Phenomenology of Large Volume String Models

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Talk Structure

- Neutrino Masses
- Large Volume Models
- Integrating out Heavy States
- Neutrino Masses in Large Volume Models

Neutrino Masses

- Neutrino masses exist:

$$0.05\text{eV} \lesssim m_\nu^H \lesssim 0.3\text{eV}.$$

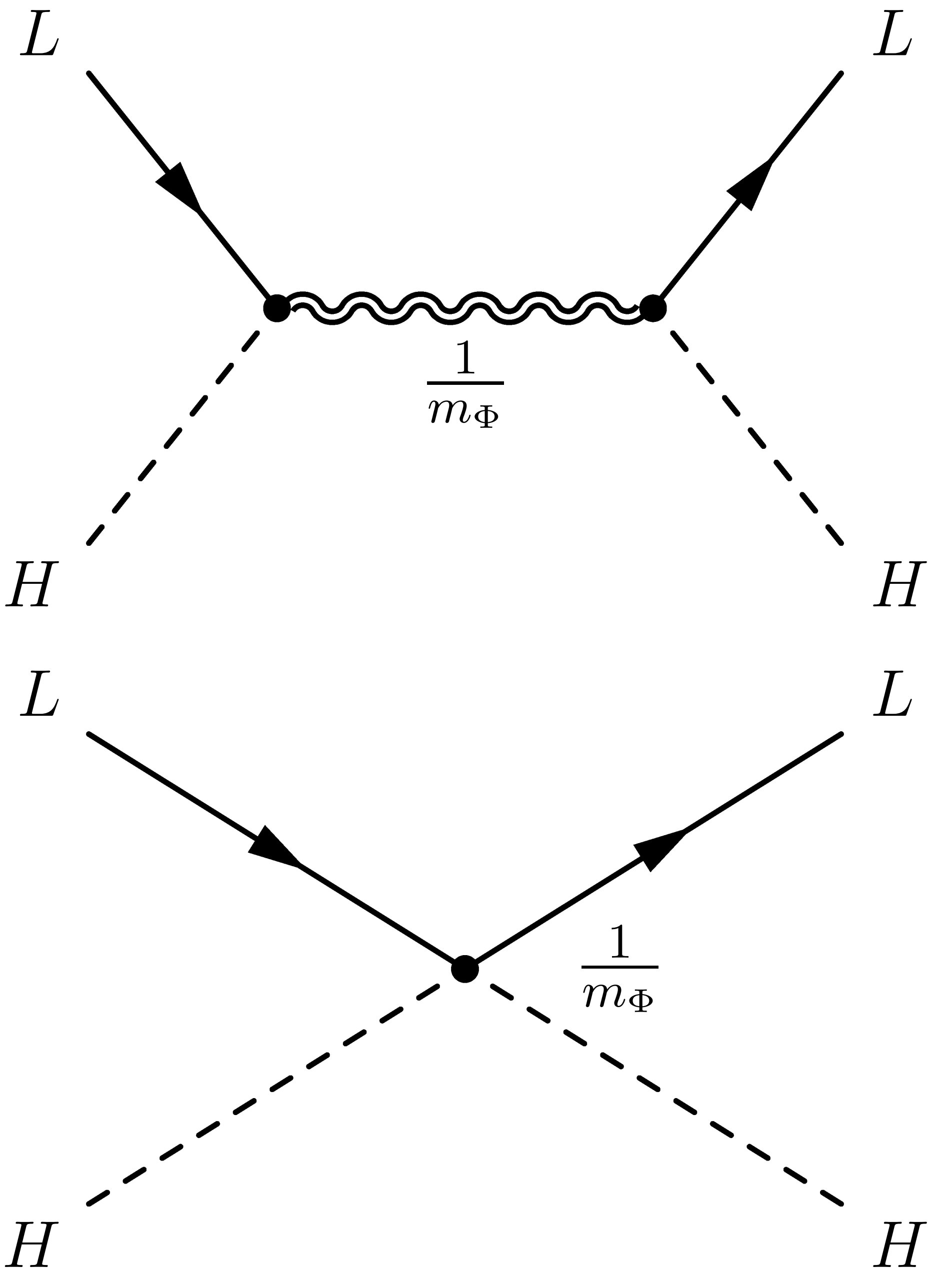
- In the seesaw mechanism, this corresponds to a Majorana mass scale for right-handed neutrinos

$$M_{\nu_R} \sim 3 \times 10^{14}\text{GeV}.$$

- Equivalently, this is the suppression scale Λ of the dimension five MSSM operator

$$\begin{aligned} \mathcal{O}_{m_\nu} &= \frac{1}{\Lambda} H_2 H_2 L L \\ \Rightarrow m_\nu &= 0.1\text{eV} \left(\sin^2\beta \times \frac{3 \times 10^{14}\text{GeV}}{\Lambda} \right). \end{aligned}$$

The Seesaw Mechanism



Neutrino Masses

Neutrino masses imply a scale $\Lambda \sim 3 \times 10^{14}$GeV which is

- not the Planck scale 10^{18}GeV
- not the GUT scale 10^{16}GeV
- not the intermediate scale 10^{11}GeV
- not the TeV scale 10^{3}GeV

Can string theory give a quantitative understanding of this scale?

Large-Volume Models

In IIB flux compactifications, the appropriate 4-dimensional supergravity theory is

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln\left(S + \bar{S}\right),$$

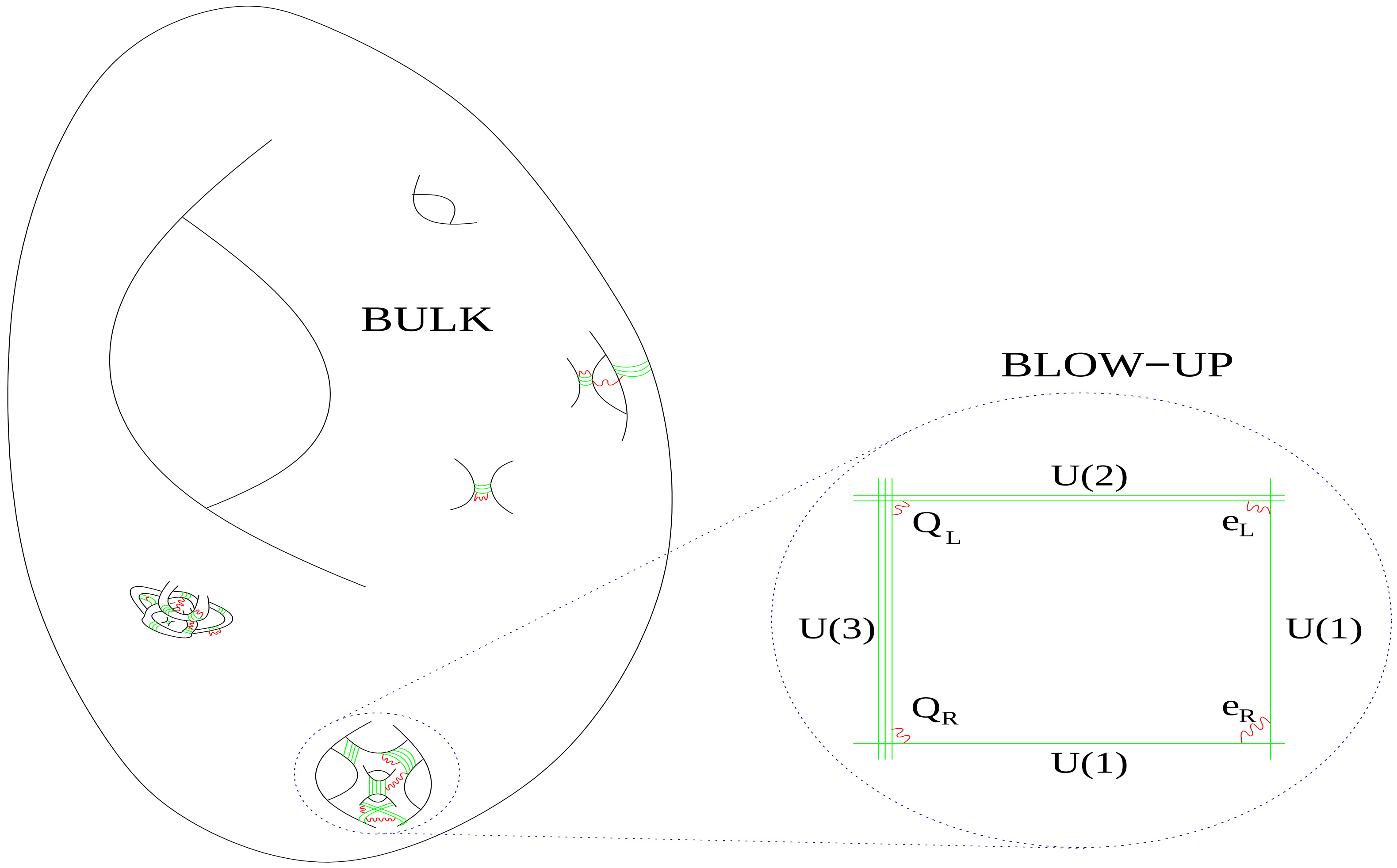
$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-a_i T_i}.$$

Including the leading stringy α' corrections to the Kähler potential gives dramatic changes in the structure of the potential

$\Longrightarrow$ a new minimum appears at exponentially large volume $\mathcal{V} \gg 1$ (Quevedo's talk).

Large Volume Models

We take $\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} = 10^{15} l_s^6$, with $\tau_b \sim 10^{10}, \tau_s \sim 20$.



Moduli Stabilisation: Large-Volume

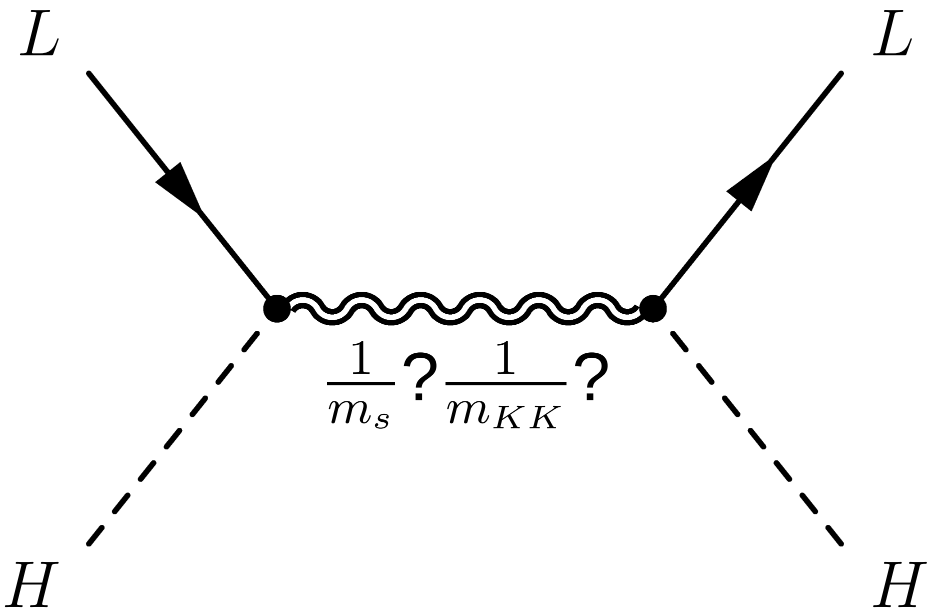
We take the overall volume to be $\mathcal{V} = 10^{14} l_s^6$.

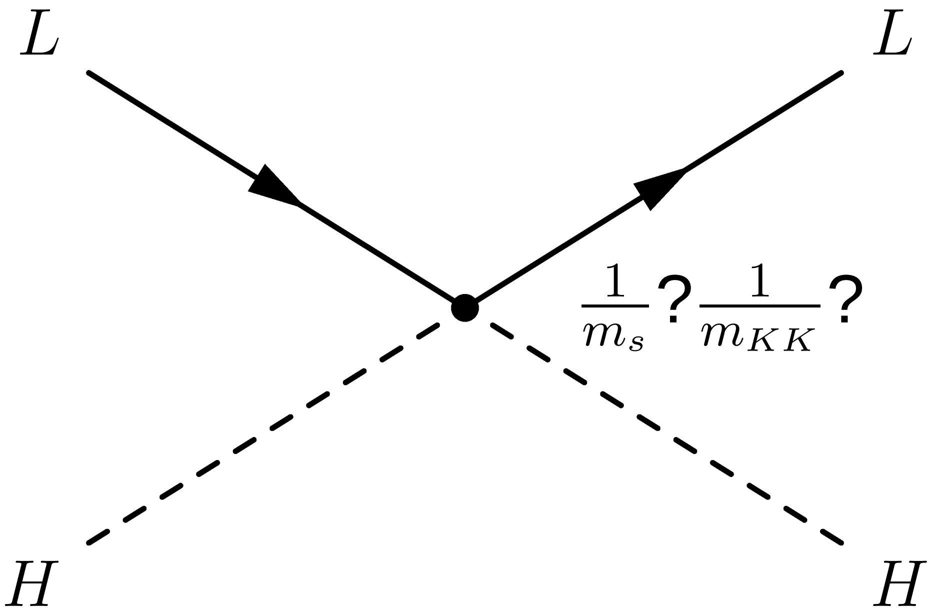
The mass scales present are:

- Planck scale: $M_P = 2.4 \times 10^{18}$GeV.
- String scale: $M_S = \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
- Axion decay constant $f_a \sim M_S \sim 10^{11}$GeV.
- KK scale $M_{KK} = \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^9$GeV.
- Gravitino mass $m_{3/2} = \frac{M_P}{\mathcal{V}} \sim 30$TeV.
- Soft terms $m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.

What scale should we expect for neutrino masses?

The Seesaw Mechanism





Heavy States in 4d Supergravity

How to describe a Kaluza-Klein or string state in 4d supergravity?

$$m_{heavy} = \frac{m_s}{\mathcal{V}^{\alpha}} = \frac{M_P}{\mathcal{V}^{1/2+\alpha}},$$

- WRONG:

$$K = \Phi \bar{\Phi}$$

$$W = M_{heavy} \Phi^2 = \frac{M_P}{\mathcal{V}^{1/2+\alpha}} \Phi^2 = \frac{M_P}{(T + \bar{T})^{\frac{3+6\alpha}{4}}} \Phi^2.$$

- RIGHT:

$$K = \frac{1}{\mathcal{V}^{1/2-\alpha}} \Phi \bar{\Phi}$$

$$W = M_P \Phi^2$$

States

The Lagrangian is

$$\begin{aligned}\mathcal{L} &= K_{\Phi\bar{\Phi}}\partial_\mu\Phi\partial^\mu\bar{\Phi} + e^K\left(K^{i\bar{j}}D_iWD_jW - 3|W|^2\right)\\ &= K_{\Phi\bar{\Phi}}\partial_\mu\Phi\partial^\mu\bar{\Phi} + \frac{M_P^2}{\mathcal{V}^2}K^{\Phi\bar{\Phi}}\Phi\bar{\Phi}.\end{aligned}$$

- For KK states,

$$K = \frac{1}{\mathcal{V}^{1/3}}\Phi\bar{\Phi} \text{ gives } m_{KK} = \frac{M_P}{\mathcal{V}^{2/3}}.$$

- For stringy states,

$$K = \frac{1}{\mathcal{V}^{1/2}}\Phi\bar{\Phi} \text{ gives } m_s = \frac{M_P}{\mathcal{V}^{\frac{1}{2}}}.$$

Yukawa Couplings

Consider a KK state as a right-handed neutrino

$$\begin{aligned} W &= M_P \Phi^2 + Y_{\Phi H L} \Phi H L \\ K &= \frac{1}{\mathcal{V}^{1/3}} \Phi \bar{\Phi} + \frac{1}{\mathcal{V}^{2/3}} H \bar{H} + \frac{1}{\mathcal{V}^{2/3}} L \bar{L} \end{aligned}$$

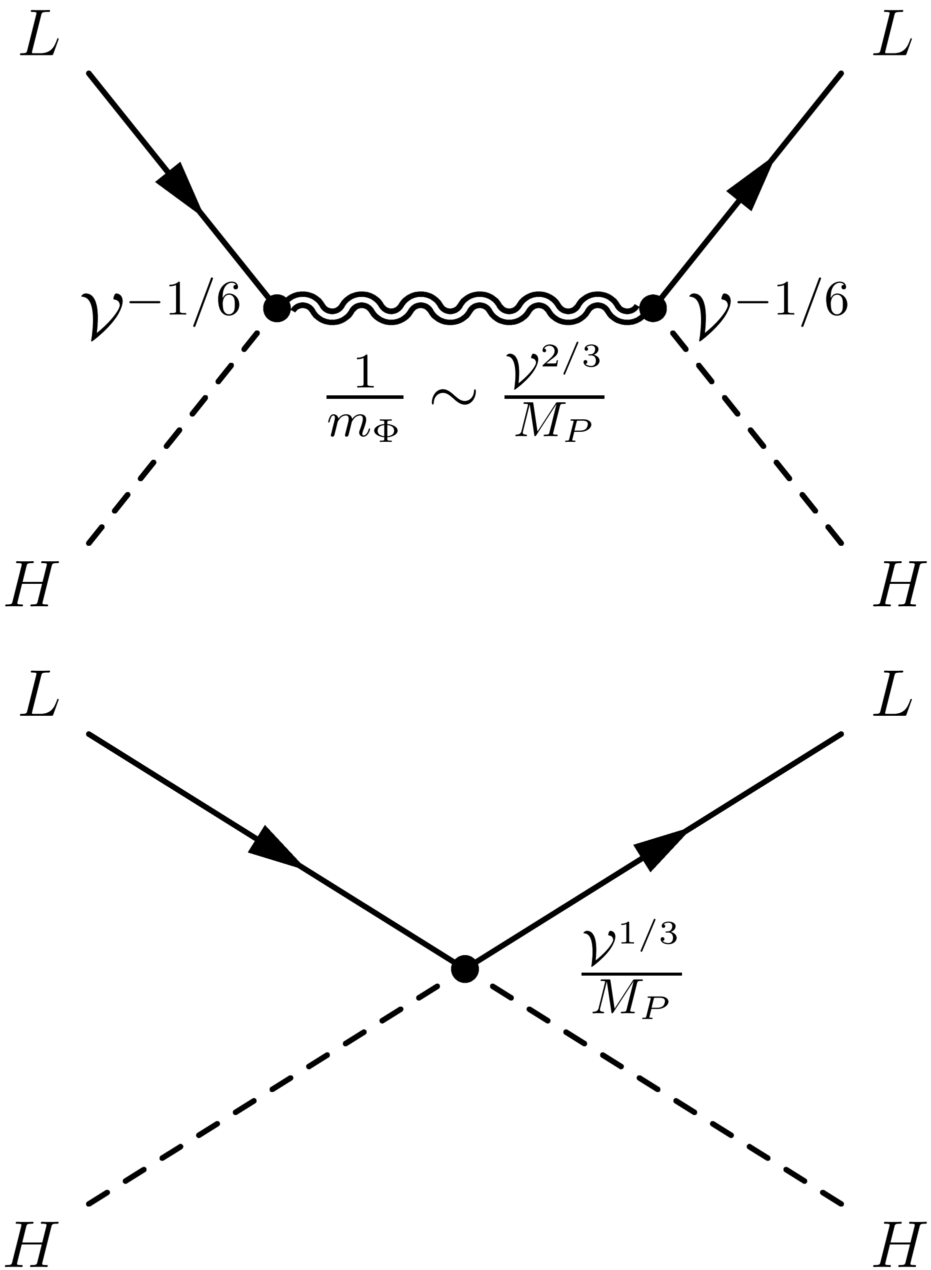
($K_{H\bar{H}}, K_{L\bar{L}} \sim \mathcal{V}^{-2/3}$ follows from locality)

The physical Yukawa is

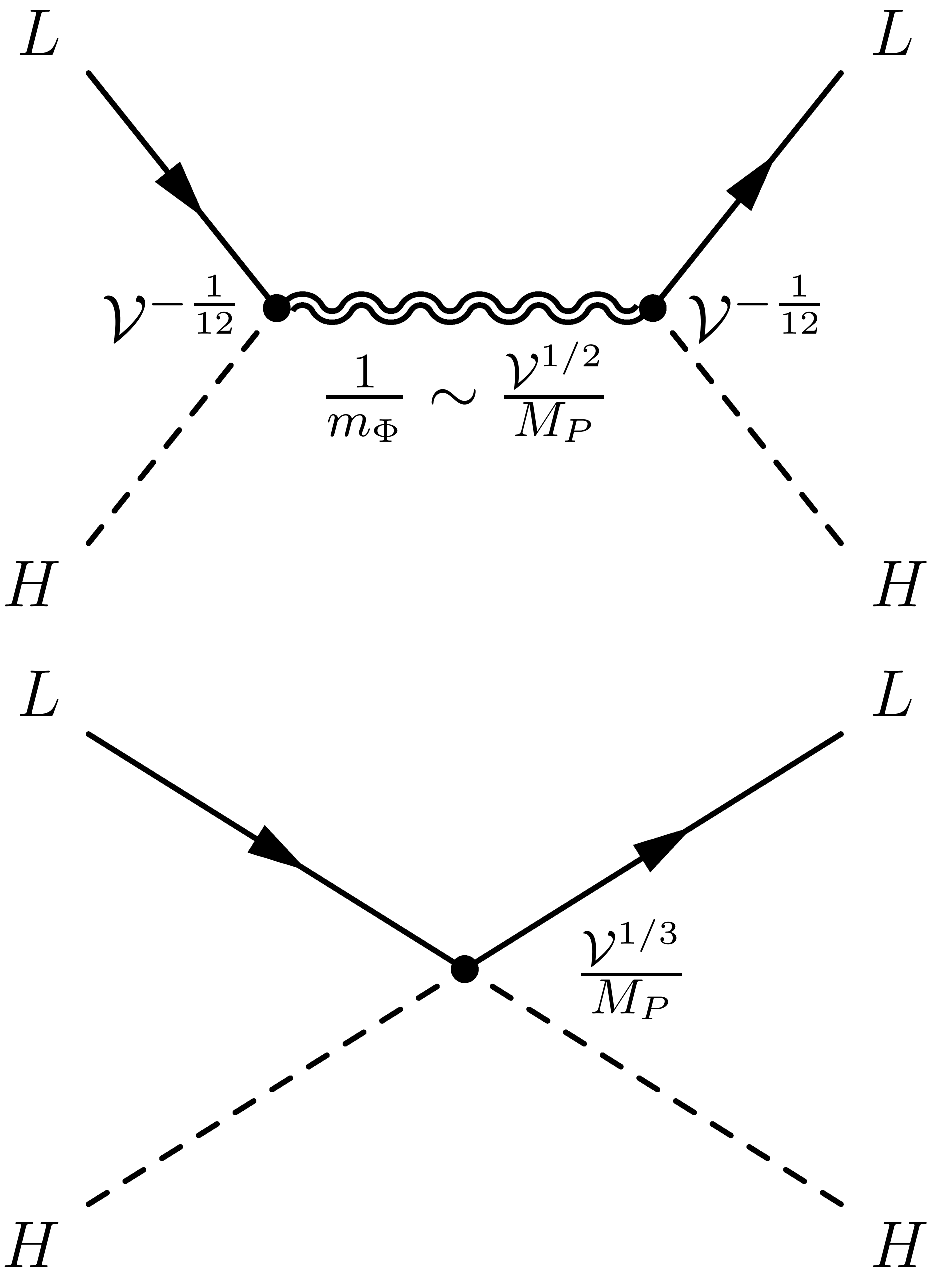
$$\begin{aligned} \hat{Y}_{\Phi H L} &= e^{\hat{K}/2} \frac{Y_{\Phi H L}}{\sqrt{K_{\Phi\bar{\Phi}} K_{L\bar{L}} K_{H\bar{H}}}} \\ &= \mathcal{V}^{-\frac{1}{6}} Y_{\Phi H L}. \end{aligned}$$

For string states, $\hat{Y}_{\Phi H L} = \mathcal{V}^{-\frac{1}{12}} Y_{\Phi H L}$.

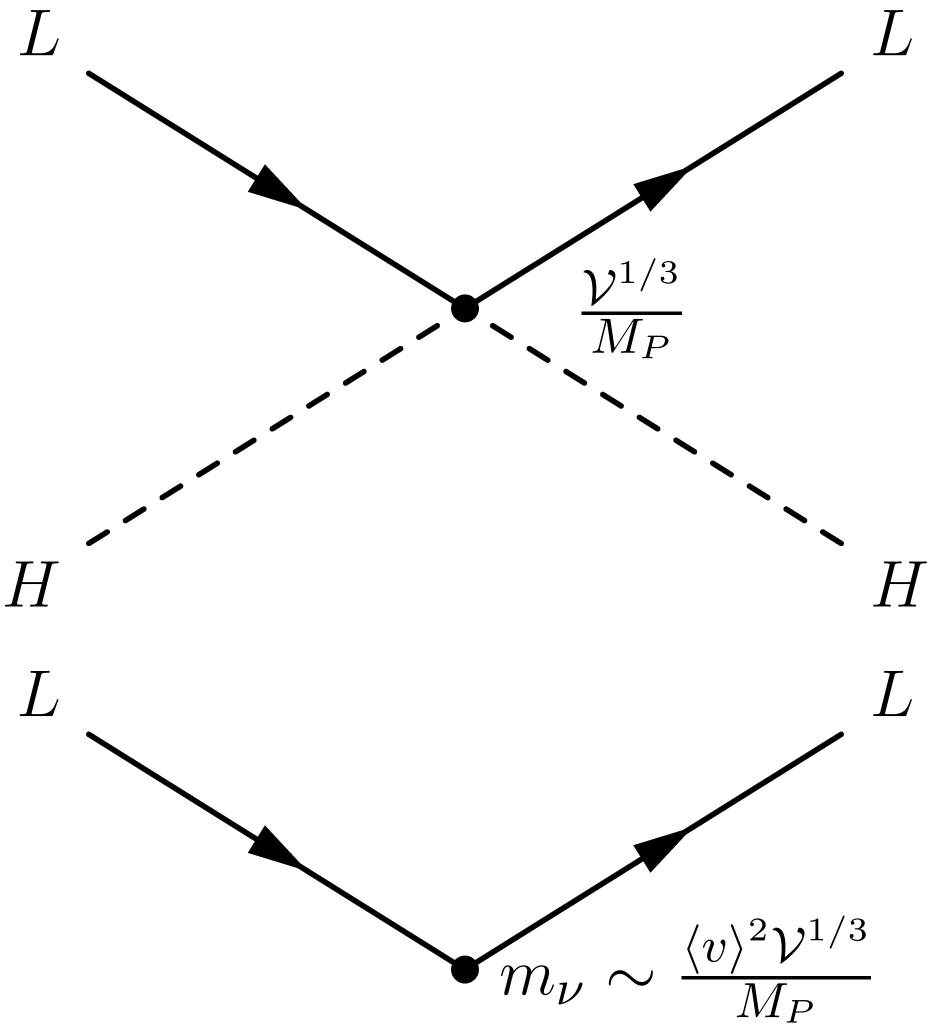
Integrating out KK modes



Integrating out stringy modes



Neutrino Masses



Integrating out Heavy States

Integrating out string / KK states generates a dimension-five operator suppressed by

(string) $$\mathcal{V}^{-1/12} \times \frac{\mathcal{V}^{\frac{1}{2}}}{M_P} \times \mathcal{V}^{-1/12} \sim \frac{\mathcal{V}^{1/3}}{M_P}$$

(KK) $$\mathcal{V}^{-1/6} \times \frac{\mathcal{V}^{2/3}}{M_P} \times \mathcal{V}^{-1/6} \sim \frac{\mathcal{V}^{1/3}}{M_P}$$

- Integrating out heavy states of mass M does not produce operators suppressed by M^{-1}.
- The dimension-five suppression scale is independent of the masses of the heavy states integrated out.

Neutrino Masses

Fully,

$$K_{H\bar{H}} \sim K_{L\bar{L}} \sim \frac{\tau_s^{1/3}}{\mathcal{V}^{2/3}}.$$

As $\tau_s \sim \alpha_{SM}^{-1}(m_s)$, we have

$$\begin{aligned} m_\nu &\simeq \frac{\langle v \rangle^2 \sin^2\beta \left(\alpha_{SM}(m_s)\right)^{2/3}}{2M_P^{2/3} m_{3/2}^{1/3}} \\ &\simeq 0.09\text{eV} \left(\sin^2\beta \times \left(\frac{20\text{TeV}}{m_{3/2}} \right)^{1/3} \right) \end{aligned}$$

This works remarkably well!

Conclusions

- In supergravity, integrating out heavy states of mass M does not produce dimension-five operators suppressed by M^{-1}.
- For large-volume models, the dimension-five suppression scale is independent of the masses of the particles integrated out.
- This suppression scale is

$$\Lambda = \frac{M_P}{\mathcal{V}^{1/3}} = m_s \left(\frac{M_P}{m_s} \right)^{1/3}$$

- For an intermediate string scale, this gives precisely the scale 10^{14}GeV required for neutrino masses.

Conclusions

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Yes - with an intermediate string scale $m_s \sim 10^{11}$GeV.