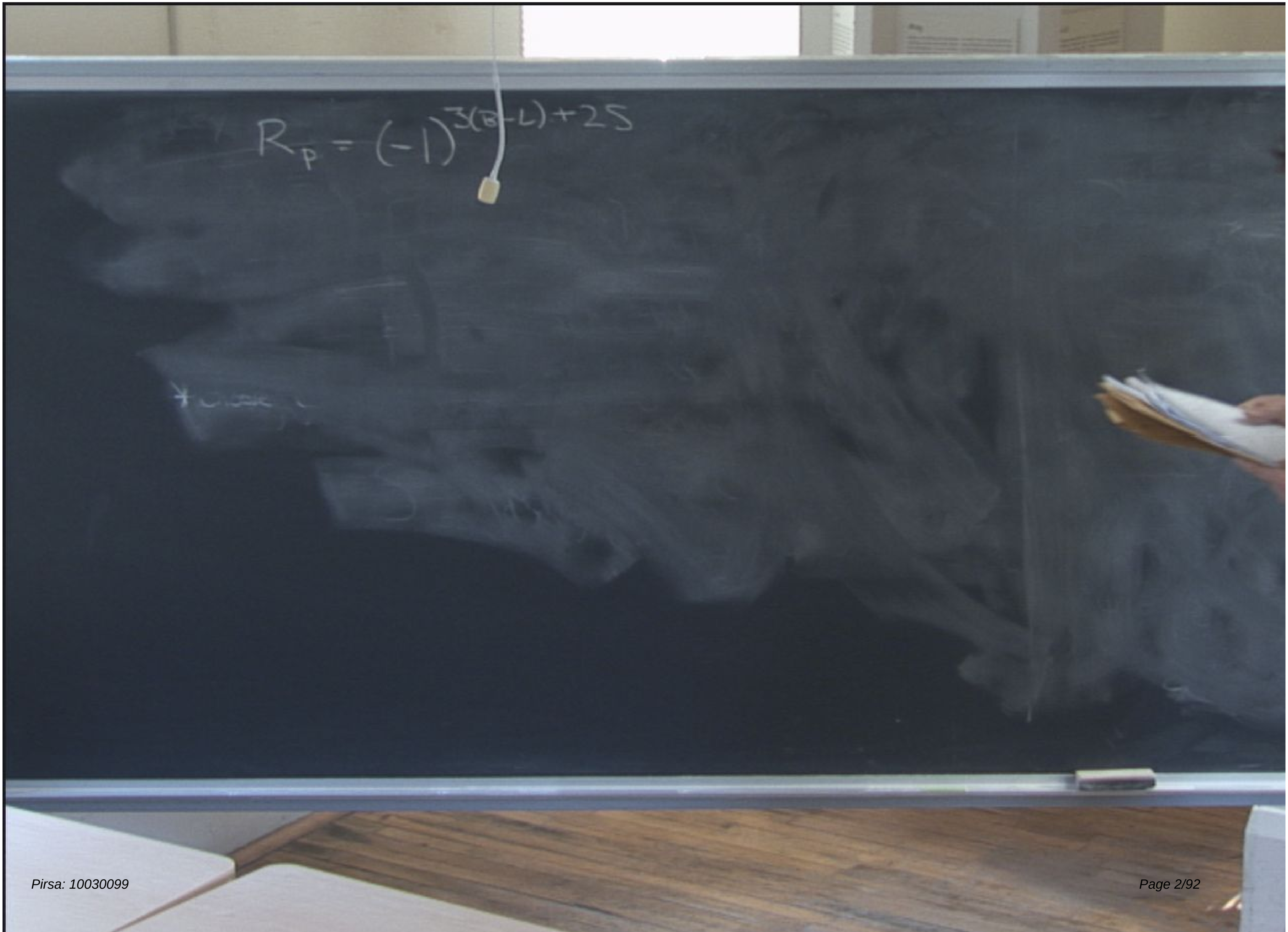
Title: Explorations in Particle Theory (PHYS 646) - Lecture 14

Date: Mar 31, 2010 10:10 AM

URL: http://pirsa.org/10030099

Abstract:


$R_p = (-1)^{3(B-L)+2S}$

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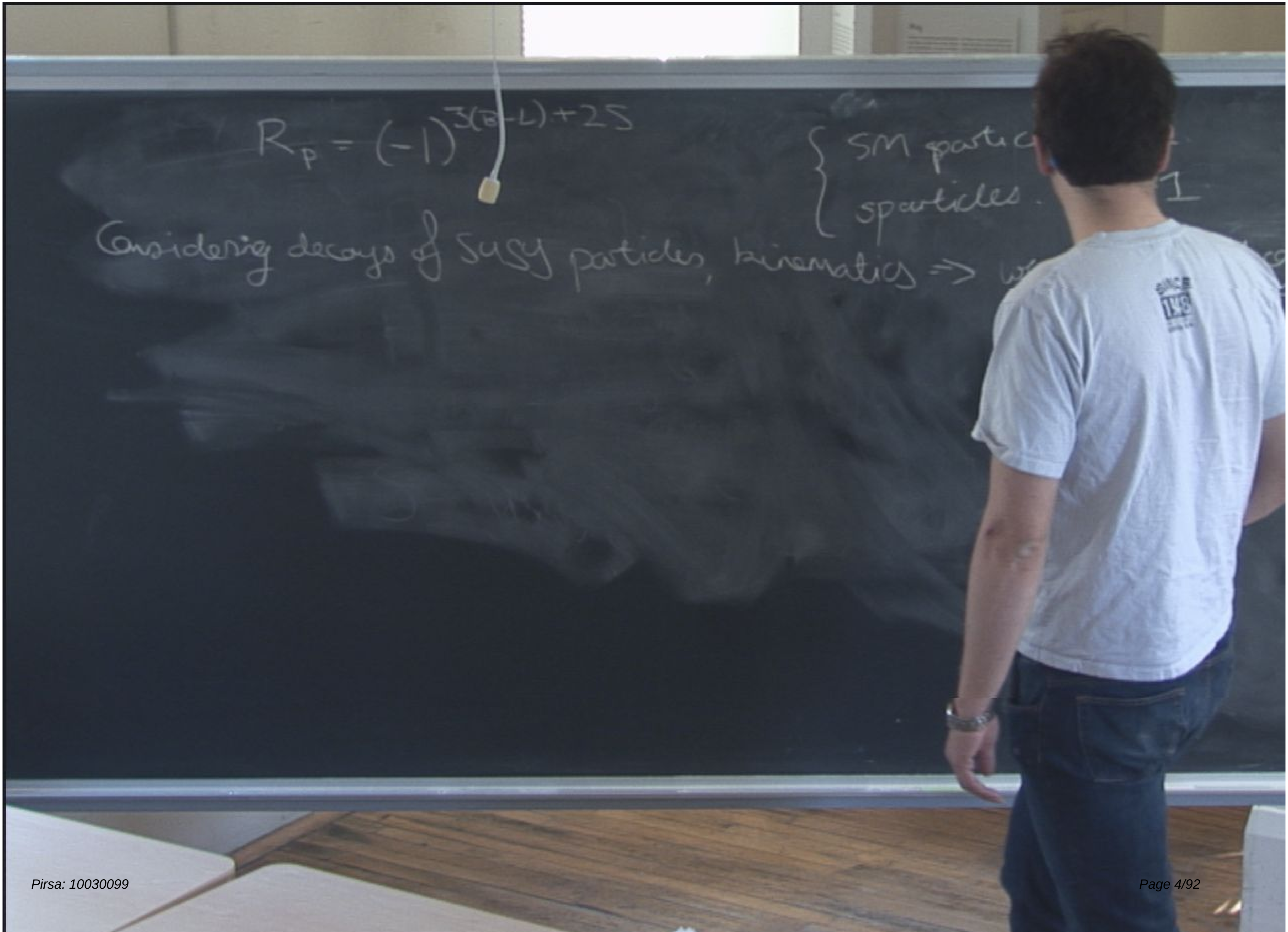
$$\begin{cases} \text{SM particles} & +1 \\ \text{sparticles} & -1 \end{cases}$$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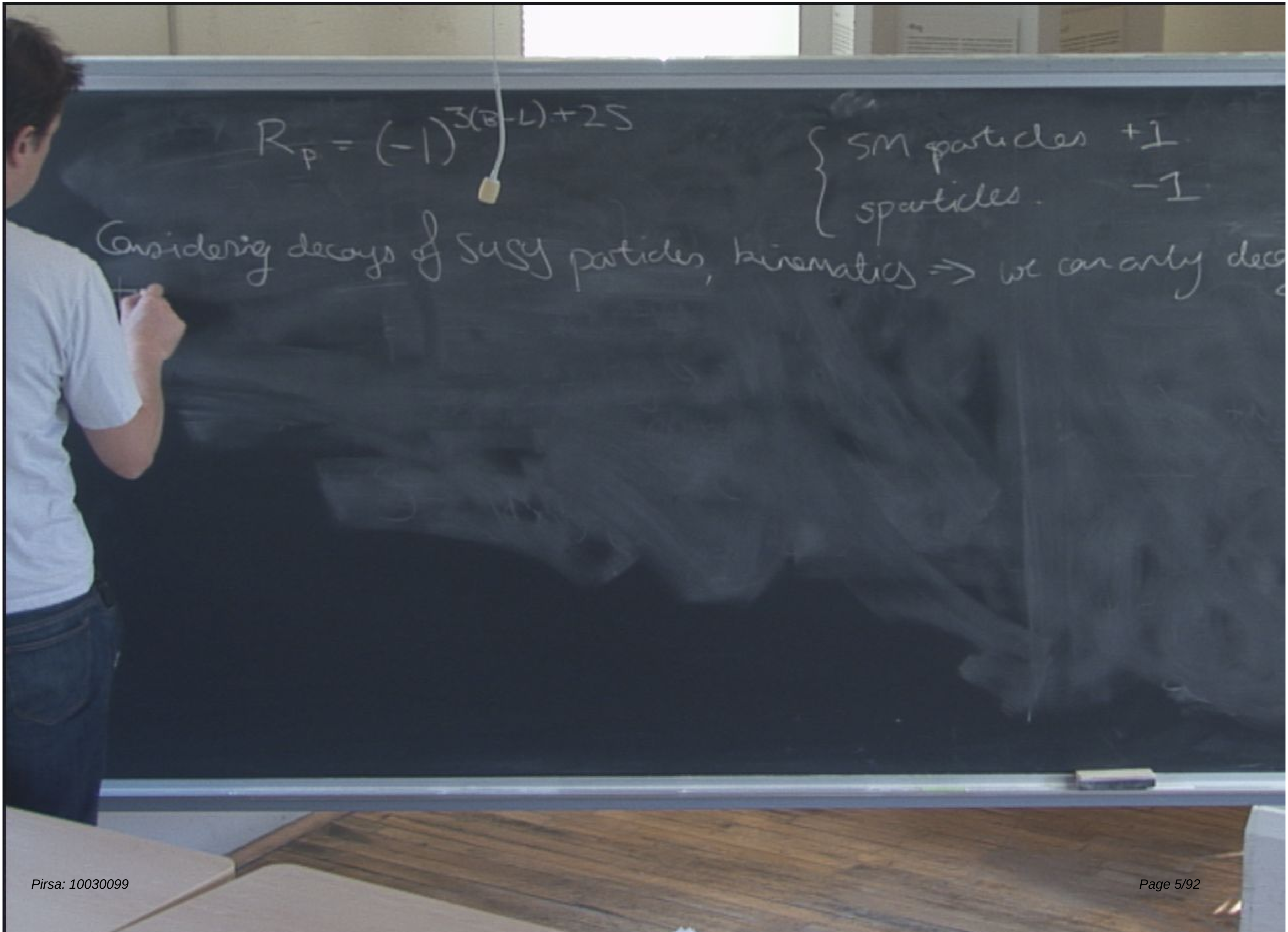
Considering decays of SUSY particles, kinematics =>



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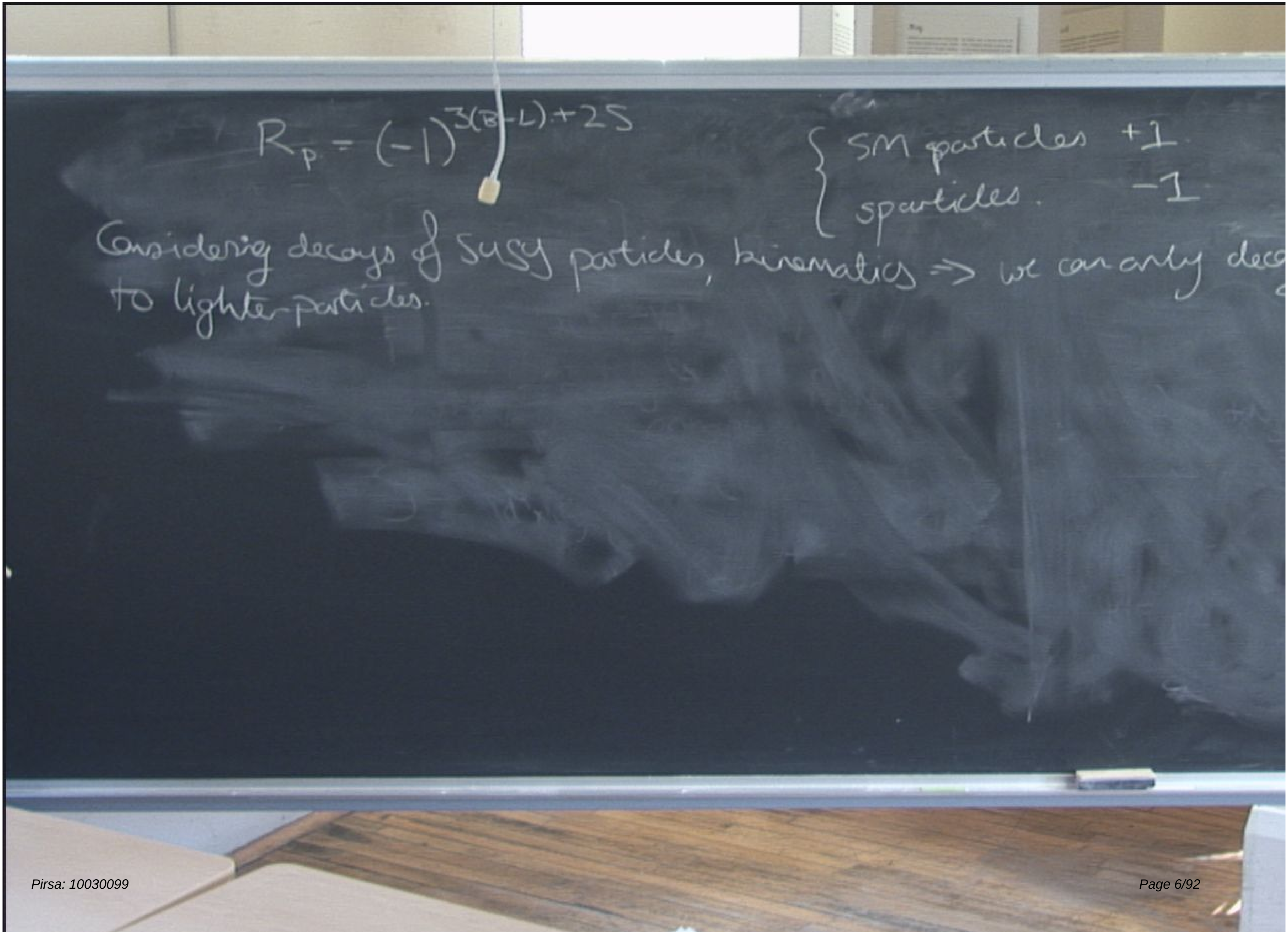
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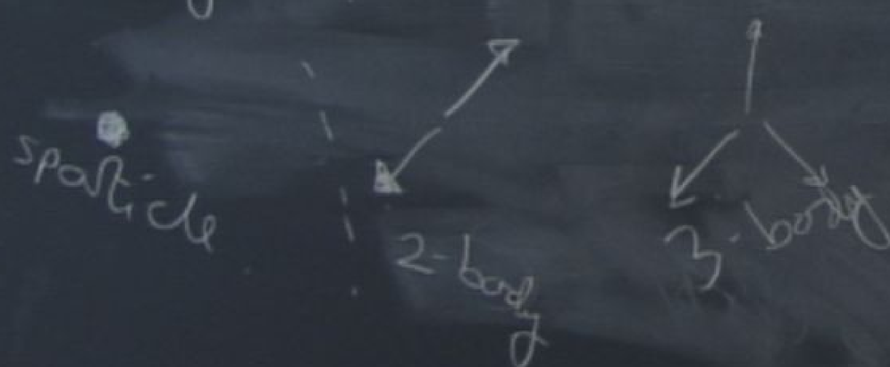

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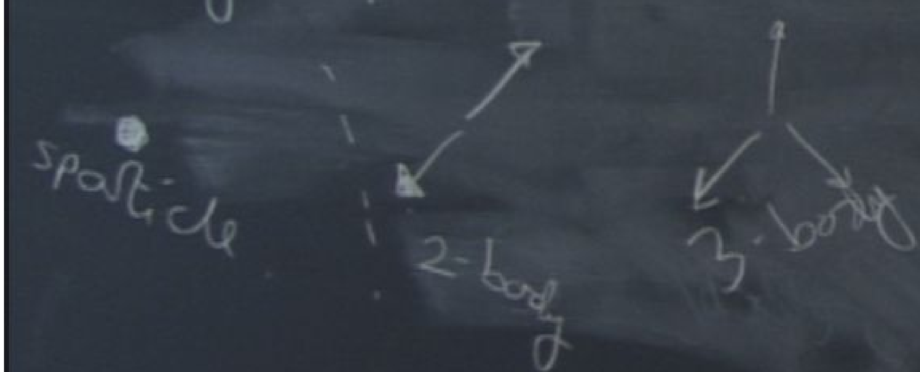

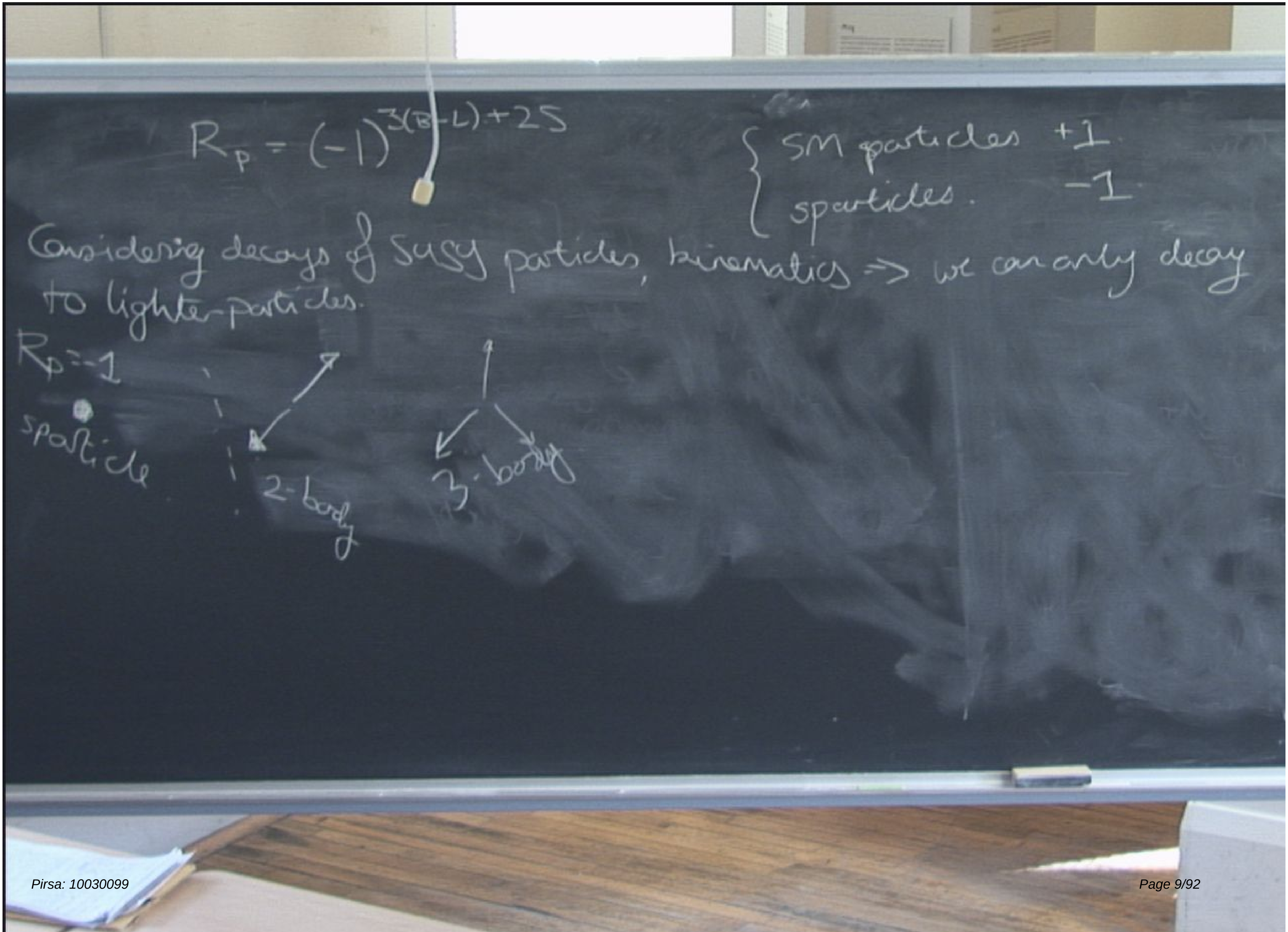

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$R_p = -1$
sparticle
2-body
3-body

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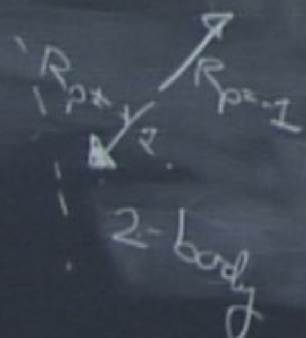

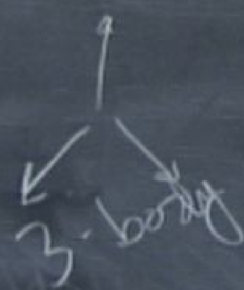

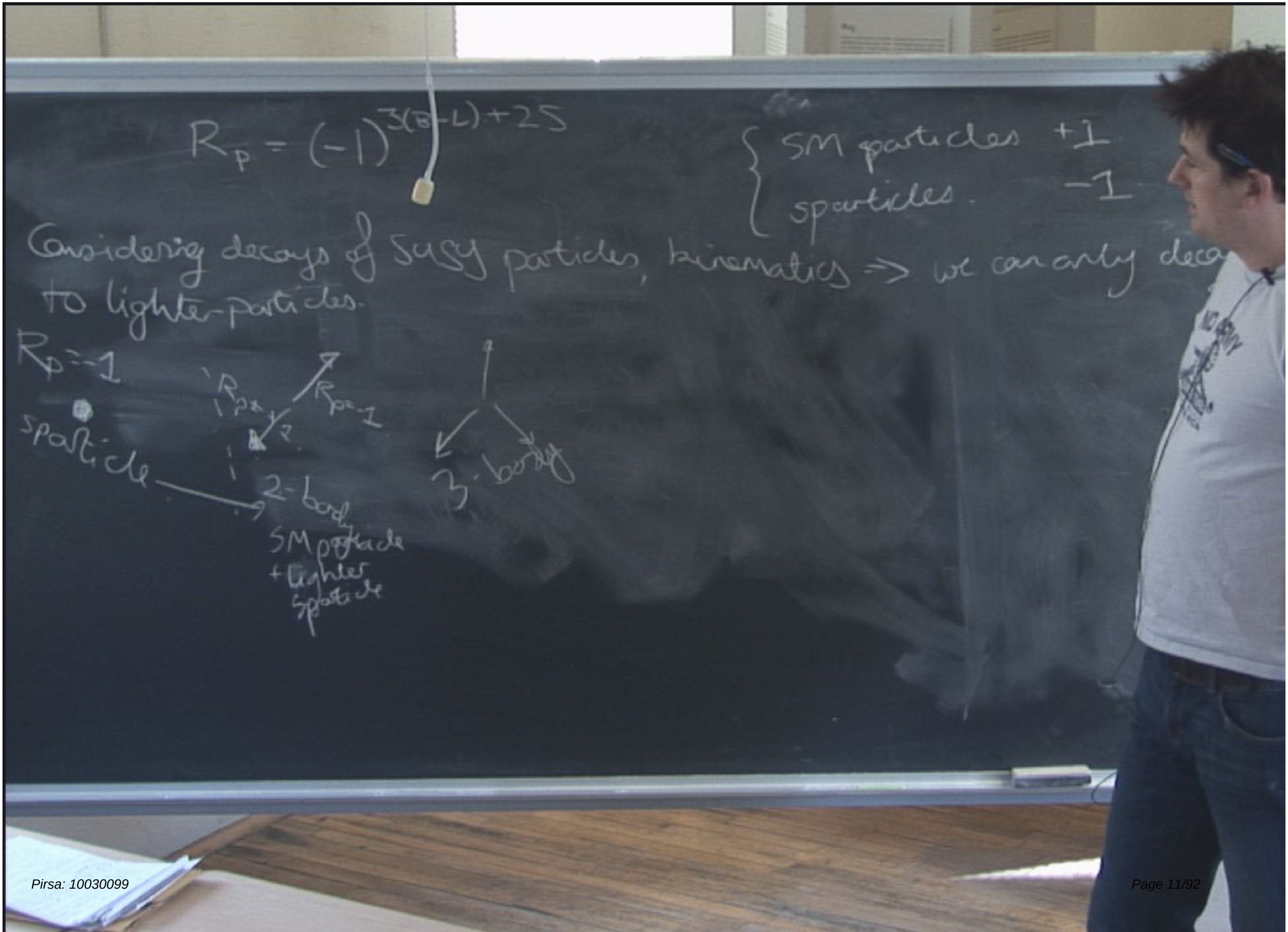
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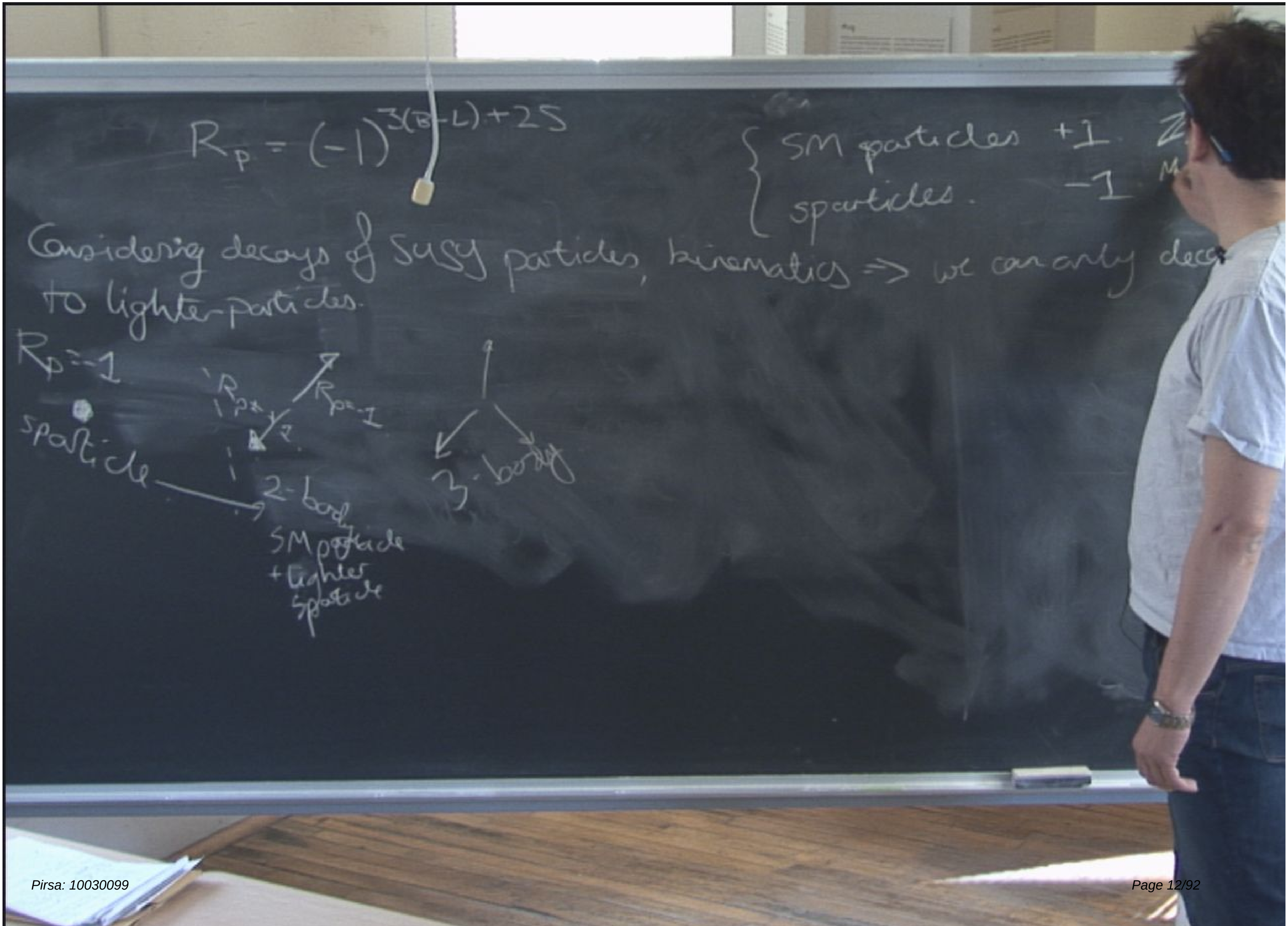
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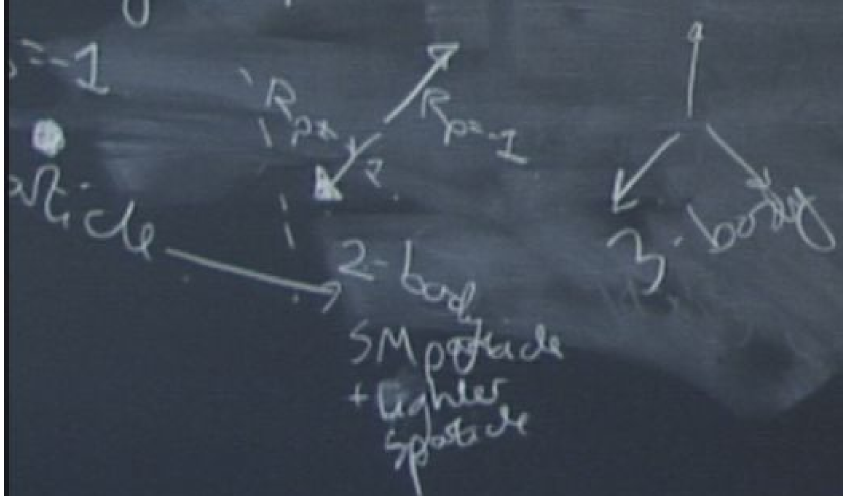

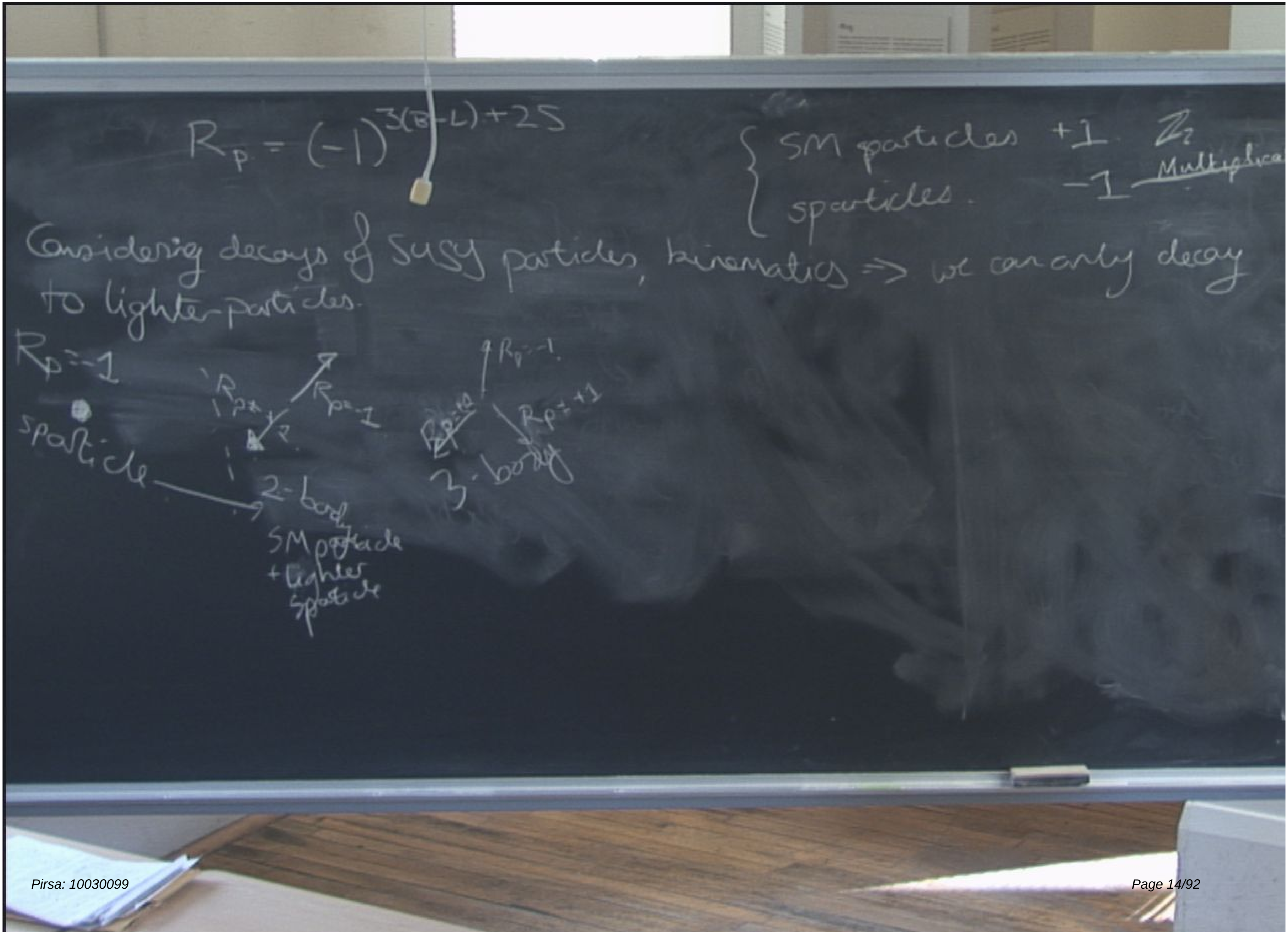
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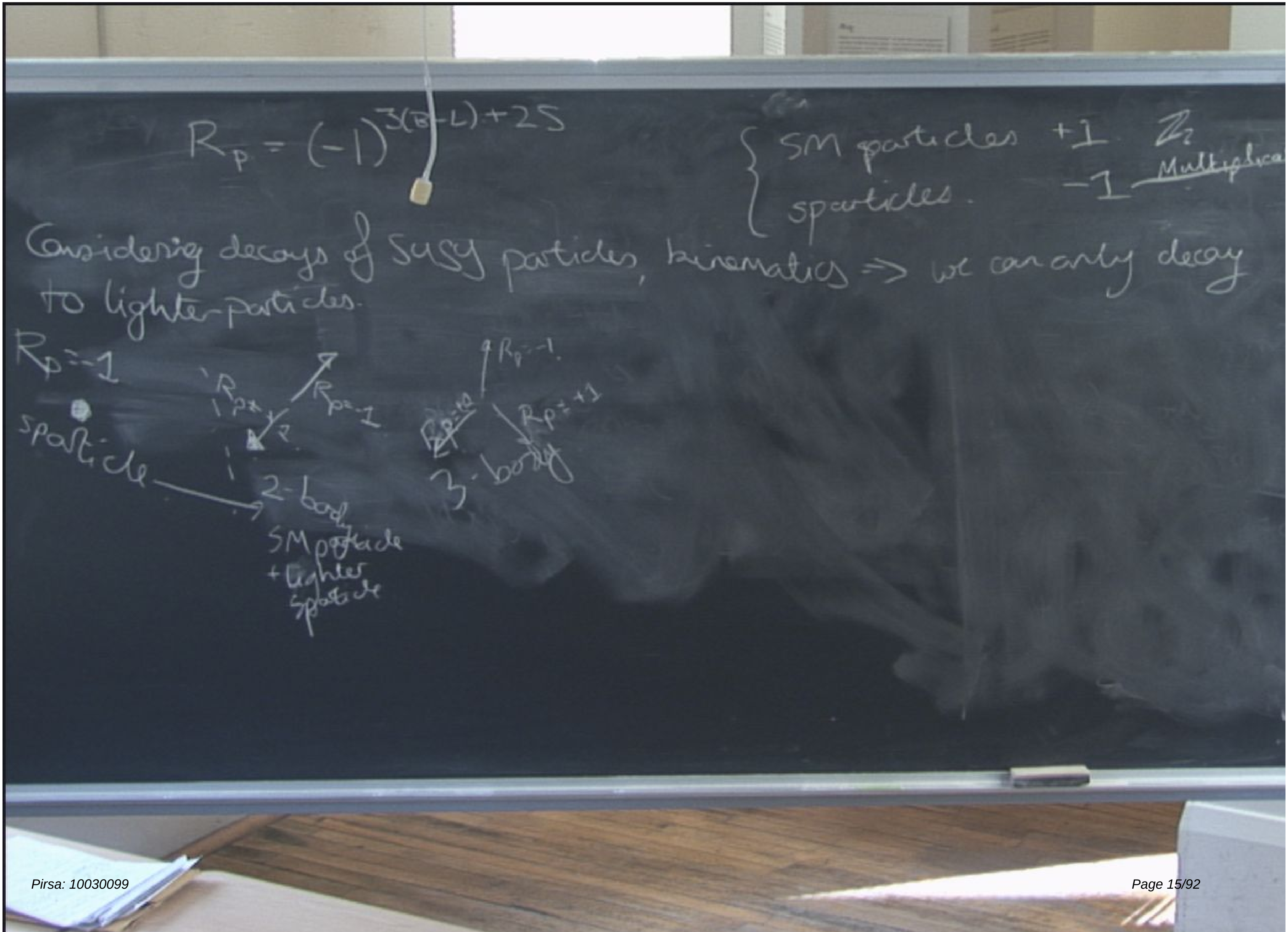
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Considering decays of SUSY particles, kinematics => we can only decay to lighter particles.

$R_p = -1$

sparticle → 2-body

SM particle + lighter sparticle

dominant

$R_p = -1$

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3-body

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Considering decays of SUSY particles, kinematics ⇒ we can only decay to lighter particles.

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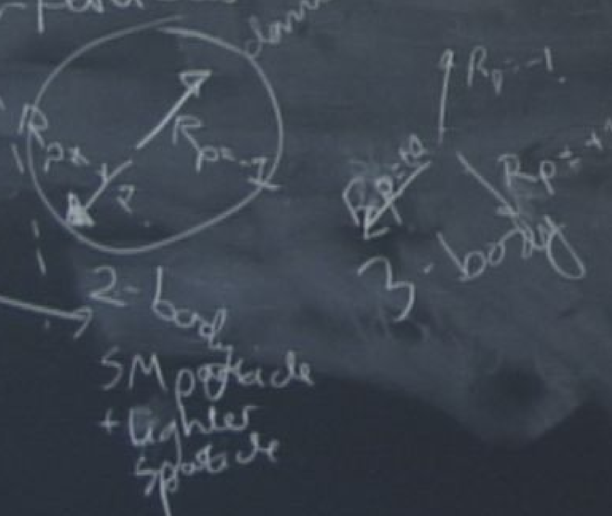
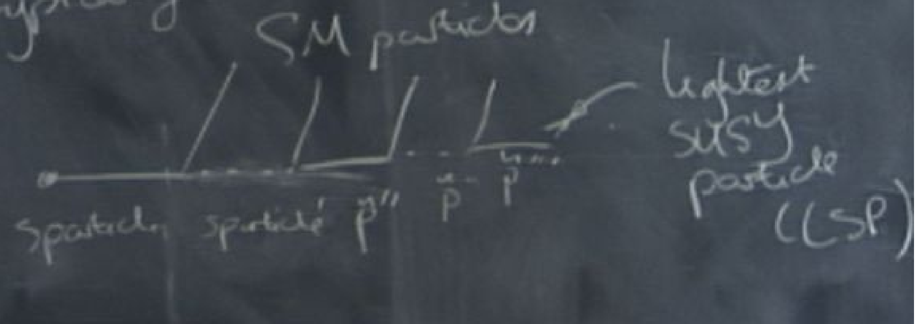


→ phase space suppressed typically



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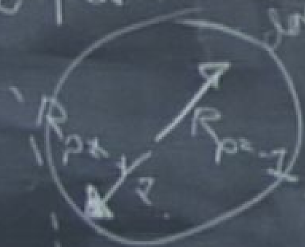
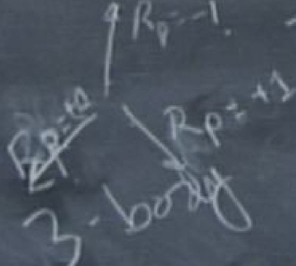
...$=-1$

...article → 2-body SM particle + lighter sparticle





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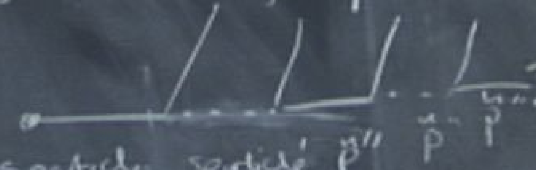
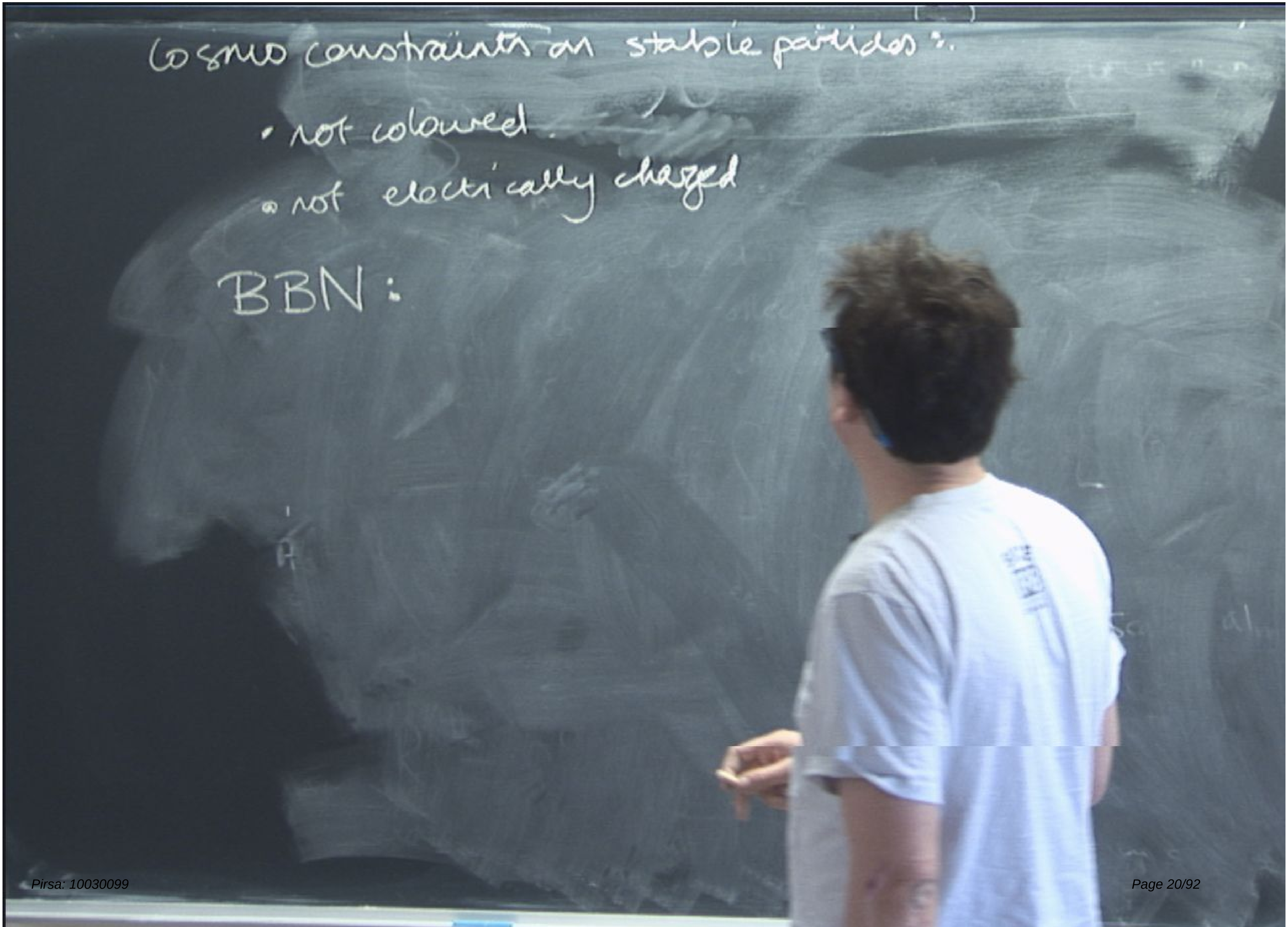


lightest SUSY particle (LSP) stable

Cosmo constraints on stable particles:

- not coloured
- not electrically charged


Cosmo constraints on stable particles:
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• not electrically charged
BBN:

Cosmo constraints on stable particles additional to SM

- not coloured
- not electrically charged

BBN: calculate thermal abundance of LSP

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- "quite a lot"

Cosmo constraints on stable particles additional to SM.

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BBN: calculate thermal abundance of LSP

- "quite a lot" — comparable to # protons.

Calculate probability of capture by some nucleus (eg p).

Cosmo constraints on stable particles additional to SM.

- not coloured.
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: calculate thermal abundance of LSP.

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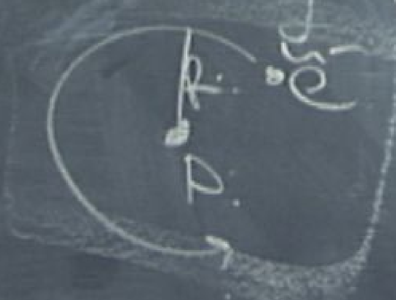

$R < \frac{1}{m_p}$ – would be absorbed into nucleus.

$\Rightarrow$

Cosmo constraints on stable particles additional to SM.

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Look in old rocks for anomalously heavy isotopes – don't find any.

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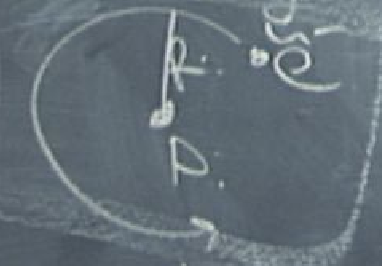

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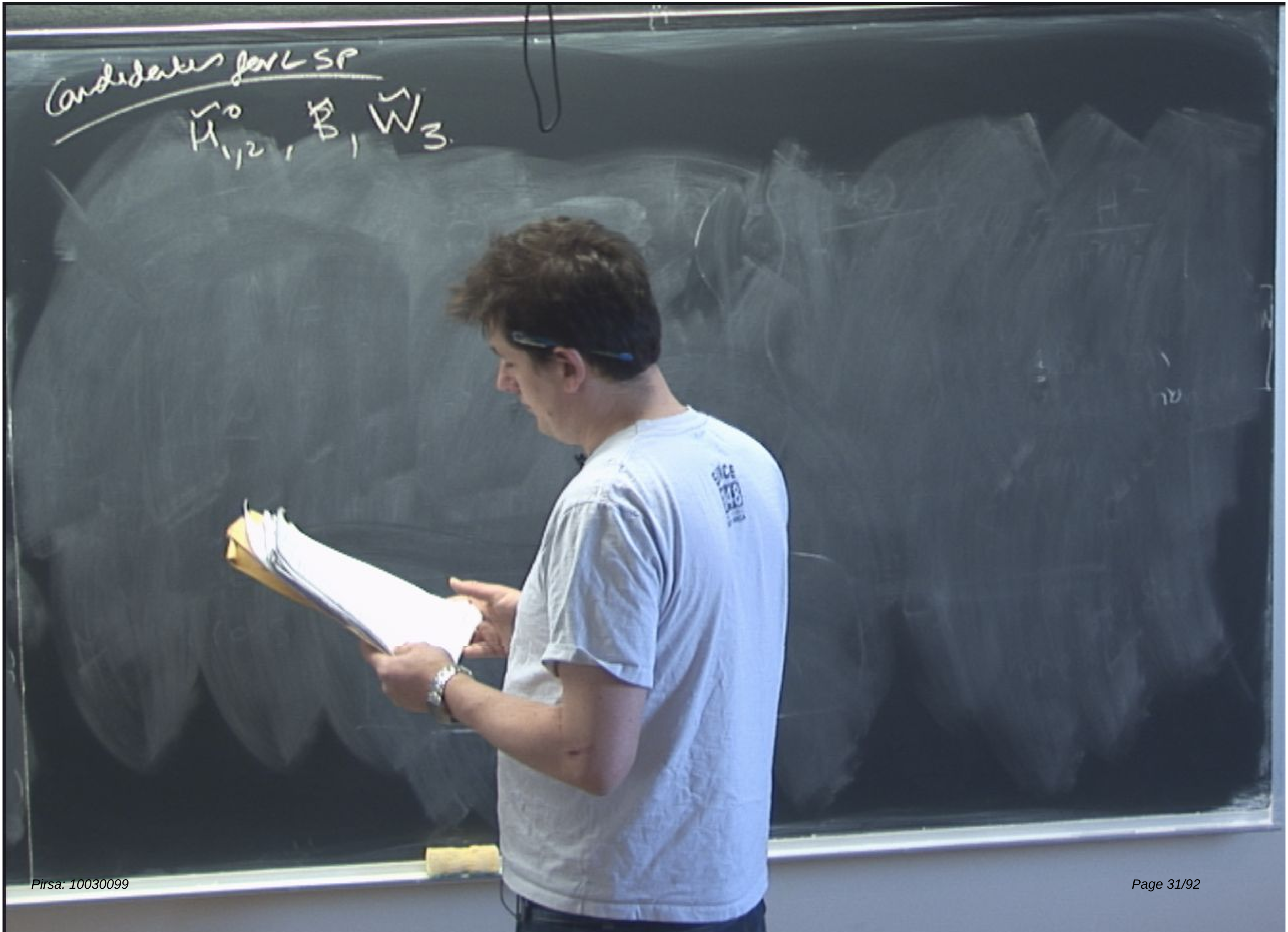
Candidates for LSP
$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$.

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$(-\delta) = \frac{1}{4}$ 2ϵ

Candidates for LSP

$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$, $\tilde{\nu}$, $\tilde{G}$.

Potentially, they can be cold dark matter.

(-8) $\frac{1}{1}$ 2ϵ


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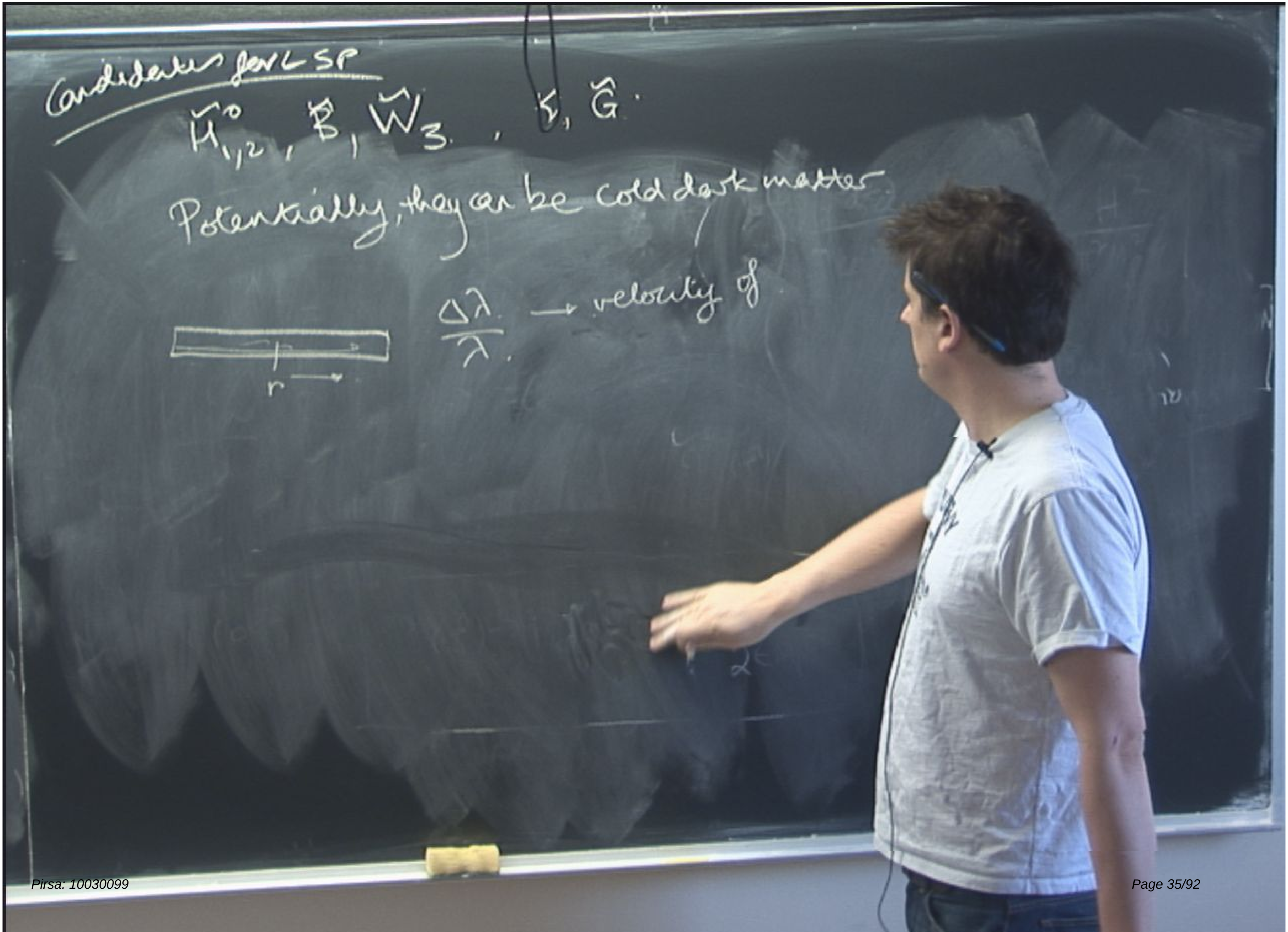
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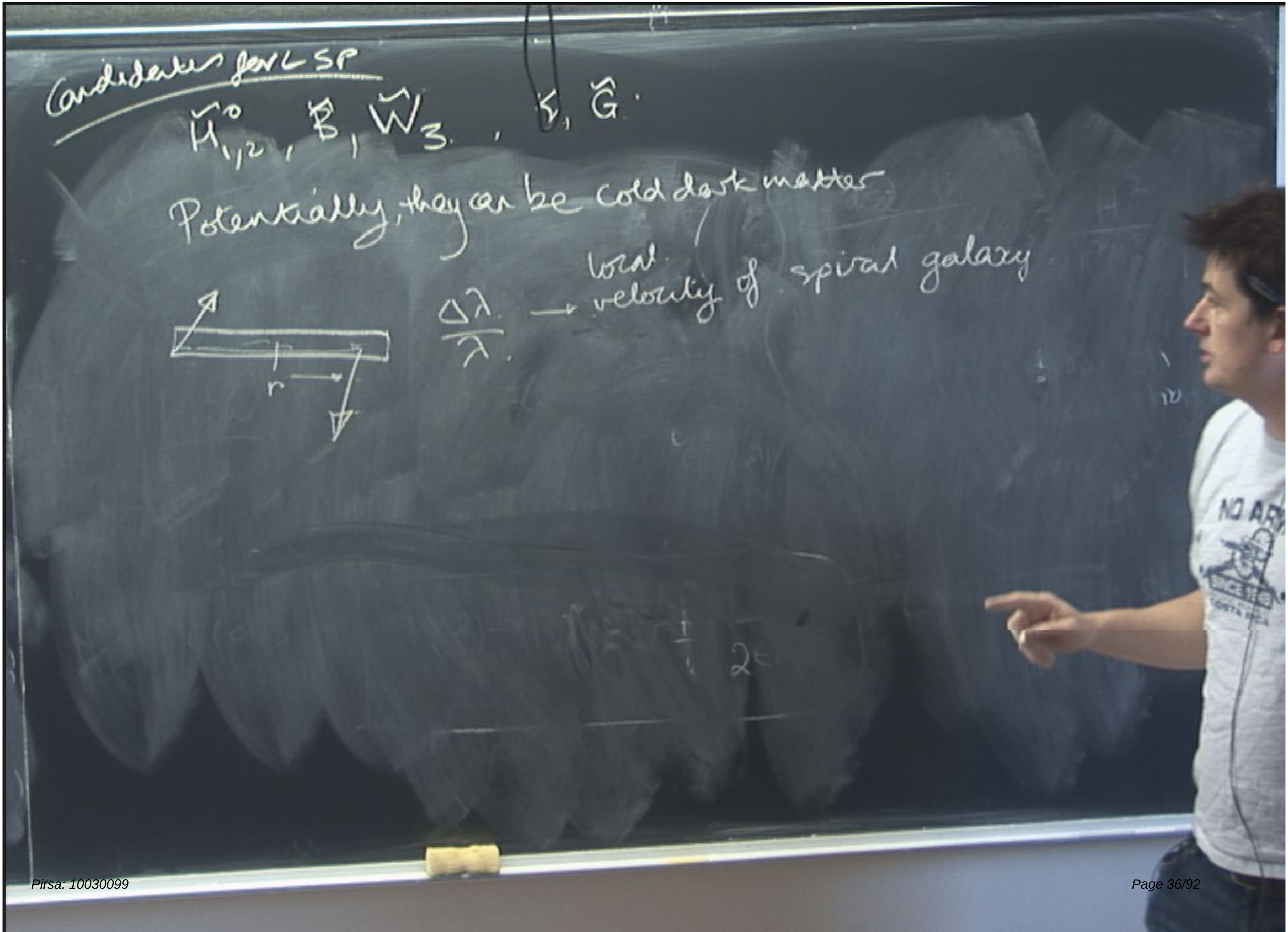
Candidates for LSP
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local
$\frac{\Delta\lambda}{\lambda}$ → velocity of spiral galaxy
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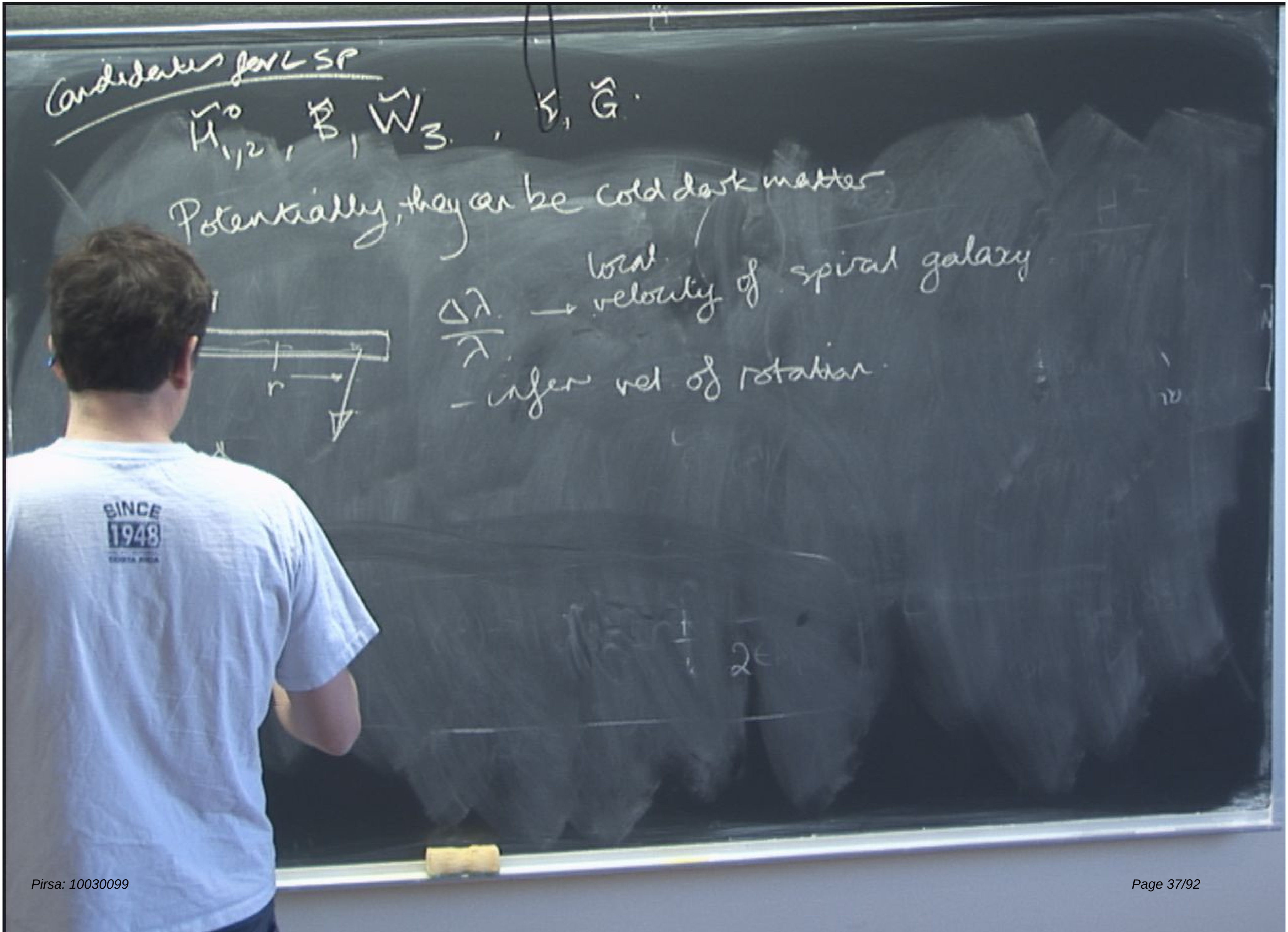
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- infer vel of rotation
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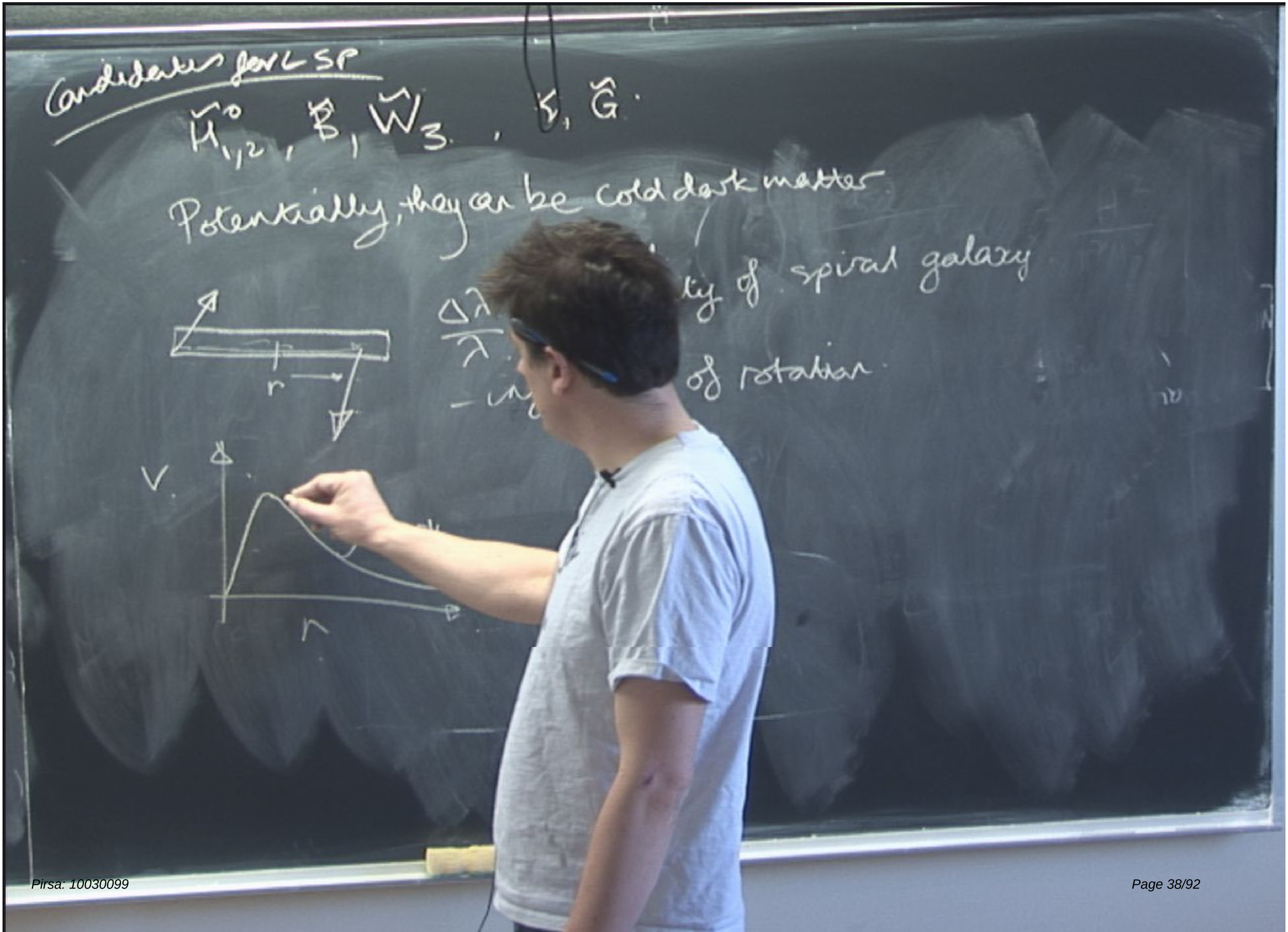
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$\frac{\Delta\lambda}{\lambda} \rightarrow$ local velocity of spiral galaxy

– infer vel of rotation

observation

$\propto r^{-1/2}$ Newtonian prediction, assuming mass distribution $\propto$ visible mass dist$^{\underline{n}}$.

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mass distribution

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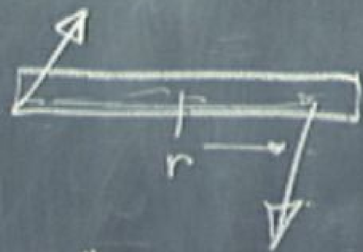

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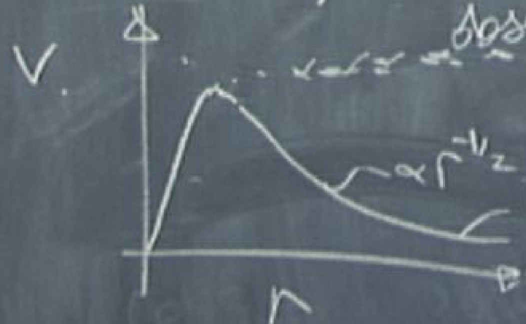

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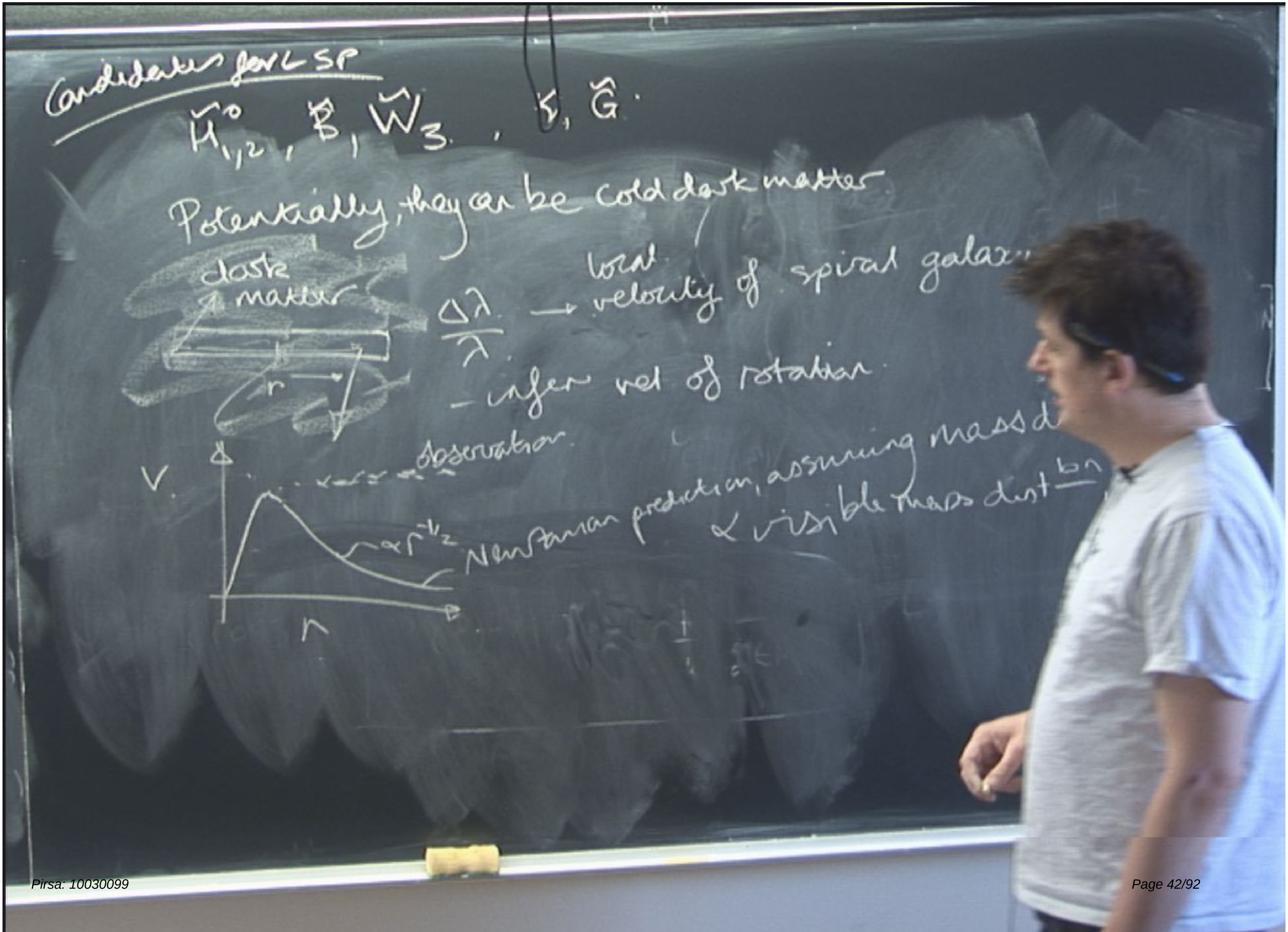
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Newtonian prediction, assuming mass distribution $\propto$ visible mass dist^{bn}.

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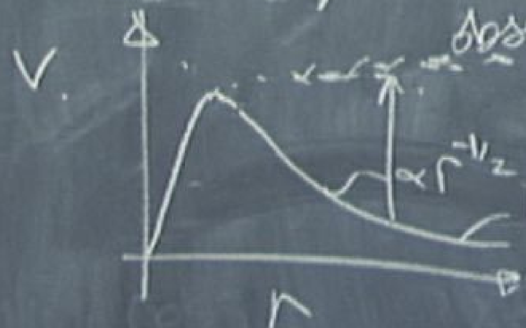

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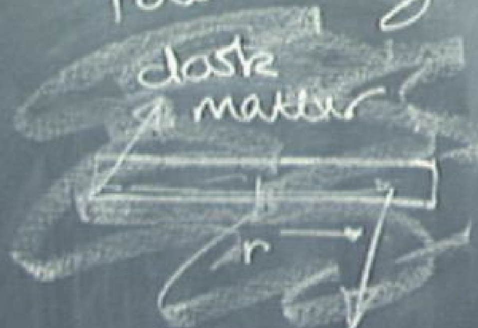

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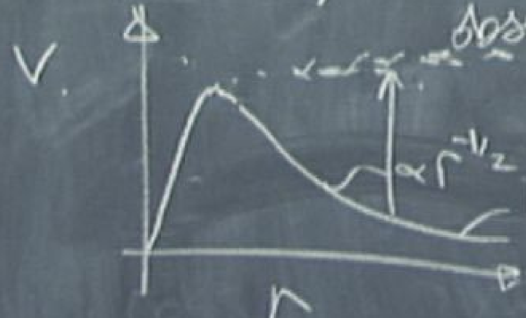
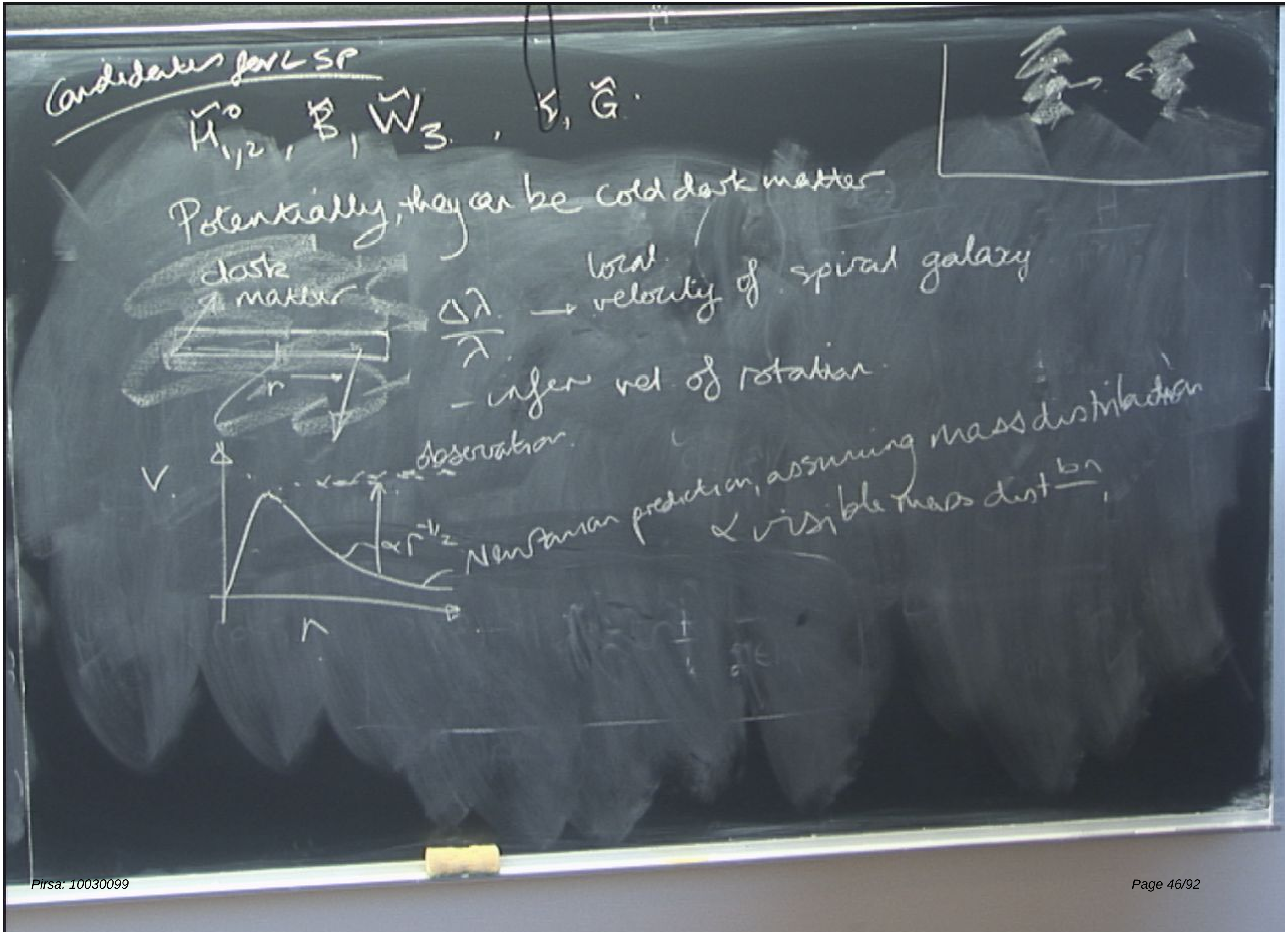


Newtonian prediction, assuming mass distribution $\propto$ visible mass dist $\frac{bn}{}$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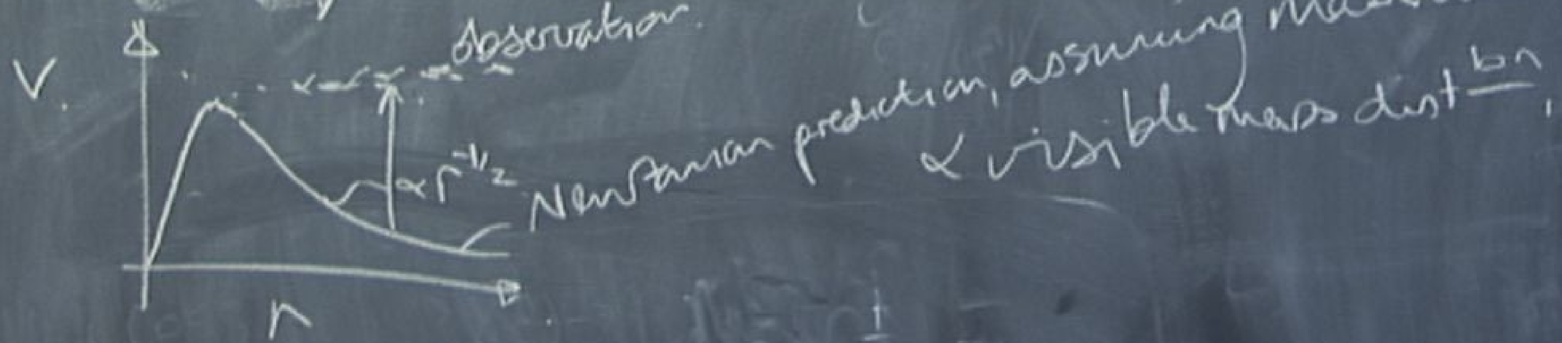

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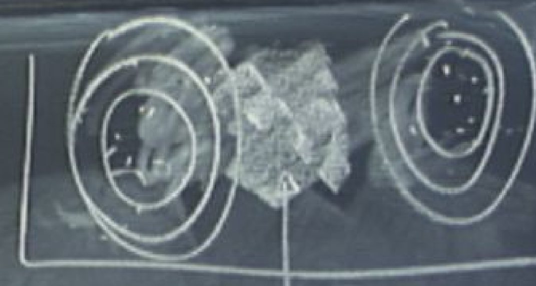
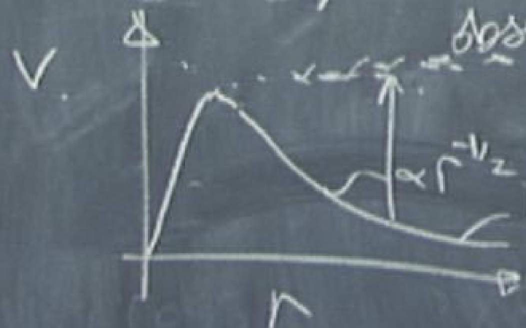


Potentially, they can be cold dark matter

$\frac{\Delta\lambda}{\lambda} \to$ local velocity of spiral galaxy

95% visible mass in gas

— infer vel of rotation



Newtonian prediction, assuming mass distribution $\propto$ visible mass dist$^{\underline{bn}}$.

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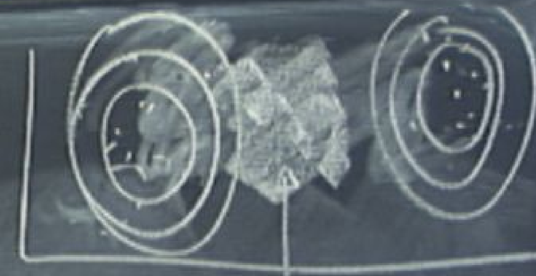

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Newtonian prediction, assuming mass distribution $\frac{bn}{}$,

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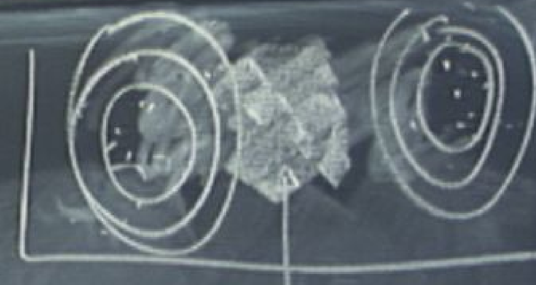

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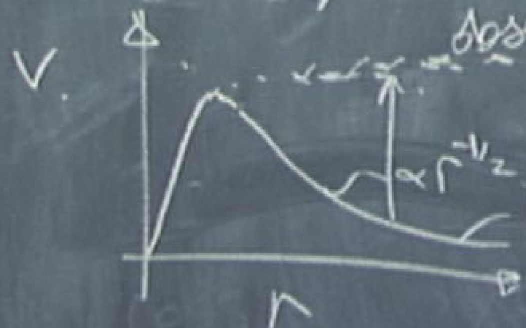
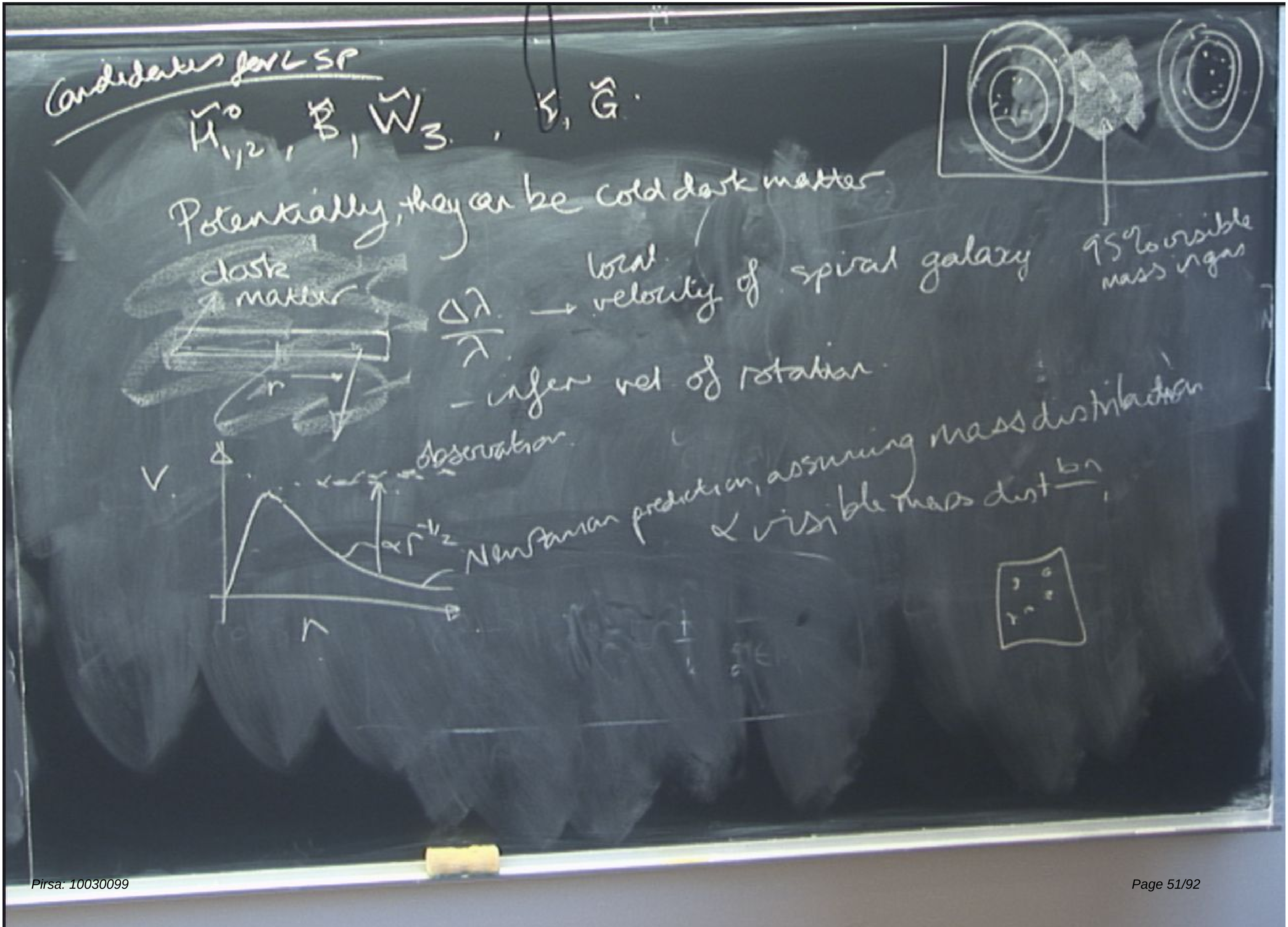
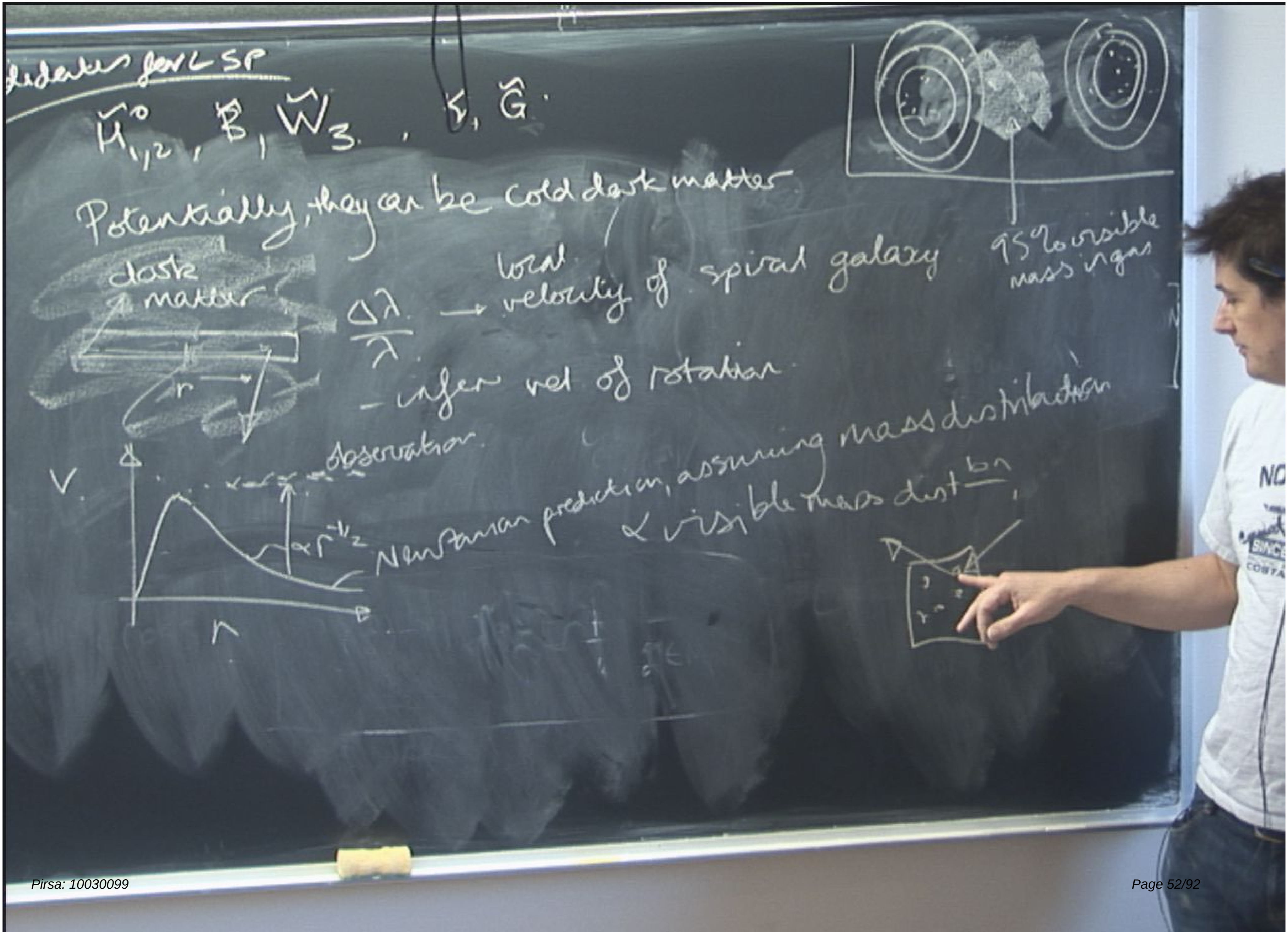


Newtonian prediction, assuming mass distribution $\propto$ visible mass distn


Candidates for LSP
$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$, $\tilde{G}$.
Potentially, they can be cold dark matter
dark matter
r
$\frac{\Delta\lambda}{\lambda}$ → local velocity of spiral galaxy
- infer vel of rotation
95% visible mass in gas
observation
V
$\propto r^{-1/2}$
Newtonian prediction, assuming mass distribution $\propto$ visible mass dist
r



didates for LSP
$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$, $\tilde{\nu}$, $\hat{G}$.
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$\frac{\Delta\lambda}{\lambda} \rightarrow$ local velocity of spiral galaxy
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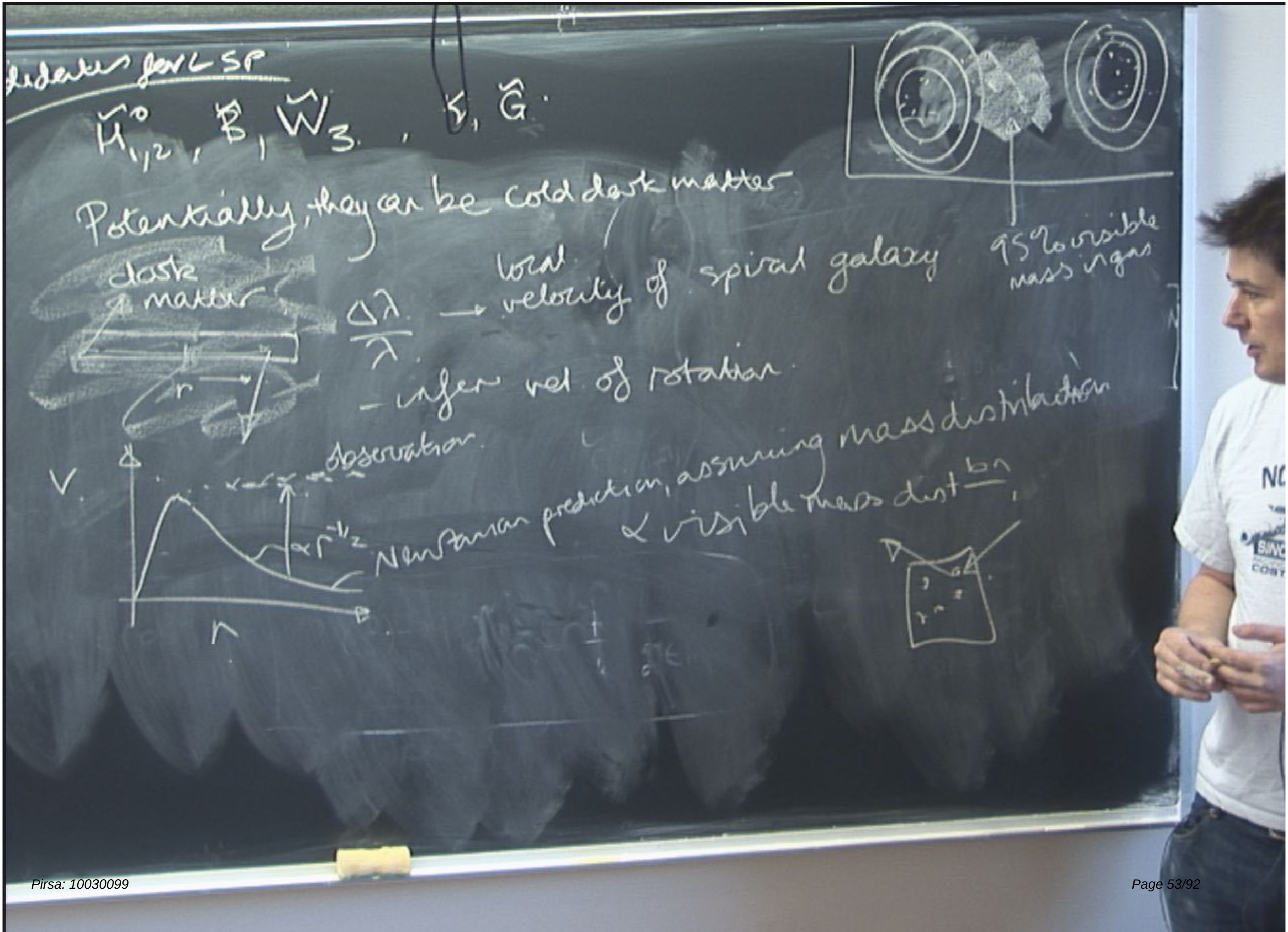

...didates for LSP
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Newtonian prediction, assuming mass distribution $\propto$ visible mass distribution.

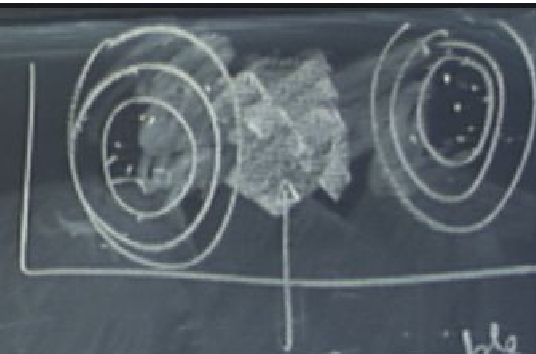
Candidates for LSP

$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$, $\tilde{\nu}$, $\tilde{G}$.

Potentially, they can be cold dark matter

$\frac{\Delta\lambda}{\lambda} \rightarrow$ local velocity of spiral galaxy

– infer vel of rotation



Newtonian prediction, assuming mass distribution $\propto$ visible mass distbn.

Candidates for LSP

$\tilde{H}^0_{1,2}$, $\tilde{B}$, $\tilde{W}_3$, $\tilde{\nu}$, $\tilde{G}$

→ too little DM

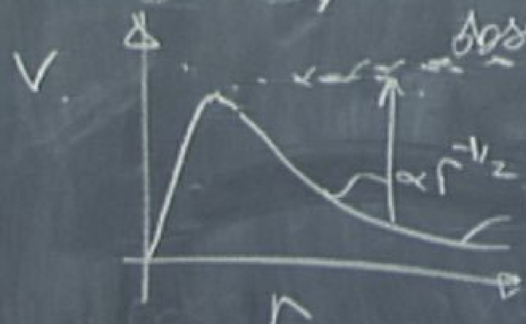
→ works ☺

95% visible mass in gas

Potentially, they can be cold dark matter.

$\frac{\Delta\lambda}{\lambda}$ → local velocity of spiral galaxy

– infer vel of rotation



Newtonian prediction, assuming mass distribution $\propto$ visible mass dist

After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all <u>mix</u>

$$\boxed{\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}}$$

After EWSB,

$\tilde{H}^0_2, \tilde{H}^0_1, \tilde{B}, \tilde{W}_3$ all mix

- mass e'states. $\chi^0_{1,2,3,4}$ "neutralinos"

After EWSB,

$\tilde{H}^0_2, \tilde{H}^0_1, \tilde{B}, \tilde{W}_3$ all <u>mix</u>

- mass e'states. $\chi^0_{1,2,3,4}$ "neutralinos"

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c\theta_w & s\theta_w \\ -s\theta_w & c\theta_w \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

$$\boxed{\begin{pmatrix} B^\mu \\ W^{3\mu}\end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W}\end{pmatrix}\begin{pmatrix}\gamma^\mu \\ Z^\mu\end{pmatrix}}$$

After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all mix.

...s e'states. $\chi^0_{1,2,3,4}$ "neutralinos".

...l particles with identical spins and $SU(3)\times U(1)_{em}$ ...uantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R$

After EWSB,

$\tilde{H}^0_2, \tilde{H}^0_1, \tilde{B}, \tilde{W}_3$ all mix

- mass e'states. $\chi^0_{1,2,3,4}$ "neutralinos"

- all particles with identical spins and $SU(3)\times U(1)_{em}$ quantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

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After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all mix.

e'states. $\chi^0_{1,2,3,4}$ "neutralinos"

particles with identical spins and $SU(3)\times U(1)_{em}$

antum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$\tilde{H}_2^+, W$

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

After EWSB,

$\tilde{H}^0_2, \tilde{H}^0_1, \tilde{B}, \tilde{W}_3$ all mix

- mass e'states. $\chi^0_{1,2,3,4}$ "neutralinos"
- all particles with identical spins and $SU(3) \times U(1)_{em}$ quantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$\tilde{H}^+_2, \dfrac{\tilde{W}_1 + i\tilde{W}_2}{\sqrt{2}}$

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all mix

- mass e'states. $\chi^0_{1,2,3,4}$ "neutral

- all particles with identical spins $\times\, U(1)_{em}$ quantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$$\left\{ \tilde{H}_2^+ ,\ \frac{\tilde{W}_1 + i\tilde{W}_2}{\sqrt{2}} \equiv \tilde{W}^+ \right\} \longrightarrow$$

After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all mix

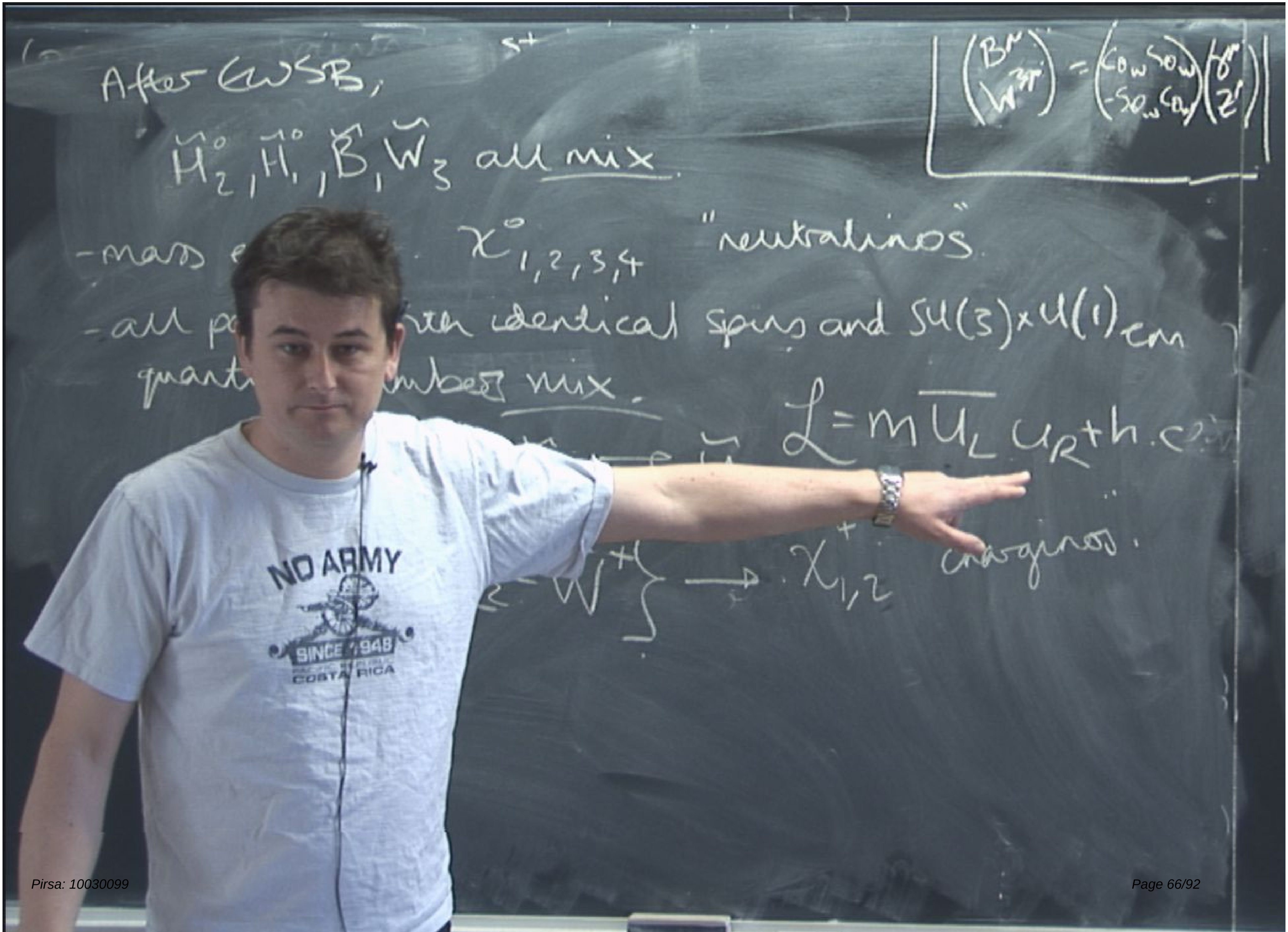
- mass e'states $\chi^0_{1,2,3,4}$ "neutralinos"

- all particles with identical spins and $SU(3)\times U(1)_{em}$ quantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$$\left\{ \tilde{H}_2^+ , \frac{\tilde{W}_1 + i\tilde{W}_2}{\sqrt{2}} \equiv \tilde{W}^+ \right\} \longrightarrow \chi^+_{1,2} \quad \text{"charginos"}$$

$$\boxed{\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}}$$


After EWSB,
H̃₂⁰, H̃₁⁰, B̃, W̃₃ all mix
-mass e
χ⁰ 1,2,3,4 "neutralinos"
-all p ith identical spins and SU(3)×U(1)em
quant umbers mix.
L = m ū_L u_R + h.c.
W̃⁺ → χ⁺ 1,2 "charginos".
NO ARMY
SINCE 1948
COSTA RICA

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

After EWSB,

$\tilde{H}_2^0, \tilde{H}_1^0, \tilde{B}, \tilde{W}_3$ all mix

- mass e'states. $\chi^0_{1,2,3,4}$ "neutralinos"
- all particles with identical spins and $SU(3) \times U(1)_{em}$ quantum numbers mix.

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$ $\quad \mathcal{L} = m\overline{u_L}u_R + h.c.$

$$\left\{ \tilde{H}_2^+, \frac{\tilde{W}_1 + i\tilde{W}_2}{\sqrt{2}} \equiv \tilde{W}^+ \right\} \to \chi^+_{1,2} \quad \text{"charginos"}$$

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \end{pmatrix} = \begin{pmatrix} c_{\theta_W} & s_{\theta_W} \\ -s_{\theta_W} & c_{\theta_W} \end{pmatrix} \begin{pmatrix} \gamma^\mu \\ Z^\mu \end{pmatrix}$$

After EWSB,

$\tilde{H}^0_2, \tilde{H}^0_1, \tilde{B}, \tilde{W}_3$ all mix

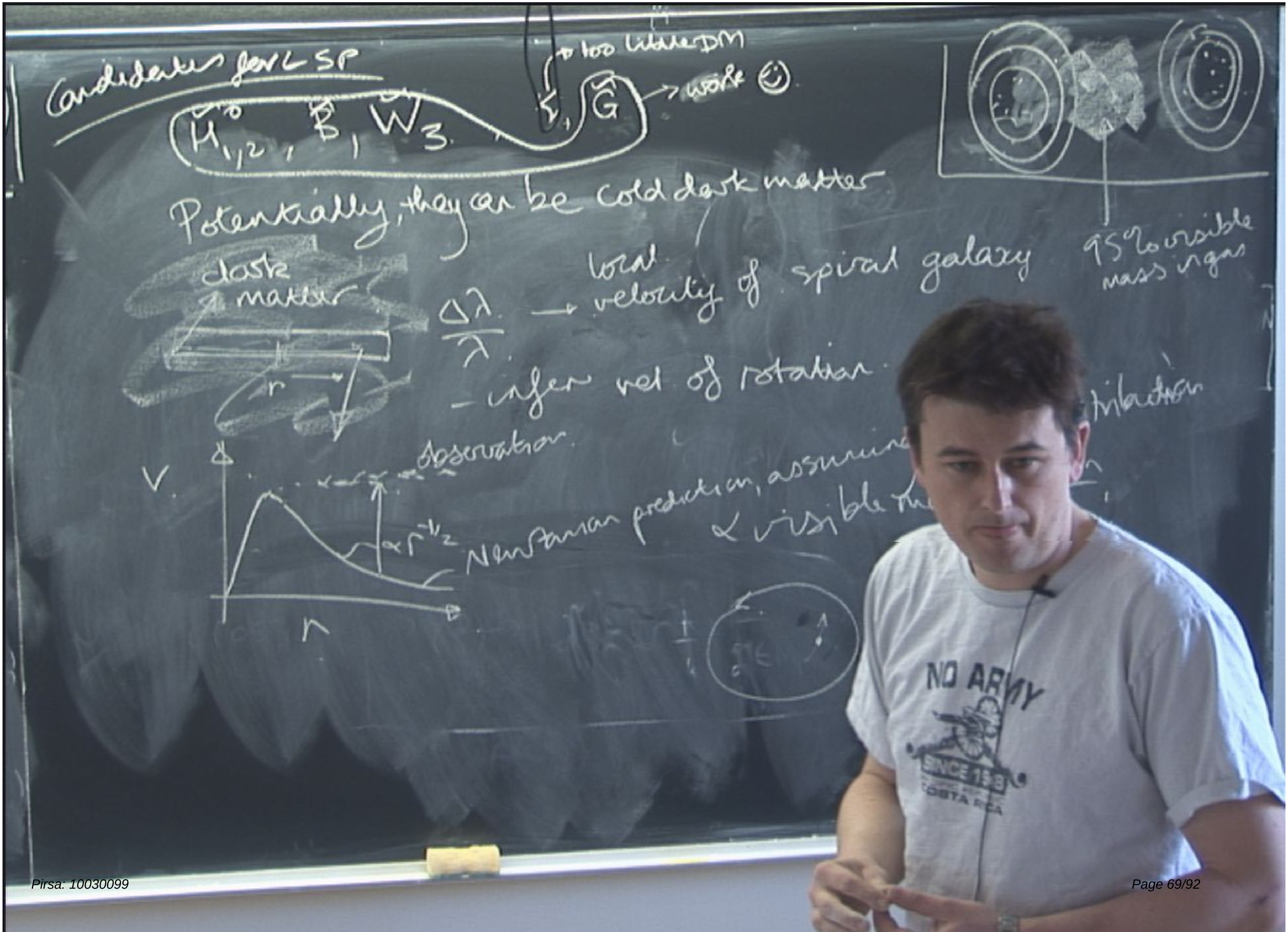
- mass e'states $\boxed{\chi^0_1}, {}_{2,3,4}$ "neutralinos"

- all particles with identical spins and $SU(3)\times U(1)_{em}$ quantum numbers mix.

$\mathcal{L} = m\,\overline{\tilde{u}_L}\,\tilde{u}_R + h.c.$

eg $\tilde{u}_L, \tilde{u}_R \to \tilde{u}_{1,2}$

$$\left\{ \tilde{H}^+_2,\ \frac{\tilde{W}_1 + i\tilde{W}_2}{\sqrt{2}} \equiv \tilde{W}^+ \right\} \longrightarrow \chi^+_{1,2}$$ "charginos".


Candidates for LSP
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Potentially, they can be cold dark matter
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velocity of spiral galaxy
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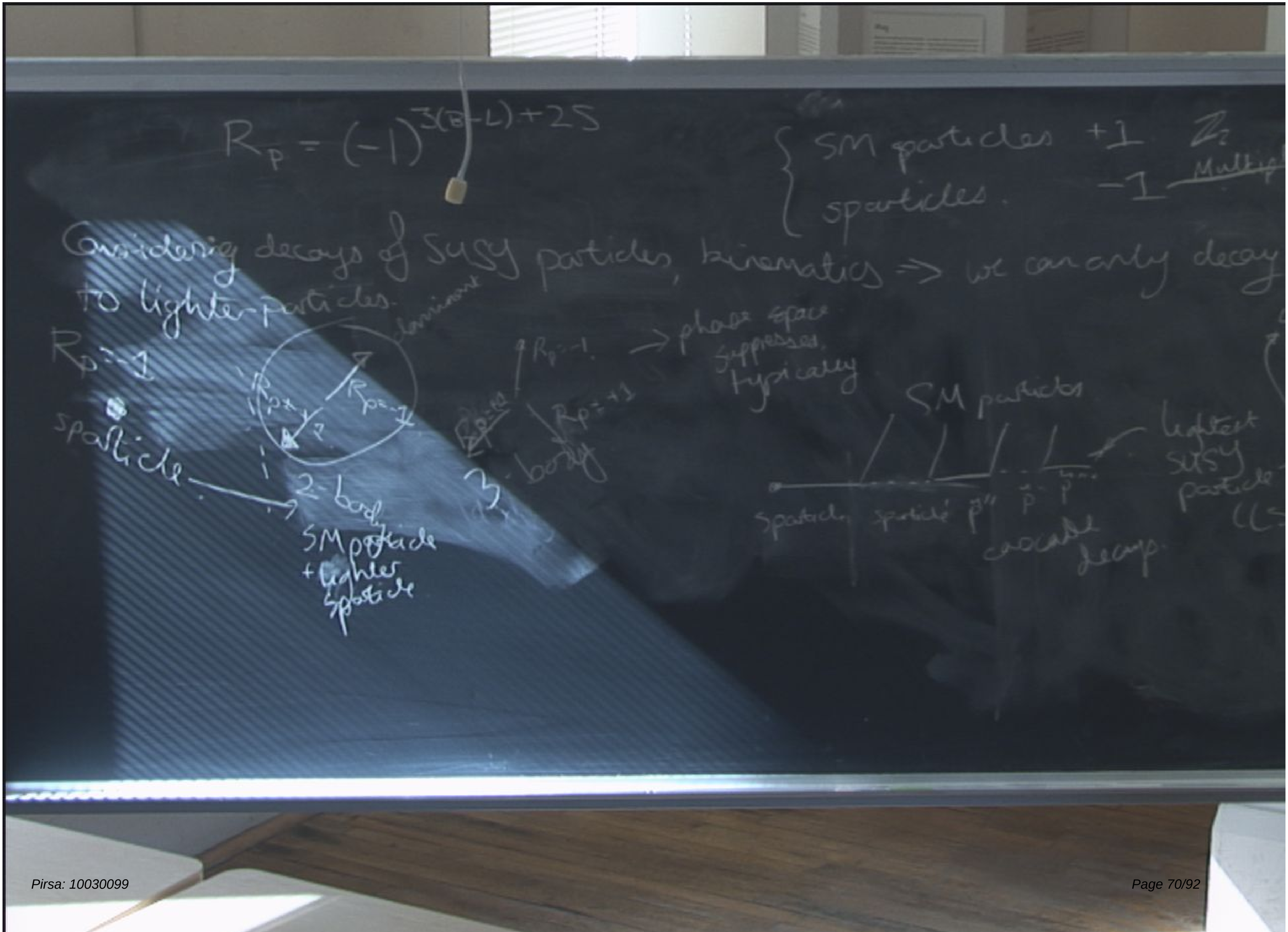
mass in gas
infer vel of rotation
observation
Newtonian prediction, assuming
∝ visible
$\propto r^{-1/2}$

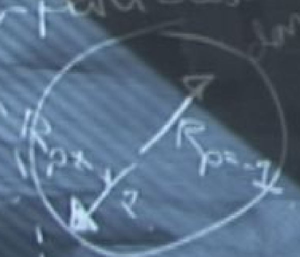


$R_p = (-1)^{3(B-L)+2S}$
SM particles +1 Z_2
sparticles −1
Considering decays of SUSY particles, kinematics => we can only decay
to lighter particles.
$R_p = -1$
sparticle
dominant
$R_p = -1$
$R_p = +1$
2-body
SM particle + lighter sparticle
3-body
phase space suppressed, typically
SM particles
lightest SUSY particle
sparticle sparticle
cascade decays

$$R_p = (-1)^{3(B-L)+2S}$$

$\left\{ \begin{array}{ll} \text{SM particles} & +1 \\ \text{sparticles} & -1 \end{array} \right.$ $\mathbb{Z}_2$ Multiplicative

...dering decays of SUSY particles, kinematics $\Rightarrow$ we can only decay ... lighter particles.

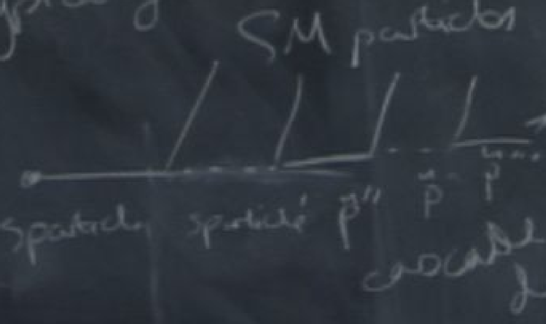


...cle $\longrightarrow$ 2-body SM particle + lighter sparticle

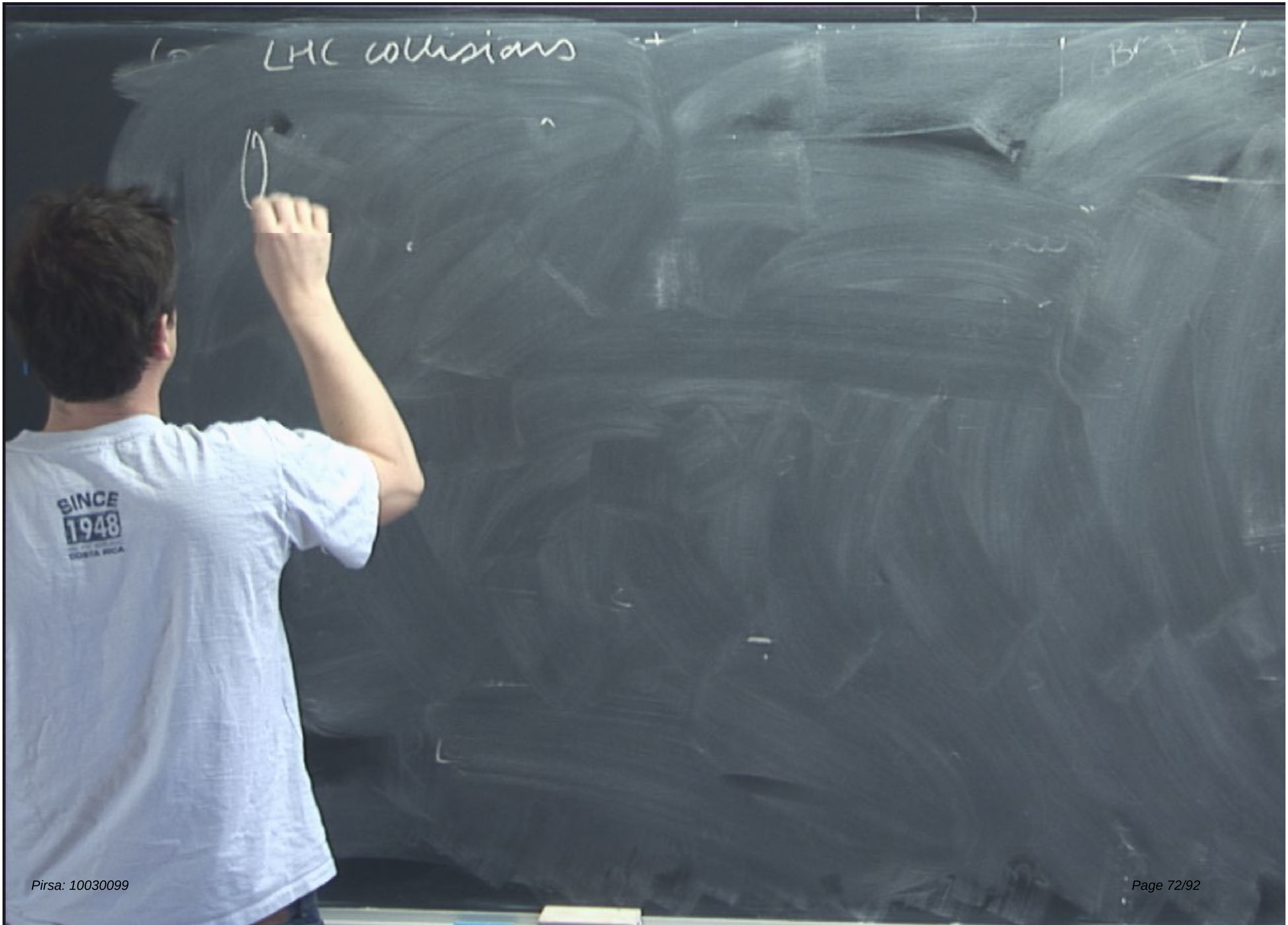
$R_p = -1$ $\rightarrow$ phase space suppressed, typically

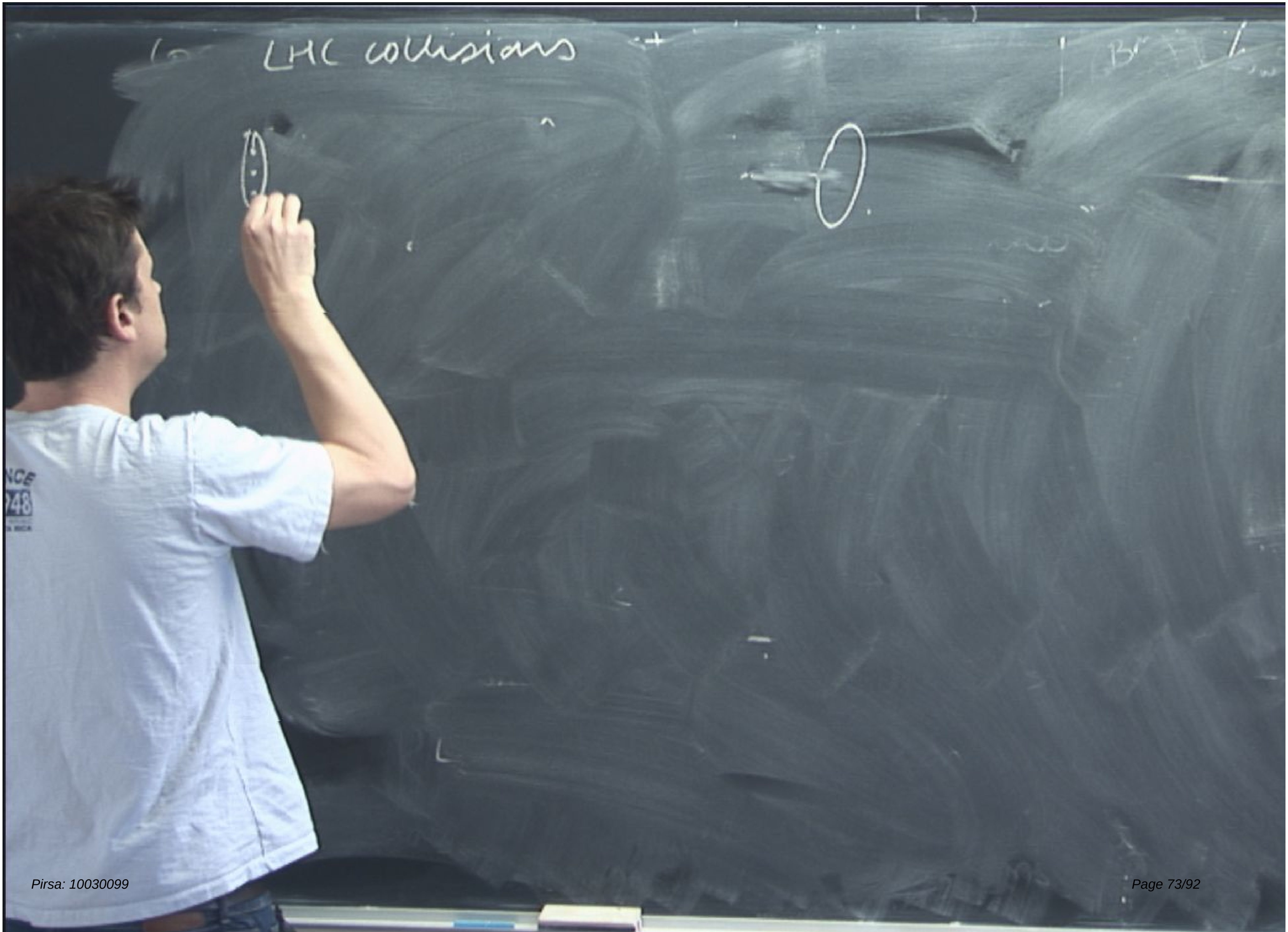
$R_p = -1$, $R_p = +1$

3-body

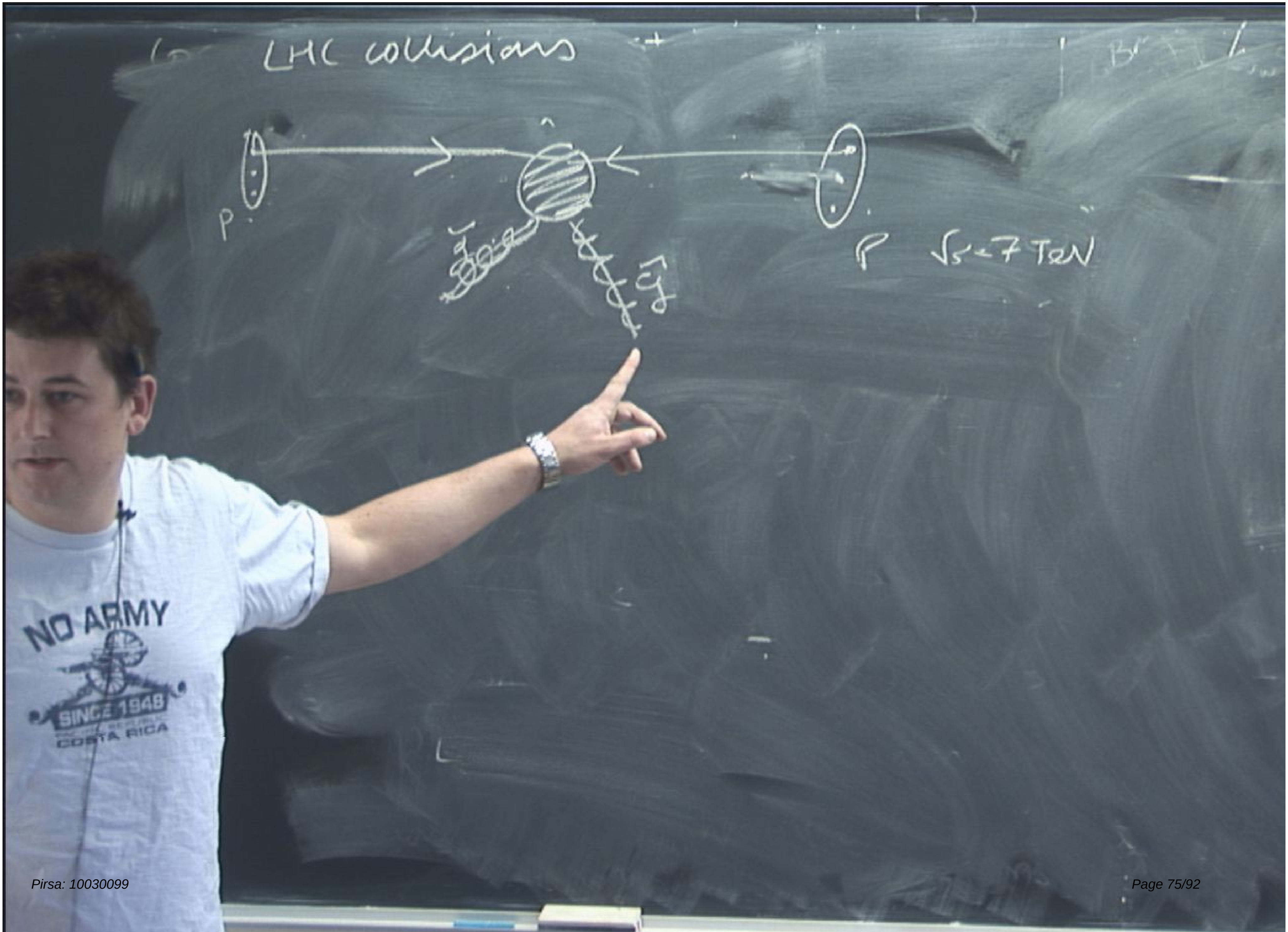


lightest SUSY particle (LSP) stable


LHC collisions


LHC collisions

LHC collisions

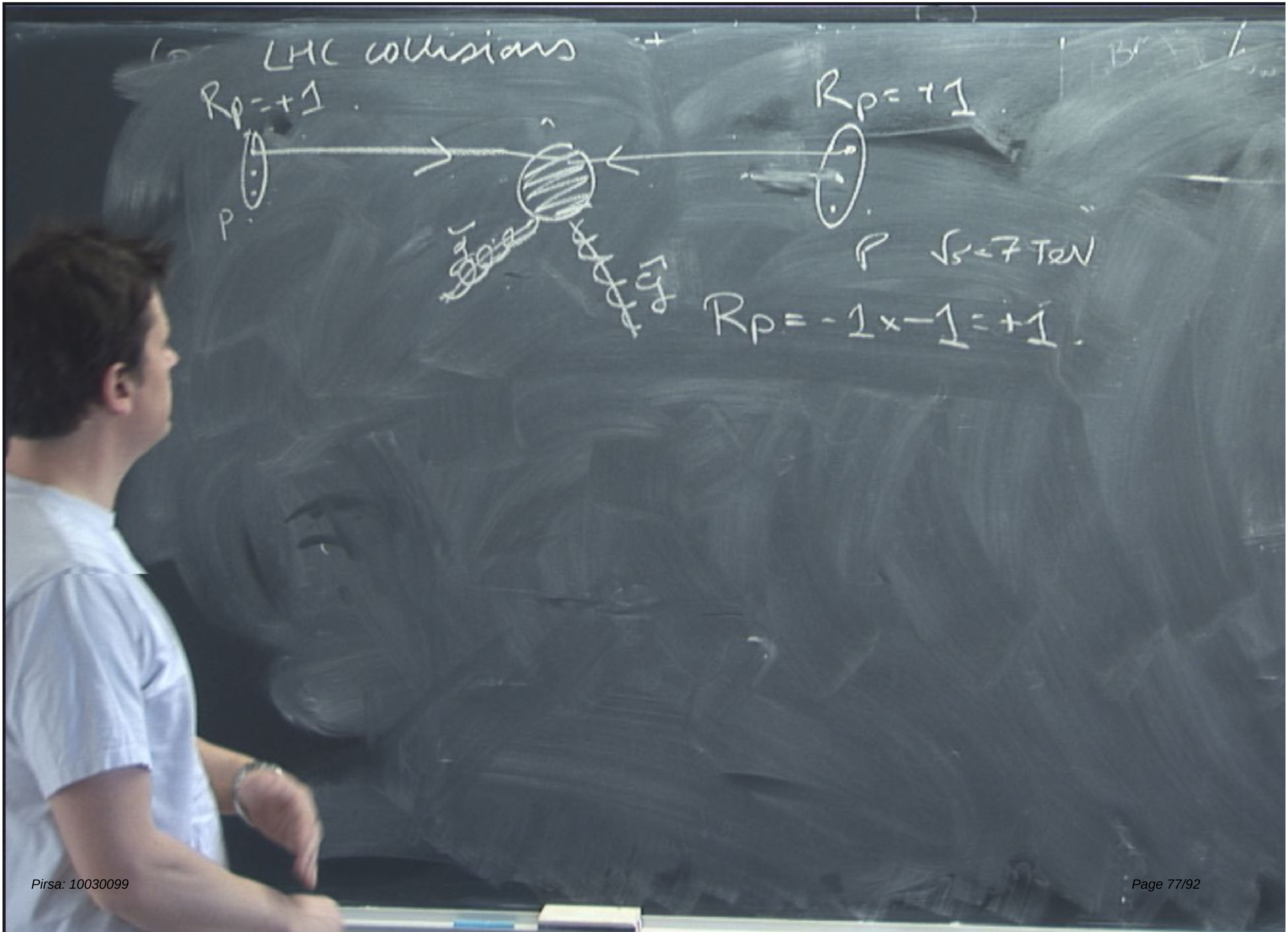

LHC collisions
p
p
√s = 7 TeV
NO ARMY
SINCE 1948
COSTA RICA

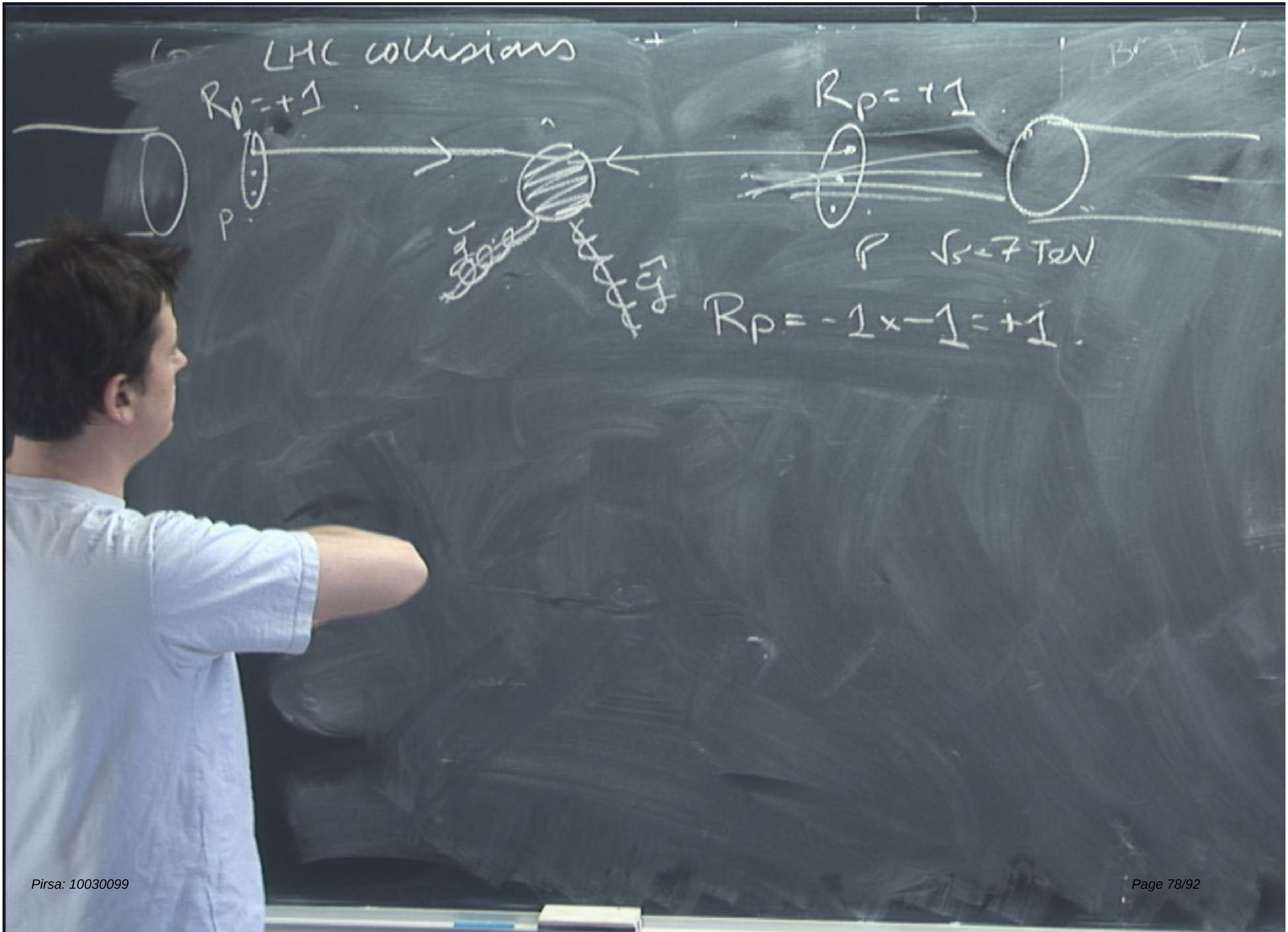
LHC collisions

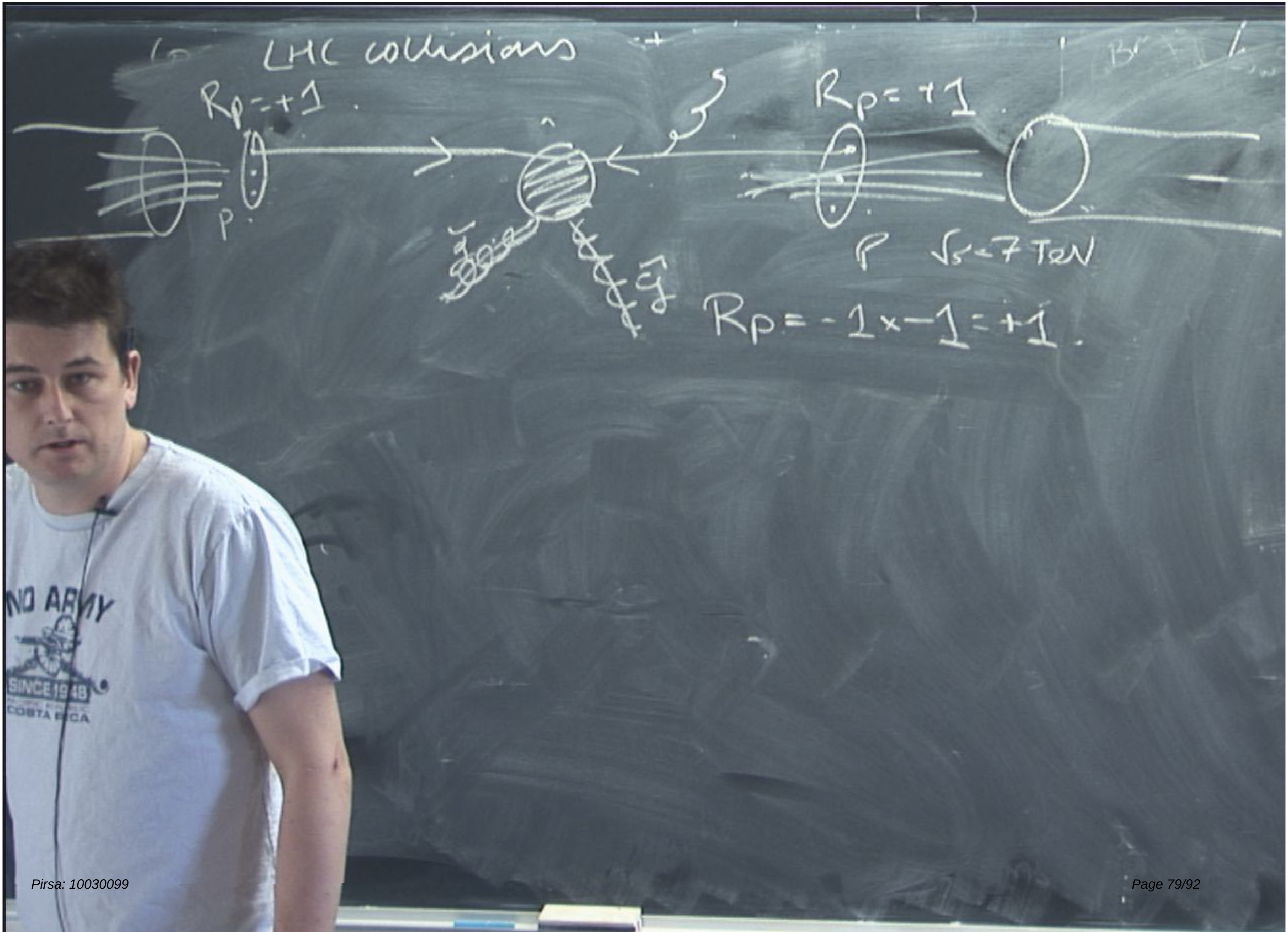
$R_p = +1$ $\qquad\qquad$ $R_p = +1$

$\sqrt{s} = 7\ \mathrm{TeV}$

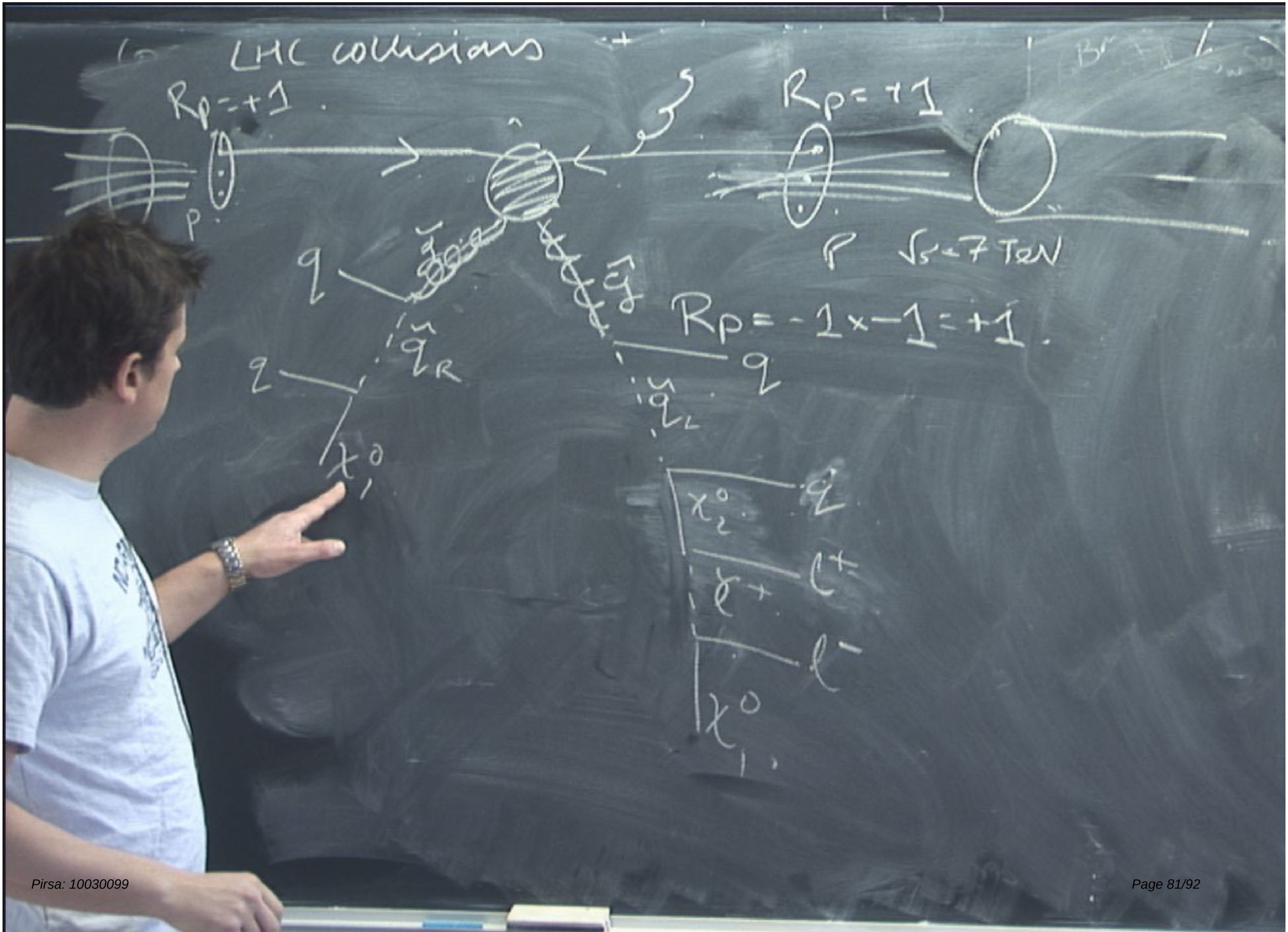
$R_p =$

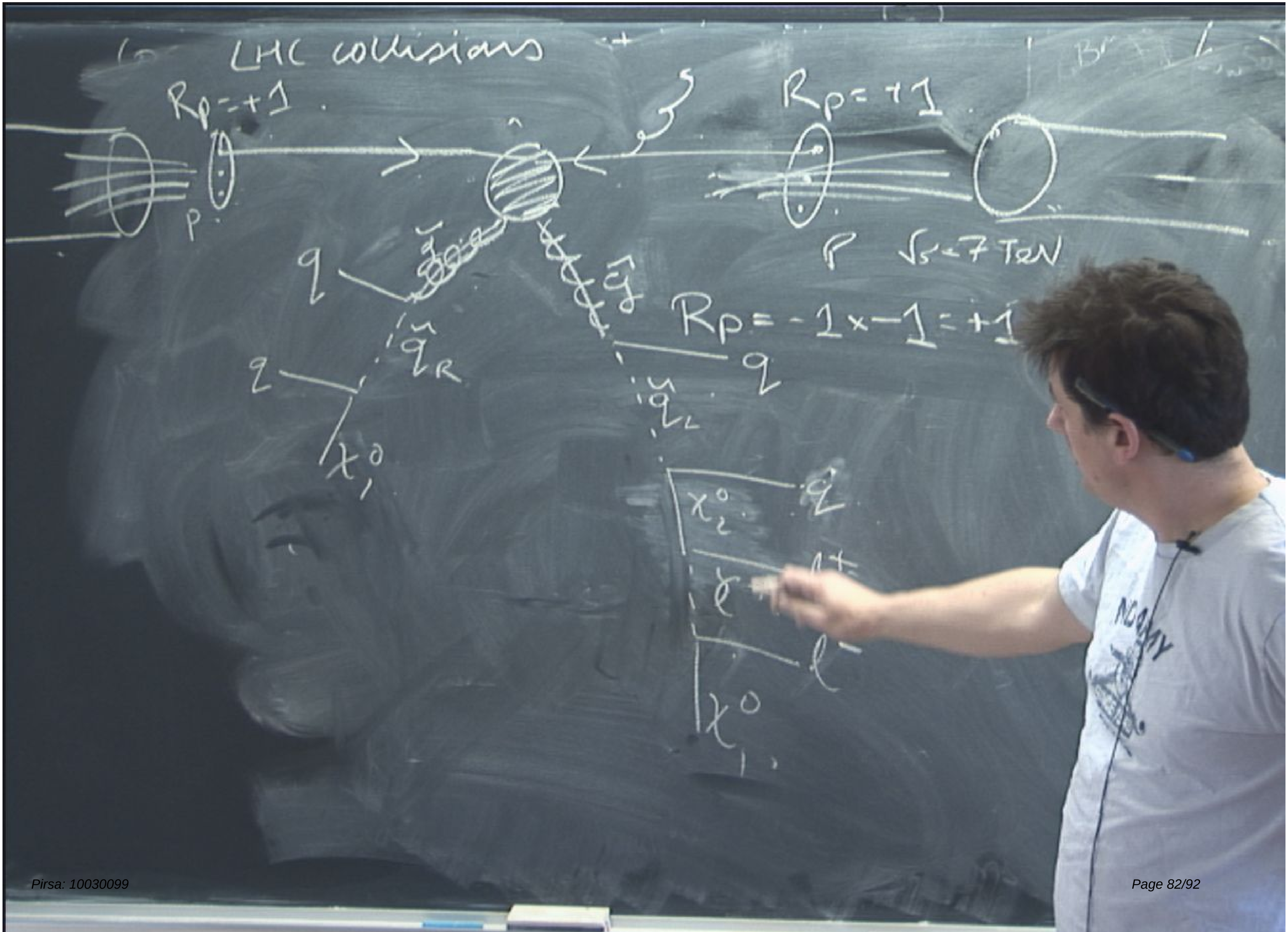

LHC collisions
Rp = +1
p
Rp = +1
p √s = 7 TeV
g̃
g̃
Rp = -1 × -1 = +1

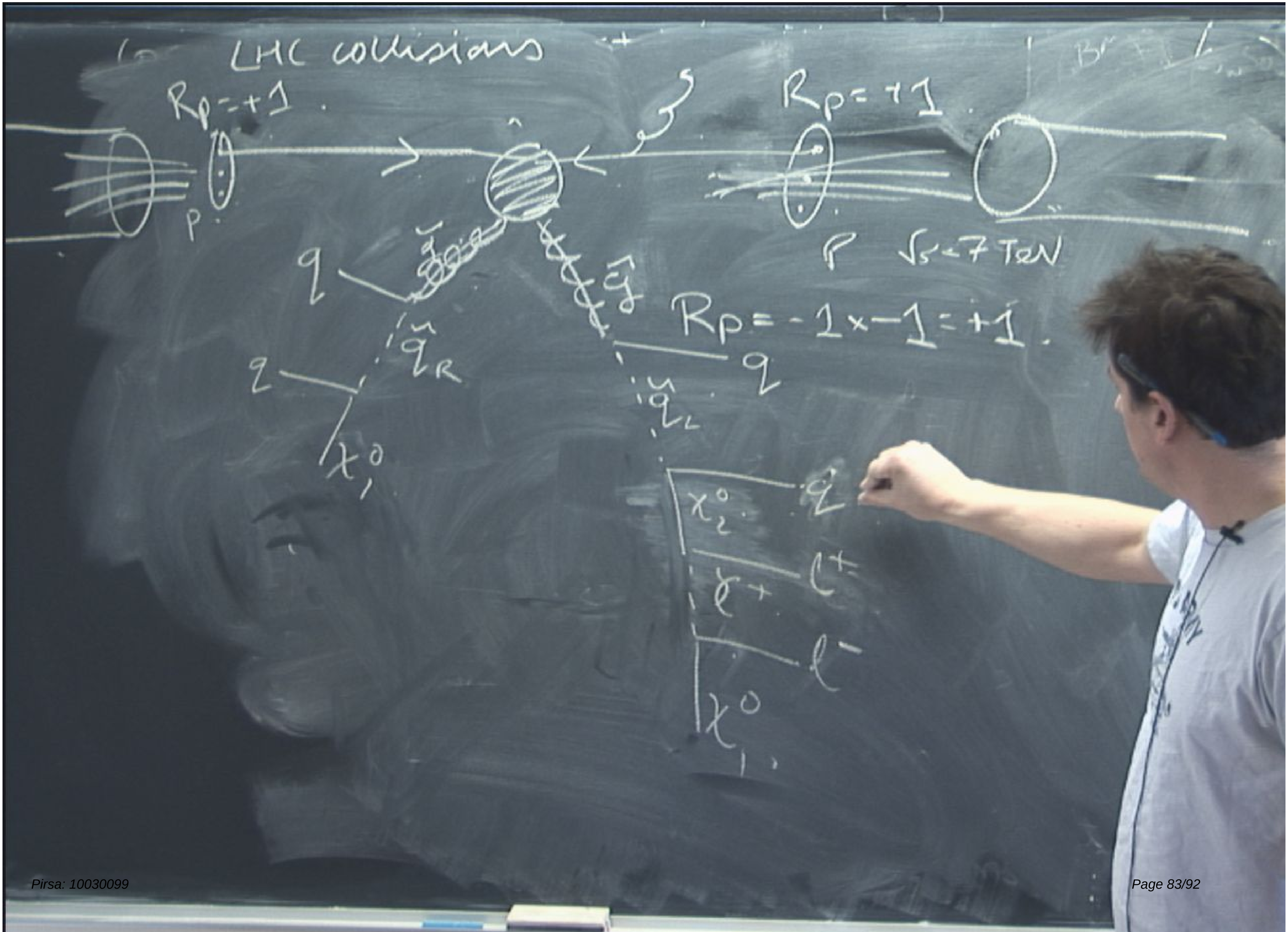

LHC collisions
Rp = +1
p
Rp = +1
p
√s = 7 TeV
g̃
g̃
Rp = -1 × -1 = +1


LHC collisions
$R_p = +1$.
p
$R_p = +1$.
p $\sqrt{s} = 7$ TeV
$\tilde{g}$
$\tilde{g}$
$R_p = -1 \times -1 = +1$.


LHC collisions
Rp = +1
Rp = +1
p
√s = 7 TeV
q
g̃
q̃
Rp = -1 × -1 = +1
q
q̃L
χ02
q
χ+
l+
l-
χ01


LHC collisions
$R_p = +1$
p
$R_p = +1$
p
$\sqrt{s} = 7$ TeV
q
$\tilde{g}$
$\tilde{q}_R$
q
χ^0_1
$\tilde{g}$
$R_p = -1 \times -1 = +1$
q
$\tilde{q}_L$
χ^0_2
q
$\tilde{\ell}^+$
ℓ^+
ℓ^-
χ^0_1


LHC collisions
Rp = +1
Rp = +1
p
p
√s = 7 TeV
Rp = -1 × -1 = +1
q
q
q
q
q̃R
q̃L
χ₁⁰
χ₂⁰
ℓ+
ℓ̃
ℓ-
χ₁⁰


LHC collisions
Rp = +1
Rp = +1
p
p
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Rp = -1 × -1 = +1
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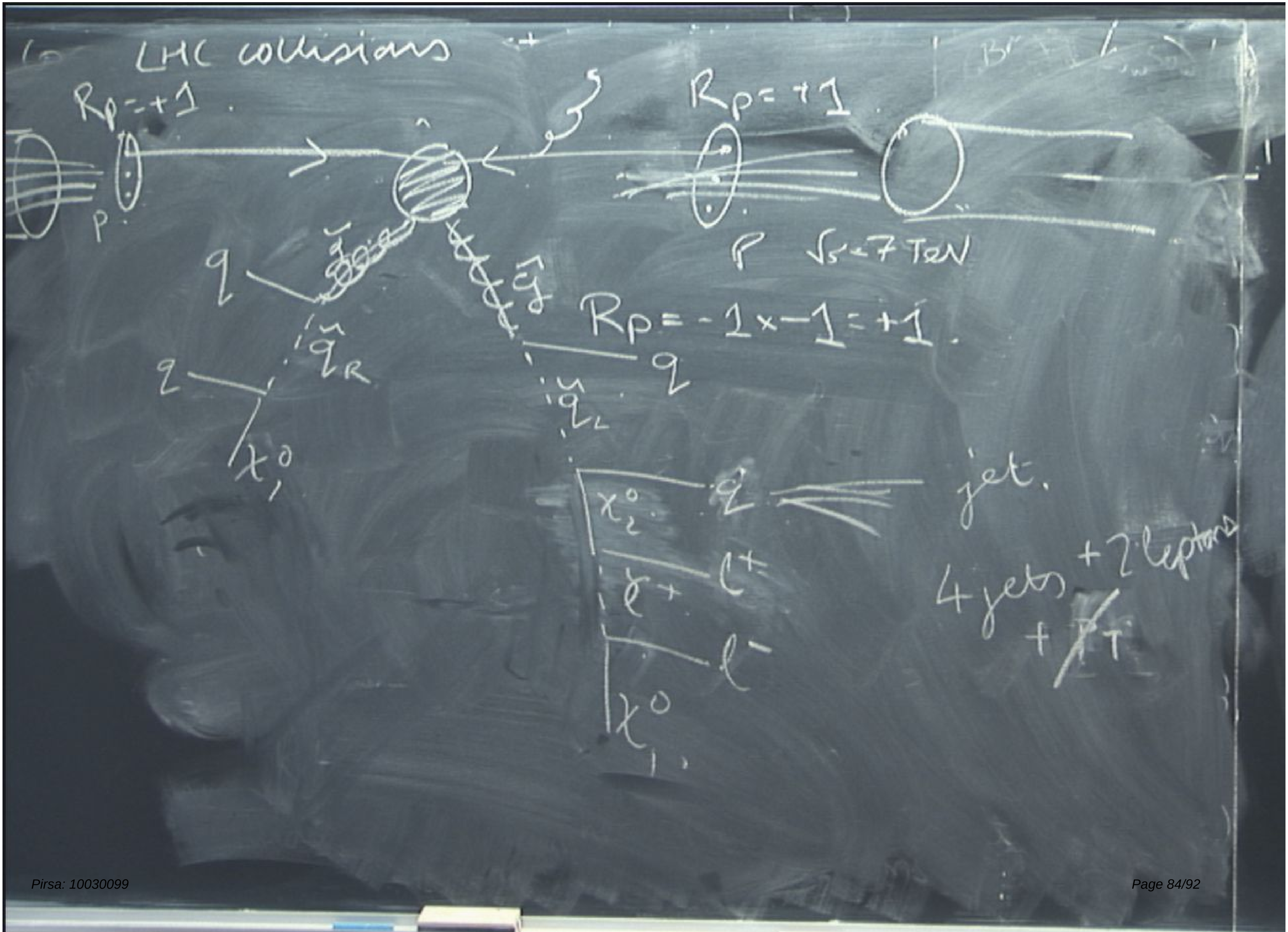
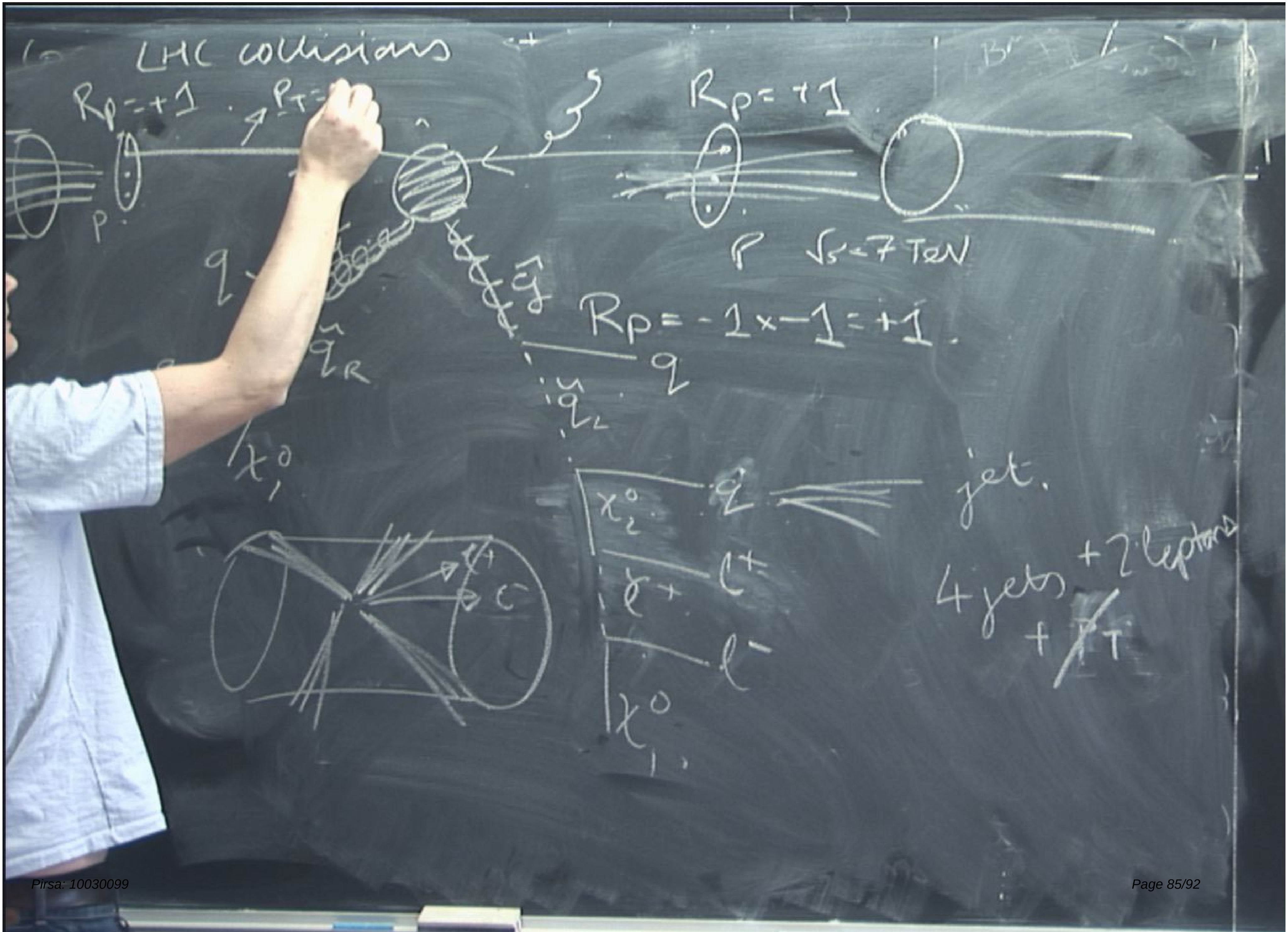
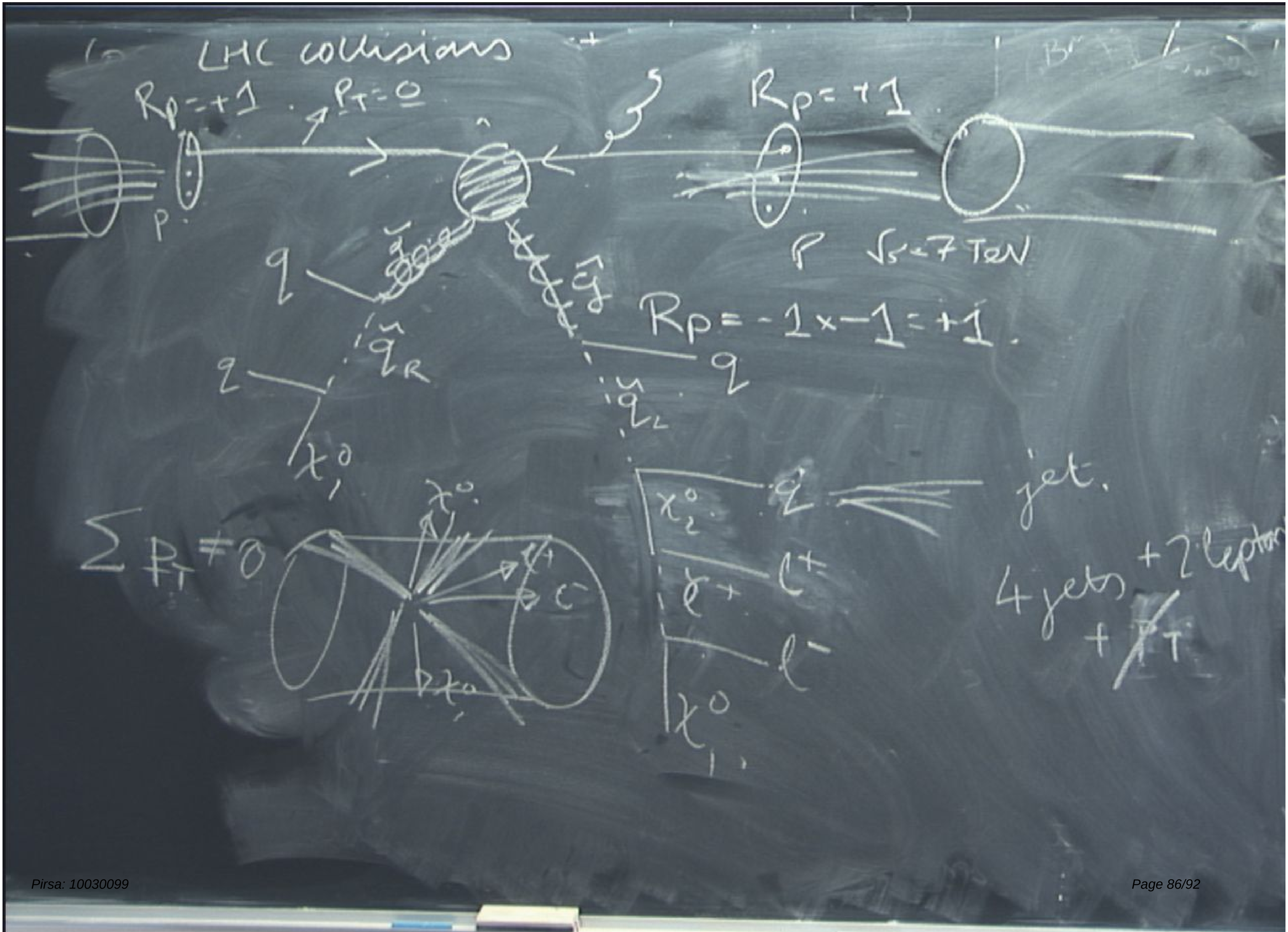
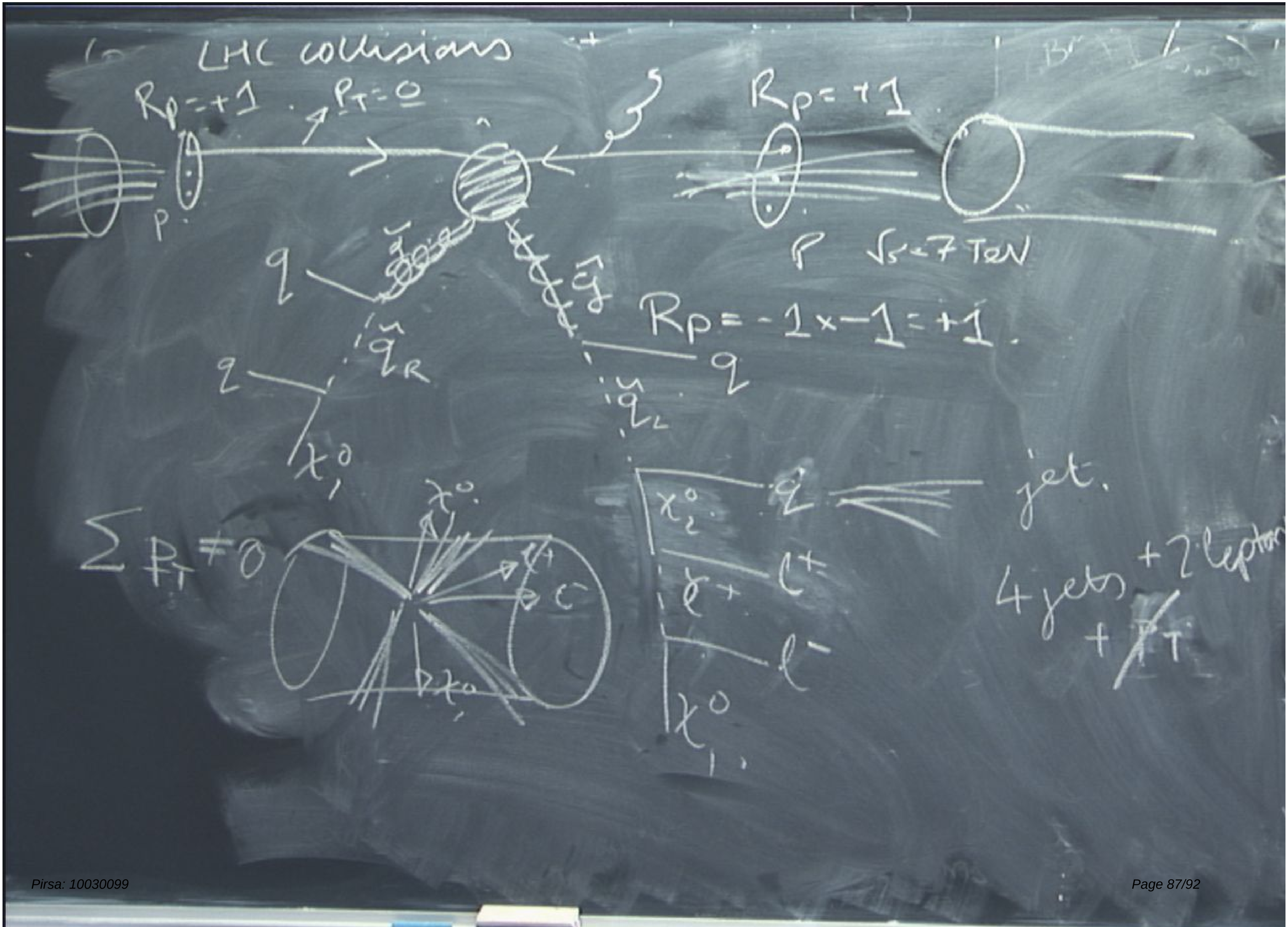
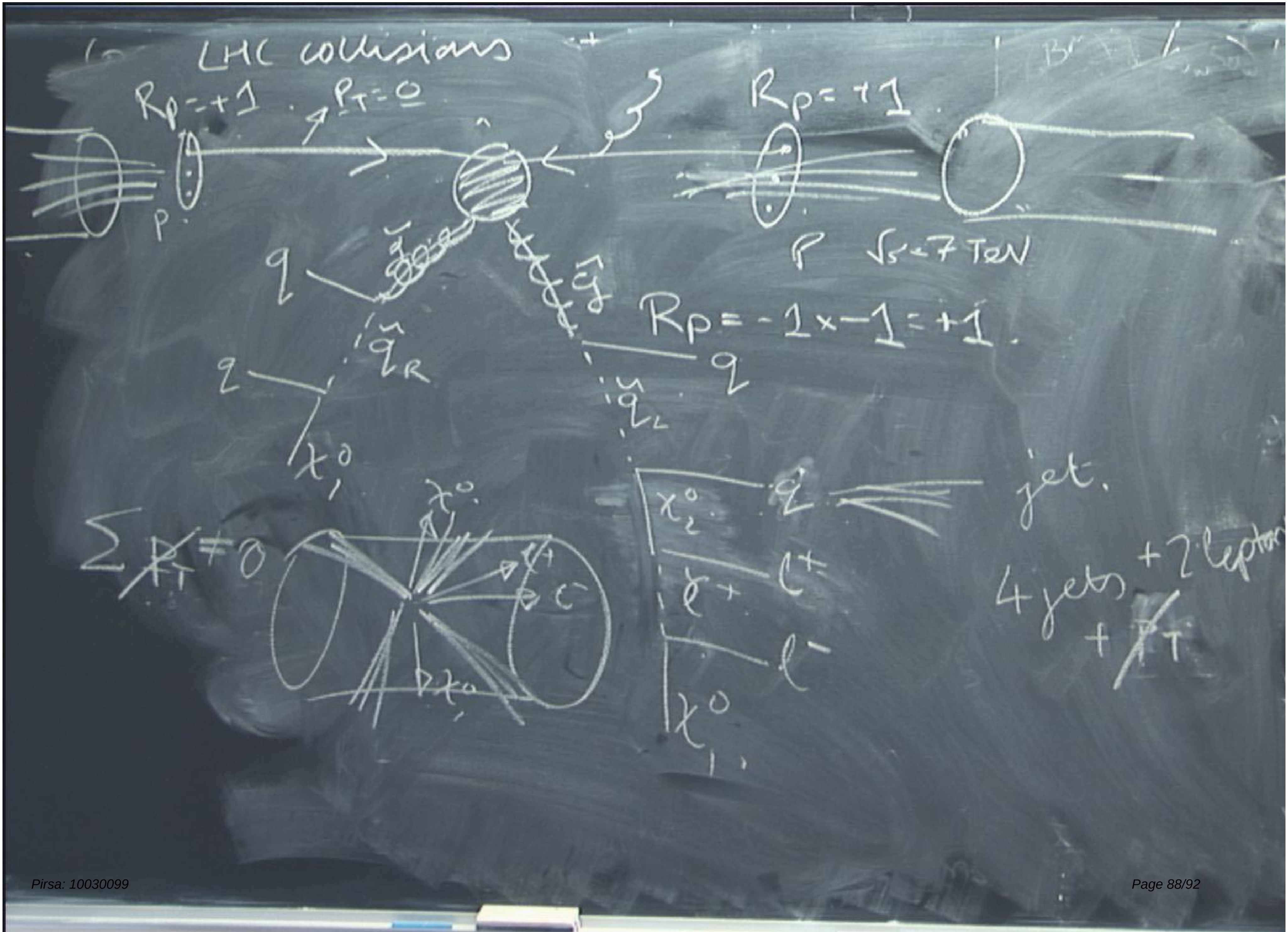
q
q
q
q̃R
q̃L
χ₁⁰
χ₂⁰
l⁺
l⁻
l̃⁺
χ₁⁰

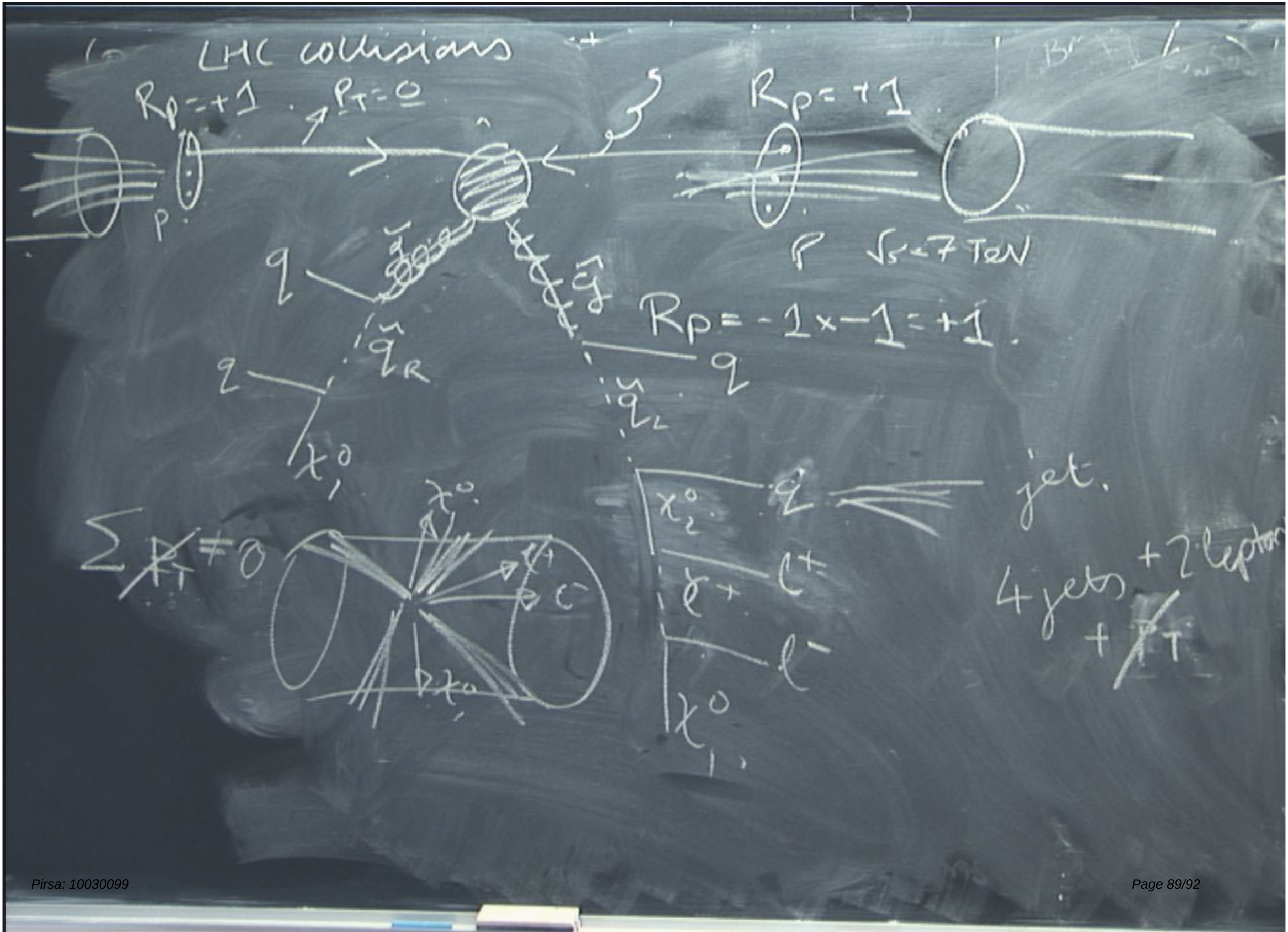

LHC collisions
Rp = +1
Rp = +1
p
p
√s = 7 TeV
q
g̃
q̃R
q
χ1 0
q̃
Rp = -1 × -1 = +1
q
q̃L
χ2 0
q
jet.
l+
l̃+
l-
χ1 0
4 jets + 2 leptons
+ E̸T


LHC collisions
Rp = +1
pT =
p
q
q̃R
χ1⁰
Rp = +1
p
√s = 7 TeV
g̃
Rp = -1 × -1 = +1
q
q̃L
χ2⁰
q
jet.
ℓ+
ℓ+
ℓ-
χ1⁰
ℓ+
ℓ-
4 jets + 2 leptons
+ E̸T


LHC collisions
$R_p = +1$
$p_T = 0$
p
$R_p = +1$
p
$\sqrt{s} = 7$ TeV
q
$\tilde{g}$
$\tilde{g}$
$R_p = -1 \times -1 = +1$
q
$\tilde{q}_R$
q
$\tilde{q}_L$
χ^0_1
χ^0
$\Sigma p_T \neq 0$
l^+
l^-
χ^0
χ^0_2
q
jet.
l^+
l^+
l^-
χ^0_1
4 jets + 2 lepto
+ $\not{p}_T$


LHC collisions
$R_p = +1$
$P_T = 0$
$R_p = +1$
p
p
$\sqrt{s} = 7$ TeV
q
$\tilde{g}$
$\tilde{g}$
$R_p = -1 \times -1 = +1$
q
$\tilde{q}_R$
q
$\tilde{q}_L$
χ^0_1
χ^0_2
q
jet.
$\Sigma p_T \neq 0$
χ^0
ℓ^+
ℓ^-
ℓ^+
ℓ^+
ℓ^-
χ^0_1
χ^0_1
4 jets + 2 leptons
+ $\not{p}_T$


LHC collisions
Rp = +1
PT = 0
p
Rp = +1
p
√s = 7 TeV
Rp = -1 × -1 = +1
q
q
q
jet.
4 jets + 2 leptons
+ PT
Σ PT ≠ 0


LHC collisions
Rp = +1
PT = 0
Rp = +1
p
p √s = 7 TeV
Rp = -1 × -1 = +1
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4 jets + 2 lepton
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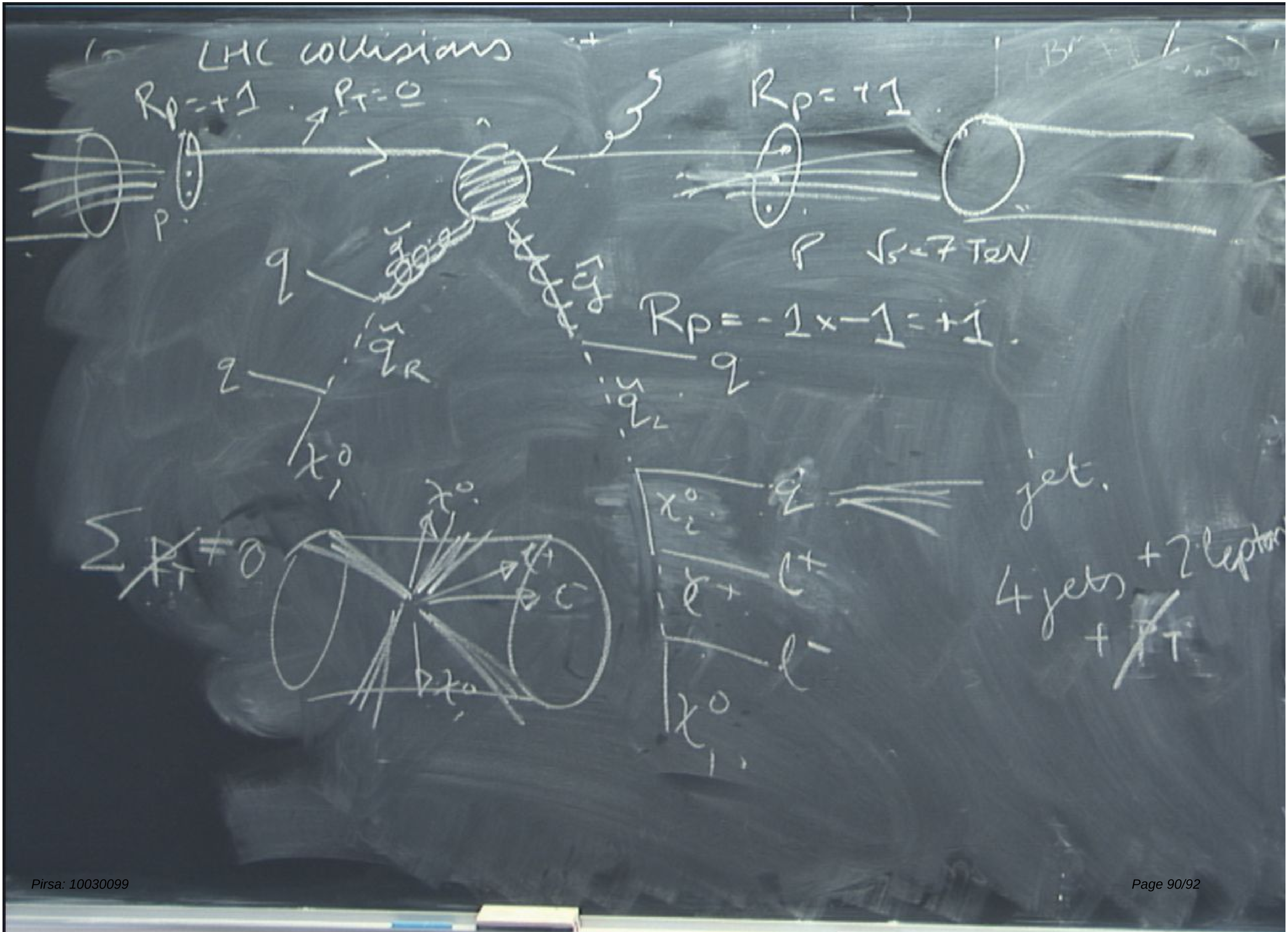
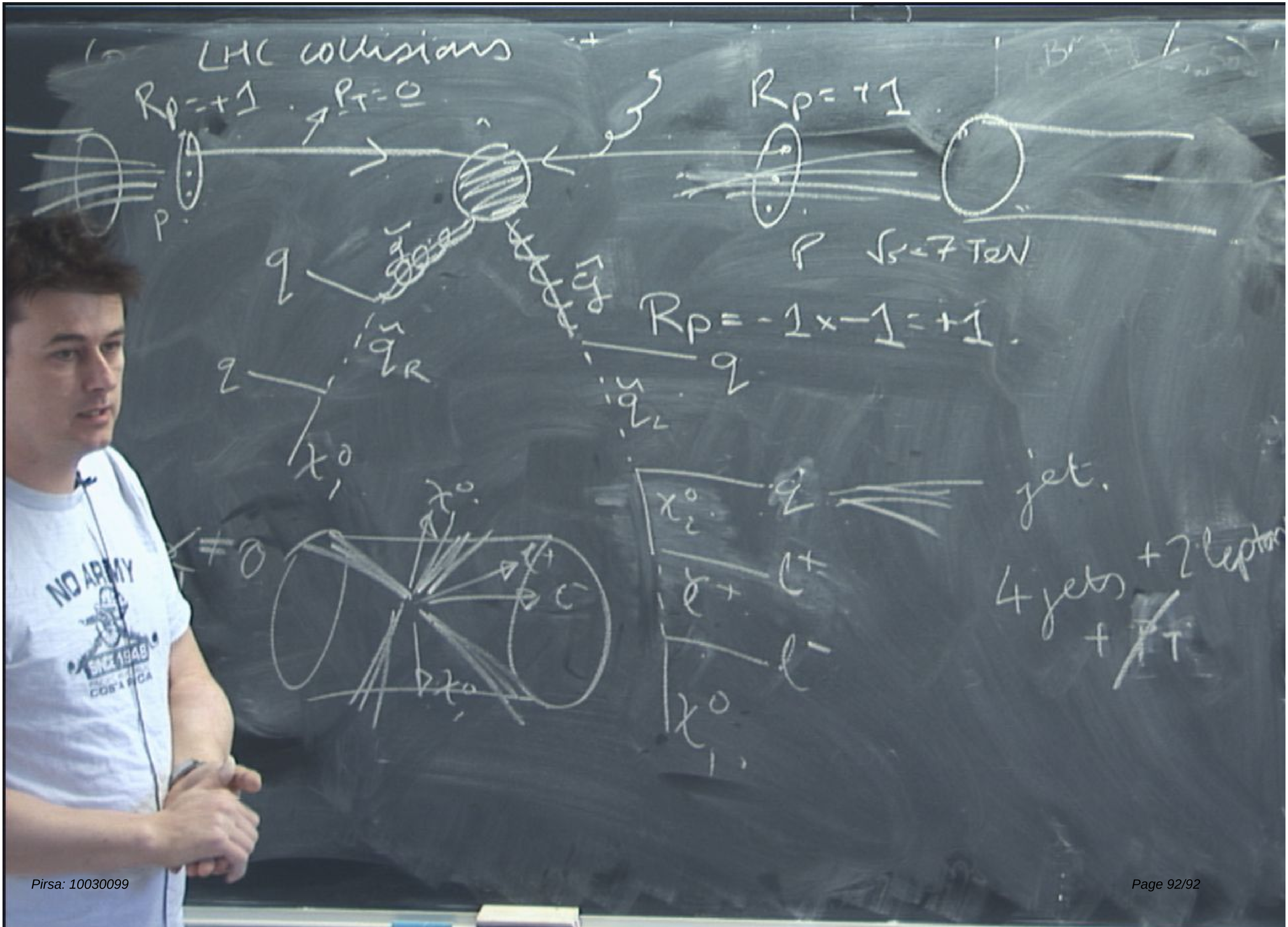
ΣPT ≠ 0


LHC collisions
Rp = +1
pT = 0
p
Rp = +1
p √s = 7 TeV
q
q̃R
q
χ⁰1
g̃
g̃
Rp = -1×-1 = +1
q
q̃L
jet
χ⁰2
q
ℓ+
ℓ+
ℓ-
χ⁰1
ΣpT = 0
χ⁰
ℓ+
ℓ-
χ⁰
4 jets + 2 lepton
+ pT


LHC collisions
Rp = +1
PT = 0
Rp = +1
p
q
q
χ1⁰
χ⁰
l⁺
l⁻
χ1⁰
+2 leptons



LHC collisions
Rp = +1
PT = 0
Rp = +1
p
p
√s = 7 TeV
q
q̃R
q
χ1⁰
g̃
Rp = -1 × -1 = +1
q
q̃L
χ2⁰
q
jet
l+
l+
l-
χ1⁰
4 jets + 2 leptons
+ PT