Phenomenological Aspects of LARGE Volume String Compactifications

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Papers

Moduli Stabilisation: hep-th/0502058 (Balasubramanian, Berglund, JC, Quevedo), hep-th/0505076 (JC, Quevedo, Suruliz), arXiv:0704.0737 (Berg, Haack, Pajer), arXiv:0708.1873, 0805.1029 (Cicoli, JC, Quevedo), arXiv:0711.3389 (Blumenhagen, Moster, Plauschinn), arXiv:0804.1248 (Palti, Tasinato, Ward)

Soft terms: hep-th/0505076 (JC. Quevedo, Suruliz),
hep-th/0605141 (JC, Quevedo),
hep-th/0609180 (JC, Cremades, Quevedo),
hep-th/0610129 (JC, Abdussalam, Quevedo, Suruliz),
arXiv:0704.0737 (Berg, Haack, Pajer),
arXiv:0704.3403 (JC, Kom, Suruliz, Allanach, Quevedo).

Cosmology: hep-th/0509012, arXiv:0705.3460 (JC, Quevedo), astro-ph/0605371, arXiv:0712.1875 (Simon *et al*), hep-th/0612197 (Bond *et al*), arXiv:0712.1260 (Misra, Shukla)

Axions and Neutrino Masses: hep-th/0602233 (JC), hep-ph/0611144 (JC, Cremades)

Thanks to my collaborators on these topics:

Shehu Abdussalam, Ben Allanach, Vijay Balasubramanian, Per Berglund, Cliff Burgess, Michele Cicoli, Daniel Cremades, Ling-Han Hung, Chun-Hay (Steve) Kom, Fernando Quevedo, Kerim Suruliz

This talk is particularly based on the paper

0805.xxxx C. Burgess, J. P. Conlon, L-H. Hung, C. Kom, A. Maharana, F. Quevedo

Talk Structure

- String Phenomenology and LARGE Volume Models
- Neutrino Masses
- Continuous Global Non-Abelian Symmetries
- Hyper-Weak Gauge Groups
- Conclusions

Hierarchies in Nature

Nature likes hierarchies:

- The Planck scale, $M_P = 2.4 \times 10^{18}$GeV.
- The GUT/inflation scale, $M \sim 10^{16}$GeV.
- The axion scale, 10^9GeV $\lesssim f_a \lesssim 10^{12}$GeV
- The weak scale : $M_W \sim 100$GeV
- The QCD scale $\Lambda_{QCD} \sim 200$MeV
- The neutrino mass scale, 0.05eV $\lesssim m_\nu \lesssim 0.3$eV.
- The cosmological constant, $\Lambda \sim (10^{-3}\text{eV})^4$

These demand an explanation!

Hierarchies in Nature

This talk will argue for

- an intermediate string scale $m_s \sim 10^{11}$GeV
- stabilised exponentially large extra dimensions ($\mathcal{V} \sim 10^{15} l_s^6$).

and describe some phenomenological aspects of this scenario.

LARGE volume allows different hierarchies to be generated as different powers of the LARGE volume.

Moduli Stabilisation

- String theory lives in ten dimensions.
- Compactify on a Calabi-Yau manifold to give a four-dimensional theory.
- The geometry determines the four-dimensional particle spectrum.
- The spectrum always includes uncharged scalar particles - moduli - describing the size and shape of the extra dimensions.

Moduli Stabilisation

- Moduli are naively massless scalars which couple gravitationally.
- These generate fifth forces and so must be given masses.
- Generating potentials for moduli is the field of moduli stabilisation.
- This talk is on the large-volume models which represent a particular moduli stabilisation scenario.

Moduli Stabilisation: Fluxes

- Fluxes carry an energy density which generates a potential for the cycle moduli.
- In IIB compactifications, 3-form fluxes generate a superpotential

$$
\begin{aligned}
K &= -2\ln(\mathcal{V}) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S}) \\
W &= \int (F_3 + iSH_3) \wedge \Omega \equiv \int G_3 \wedge \Omega.
\end{aligned}
$$

- This stabilises the dilaton and complex structure moduli.

$$D_S W = D_U W = 0.$$

$$W = \int G_3 \wedge \Omega = W_0.$$

Moduli Stabilisation: Fluxes

$$
\begin{aligned}
\hat{K} &= -2 \ln \left(\mathcal{V}(T_i + \bar{T}_i) \right) , \\
W &= W_0 \, . \\
V &= e^{\hat{K}} \left(\sum_T \hat{K}^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2 \right) \\
&= 0
\end{aligned}
$$

No-scale model :

- vanishing vacuum energy
- broken susy
- T unstabilised

No-scale is broken perturbatively and non-pertubatively.

Moduli Stabilisation: KKLT

$$\hat{K} = -2\ln(\mathcal{V}),$$
$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Non-perturbative ADS superpotential.
- The T-moduli are stabilised by solving $D_T W = 0$.
- This gives a susy AdS vacuum which is uplifted by anti-branes/magnetic fluxes/IASD 3-form fluxes/F-terms/something else.
- Susy breaking is sourced by the uplift.

Moduli Stabilisation: KKLT

KKLT stabilisation has three phenomenological problems:

1. No susy hierarchy: fluxes prefer $W_0 \sim 1$ and $m_{3/2} \gg 1$TeV.
2. Susy breaking not well controlled - depends entirely on uplifting.
3. α' expansion not well controlled - volume is small and there are large flux backreaction effects.

Moduli Stabilisation: Large-Volume

$$\hat{K} = -2\ln\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right), \qquad \left(\xi = \frac{\chi(\mathcal{M})\zeta(3)}{2(2\pi)^3 g_s^{3/2}}\right)$$

$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Include perturbative as well as non-perturbative corrections to the scalar potential.
- Add the leading α' corrections to the Kähler potential (Becker-Becker-Haack-Louis).
- These descend from the $\mathcal{R}^4$ term in 10 dimensions.
- This leads to dramatic changes in the large-volume vacuum structure.

Moduli Stabilisation: Large-Volume

The simplest model $\mathbb{P}^4_{[1,1,1,6,9]}$ has two Kähler moduli.

$$\mathcal{V} = \left(\frac{T_b + \bar{T}_b}{2}\right)^{3/2} - \left(\frac{T_s + \bar{T}_s}{2}\right)^{3/2} \equiv \left(\tau_b^{3/2} - \tau_s^{3/2}\right).$$

If we compute the scalar potential, we get for $\mathcal{V} \gg 1$,

$$V = \frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

Moduli Stabilisation: Large-Volume

$$V = \underbrace{\frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s|A_s W_0|\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}}_{\text{Integrate out } \tau_s} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

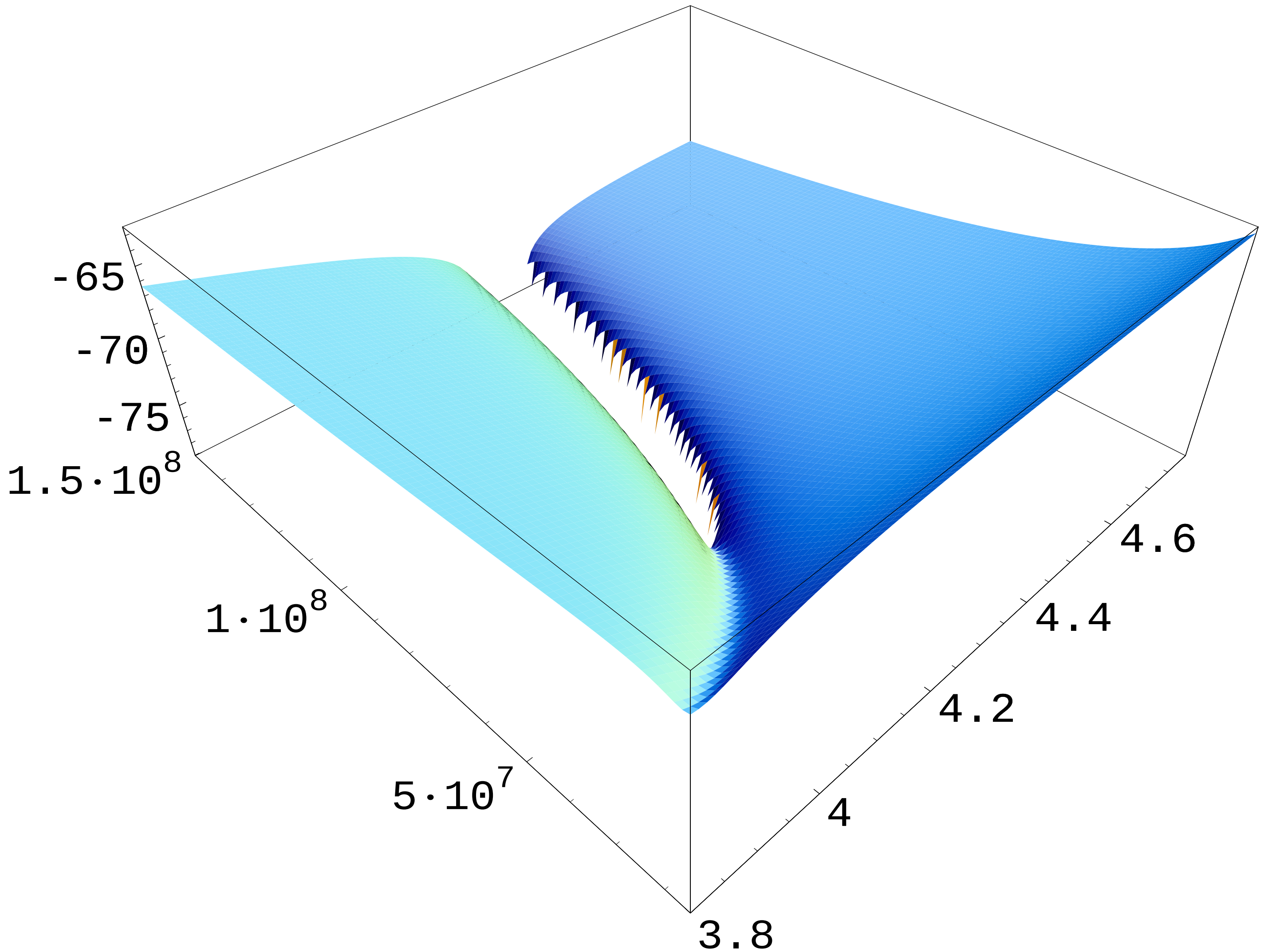
$$V = -\frac{|W_0|^2 \left(\ln \mathcal{V}\right)^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0| e^{a_s\tau_s}, \qquad \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

Moduli Stabilisation: Large-Volume



Moduli Stabilisation: Large-Volume

Higher α' corrections are suppressed by more powers of volume.

Example:

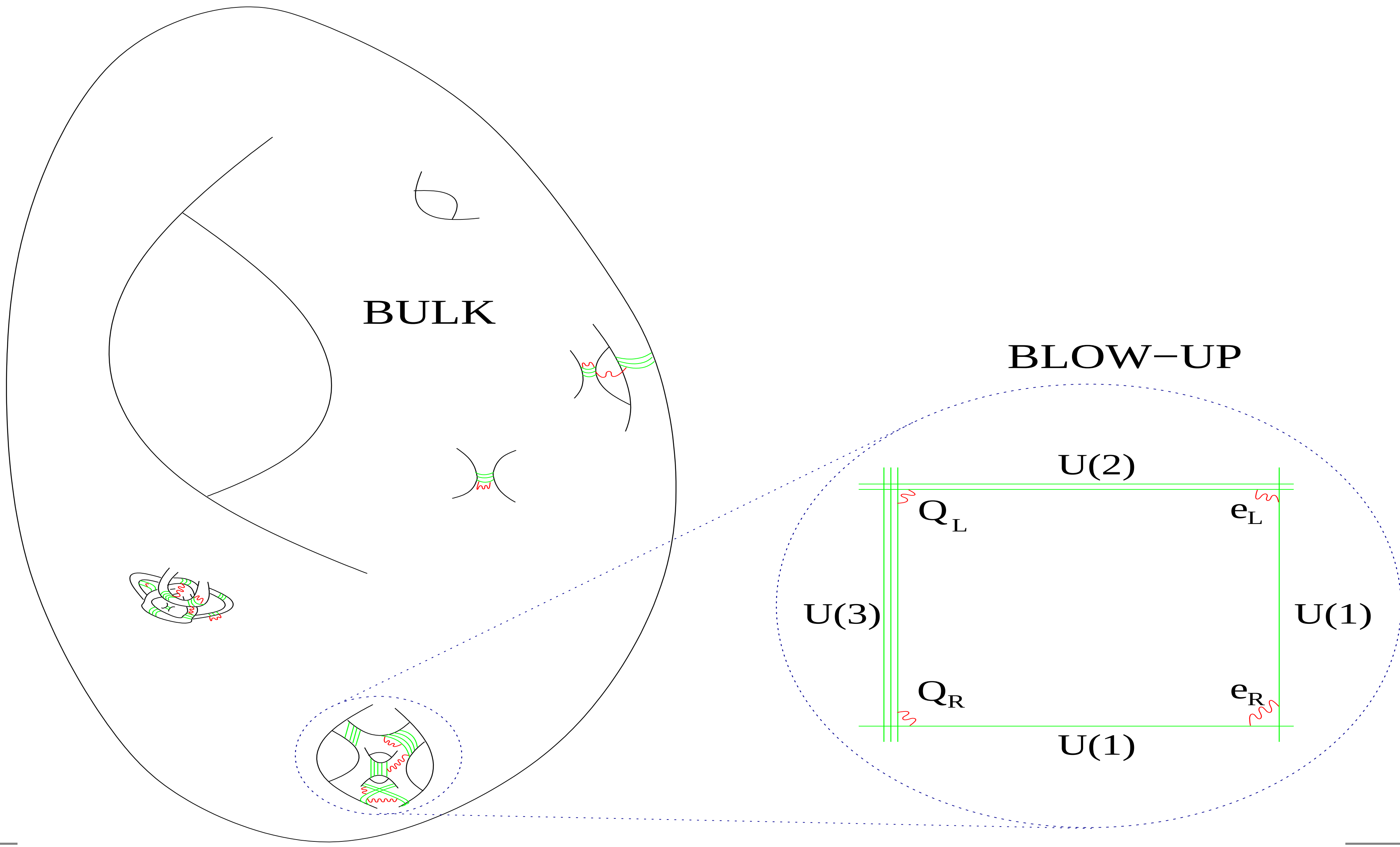
$$\begin{aligned}
\int d^{10}x\sqrt{g}\mathcal{G}_3^2\mathcal{R}^3 \quad &: \quad \int d^{10}x\sqrt{g}\mathcal{R}^4 \\
\int d^4x\sqrt{g_4}\left(\int d^6x\sqrt{g_6}\mathcal{G}_3^2\mathcal{R}^3\right) \quad &: \quad \int d^4x\sqrt{g_4}\left(\int d^6x\sqrt{g_6}\mathcal{R}^4\right) \\
\int d^4x\sqrt{g_4}\left(\mathcal{V}\times\mathcal{V}^{-1}\times\mathcal{V}^{-1}\right) \quad &: \quad \int d^4x\sqrt{g_4}\left(\mathcal{V}\times\mathcal{V}^{-4/3}\right) \\
\int d^4x\sqrt{g_4}\left(\mathcal{V}^{-1}\right) \quad &: \quad \int d^4x\sqrt{g_4}\left(\mathcal{V}^{-1/3}\right)
\end{aligned}$$

Moduli Stabilisation: Large-Volume

Loop corrections are suppressed by more powers of volume: there exists an ‘extended no scale structure’

$$
\begin{aligned}
W &= W_0, \\
K_{full} &= K_{tree} + K_{loop} + K_{\alpha'} \\
&= -3\ln(T+\bar{T}) + \underbrace{\frac{c_1}{(T+\bar{T})(S+\bar{S})}}_{loop} + \underbrace{\frac{c_2(S+\bar{S})^{3/2}}{(T+\bar{T})^{3/2}}}_{\alpha'}. \\
V_{full} &= V_{tree} + V_{loop} + V_{\alpha'} \\
&= \underbrace{0}_{tree} + \underbrace{\frac{c_2(S+\bar{S})^{3/2}}{(T+\bar{T})^{3/2}}}_{\alpha'} + \underbrace{\frac{c_1}{(S+\bar{S})(T+\bar{T})^2}}_{loop}
\end{aligned}
$$

Moduli Stabilisation: Large-Volume



Moduli Stabilisation: Large-Volume

- The stabilised volume is exponentially large.
- The large volume lowers the string scale and gravitino mass through

$$m_s = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} = \frac{M_P}{\mathcal{V}}.$$

- To solve the gauge hierarchy problem, need $\mathcal{V} \sim 10^{15}$.
- D7-branes wrapped on small cycle carry the Standard Model: need $T_s \sim 20(2\pi\sqrt{\alpha'})^4$.
- The vacuum is pseudo no-scale and breaks susy...

Moduli Stabilisation: Large-Volume

The mass scales present are:

Planck scale:	$M_P = 2.4 \times 10^{18}$GeV.
String scale:	$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
KK scale	$M_{KK} \sim \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^{9}$GeV.
Gravitino mass	$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 30$TeV.
Small modulus	$m_{\tau_s} \sim m_{3/2} \ln\left(\frac{M_P}{m_{3/2}}\right) \sim 1000$TeV.
Complex structure moduli	$m_U \sim m_{3/2} \sim 30$TeV.
Soft terms	$m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.
Volume modulus	$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 1$MeV.

Neutrino Masses

- Neutrino masses exist:

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

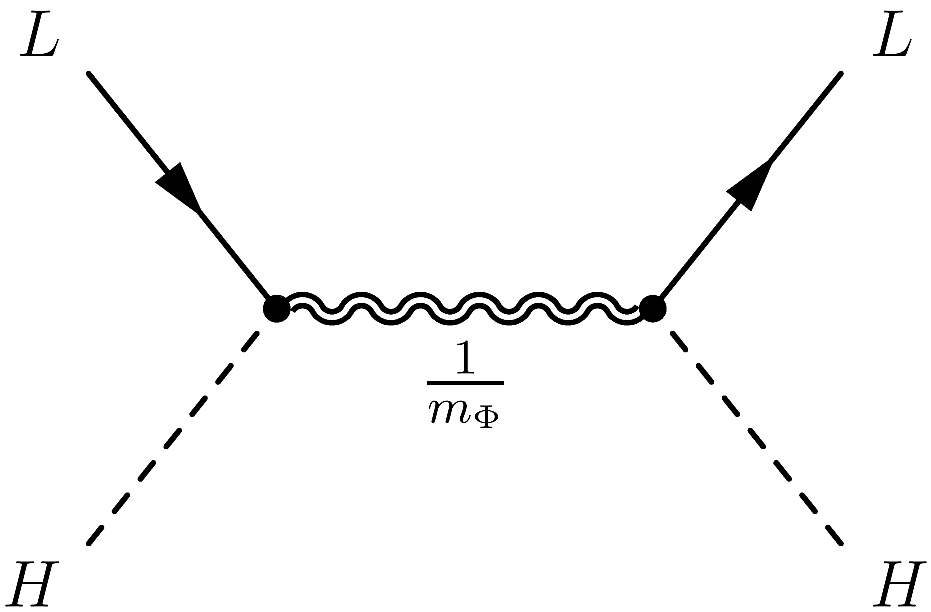
- In the seesaw mechanism, this corresponds to a Majorana mass scale for right-handed neutrinos

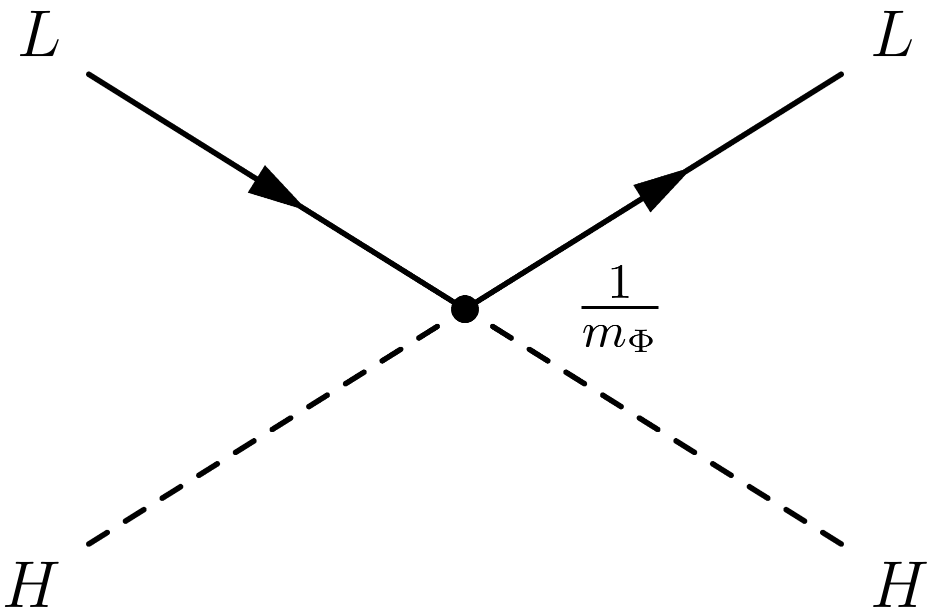
$$M_{\nu_R} \sim 3 \times 10^{14}\text{GeV}.$$

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

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

Neutrino Masses





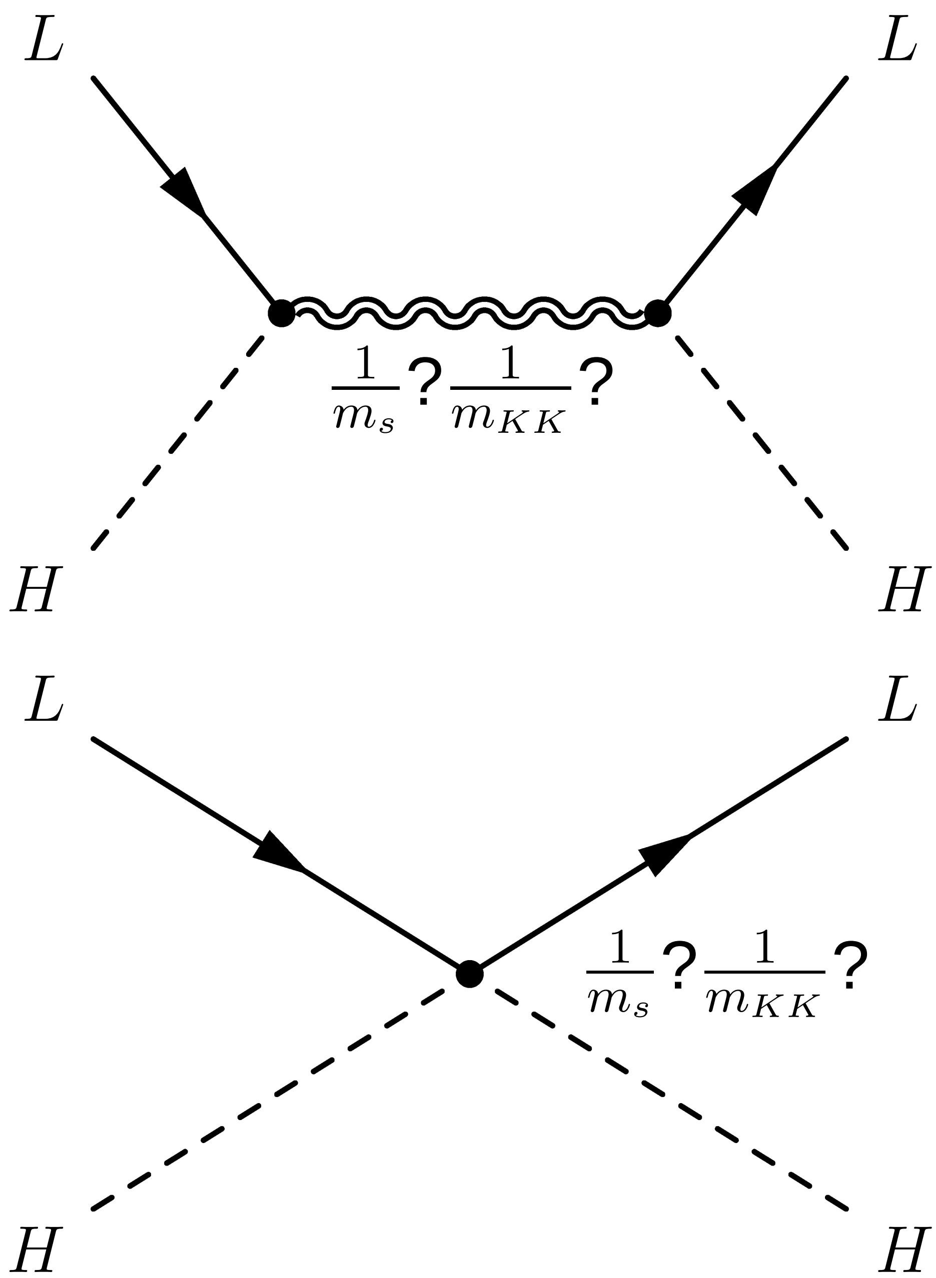
Neutrino Masses

Neutrino masses imply a scale $\Lambda \sim (\text{a few}) \times 10^{14}$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 the intermediate-scale string give a quantitative understanding of this scale?

Neutrino Masses



Neutrino Masses

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:

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

$$W = M_P\Phi^2$$

Neutrino Masses

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,

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

Neutrino Masses

Consider a KK state as a right-handed neutrino

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

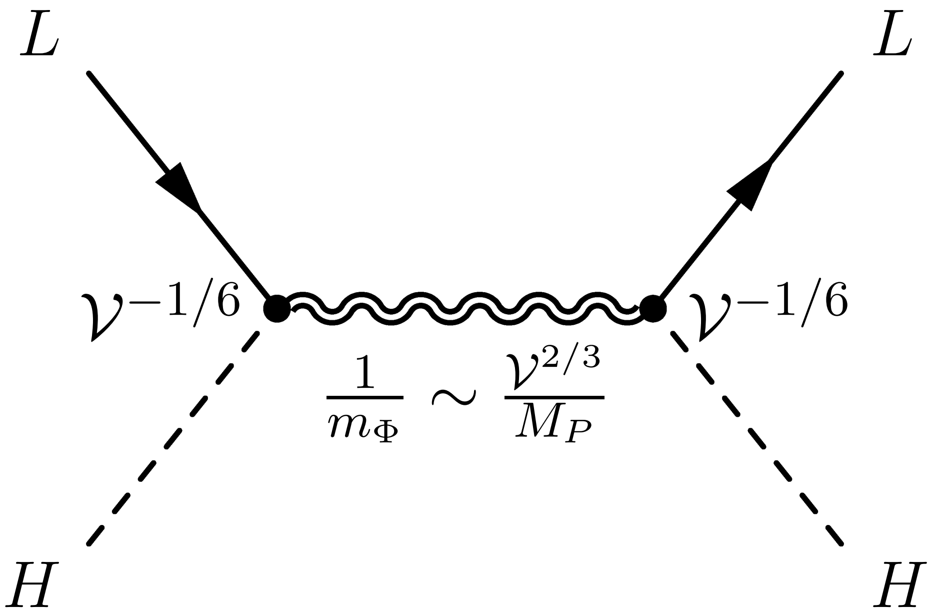
($K_{H\bar{H}}, K_{L\bar{L}} \sim \mathcal{V}^{-2/3}$ follows from locality)

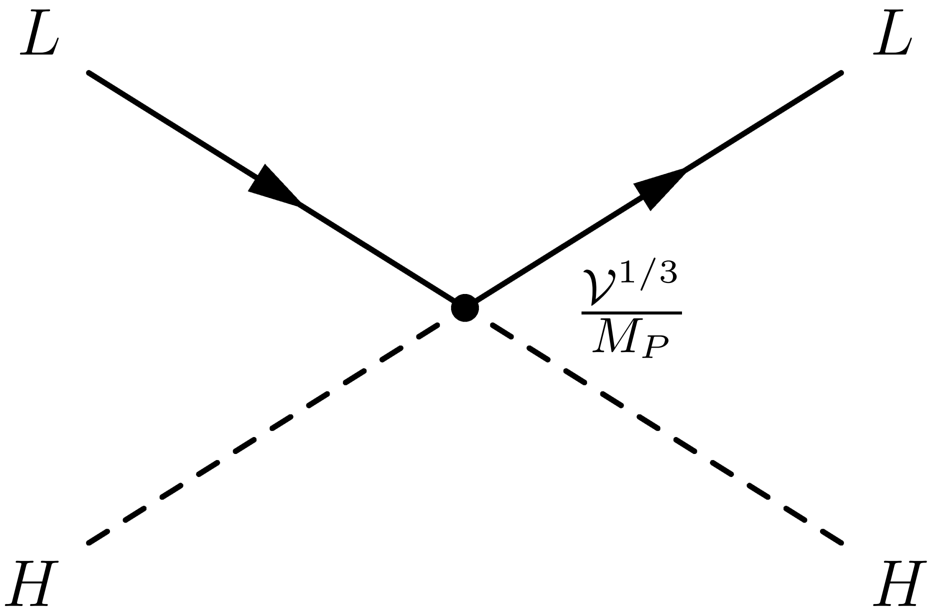
The physical Yukawa is

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

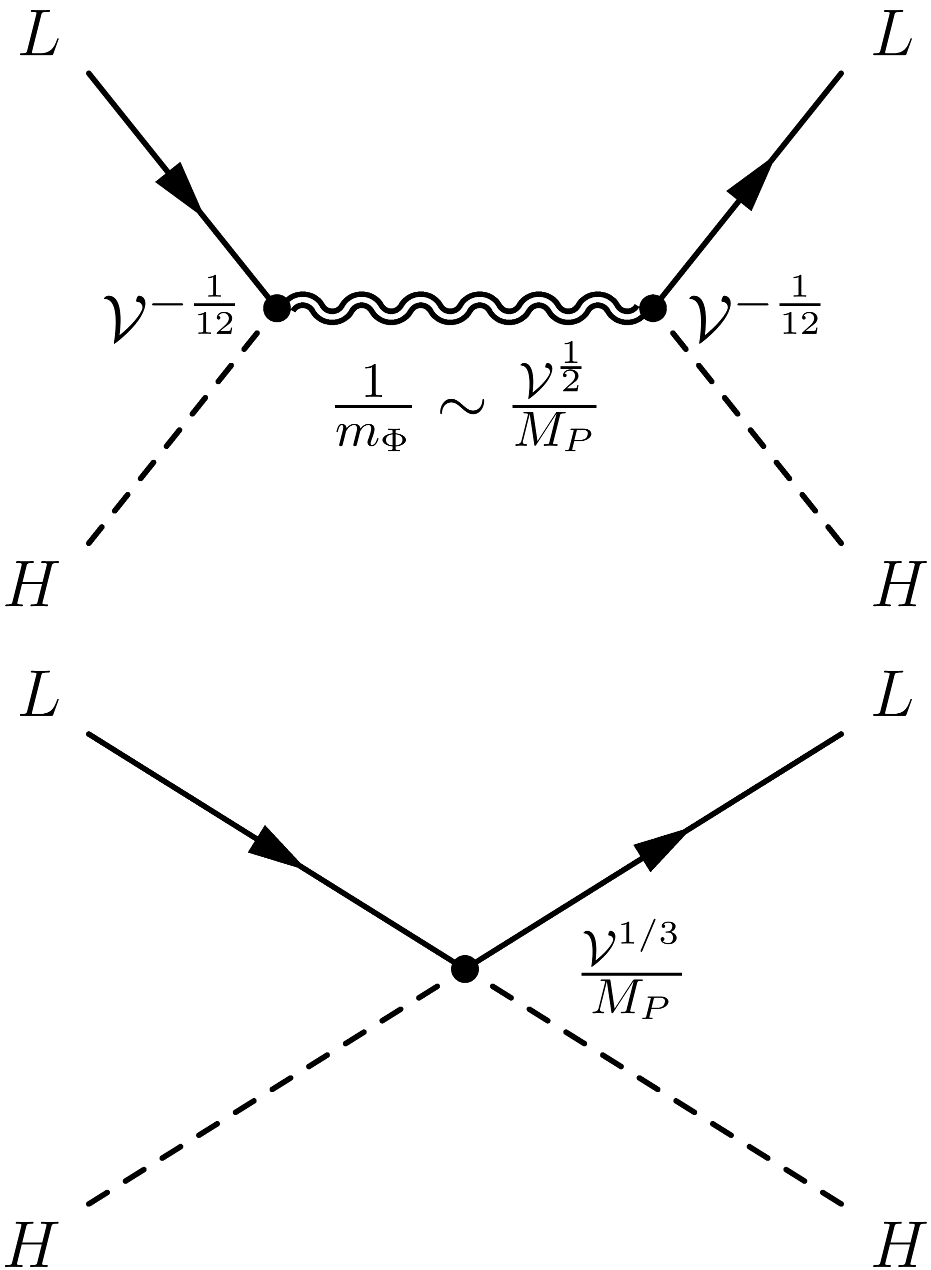
For string states, $\hat{Y}_{\Phi HL} = \mathcal{V}^{-\frac{1}{12}} Y_{\Phi HL}$.

Neutrino Masses

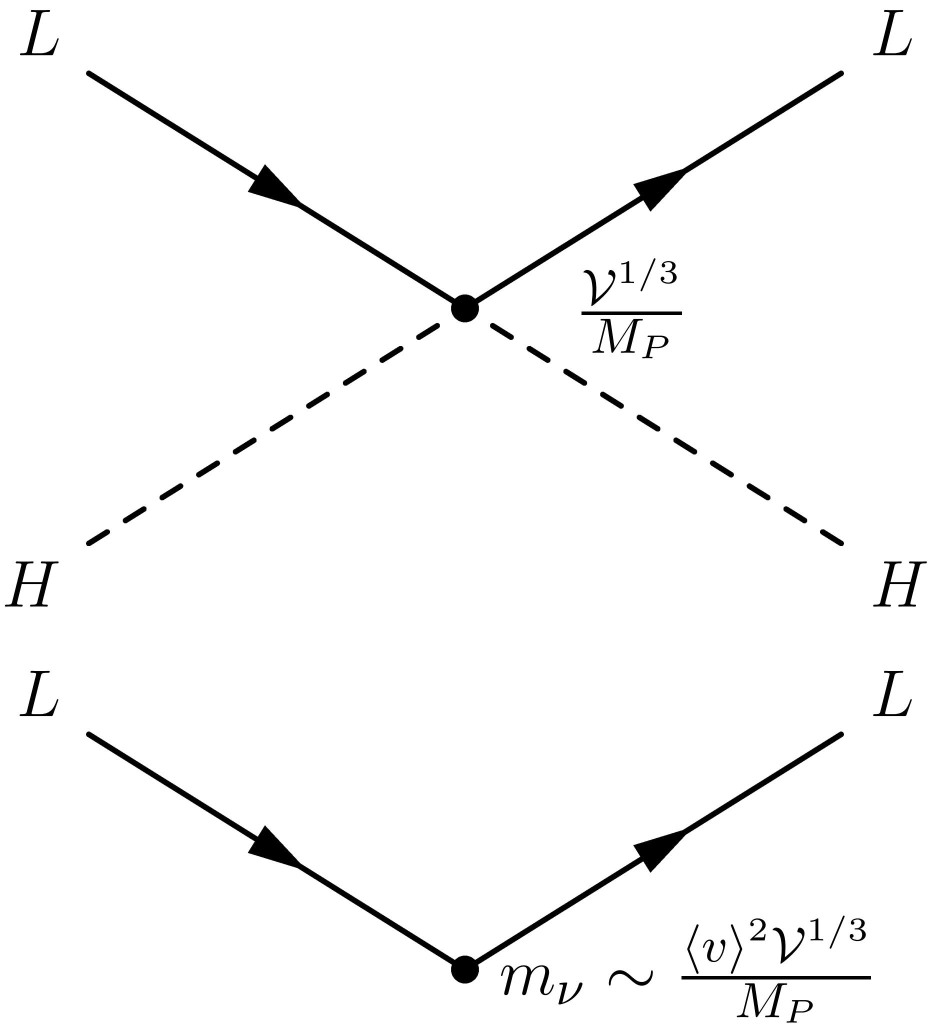




Neutrino Masses



Neutrino Masses



Neutrino Masses

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,

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

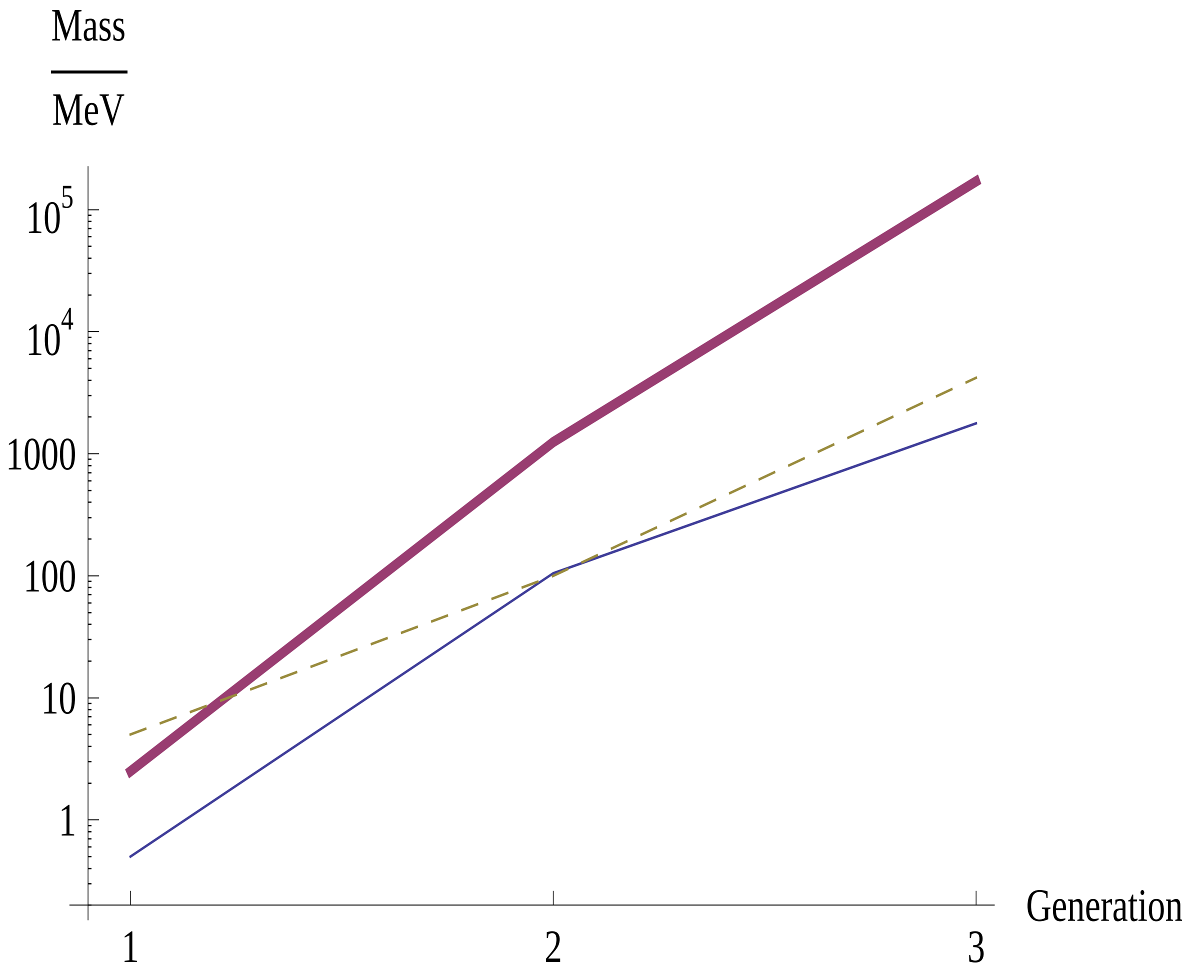
As $\tau_s \sim \alpha_{SM}^{-1}(m_s)$, we have

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

This works remarkably well!

Continuous Flavour Symmetries

Flavour symmetries are very attractive for explaining the fermion mass hierarchies.



Continuous Flavour Symmetries

- In LARGE volume models, the Standard Model is necessarily a local construction.
- The couplings of the Standard Model are determined by the local geometry and are insensitive to the bulk.
- In the limit $\mathcal{V} \to \infty$, the bulk decouples and all couplings and interactions of the Standard Model is set by the local geometry and metric.
- Global Calabi-Yau metrics are hard - local metrics are known!

Continuous Flavour Symmetries

It is a theorem that compact Calabi-Yaus have no isometries.

Local Calabi-Yau metrics often have isometries. Examples:

1. Flat space $\mathbb{C}^3$ has an $SO(6)$ isometry.
2. The (resolved) orbifold singularity $\mathbb{C}^3/\mathbb{Z}_3 = \mathcal{O}_{\mathbb{P}^2}(-3)$ has an $SU(3)/\mathbb{Z}_3$ isometry.
3. The conifold geometry $\sum z_i^2 = 0$ has an $SU(2) \times SU(2) \times U(1)$ isometry.

Local metric isometries are flavour symmetries of local brane constructions.

Continuous Flavour Symmetries

- In the limit $\mathcal{V} \to \infty$ the flavour symmetry becomes exact and the space becomes non-compact.

  New massless states exist as the bulk KK modes become massless.

- In the limit of $\mathcal{V} \gg 1$ but finite, the flavour symmetry is approximate, being softly broken.

  The bulk KK modes are massive but are hierarchially lighter than the local KK modes:

$$M_{KK,local} = \frac{M_S}{R_s}, \qquad M_{KK,bulk} = \frac{M_S}{R_b}.$$

  The bulk KK modes represent the pseudo-Goldstone bosons of the approximate flavour symmetry.

Continuous Flavour Symmetries

- There are two scales in the geometry - the size of the local metric (set by τ_s) and the size of the global metric (set by τ_b).
- The rescaling $\tau_s \rightarrow \lambda^4 \tau_s, \tau_b \rightarrow \lambda^4 \tau_b$ rescales the overall metric and is simply a scale factor.
- The presence and goodness of the isometry is set by the ratio $\frac{\tau_s}{\tau_b}$.
- This determines the extent to which the local non-compact metric is a good approximation in the compact case.

Continuous Flavour Symmetries

Phenomenological discussions of flavour symmetries start with a symmetry group

$$G_{SM} \times G_F = G_{SU(3)\times SU(2)\times U(1)} \times G_F.$$

Flavons Φ are charged under G_F and not under G_{SM}.

SM matter C_i is charged under both G_F and G_{SM}.

$$W = (\Phi_\alpha \Phi_\beta \Phi_\gamma \ldots) C_i C_j C_k.$$

Flavon vevs break G_F and generate Yukawa textures.

The order parameter for G_F breaking is $< \Phi >$.

What are the flavons in our case???

Continuous Flavour Symmetries

A puzzle:

- In 4d effective theory, flavour symmetry breaking is parametrised by the ratio $\frac{R_s}{R_b} = \frac{\tau_s^{1/4}}{\tau_b^{1/4}}$.

  This sets the relative size of the bulk and local cycles.
- However $\frac{\tau_s^{1/4}}{\tau_b^{1/4}}$ is a real singlet while the flavour symmetry group is non-Abelian.
- $\frac{\tau_s^{1/4}}{\tau_b^{1/4}}$ can only be in a trivial representation of G_F.
- So there are no flavons in the 4d effective field theory!

Continuous Flavour Symmetries

The resolution:

- There are indeed no flavons in the 4d effective field theory!
- The aproximate isometry comes from the full Calabi-Yau metric.
- The flavon modes that are charged under G_F are the higher-dimensional (Kaluza-Klein) modes.

  Yau's theorem implies that the vevs of KK modes are set by the moduli vevs.

  From a 4d perspective, it is the vevs of KK modes that break the flavour symmetry.

Continuous Flavour Symmetries

- This mechanism describes a way to realise continuous global non-Abelian flavour symmetries in string theory.
- (Approximate) flavour symmetries arise from (approximate) isometries of the compact Calabi-Yau.
- The symmetries are exact at infinite volume and are broken for any finite value of the volume.
- The breaking parameter is (R_s/R_b) : LARGE volume implies a small breaking parameter for the flavour symmetry.
- The same physics (LARGE volume $\mathcal{V} \gg 1$) may generate both the electroweak hierarchy and the fermion mass hierarchy.

Hyper-weak Gauge Groups

- In LARGE volume models, the Standard Model is a local construction and branes only wrap small cycles.
- There are also bulk cycles associated to the overall volume. These have cycle size

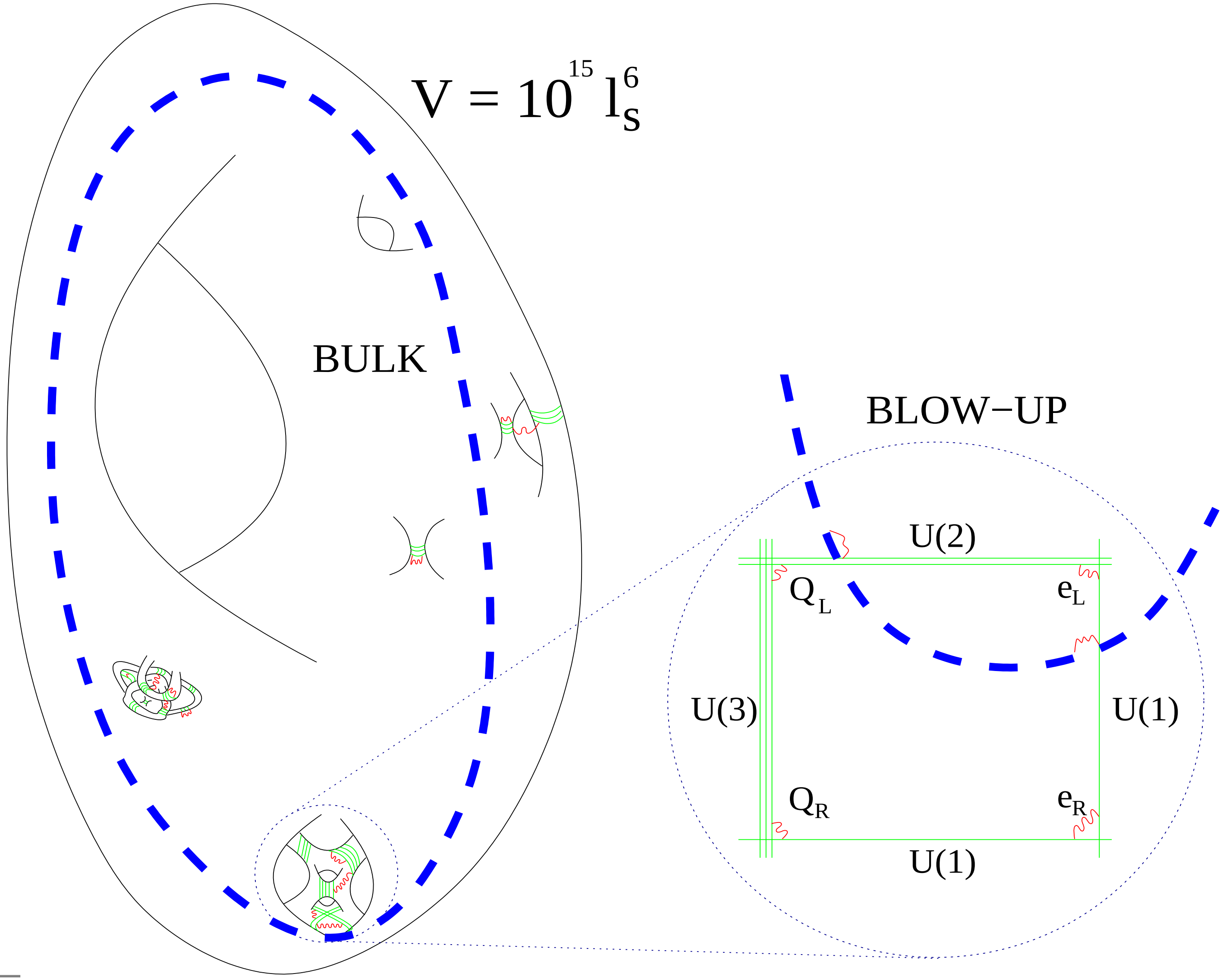
$$\tau_b \sim \mathcal{V}^{2/3} \sim 10^{10}.$$

- There is no reason not to have D7 branes wrapping these cycles!
- The gauge coupling for such branes is

$$\frac{4\pi}{g^2} = \tau_b$$

with $g \sim 10^{-4}$.

Hyper-Weak Gauge Groups



Hyper-weak Gauge Groups

In LARGE volume models it is a generic expectation that there will exist additional gauge groups with very weak coupling

$$\alpha^{-1} \sim 10^9.$$

Two phenomenological questions to ask:

1. How heavy is the hyper-weak Z' gauge boson?
2. How does Standard Model matter couple to the hyper-weak force?

Hyper-Weak Gauge Groups

- Standard Model can couple directly to bulk D7.
- If weak-scale vevs of H_1, H_2 break the bulk D7 gauge group, then

$$M_{Z'} \sim gv \sim 10^{-4} \times 100\text{GeV} \sim 10\text{MeV}.$$

- Gauge group may couple directly to electrons, but with

$$g_e \sim 10^{-4}, \qquad g_e^2 \sim 10^{-8}.$$

- In this case we have a new (relatively) light very weakly coupled gauge boson.

Hyper-Weak Gauge Groups

- There may also be kinetic mixing between the new gauge boson and the photon (cf Z/γ mixing).
- If the new gauge boson is light, the mixing allows the new boson to couple to electromagnetic currents:

$$\mathcal{L}_{int} = \frac{(\bar{\psi}\gamma^{\mu}\psi)\gamma_{\mu}}{\sqrt{1-\lambda^2}} - \frac{(\bar{\psi}\gamma^{\mu}\psi)\lambda Z^{'}_{\mu}}{\sqrt{1-\lambda^2}}$$

  where λ is the mixing parameter.
- This can give milli-charged fermions under the new gauge boson $Z^{'}$.

Hyper-Weak Gauge Groups

- In string theory the presence of gauge groups with very small intrinsic coupling can only occur if $M_S \ll M_{planck}$.
- (This is related to the statement that 'gravity is the weakest force').
- Any observation of such gauge groups would be a distinctive signature of LARGE volume physics.

Conclusions

In LARGE volume models, an exponentially large volume naturally appears ($\mathcal{V} \sim e^{\frac{c}{g_s}}$). This generates hierarchies and low-energy supersymmetry breaking. It also

- allows a natural generation of the suppression scale of neutrino masses
- leads to the generation of approximate flavour symmetries that may help in explaining the Standard Model fermion masses.
- suggest the existence of new hyper-weakly coupled gauge bosons that would be a distinctive signature of the LARGE volume scenario.