Title: PSI 2018/2019 - Beyond Standard Model - Lecture 6

Speakers: Latham Boyle

Collection: PSI 2018/2019 - Beyond Standard Model (Boyle)

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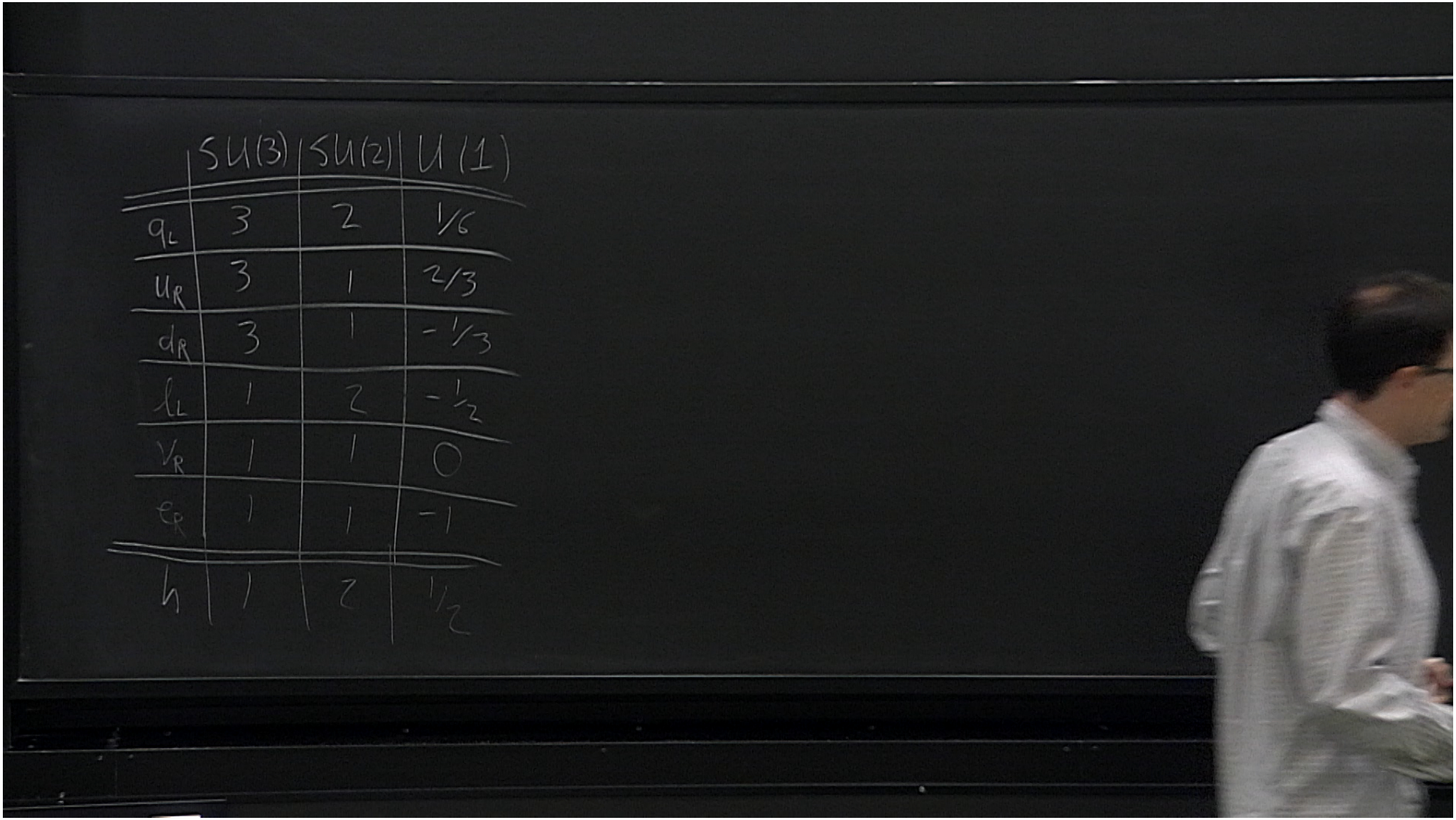
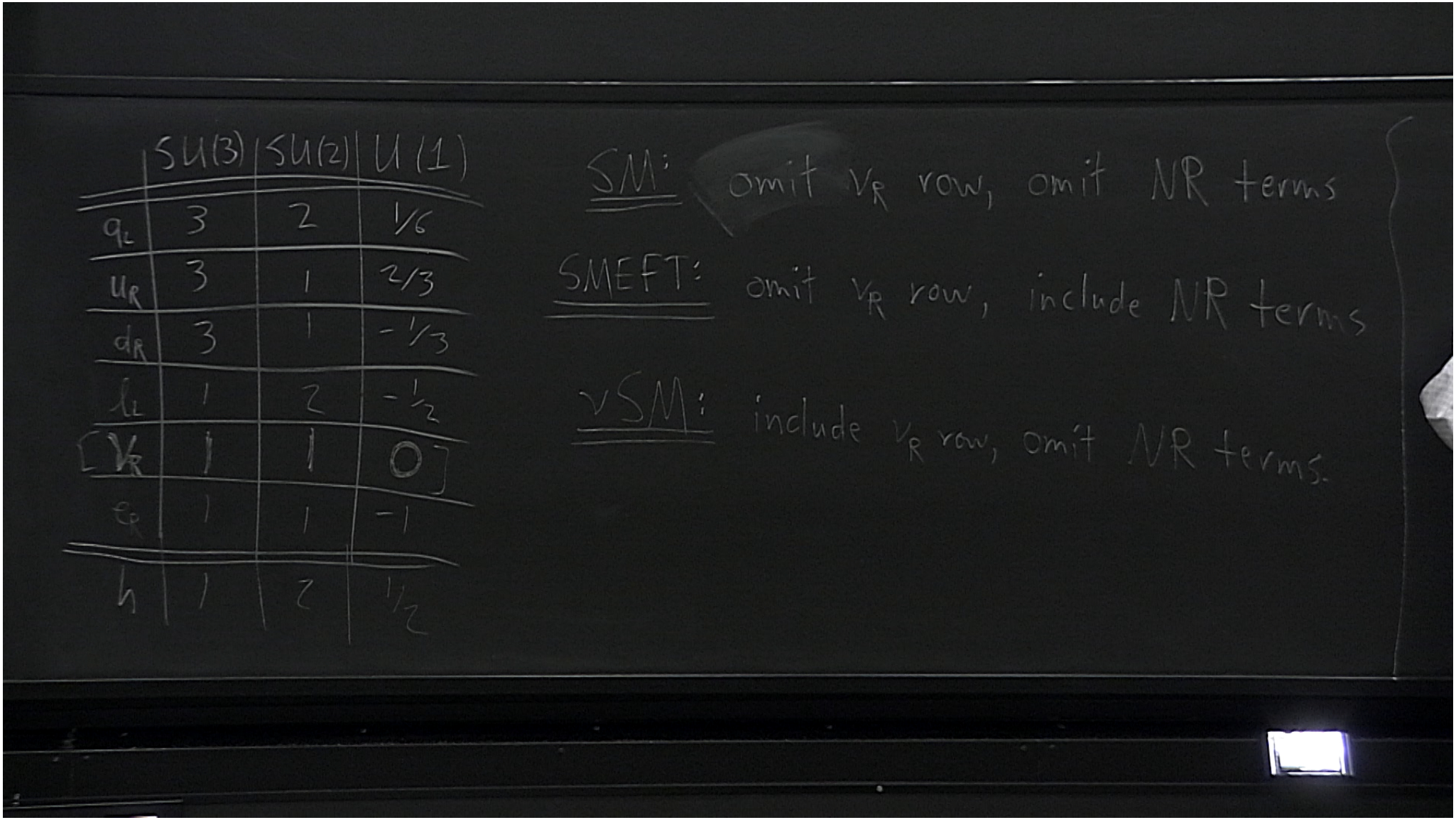

SU(3) SU(2) U(1)
$q_L$ 3 2 1/6
$u_R$ 3 1 2/3
$d_R$ 3 1 -1/3
$l_L$ 1 2 -1/2
$\nu_R$ 1 1 0
$e_R$ 1 1 -1
h 1 2 1/2


SU(3) SU(2) U(1)
$q_L$ 3 2 1/6
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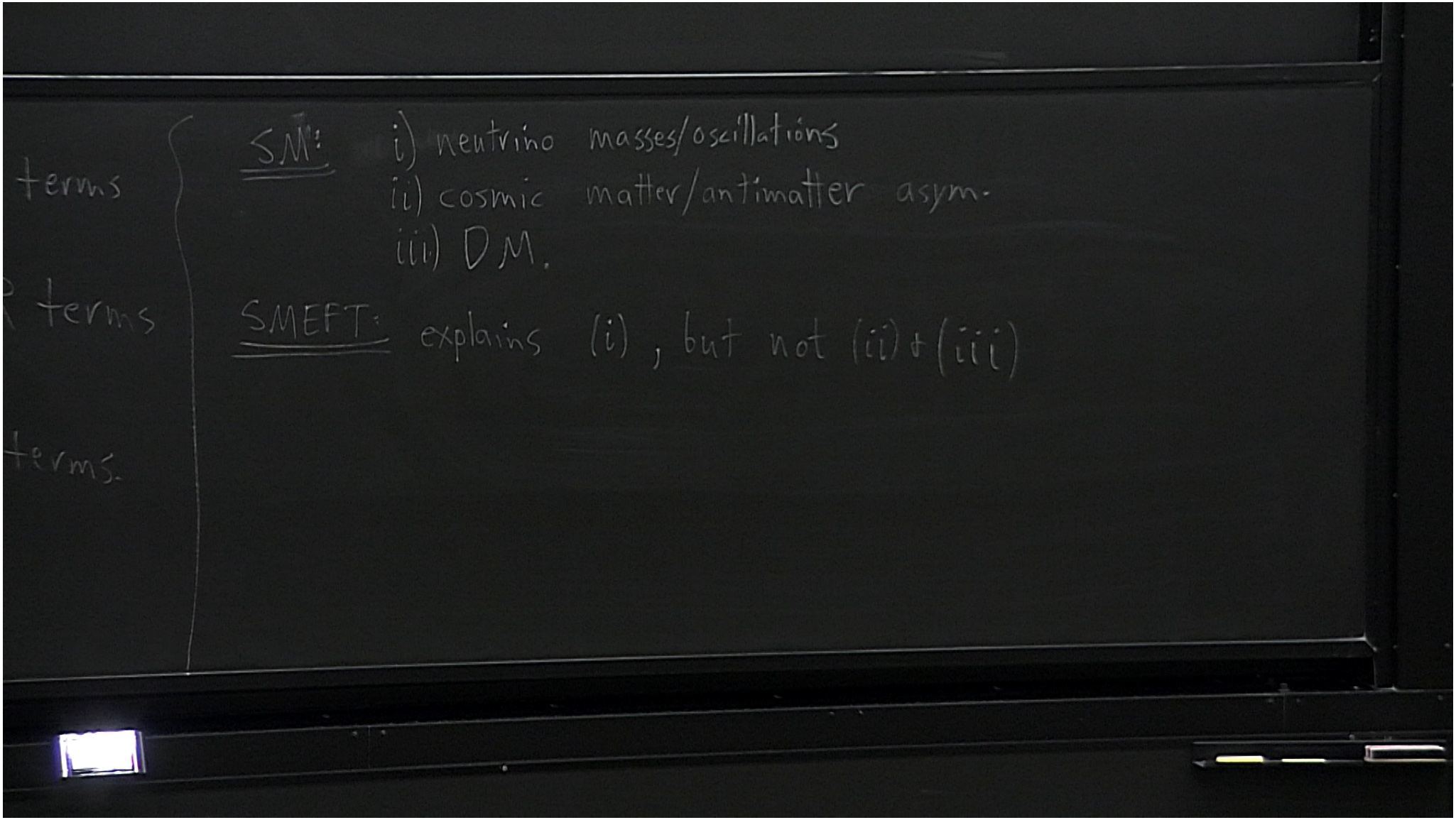
$[\nu_R$ 1 1 0]
$e_R$ 1 1 -1
h 1 2 1/2
SM: omit $\nu_R$ row, omit NR terms
SMEFT: omit $\nu_R$ row, include NR terms
νSM: include $\nu_R$ row, omit NR terms.


terms
terms
terms.
SM: i) neutrino masses/oscillations
ii) cosmic matter/antimatter asym.
iii) DM.
SMEFT: explains (i), but not (ii) & (iii)

terms

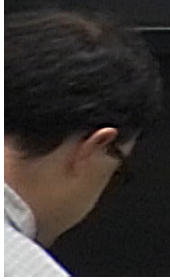
terms

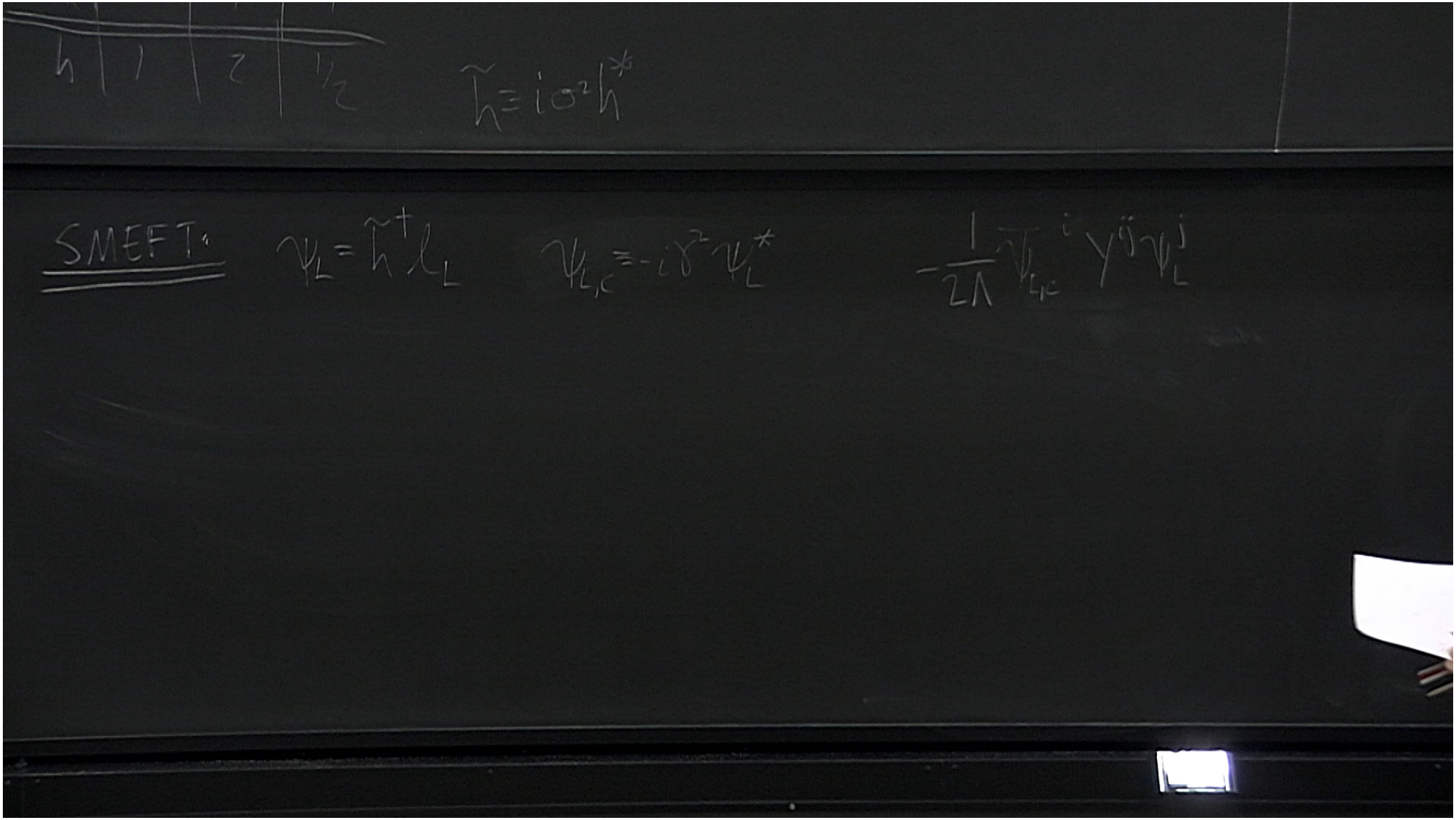
terms.

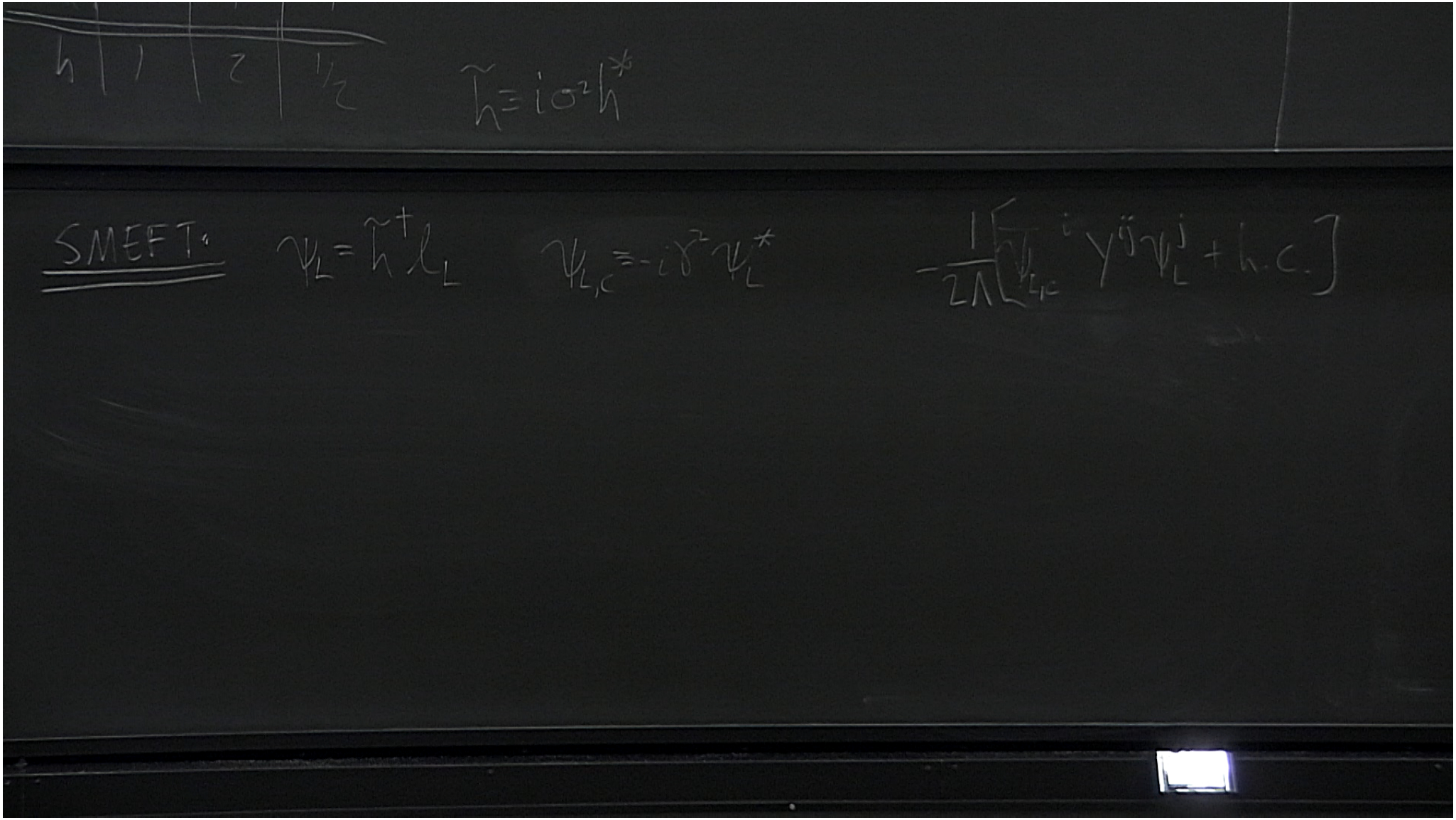
SM: i) neutrino masses/oscillations
ii) cosmic matter/antimatter asym.
iii) DM.

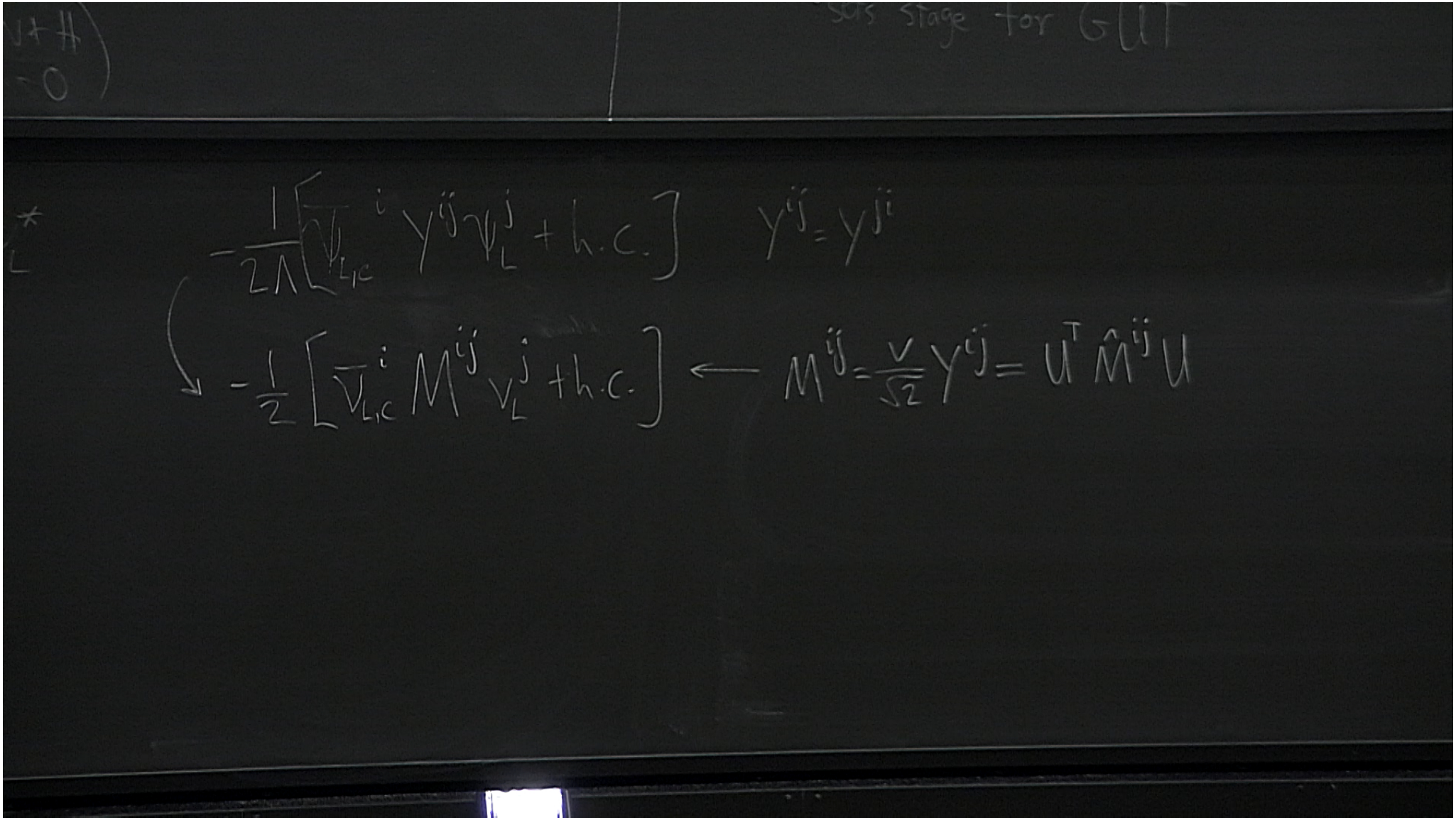
SMEFT: explains (i), but not (ii) & (iii)

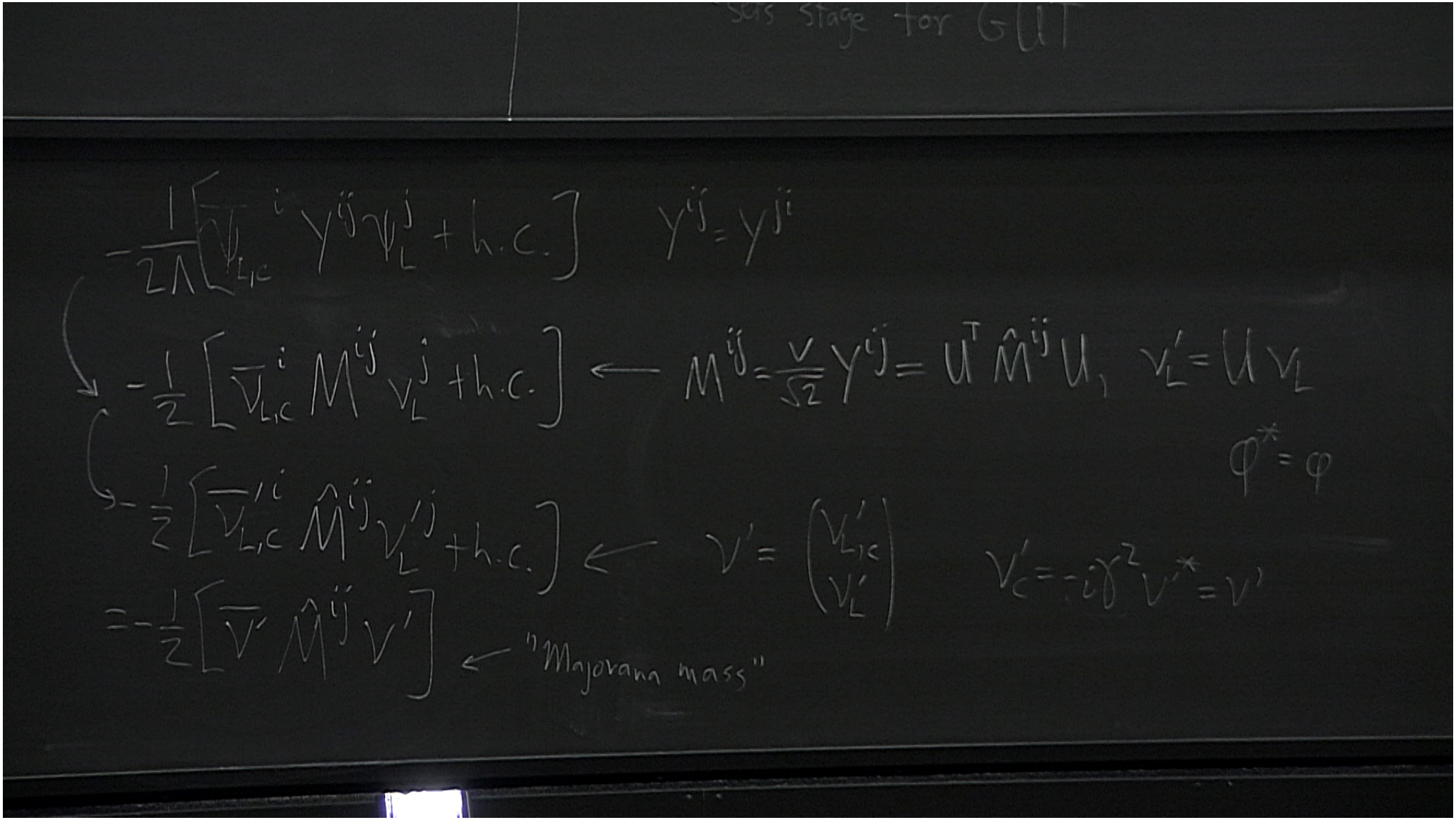
νSM:
- explains (i), (ii), (iii)
- reduces SMEFT
- sets stage for GUT

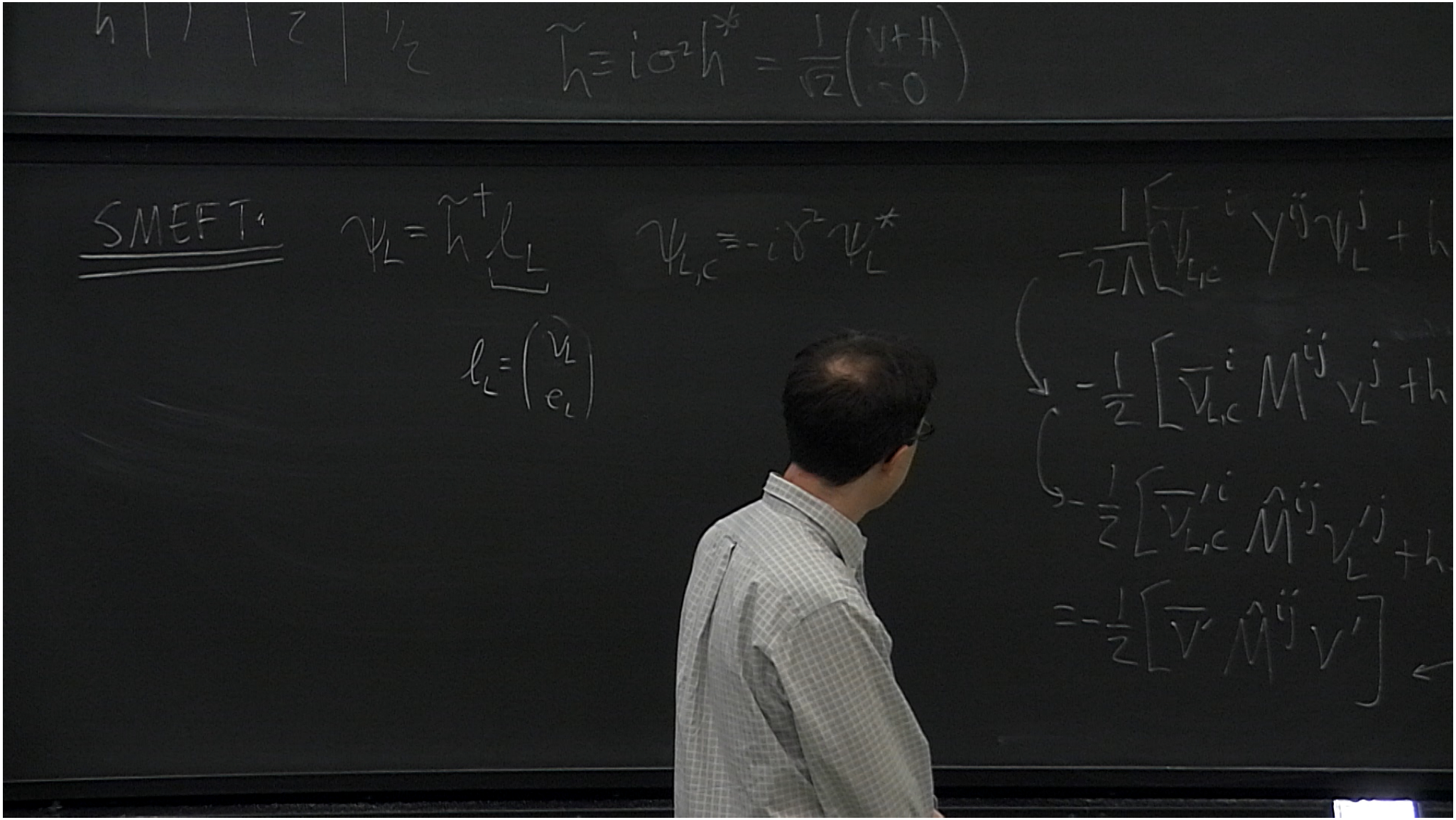


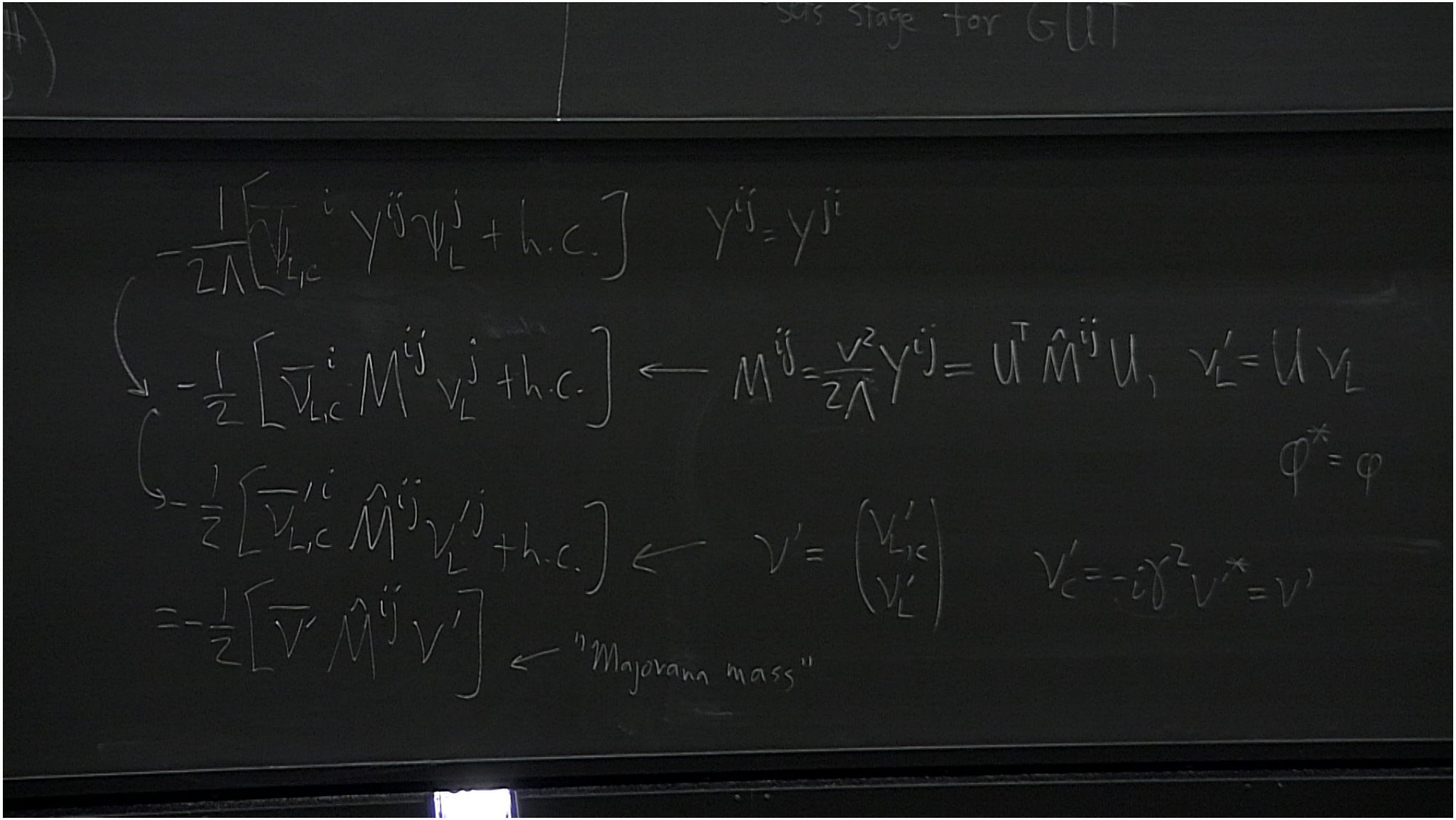

$\tilde{h} = i\sigma^2 h^*$
SMEFT: $\psi_L = \tilde{h}^\dagger \ell_L$ $\psi_{L,c} = -i\gamma^2 \psi_L^*$ $-\frac{1}{2\Lambda} \bar{\psi}_{L,c}{}^i Y^{ij} \psi_L^j$

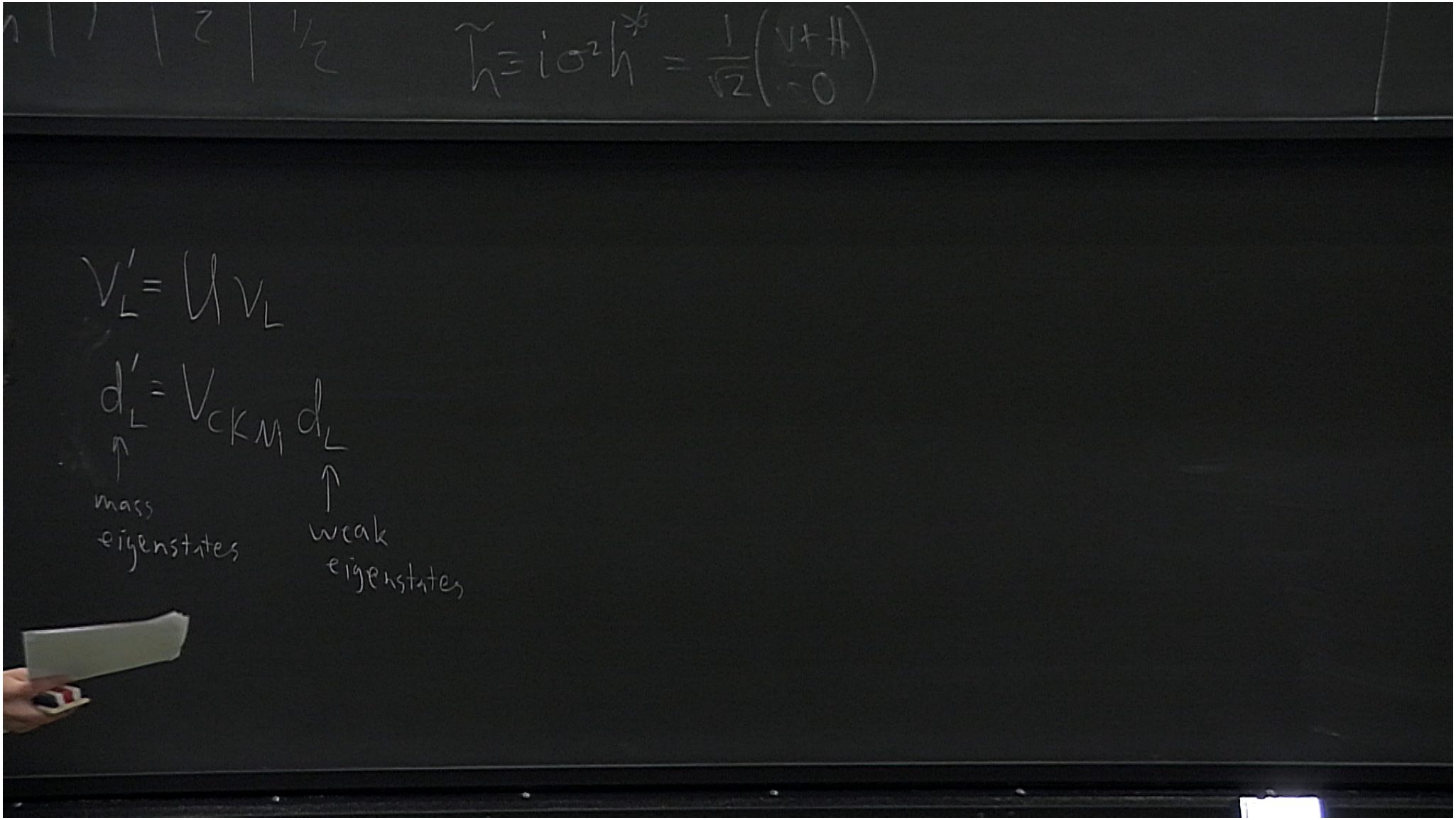

$\tilde{h} = i\sigma^2 h^*$
SMEFT: $\psi_L = \tilde{h}^\dagger \ell_L$ $\psi_{L,C} = -i\gamma^2 \psi_L^*$ $-\frac{1}{2\Lambda}[\bar{\psi}_{L,C}\, y^{ij} \psi_L^j + h.c.]$


sors stage for GUT
$-\frac{1}{2\Lambda}\left[\bar{\psi}_{L,c}^{\,i}\, Y^{ij}\psi_L^j + h.c.\right] \quad Y^{ij} = Y^{ji}$
$-\frac{1}{2}\left[\bar{\nu}_{L,c}^{\,i}\, M^{ij}\nu_L^j + h.c.\right] \leftarrow M^{ij} = \frac{v}{\sqrt{2}} Y^{ij} = U^T \hat{M}^{ij} U$


seesaw stage for GUT
$-\frac{1}{2\Lambda}\left[\bar{\psi}_{L,c}^{\,i}\, Y^{ij}\psi_L^j + h.c.\right]$ $\quad Y^{ij}=Y^{ji}$
$-\frac{1}{2}\left[\bar{\nu}_{L,c}^{\,i} M^{ij} \nu_L^j + h.c.\right] \leftarrow M^{ij}=\frac{v}{\sqrt{2}}Y^{ij}=U^T\hat{M}^{ij}U,\ \nu_L'=U\nu_L$
$\varphi^*=\varphi$
$-\frac{1}{2}\left[\bar{\nu}_{L,c}'^{\,i}\hat{M}^{ij}\nu_L'^{\,j} + h.c.\right] \leftarrow \nu'=\begin{pmatrix}\nu_{L,c}'\\ \nu_L'\end{pmatrix}\quad \nu_c'=-i\gamma^2\nu'^*=\nu'$
$=-\frac{1}{2}\left[\bar{\nu}'\hat{M}^{ij}\nu'\right]$ ← "Majorana mass"


SMEFT:


stage for GUT
$-\frac{1}{2\Lambda}\left[\bar{\nu}_{L,c}^{\,i}\, Y^{ij}\nu_L^j + h.c.\right] \quad Y^{ij}=Y^{ji}$
$-\frac{1}{2}\left[\bar{\nu}_{L,c}^{\,i} M^{ij}\nu_L^j + h.c.\right] \leftarrow M^{ij}=\frac{v^2}{2\Lambda}Y^{ij}=U^T\hat{M}^{ij}U, \quad \nu_L'=U\nu_L$
$\varphi^*=\varphi$
$-\frac{1}{2}\left[\bar{\nu}_{L,c}'^{\,i}\hat{M}^{ij}\nu_L'^{\,j} + h.c.\right] \leftarrow \nu'=\begin{pmatrix}\nu_{L,c}'\\ \nu_L'\end{pmatrix} \quad \nu_c'=-i\gamma^2\nu'^*=\nu'$
$=-\frac{1}{2}\left[\bar{\nu}'\hat{M}^{ij}\nu'\right] \leftarrow$ "Majorana mass"


$\tilde{h} = i\sigma^2 h^* = \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix}$
$\nu_L' = U \nu_L$
$d_L' = V_{CKM}\, d_L$
mass eigenstates
weak eigenstates

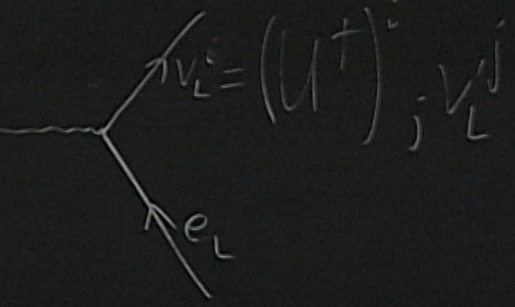
$h \mid 1 \mid 2 \mid 1/2 \qquad \tilde{h} = i\sigma^2 h^* = \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix}$

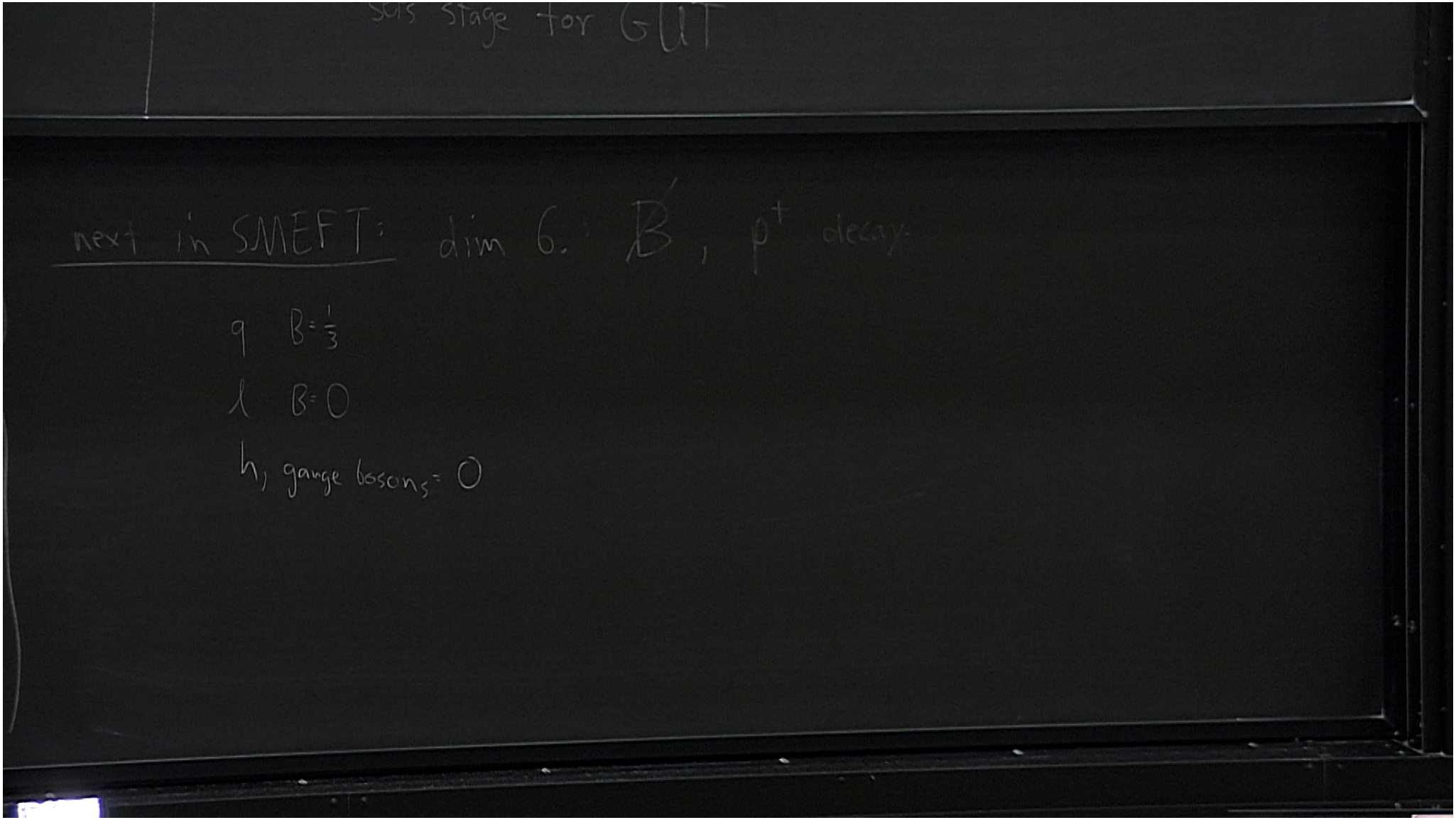
$\nu_L' = U \nu_L$

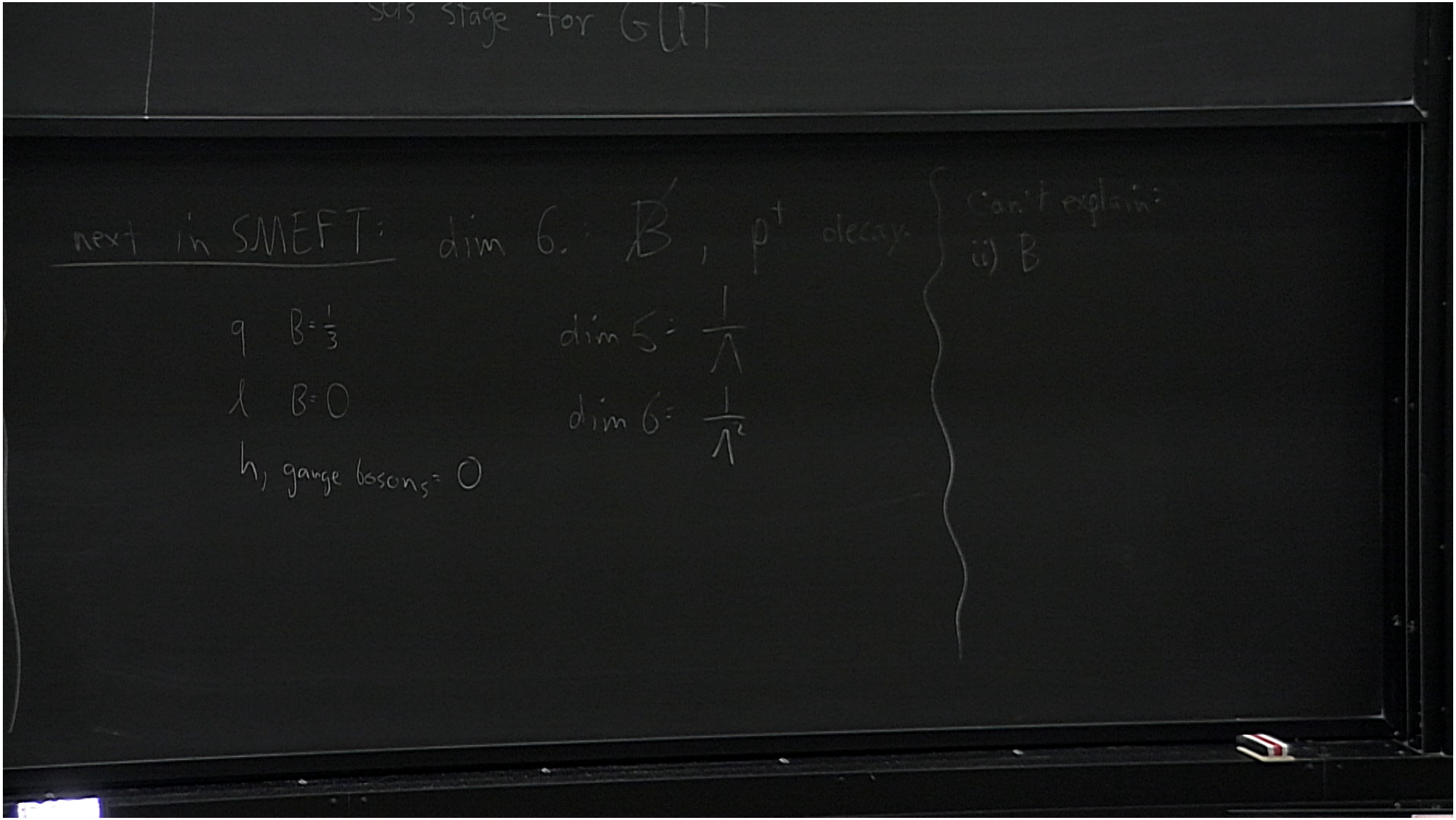
$d_L' = V_{CKM}\, d_L$

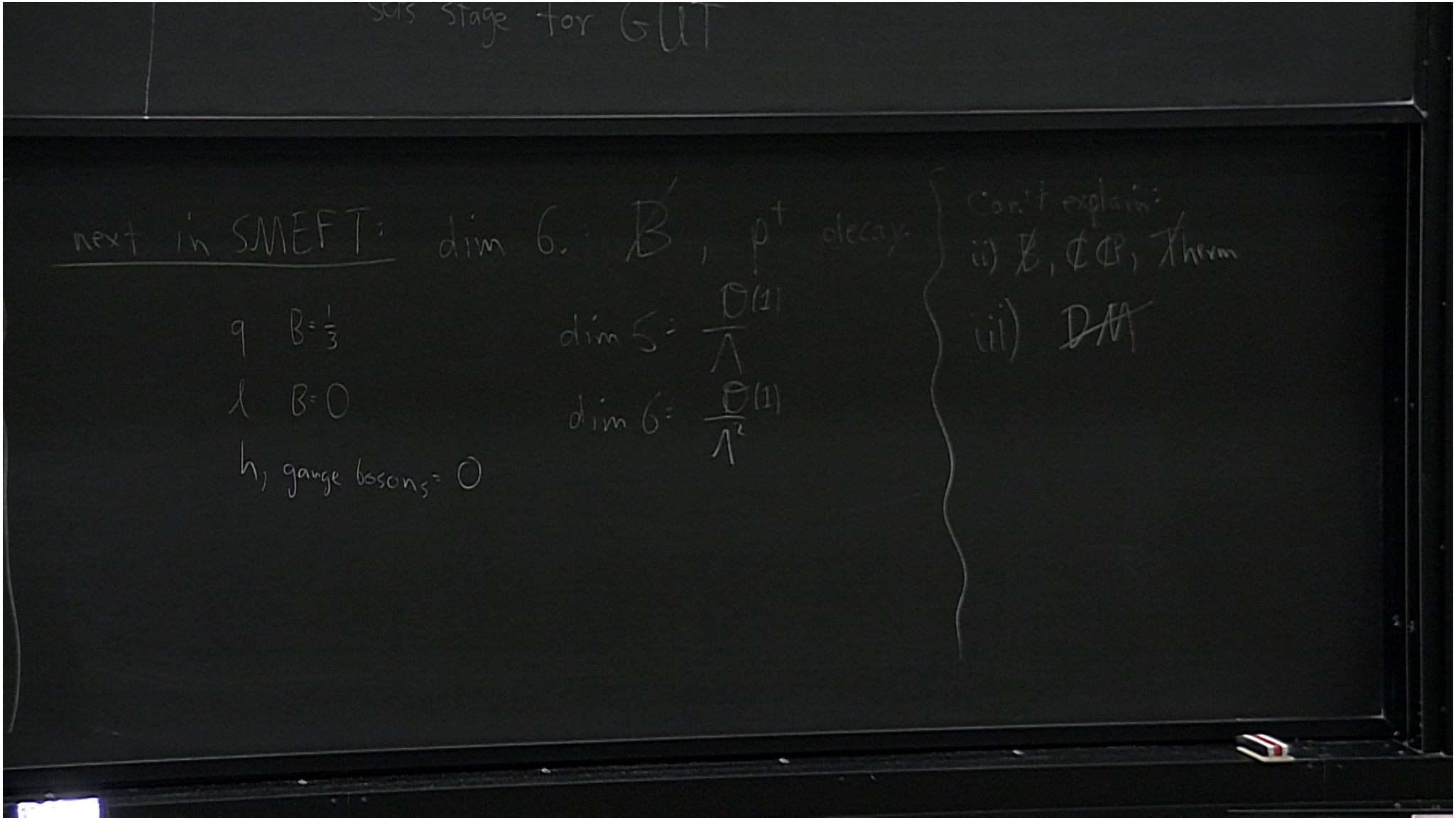
mass eigenstates

weak eigenstates

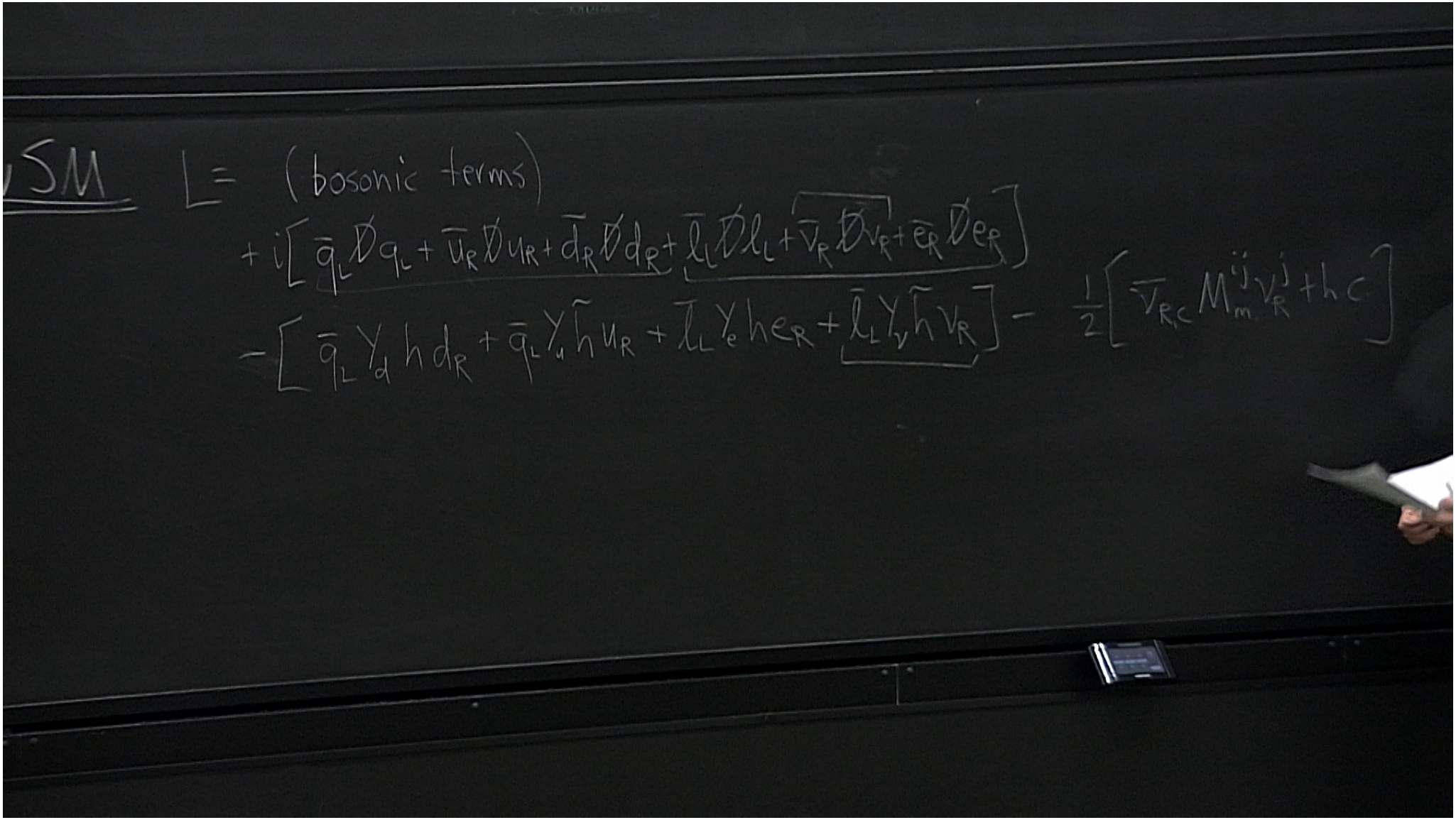


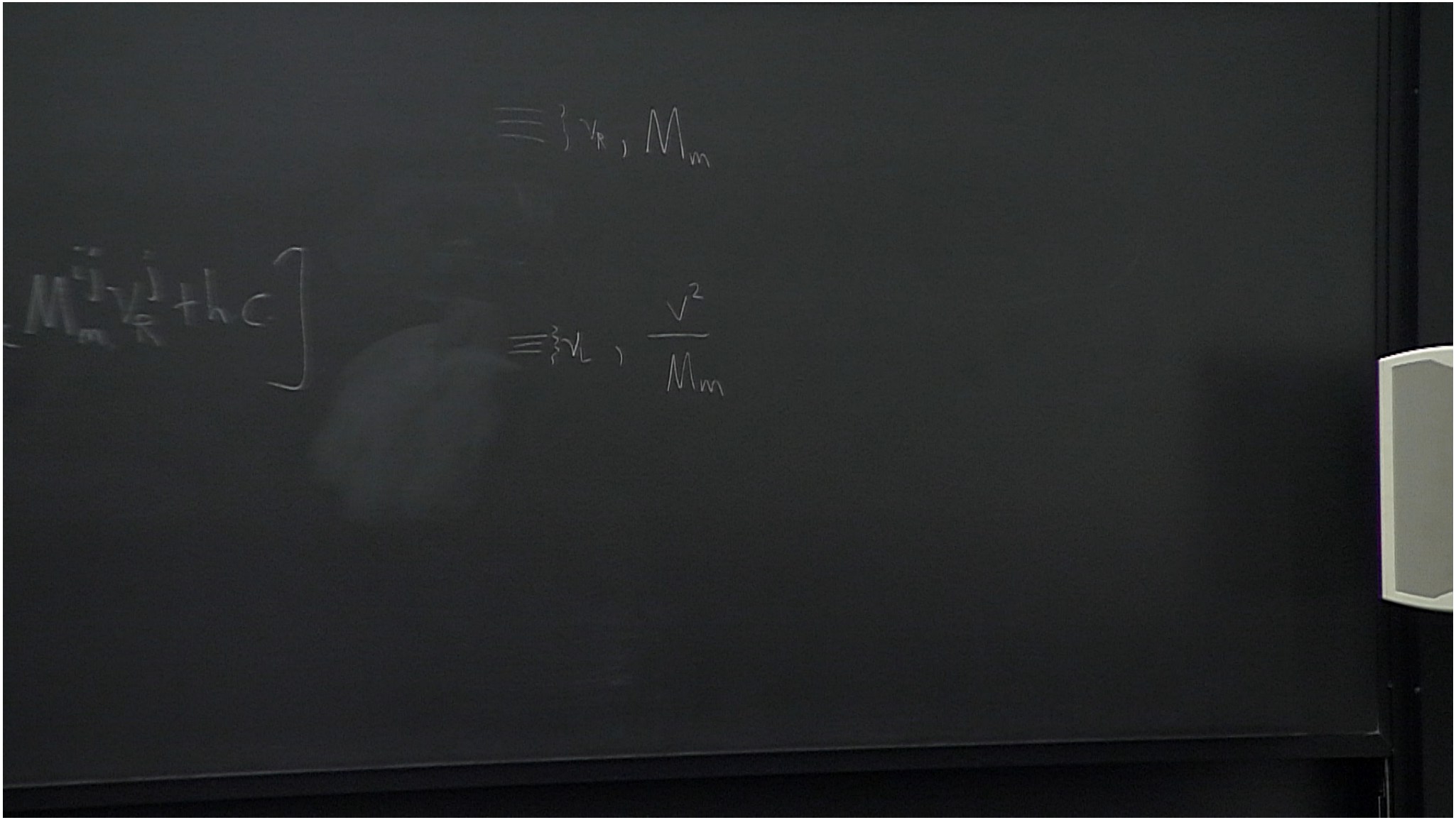


SUS stage for GUT
next in SMEFT: dim 6.: $\not{B}$, $p^+$ decays
q $B=\frac{1}{3}$
l $B=0$
h, gauge bosons $=0$

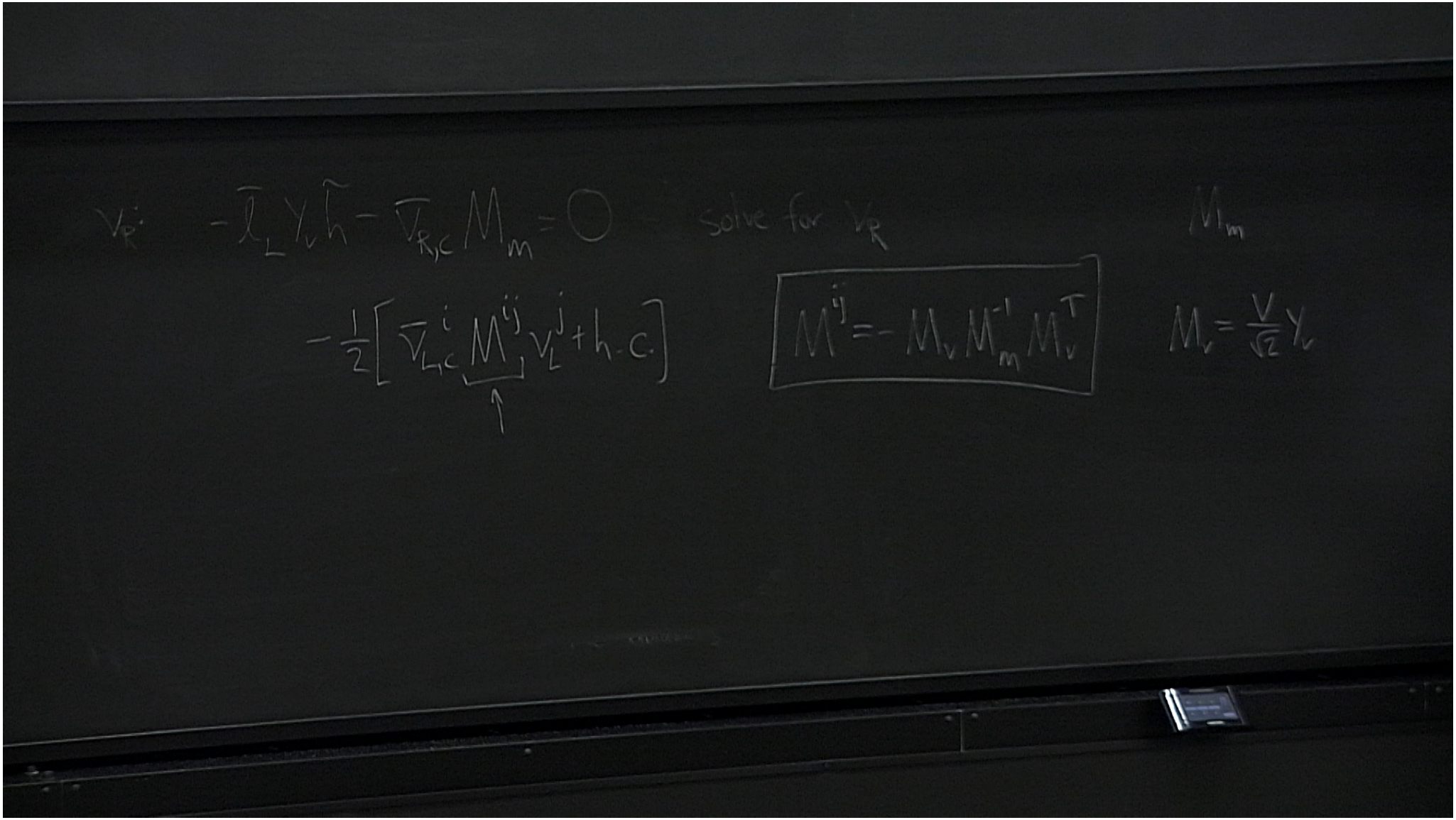

SUS stage for GUT
next in SMEFT: dim 6.: $\not{B}$, $p^+$ decays
q $B=\frac{1}{3}$
l $B=0$
h, gauge bosons $=0$
dim 5: $\frac{1}{\Lambda}$
dim 6: $\frac{1}{\Lambda^2}$
can't explain:
i) B

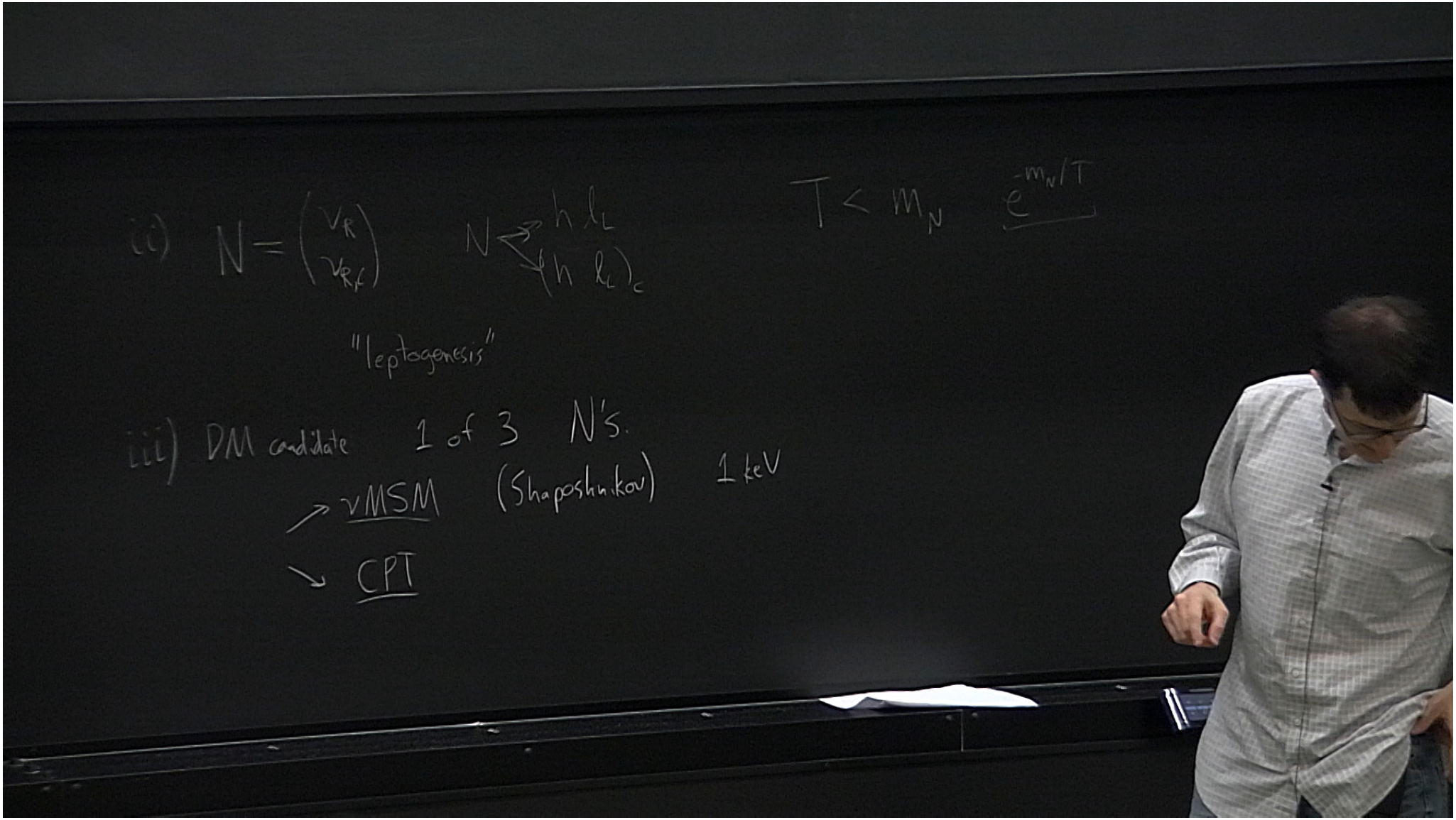

sols stage for GUT
next in SMEFT: dim 6: $\not{B}$, $p^+$ decays
q $B=\frac{1}{3}$
l $B=0$
h, gauge bosons $=0$
dim 5: $\frac{\mathcal{O}(1)}{\Lambda}$
dim 6: $\frac{\mathcal{O}(1)}{\Lambda^2}$
can't explain:
i) $\not{B}$, $\not{C}\not{B}$, Therm
ii) ~~DM~~

$$\underline{\nu SM} \quad \mathcal{L} = (\text{bosonic terms})$$
$$+ i\left[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{\ell}_L \not{D} \ell_L + \bar{\nu}_R \not{D} \nu_R + \bar{e}_R \not{D} e_R\right]$$
$$- \left[\bar{q}_L Y_d h d_R + \bar{q}_L Y_u \tilde{h} u_R + \bar{\ell}_L Y_e h e_R + \bar{\ell}_L Y_\nu \tilde{h} \nu_R\right] -$$


SM L = (bosonic terms)
+ i[ q̄_L ∂̸ q_L + ū_R ∂̸ u_R + d̄_R ∂̸ d_R + l̄_L ∂̸ l_L + ν̄_R ∂̸ ν_R + ē_R ∂̸ e_R ]
- [ q̄_L Y_d h d_R + q̄_L Y_u h̃ u_R + l̄_L Y_e h e_R + l̄_L Y_ν h̃ ν_R ] - 1/2 [ ν̄_{R,c} M^{ij}_m ν^j_R + h.c ]


$\equiv \{\nu_R, M_m$
$M_{mR}^{ij} \nu_R^i \nu_R^j + h.c.]$
$\equiv \{\nu_L, \frac{v^2}{M_m}$


$\nu_R$: $-\bar{l}_L Y_\nu \tilde{h} - \bar{\nu}_{R,c} M_m = 0$
solve for $\nu_R$
$M_m$
$-\frac{1}{2}\left[\bar{\nu}^i_{L,c} M^{ij} \nu^j_L + h.c.\right]$
$M^{ij} = -M_\nu M_m^{-1} M_\nu^T$
$M_\nu = \frac{v}{\sqrt{2}} Y_\nu$


ii) $N = \begin{pmatrix} \nu_R \\ \nu_{R^c} \end{pmatrix}$
$N \rightarrow h\,\ell_L$
$(h\,\ell_L)_c$
$T < m_N$
$e^{-m_N/T}$
"leptogenesis"
iii) DM candidate 1 of 3 N's.
→ νMSM (Shaposhnikov) 1 keV
↘ CPT