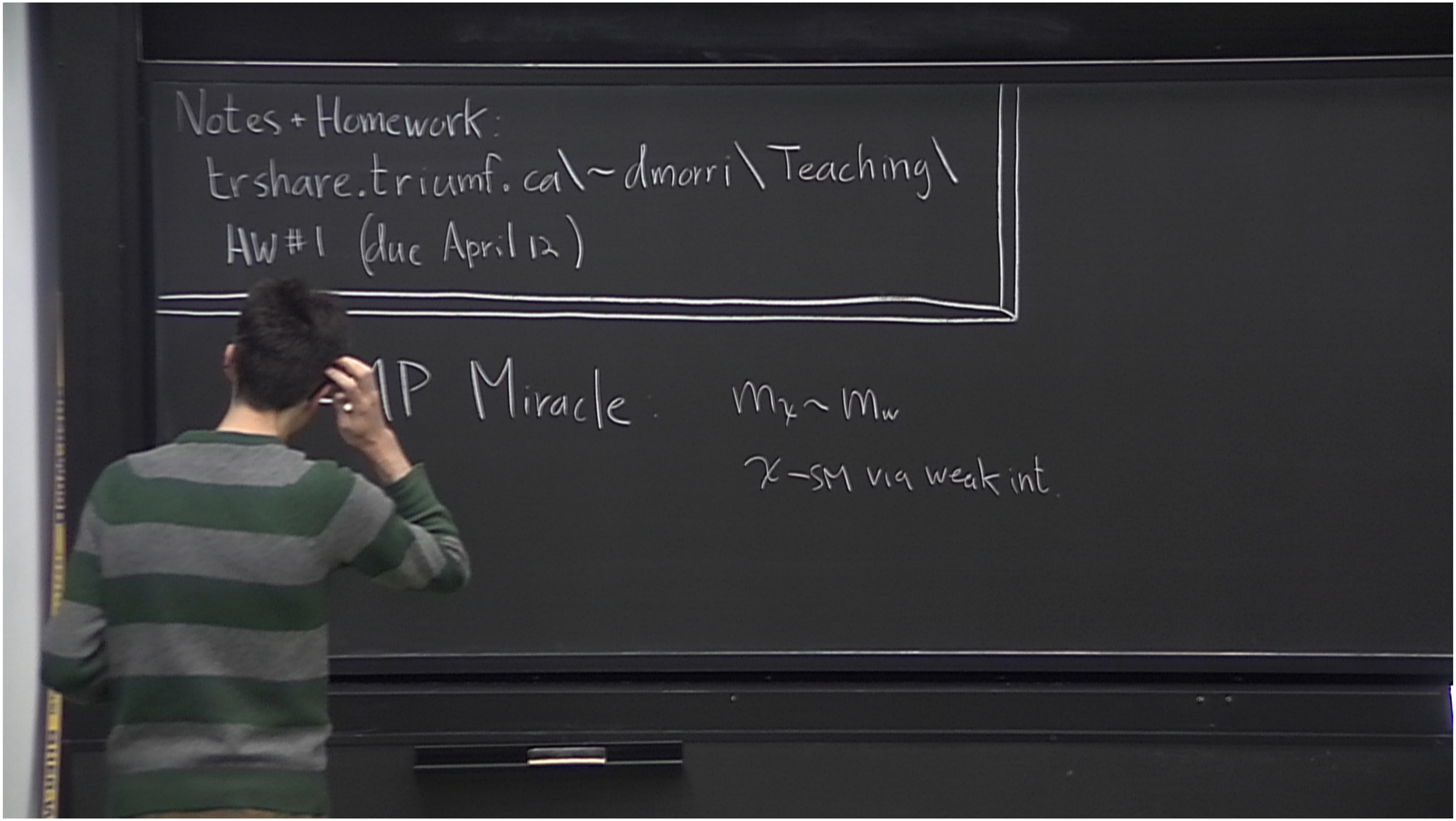
Title: Explorations in Particle Theory - Lecture 5

Date: Apr 09, 2012 09:00 AM

URL: http://pirsa.org/12040007

Abstract:


Notes + Homework:
trshare.triumf.ca\~dmorri\Teaching\
HW #1 (due April 12)
IP Miracle:
$m_\chi \sim m_W$
χ – SM via weak int.

Notes + Homework:
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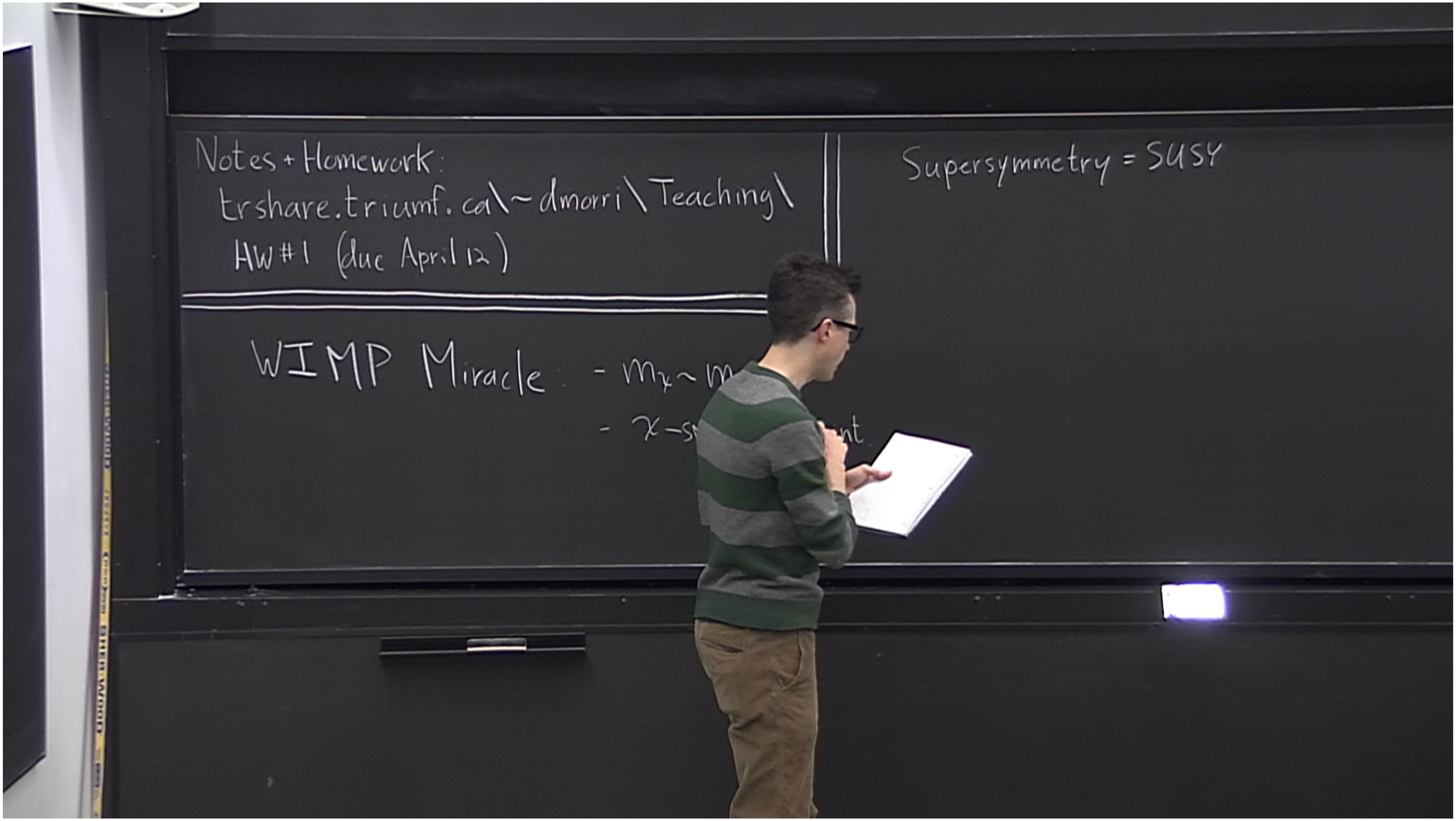
HW#1 (due April 12)

WIMP Miracle: - $m_\chi \sim m_W$

- χ–SM via weak int.



Notes + Homework:
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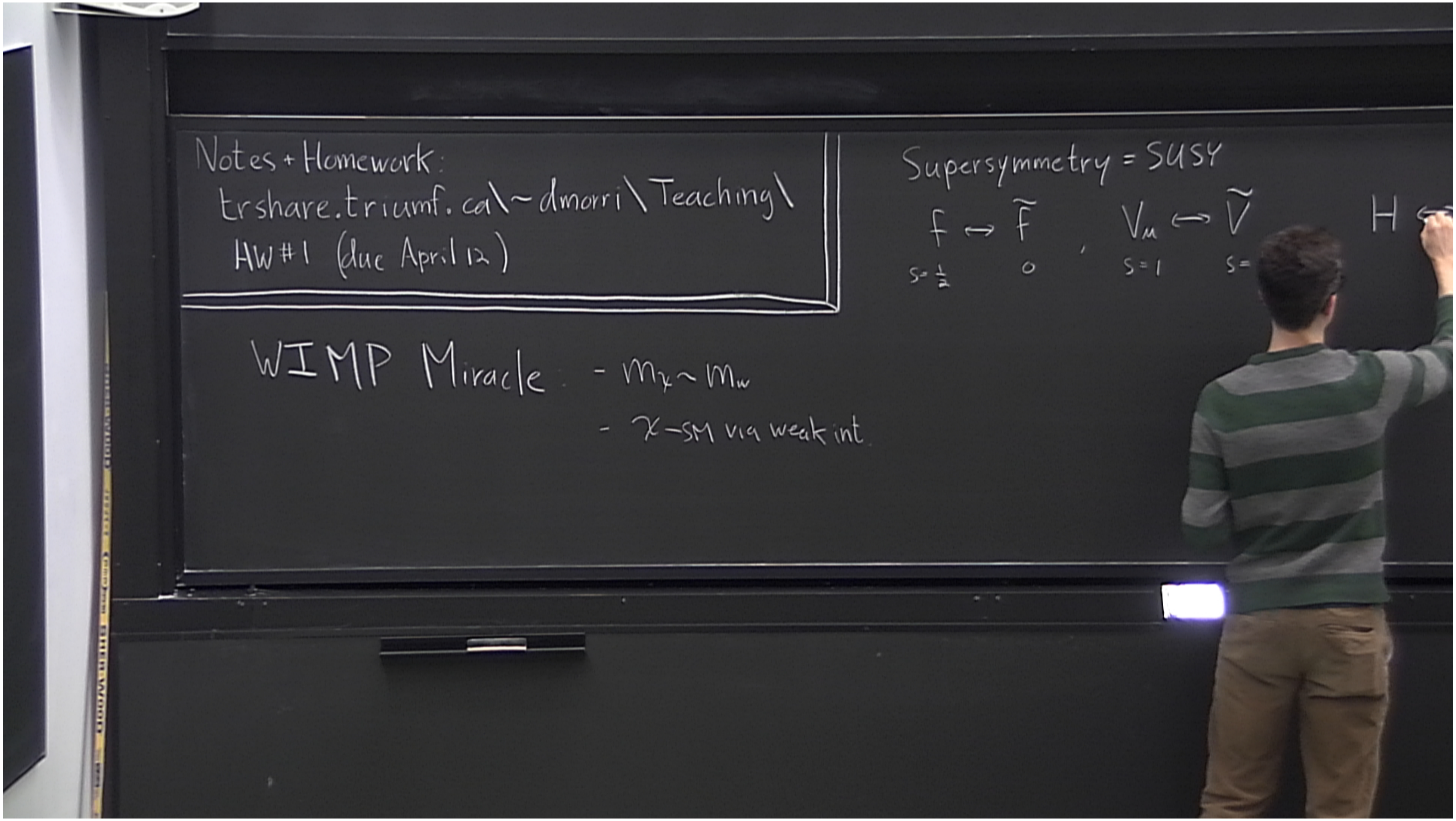
HW#1 (due April 12)
WIMP Miracle
Supersymmetry = SUSY


Notes + Homework:
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HW#1 (due April 12)
Supersymmetry = SUSY
$f \leftrightarrow \tilde{f}$, $V_\mu \leftrightarrow \tilde{V}$ H
$s=\frac{1}{2}$ 0 s=1 s=
WIMP Miracle: - $m_\chi \sim m_w$
- χ–SM via weak int.

Supersymmetry = SUSY

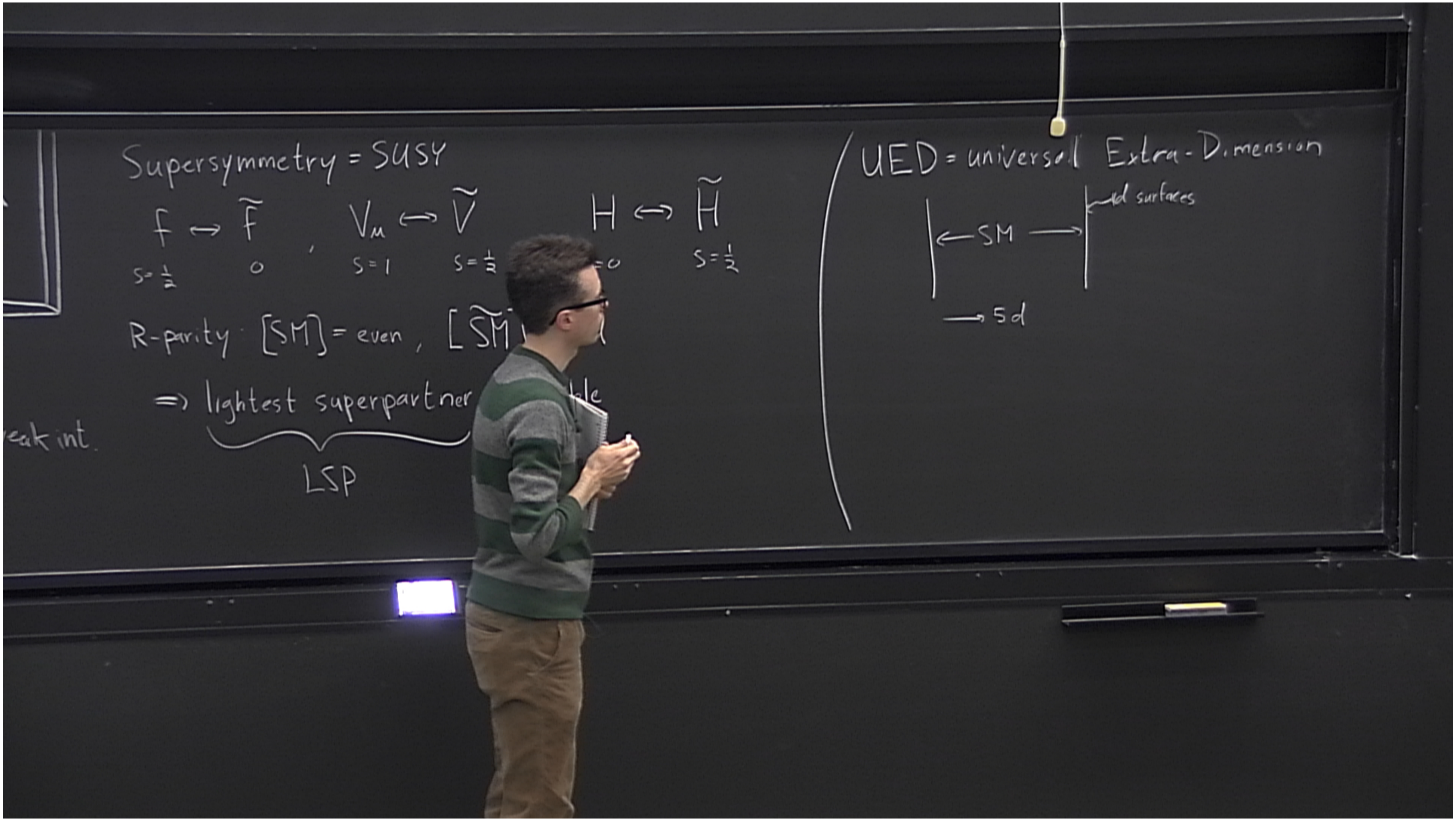
$$f \leftrightarrow \tilde{f} \quad , \quad V_\mu \leftrightarrow \tilde{V} \quad , \quad H \leftrightarrow \tilde{H}$$

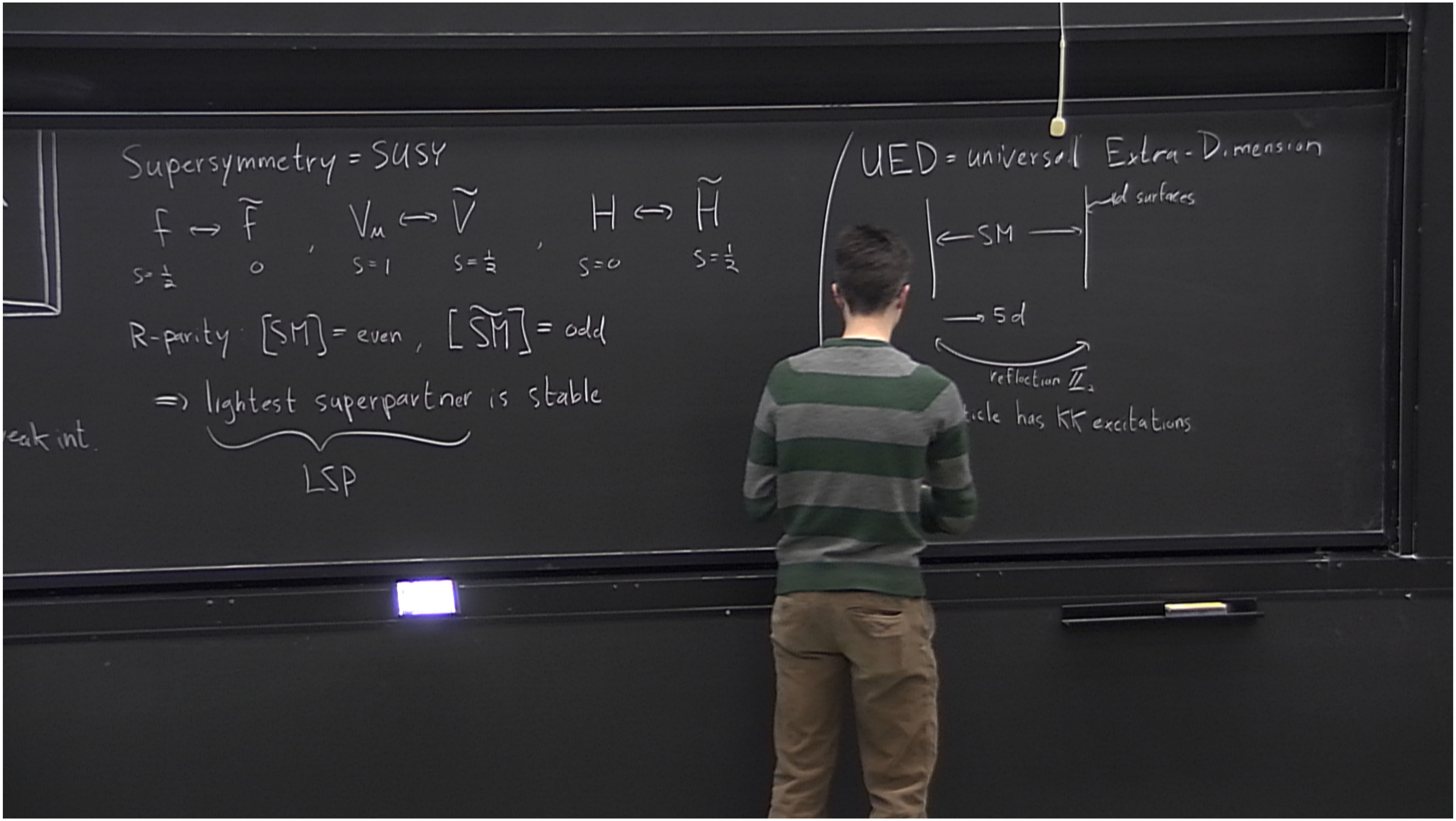
$$s=\tfrac{1}{2} \quad 0 \quad\quad s=1 \quad s=\tfrac{1}{2} \quad\quad s=0 \quad s=\tfrac{1}{2}$$

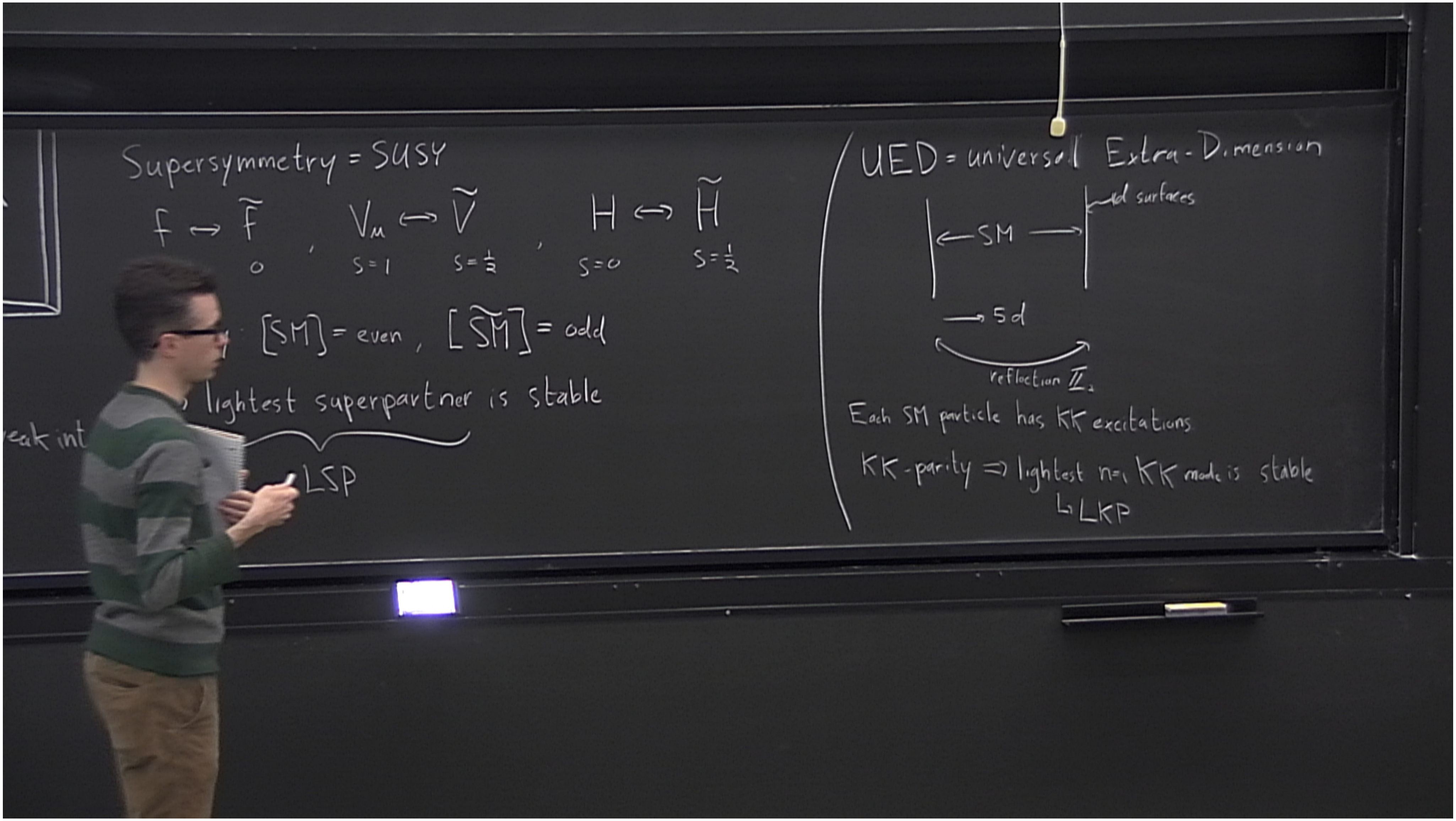
R-parity: $[SM] = \text{even}$, $[\widetilde{SM}] = \text{odd}$

$\Rightarrow$ lightest superpartner is stable

int.


Supersymmetry = SUSY
f ↔ F̃ , V_μ ↔ Ṽ
H ↔ H̃
s = 1/2
0
s = 1
s = 1/2
s = 1/2
R-parity [SM] = even , [S̃M]
⇒ lightest superpartner
LSP
eak int.
UED = universal Extra-Dimension
surfaces
SM
5d


Supersymmetry = SUSY
f ↔ F̃ , V_μ ↔ Ṽ , H ↔ H̃
s = 1/2 0 s = 1 s = 1/2 s = 0 s = 1/2
R-parity: [SM] = even , [S̃M] = odd
⇒ lightest superpartner is stable
LSP
eak int.
UED = universal Extra-Dimension
SM
5d
surfaces
reflection Z₂
has KK excitations


Supersymmetry = SUSY
f ⟷ f̃ , V_μ ⟷ Ṽ , H ⟷ H̃
0
s=1 s=½ s=0 s=½
[SM] = even , [S̃M] = odd
lightest superpartner is stable
LSP
eak int
UED = universal Extra-Dimension
d surfaces
SM
5d
reflection Z₂
Each SM particle has KK excitations
KK-parity ⟹ lightest n=1 KK mode is stable
LKP

eak int.

Supersymmetry = SUSY

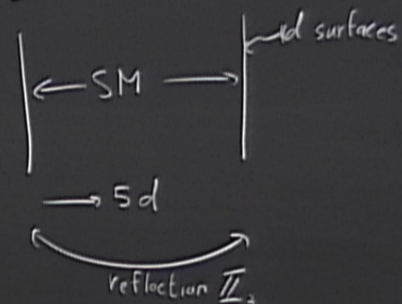
$$f \leftrightarrow \tilde{F}\ ,\quad V_\mu \leftrightarrow \tilde{V}\ ,\quad H \leftrightarrow \tilde{H}$$

$s=\frac{1}{2}$ $\quad$ 0 $\quad$ $s=1$ $\quad$ $s=\frac{1}{2}$ $\quad$ $s=0$ $\quad$ $s=\frac{1}{2}$

R-parity: $[SM] = \text{even}\ ,\ [\widetilde{SM}] = \text{odd}$

$\Rightarrow \underbrace{\text{lightest superpartner}}_{\text{LSP}}$ is stable

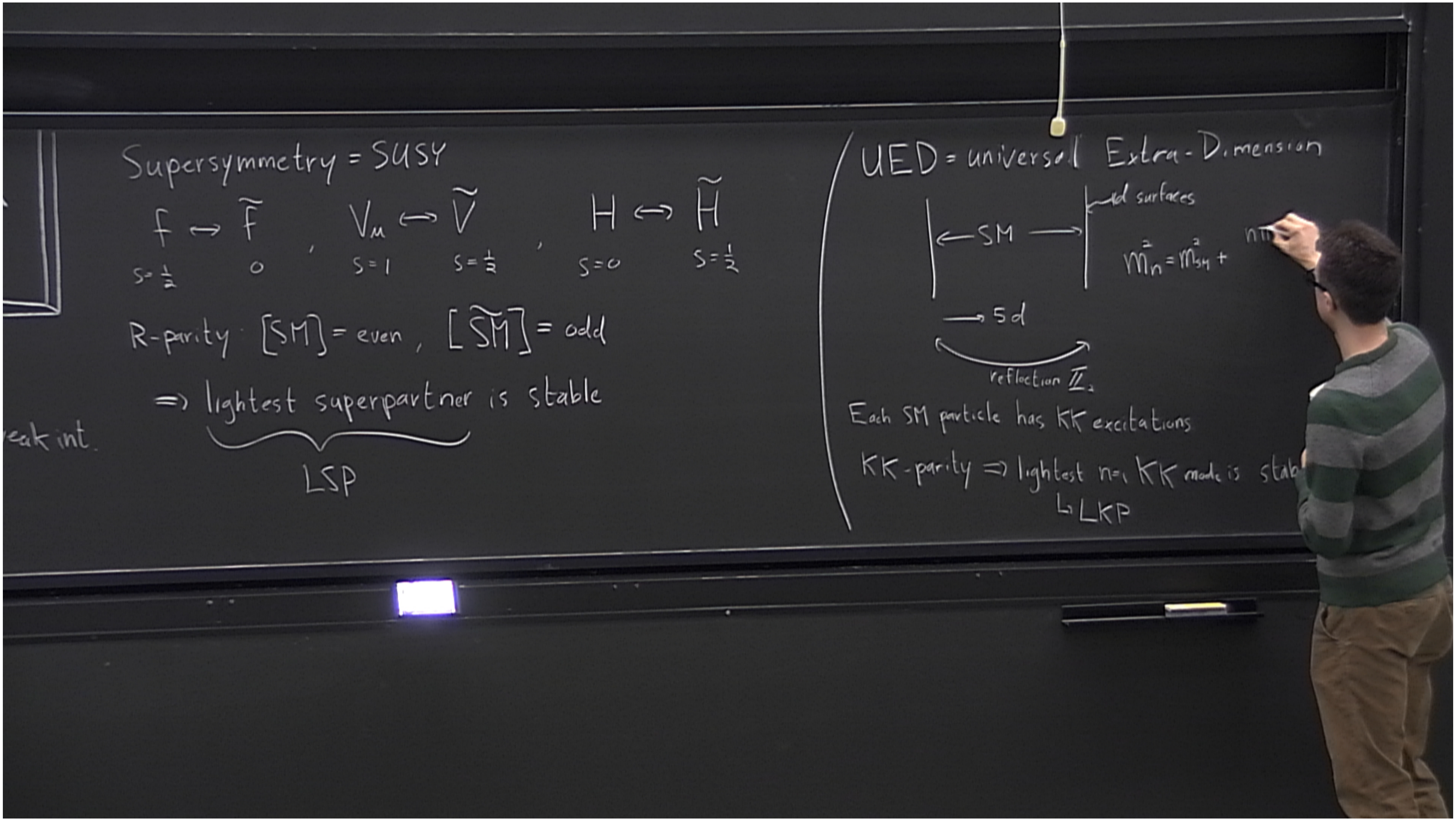
UED = universal Extra-Dimension



Each SM particle has KK excitations

KK-parity $\Rightarrow$ lightest $n=1$ KK mode is stable

↳ LKP


Supersymmetry = SUSY
f ↔ F̃ , V_μ ↔ Ṽ , H ↔ H̃
s = 1/2 0 s = 1 s = 1/2 s = 0 s = 1/2
R-parity: [SM] = even , [S̃M] = odd
⇒ lightest superpartner is stable
LSP
eak int.
UED = universal Extra-Dimension
SM
d surfaces
m_n^2 = m_SM^2 +
5d
reflection Z_2
Each SM particle has KK excitations
KK-parity ⇒ lightest n=1 KK mode is stab
LKP

eak int.

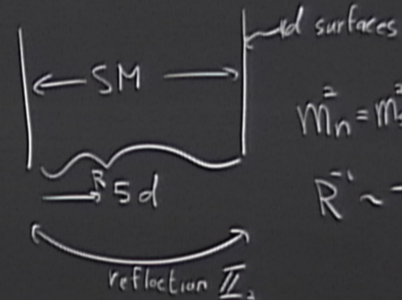
Supersymmetry = SUSY

$$\underset{s=\frac{1}{2}}{f} \leftrightarrow \underset{0}{\tilde{f}}\ , \quad \underset{s=1}{V_\mu} \leftrightarrow \underset{s=\frac{1}{2}}{\tilde{V}}\ , \quad \underset{s=0}{H} \leftrightarrow \underset{s=\frac{1}{2}}{\tilde{H}}$$

R-parity: $[SM] =$ even , $[\widetilde{SM}] =$ odd

$\Rightarrow$ $\underbrace{\text{lightest superpartner}}_{\text{LSP}}$ is stable

UED = universal Extra-Dimension



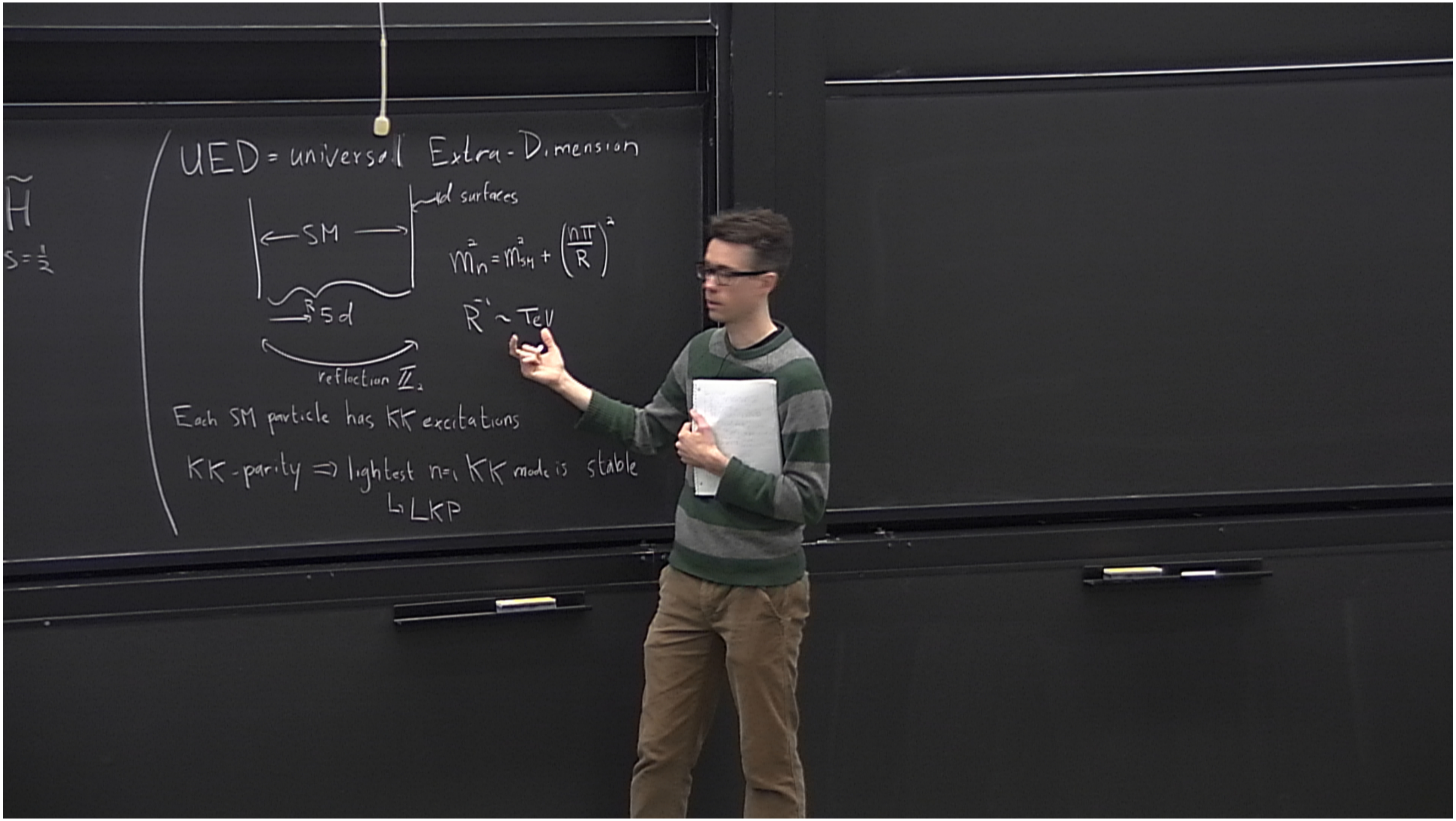
$$m_n^2 = m_{SM}^2 + \left(\frac{n\pi}{R}\right)^2$$

$R^{-1} \sim$ TeV

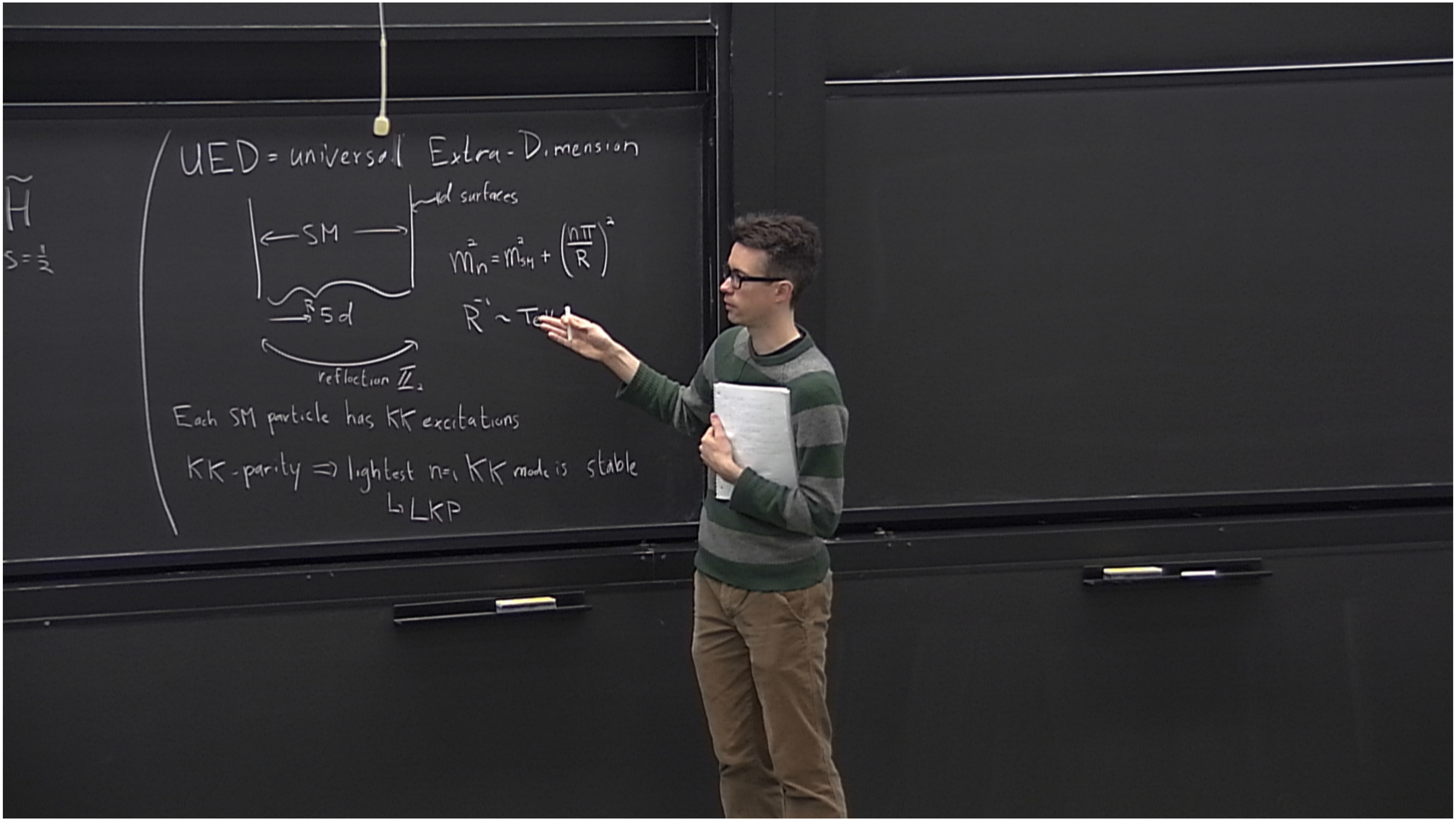
Each SM particle has KK excitations

KK-parity $\Rightarrow$ lightest $n=1$ KK mode is stable

↳ LKP



UED = universal Extra-Dimension
surfaces
SM
5d
reflection $\mathbb{Z}_2$
$m_n^2 = m_{SM}^2 + \left(\frac{n\pi}{R}\right)^2$
$R^{-1} \sim$ TeV
Each SM particle has KK excitations
KK-parity ⇒ lightest n=1 KK mode is stable
LKP
$\tilde{H}$
$s = \frac{1}{2}$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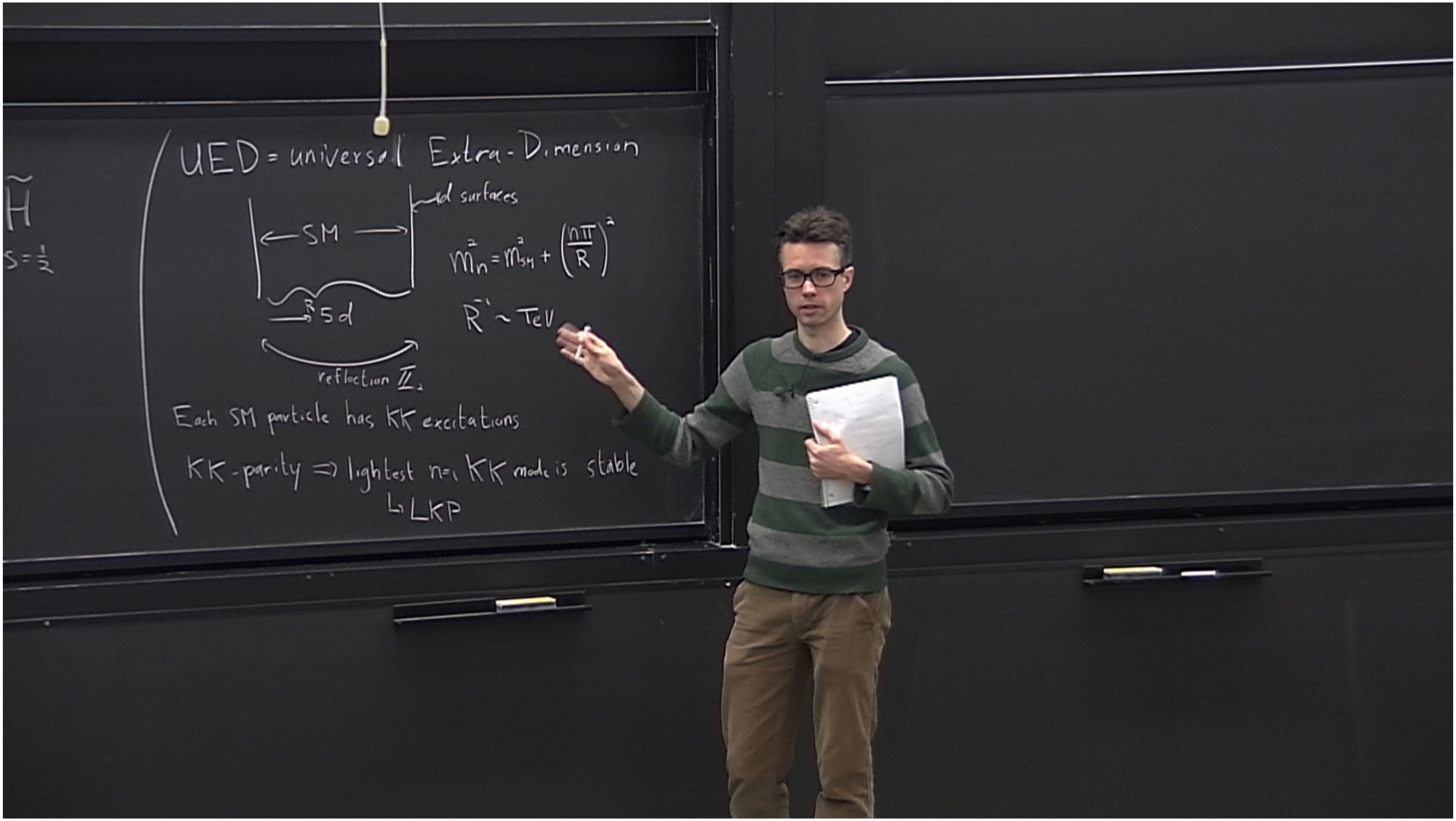
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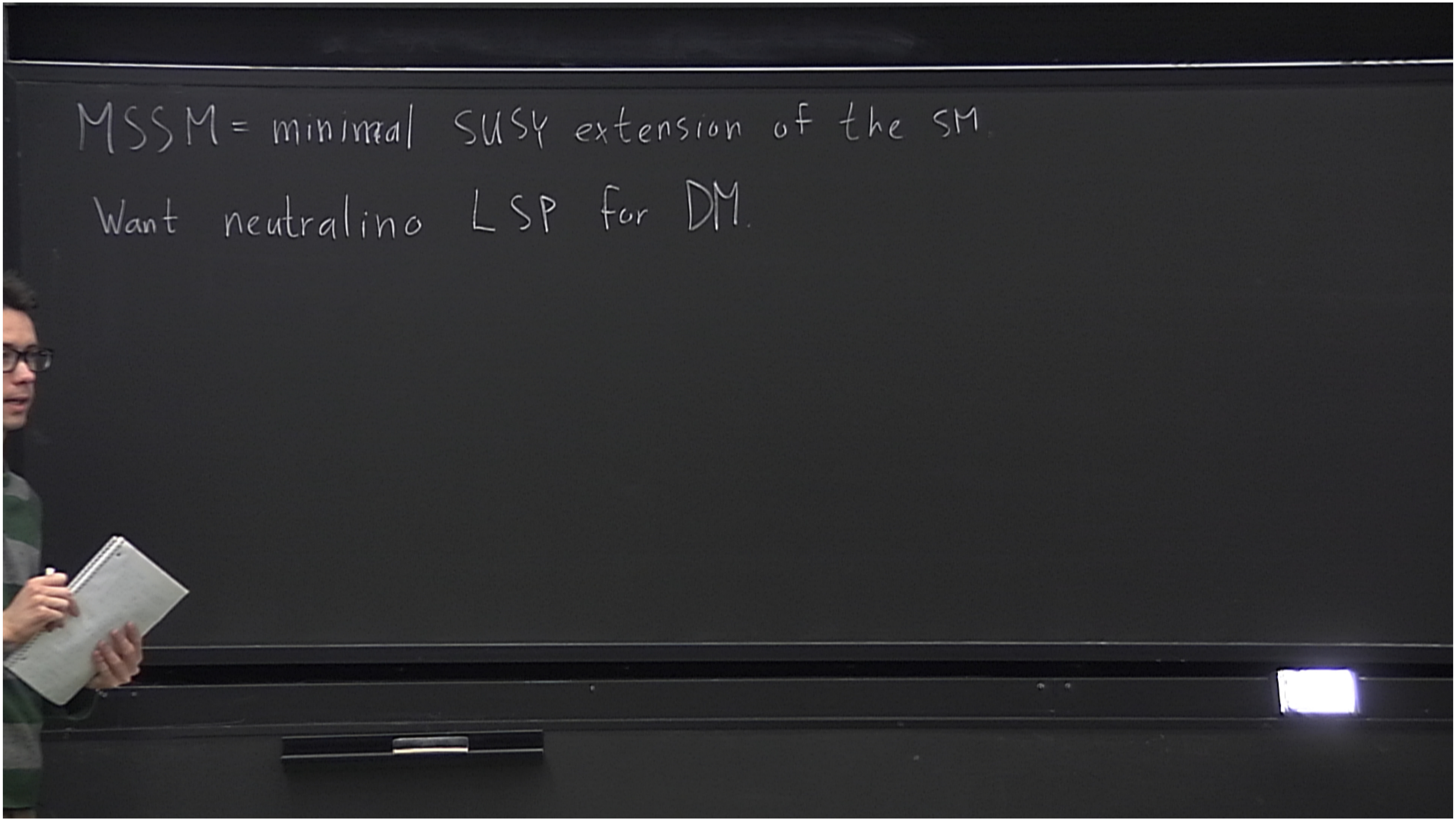
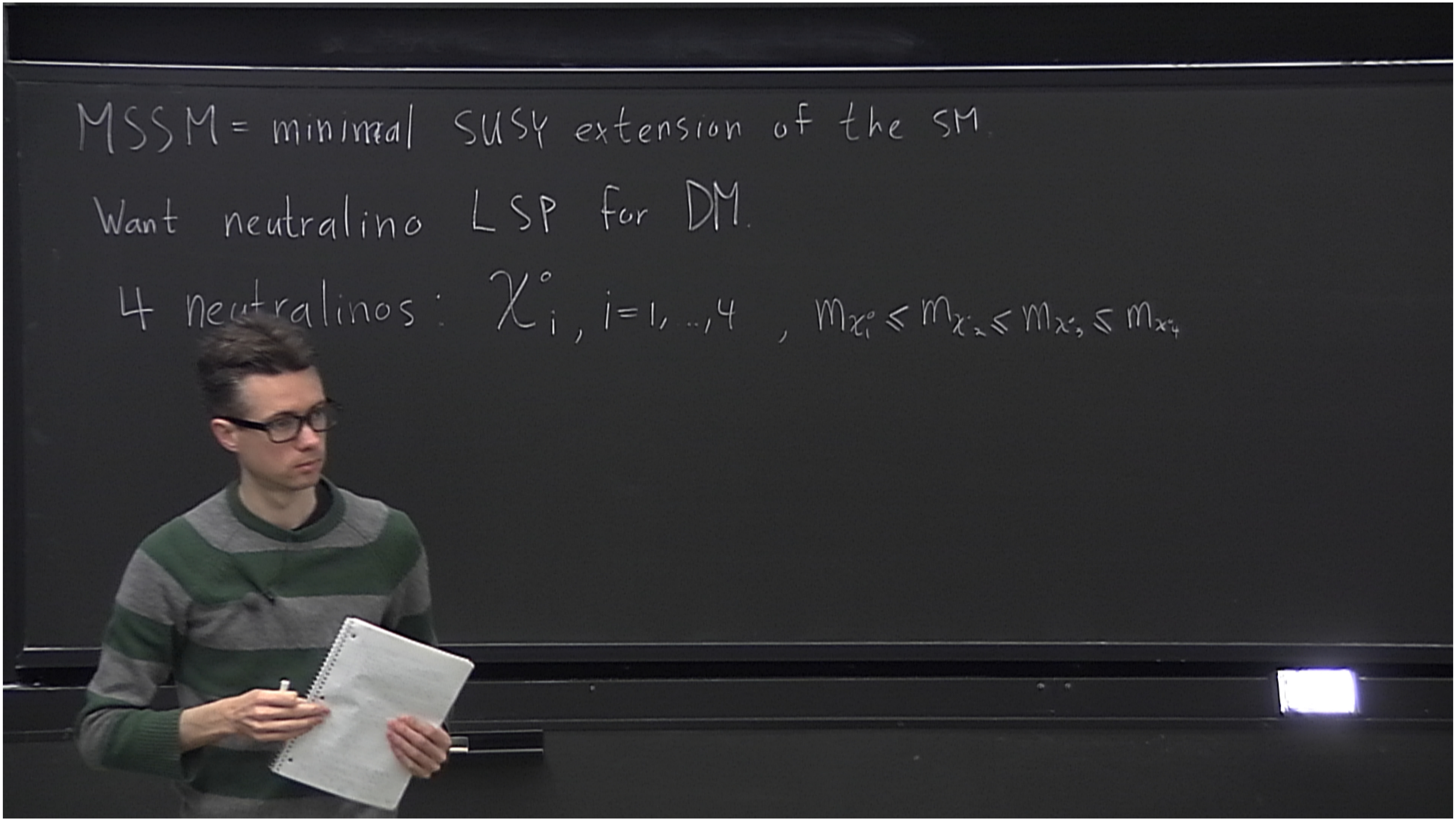
$s = \frac{1}{2}$


MSSM = minimal SUSY extension of the SM.
Want neutralino LSP for DM.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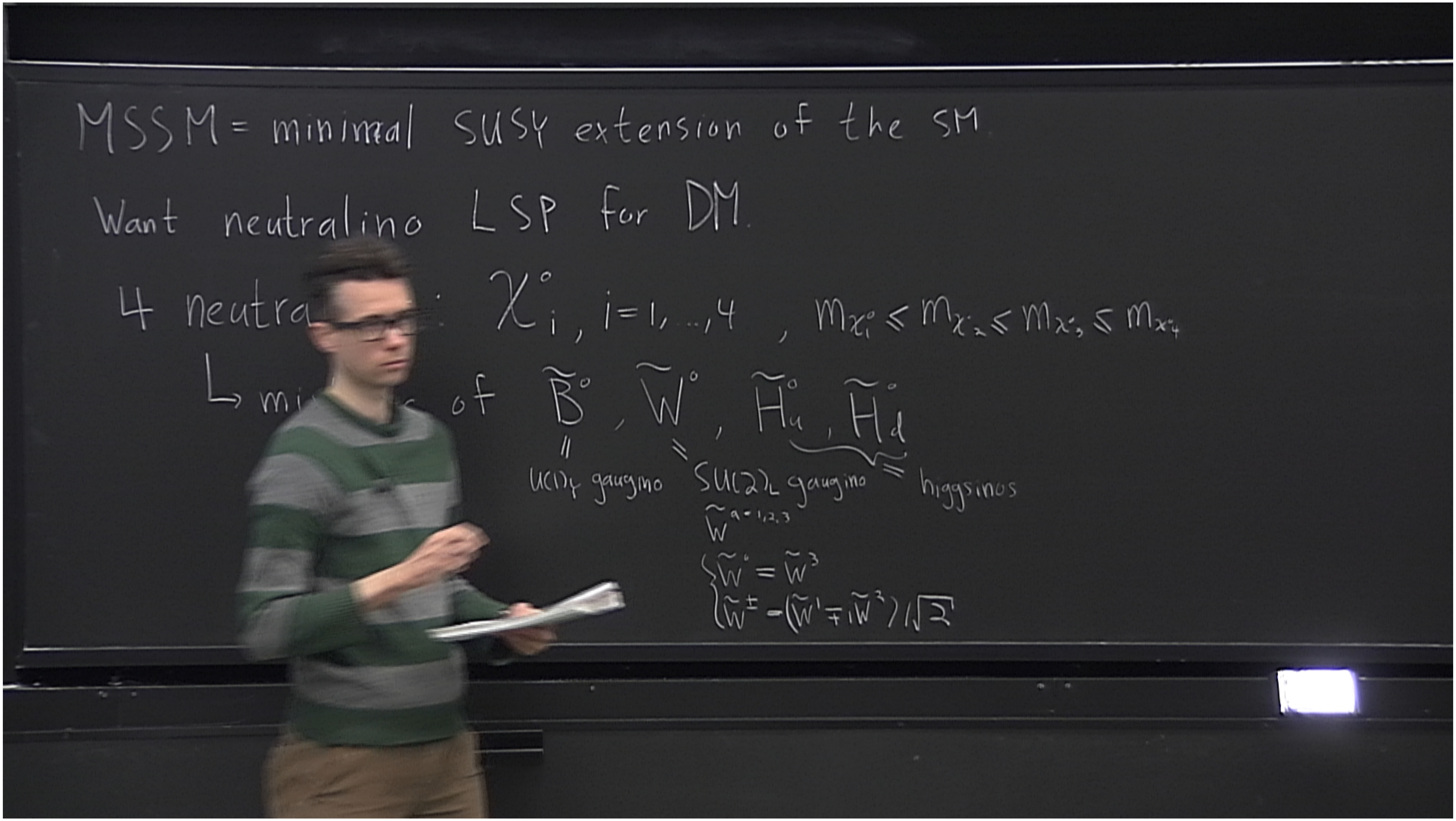
Want neutralino LSP for DM.
4 neutralinos: χ^0_i, $i=1,..,4$, $m_{\chi^0_1} \leqslant m_{\chi^0_2} \leqslant m_{\chi^0_3} \leqslant m_{\chi^0_4}$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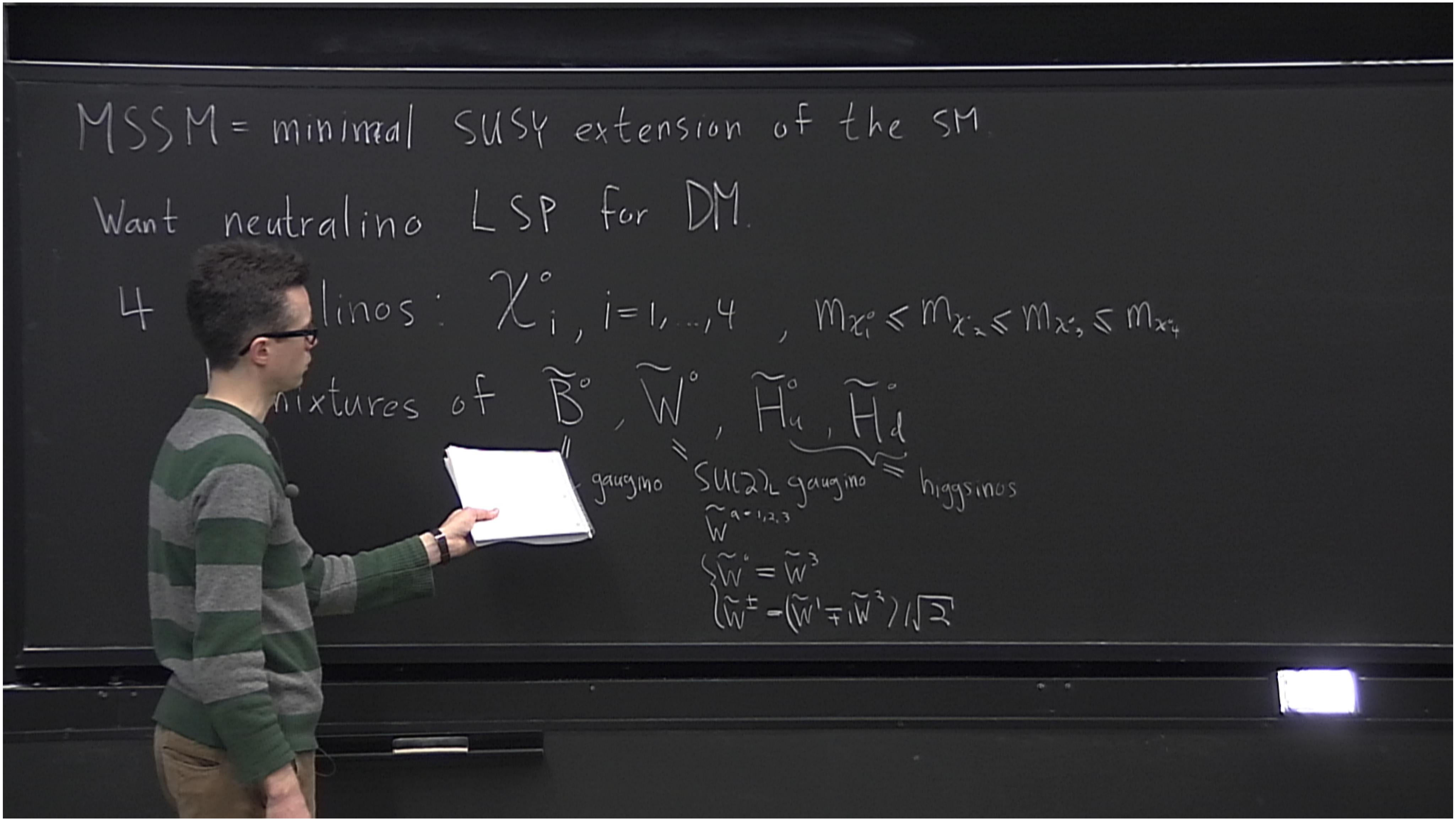
4 neutra
χ^0_i, $i = 1, \dots, 4$, $m_{\chi^0_1} \leq m_{\chi^0_2} \leq m_{\chi^0_3} \leq m_{\chi^0_4}$
of $\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_u$, $\tilde{H}^0_d$
$U(1)_Y$ gaugino
$SU(2)_L$ gaugino
higgsinos
$\tilde{W}^{a=1,2,3}$
$\tilde{W}^0 = \tilde{W}^3$
$\tilde{W}^\pm = (\tilde{W}^1 \mp i\tilde{W}^2)/\sqrt{2}$



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mixtures of $\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_u$, $\tilde{H}^0_d$
gaugino
$SU(2)_L$ gaugino
higgsinos
$\tilde{W}^{a=1,2,3}$
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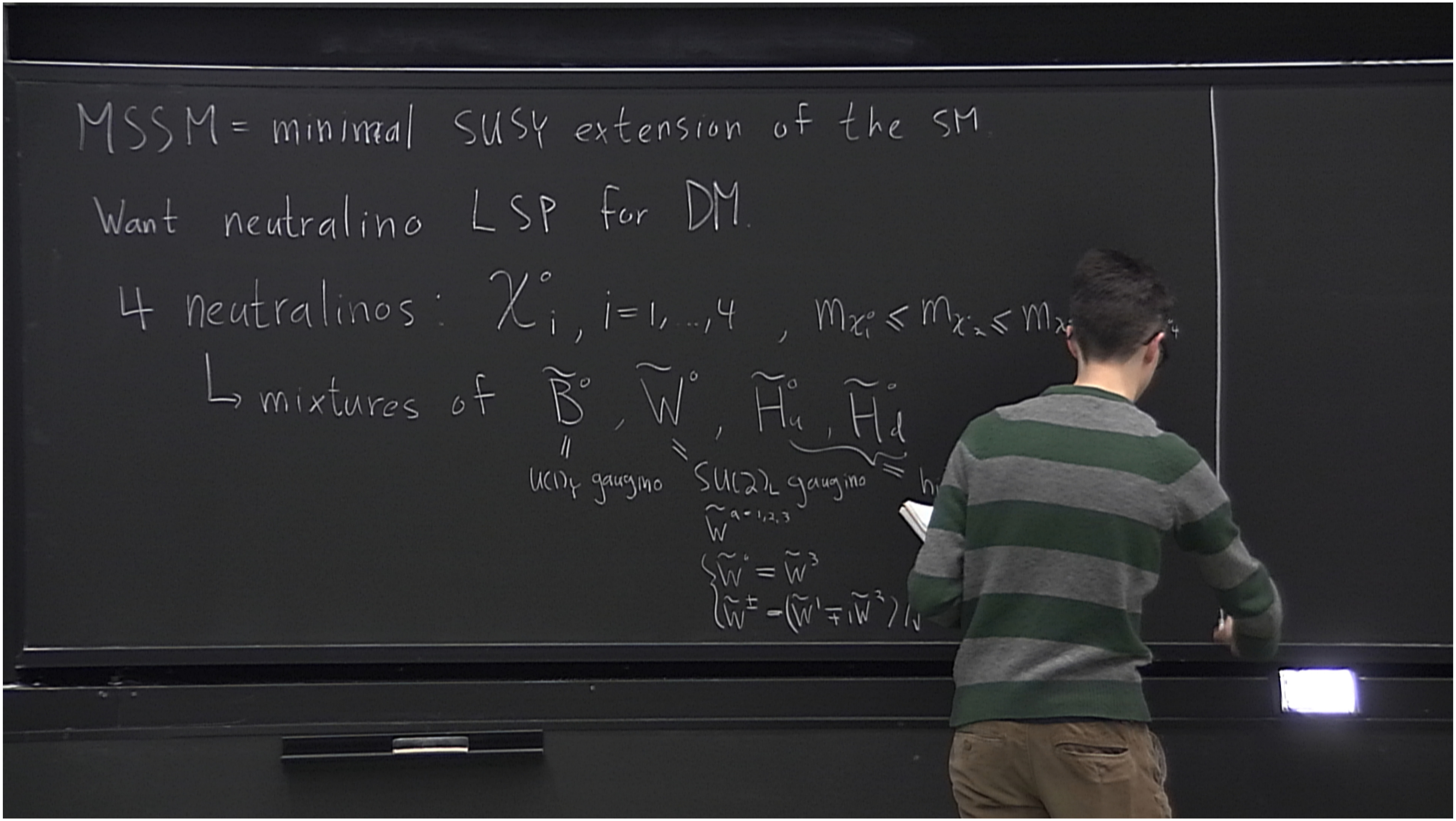
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4 neutralinos: χ^0_i, $i=1,\dots,4$, $m_{\chi^0_1} \leq m_{\chi^0_2} \leq m_{\chi}$
↳ mixtures of $\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_u$, $\tilde{H}^0_d$
$U(1)_Y$ gaugino
$SU(2)_L$ gaugino
$\tilde{W}^{a=1,2,3}$
$\tilde{W}^0 = \tilde{W}^3$
$\tilde{W}^\pm = (\tilde{W}^1 \mp i\tilde{W}^2)/$

χ^0_1 is LSP.

$$\chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

$$\sum_{i=1}^{4} |N_{1i}|^2 = 1$$

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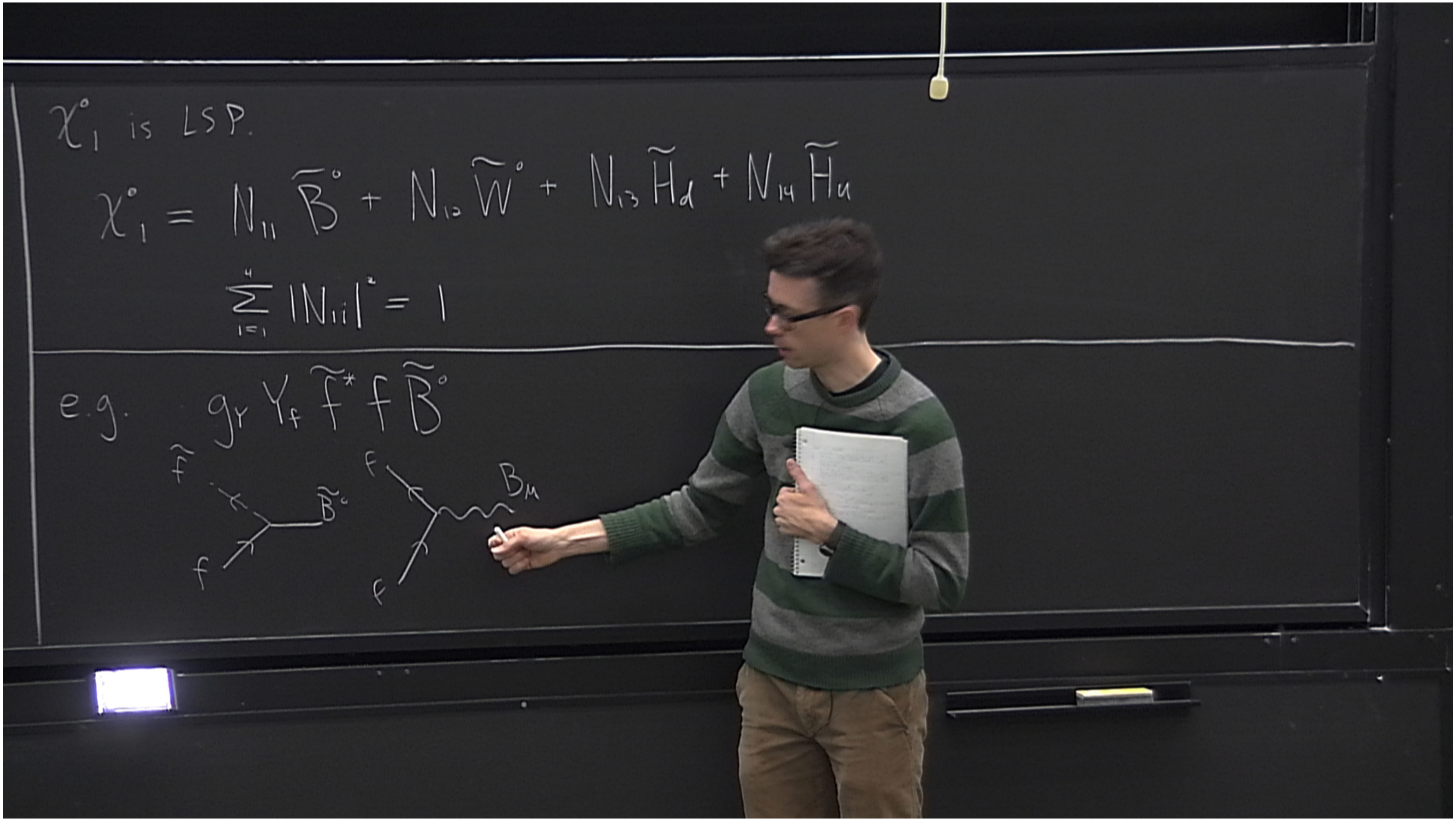
WIMP Miracle
LSP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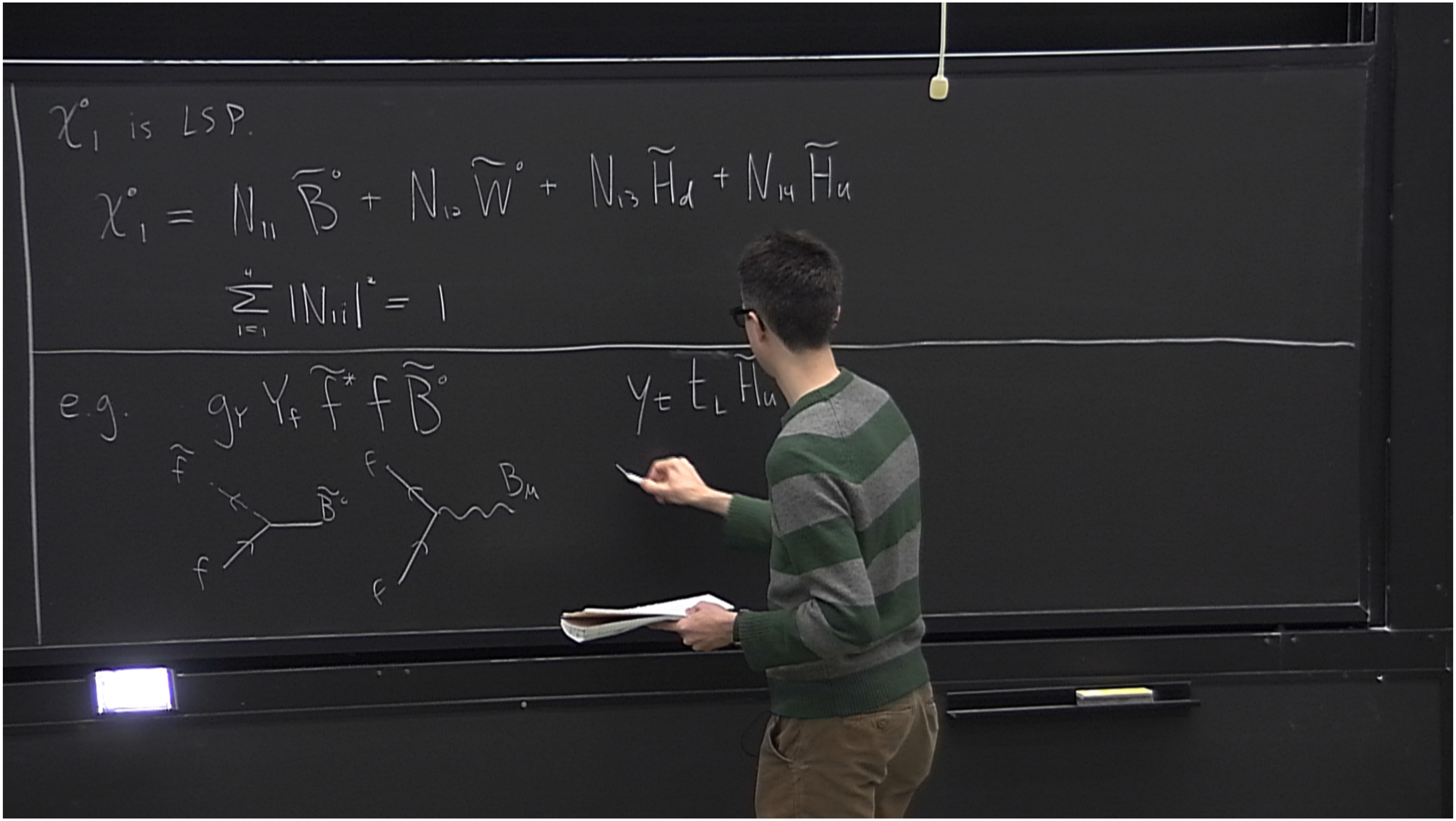
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$
$\tilde{f}$
$\tilde{B}^0$
f
f
B_μ
f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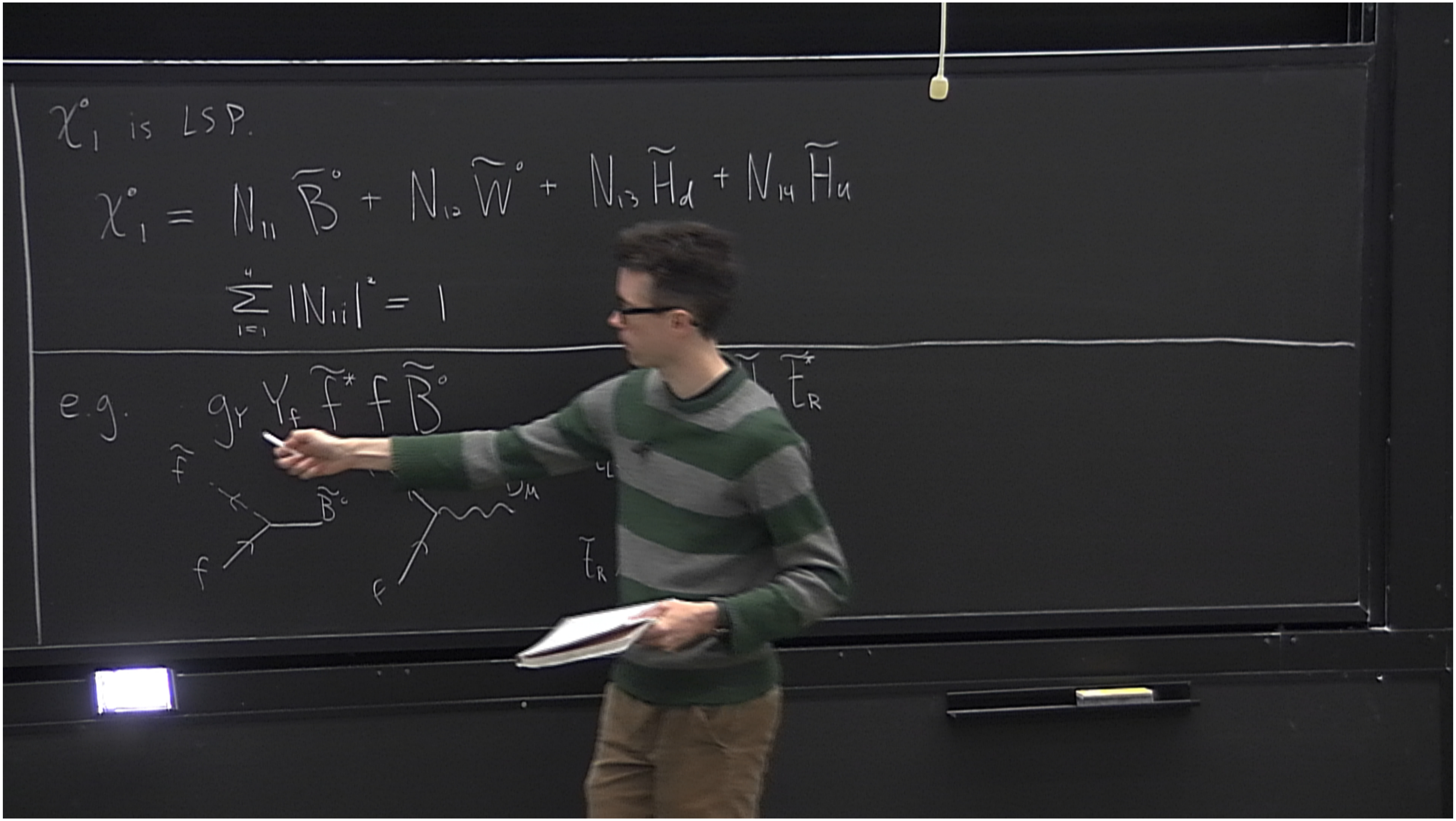
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$
$y_t t_L \tilde{H}_u$
$\tilde{f}$
$\tilde{B}^0$
f
f
B_μ
f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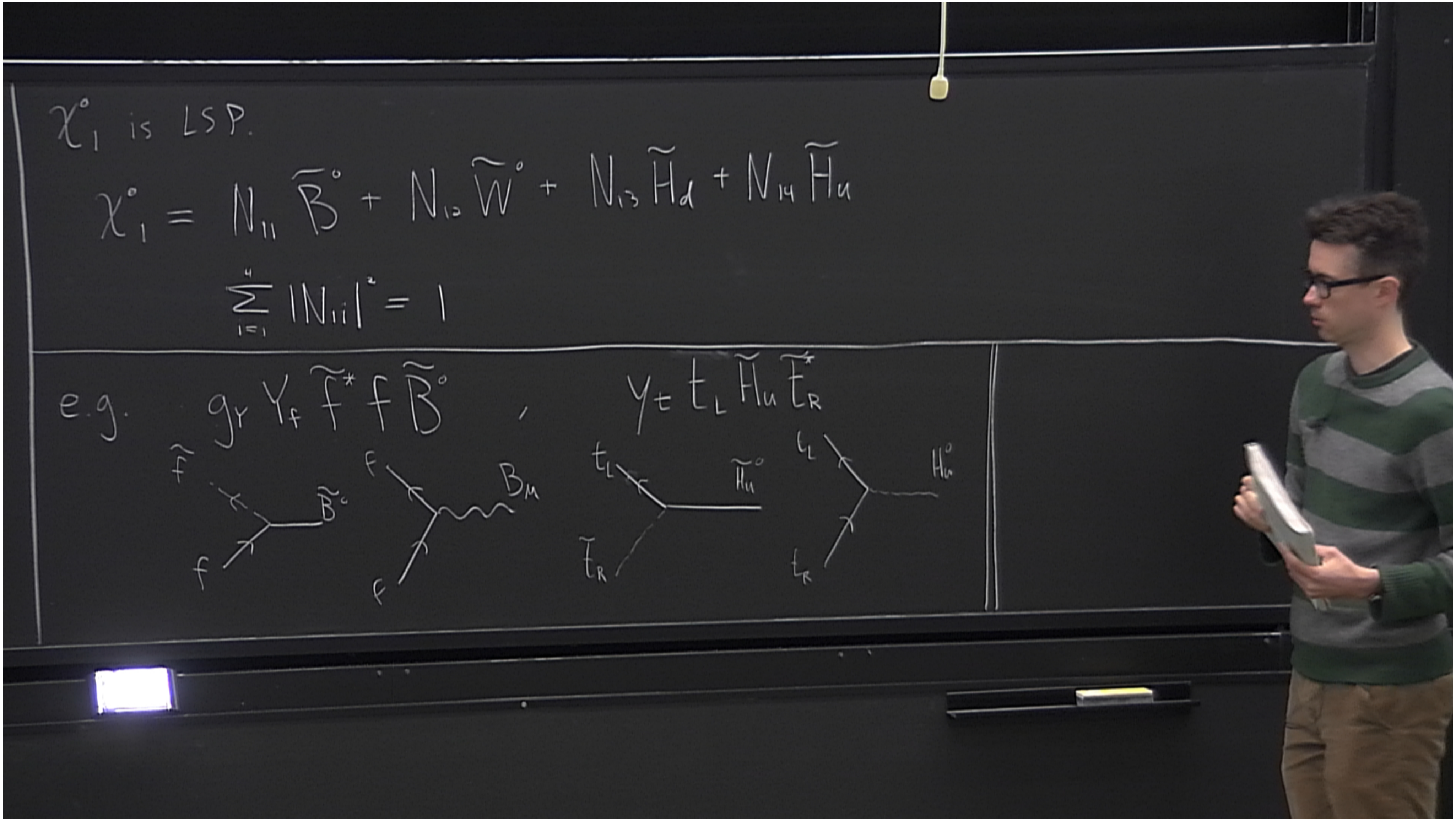
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$

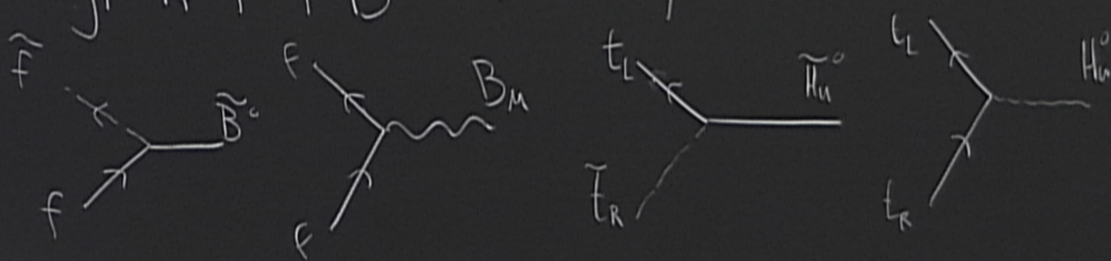

χ^0_1 is LSP.
$\chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L \tilde{H}_u \tilde{t}^*_R$
$\tilde{f}$ $\tilde{B}^0$ f
f B_μ f
t_L $\tilde{H}^0_u$ $\tilde{t}_R$
$\tilde{t}_L$ H^0_u t_R

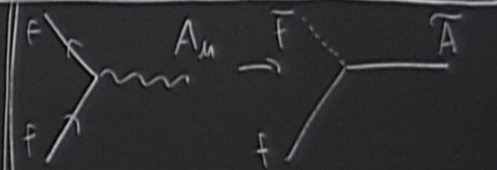
χ^0_1 is LSP.

$$\chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

$$\sum_{i=1}^{4} |N_{1i}|^2 = 1$$

e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L \tilde{H}_u \tilde{t}_R^*$



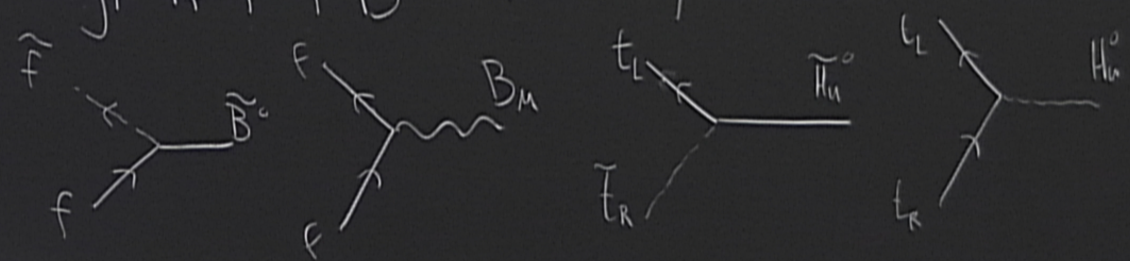


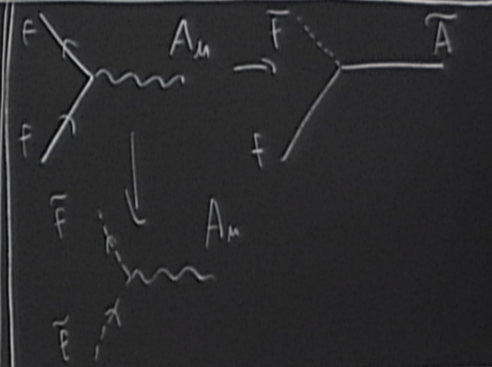
χ_1^0 is LSP.

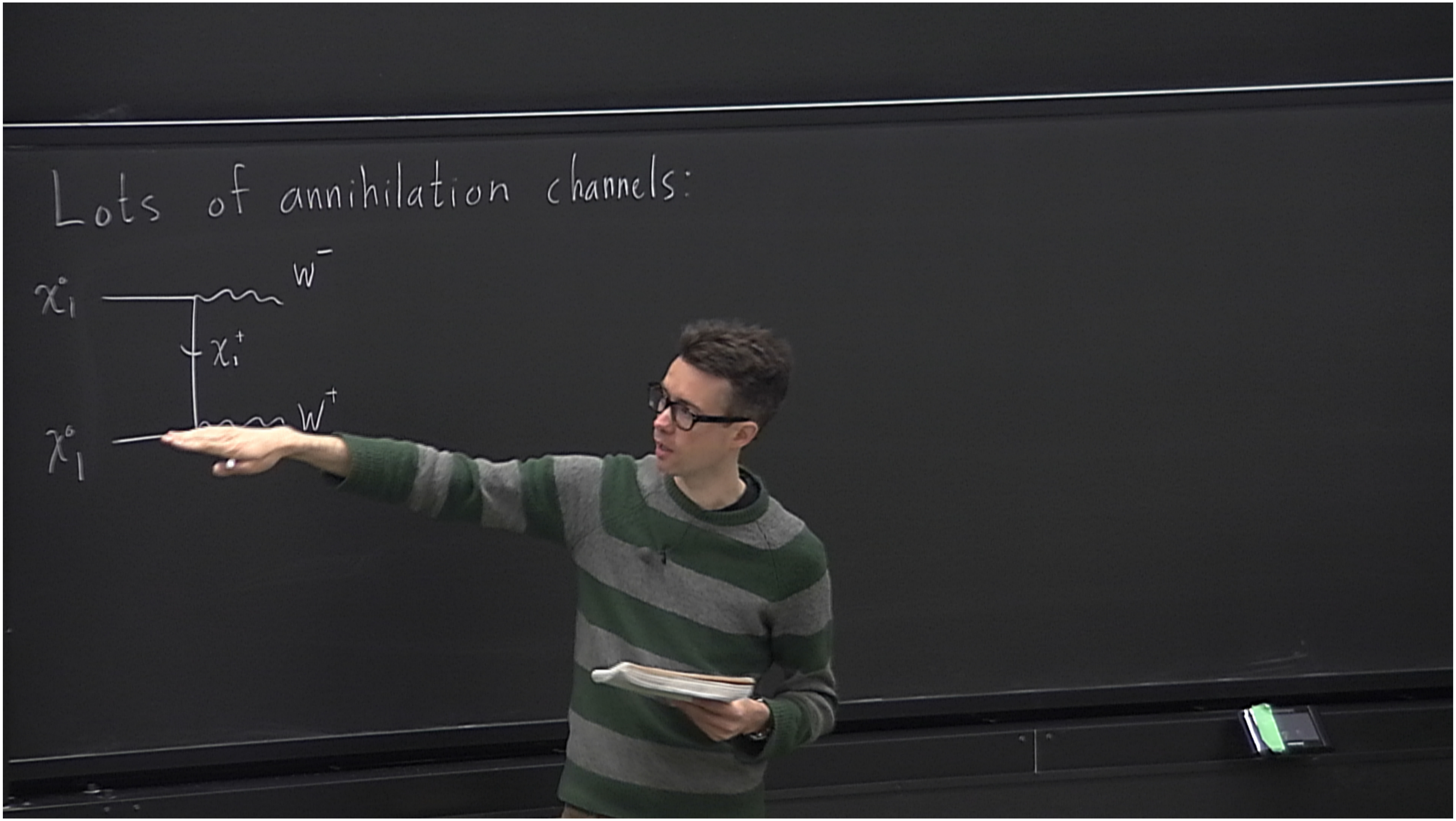
$$\chi_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

$$\sum_{i=1}^{4} |N_{1i}|^2 = 1$$

e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L \tilde{H}_u \tilde{t}_R^*$






Lots of annihilation channels:
χ_1^0
W^-
χ_1^+
W^+
χ_1^0

MSSM = minimal SUSY extension of the SM

Want neutralino LSP for DM.

4 neutralinos: χ^0_i, $i=1,\dots,4$, $m_{\chi^0_1} \leq m_{\chi^0_2} \leq m_{\chi^0_3} \leq m_{\chi^0_4}$

↳ mixtures of $\tilde{B}^0$, $\tilde{W}^0$, $\underbrace{\tilde{H}^0_u, \tilde{H}^0_d}_{=\text{ higgsinos}}$

$\tilde{B}^0 =$ $U(1)_Y$ gaugino

$\tilde{W}^0 =$ $SU(2)_L$ gaugino

$\tilde{W}^{a=1,2,3}$

$$\begin{cases} \tilde{W}^0 = \tilde{W}^3 \\ \tilde{W}^\pm = (\tilde{W}^1 \mp i \tilde{W}^2)/\sqrt{2} \end{cases}$$

χ^0_1 is LSP.

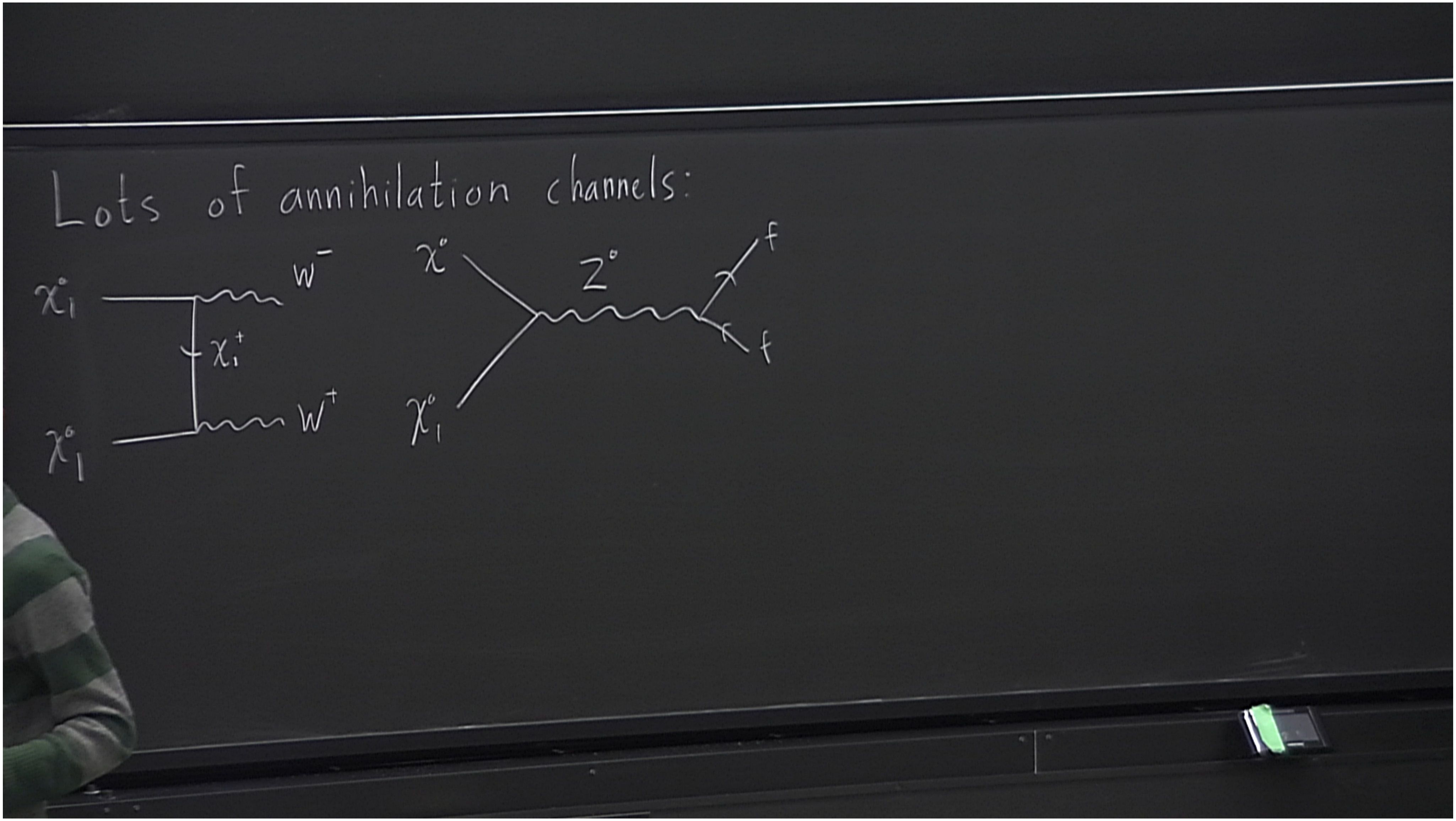
$\chi^0_1 = N$

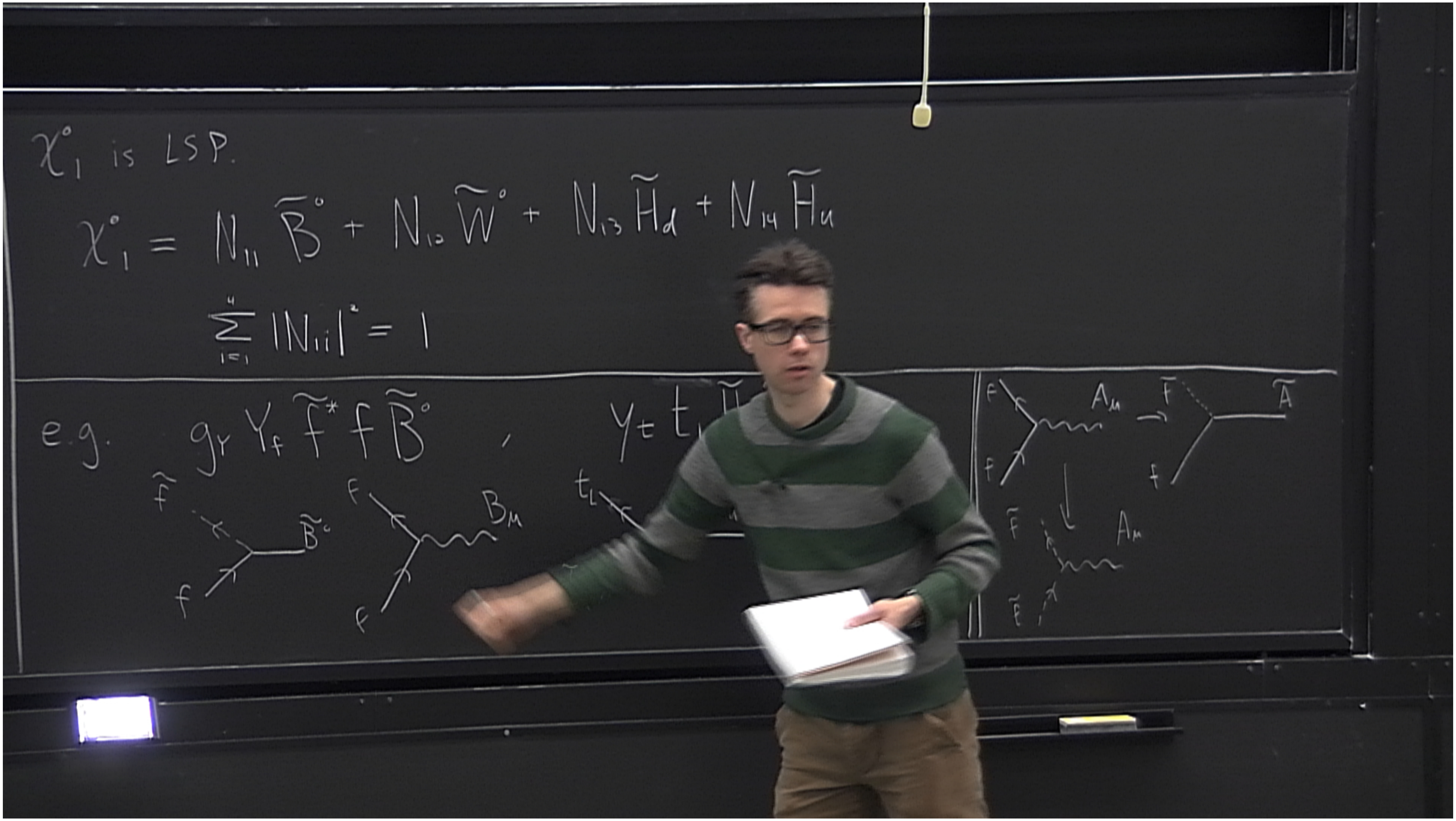
$\sum_{i=1}^{4}$

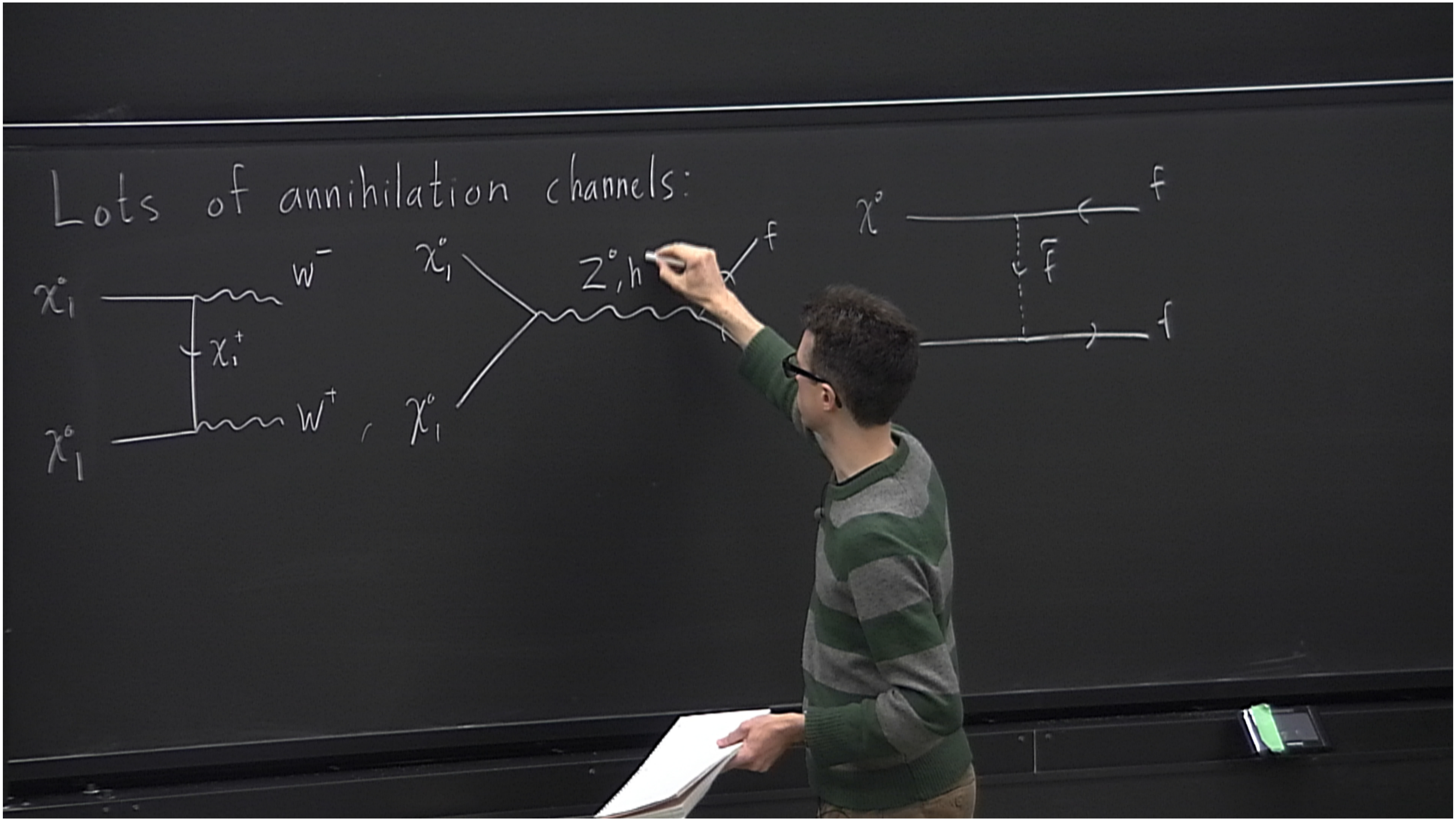
e.g. g_Y

$\tilde{f}$

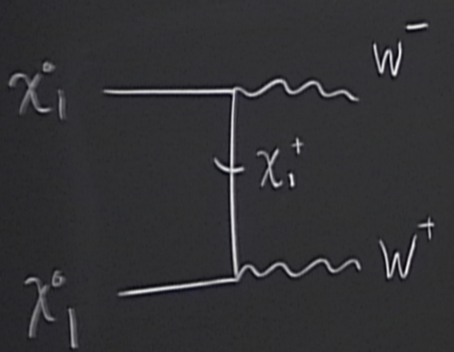
f


Lots of annihilation channels:
χ°_1
W^-
χ^+_1
W^+
χ°_1
χ°
Z°
f
f
χ°_1


χ^0_1 is LSP.
$\chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L$


Lots of annihilation channels:
χ₁⁰
W⁻
χ₁⁺
χ₁⁰
W⁺
χ₁⁰
Z⁰, h
f
χ₁⁰
χ⁰
f
f̃
f

Lots of annihilation channels:



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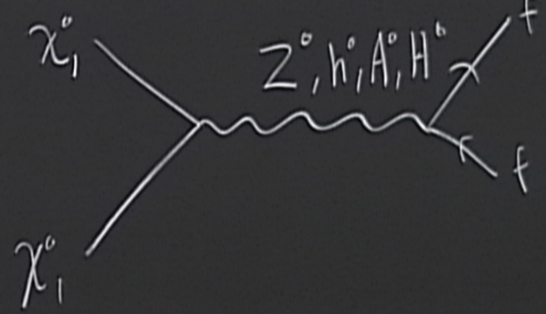
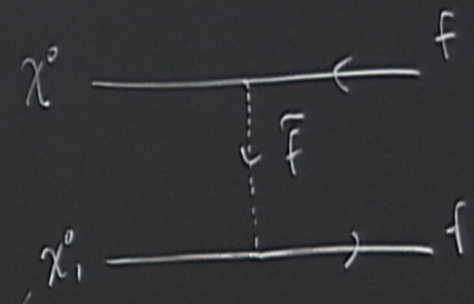
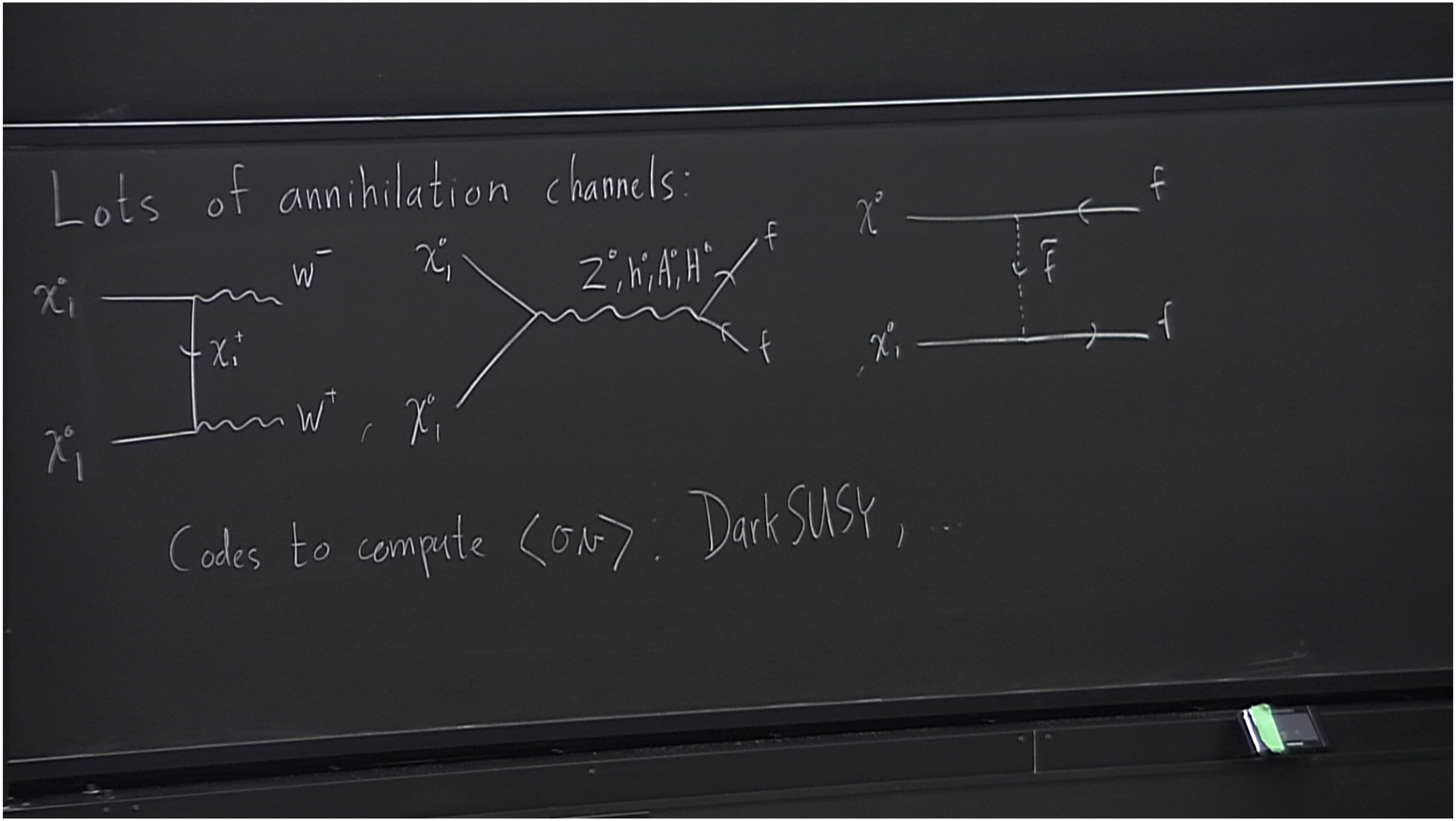
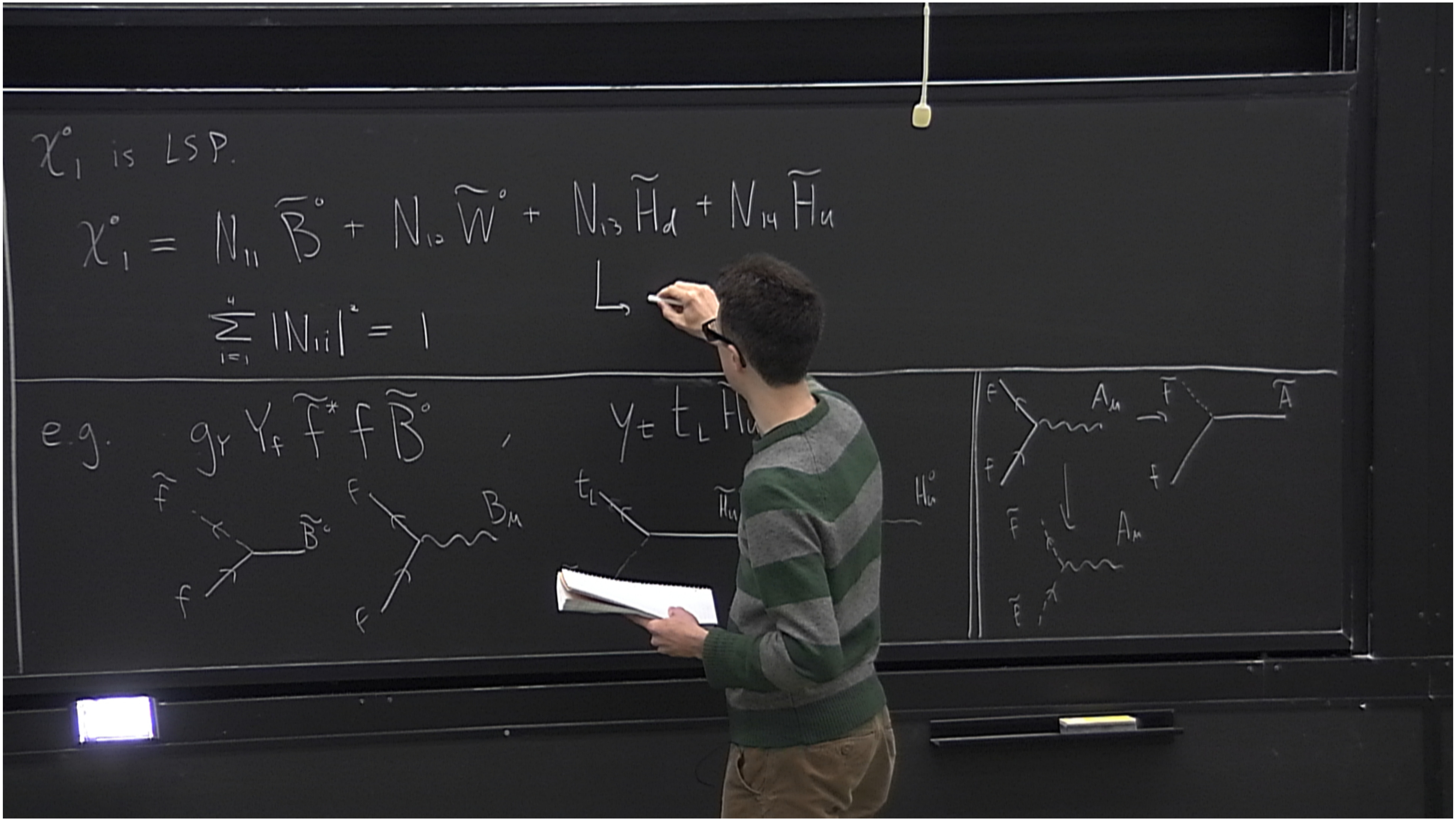
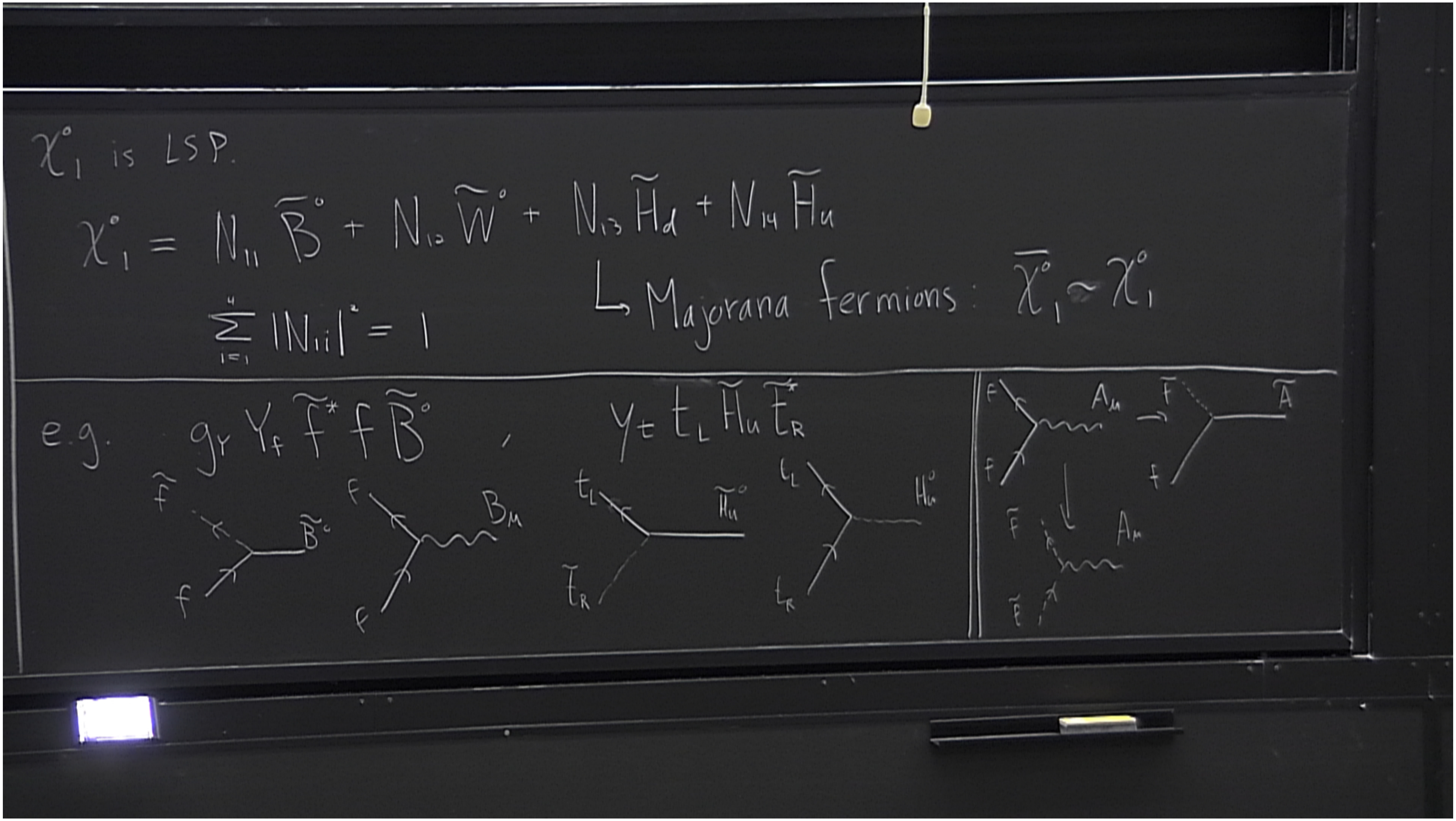





Lots of annihilation channels:
χ_1^0
W^-
χ_1^+
χ_1^0
W^+
χ_1^0
Z^0, h^0, A^0, H^0
f
f
χ_1^0
χ^0
f
$\tilde{f}$
χ_1^0
f
Codes to compute $\langle \sigma v \rangle$: DarkSUSY, ...


χ^0_1 is LSP.
$\chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L \tilde{H}_u$
$\tilde{f}$
$\tilde{B}^0$
f
f
B_μ
f
t_L
$\tilde{H}_u$
H_u^0
f
A_μ
$\tilde{f}$
$\tilde{A}$
f
f
$\tilde{f}$
A_μ
$\tilde{f}$



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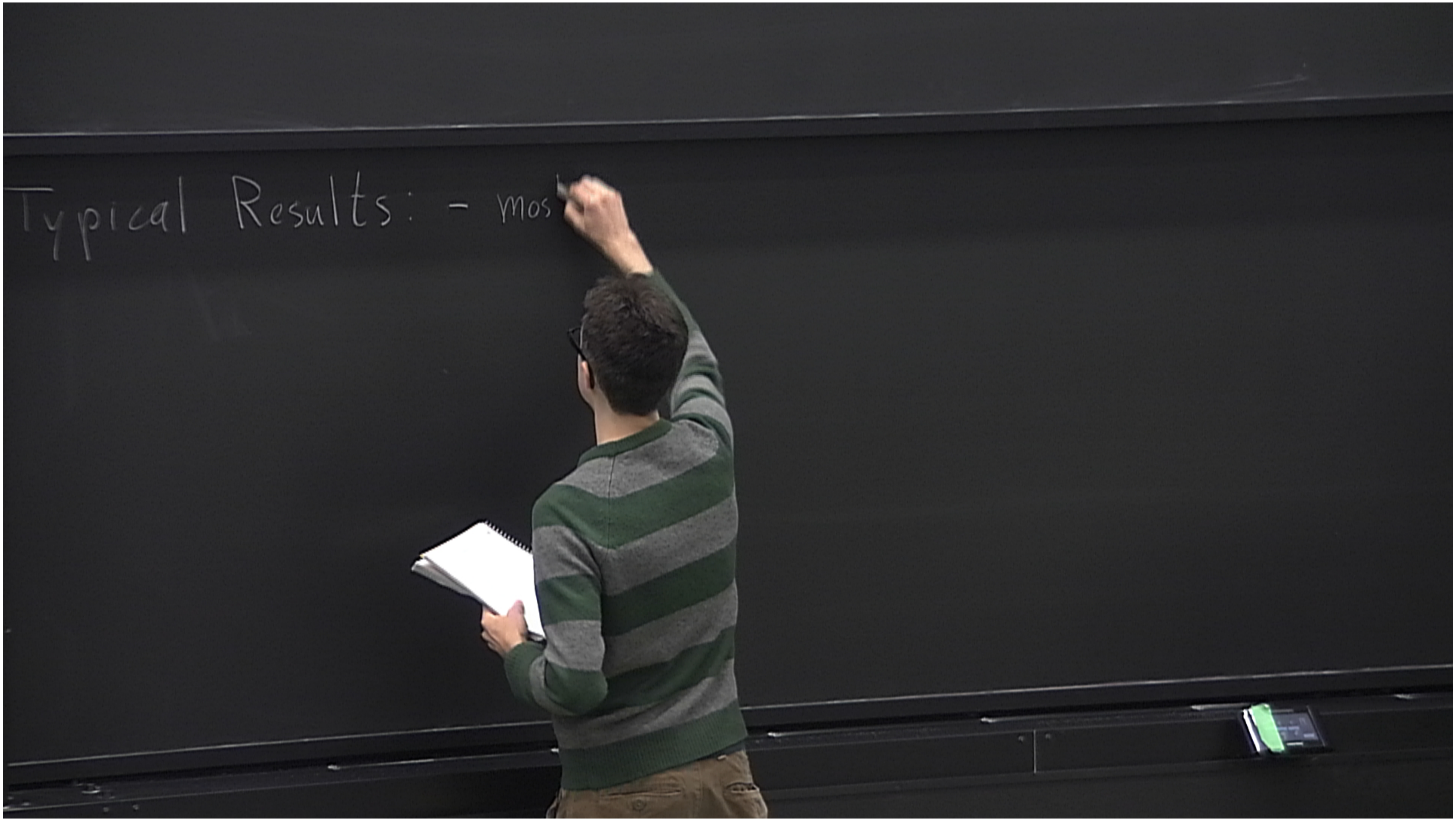
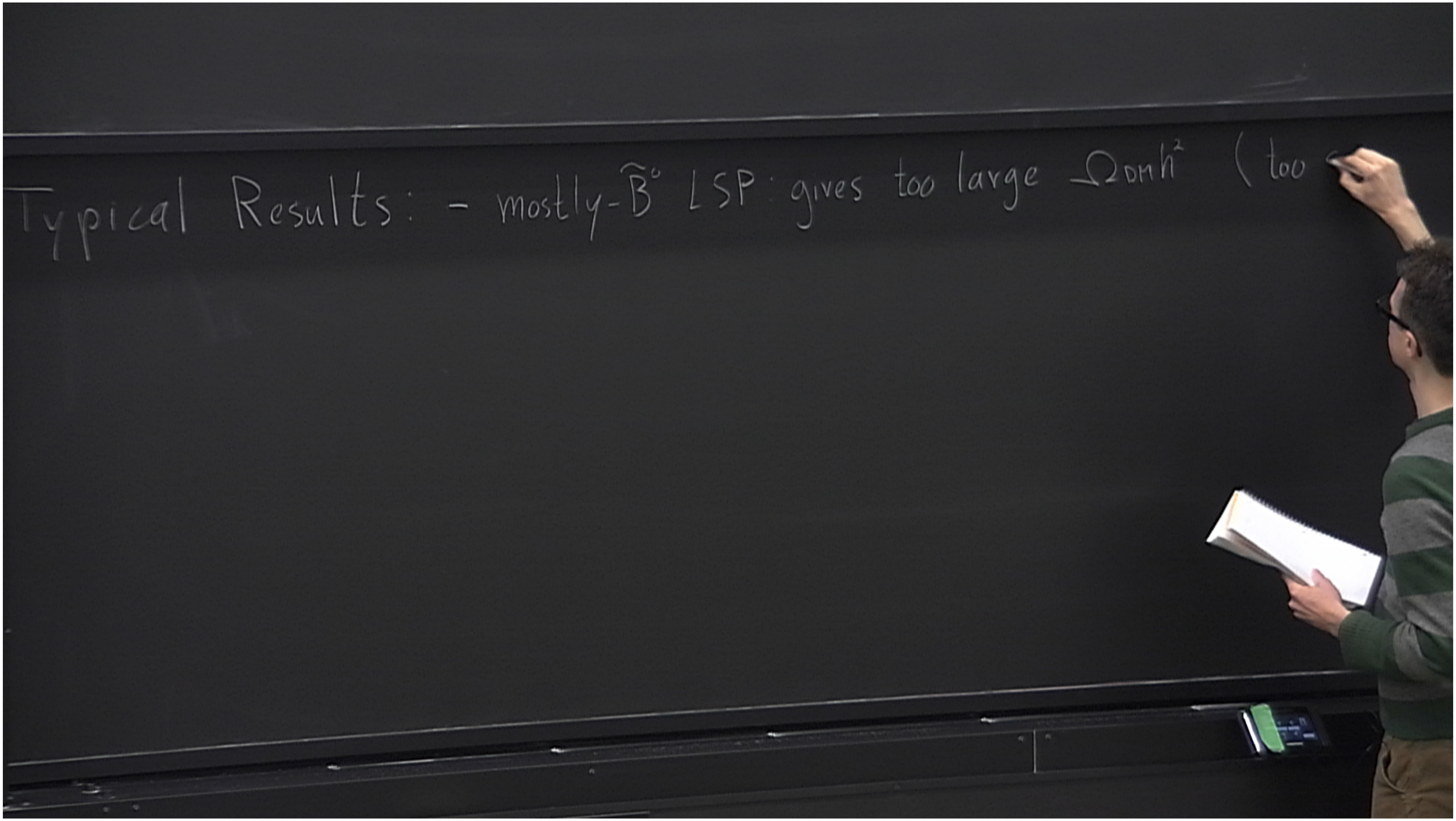
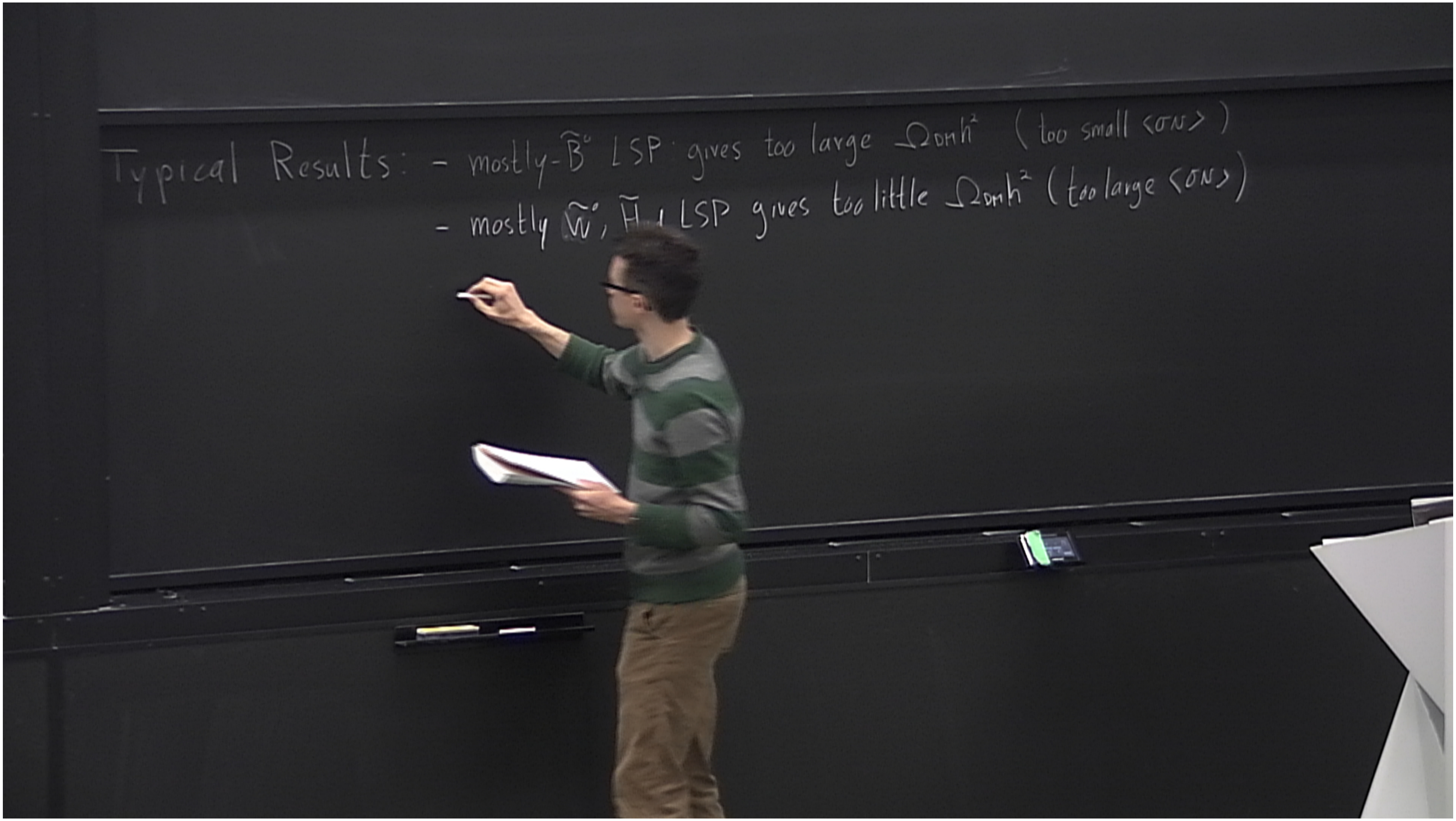
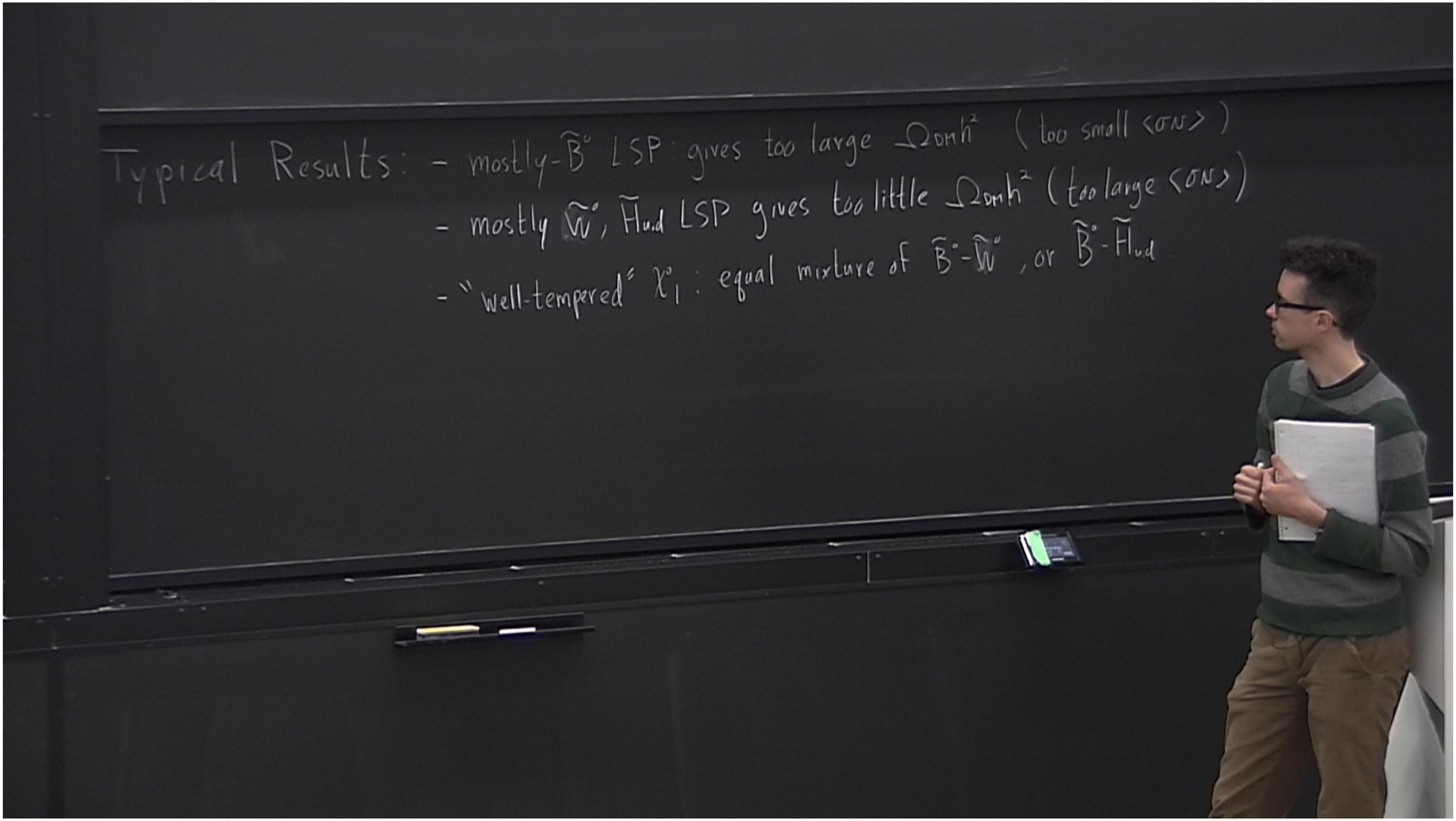
$\sum_{i=1}^{4} |N_{1i}|^2 = 1$
Majorana fermions: $\bar{\chi}^0_1 = \chi^0_1$
e.g. $g_Y Y_f \tilde{f}^* f \tilde{B}^0$, $y_t t_L \tilde{H}_u \tilde{t}^*_R$
$\tilde{f}$ f $\tilde{B}^0$ B_μ
t_L $\tilde{t}_R$ $\tilde{H}^0_u$ H^0_u t_R
A_μ $\tilde{A}$ $\tilde{f}$ f

Typical Results: -


Typical Results: - mos


Typical Results: - mostly-$\tilde{B}^0$ LSP: gives too large $\Omega_{DM} h^2$ (too


Typical Results: - mostly-$\tilde{B}^0$ LSP gives too large $\Omega_{DM}h^2$ (too small $\langle \sigma v \rangle$)
- mostly $\tilde{W}^0$, $\tilde{H}$, LSP gives too little $\Omega_{DM}h^2$ (too large $\langle \sigma v \rangle$)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- mostly $\tilde{W}^0$, $\tilde{H}_{u,d}$ LSP gives too little $\Omega_{DM}h^2$ (too large $\langle \sigma N \rangle$)
- "well-tempered" χ^0_1 : equal mixture of $\tilde{B}^0$-$\tilde{W}^0$, or $\tilde{B}^0$-$\tilde{H}_{u,d}$

Typical Results:
- mostly-$\tilde{B}^0$ LSP: gives too large $\Omega_{DM}h^2$ (too small $\langle \sigma v \rangle$)
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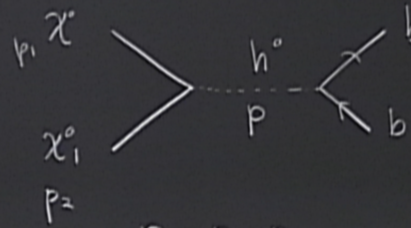
- "well-tempered" χ^0_1: equal mixture of $\tilde{B}^0$-$\tilde{W}^0$, or $\tilde{B}^0$-$\tilde{H}_{u,d}$

$\tilde{B}^0$-LSP can work in some special cases

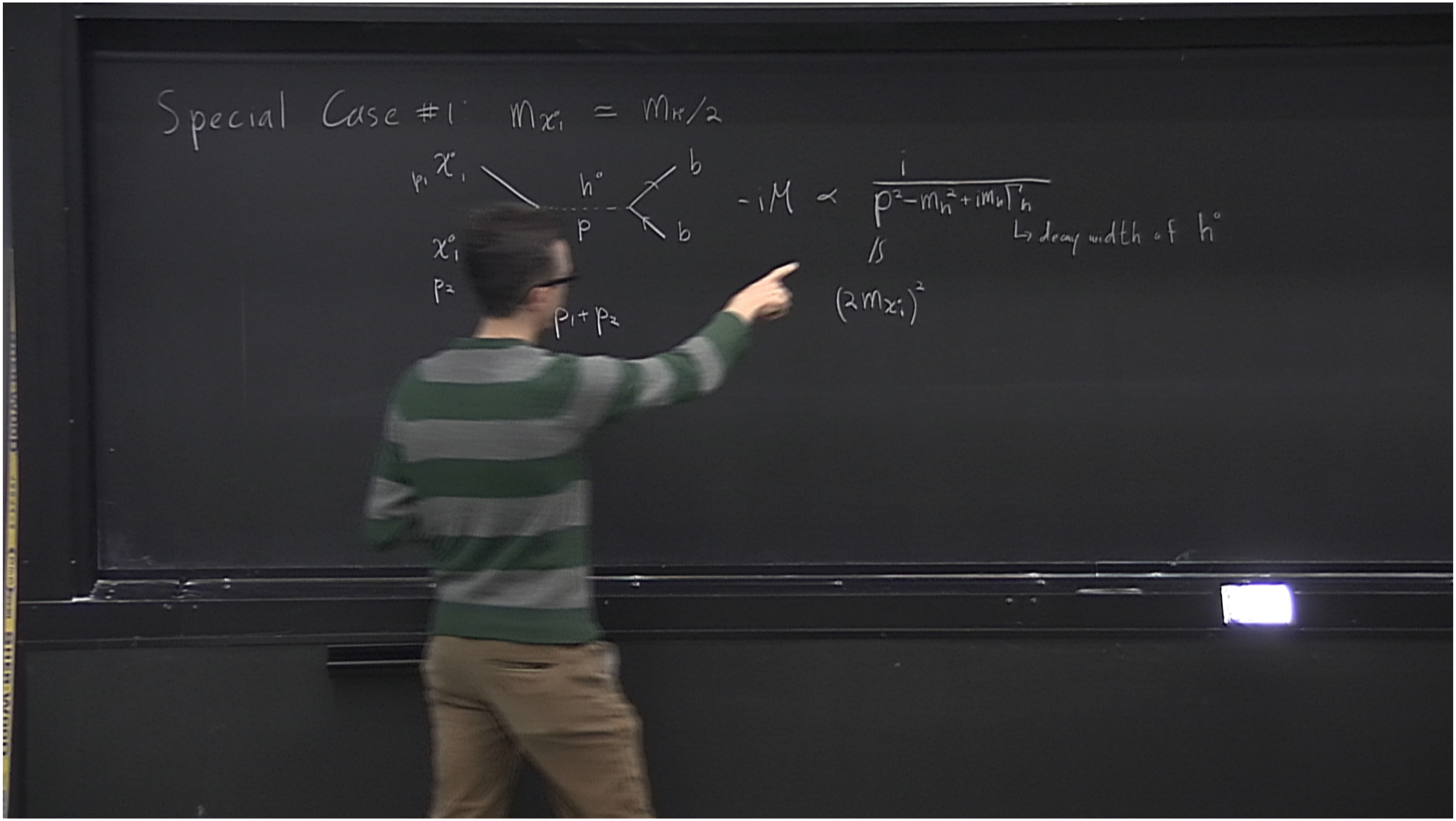
Special Case #1: $m_{\chi_1^0} = m_{h}/2$

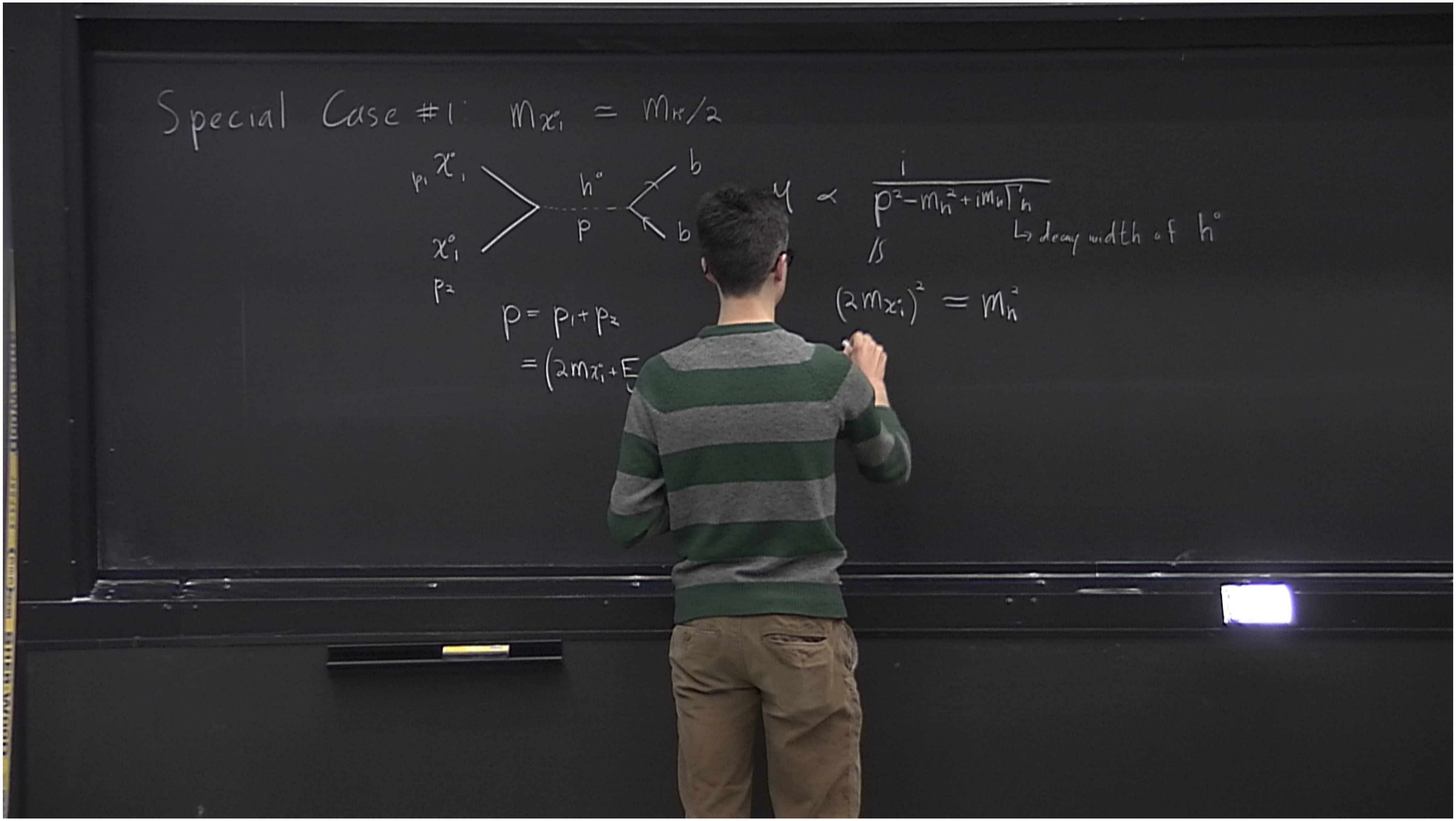


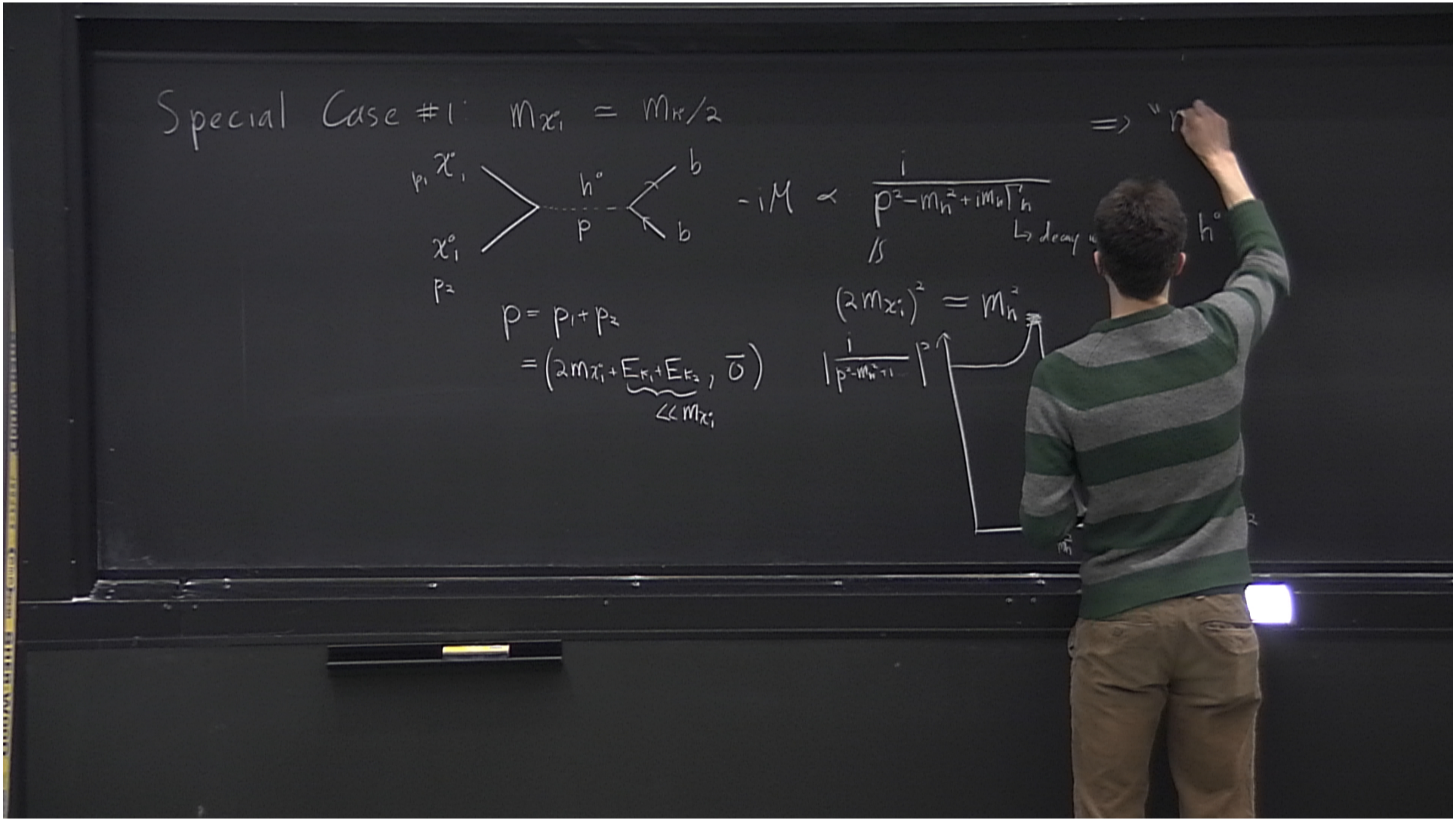
$$-i\mathcal{M} \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$$

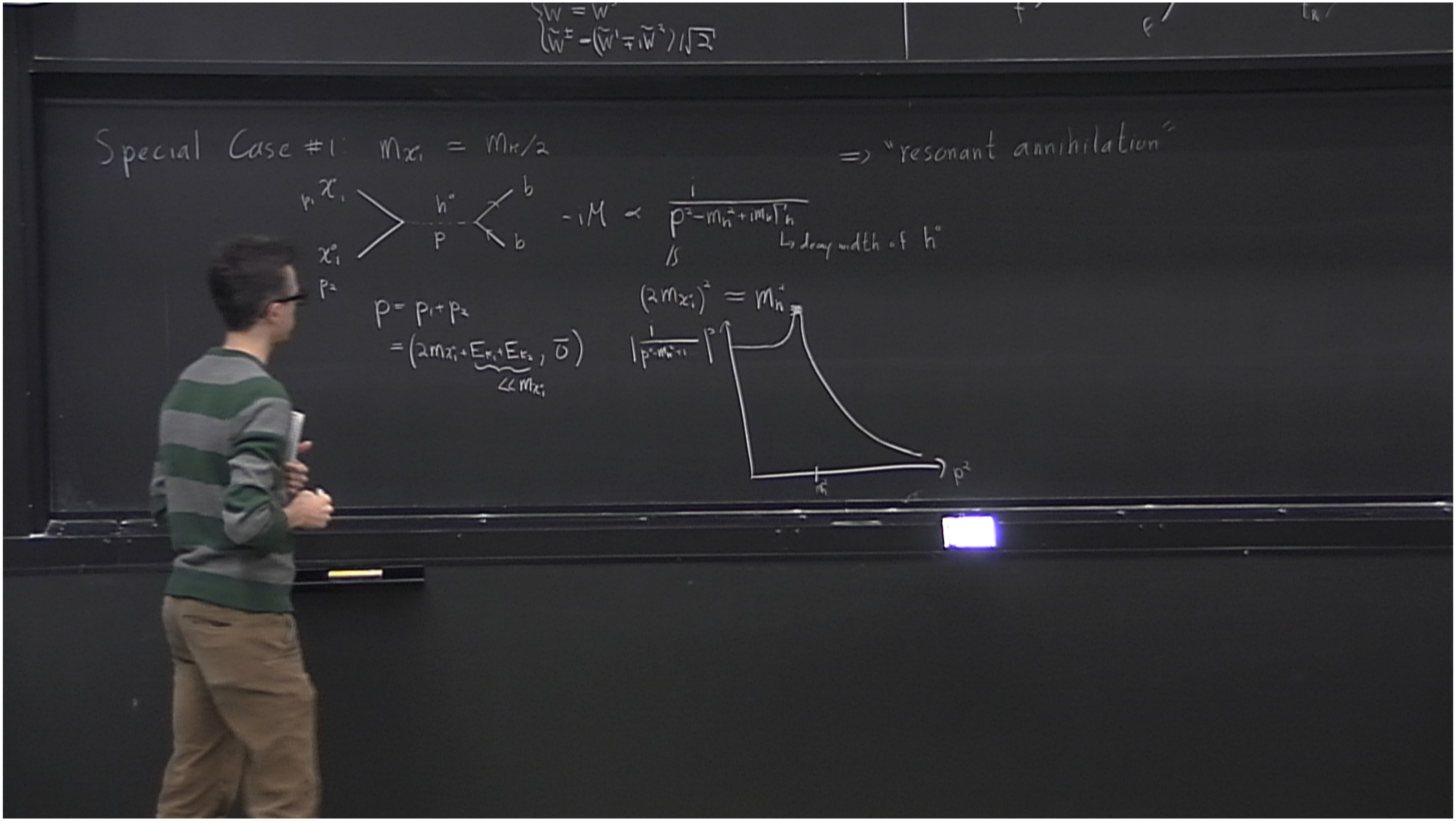
↳ decay width of h^0

$$p = p_1 + p_2$$


Special Case #1: $m_{\chi_1^0} = m_{h^0}/2$
p_1 χ_1^0
h^0
b
p
b
χ_1^0
p_2
$p_1 + p_2$
$-i\mathcal{M} \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$
↳ decay width of h^0
$(2m_{\chi_1^0})^2$


Special Case #1: $m_{\chi_1} = m_h/2$
$\mathcal{M} \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$
↳ decay width of h^0
$(2m_{\chi_1})^2 = m_h^2$
$p = p_1 + p_2$

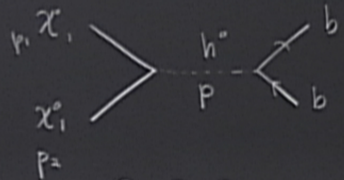

Special Case #1: $m_{\chi_1} = m_h/2$
$\Rightarrow$ "
$-i\mathcal{M} \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$
↳ decay
h^0
$p = p_1 + p_2$
$= (2m_{\chi_1} + E_{K_1} + E_{K_2}, \vec{0})$
$\ll m_{\chi_1}$
$(2m_{\chi_1})^2 = m_h^2$



Special Case #1: $m_{\chi_1} = m_h/2$
⇒ "resonant annihilation"
$-iM \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$
↳ decay width of h^0
$(2m_{\chi_1})^2 \simeq m_h^2$
$p = p_1 + p_2$
$= (2m_{\chi_1} + E_{K_1} + E_{K_2}, \vec{0})$
$\ll m_{\chi_1}$
$\left|\frac{1}{p^2 - m_h^2 + i\ldots}\right|^2$
p^2

$\tilde{W}^\pm = (\tilde{W}^1 \mp i\tilde{W}^2)/\sqrt{2}$

Special Case #1: $m_{\chi_1} = m_h/2$ $\Rightarrow$ "resonant annihilation"



$$-i\mathcal{M} \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$$

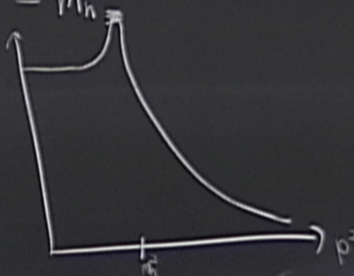
$\hookrightarrow$ decay width of h^0

$p^2 = s$

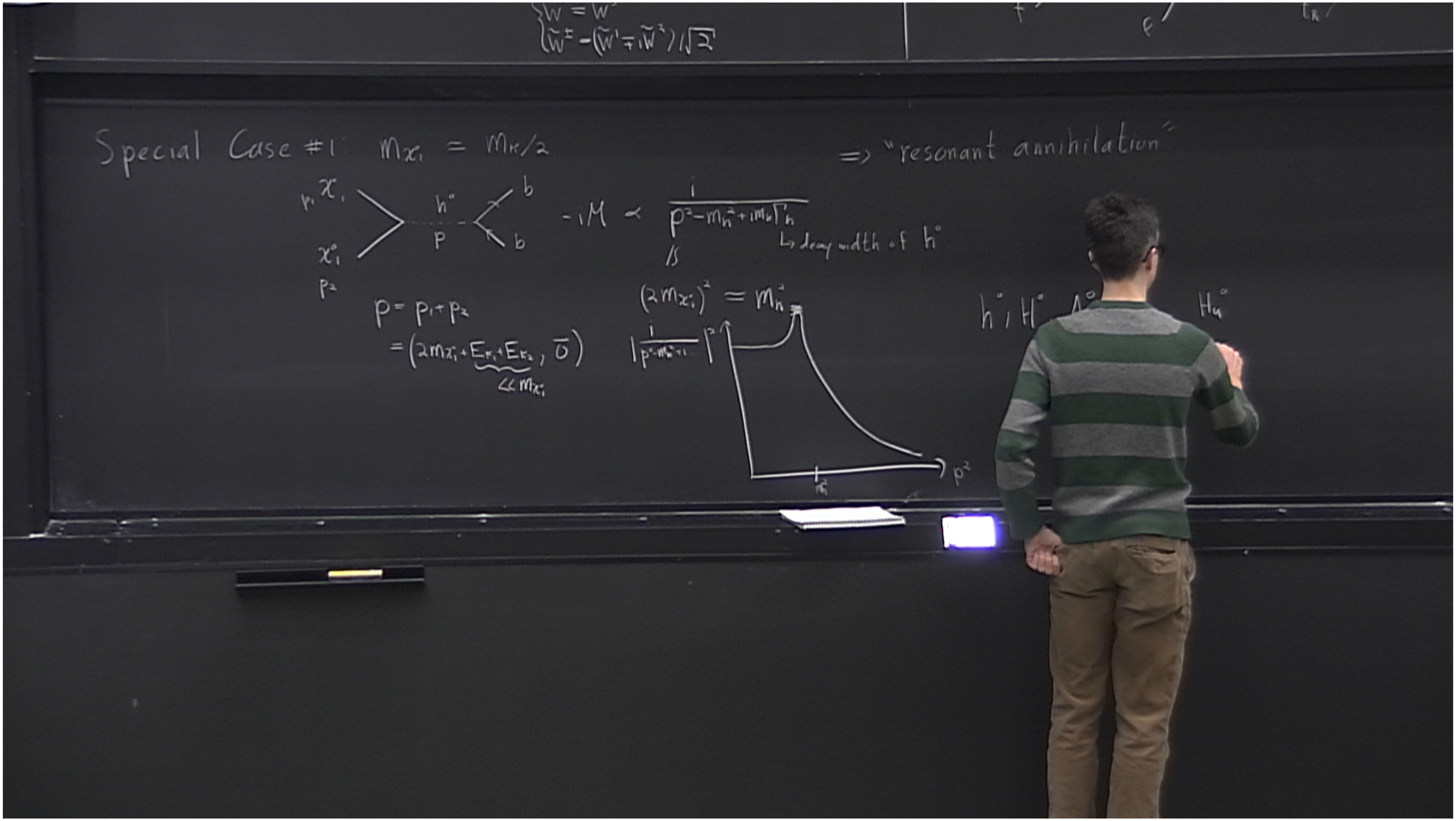
$$p = p_1 + p_2 = \left(2m_{\chi_1} + \underbrace{E_{K_1} + E_{K_2}}_{\ll m_{\chi_1}}, \vec{0}\right)$$

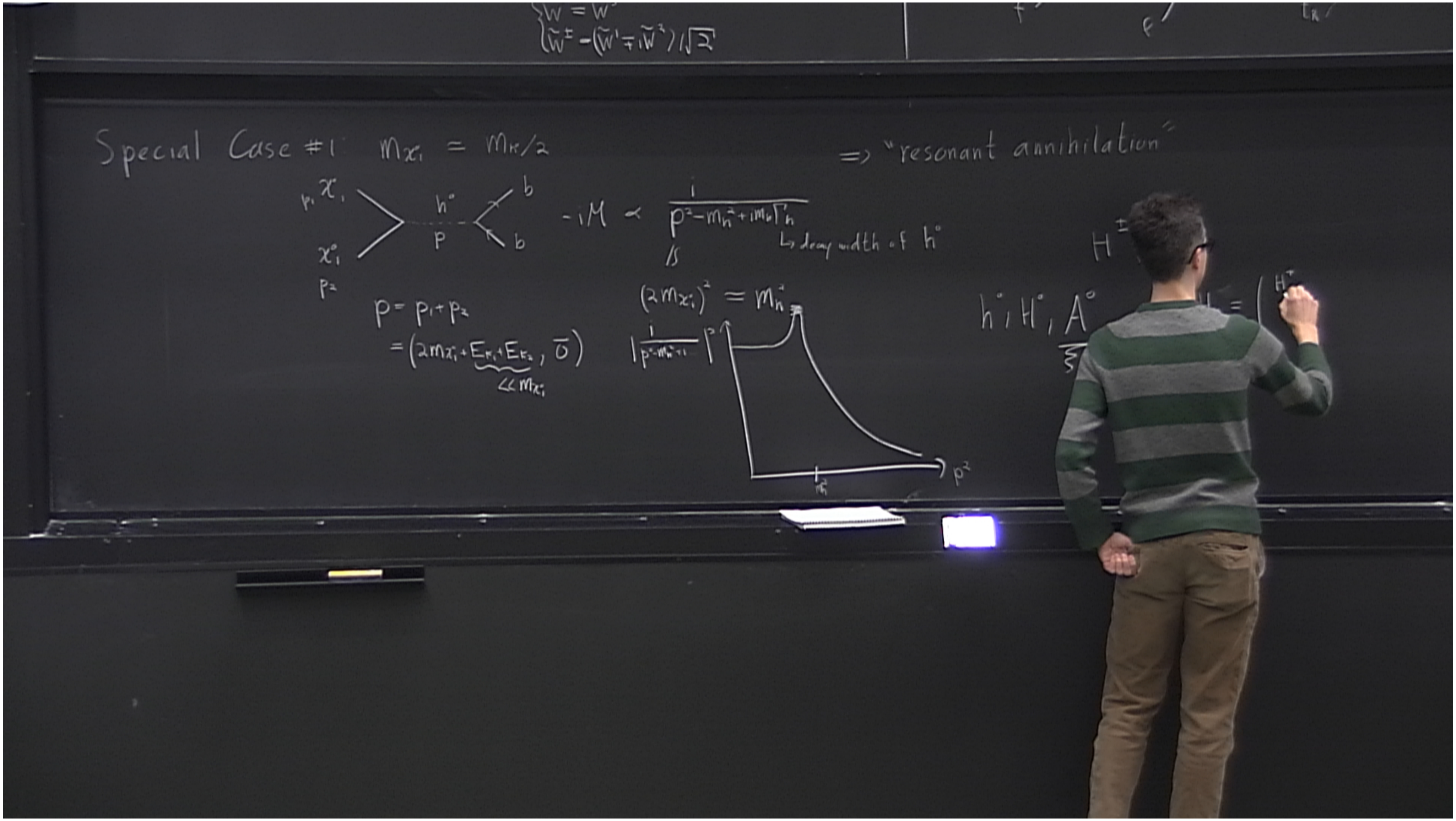
$$(2m_{\chi_1})^2 \simeq m_h^2$$

$$\left|\frac{1}{p^2 - m_h^2 + i \ldots}\right|^2$$



$h^0, H^0, \underline{A^0}$


Special Case #1: $m_{\chi_1} = m_h/2$
$\Rightarrow$ "resonant annihilation"
$-iM \propto \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h}$
$\hookrightarrow$ decay width of h^0
$p = p_1 + p_2$
$= (2m_{\chi_1} + E_{K_1} + E_{K_2}, \vec{0})$
$\ll m_{\chi_1}$
$(2m_{\chi_1})^2 \simeq m_h^2$
h^0, H^0
H_u^0
p^2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h^0, H^0, A^0
$H^\pm$
p^2

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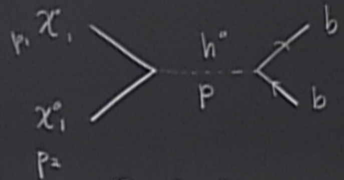


$$-iM \propto \frac{1}{p^2 - m_h^2 + i m_h \Gamma_h}$$

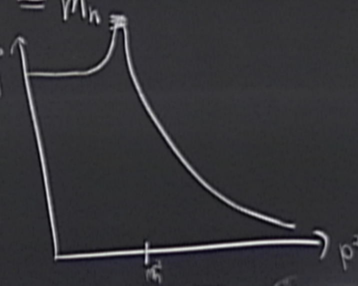
↳ decay width of h^0

$p^2 = s$

$$(2m_{\chi_1})^2 \simeq m_h^2$$

$$p = p_1 + p_2 = (2m_{\chi_1} + \underbrace{E_{K_1} + E_{K_2}}_{\ll m_{\chi_1}}, \vec{0})$$

$$\left|\frac{1}{p^2 - m_h^2 + i \ldots}\right|^2$$

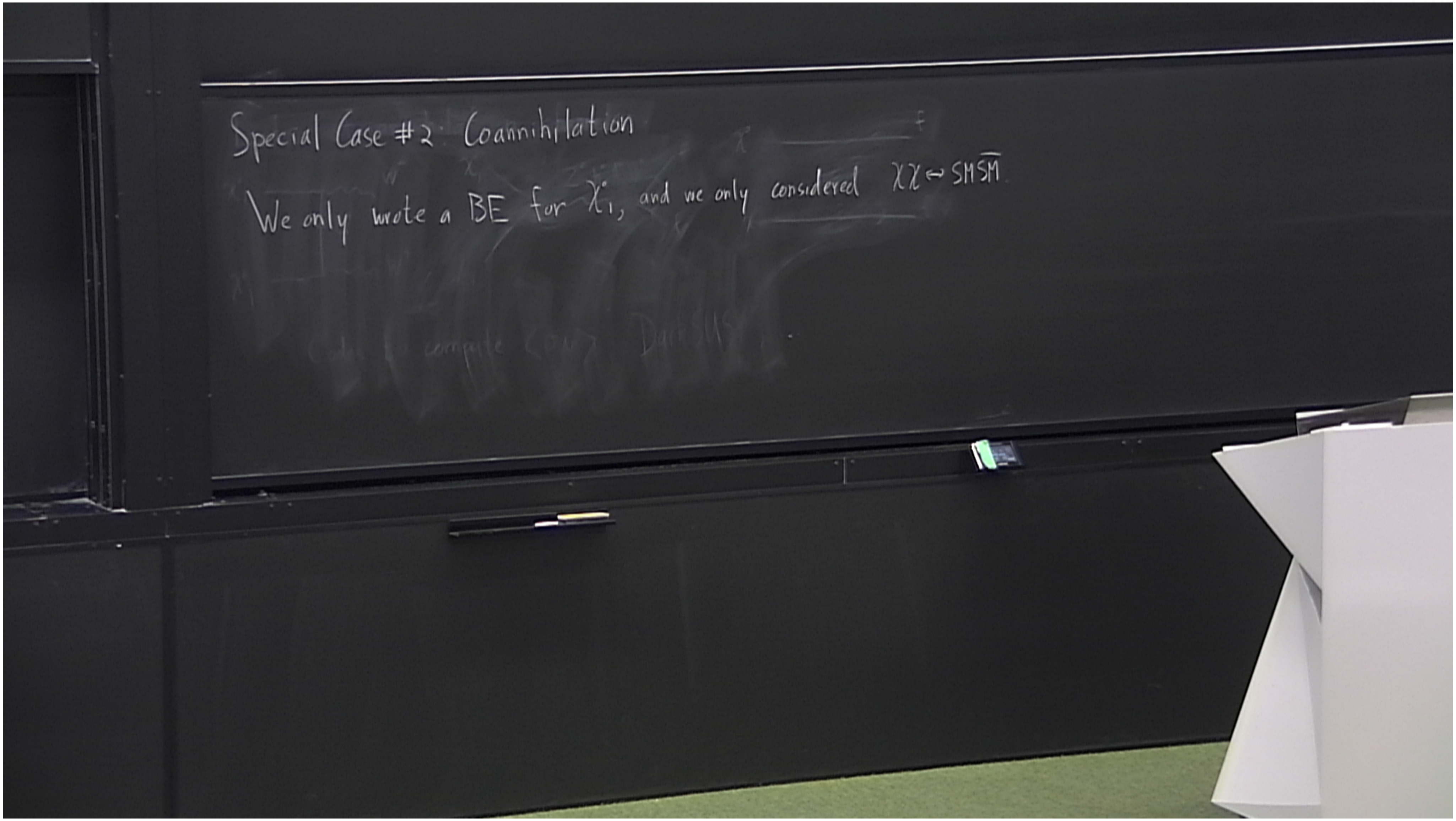


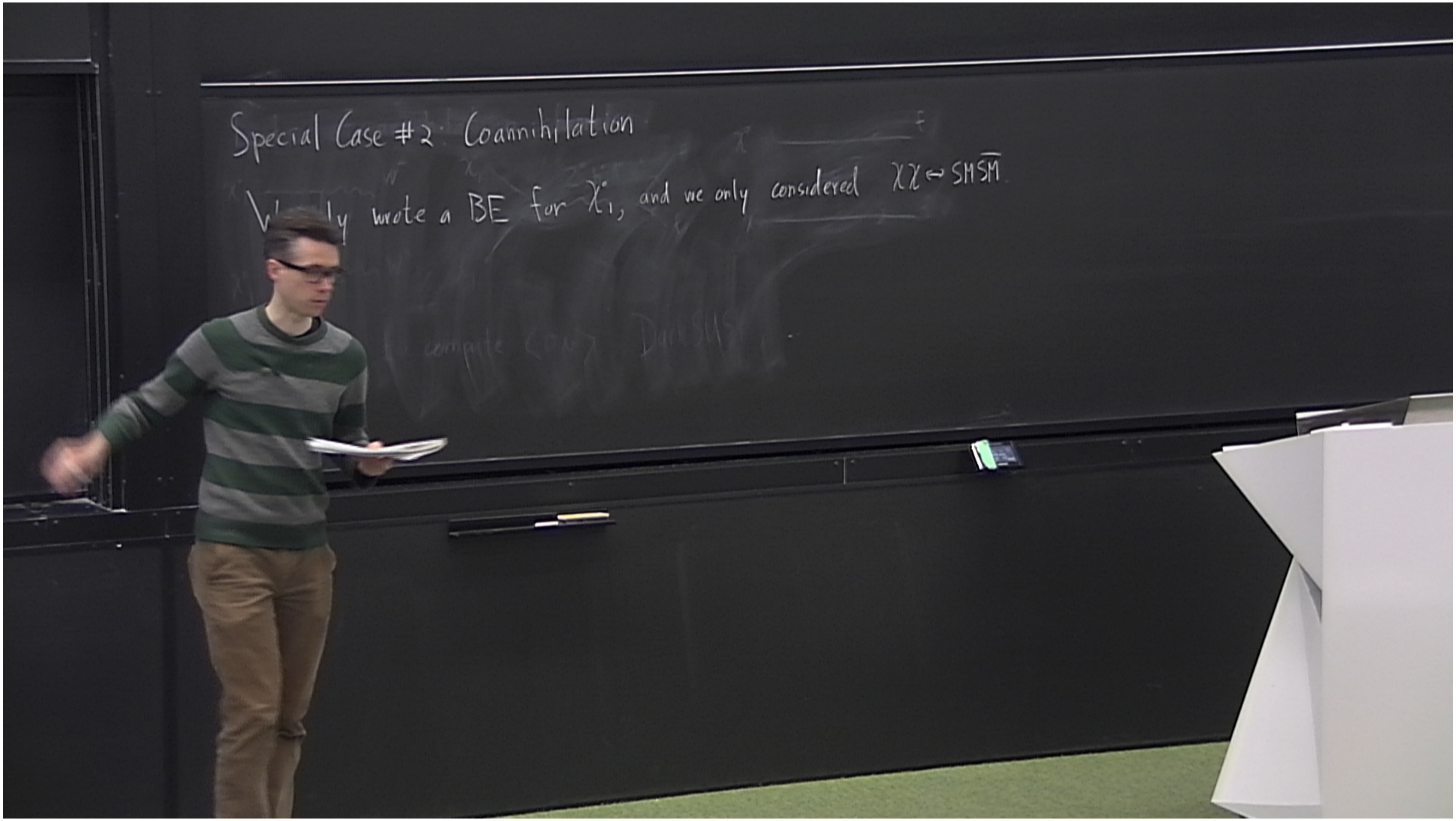
$H^\pm$

h^0, H^0, A^0

$$H_u = \begin{pmatrix} H^+ \\ v_u + \frac{1}{\sqrt{2}}(r_u + i a_u) \end{pmatrix}$$

$$H_d = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(r_d + i a_d) \\ H^- \end{pmatrix}$$


Special Case #2: Coannihilation
We only wrote a BE for χ_1, and we only considered $\chi\chi \leftrightarrow SM\overline{SM}$


Special Case #2: Coannihilation
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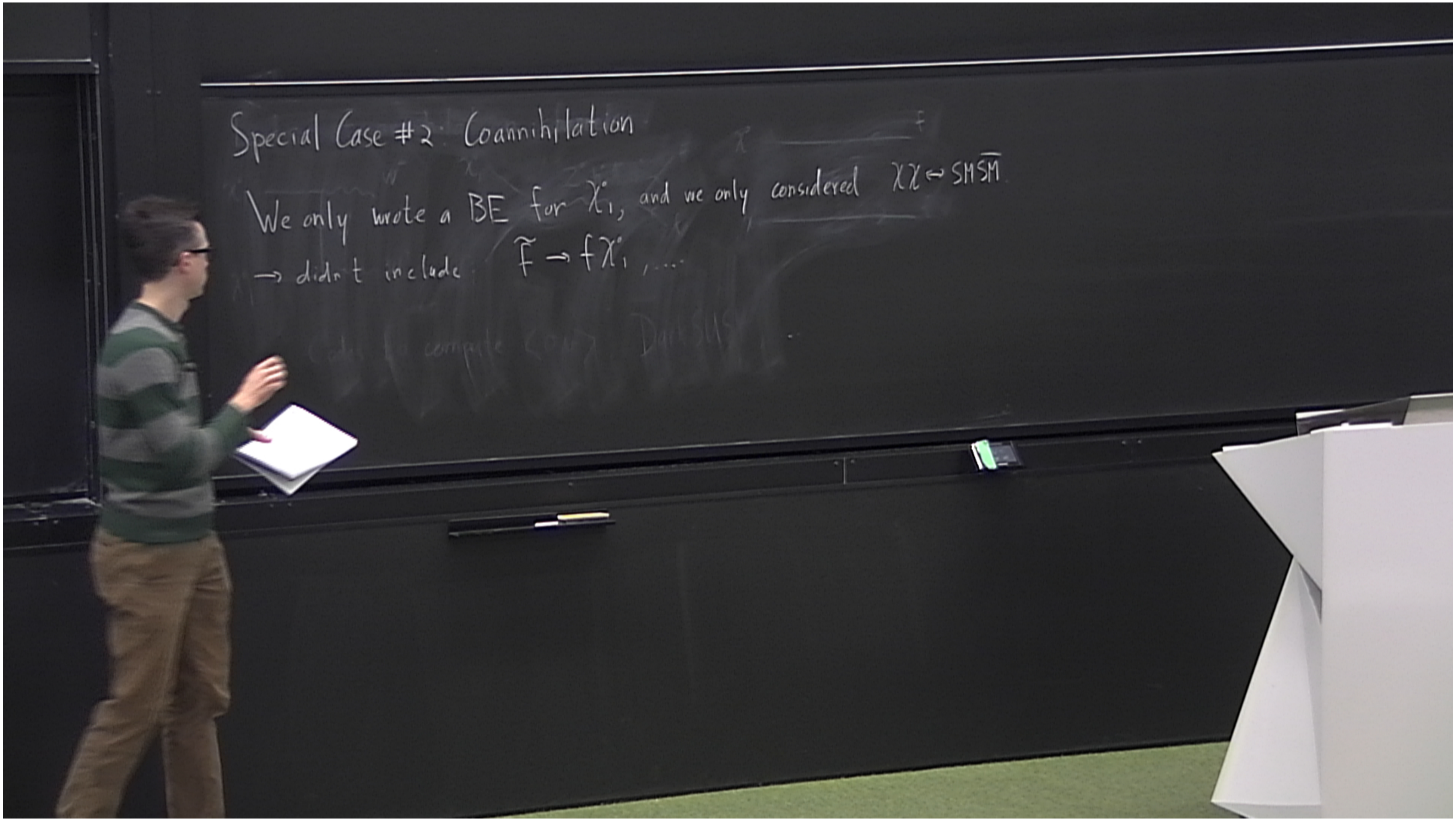
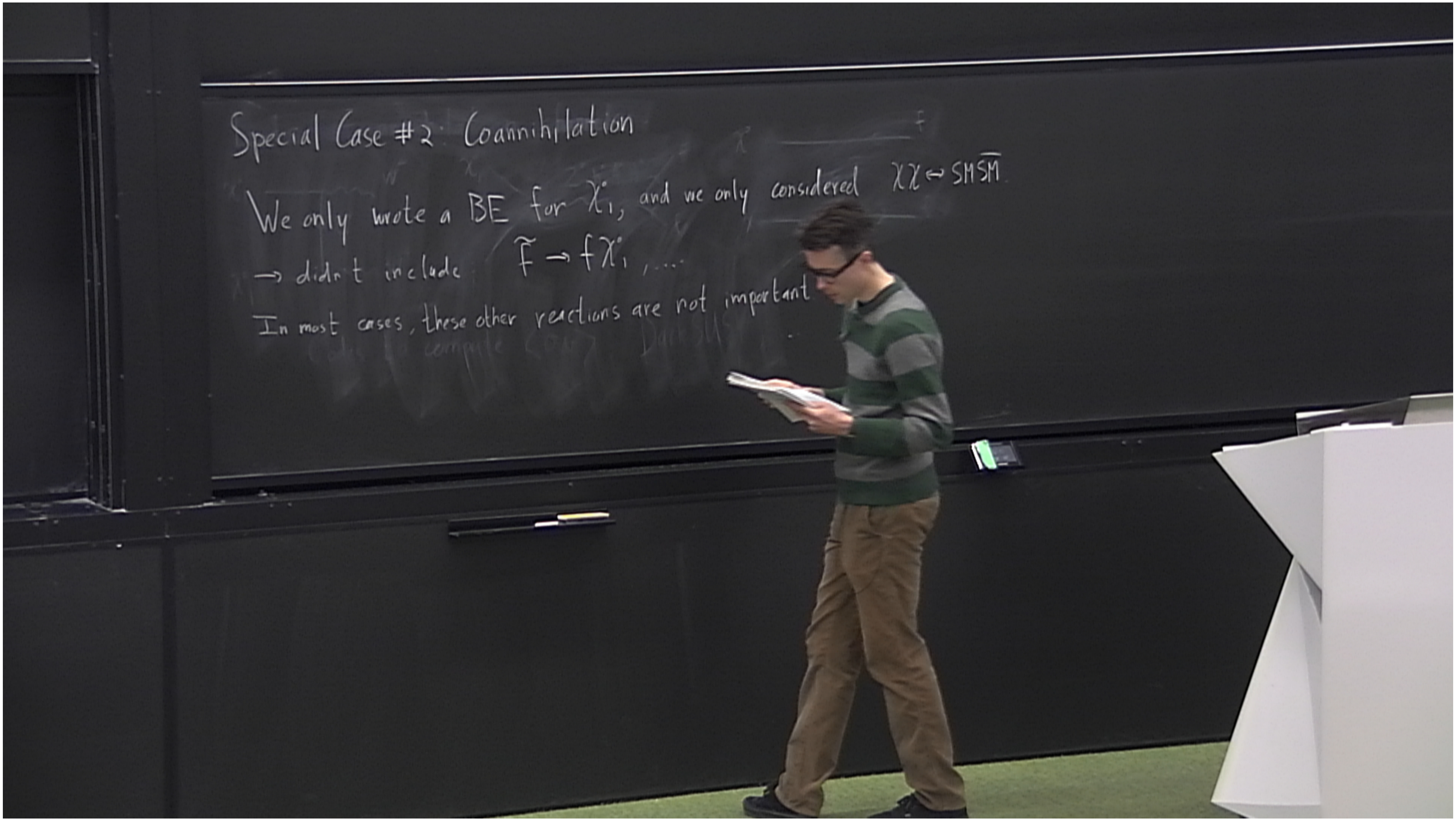
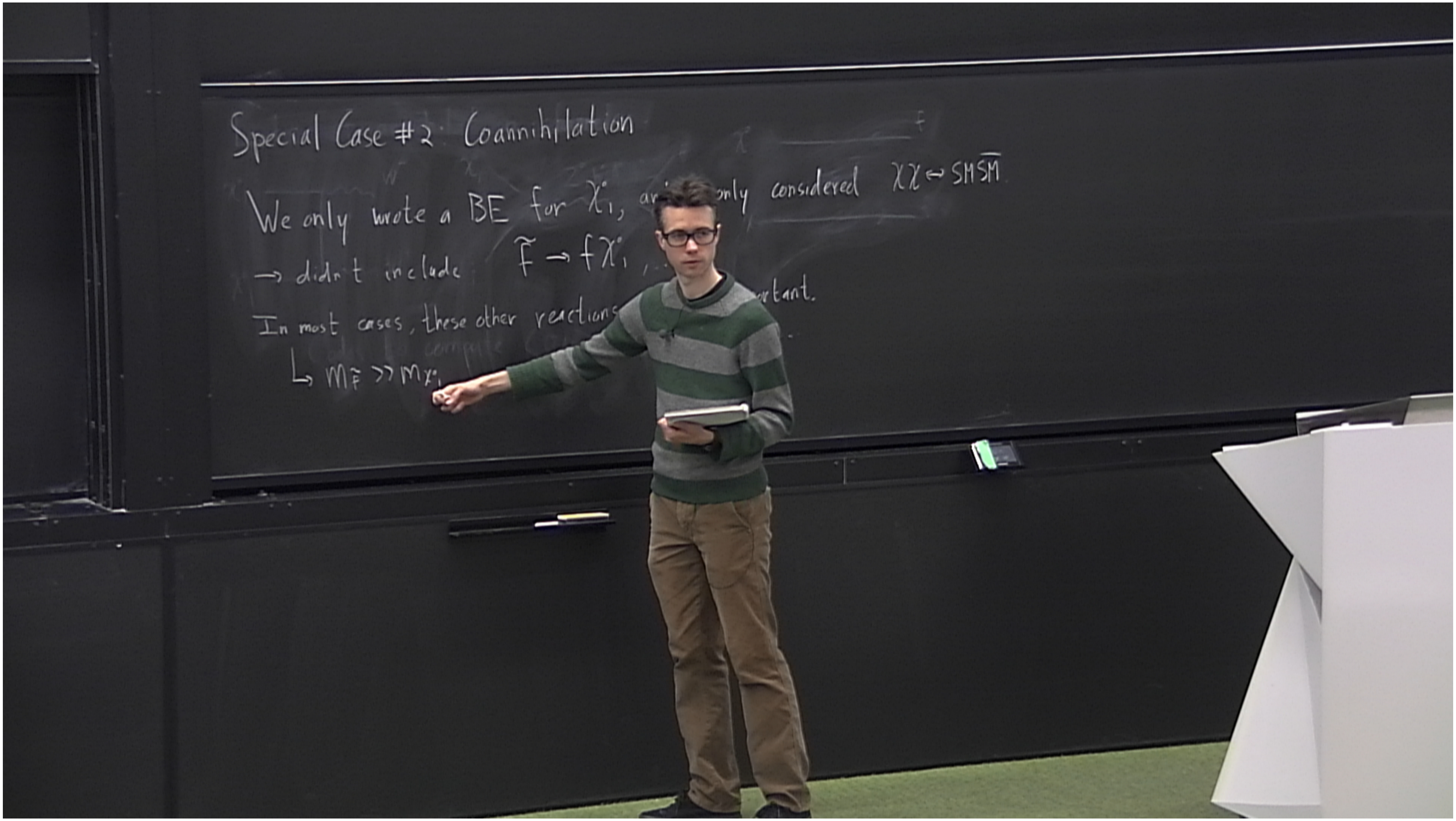
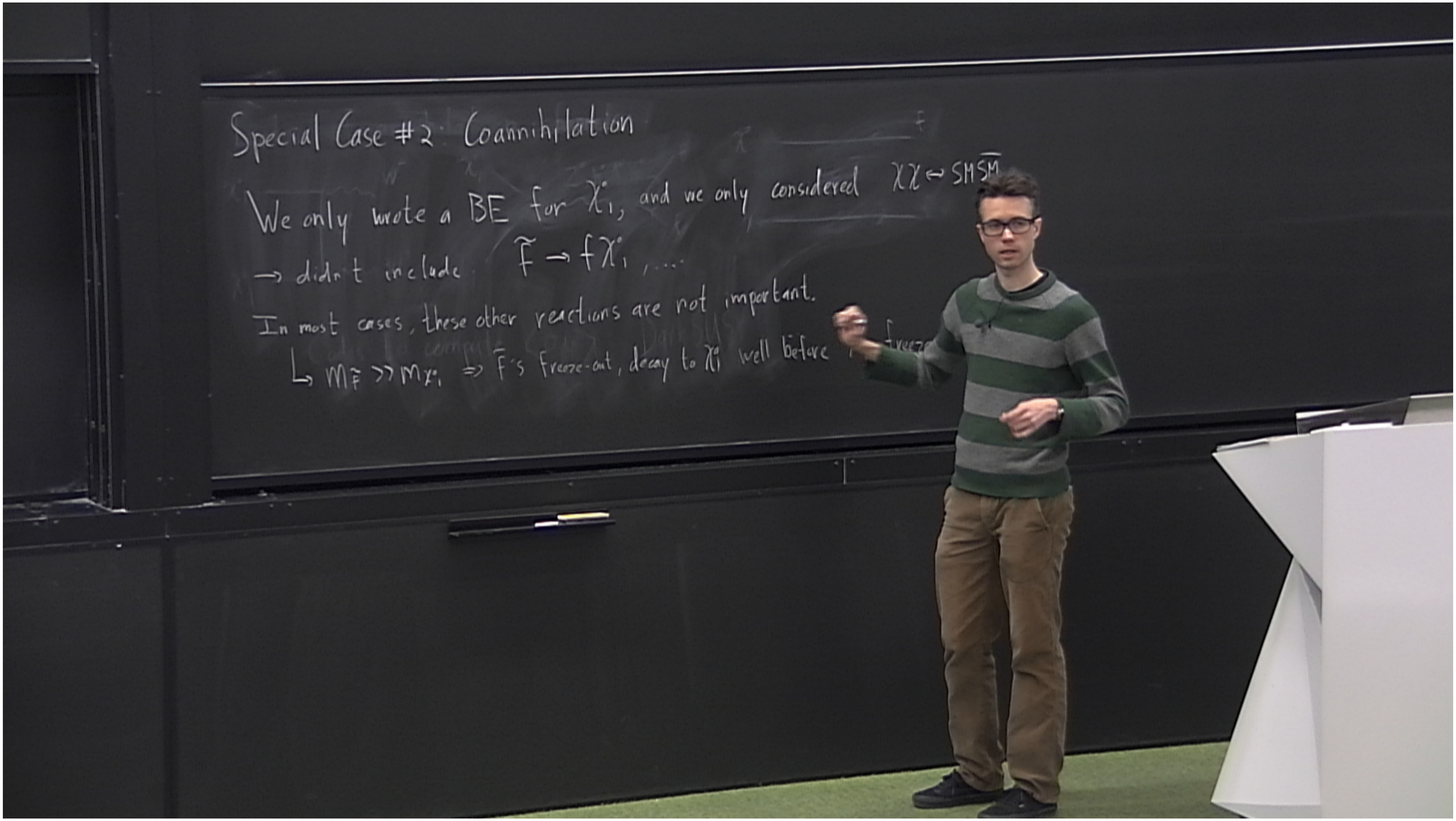
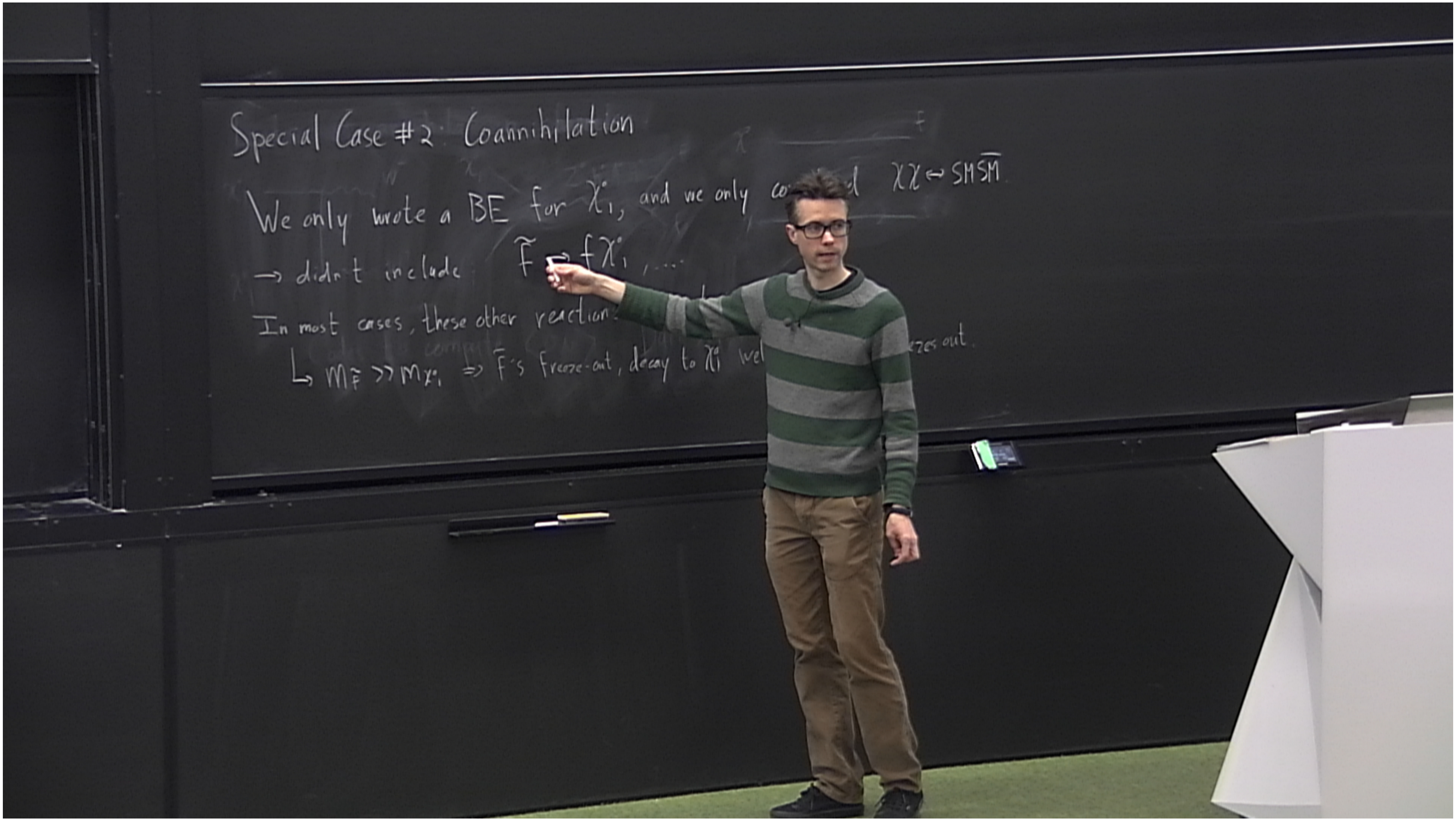
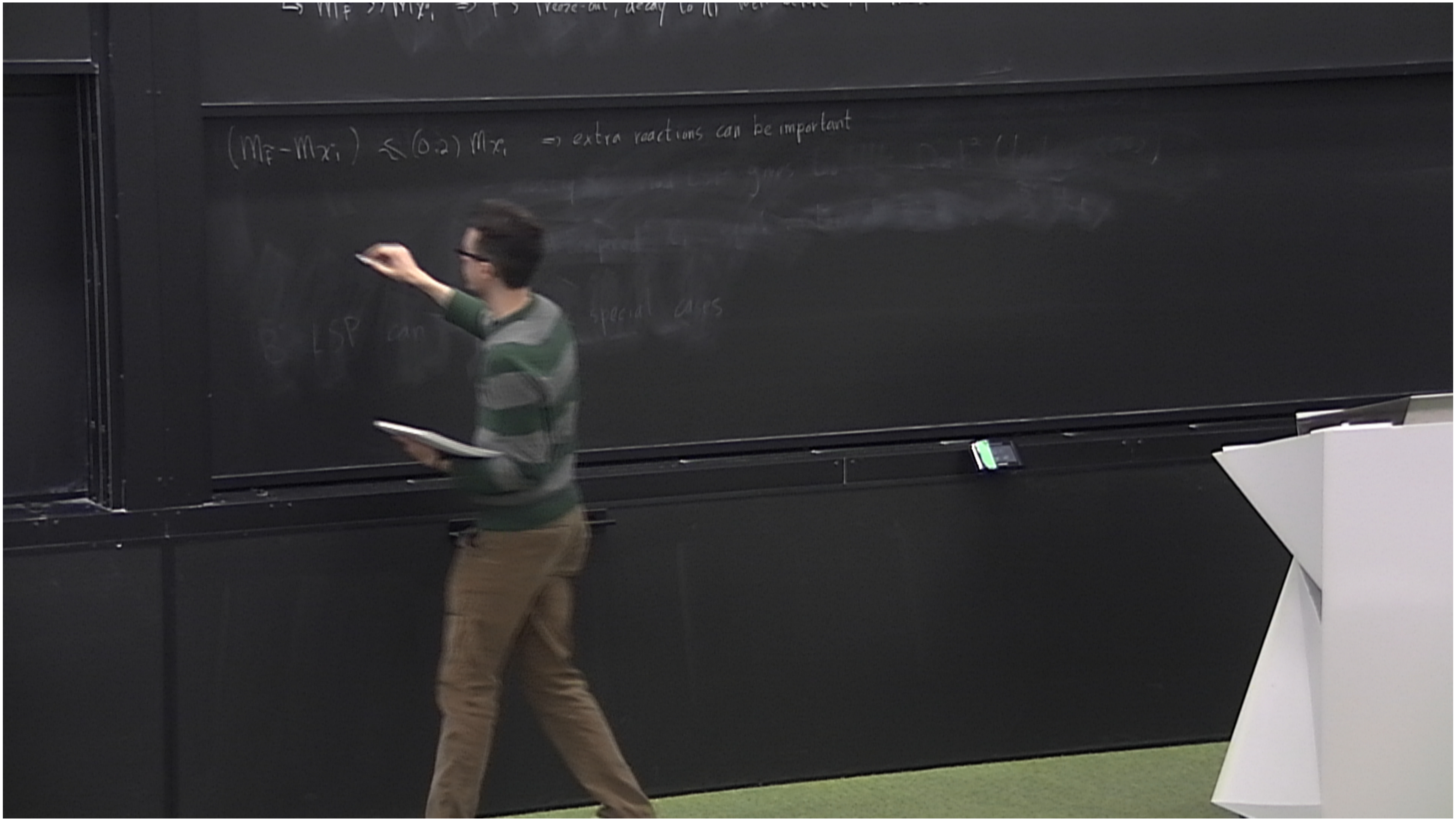

Special Case #2: Coannihilation
We only wrote a BE for χ_1, and we only considered $\chi\chi \leftrightarrow SM\,\overline{SM}$
$\rightarrow$ didn't include $\tilde{F} \rightarrow f\chi_1$, ...

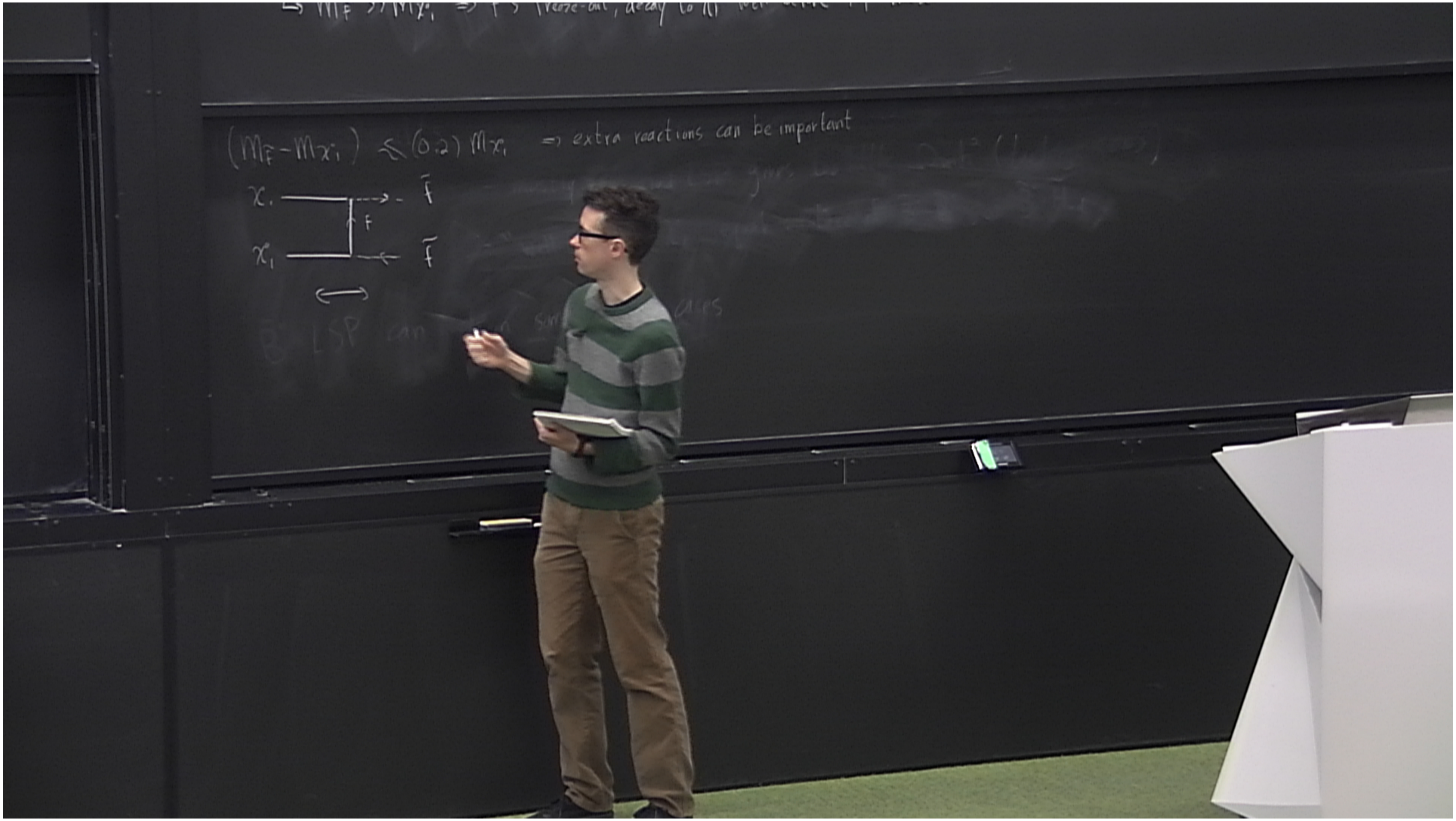

Special Case #2: Coannihilation
We only wrote a BE for χ_1, and we only considered $\chi\chi \leftrightarrow SM\overline{SM}$
→ didn't include $\tilde{F} \to f\chi_1$, ...
In most cases, these other reactions are not important

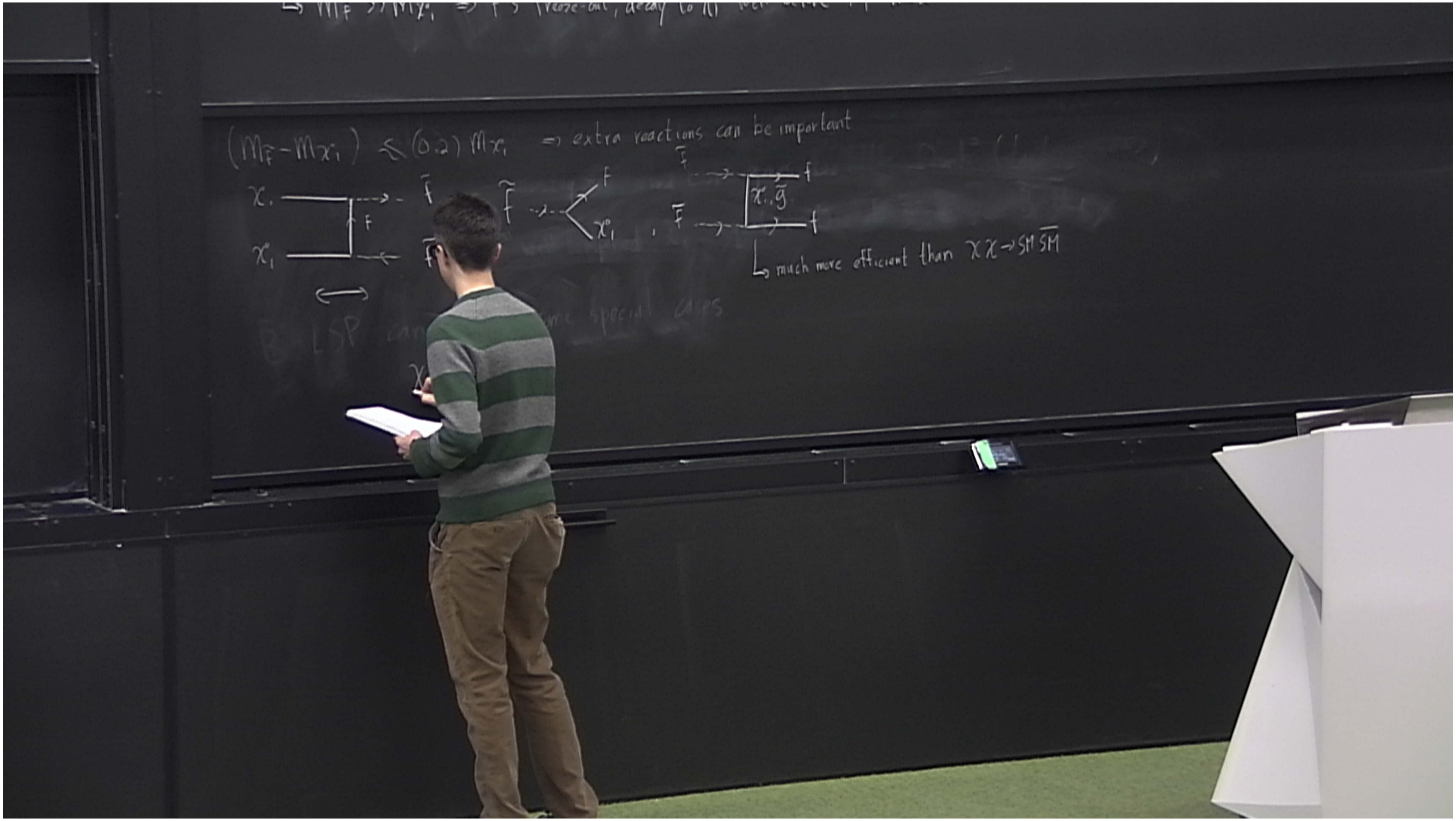

Special Case #2 Coannihilation
We only wrote a BE for $\tilde{\chi}_1$,
only considered $\chi\chi \leftrightarrow SM\overline{SM}$
→ didn't include $\tilde{F} \to f\tilde{\chi}_1$
In most cases, these other reactions
rtant.
↳ $m_{\tilde{F}} \gg m_{\tilde{\chi}_1}$

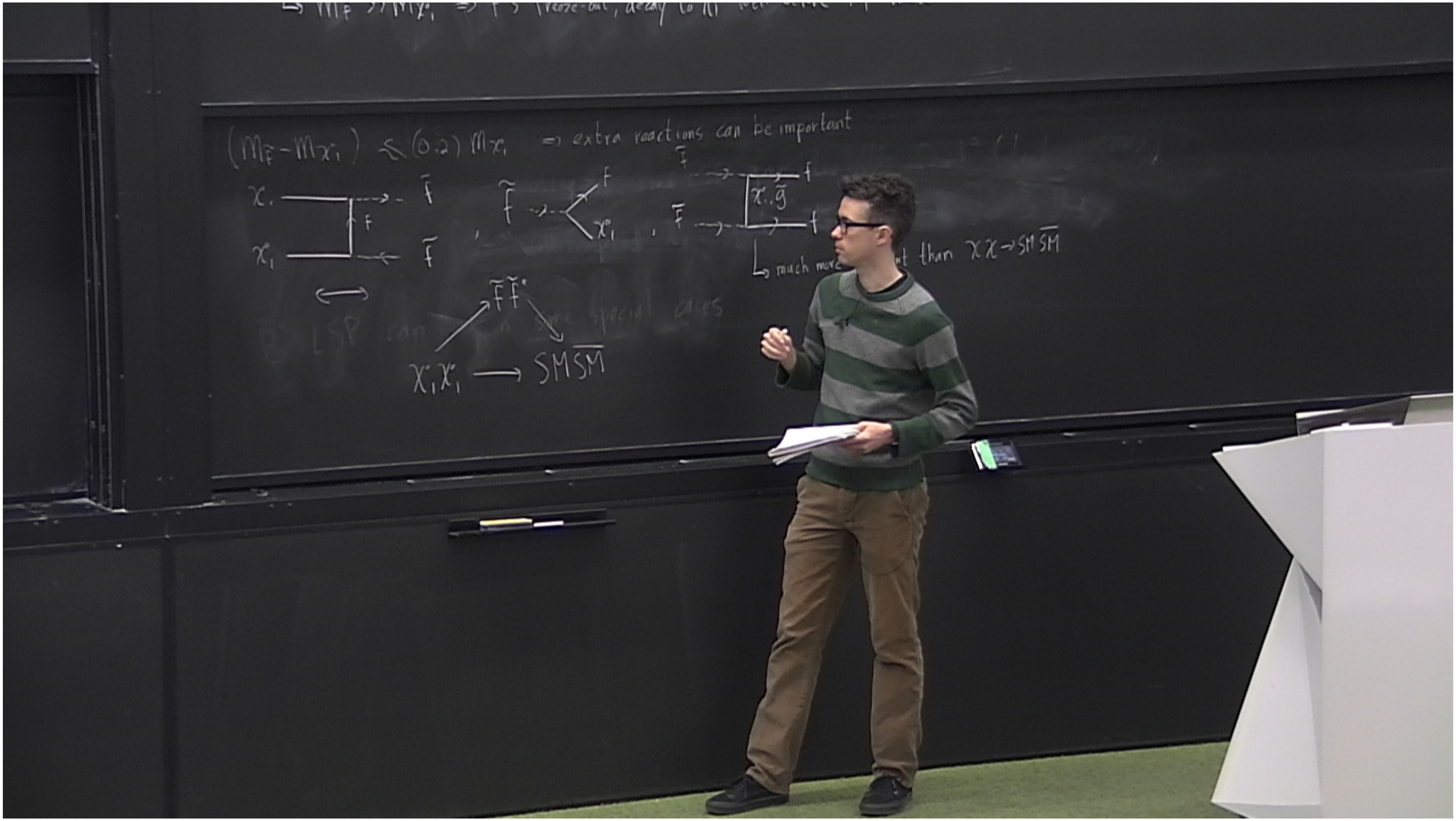

Special Case #2: Coannihilation
We only wrote a BE for χ₁⁰, and we only considered χχ ↔ SM S̄M̄
→ didn't include F̃ → f χ₁⁰, ...
In most cases, these other reactions are not important.
↳ m_F̃ >> m_χ₁⁰ ⇒ F̃'s freeze-out, decay to χ₁⁰ well before

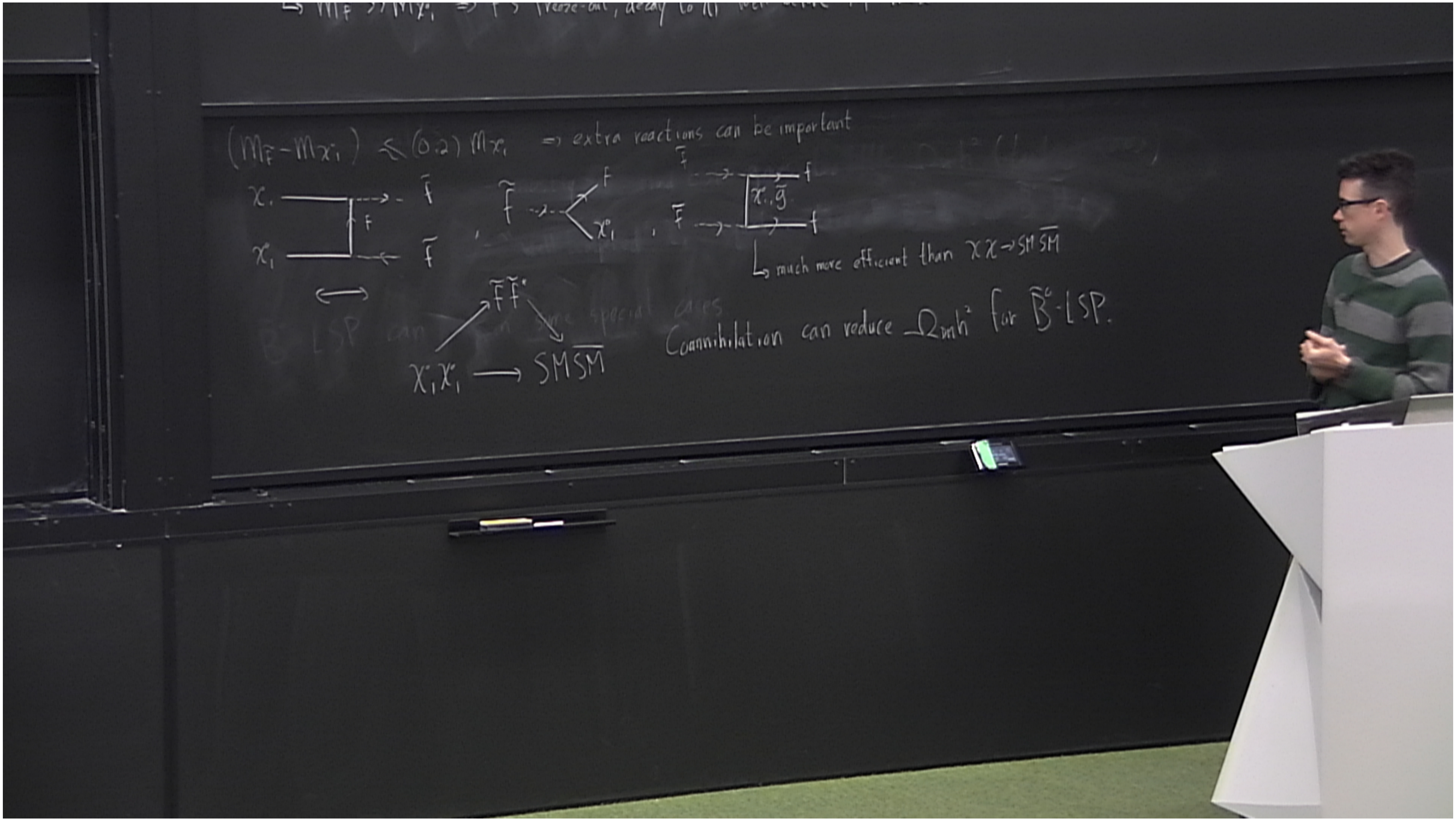

Special Case #2: Coannihilation
We only wrote a BE for χ1, and we only co
χχ ↔ SM SM
→ didn't include F̃ → f χ1, ...
In most cases, these other reaction
L→ mF̃ >> mχ1 ⇒ F̃'s freeze-out, decay to χ1 wel
zes out.

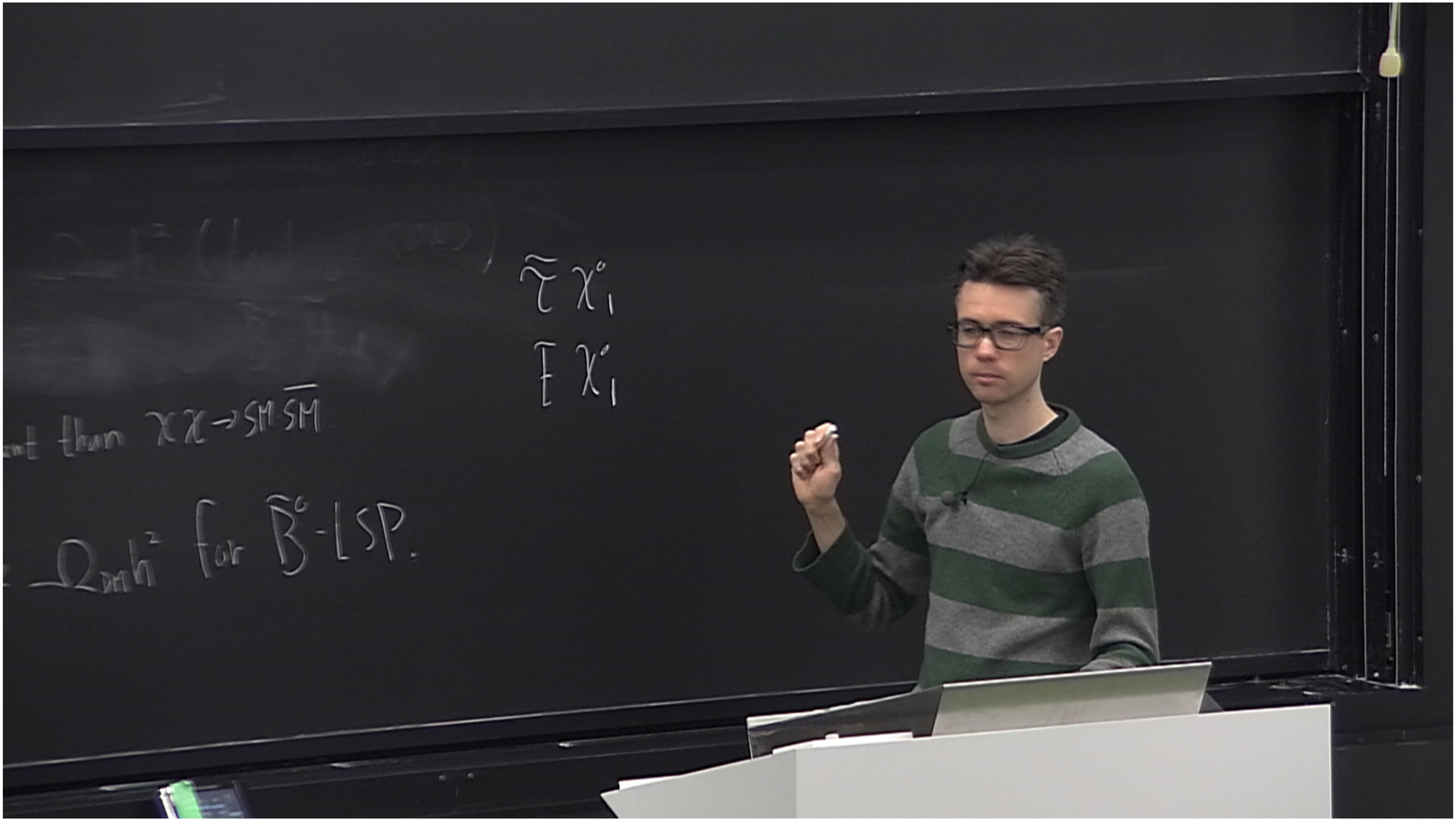

$(m_{\tilde f} - m_{\chi_1}) \lesssim (0.2)\, m_{\chi_1}$ $\Rightarrow$ extra reactions can be important

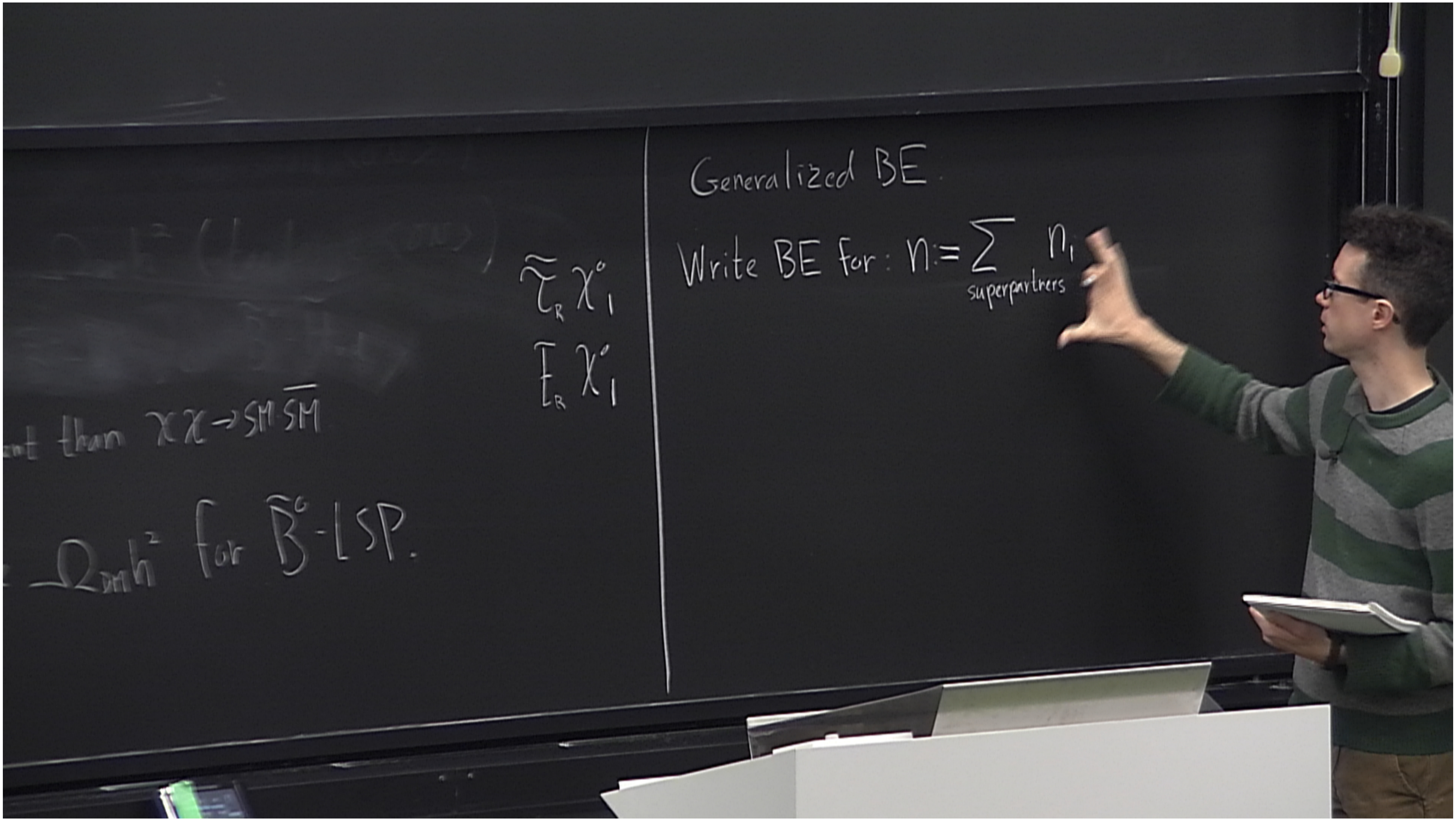

(mf̃ - mχ1) ≲ (0.2) mχ1 ⇒ extra reactions can be important


(m_f̃ − m_χ1) ≲ (0.2) m_χ1 ⇒ extra reactions can be important
much more efficient than χχ → SM S̄M̄

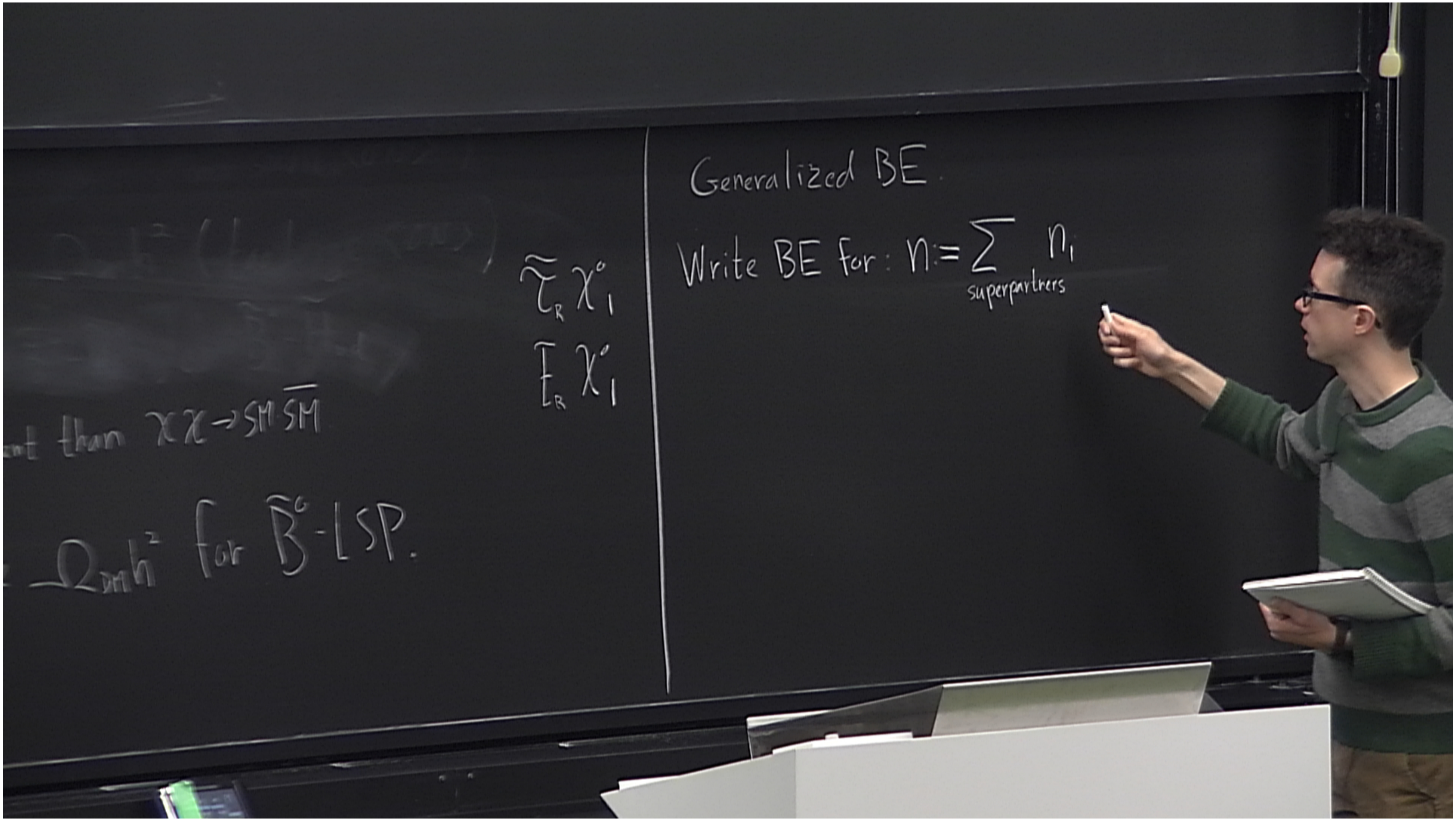

$(m_{\tilde{f}} - m_{\chi_1}) \lesssim (0.2)\, m_{\chi_1}$ ⇒ extra reactions can be important
$\chi_1 \chi_1 \longrightarrow SM\overline{SM}$


$(m_{\tilde{f}} - m_{\chi_1}) \lesssim (0.2)\, m_{\chi_1}$ ⇒ extra reactions can be important
↳ much more efficient than $\chi\chi \to SM\,\overline{SM}$
Coannihilation can reduce $\Omega_m h^2$ for $\tilde{B}^0$-LSP.
$\chi_1\chi_1 \longrightarrow SM\,\overline{SM}$


$\tilde{\tau}\ \chi^0_1$
$\tilde{e}\ \chi^0_1$
nt than $\chi\chi \to SM\ \overline{SM}$
$\Omega_{DM} h^2$ for $\tilde{B}^0$-LSP.



Generalized BE
Write BE for: n = Σ n_i
superpartners
than χχ → SM SM
Ω_DM h² for B̃⁰-LSP.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Write BE for: n = Σ n_i
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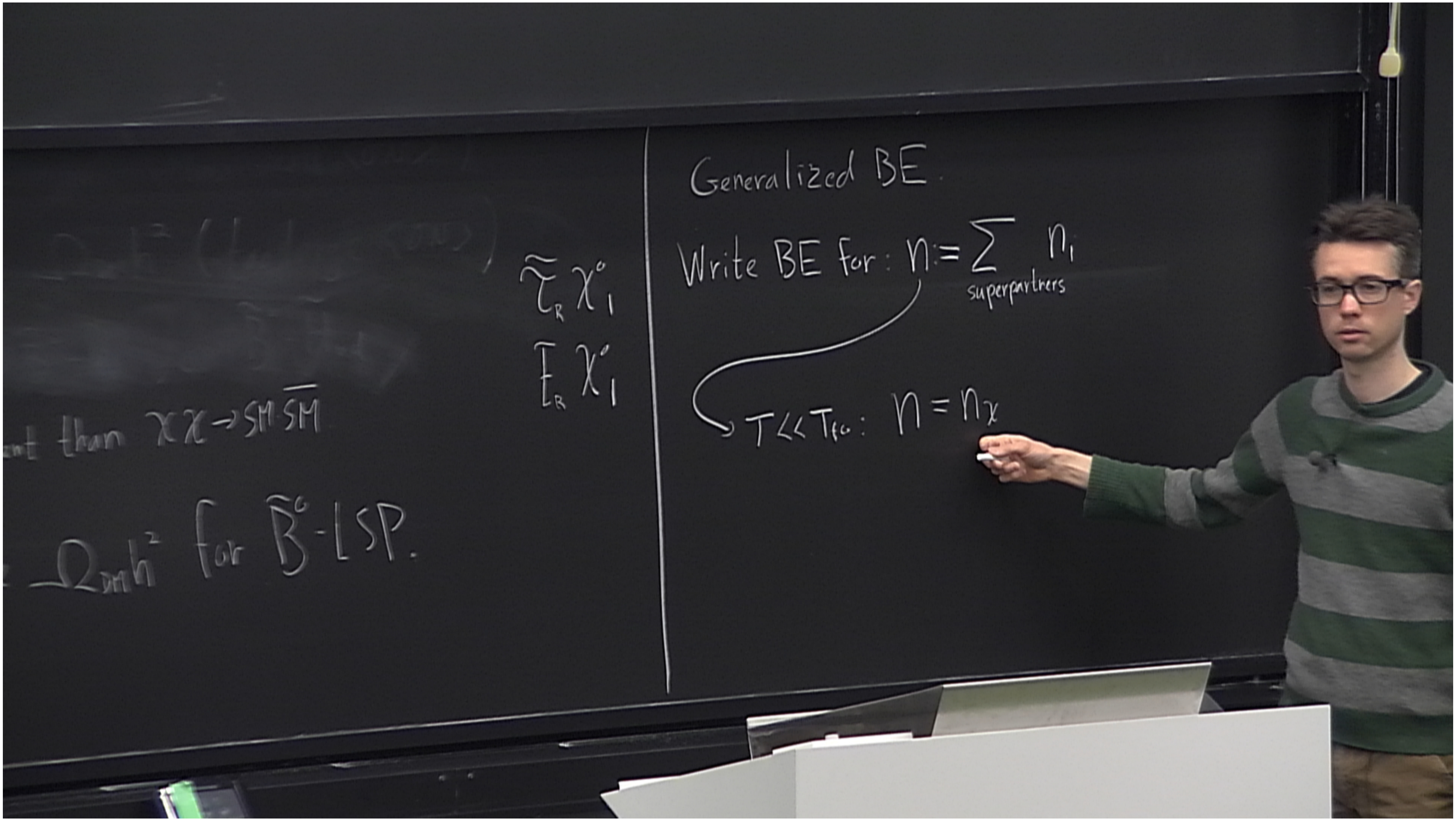
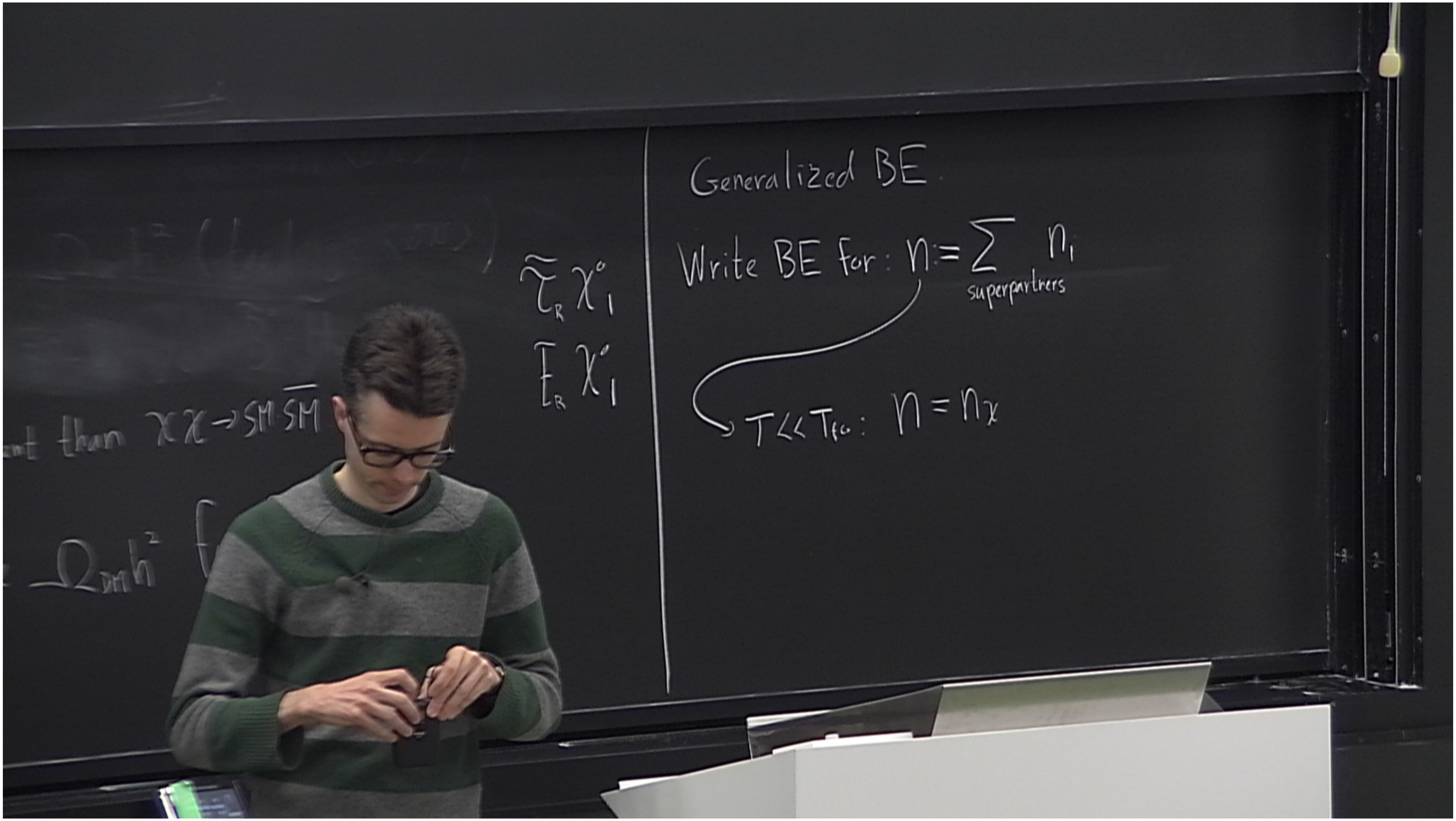

Generalized BE
Write BE for: n = Σ n_i
superpartners
T << T_fo: n = n_χ
than χχ → SM SM
Ω_DM h² for B̃⁰-LSP.
τ̃_R χ⁰_1
ẽ_R χ⁰_1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Write BE for : n = Σ n_i
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T << T_fo : n = n_χ
τ̃_R χ⁰_1
ẽ_R χ⁰_1
than χχ → SM S̄M̄
Ω_DM h²