Title: BSM Theory

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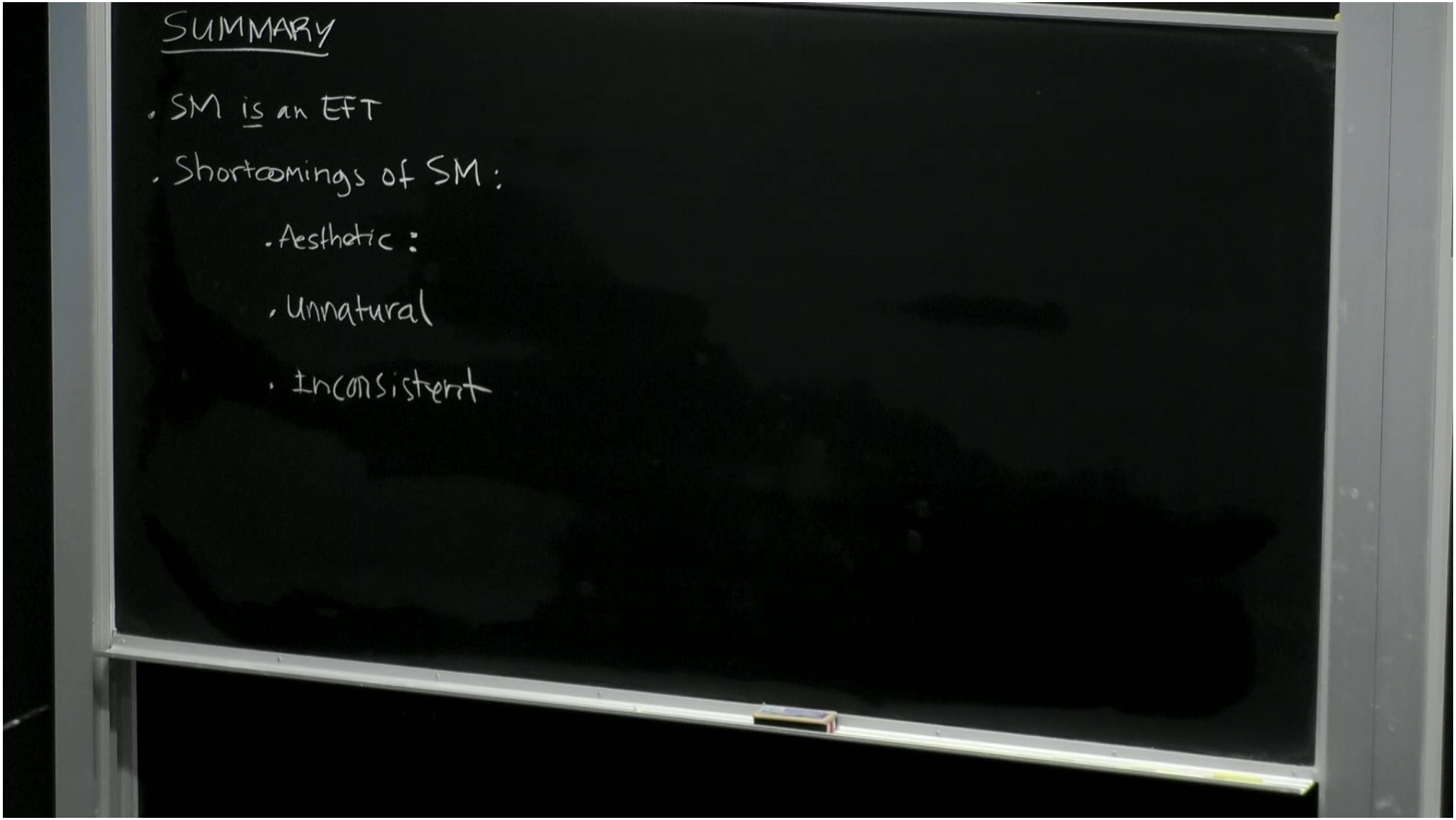
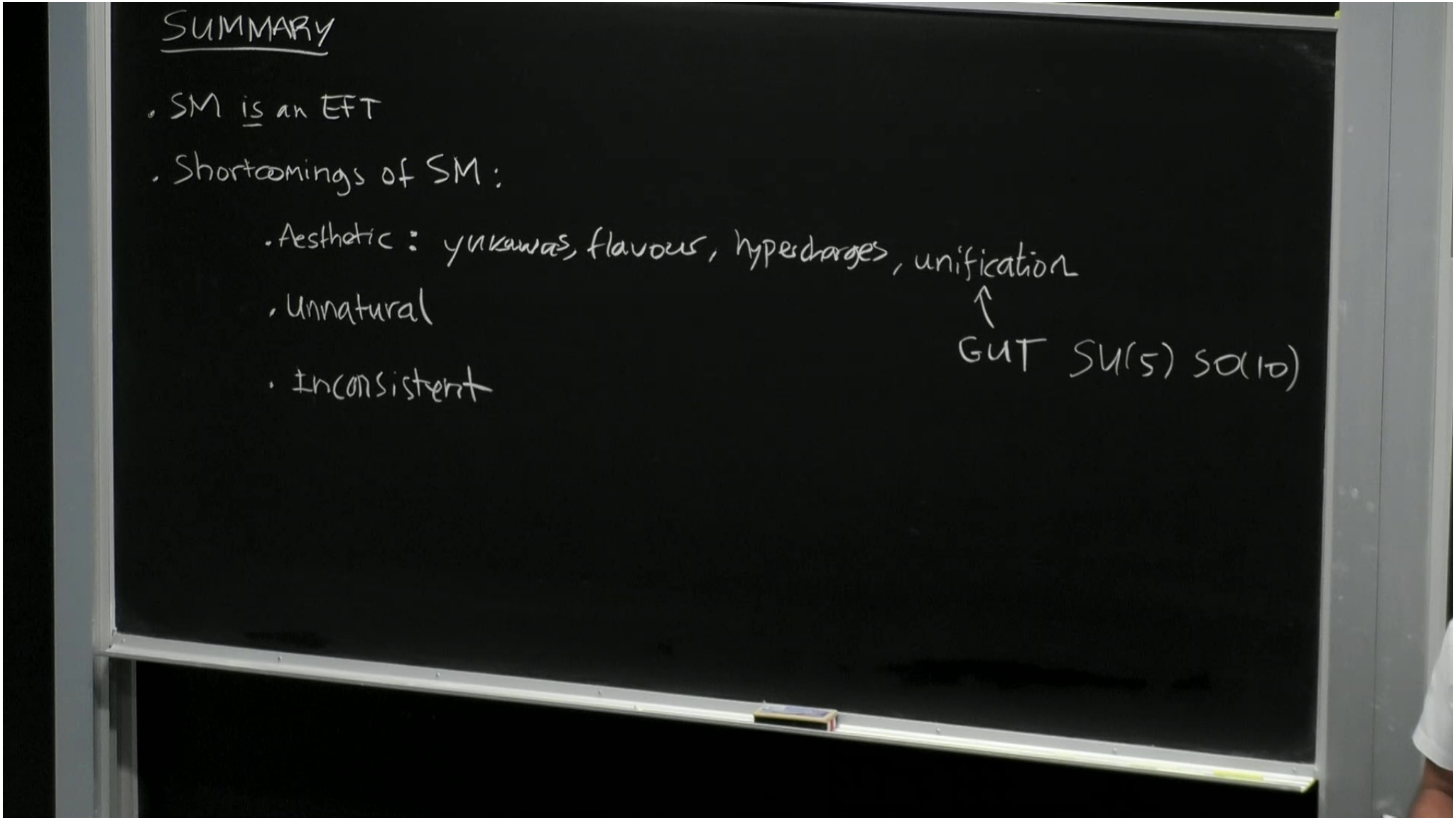

SUMMARY
. SM is an EFT
. Shortcomings of SM:
. Aesthetic:
. Unnatural
. Inconsistent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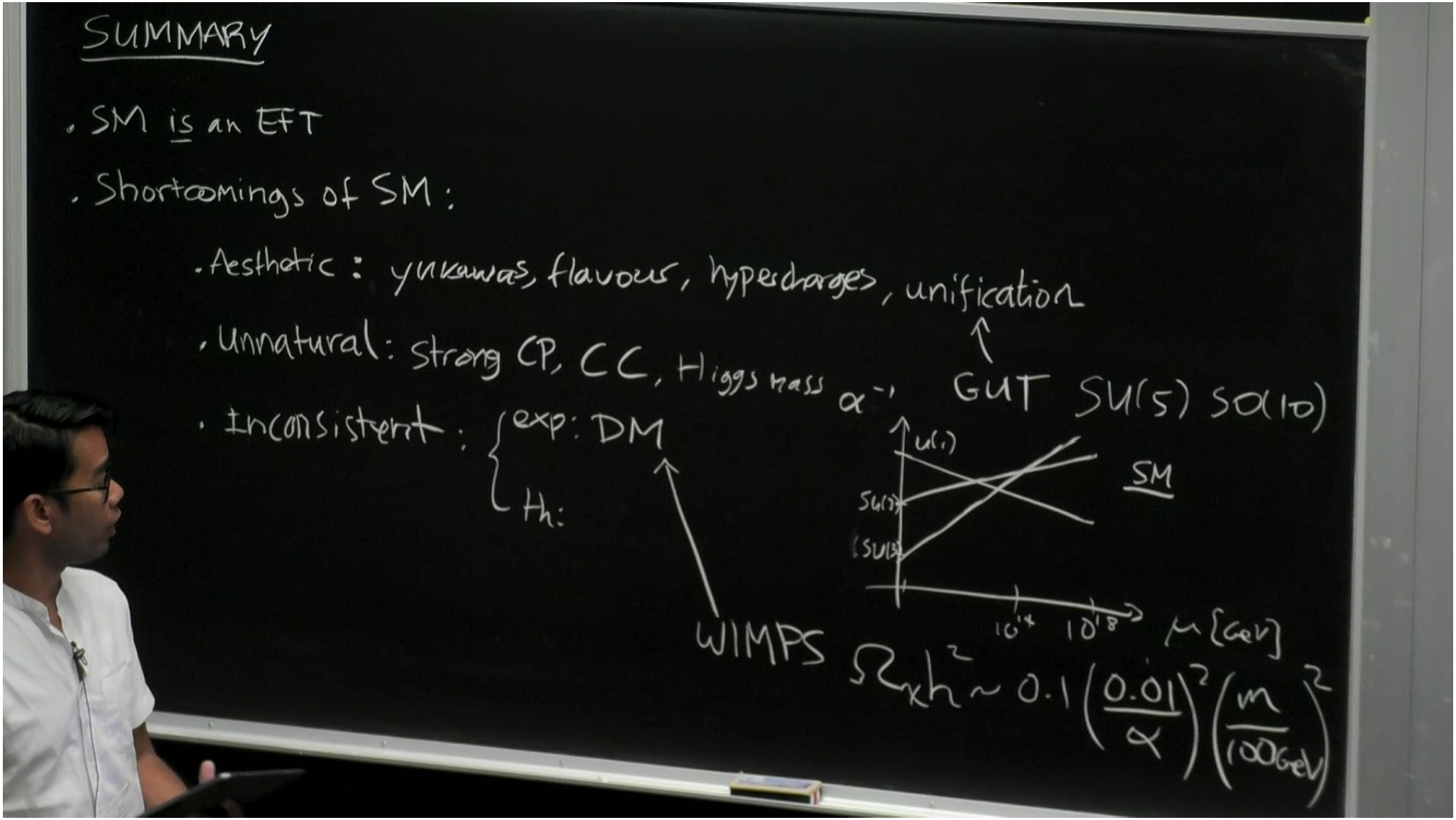
. Aesthetic: yukawas, flavours, hypercharges, unification
. Unnatural
. Inconsistent
GUT SU(5) SO(10)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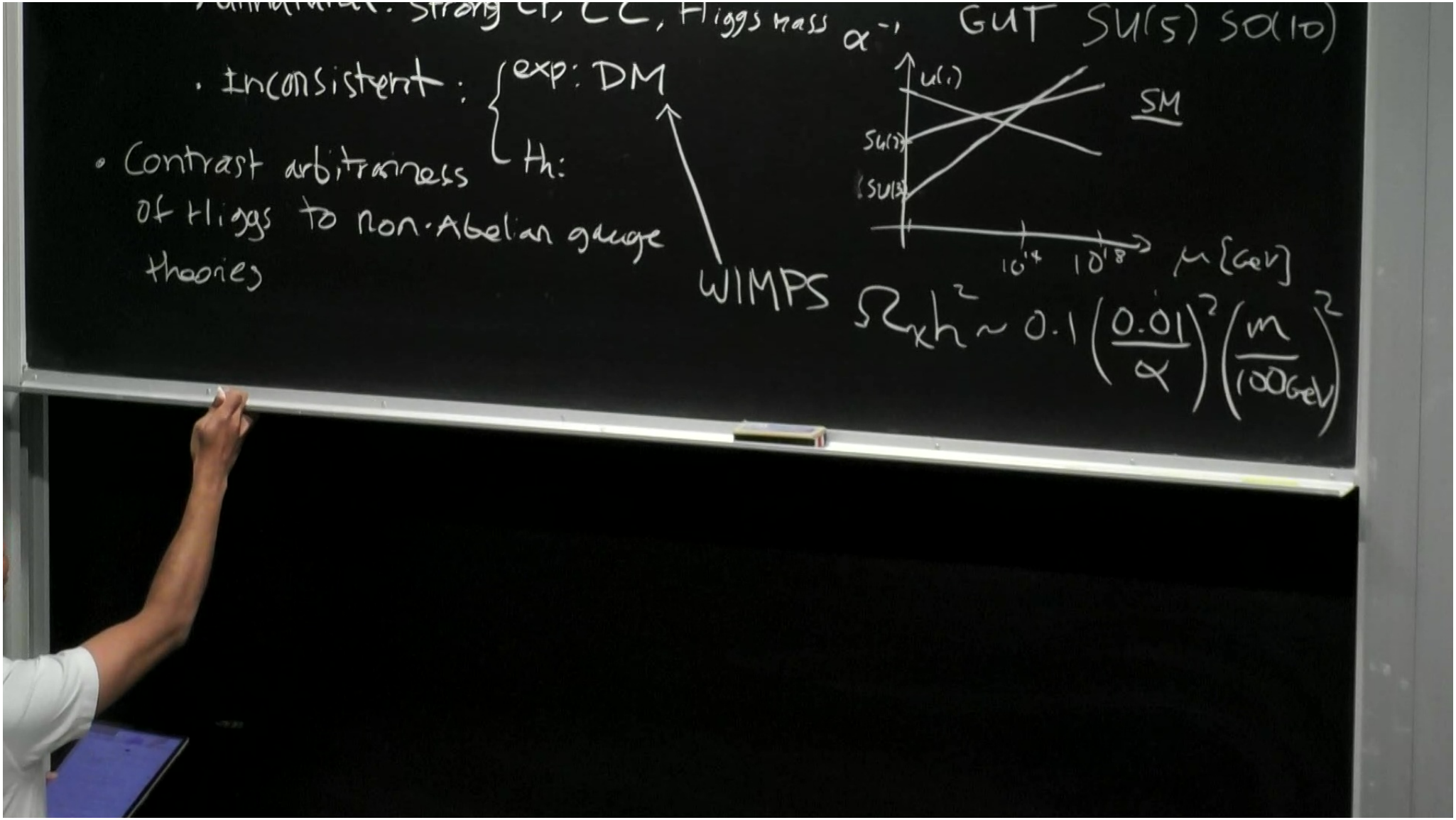
• SM is an EFT
• Shortcomings of SM:
• Aesthetic: yukawas, flavours, hypercharges, unification
• Unnatural: strong CP, CC, Higgs mass
• Inconsistent: { exp: DM, th:
GUT SU(5) SO(10)
α⁻¹
U(1)
SU(2)
SU(3)
SM
10¹⁴ 10¹⁸ μ [GeV]
WIMPS
$\Omega_\chi h^2 \sim 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\,\mathrm{GeV}}\right)^2$


Strong CP, EC, Higgs mass
GUT SU(5) SO(10)
• Inconsistent: exp: DM
Th:
• Contrast arbitrariness of Higgs to non-Abelian gauge theories
U(1)
SM
SU(2)
SU(3)
$10^{14}$ $10^{18}$ μ [GeV]
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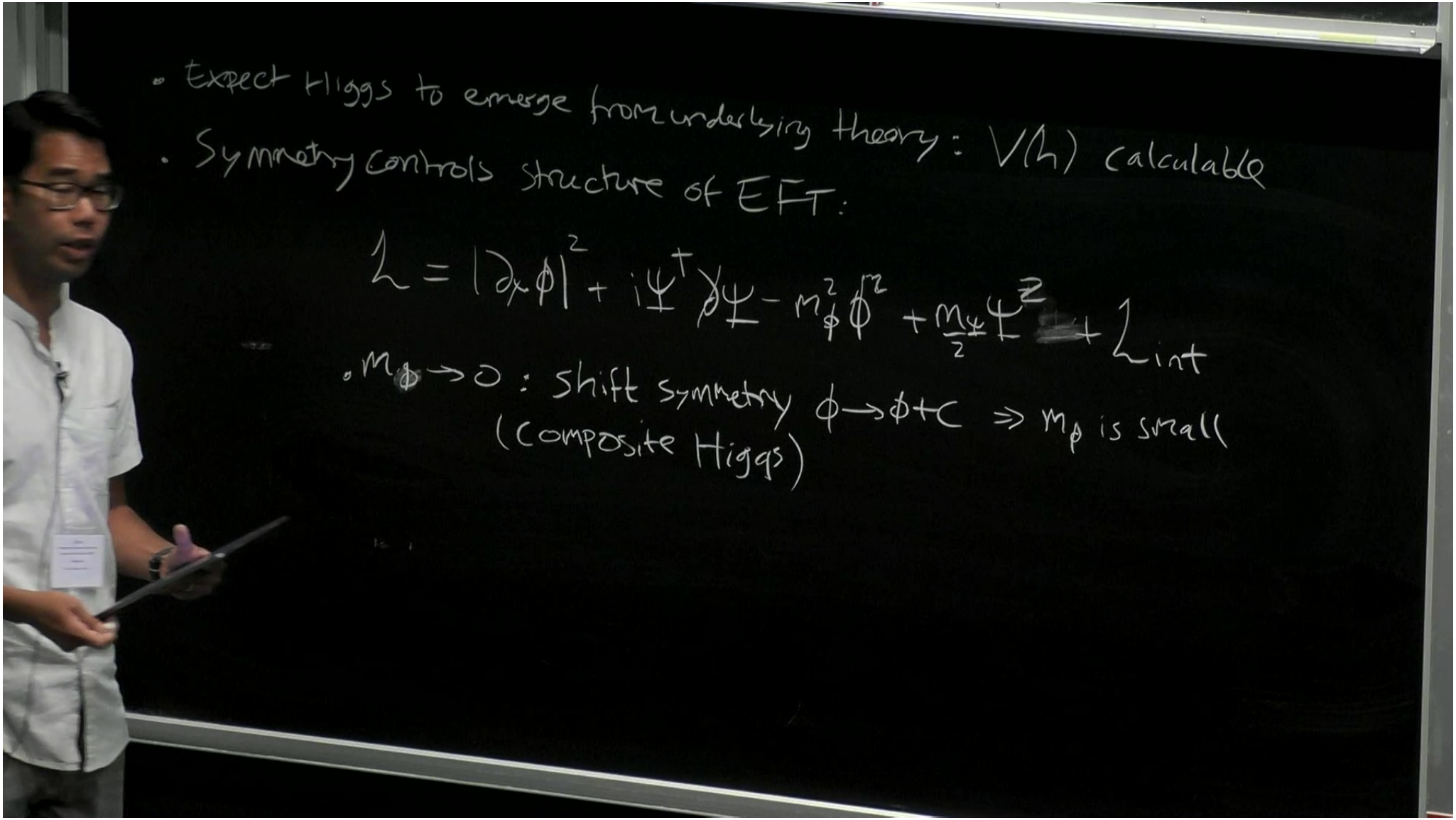
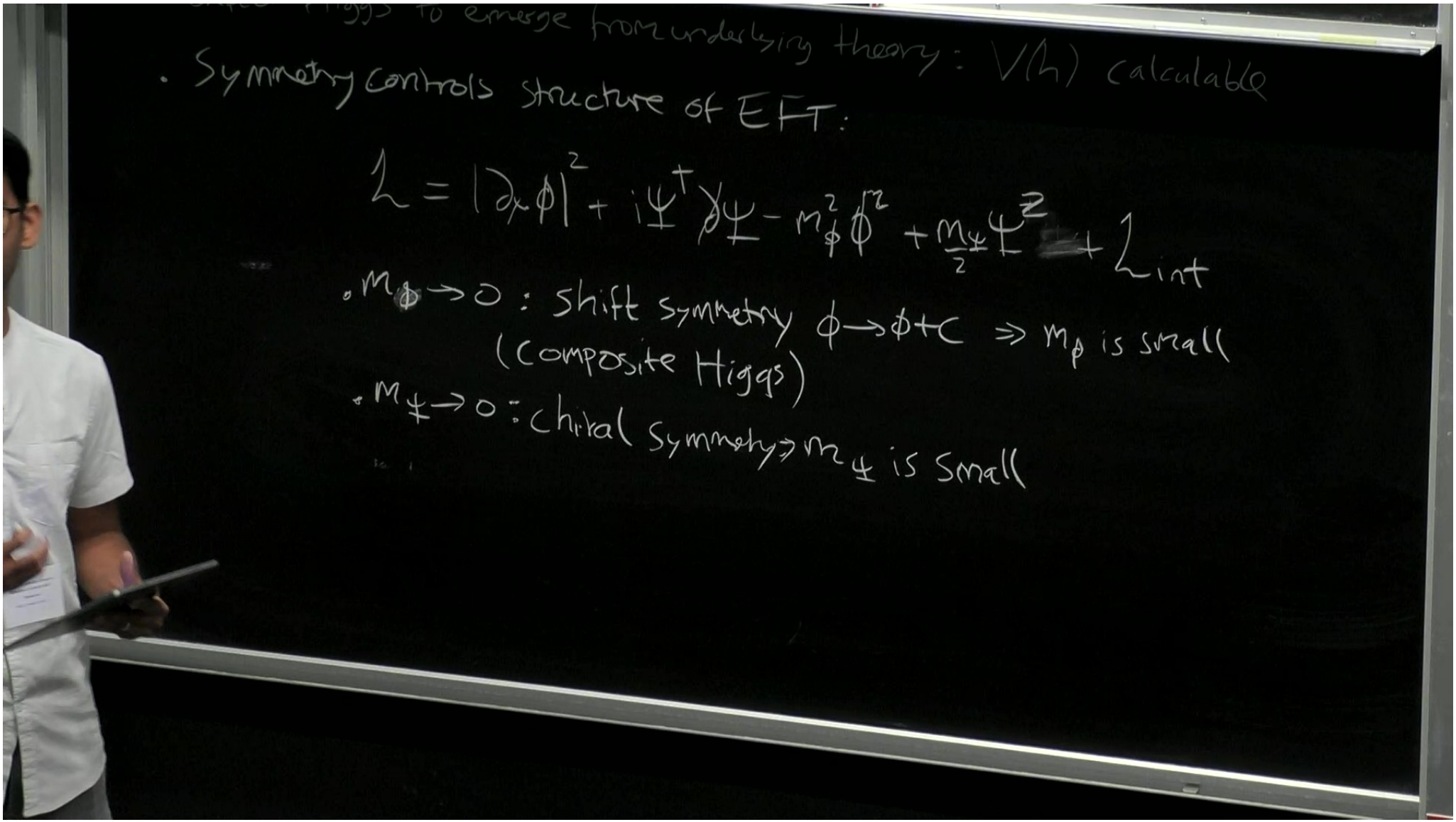

• Expect Higgs to emerge from underlying theory: V(h) calculable
• Symmetry controls structure of EFT:
$\mathcal{L} = |\partial_\mu \phi|^2 + i\Psi^\dagger \bar{\sigma}^\mu \partial_\mu \Psi - m_\phi^2 \phi^2 + \frac{m_\Psi}{2} \Psi^2 + \mathcal{L}_{int}$
• $m_\phi \to 0$ : shift symmetry $\phi \to \phi + c$ ⇒ $m_\phi$ is small
(composite Higgs)


to emerge from underlying theory: V(h) calculable
Symmetry controls structure of EFT:
$\mathcal{L} = |\partial_\mu \phi|^2 + i\Psi^\dagger \gamma \Psi - m_\phi^2 \phi^2 + \frac{m_\Psi}{2} \Psi^2 + \mathcal{L}_{int}$
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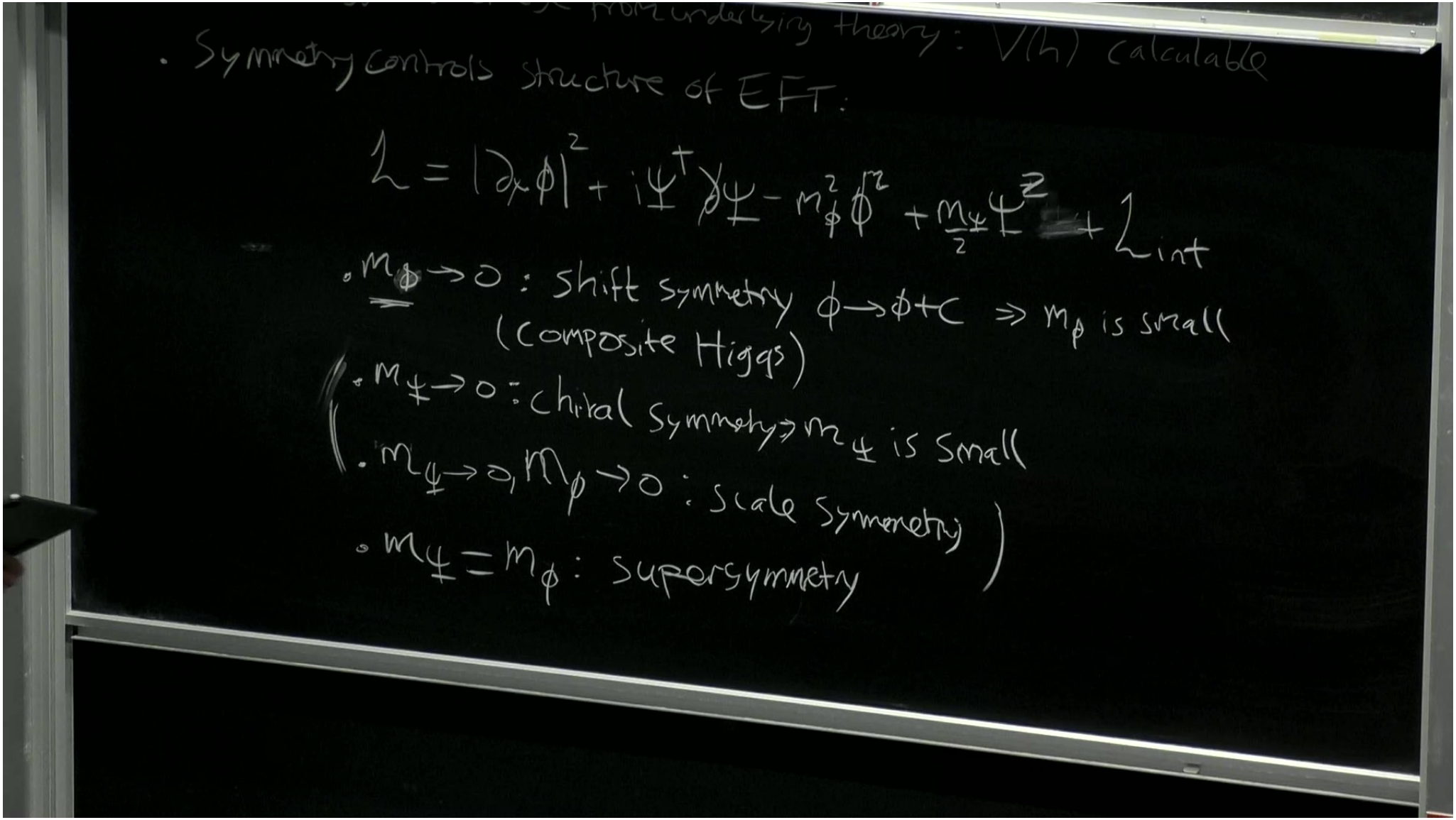
(composite Higgs)
$m_\Psi \to 0$: chiral symmetry $\Rightarrow m_\Psi$ is small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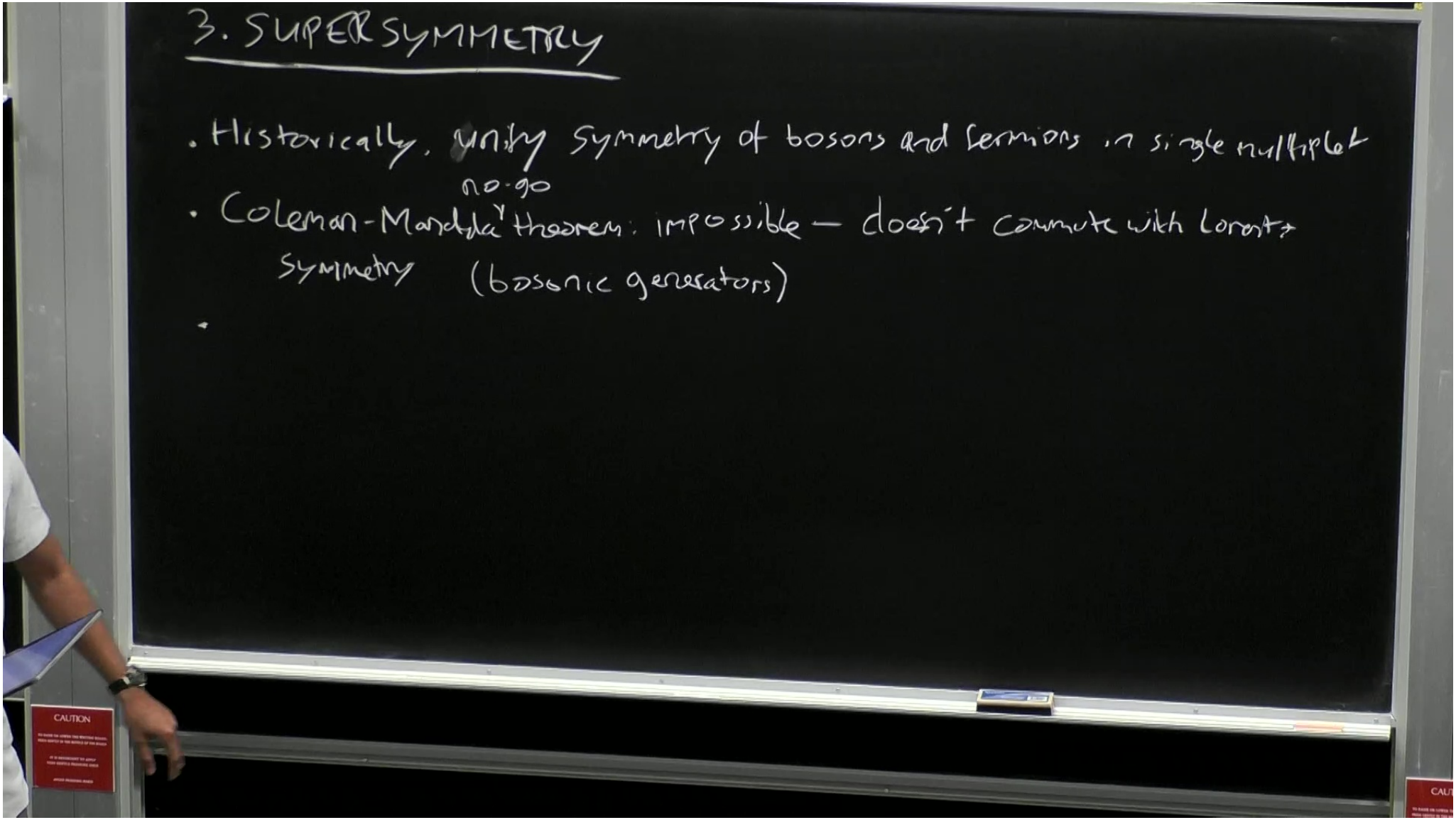
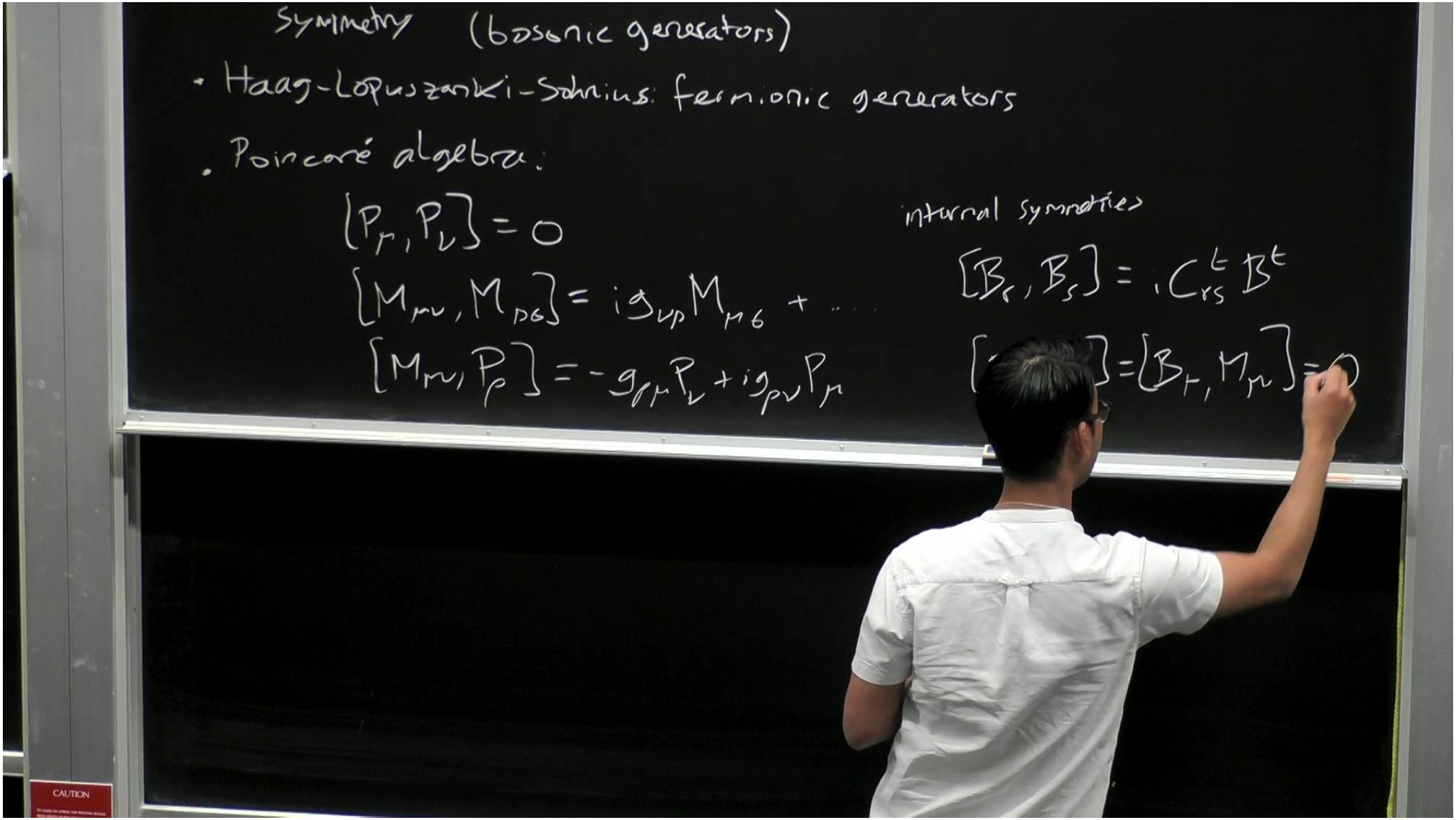
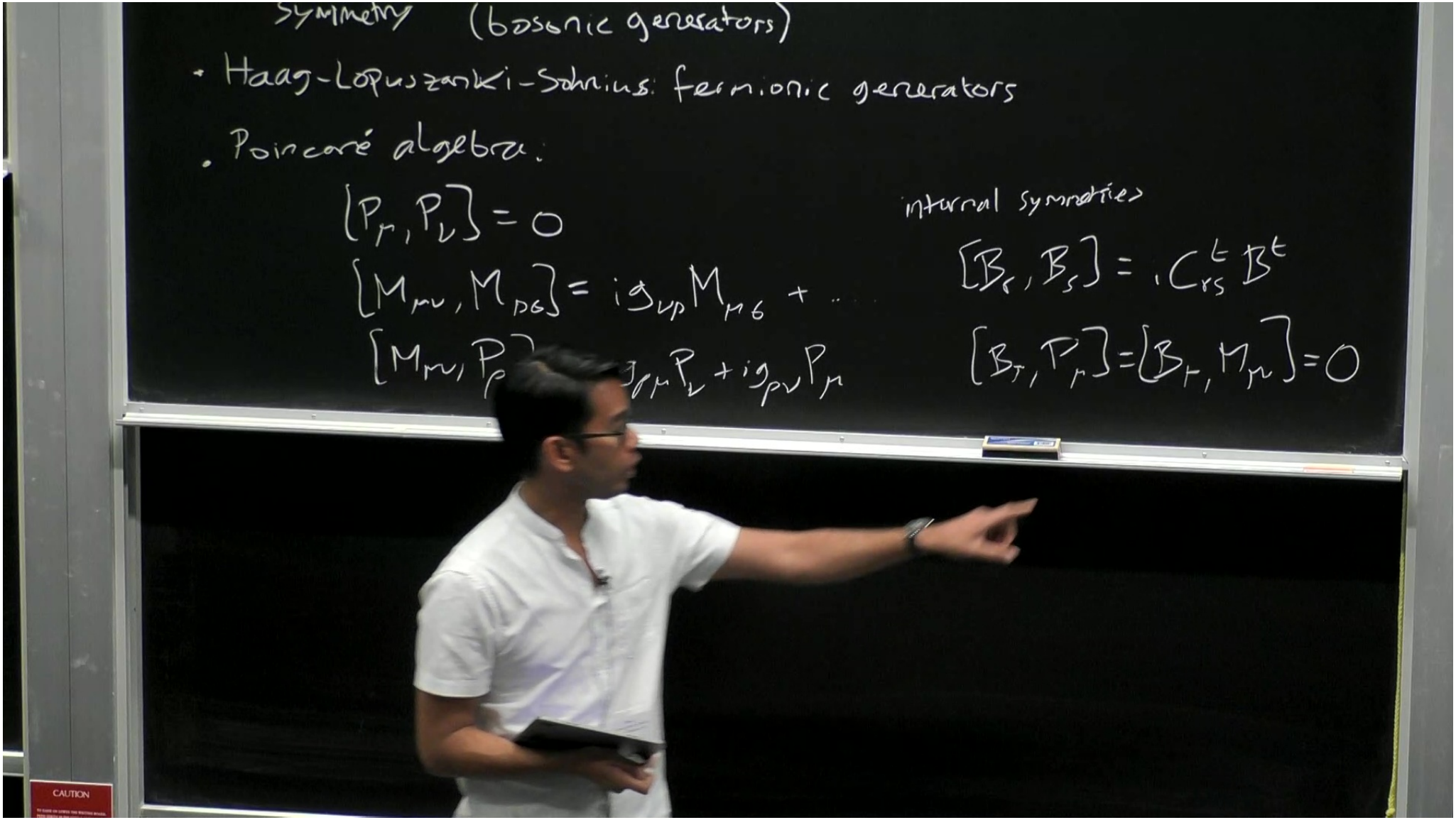
$m_\psi \to 0$: chiral symmetry $\Rightarrow m_\psi$ is small
$m_\psi \to 0, m_\phi \to 0$: scale symmetry
$m_\psi = m_\phi$: supersymmetry


3. SUPERSYMMETRY
• Historically, unity Symmetry of bosons and fermions in single multiplet
no-go
• Coleman-Mandula theorem: impossible — doesn't commute with Lorentz
Symmetry (bosonic generators)
•
CAUTION


Symmetry (bosonic generators)
• Haag-Lopuszanski-Sohnius: fermionic generators
• Poincaré algebra:
$[P_\mu, P_\nu] = 0$
$[M_{\mu\nu}, M_{\rho\sigma}] = i g_{\nu\rho} M_{\mu\sigma} + \ldots$
$[M_{\mu\nu}, P_\rho] = -g_{\rho\mu} P_\nu + i g_{\rho\nu} P_\mu$
internal symmetries
$[B_r, B_s] = i C_{rs}^t B^t$
$[\ ] = [B_r, M_{\mu\nu}] = 0$
CAUTION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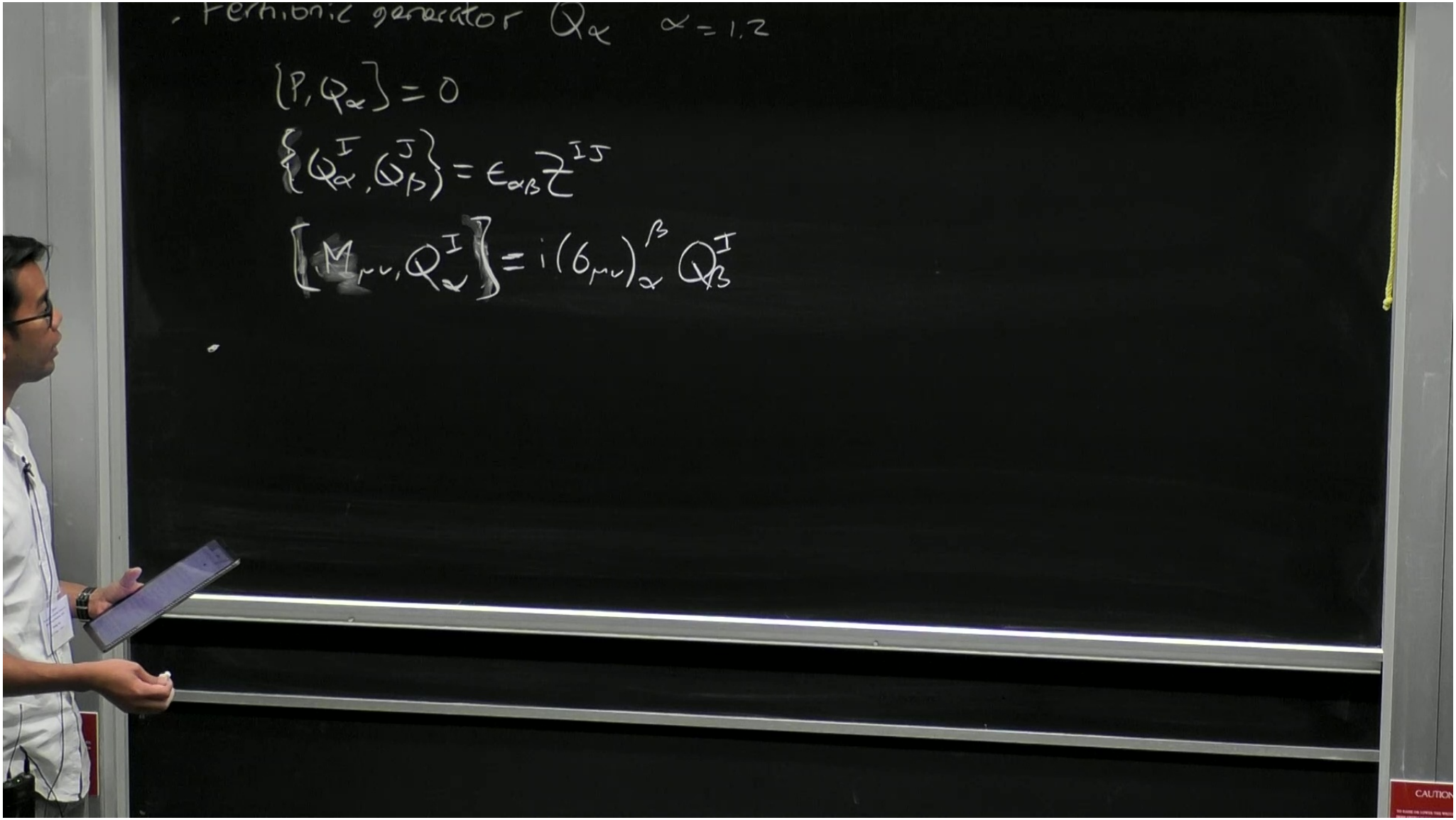
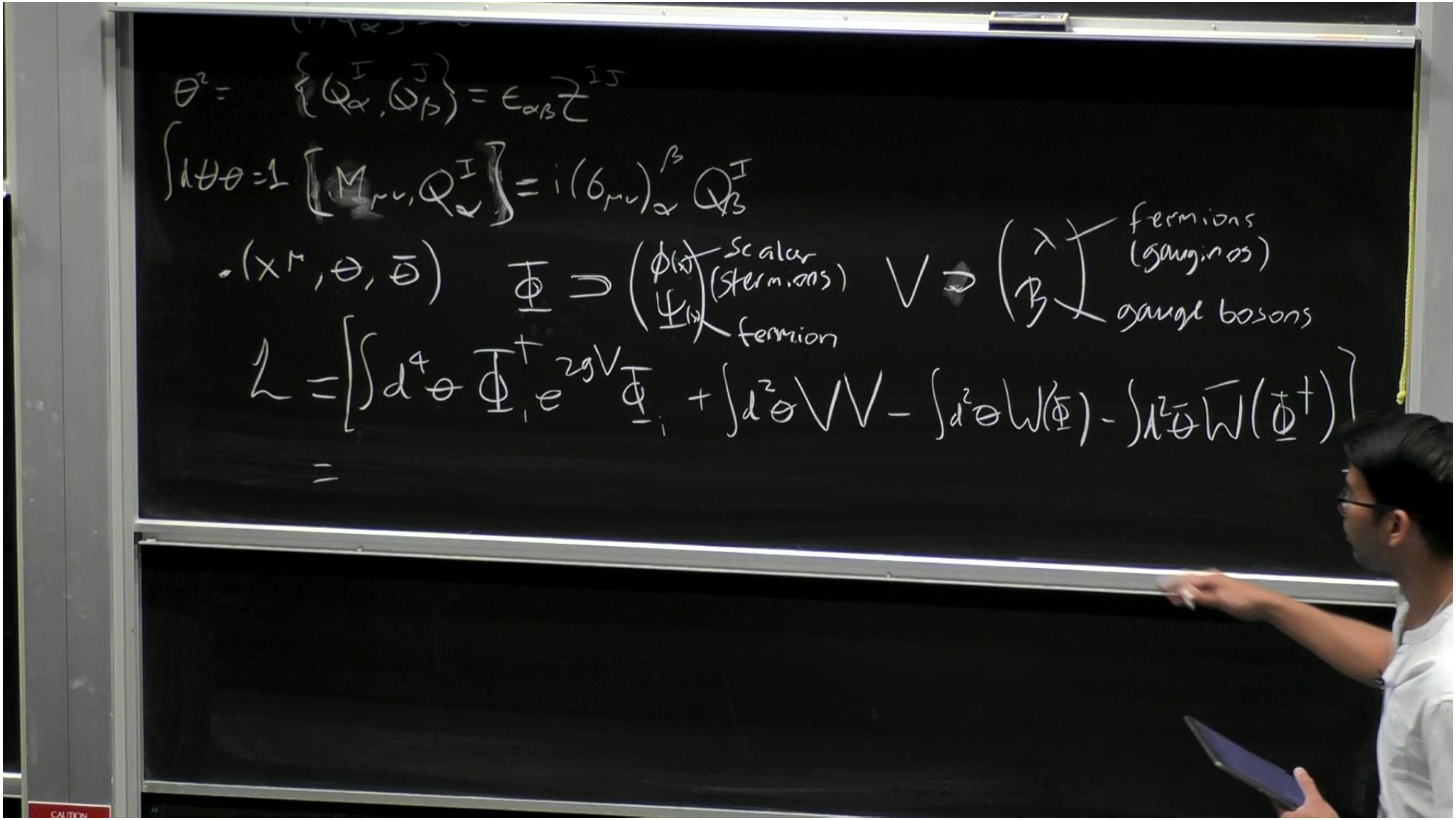
$[B_r, P_\mu] = [B_r, M_{\mu\nu}] = 0$
CAUTION

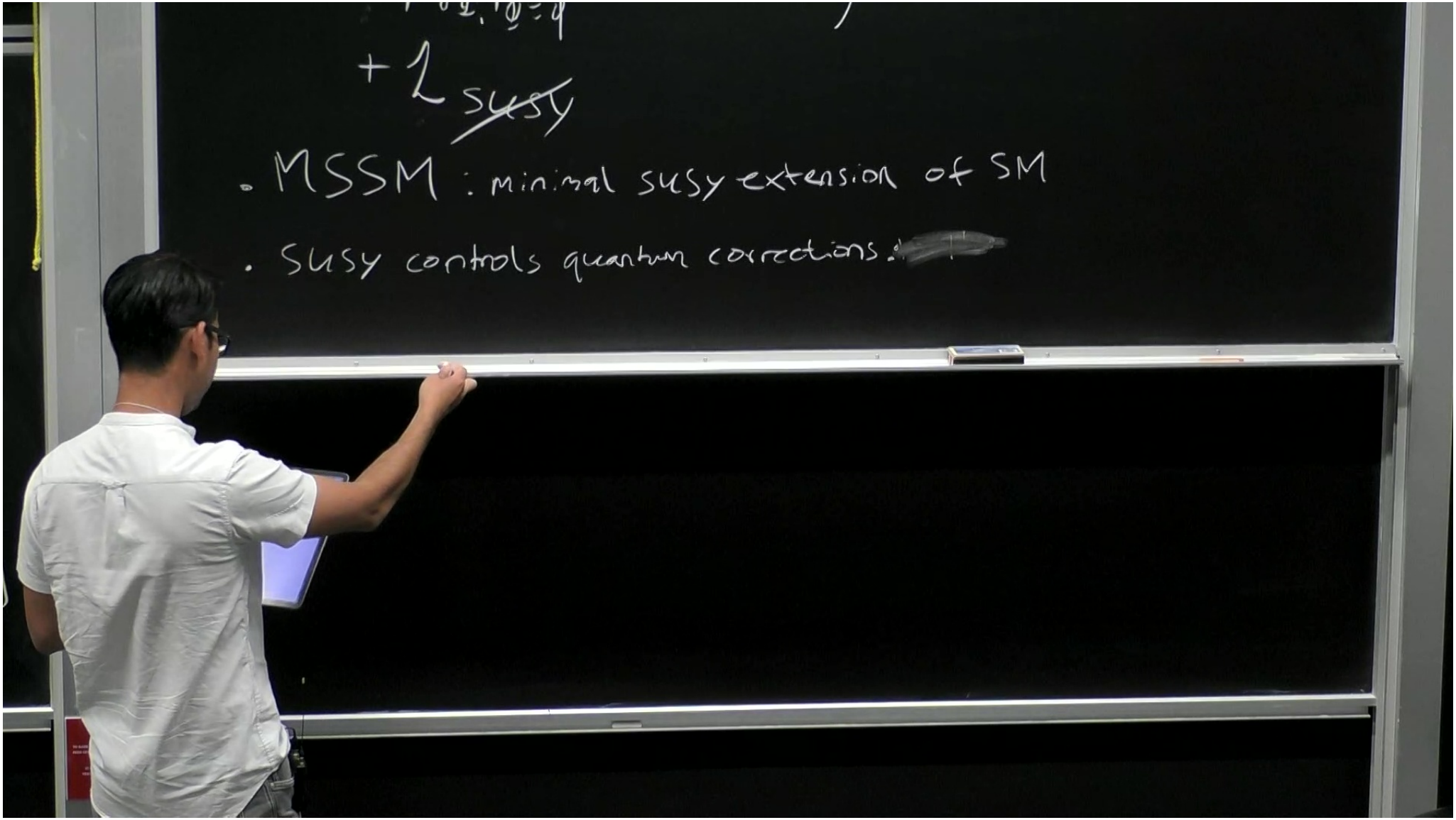

Fermionic generator $Q_\alpha$ $\alpha = 1,2$
$\{P, Q_\alpha\} = 0$
$\{Q^I_\alpha, \bar{Q}^J_\beta\} = \epsilon_{\alpha\beta} Z^{IJ}$
$[M_{\mu\nu}, Q^I_\alpha] = i(\sigma_{\mu\nu})^\beta_\alpha Q^I_\beta$

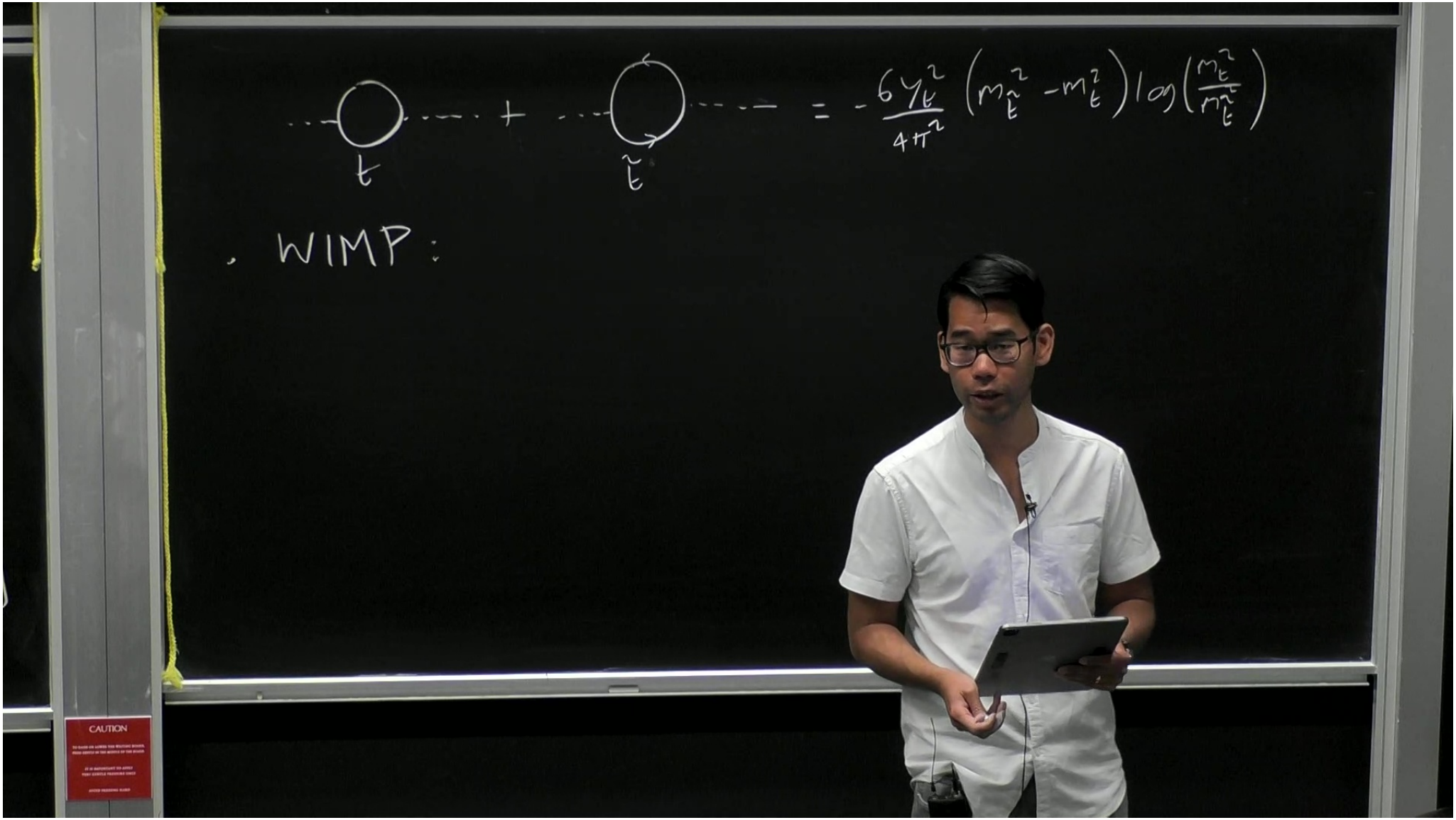

$\theta^2 = \{Q_\alpha^I, Q_\beta^J\} = \epsilon_{\alpha\beta} Z^{IJ}$
$\int d\theta\theta = 1$
$[M_{\mu\nu}, Q_\nu^I] = i(\sigma_{\mu\nu})_\alpha^\beta Q_\beta^I$
$(x^\mu, \theta, \bar{\theta})$
$\Phi \supset (\phi(x), \psi(x))$
scalar (sfermions)
fermion
$V \supset (\lambda, A)$
fermions (gauginos)
gauge bosons
$\mathcal{L} = [\int d^4\theta \Phi_i^\dagger e^{2gV} \Phi_i + \int d^2\theta VV - \int d^2\theta W(\Phi) - \int d^2\bar{\theta} \bar{W}(\Phi^\dagger)]$
=

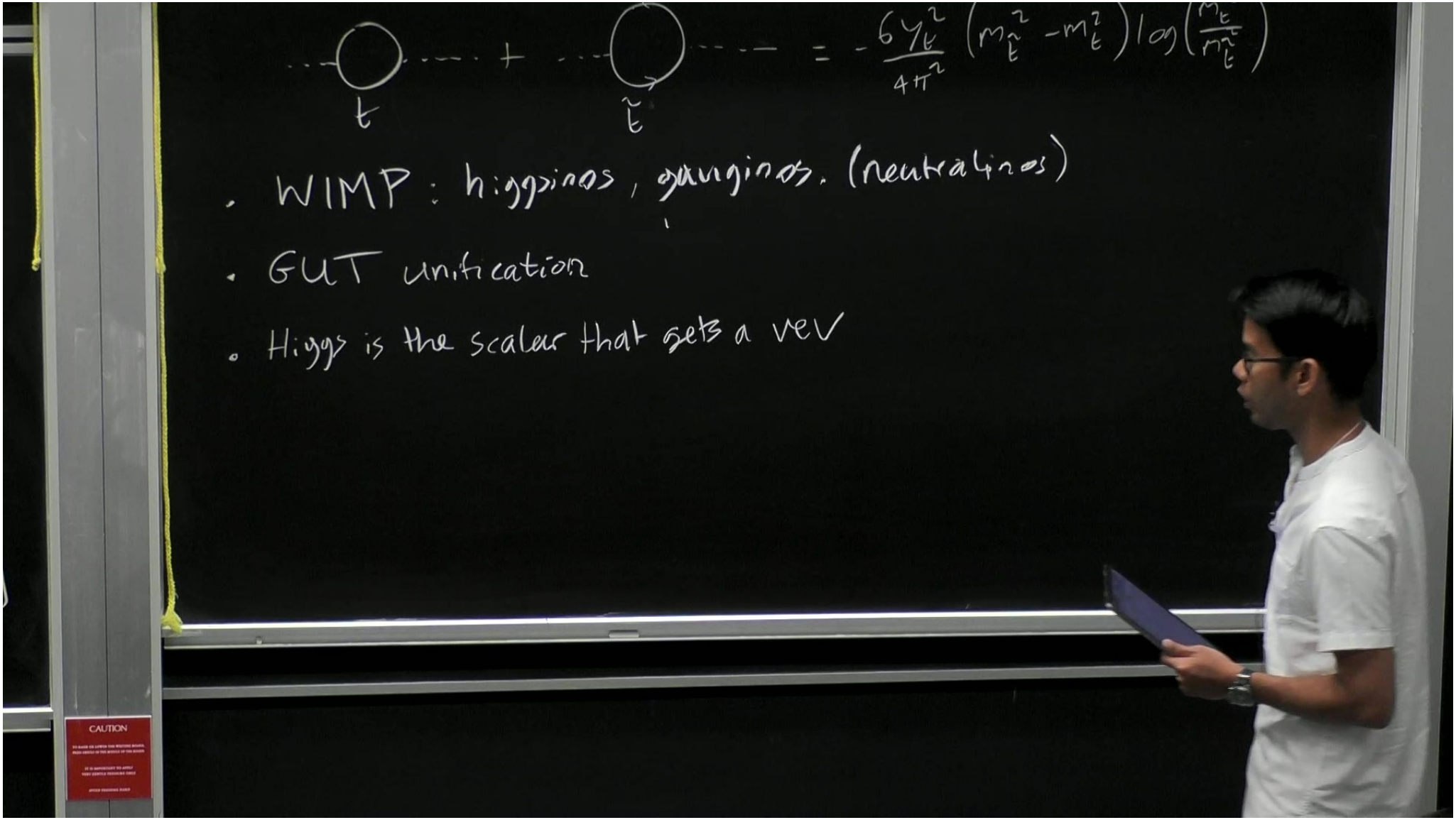
$$\mathcal{L} = D_\mu \phi_i^\dagger D^\mu \phi_i + \bar{\Psi} i\gamma^\mu \partial_\mu \Psi - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{\lambda}^a i \not{D} \lambda^a \Big\} \text{kinetic terms}$$

$$- \sqrt{2} g \left( \phi^\dagger T^a \lambda^a \Psi \right) - \frac{1}{2} \left. \frac{\partial^2 W}{\partial \Phi_i \partial \Phi_j} \right|_{\Phi = \phi} \bar{\Psi}_i \Psi_j \Big\} \quad \begin{matrix} \text{Sfermion - fermion} \\ \text{- gaugino} \end{matrix}$$

$$- \left| \frac{\partial W}{\partial \Phi_i} \right|^2_{\Phi = \phi} - \frac{g^2}{2} \left( \phi^\dagger T^a \phi \right)^2 \Big\} \text{ scalar potential}$$


+ 2 susy
. MSSM : minimal susy extension of SM
. susy controls quantum corrections:


t
$\tilde{t}$
$= -\frac{6y_t^2}{4\pi^2}\left(m_{\tilde{t}}^2 - m_t^2\right)\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$
. WIMP:
CAUTION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. WIMP : higgsinos, gauginos. (neutralinos)
. GUT unification
. Higgs is the scalar that gets a vev
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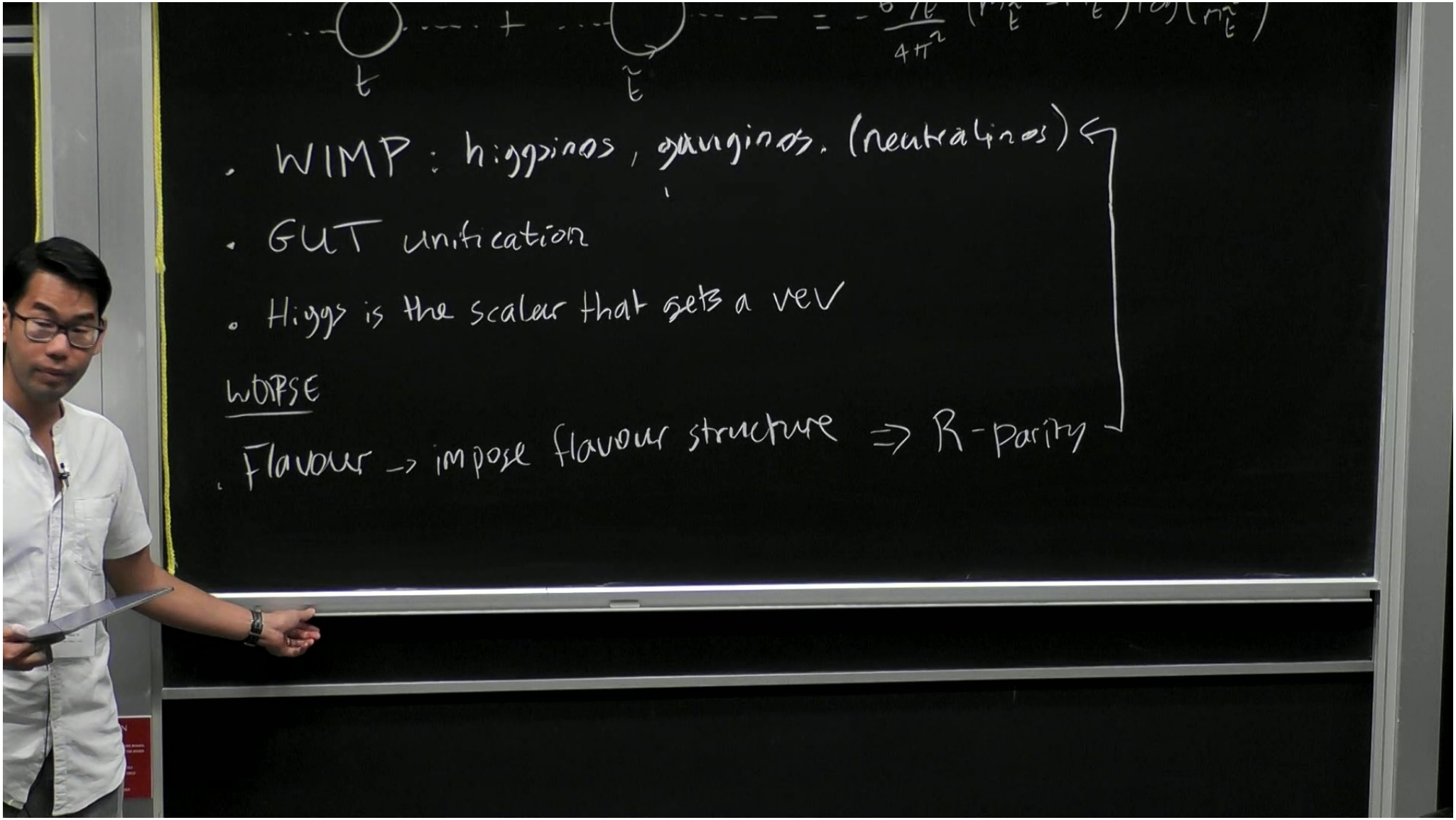
t
t̃
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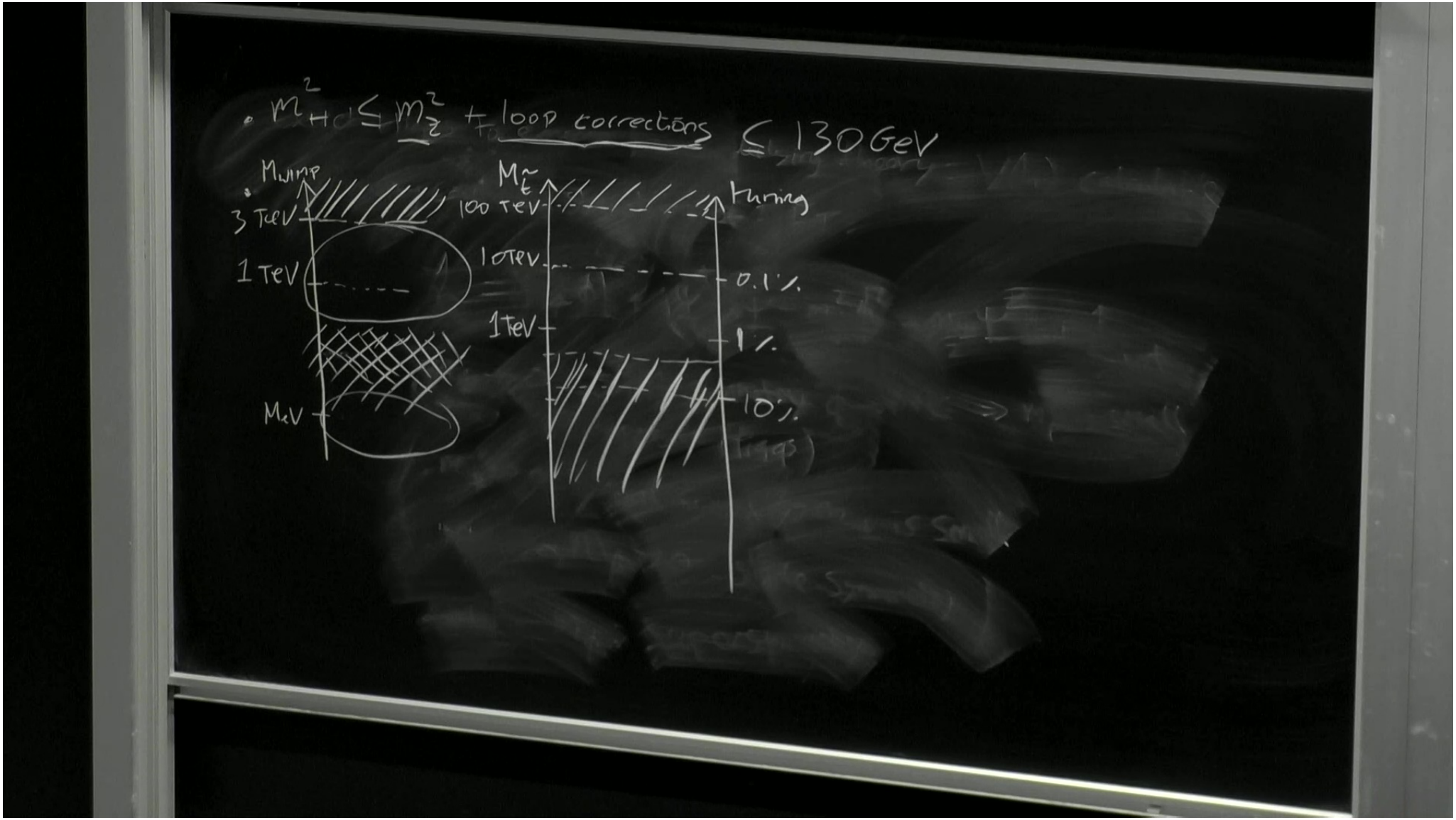
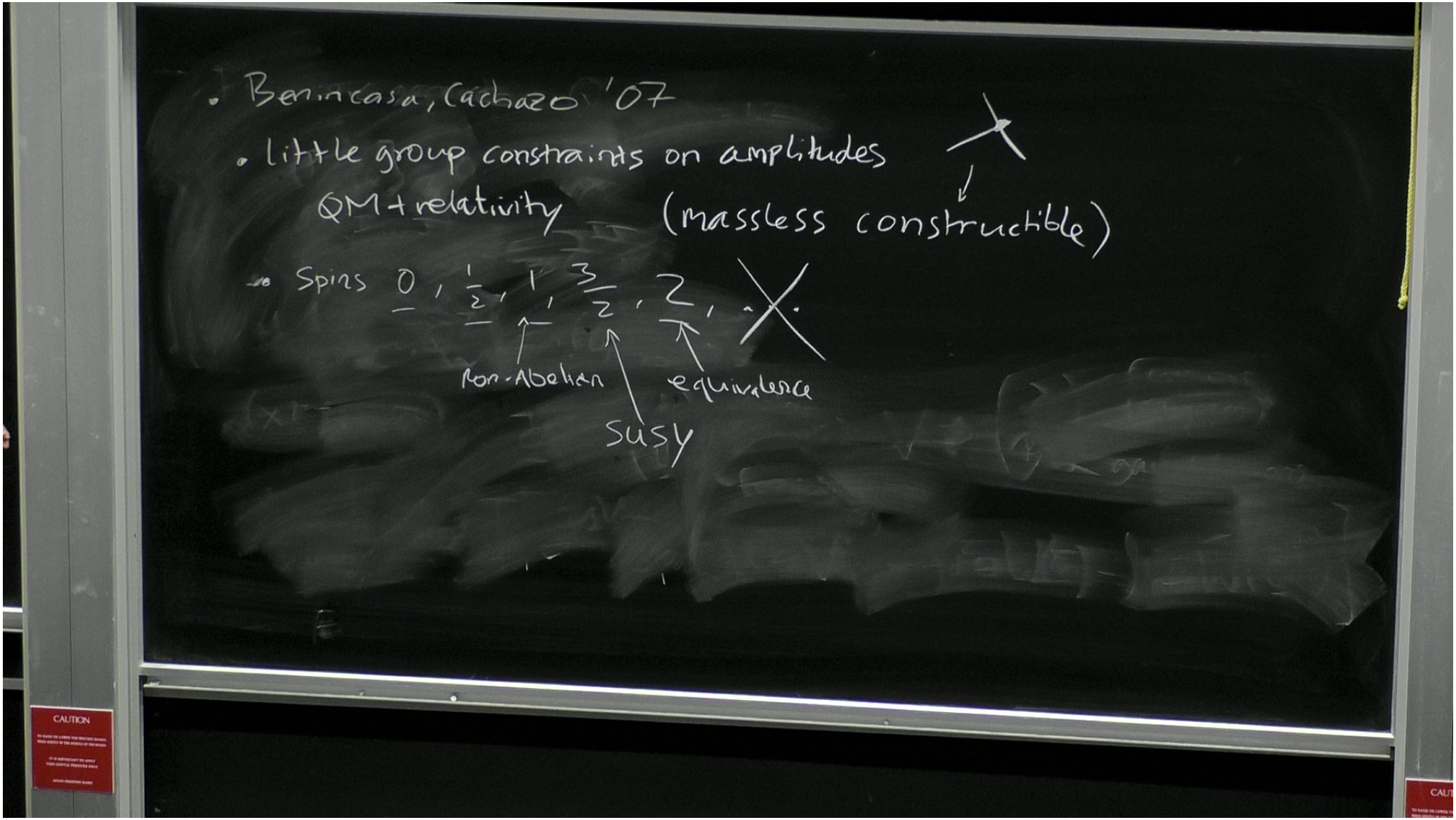
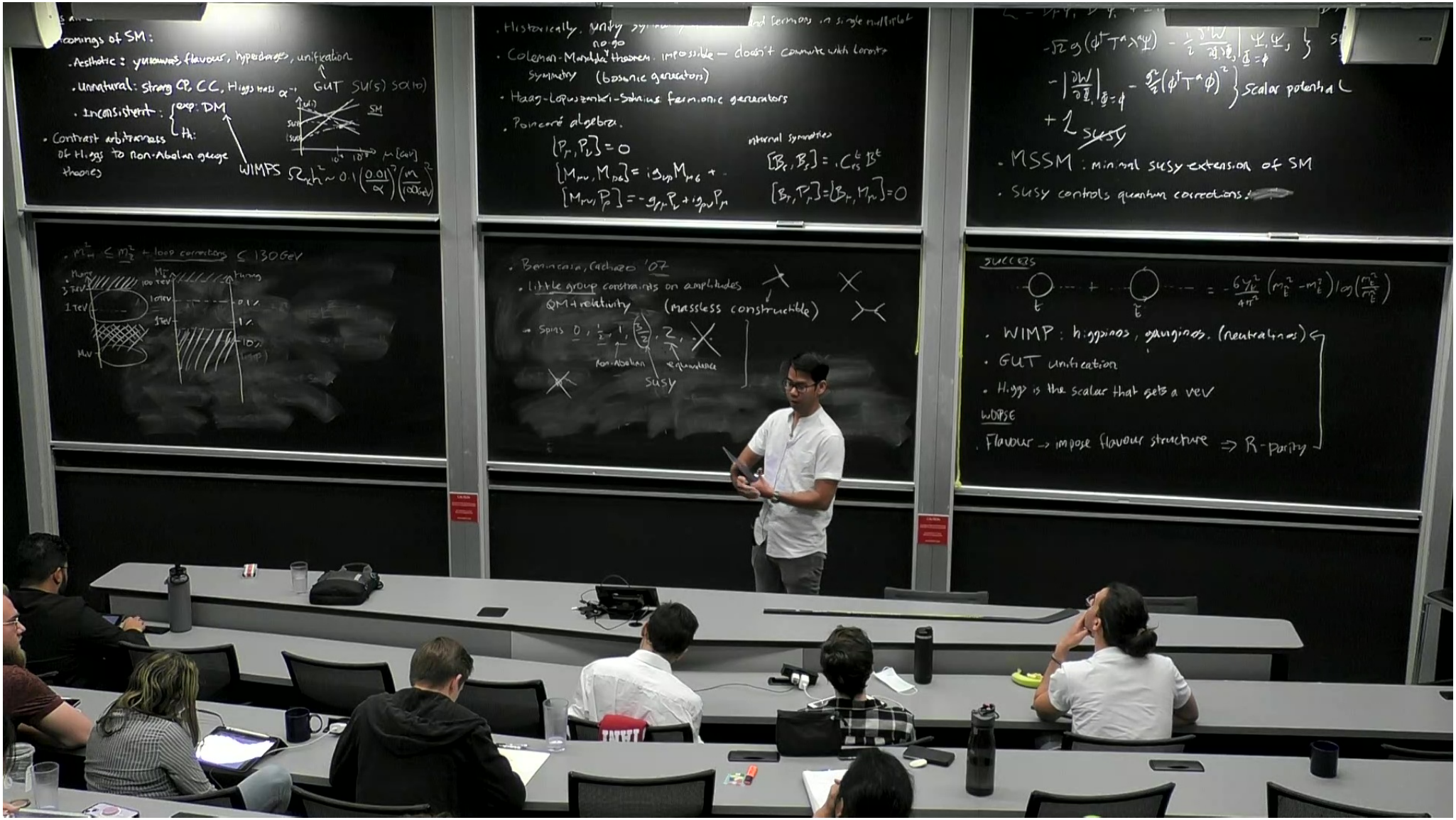
WORSE
. Flavour -> impose flavour structure ⇒ R-parity


$m^2_{H_d} \leq m^2_{\tilde{z}}$ + loop corrections $\leq$ 130 GeV
$M_{WIMP}$
3 TeV
1 TeV
MeV
$M_{\tilde{t}}$
100 TeV
10 TeV
1 TeV
tuning
0.1%
1%
10%


• Benincasa, Cachazo '07
• little group constraints on amplitudes
QM + relativity
(massless constructible)
• Spins 0, 1/2, 1, 3/2, 2, ...
non-Abelian
susy
equivalence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Poincaré algebra.
internal symmetries
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QM + relativity
(massless constructible)
Spins
non-Abelian
susy
MSSM: minimal sussy extension of SM
sussy controls quantum corrections
SUCCESS
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WORSE
Flavour → impose flavour structure ⇒ R-parity