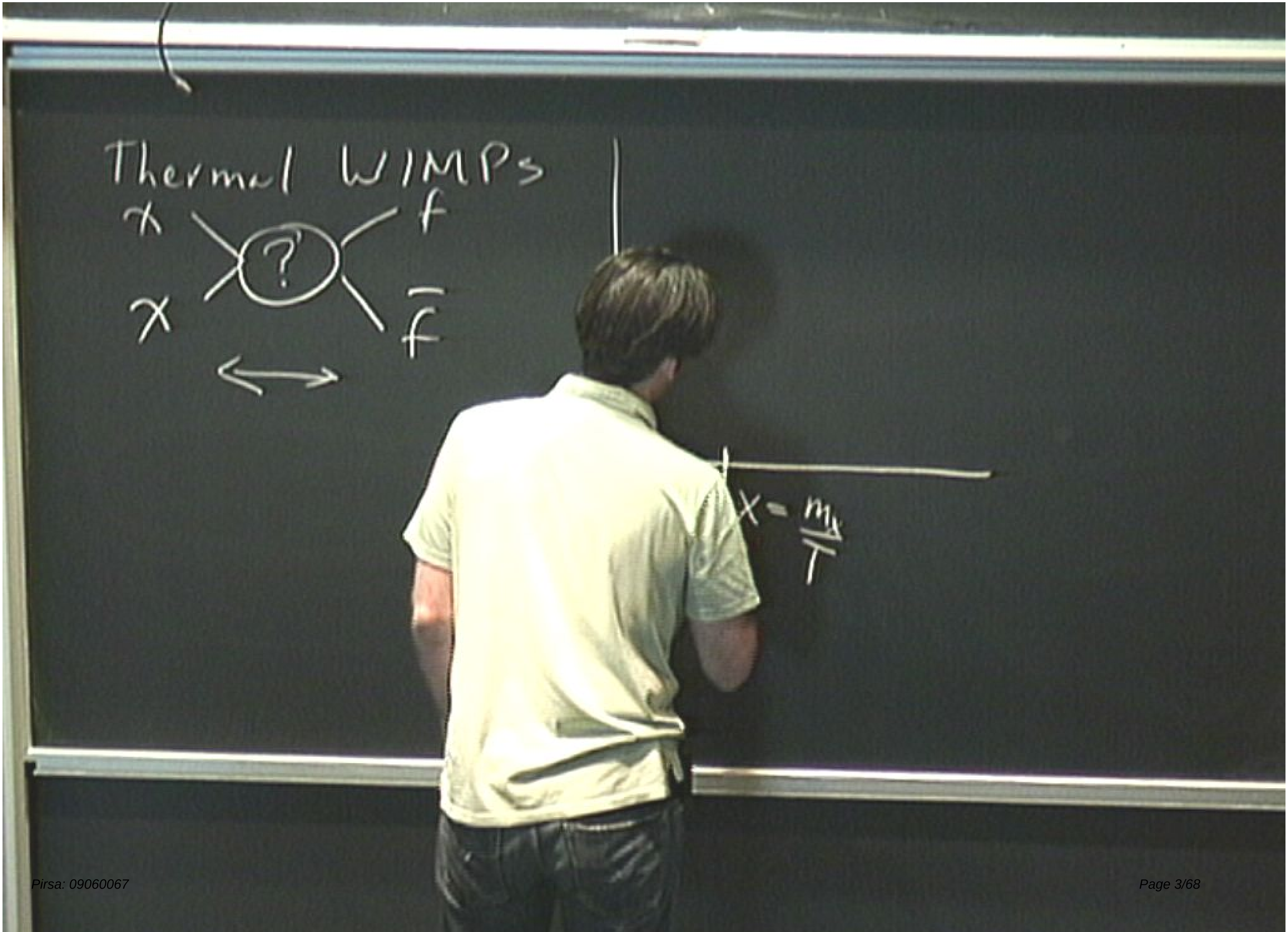
Abstract:

$n_R \sim T^3$

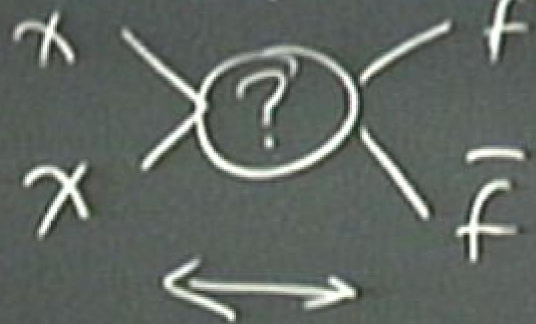
$n_{NR} \sim (mT)^{3/2} e^{-m/T}$

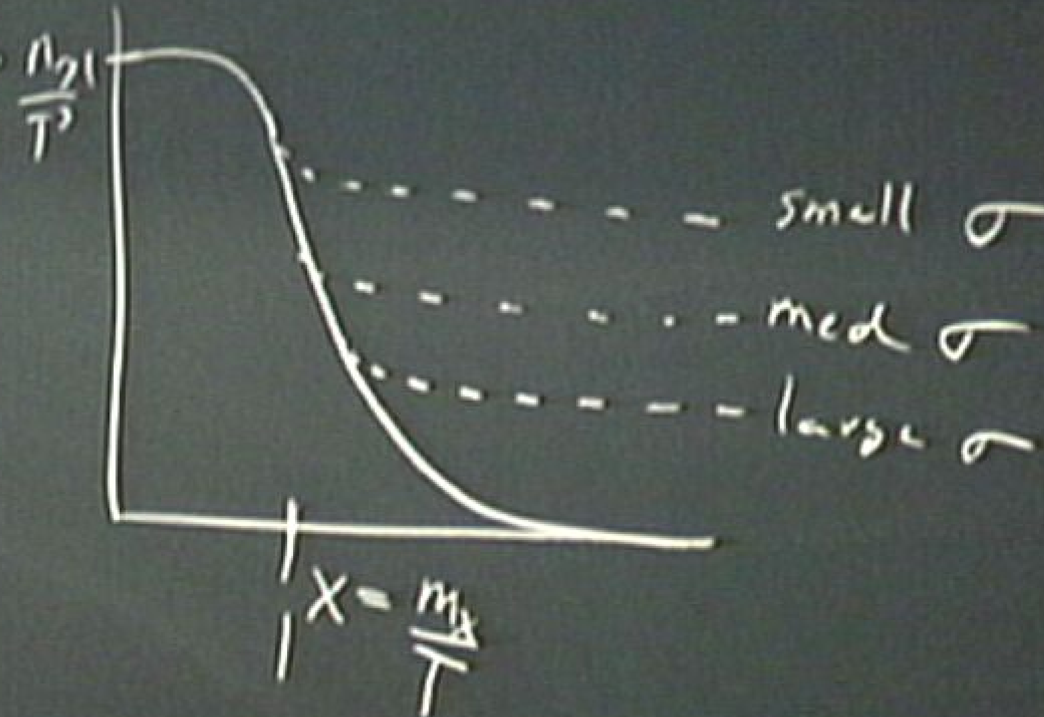
$n \sigma v \sim H_F$ (freezeout)

$H \sim \frac{T^2}{M_{pl}}$ (R.d)


Thermal WIMPs
χ
χ
?
f
f̄
x = m/T

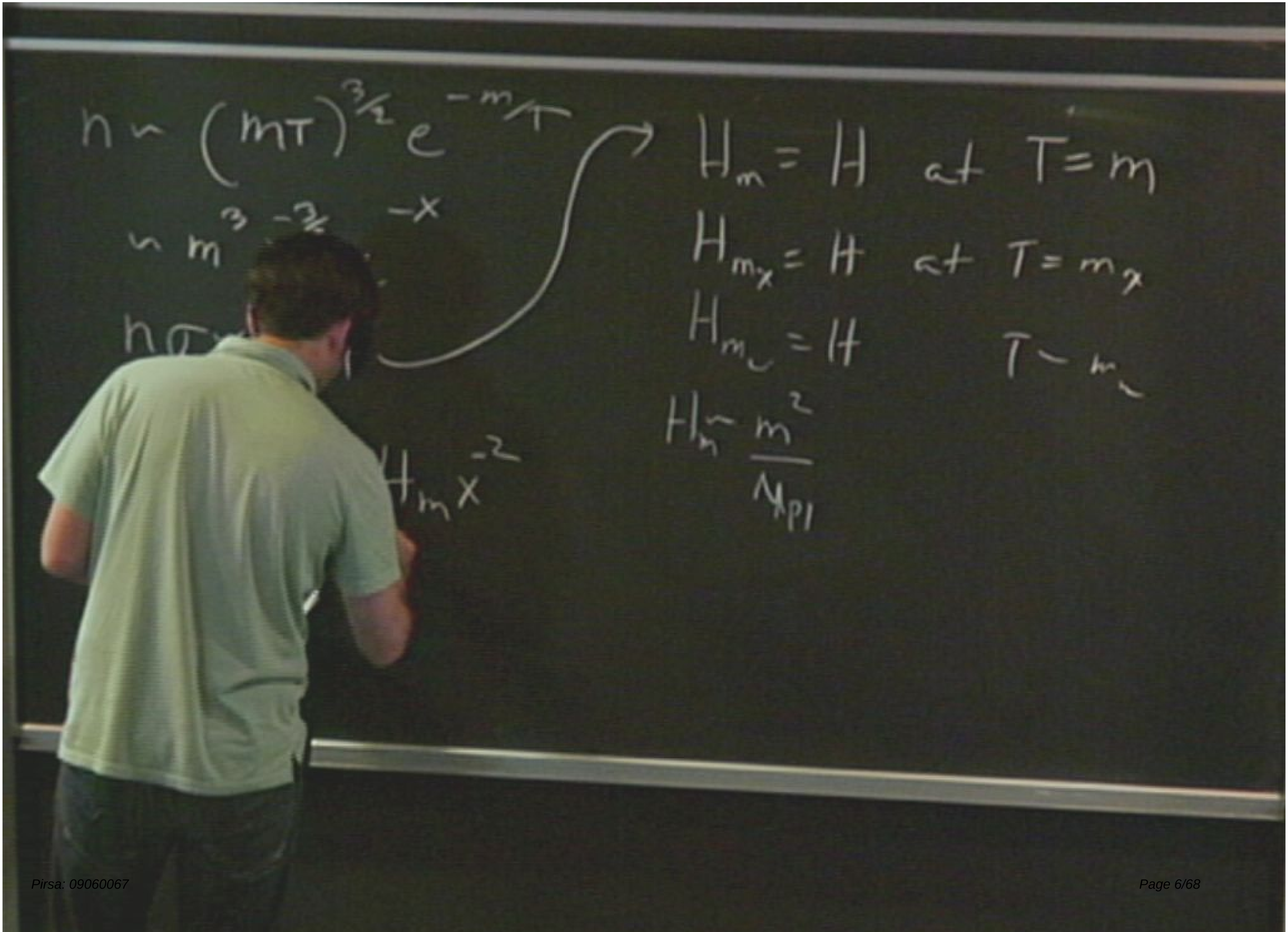
Thermal WIMPs





$$n \sim (mT)^{3/2} e^{-m/T}$$

$$\sim m^{3} x^{-3/2} e^{-x}$$


$n \sim (mT)^{3/2} e^{-m/T}$
$\sim m^3 \; ^{-3/2} \; ^{-x}$
$n\sigma$
$H_m x^{-2}$
$H_m = H$ at $T = m$
$H_{m_\chi} = H$ at $T = m_\chi$
$H_{m_\nu} = H$ $T \sim m_\nu$
$H_m \sim \frac{m^2}{M_{Pl}}$

$$n \sim (mT)^{3/2} e^{-m/T}$$

$$\sim m^3 x^{-3/2} e^{-x}$$

$$n \sigma v = H$$

$$x^{-3/2} \ldots m\, e^{-x} = \frac{H_{m_x} x^{-2}}{\langle \sigma v \rangle}$$

$$e^{-x} = \frac{H_{m_x} x^{-1/2}}{m_x^2 \langle \sigma v \rangle}$$

$H_m = H$ at $T = m$

$H_{m_\chi} = H$ at $T = m_\chi$

$H_{m_\sim} = H \quad T \sim m_\sim$

$$H_m \sim \frac{m^2}{M_{Pl}}$$

$$n \sim (mT)^{3/2} e^{-m/T}$$

$$\sim m^3 x^{-3/2} e^{-x}$$

$$n\sigma v = H$$

$$H_m = H \text{ at } T = m$$

$$H_{m_\chi} = H \text{ at } T = m_\chi$$

$$H_{m_\sim} = H \quad T \sim m_\sim$$

$$H_m \sim \frac{m^2}{M_{Pl}}$$

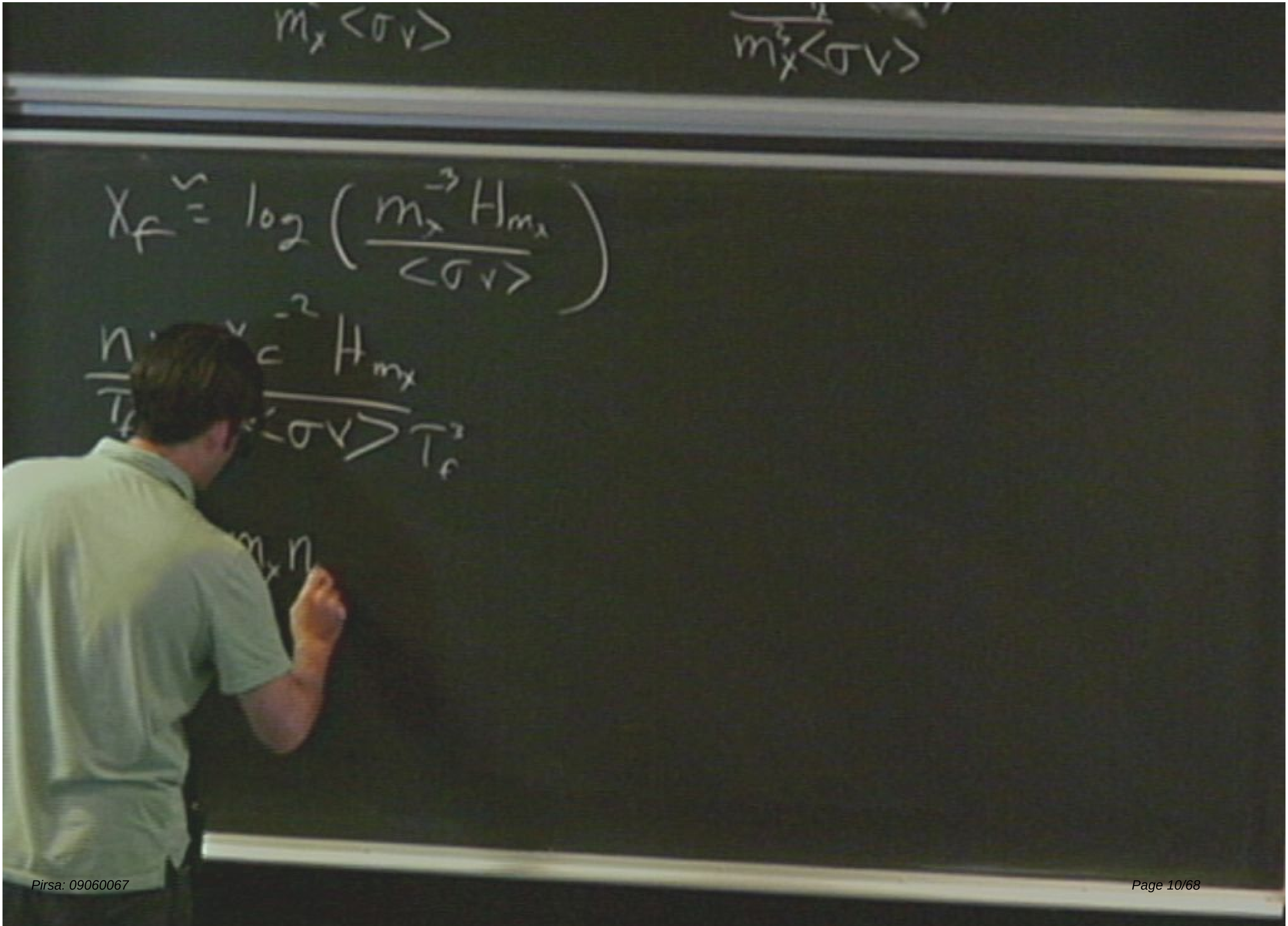
$$x^{-3/2} m^3 e^{-x} = \frac{H_{m_\chi} x^{-2}}{\langle\sigma v\rangle}$$

$$e^{-x} = \frac{H_{m_\chi} x^{-1/2}}{m_\chi^2 \langle\sigma v\rangle} \Longrightarrow e^{-x_f} = \frac{H_{m_\chi}}{m_\chi^2 \langle\sigma v\rangle}(x_f = 1)^{1/2}$$

$$m_\chi \langle \sigma v \rangle \qquad\qquad m_\chi^2 \langle \sigma v \rangle$$

$$x_f \simeq \log\left(\frac{m_\chi^{-3} H_{m_\chi}}{\langle \sigma v \rangle} \right)$$

$$\frac{n}{T_f^3} \sim \frac{x_f^{-2} H_{m_\chi}}{\langle \sigma v \rangle T_f^3}$$



$m_x \langle \sigma v \rangle$
$m_x^3 \langle \sigma v \rangle$
$x_f \simeq \log\left(\frac{m_x^{-3} H_{m_x}}{\langle \sigma v \rangle} \right)$

$$m_\chi \langle \sigma v \rangle \qquad m_\chi^2 \langle \sigma v \rangle$$

$$x_f \simeq \log\left(\frac{m_\chi^{-3} H_{m_\chi}}{\langle \sigma v \rangle} \right)$$

$$\frac{n}{T_f^3} \sim \frac{x_f^{-2} H_{m_\chi}}{\langle \sigma v \rangle T_f^3}$$

$$\frac{\ }{T_f^3} = \frac{m_\chi n_\chi}{T_f^3} = \frac{x_f^{-2} H_{m_\chi}}{\langle \sigma v \rangle T_f^3} m$$

$$m_\chi \langle \sigma v \rangle \qquad m_\chi^2 \langle \sigma v \rangle$$

$$x_f \simeq \log\left(\frac{m_\chi^{-3} H_{m_\chi}}{\langle \sigma v \rangle}\right)$$

$$\frac{n}{T_f^3} \sim \frac{x_f^{-2} H_{m_\chi}}{\langle \sigma v \rangle T_f^3}$$

$$\frac{\rho}{T_f^3} = \frac{m_\chi n_\chi}{T_f^3} = \frac{\overset{m_\chi^2}{x_f^{-2}} H_{m_\chi}}{\langle \sigma v \rangle \underset{m_\chi^3}{T_f^3}} \overset{m}{\cancel{m}} \Rightarrow \frac{x_f^{\alpha}}{M_{pl} \langle \sigma v \rangle}$$

$$x_f \simeq \log\left(\frac{m_\chi^{-3} H_{m_\chi}}{\langle \sigma v \rangle}\right)$$

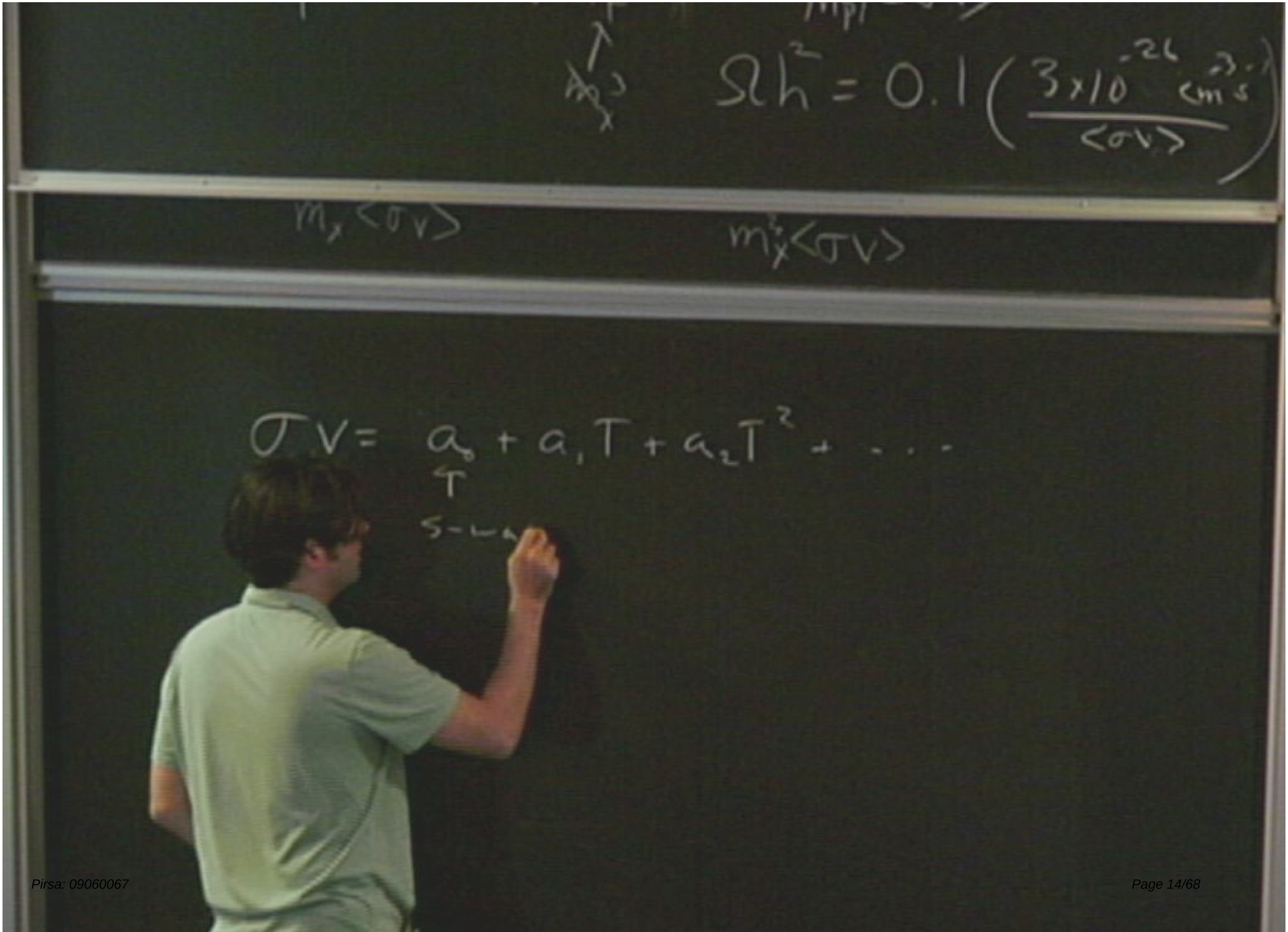
$$\frac{n}{T_f^3} \sim \frac{x_f^{-2} H_{m_\chi}}{\langle \sigma v \rangle T_f^3}$$

m_χ^2 $\quad$ m

$$\frac{\rho}{T_f^3} = \frac{m_\chi n_\chi}{T_f^3} = \frac{x_f^{-2} H_{m_\chi} \cancel{m}}{\langle \sigma v \rangle T_f^3} \Rightarrow \frac{x_f}{M_{pl} \langle \sigma v \rangle}$$

m_χ^3

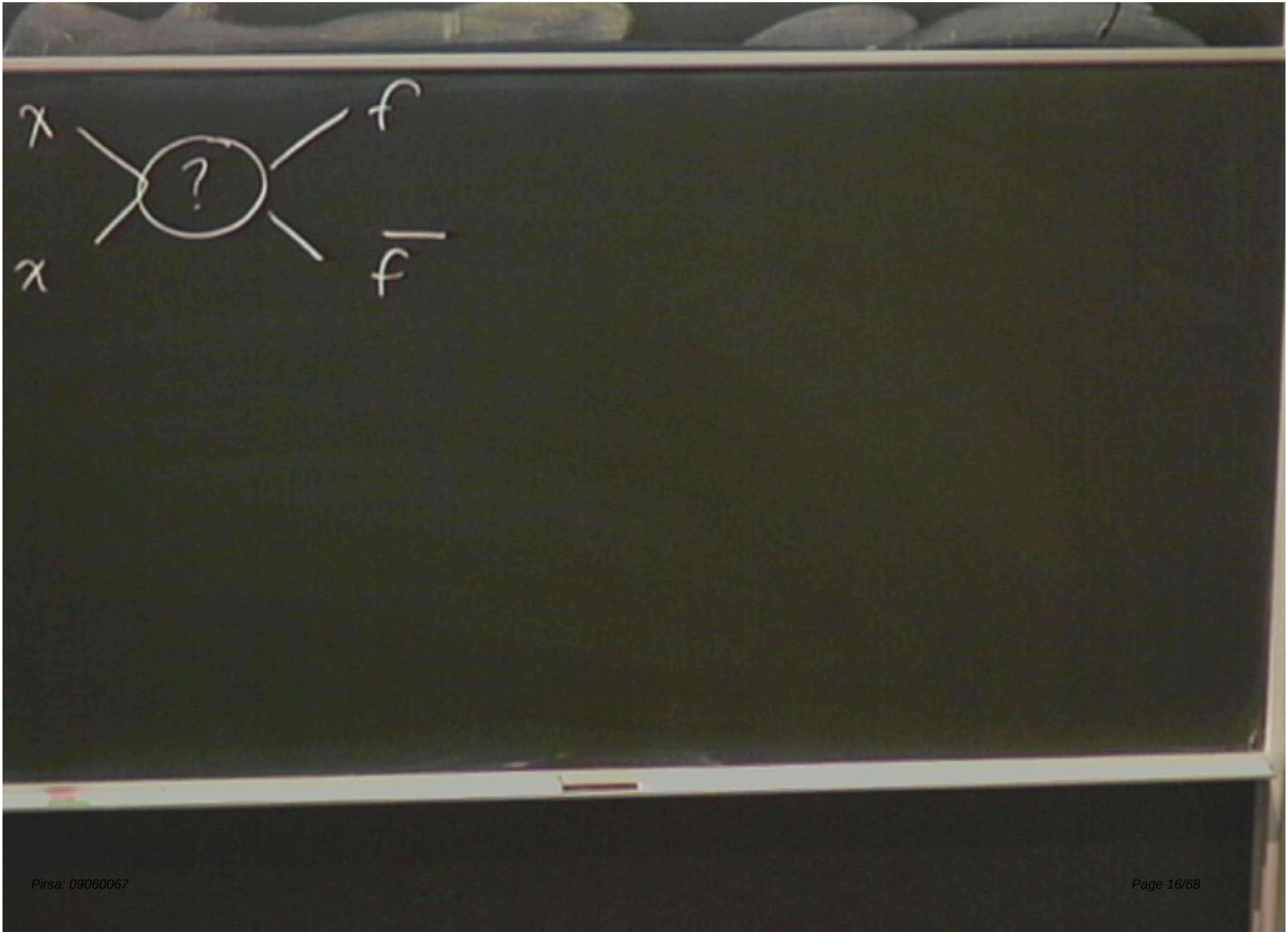
$$\Omega h^2 = 0.1 \left(\frac{\ldots^{26} \, cm^{3} s^{-1}}{\ldots\rangle} \right)$$


$\Omega h^2 = 0.1 \left(\frac{3\times10^{-26}\ cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$
$m_\chi \langle \sigma v \rangle$
$m_\chi^2 \langle \sigma v \rangle$
$\sigma v = a_0 + a_1 T + a_2 T^2 + \ldots$

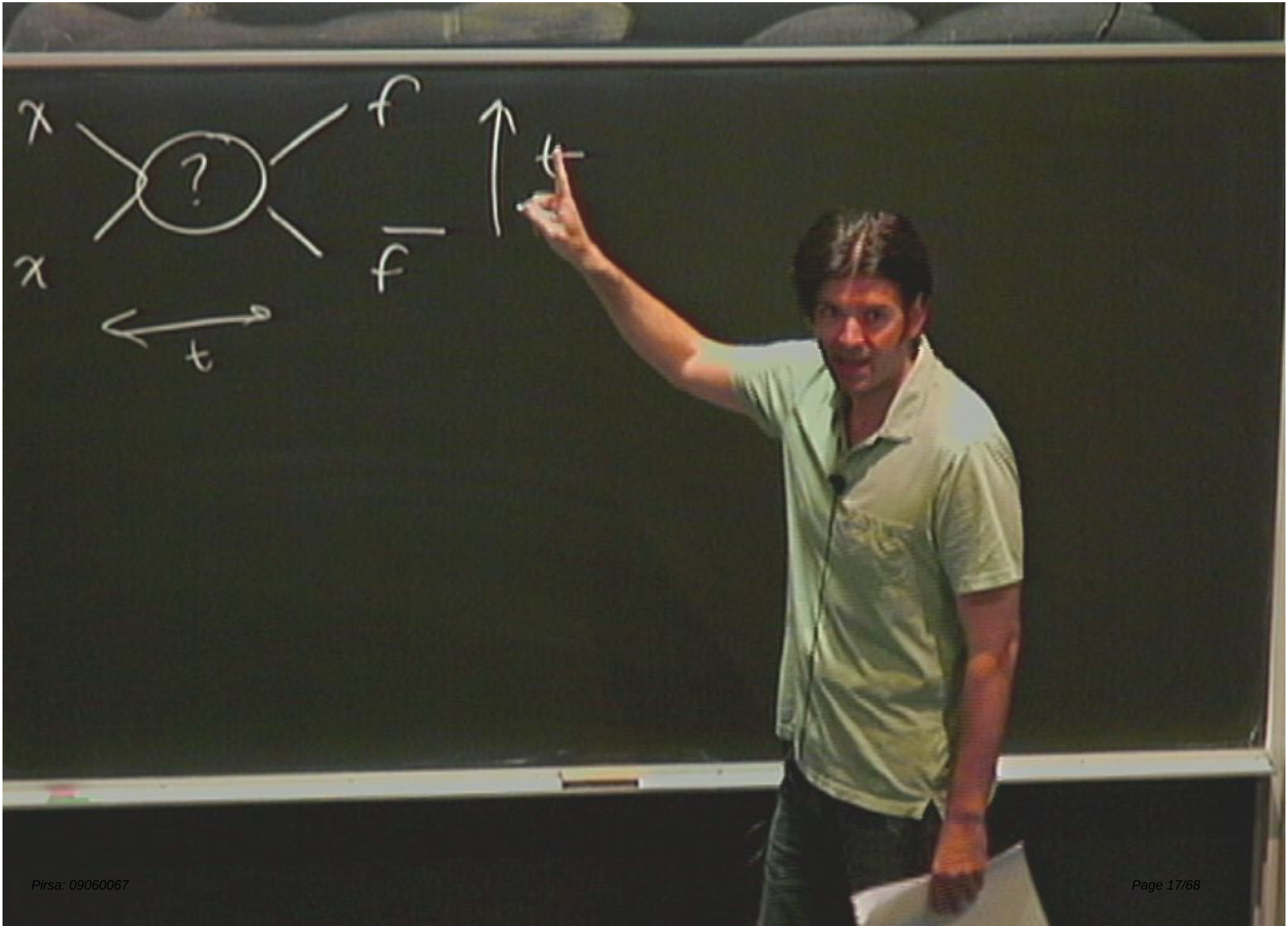
$m_\chi \langle \sigma v \rangle$

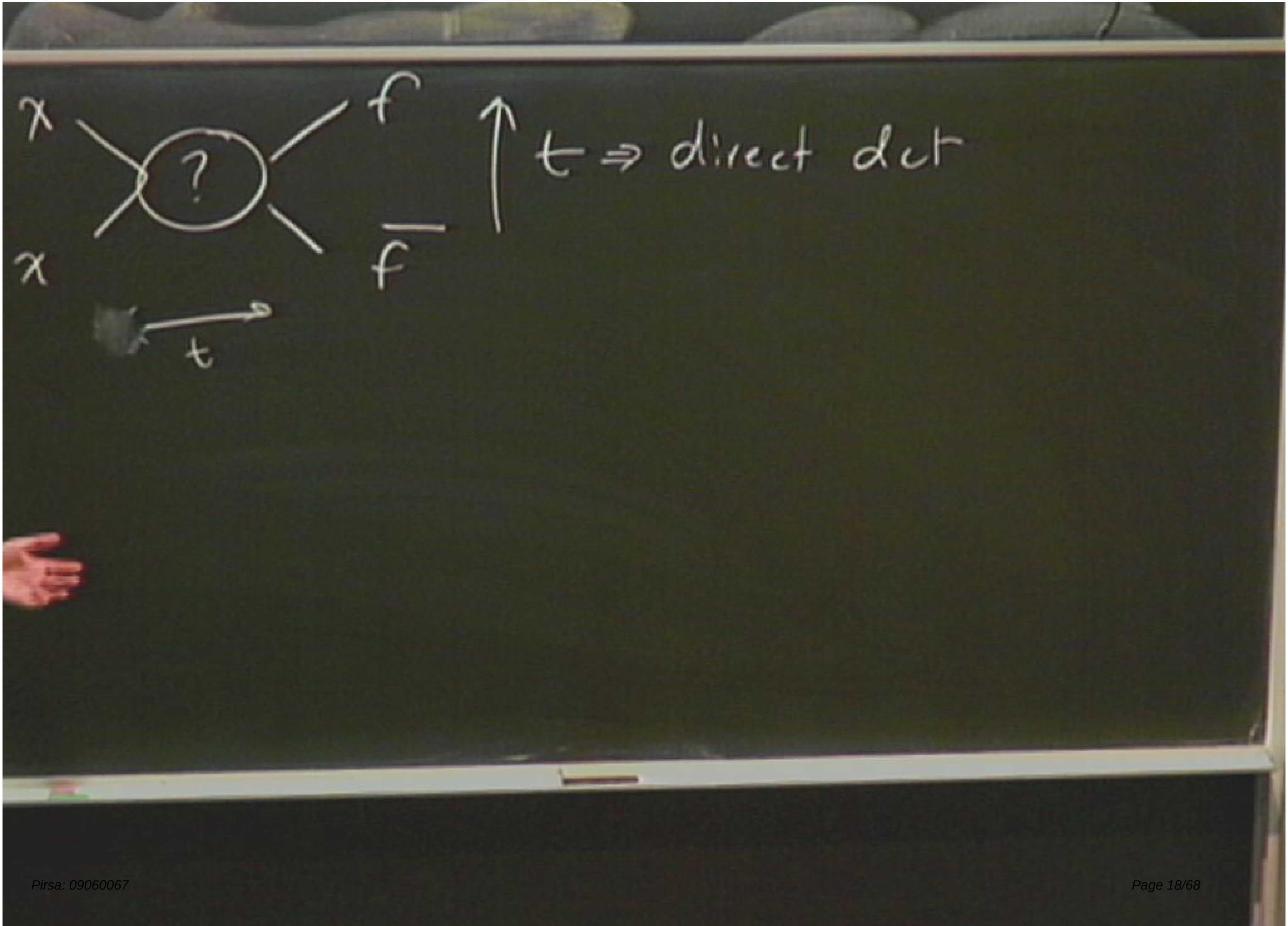
$$\sigma v = a_0 + a_1 T + a_2 T^2 + \dots$$

s-wave p-wave

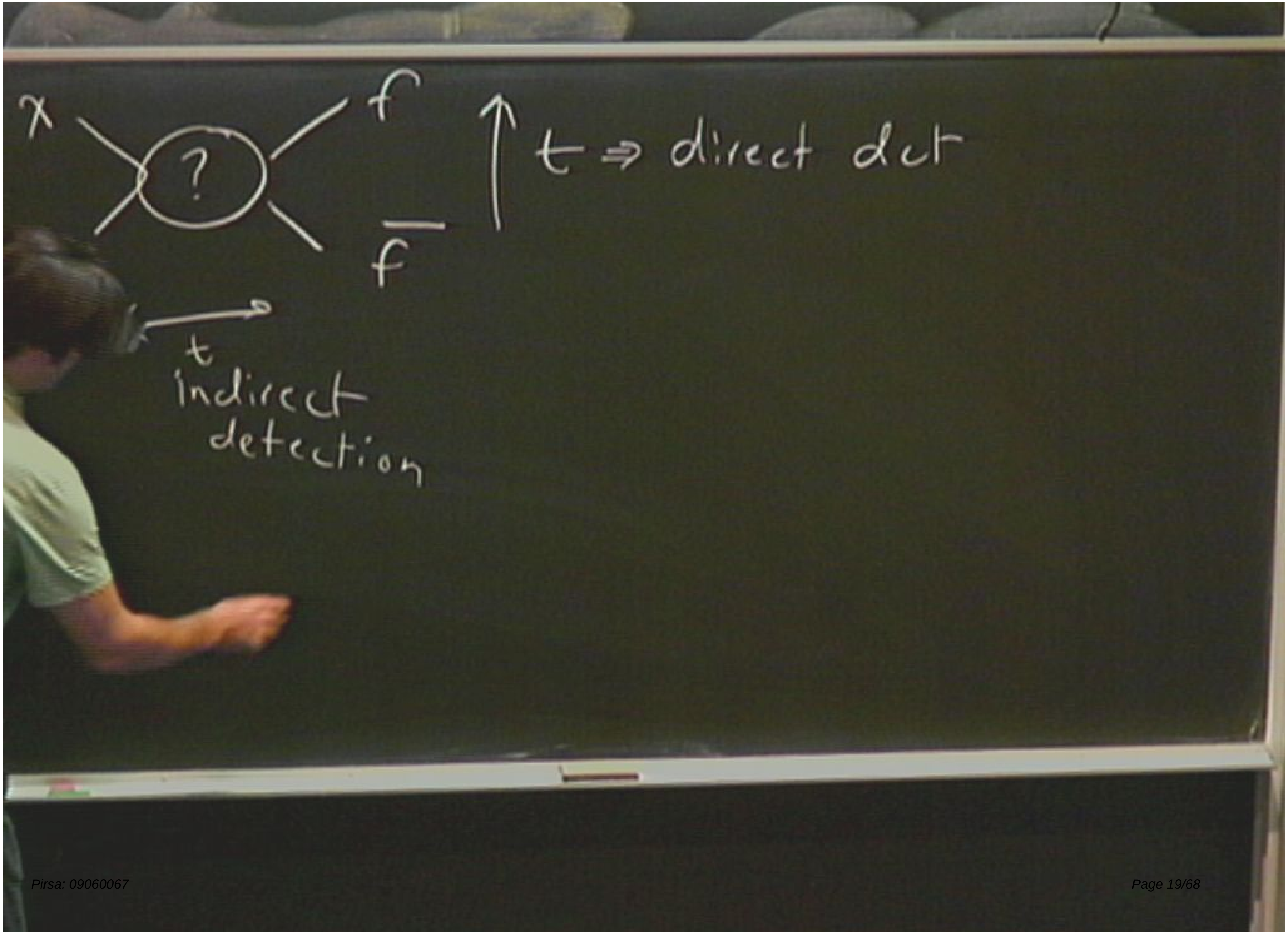


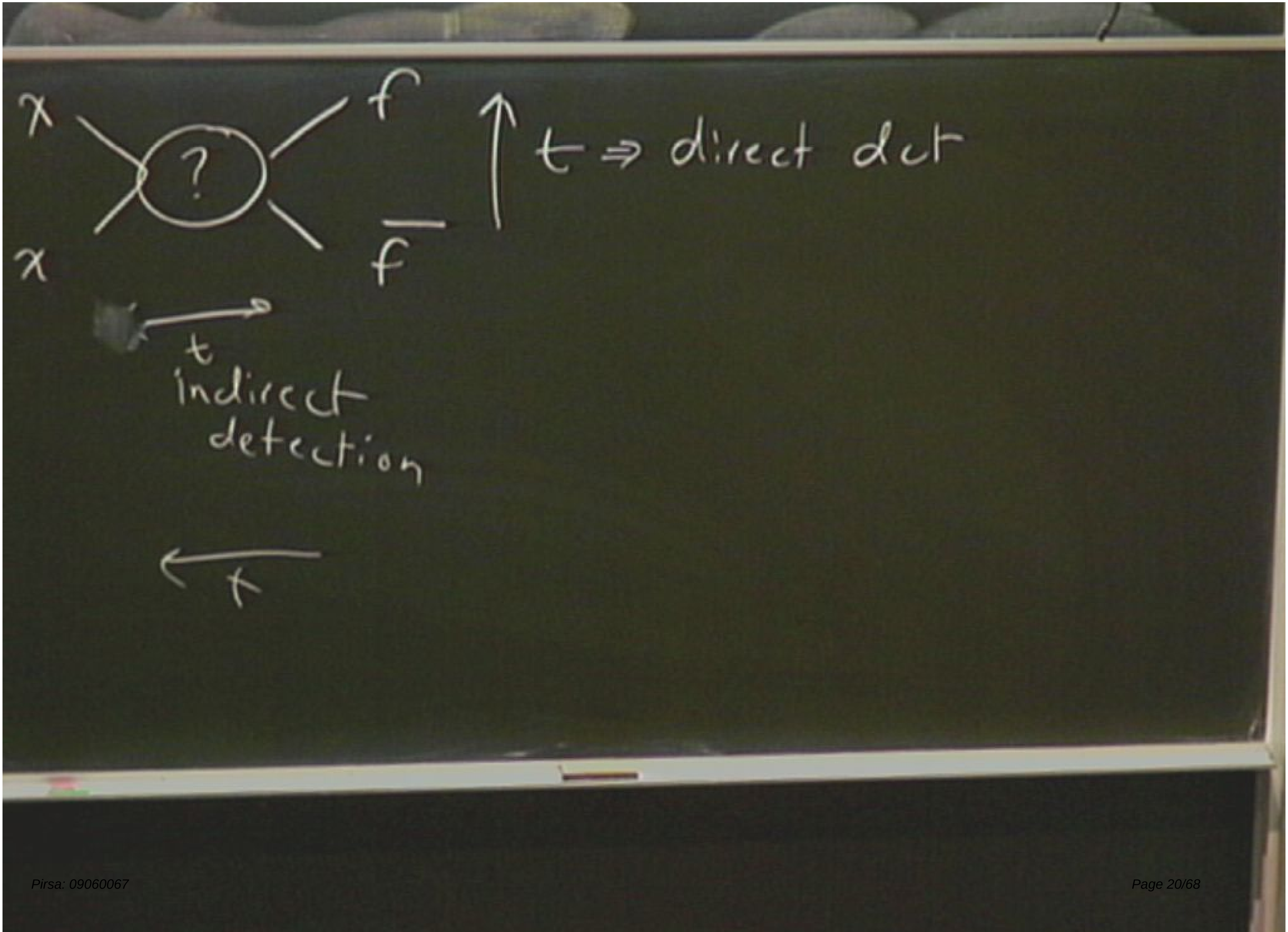
χ
f
?
χ
$\bar{f}$

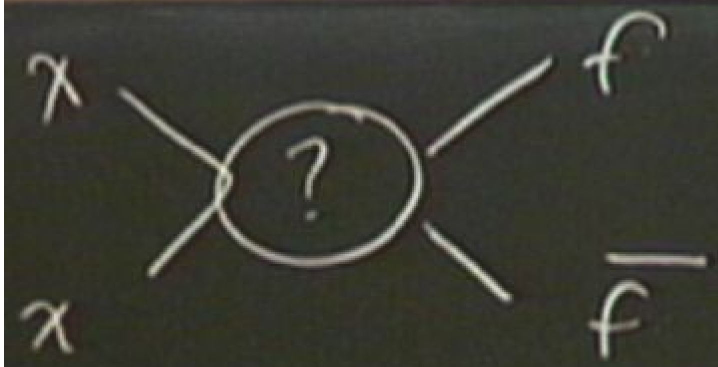

x
f
?
x
f
t
t



χ
f
?
t ⇒ direct det
χ
f̄
t


χ
?
f
f̄
t ⇒ direct det
t
indirect
detection


χ
χ
f
?
f̄
t ⇒ direct det
t
indirect
detection
t



$\uparrow t \Rightarrow$ direct det

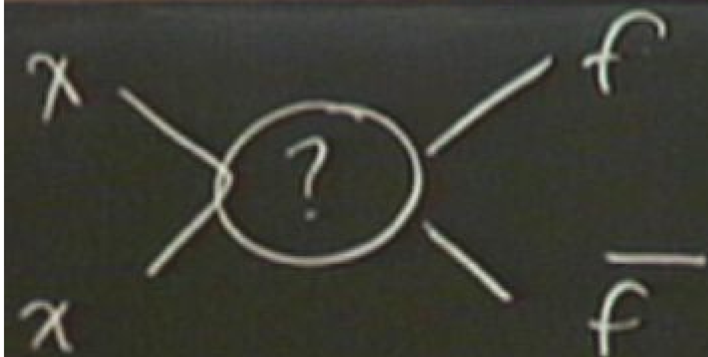
$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm^3\,s^{-1}}$$

$$\sim \frac{\alpha^2}{(200\,\mathrm{GeV})^2}$$

"WIMP miracle"

$\xrightarrow{t}$ indirect detection

$\xleftarrow{t}$ collider physics



$\uparrow t \Rightarrow$ direct det

$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$\sim \frac{\alpha^2}{(200\,\mathrm{GeV})^2}$$

"WIMP miracle"

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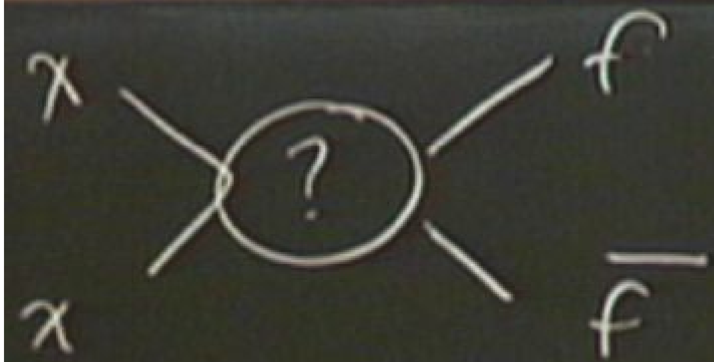


$t \Rightarrow$ direct det

t
indirect detection

t
Collider physics

$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm^3\,s^{-1}}$$

$$\sim \frac{\alpha^2}{(200\,\mathrm{GeV})^2}$$

"WIMP miracle"

4th gen neutrino

$$\Omega h^2 = \left(\frac{\sum m_\nu}{9\,eV}\right) 0.1$$

4th gen neutrino

$$\Omega h^2 = \left(\frac{\sum m_\nu}{9\,eV}\right) 0.1 \quad (3\ \nu\text{'s})$$

$L e_R h$ chiral fermions

4th gen neutrino

$$\Omega h^2 = \left(\frac{\Sigma m_\nu}{9\,eV}\right) 0.1 \quad (3\ \nu's)$$

$L e_R h$ chiral fermions

$L \nu_R h^*$ chiral Dirac ν'

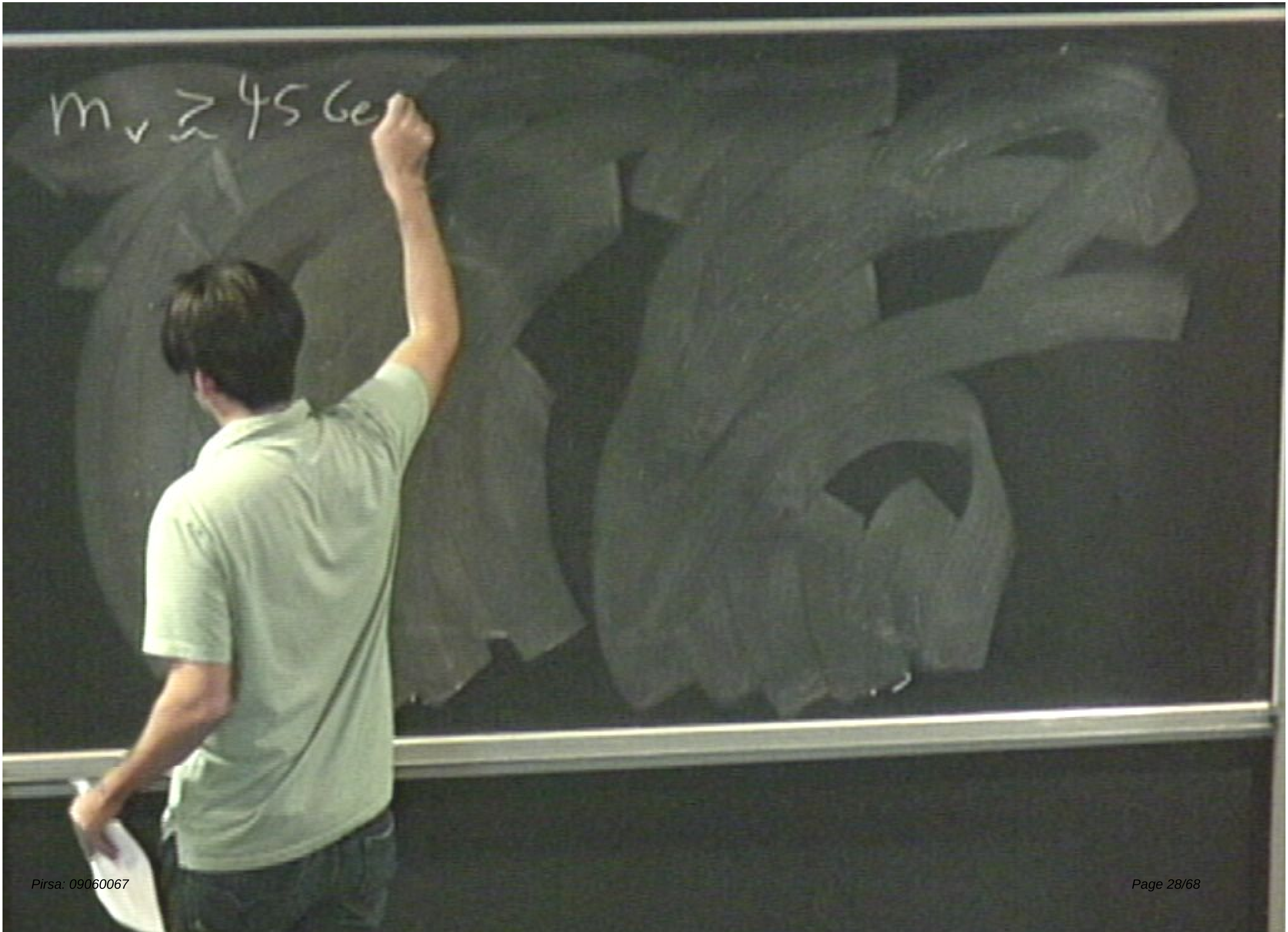
4^{th} gen neutrino

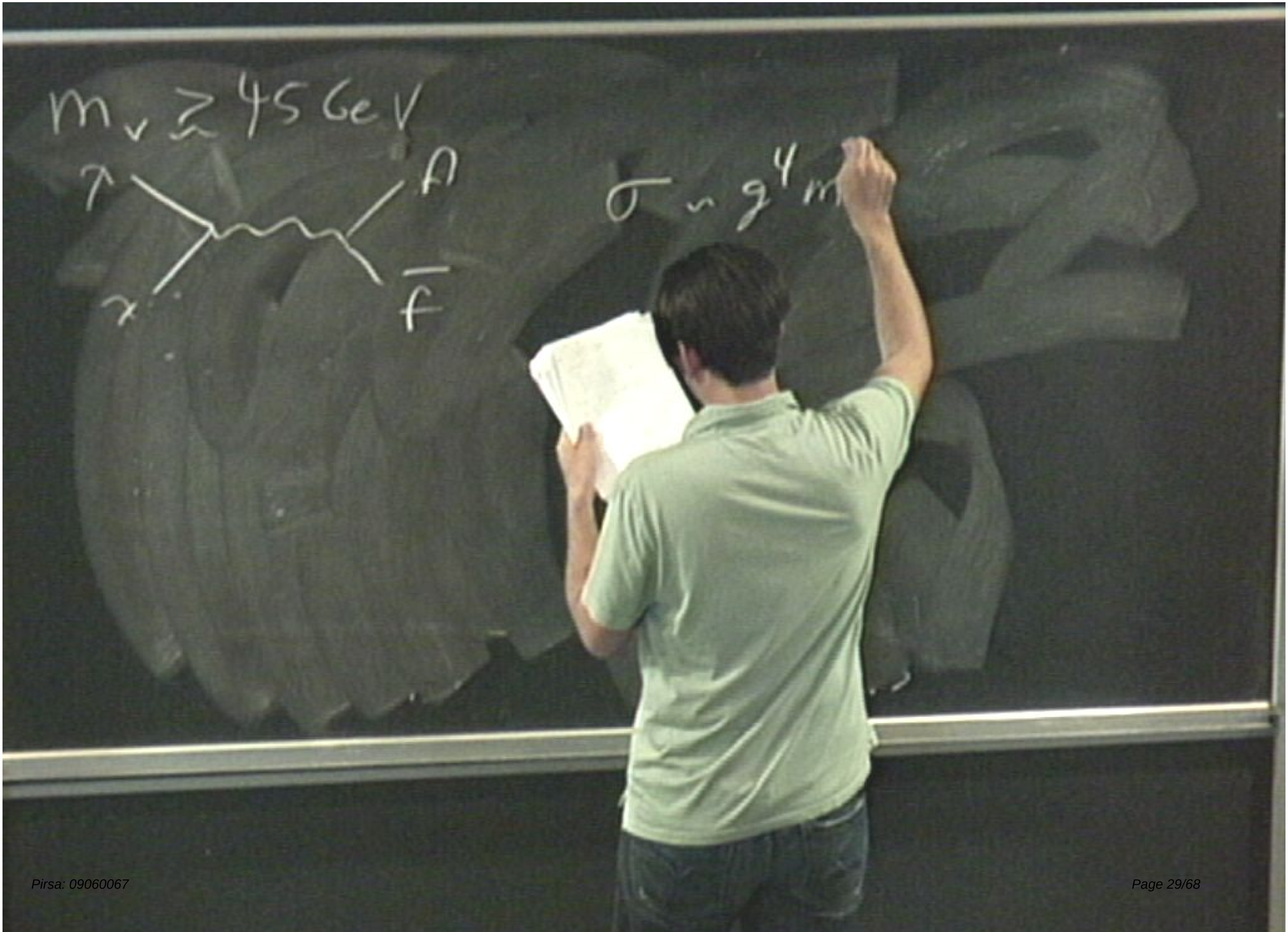
$$\Omega h^2 = \left(\frac{\Sigma m_\nu}{9\,eV}\right) 0.1 \quad (3\ \nu\text{'s})$$

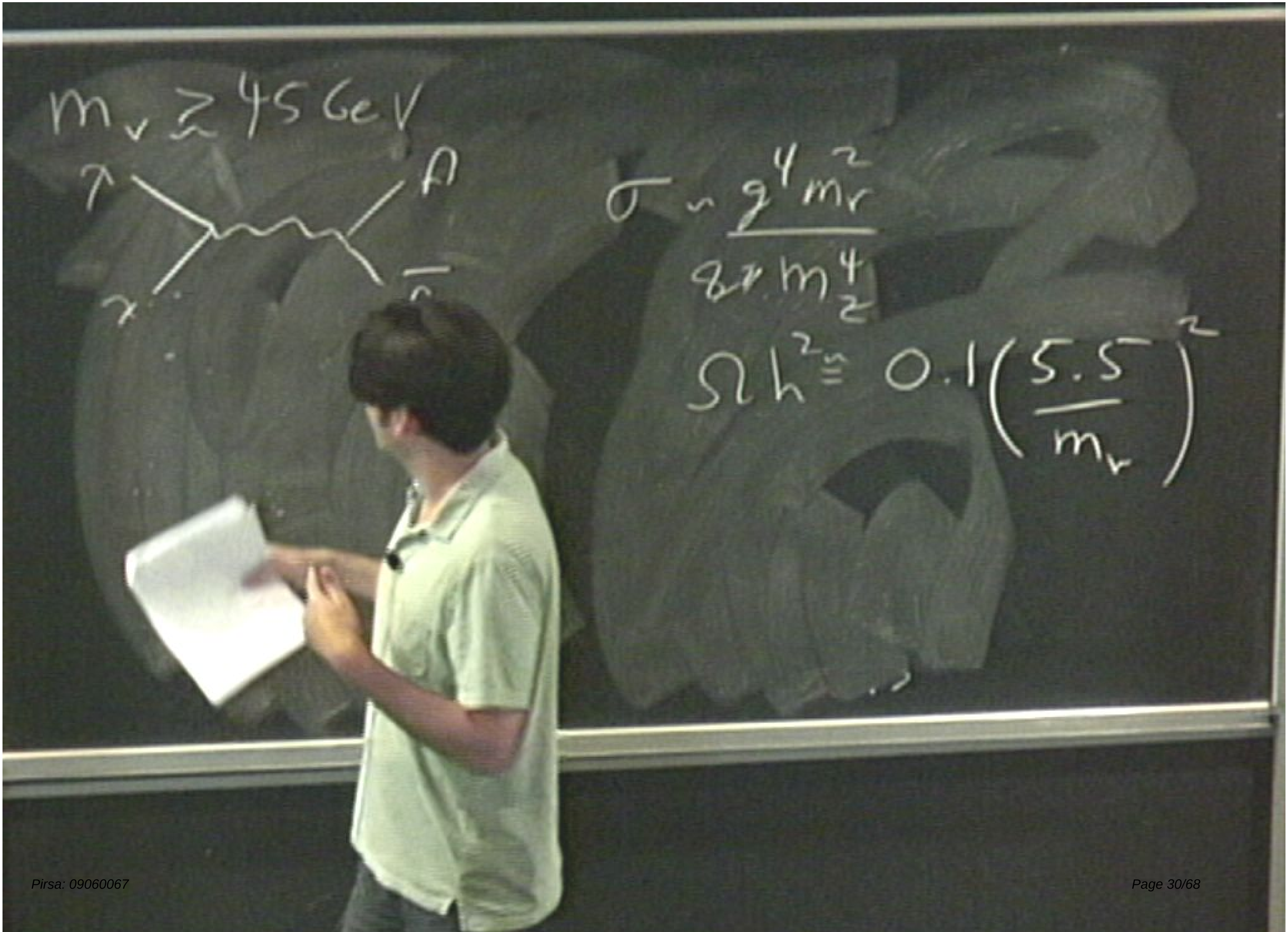
$\bar{L} e_R h$ chiral fermions

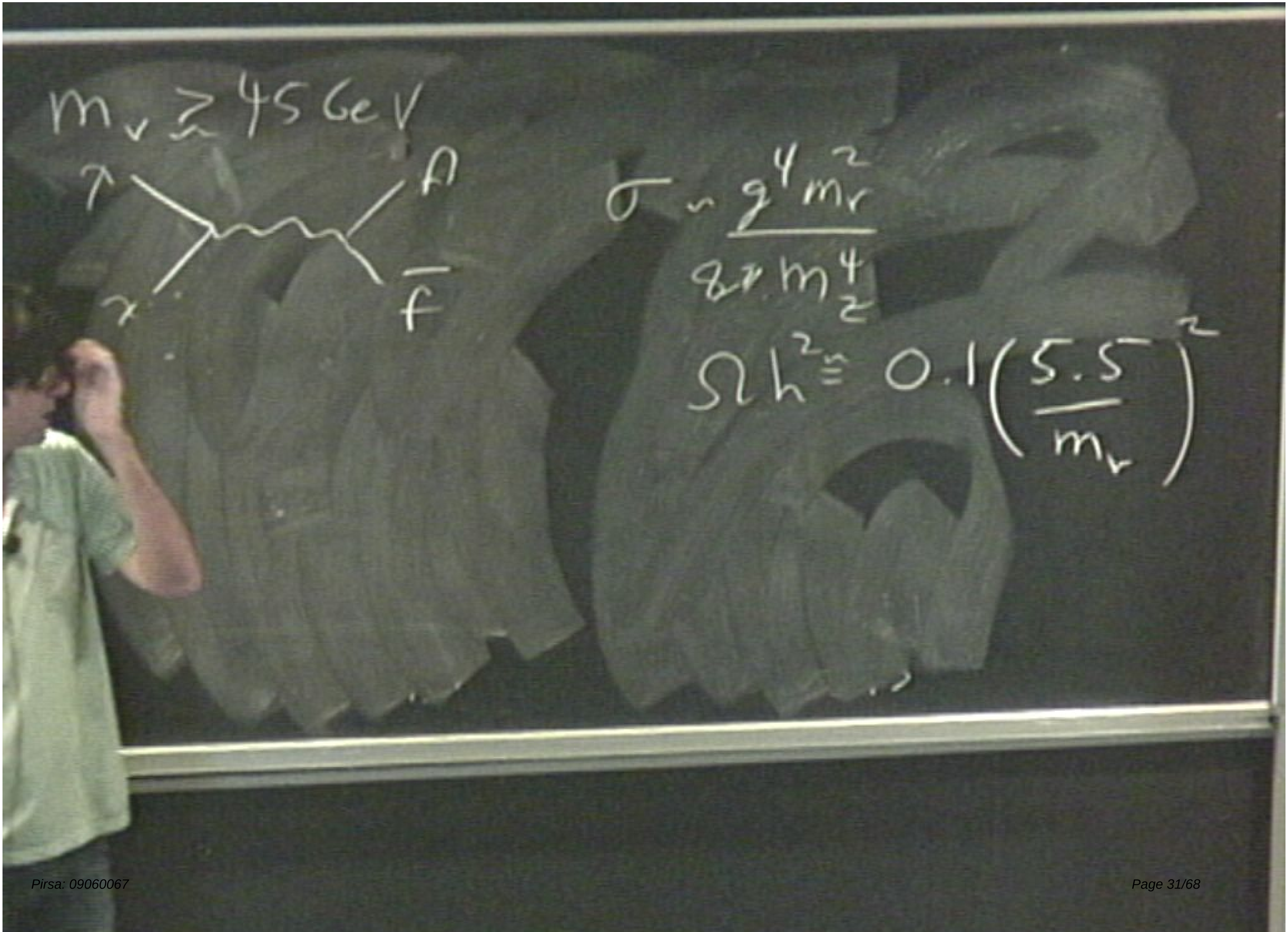
$\bar{L} \nu_R h$ chiral Dirac ν'

$(L_4, \bar{L}_4\ (2, \pm\frac{1}{2})$ $\quad m_\nu \bar{L} L$

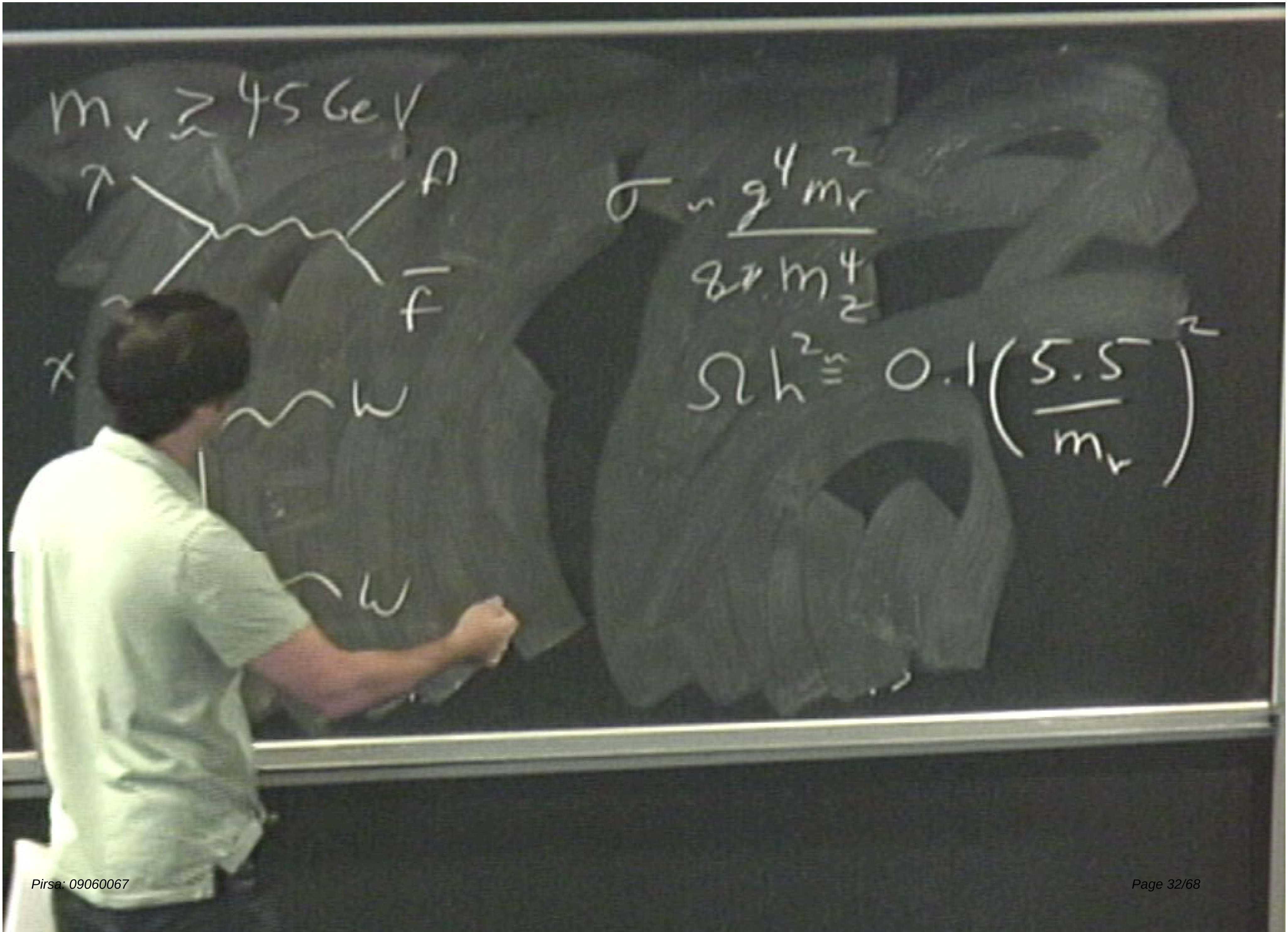

$m_\nu \gtrsim 45$ Ge

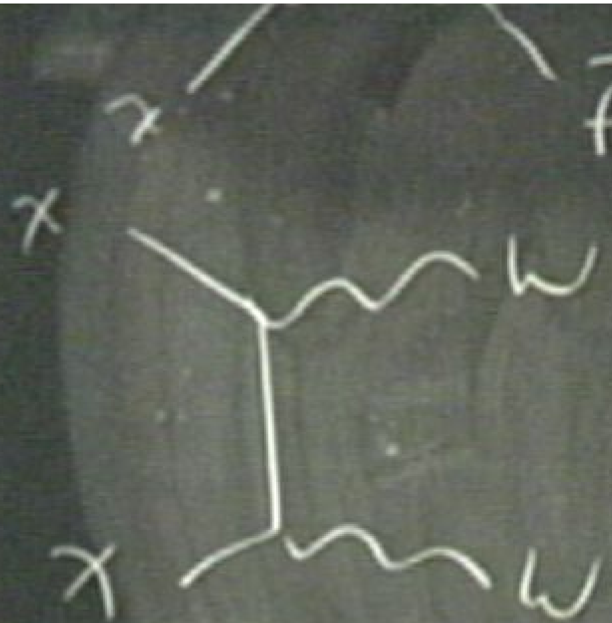

$m_\nu \gtrsim 45\ GeV$
χ
χ
f
$\bar{f}$
$\sigma \sim g^4 m$


$m_\nu \gtrsim 45\ \mathrm{GeV}$
$\sigma \sim \dfrac{g^4 m_\nu^2}{8\pi m_Z^4}$
$\Omega h^2 \cong 0.1 \left(\dfrac{5.5}{m_\nu}\right)^2$

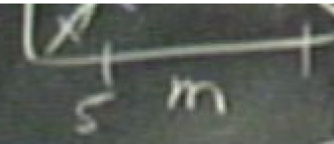


$m_\nu \gtrsim 45\ \text{GeV}$
f
$\bar{f}$
$\sigma \sim \frac{g^4 m_\nu^2}{8\pi m_Z^4}$
$\Omega h^2 \simeq 0.1\left(\frac{5.5}{m_\nu}\right)^2$


$m_\nu \gtrsim 45$ GeV
ν
f
$\bar{f}$
x
W
W
$\sigma \sim \frac{g^4 m_\nu^2}{8\pi m_Z^4}$
$\Omega h^2 \cong 0.1 \left(\frac{5.5}{m_\nu}\right)^2$



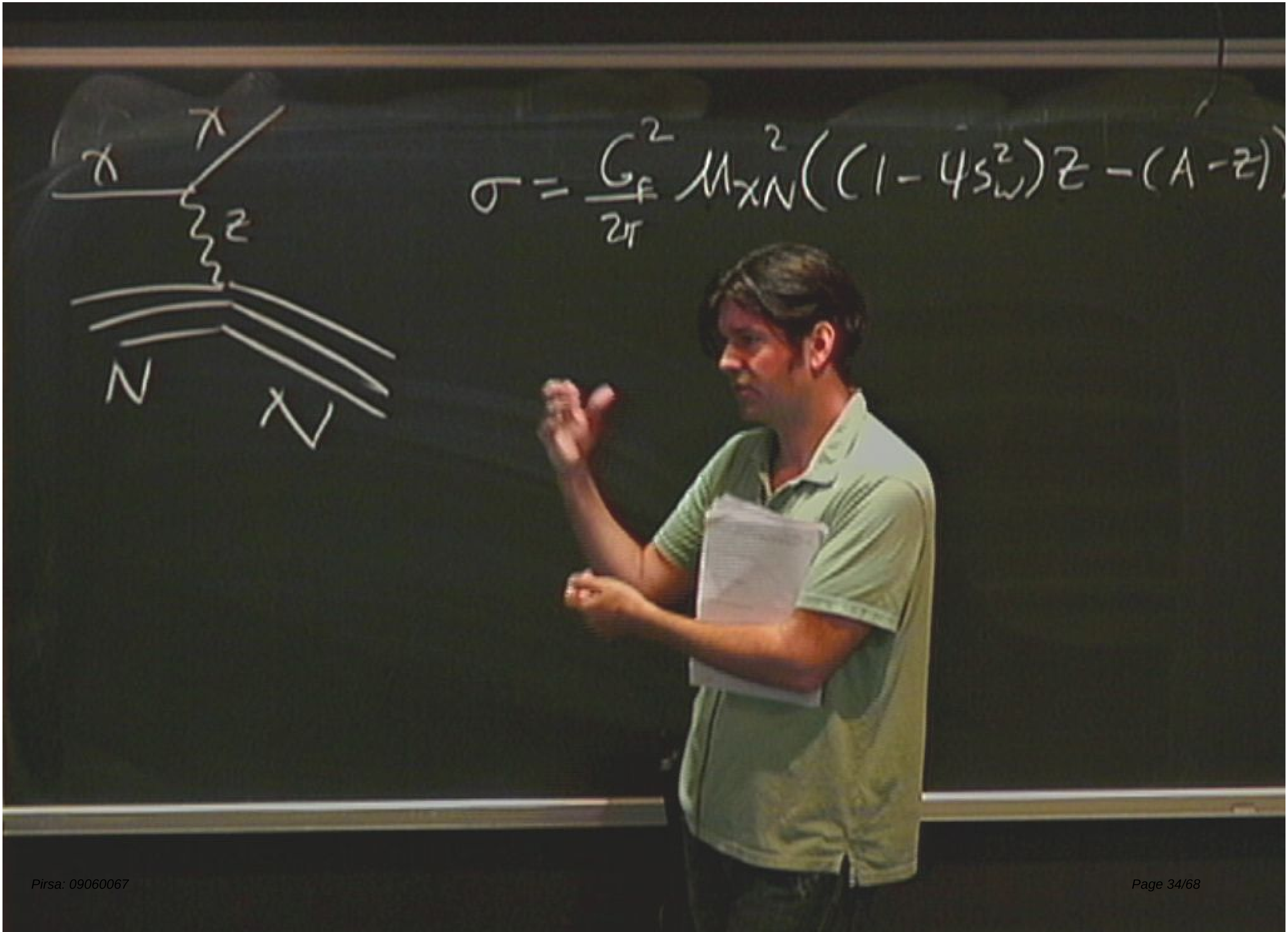
$$8\pi m_Z^4$$

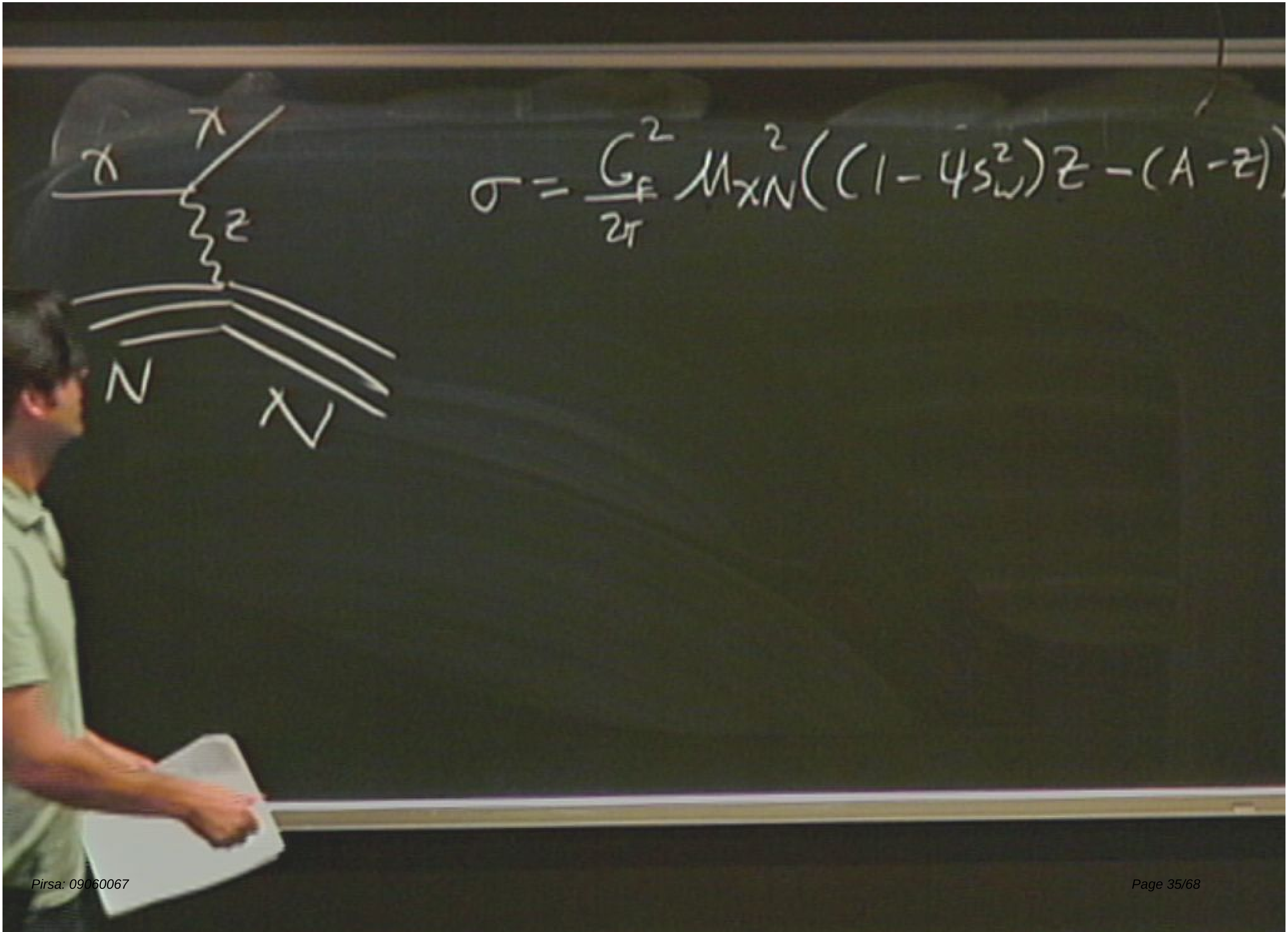


$$\Omega h^2 \cong 0.1 \left(\frac{5.5}{m_r} \right)^2$$

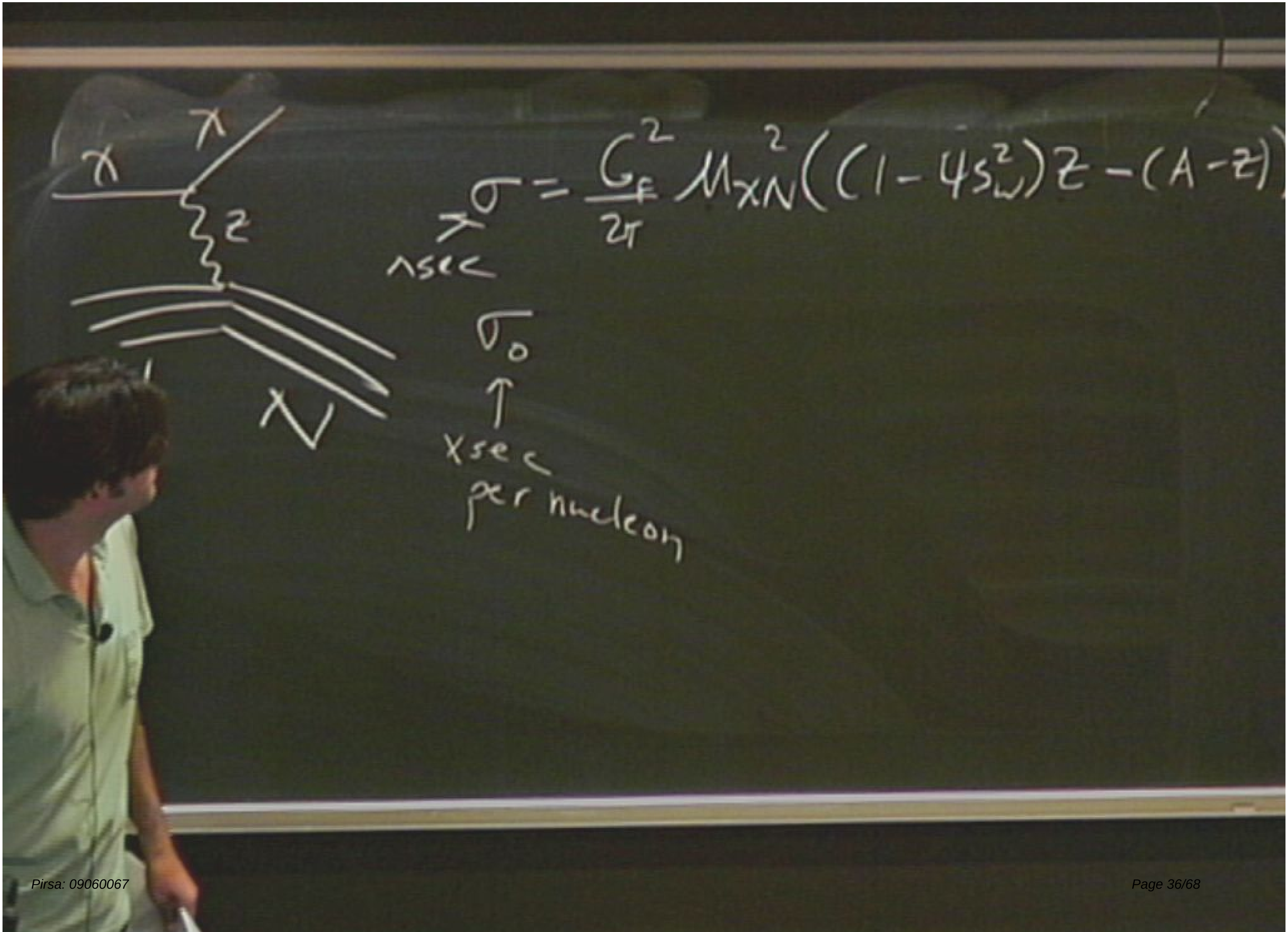
$$\sigma v = \frac{g^4}{512 \pi m_\chi^2} \left(21 + 3 t_w^2 + 11 t_w^4 \right)$$

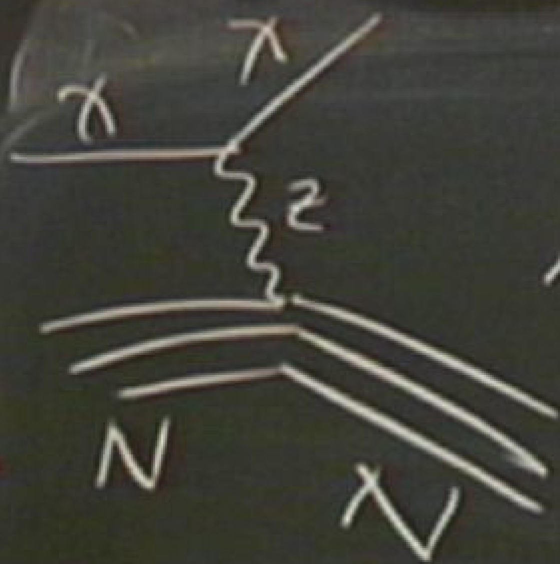
$$\Omega h^2 \simeq 0.1 \left(\frac{m_r}{\text{TeV}} \right)^2$$


χ
χ
Z
N
N
σ = G_F^2 / 2π μ_χN^2 ((1 - 4s_w^2) Z - (A - Z))



χ
χ
Z
N
N
$\sigma = \frac{G_F^2}{2\pi} \mu_{\chi N}^2 \left((1 - 4 s_w^2) Z - (A - Z) \right)$


χ
χ
Z
N
σ = G_F^2 / 2π μ_{χN}^2 ((1 - 4s_w^2) Z - (A - Z))
xsec
σ_0
xsec
per nucleon



xsec

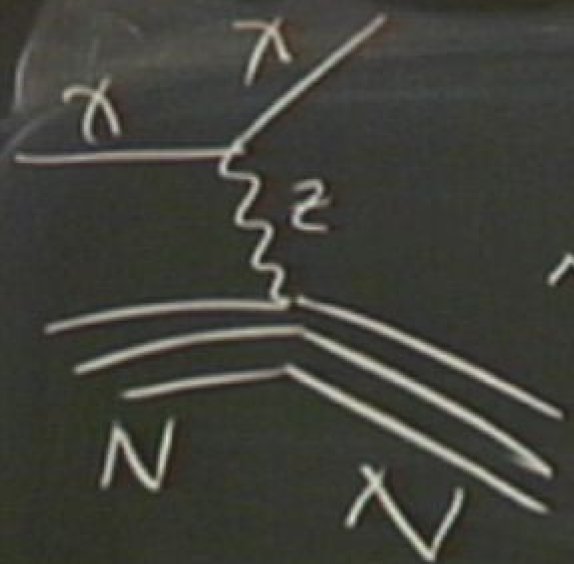
$$\sigma = \frac{G_F^2}{2\pi}\,\mu_{\chi N}^2\left((1-4s_w^2)Z-(A-Z)\right)$$

$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

σ_0

↑

xsec per nucleon



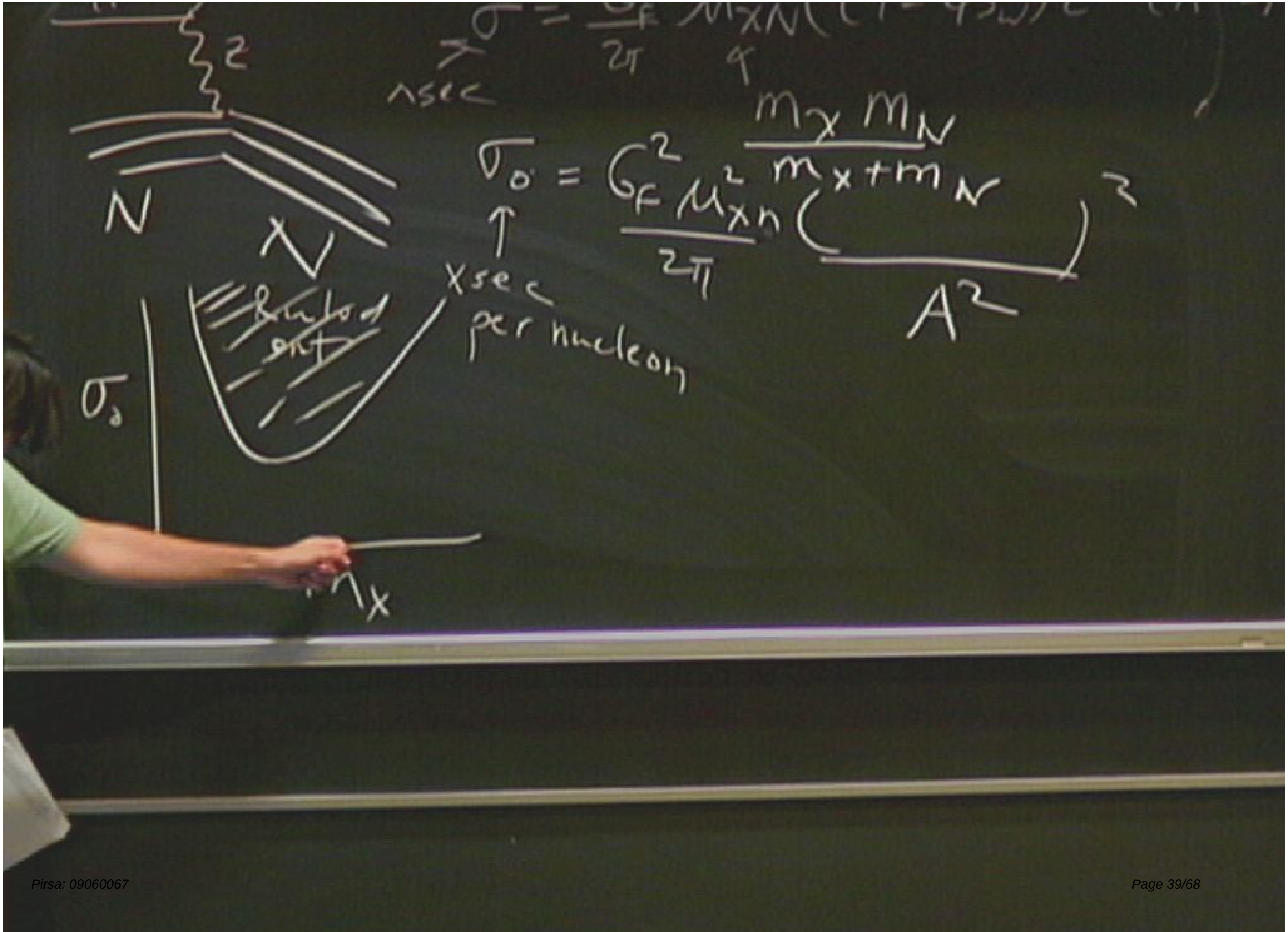
$$\sigma = \frac{G_F^2}{2\pi}\, \mu_{\chi N}^2 \left((1-4s_w^2)Z - (A-Z) \right)$$

xsec

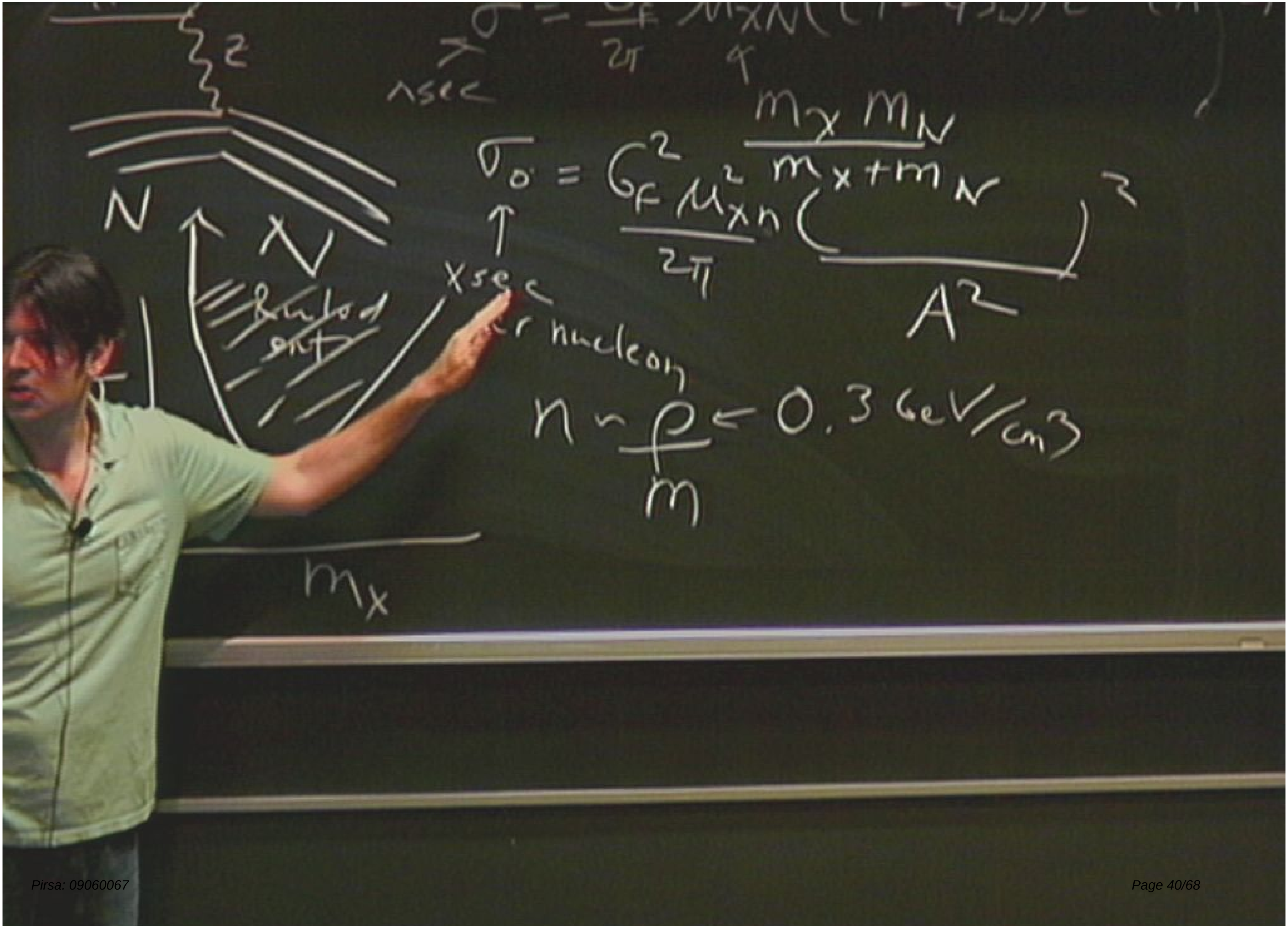
$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

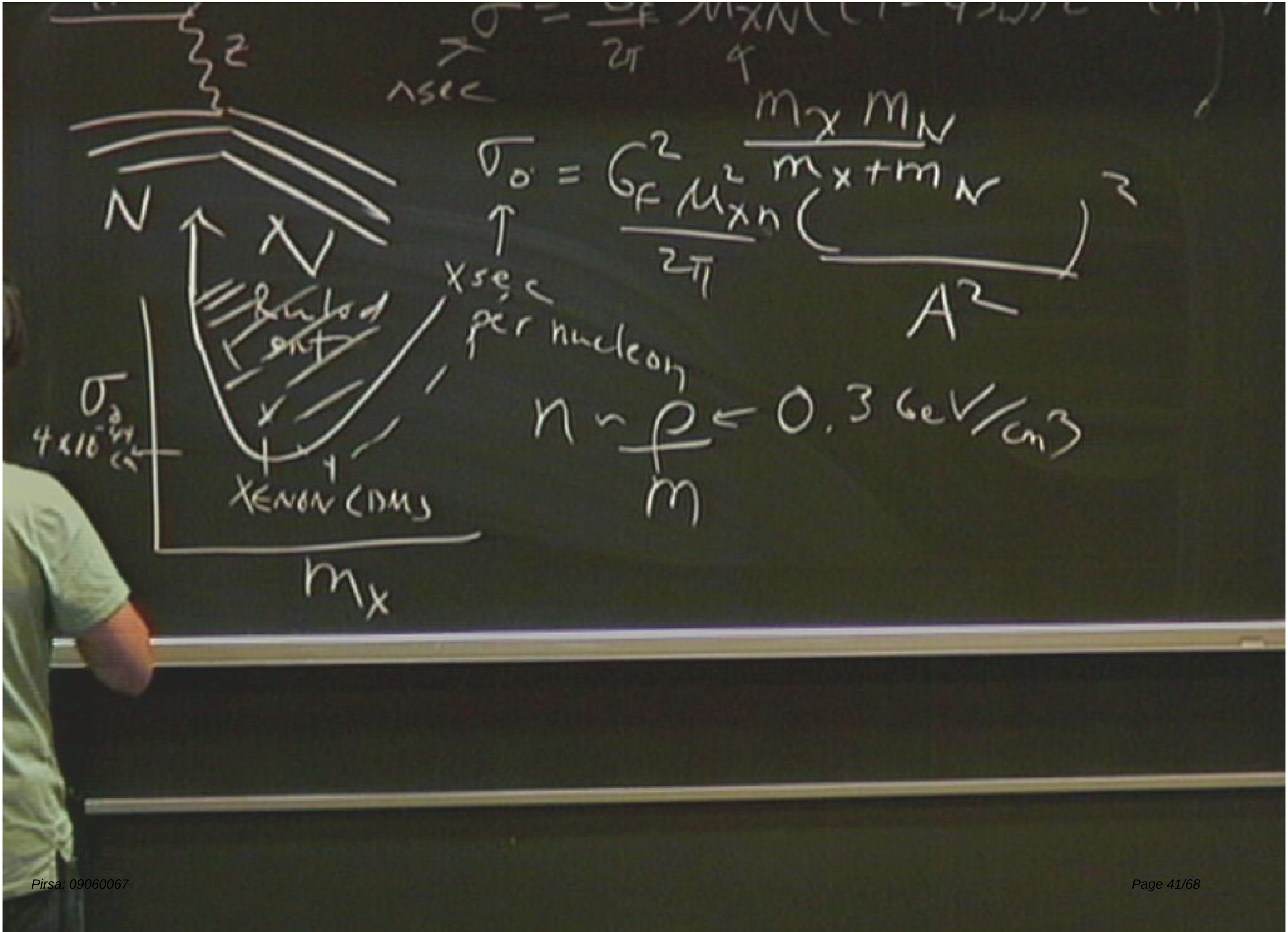
$$\sigma_0 = \frac{G_F^2}{2\pi}\, \mu_{\chi n}^2 \left(\frac{\quad}{A^2} \right)^2$$

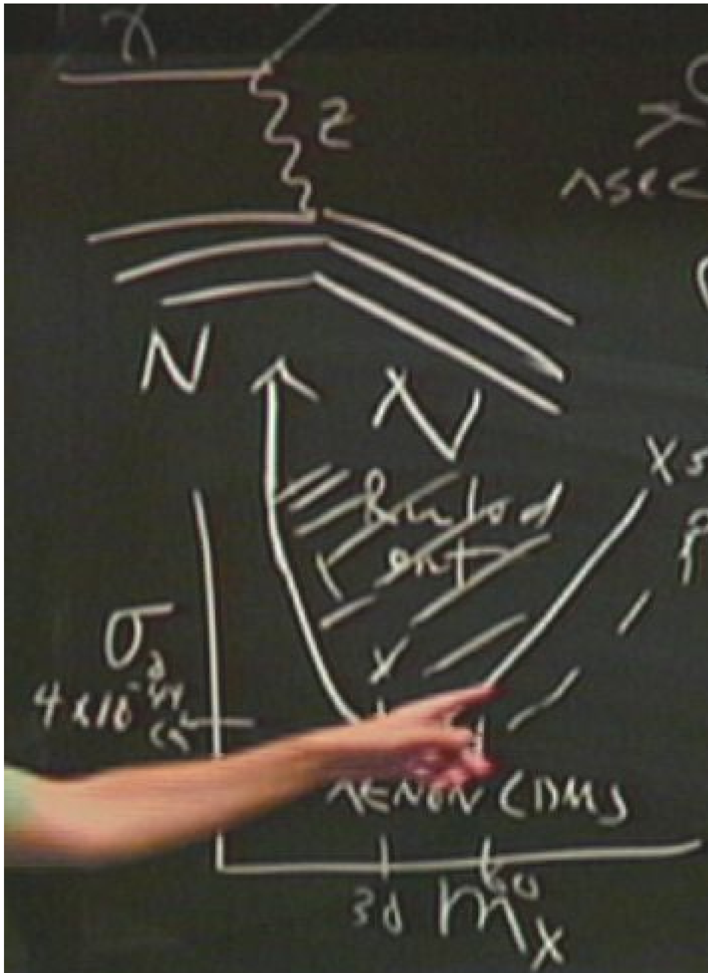
xsec
per nucleon



Z
xsec
N
N
$\sigma_0 = \frac{G_F^2 \mu_{xn}^2}{2\pi} \left(\frac{\frac{m_x m_N}{m_x + m_N}}{A^2} \right)^2$
xsec per nucleon
σ_0
m_x


Z
xsec
N
N
$\sigma_0 = \frac{G_F^2 \mu_{xn}^2}{2\pi} \left(\frac{\frac{m_\chi m_N}{m_x + m_N}}{A^2} \right)^2$
xsec
per nucleon
$n \sim \frac{\rho}{m} \leftarrow 0.3\ \mathrm{GeV/cm^3}$
m_x


Z
xsec
$\sigma_0 = \frac{G_F^2 \mu_{\chi n}^2}{2\pi} \left(\frac{\frac{m_\chi m_N}{m_\chi + m_N}}{A^2} \right)^2$
xsec per nucleon
N
N
σ_0
$4 \times 10^{-44}\ \mathrm{cm}^2$
XENON CDMS
m_χ
$n \sim \frac{\rho}{m} \leftarrow 0.3\ \mathrm{GeV/cm^3}$



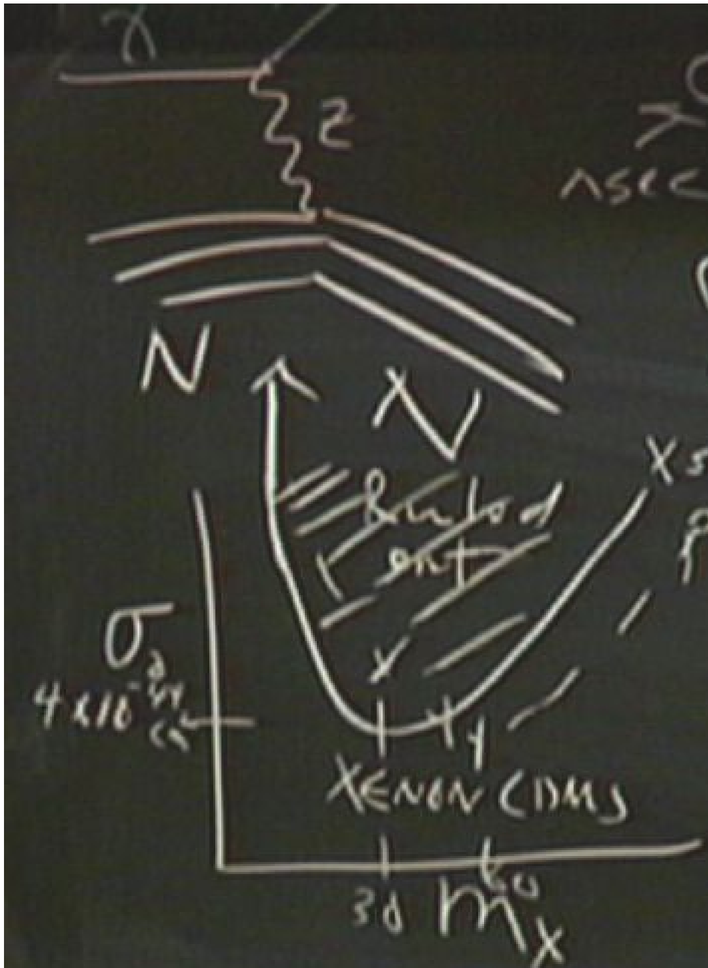
$$\sigma = \frac{G_F}{2\pi} \frac{\mu_{\chi N}}{4} \left((1-4s_W^2)Z - (A-Z) \right)$$

xsec

$$\sigma_0 = \frac{G_F^2 \mu_{\chi n}^2}{2\pi} \left(\frac{\frac{m_\chi m_N}{m_\chi + m_N}}{A^2} \right)^2 \approx 10^{-39}\ \text{cm}^2$$

xsec per nucleon

$$n \sim \frac{\rho}{m} \qquad \rho \leftarrow 0.3\ \text{GeV/cm}^3$$



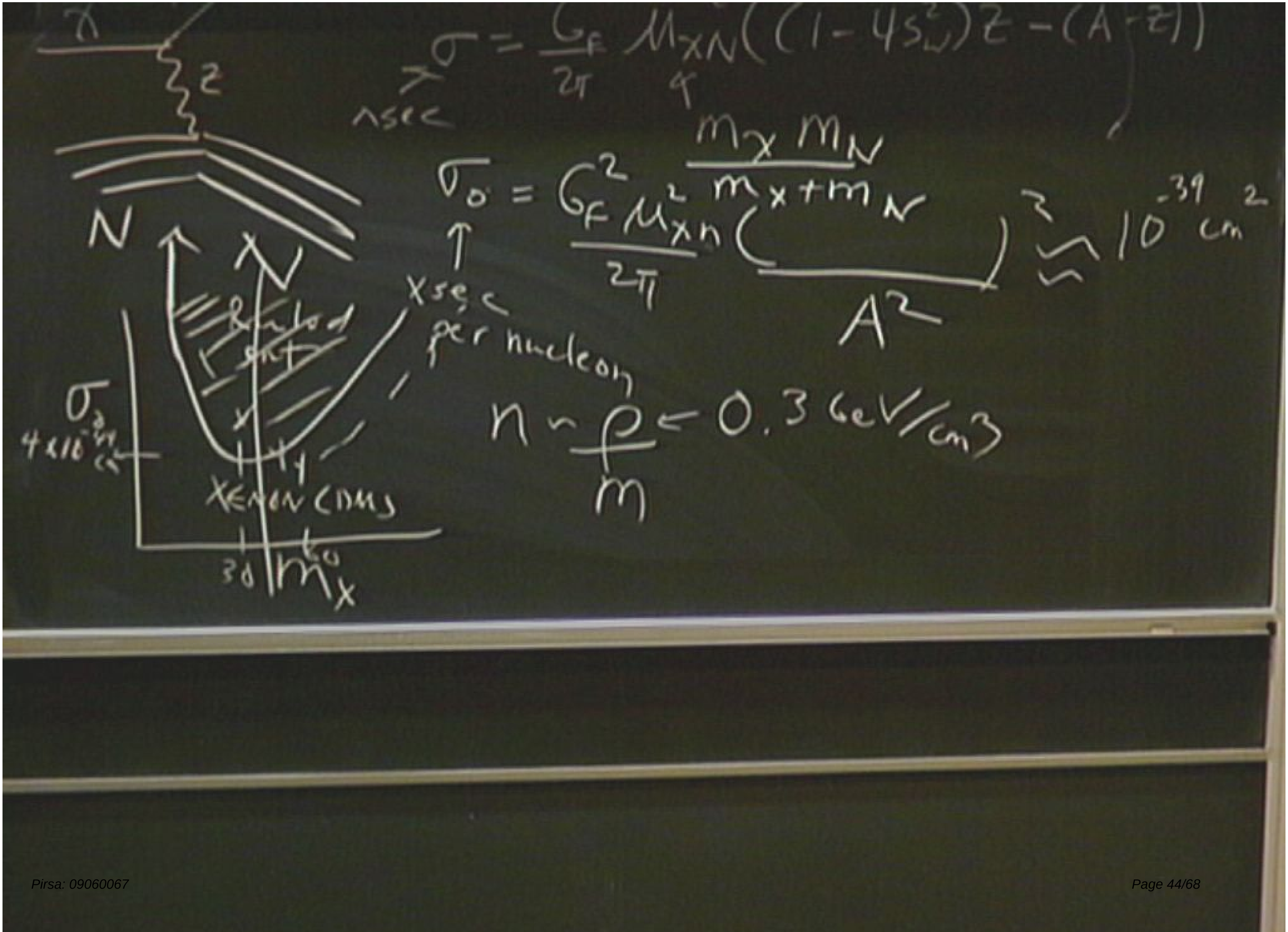
$$\sigma = \frac{G_F}{2\pi}\,\mu_{\chi N}\left((1-4s_w^2)Z-(A-Z)\right)$$

xsec

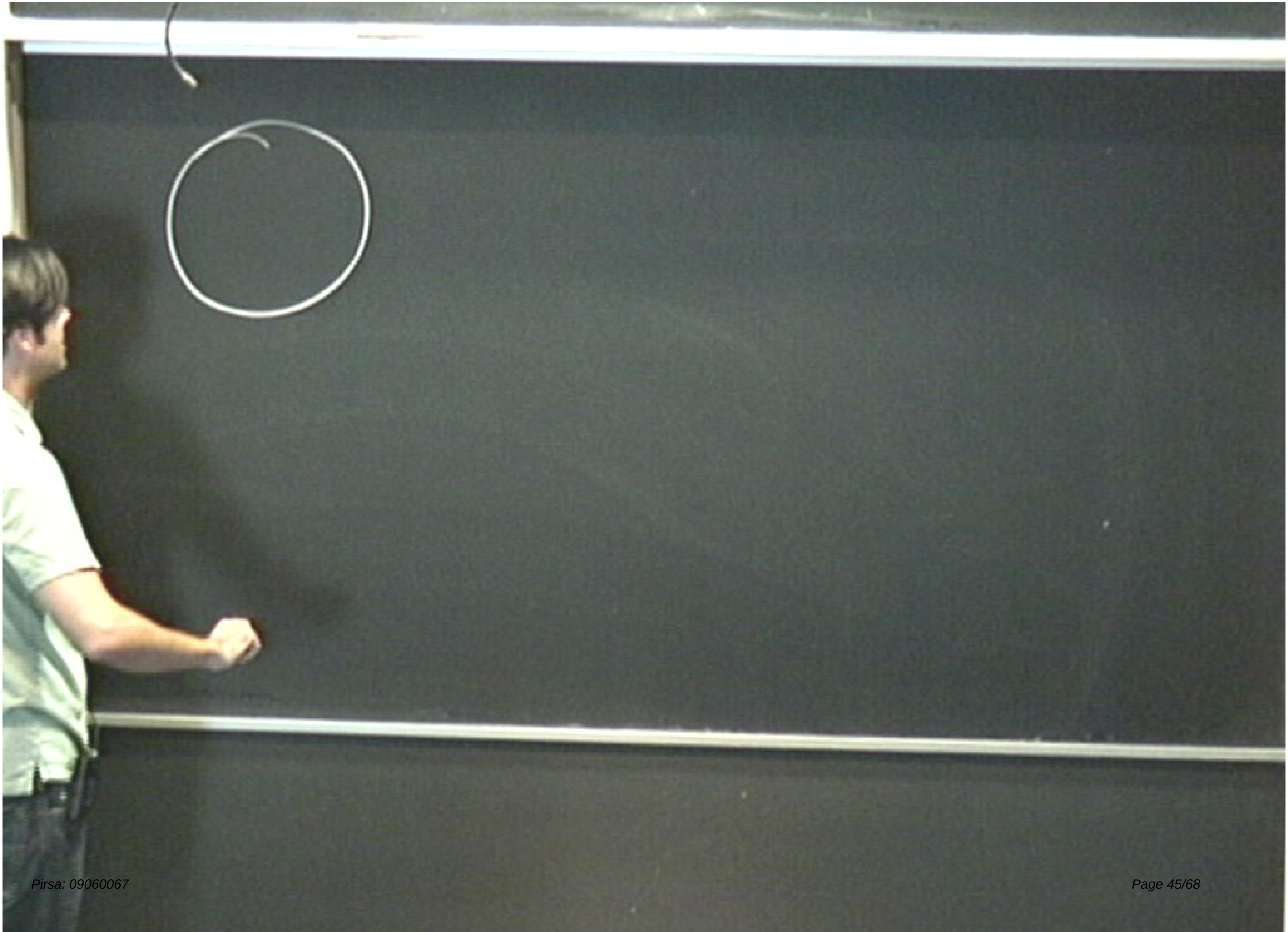
$$\sigma_0 = \frac{G_F^2\,\mu_{\chi n}^2}{2\pi}\left(\frac{\frac{m_\chi m_N}{m_\chi + m_N}}{A^2}\right)^2 \approx 10^{-39}\ \mathrm{cm}^2$$

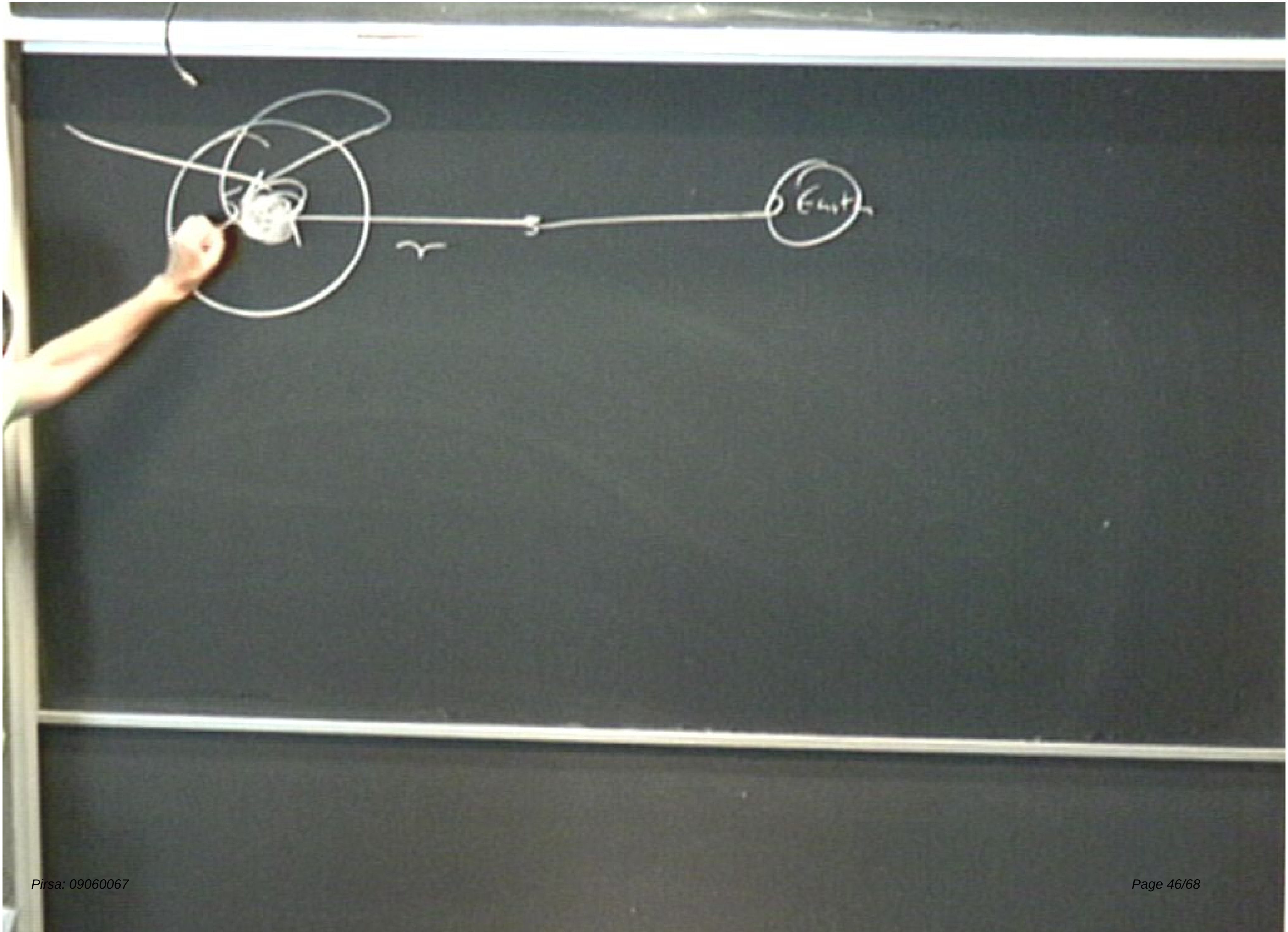
xsec per nucleon

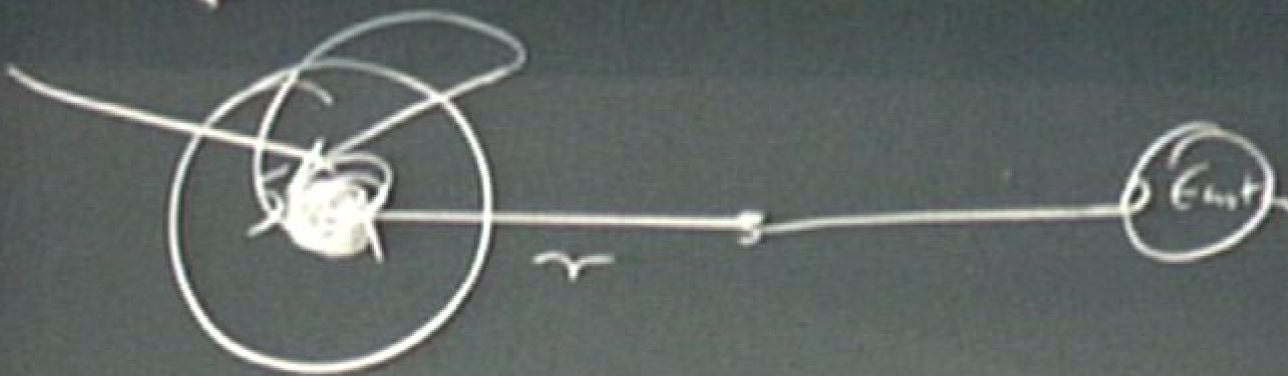
$$n \sim \frac{\rho}{m} \leftarrow 0.3\ \mathrm{GeV/cm^3}$$

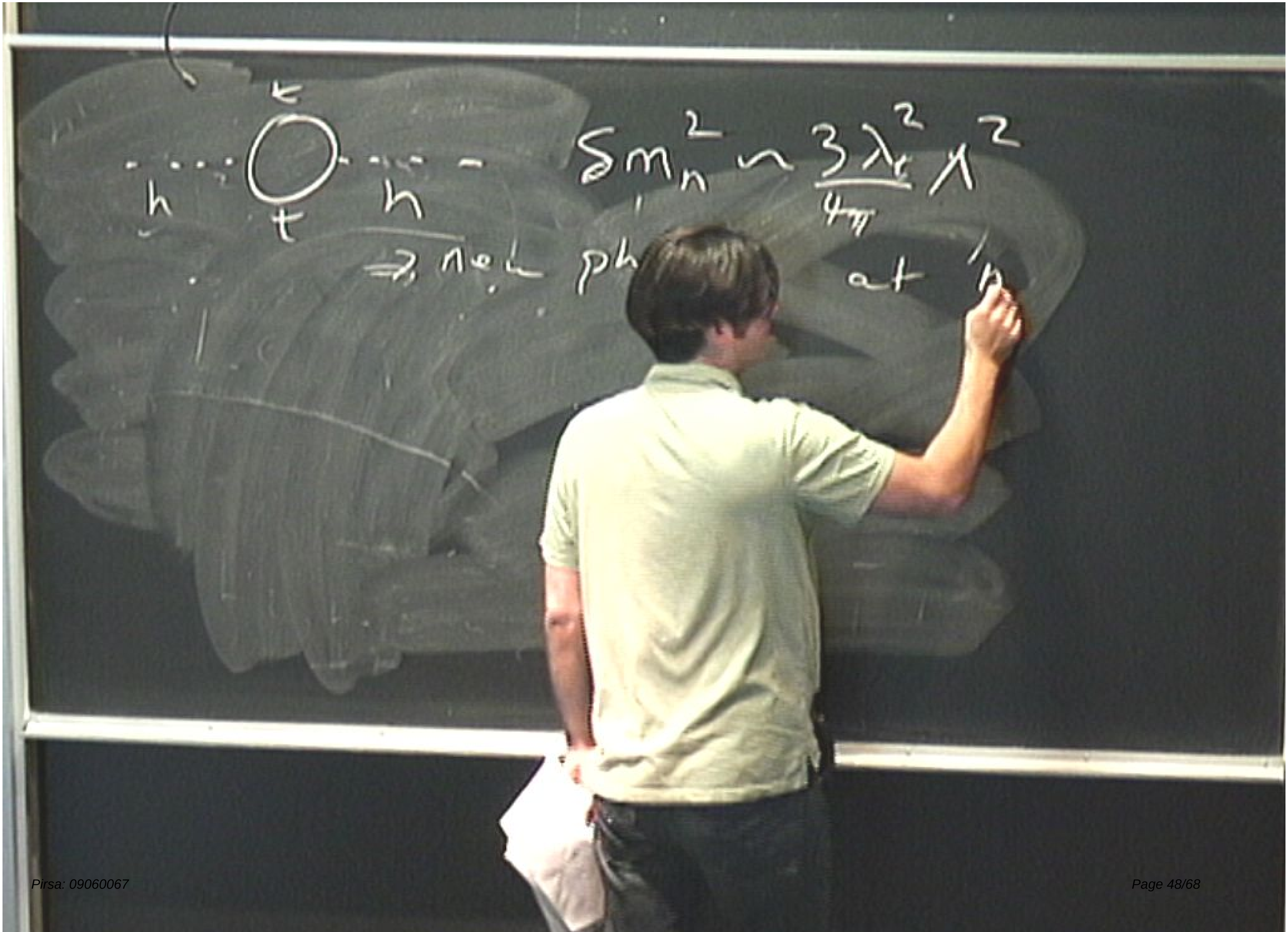


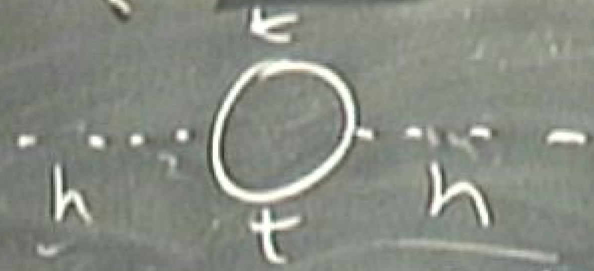
Z
N
N
xsec per nucleon
$\sigma_0 = \frac{G_F^2 \mu_{\chi n}^2}{2\pi}\left(\frac{m_\chi + m_N}{A^2}\right)^2 \approx 10^{-39}\ cm^2$
$n \sim \frac{\rho}{m}$ $\rho \approx 0.3\ GeV/cm^3$
XENON CDMS
σ_0
m_χ




Earth

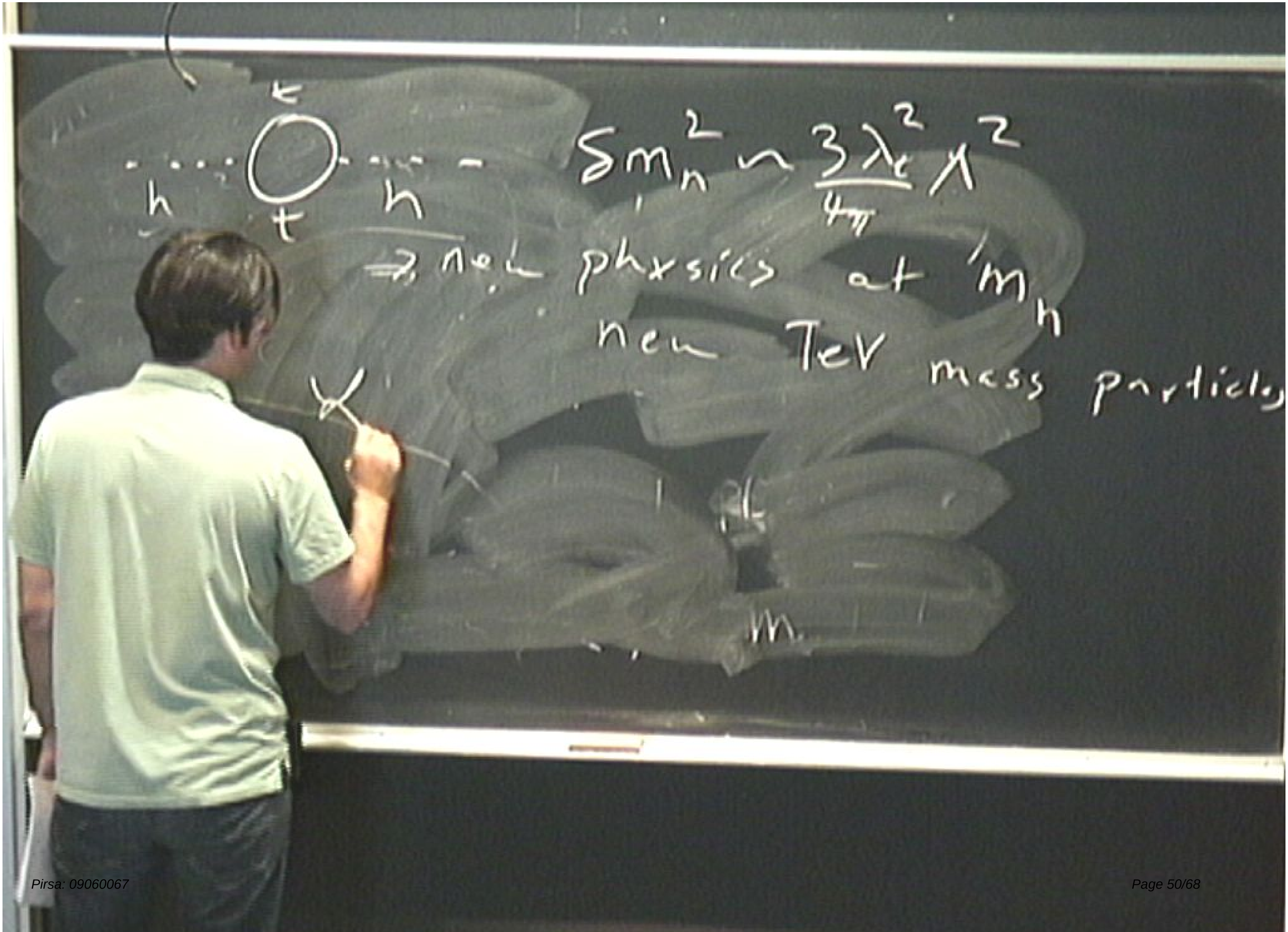

r
Earth

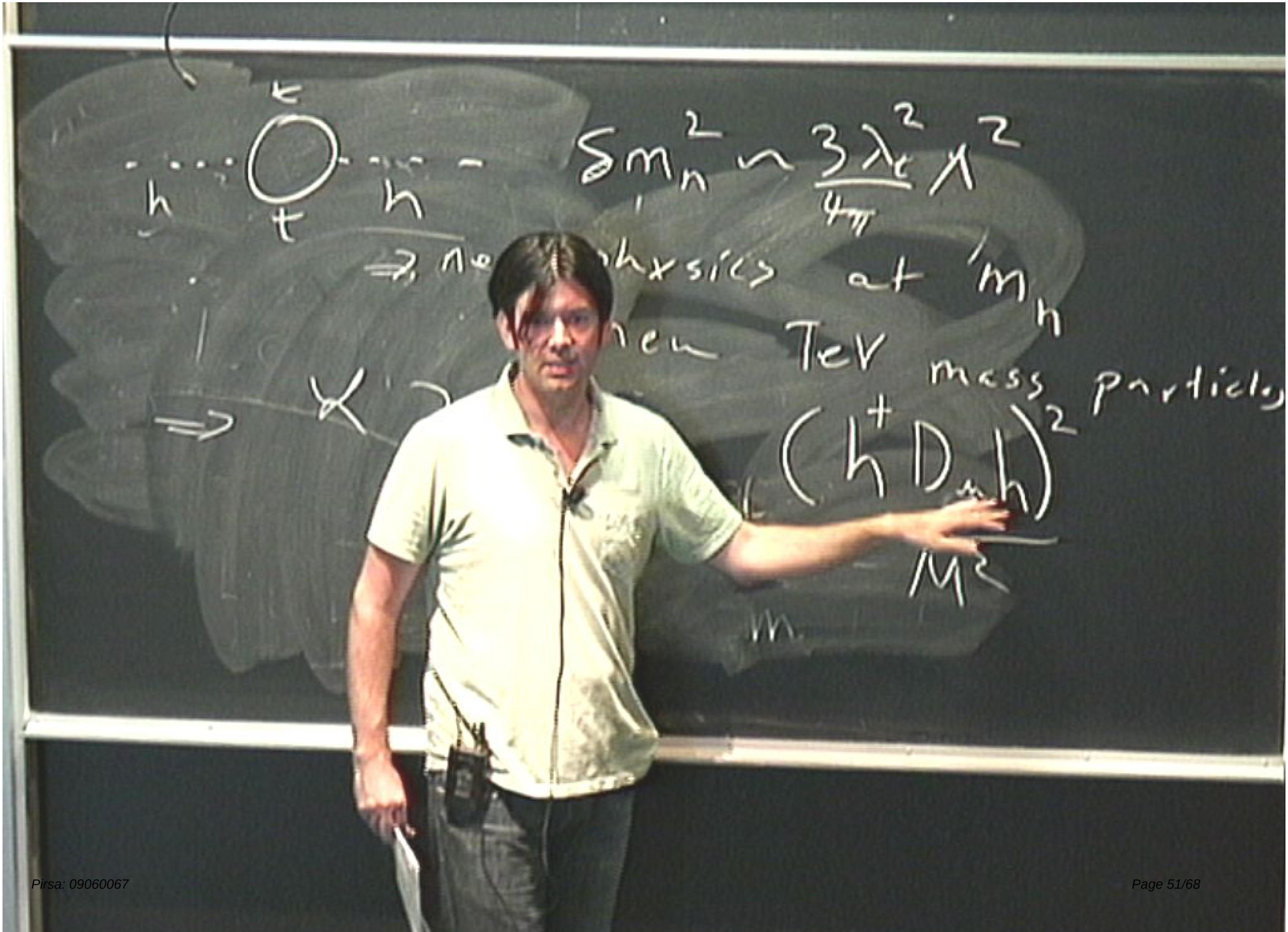

$\delta m_h^2 \sim \frac{3\lambda_t^2}{4\pi}\Lambda^2$
h t h
⇒ new ph
at



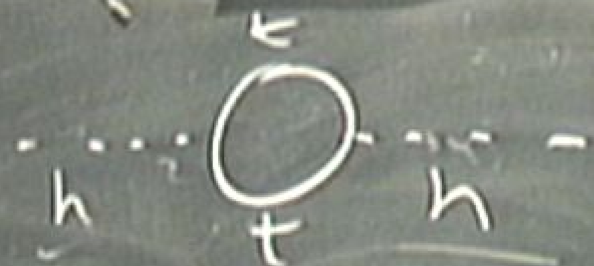
$$\delta m_h^2 \sim \frac{3\lambda_t^2}{4\pi}\Lambda^2$$

$\Rightarrow$ new physics at $\sim m_h$


t
h t h
$\delta m_h^2 \sim \frac{3\lambda_t^2}{4\pi}\Lambda^2$
⇒ new physics at m_h
new TeV mass particles



$\delta m_h^2 \sim \frac{3\lambda_t^2}{4\pi}\Lambda^2$
physics at m_h
new TeV mass particles
$\frac{(h^\dagger D_\mu h)^2}{M^2}$

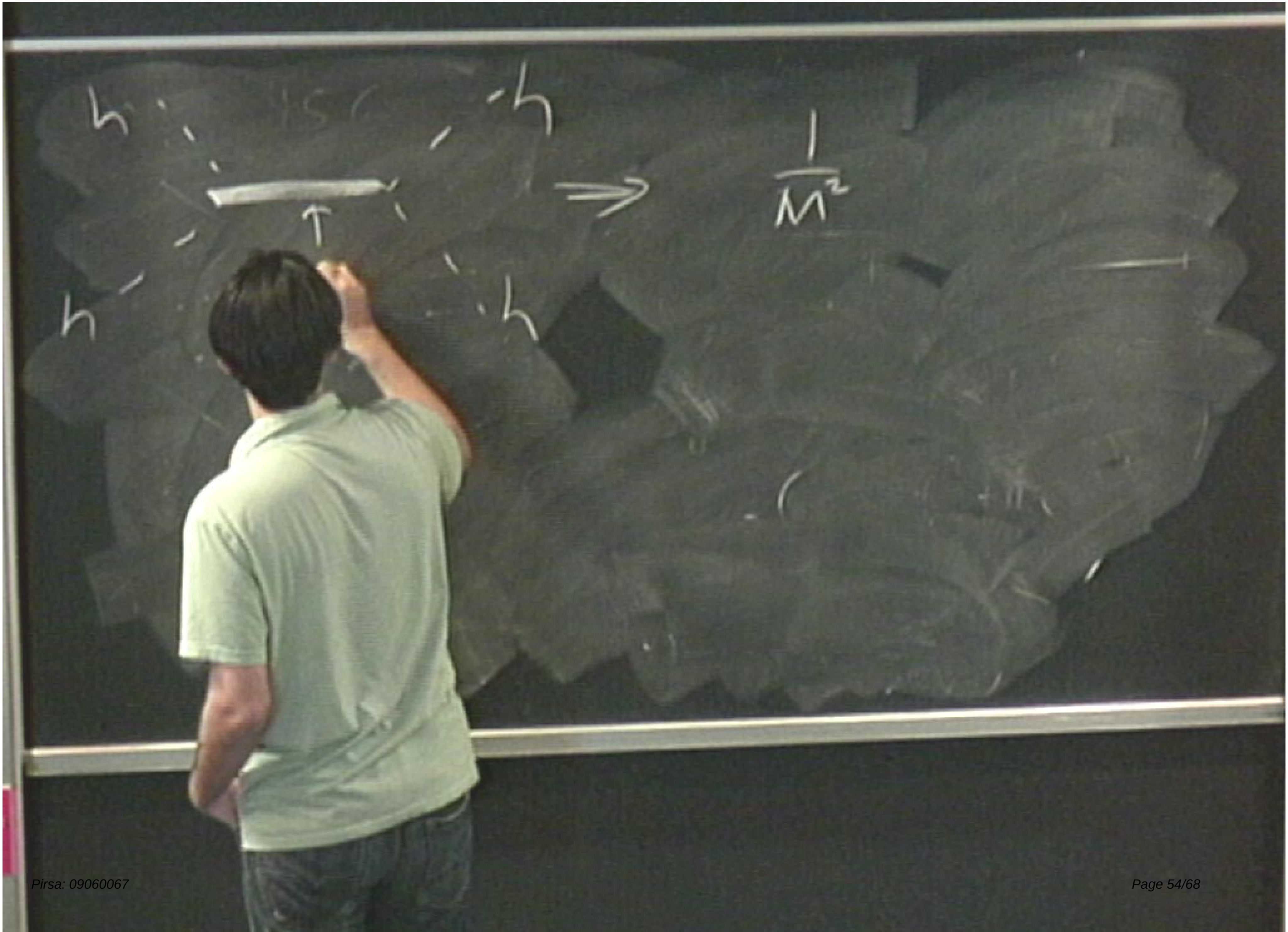


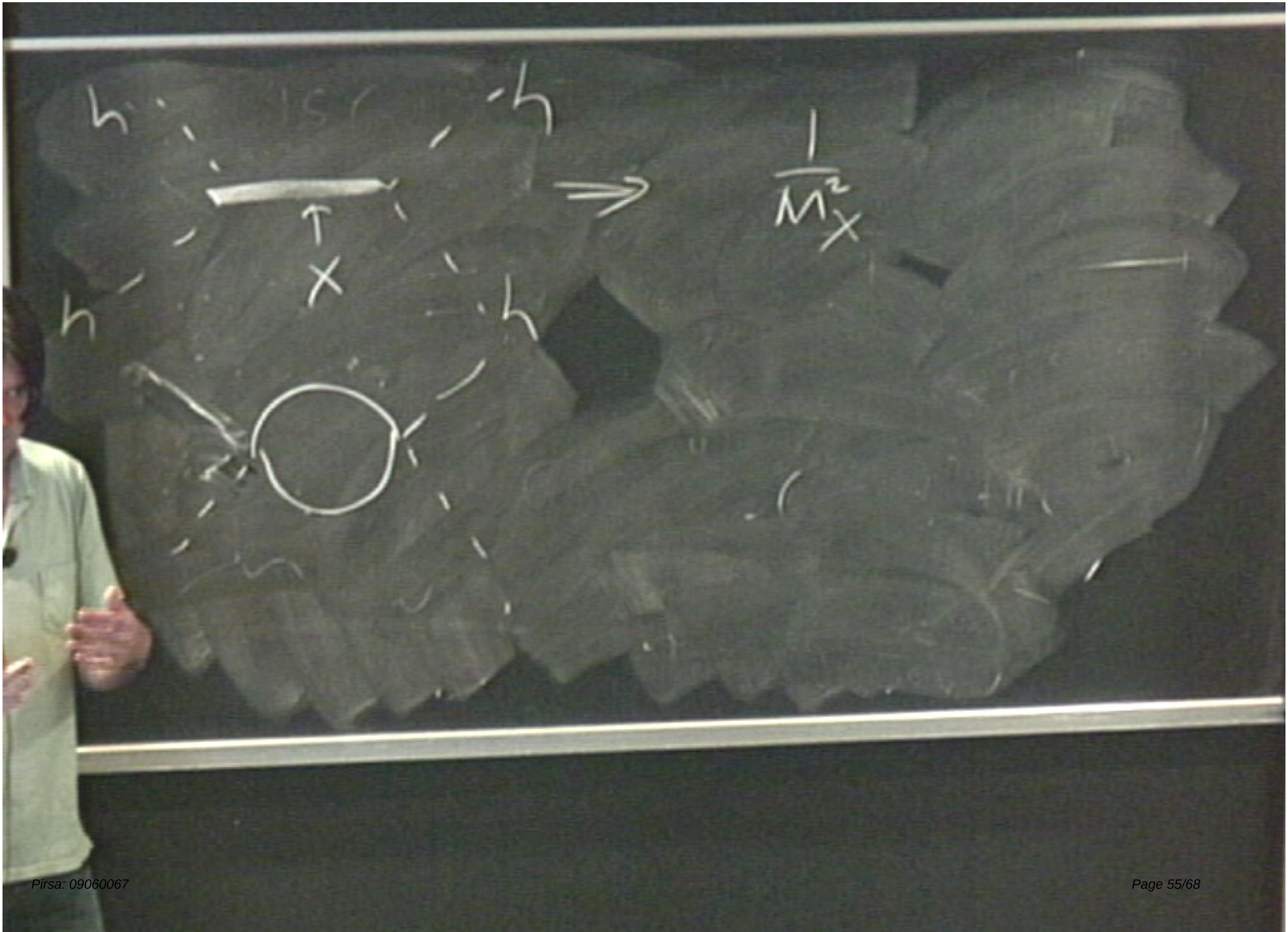
$$\delta m_h^2 \sim \frac{3\lambda_t^2}{4\pi}\Lambda^2$$

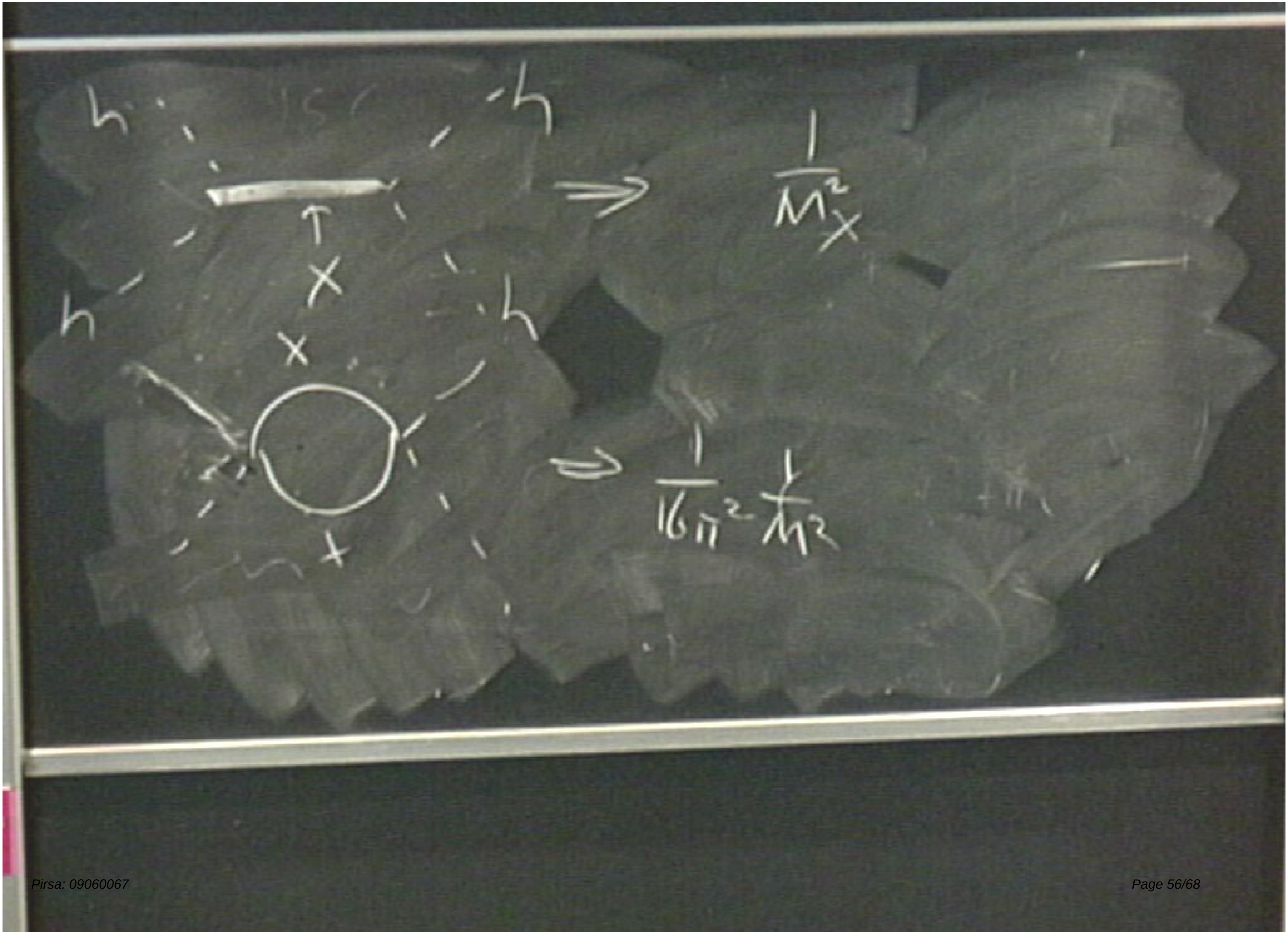
$\Rightarrow$ new physics at m_h

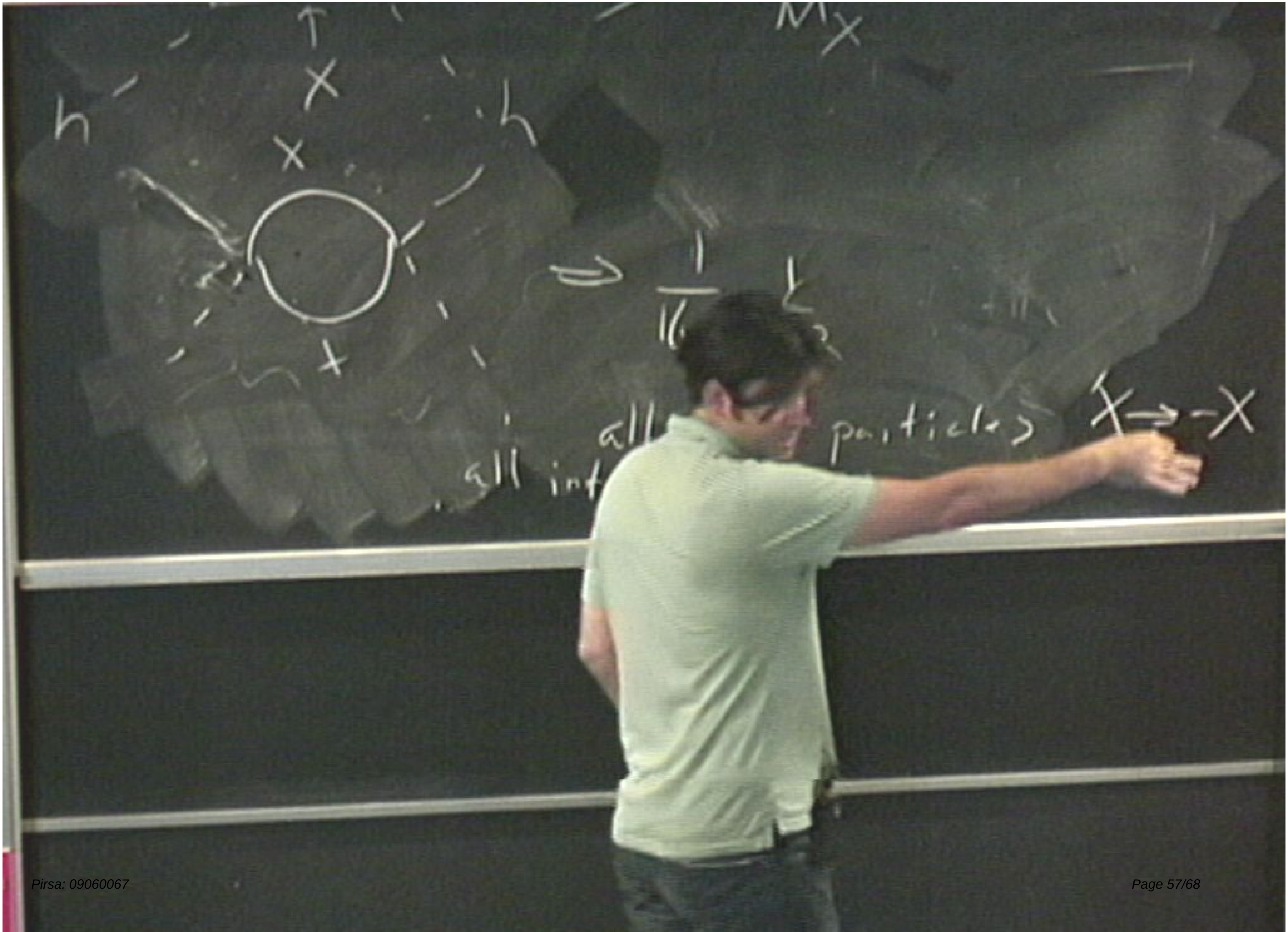
new TeV mass particles

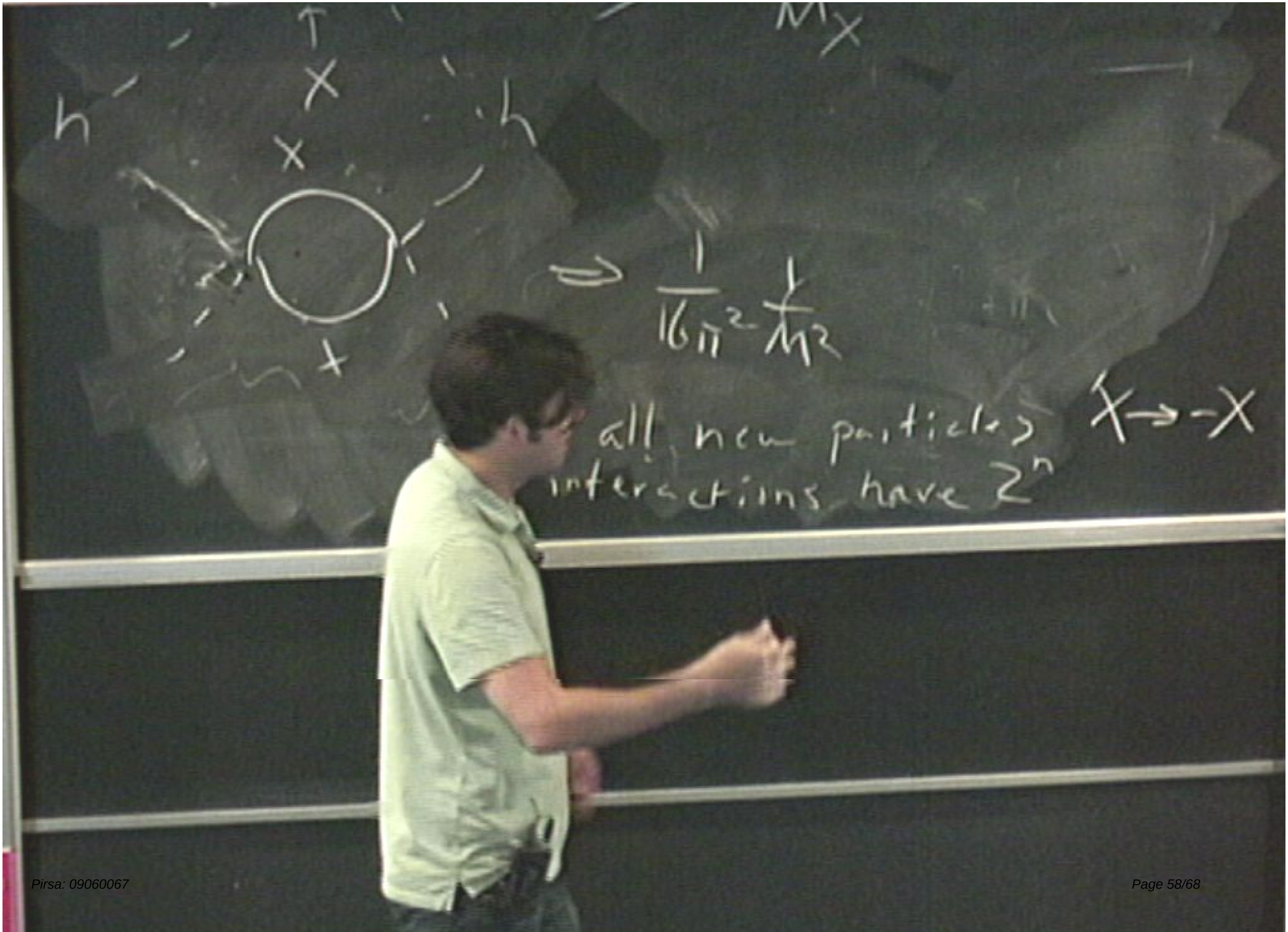
$$\Rightarrow \mathcal{L} \supset \frac{O^n_{SM}}{M^{4-n}} \qquad \frac{(h^\dagger D_\mu h)^2}{M^2}$$

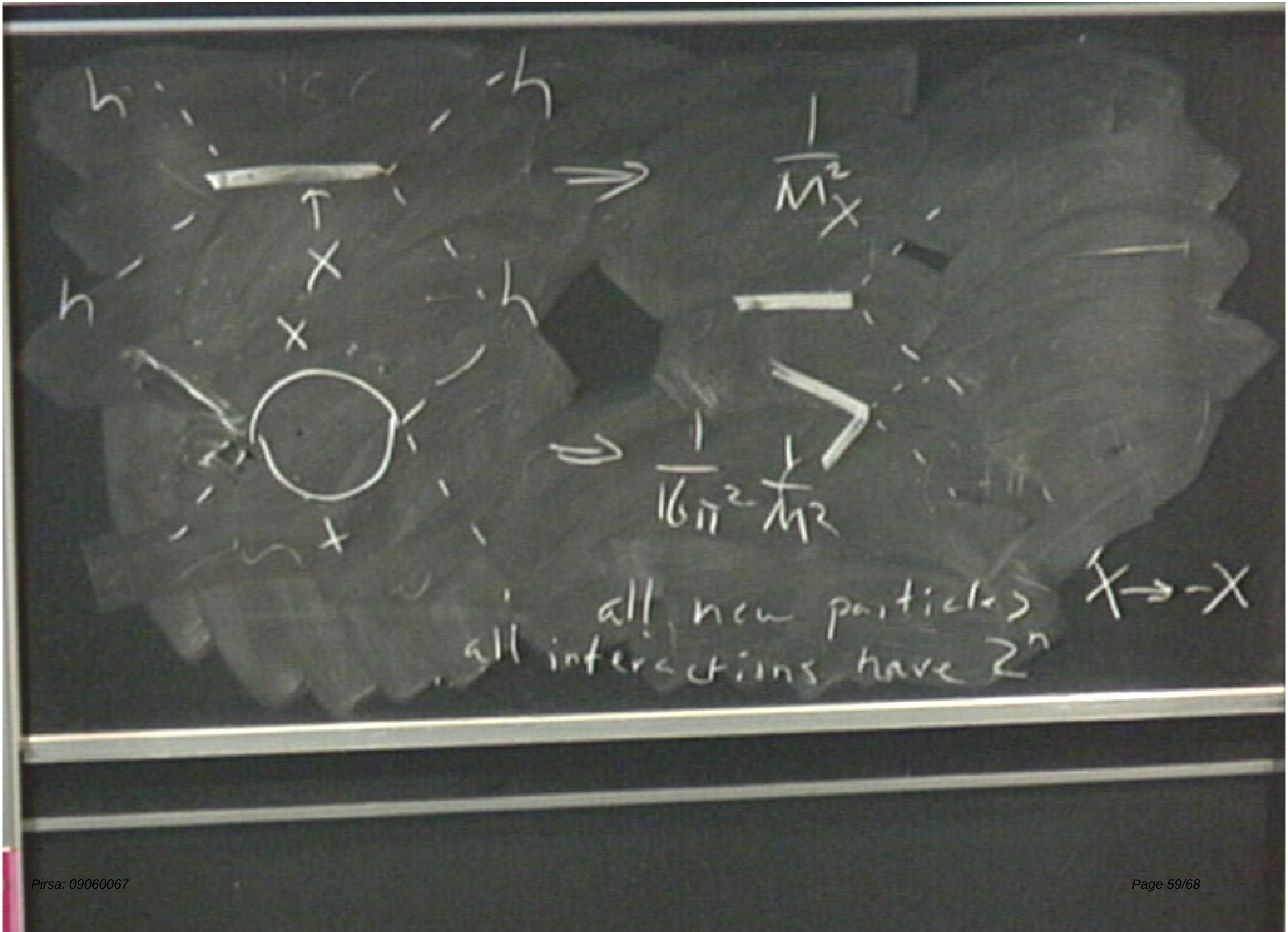

h
h
h
h
T
$\Rightarrow \frac{1}{M^2}$


h
h
X
h
h
1/M_X^2

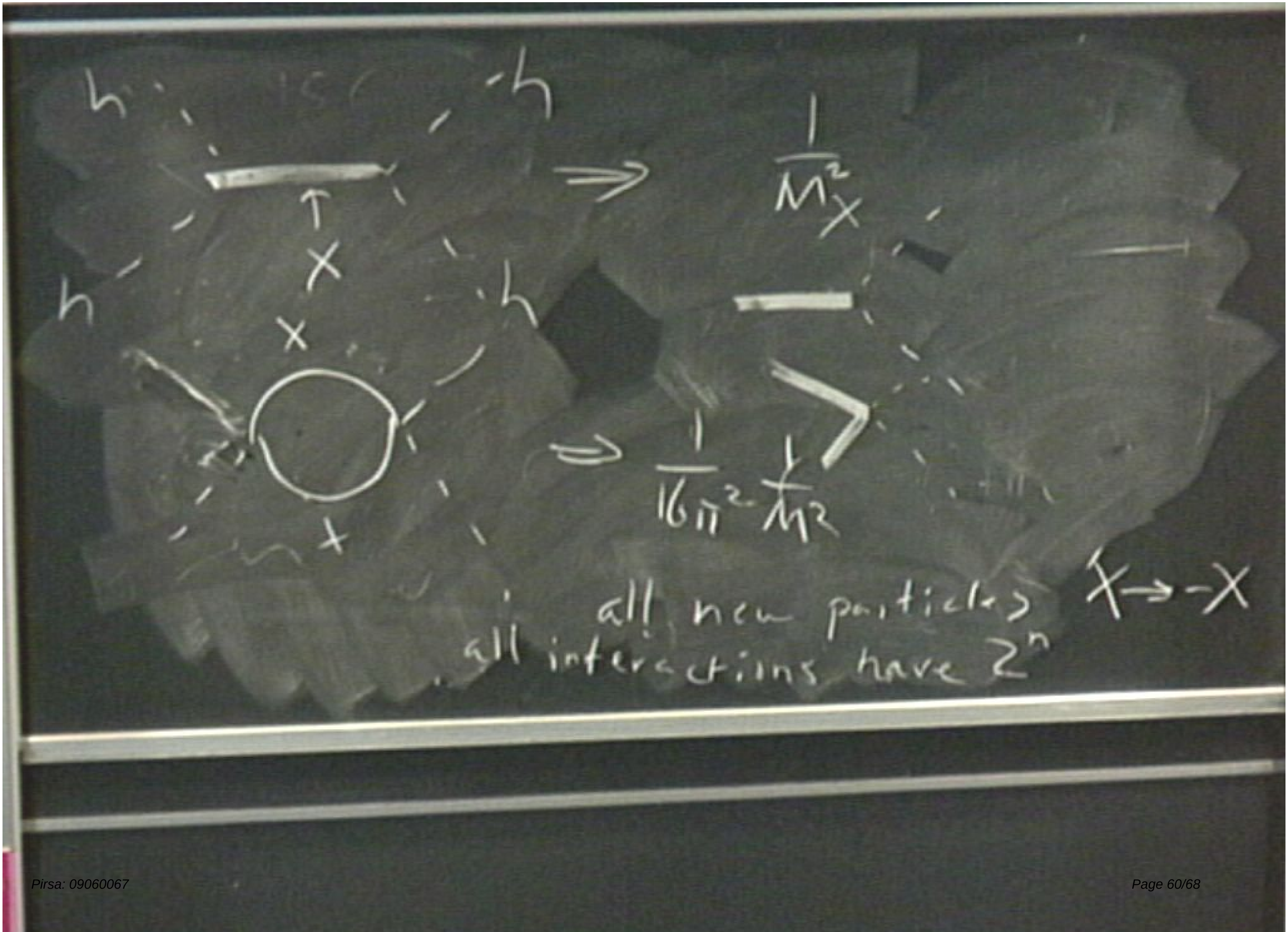

h
h
h
h
T
X
X
X
1
M_X^2
1
16π^2
1
M^2

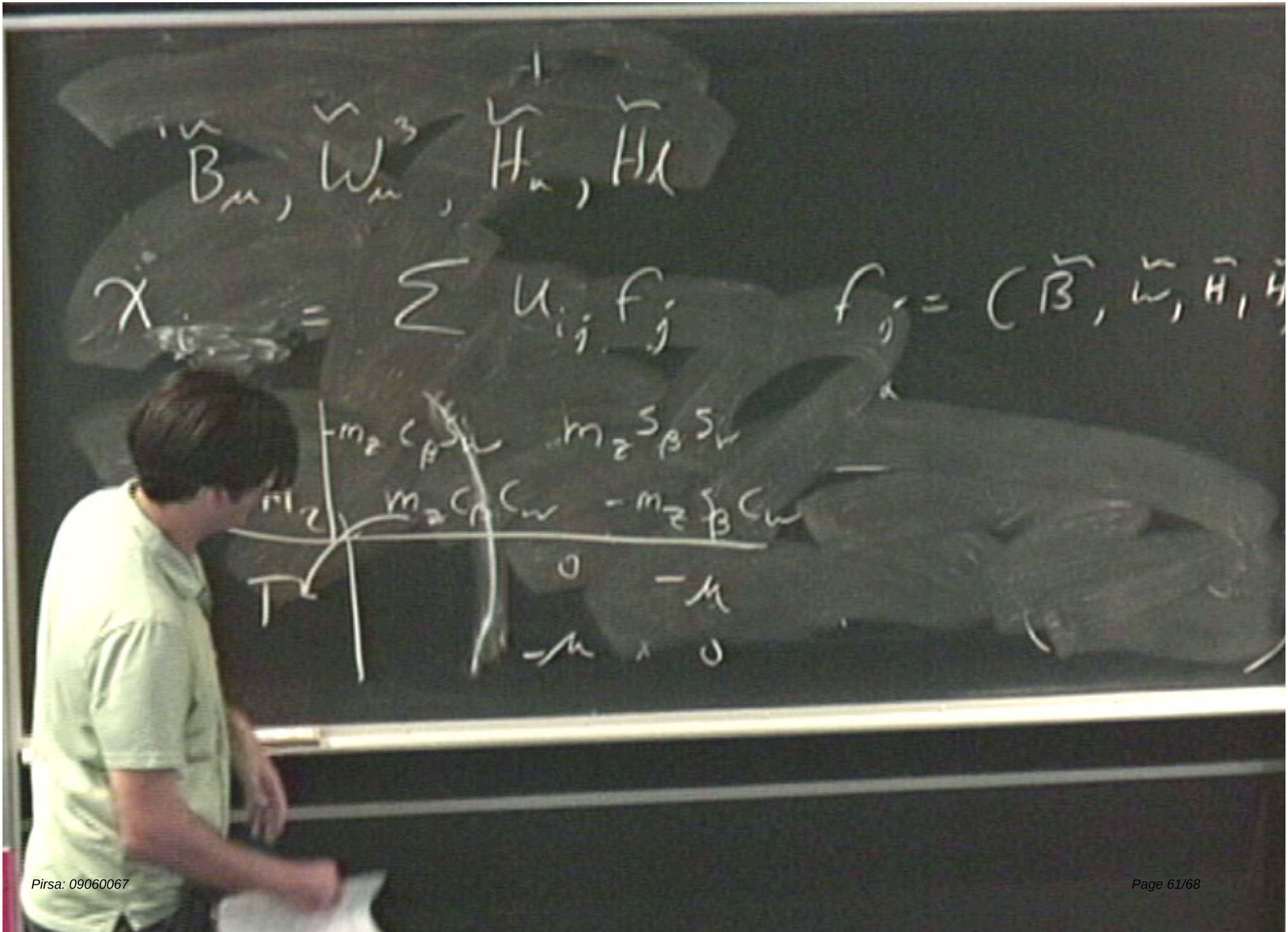

h
h
M_X
all
particles
X → −X
all int


X → -X
all new particles
interactions have



h
h
h
h
X
$\frac{1}{M_X^2}$
$\frac{1}{16\pi^2}\frac{1}{M^2}$
$X \to -X$
all new particles
all interactions have Z


h
h
h
h
X
X
X
$\frac{1}{M_X^2}$
$\frac{1}{16\pi^2}\frac{1}{M^2}$
all new particles
$X \to -X$
all interactions have



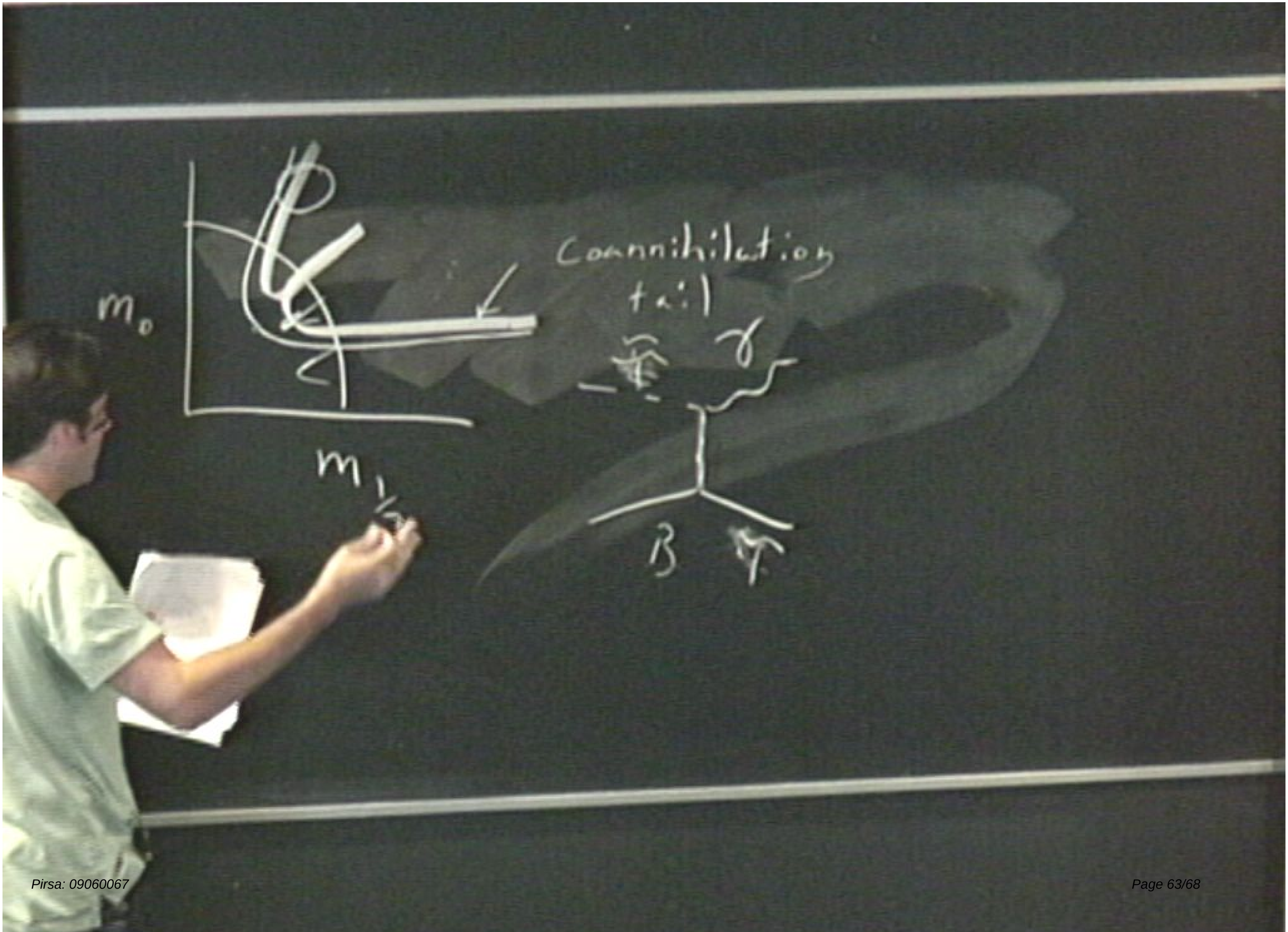
B̃μ, W̃³μ, H̃u, H̃d
χi = Σ Uij fj
fj = (B̃, W̃, H̃, H̃
−mZ cβ sw
mZ sβ sw
mZ
mZ cβ cw
−mZ sβ cw
T
0
−μ
−μ
0

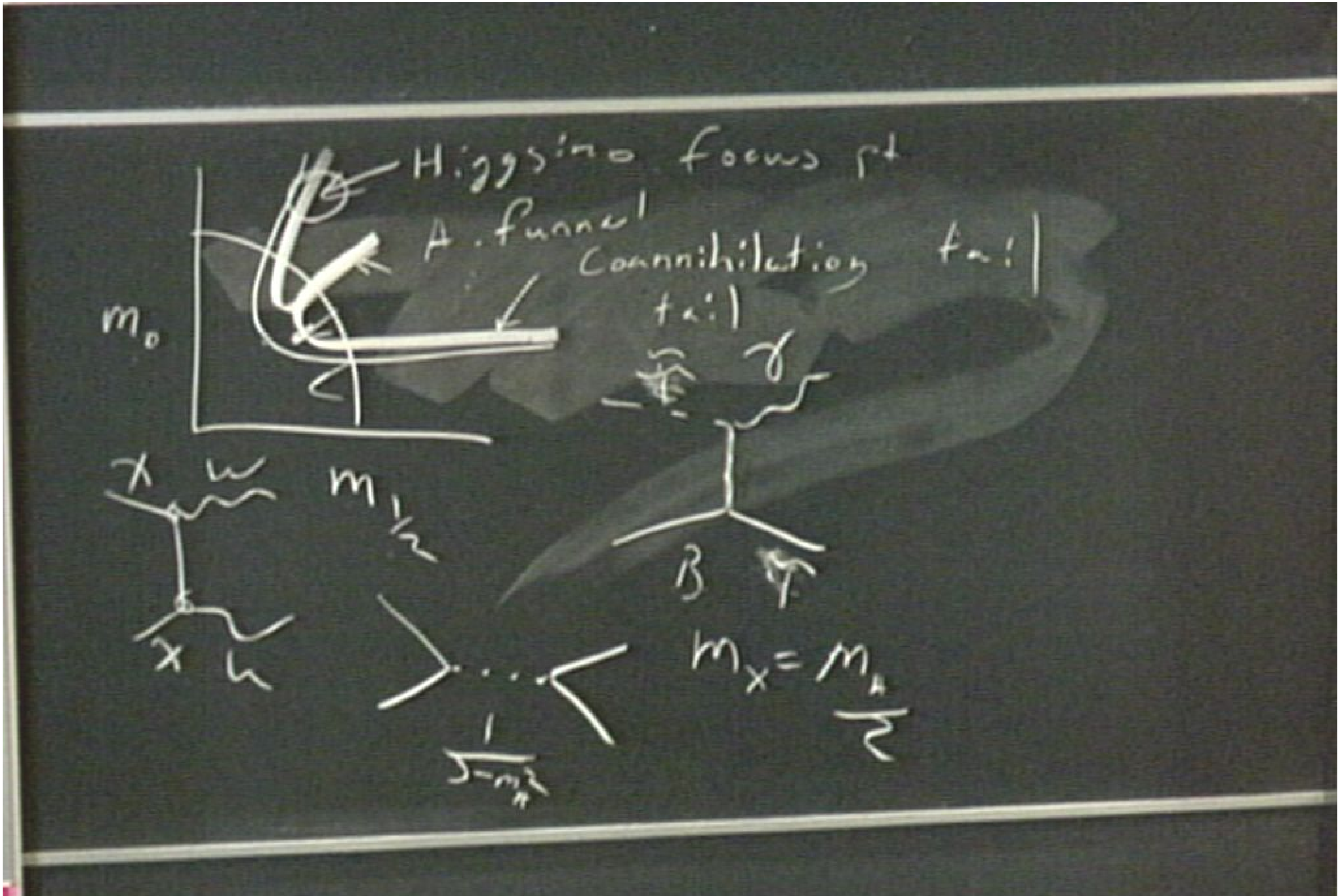
$$\tilde{B}_\mu, \quad \tilde{W}^3_\mu, \quad \tilde{H}_u, \quad \tilde{H}_d$$

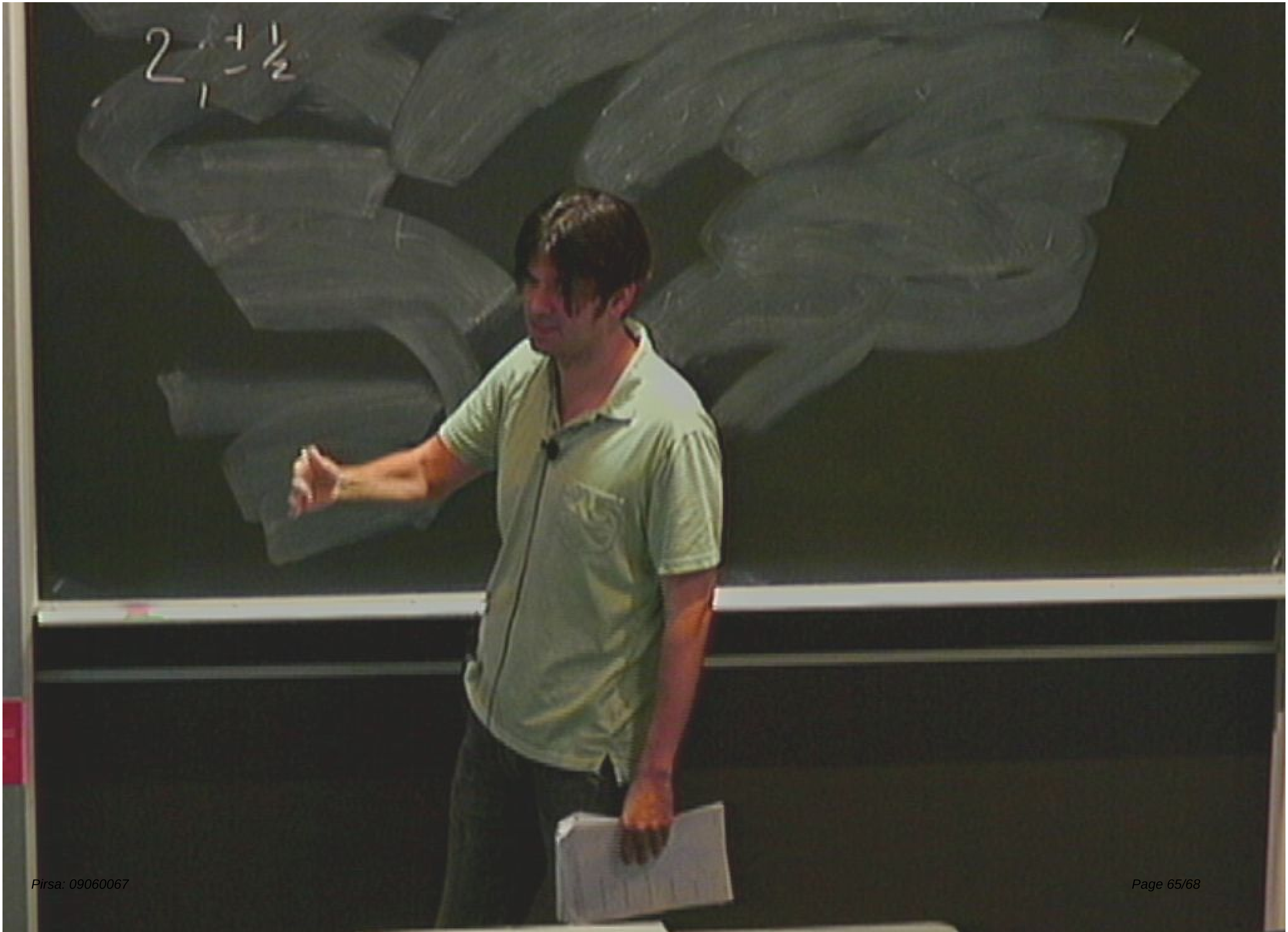
$$\tilde{\chi}_i = \sum U_{ij} f_j \qquad f_j = (\tilde{B}, \tilde{w}, \tilde{H}, \tilde{H}$$

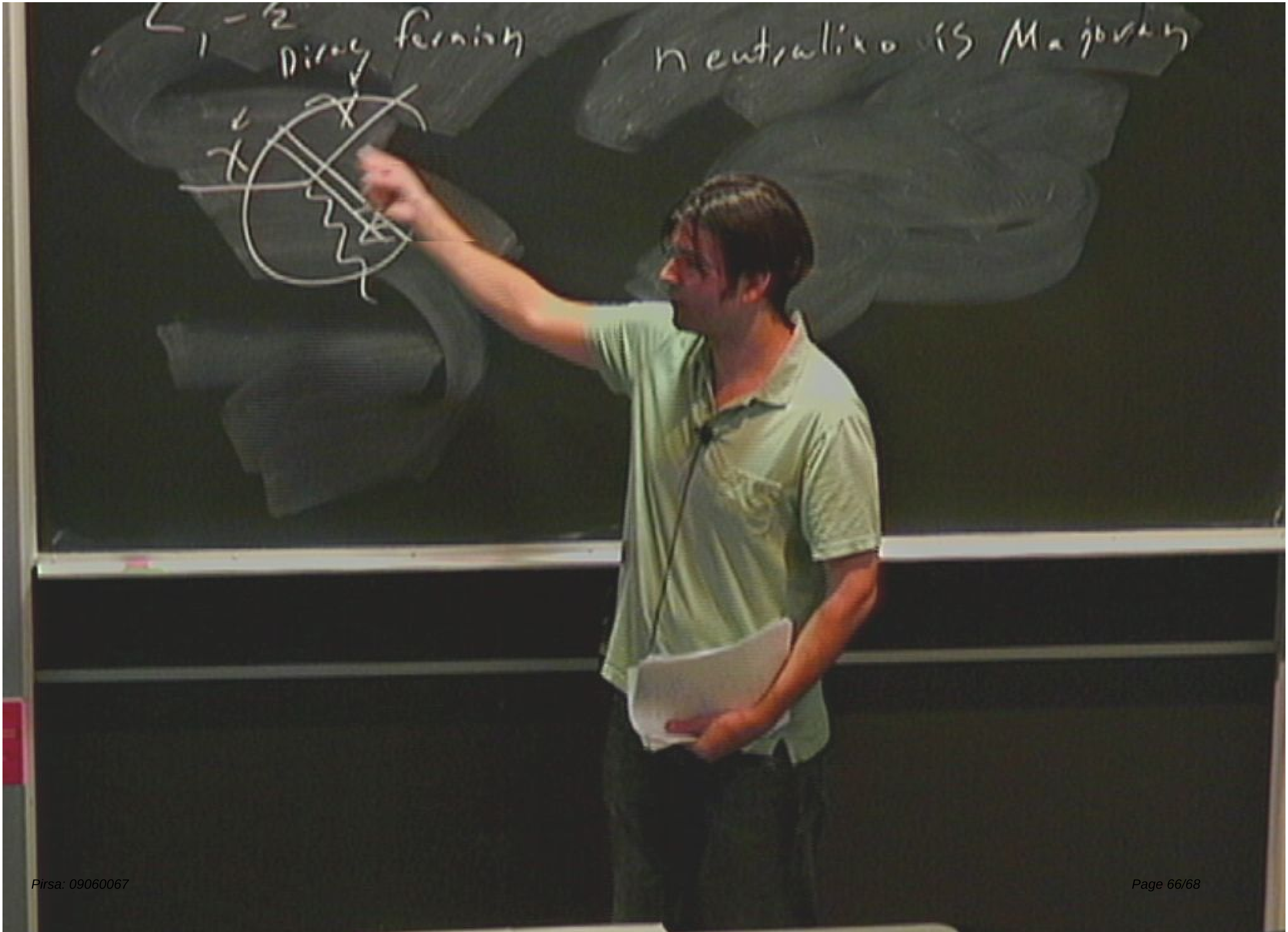
$$\tan\beta = \frac{V_u}{V_d}$$

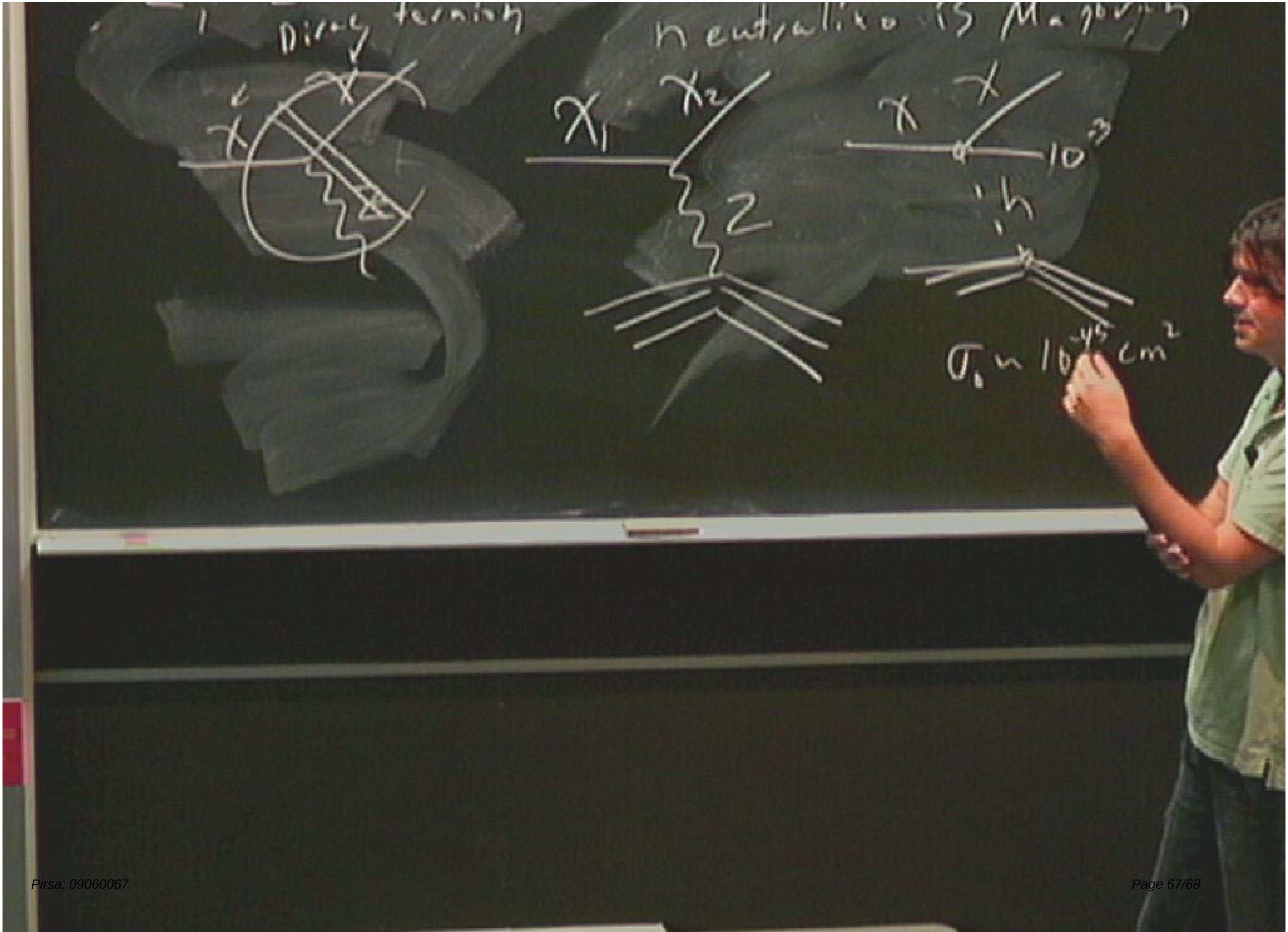
$$\left(\begin{array}{cc|cc}
M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\
0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\
\hline
\multicolumn{2}{c|}{T} & 0 & -\mu \\
 & & -\mu & 0
\end{array}\right)$$

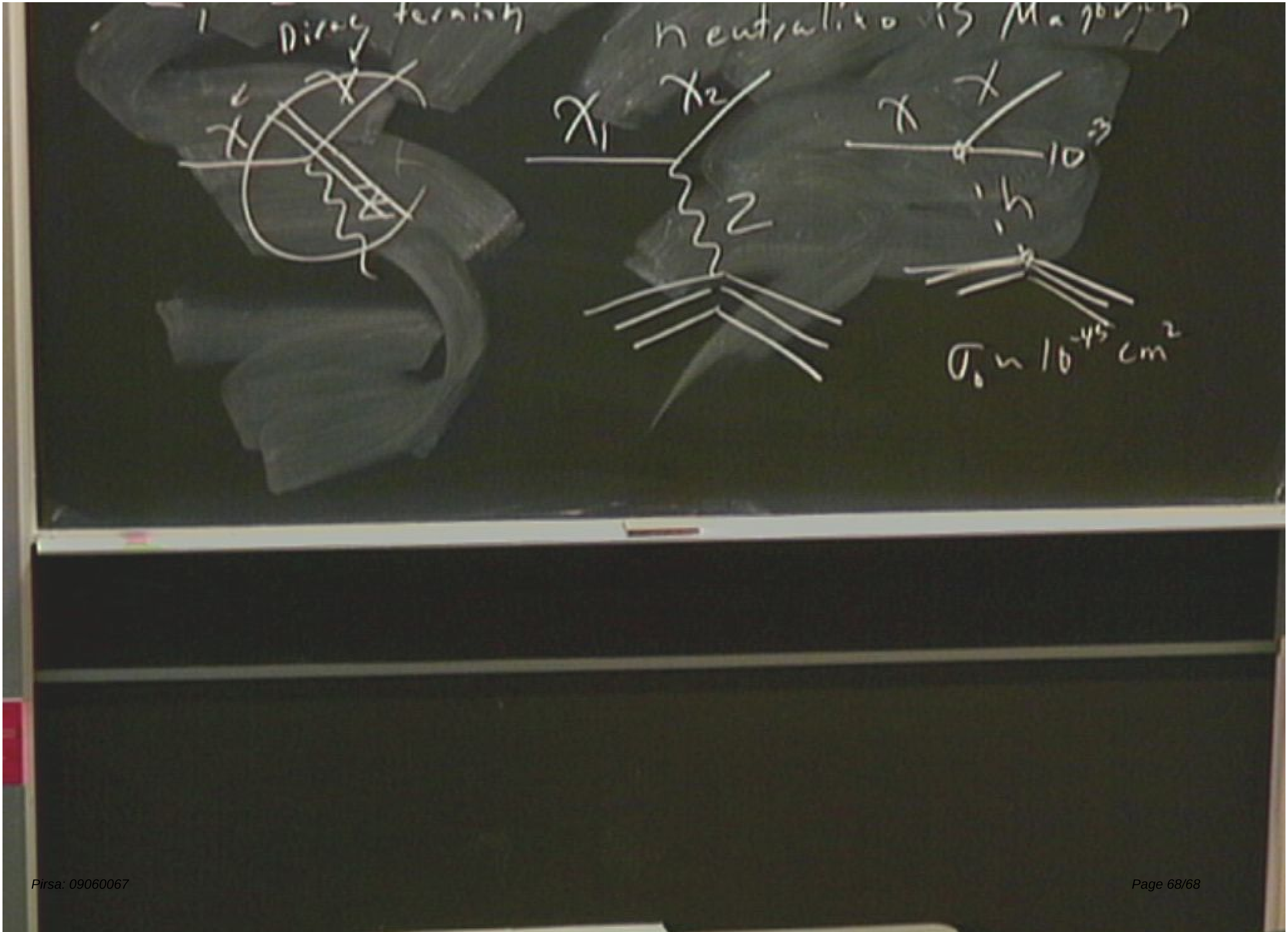

m_0
coannihilation
tail
γ
$m_{1/2}$
B


Higgsino focus pt
A. funnel
Coannihilation tail
tail
m_0
$m_{1/2}$
γ
B
χ W
χ h
$m_\chi = \frac{m_A}{2}$
$\frac{1}{s - m_A^2}$




Dirac fermion
neutralino is Majorana


Dirac fermion
neutralino is Majorana
χ_1
χ_2
Z
10^{-3}
h
$\sigma_0 \sim 10^{-45}\ cm^2$


Dirac fermion
neutralino is Majorana
χ1
χ2
Z
χ
χ
10^-3
h
σ0 ~ 10^-45 cm^2