LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

MAX PLANCK INSTITUTE FOR PHYSICS

Towards the Realization of the Dark Dimension Scenario in Hořava-Witten Theory

Based on 2605.11068 with Ralph Blumenhagen

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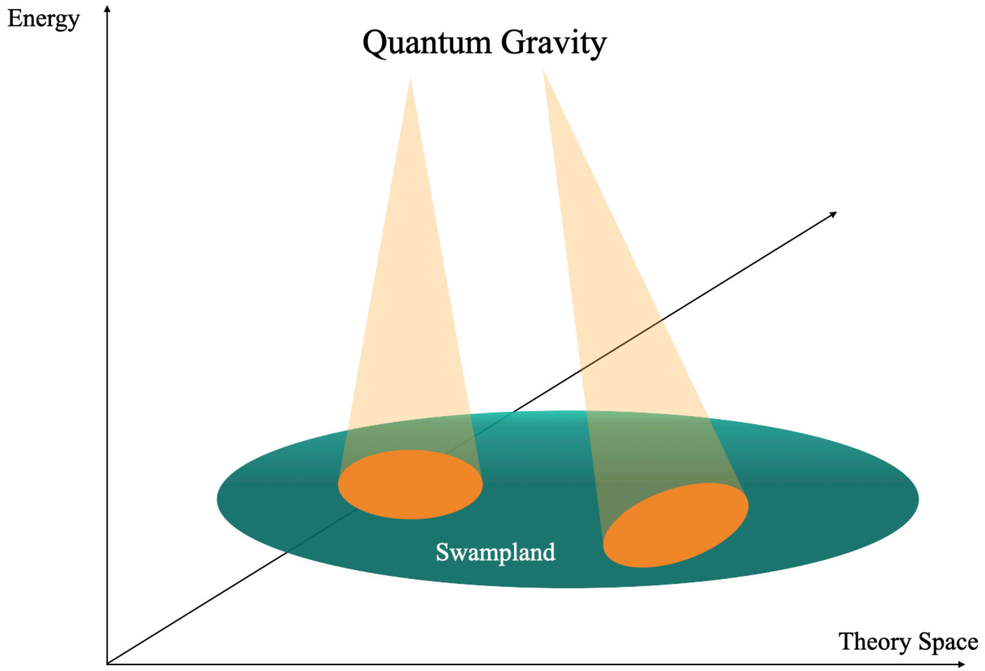
Introduction: Dark Dimension Scenario



General Framework: Swampland Program

Swampland Distance Conjecture: $m \sim e^{-\alpha d(\phi)}$

[Ooguri, Vafa '06]

Emergent String Conjecture

[Lee, Lerche, Weigand '18]

- decompactification limit
- emergent string limit

Dark Dimension Scenario:

[Montero, Vafa, Valenzuela '22]

$m \sim \Lambda^{\alpha}$ + observational input ⟶ single mesoscopic extra dimension

[Lüst, Palti, Vafa '19]

$\Lambda^{1/4} \simeq m_{\rm KK}$

(possibly also two extra dimensions)

[Anchordoqui, Antoniadis, Lüst '25]

Species Scale:

[Dvali '08]

$$\Lambda_{\rm sp} = \frac{M_{{\rm Pl},d}}{N_{\rm sp}^{\frac{1}{d-2}}} \begin{cases} M_{{\rm Pl},d+n} \\ M_{\rm string} \end{cases}$$

See also later studies, e.g.:

[van de Heisteeg, Vafa, Wiesner, Wu '22-24, Calderon-Infante, Castellano, Herraez '25]

Scenario→Model?

Pheno/cosmological observations? Possible [Anchordoqui, Antoniadis, Bedroya, Cribiori, Gonzalo, Lüst, Obied, Montero, Vafa, Valenzuela…]

Top down constructions? Several attempts [Blumenhagen, Brinkmann, Makridou '22, Basile, Lüst '24, Nian, Vandoren '24, Schwarz '24, Dudas, Parameswaran, Serra '25]

Natural candidate: **Hořava-Witten theory** [Hořava, Witten '96]

M theory on the interval S^1/Z_2, standard model localized on the ETW branes.

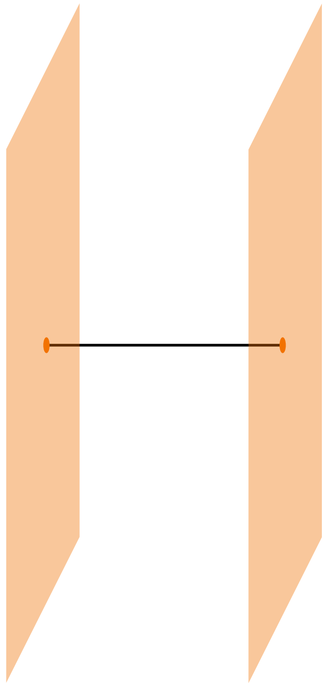
$$dH_3 \sim \mathrm{Tr}(F_1 \wedge F_1) + \mathrm{Tr}(F_2 \wedge F_2) - \mathrm{Tr}(R \wedge R)$$

Further compactifying on a Calabi-Yau [Witten '96]

$$\frac{1}{M_* R_{11}^{\mathrm{crit}}} \sim \left| \int_X J \wedge \left(\mathrm{Tr}(F_i \wedge F_i) - \frac{1}{2}\mathrm{Tr}(R \wedge R) \right) \right|$$

Resolution of the singularity? [Cvetic, Wiesner '24]

Pheno constraints? [Reig, Ruiz '25]



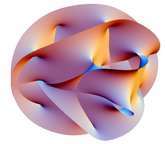
Elements of realization in Hořava-Witten

Avoid warping:

$$\mathrm{Tr}(F_i \wedge F_i) - \frac{1}{2}\mathrm{Tr}(R \wedge R) = 0\,, \quad i = 1,2$$

"symmetric tadpole cancellation" ——— ×

(see also symmetric vacua) [Lukas, Ovrut '99]



Then we can achieve Dark Dimension hierarchies for $r_{11} \sim 10^{20}\,, \quad r_{\rm CY} \sim \mathcal{O}(1) \sim \alpha_{\rm SM}^{1/6}$

$$\Lambda_{\rm sp} \sim M_{\rm Pl,11} \sim 10^{9}{\rm GeV}\,, \quad M_s \sim M_{\rm Pl,4} \sim 10^{19}{\rm GeV}\,, \quad m_{\rm KK} \sim 10^{-12}{\rm GeV}$$

No GUT: $M_{\rm GUT} \sim \dfrac{M_{\rm Pl,11}}{r_{\rm CY}}$

For considerations in the context of GUT's see e.g. [Heckman, Vafa, Weigand, Xu '24]

Line bundles $\longrightarrow$ abelian groups $\xrightarrow{\text{GS}}$ appr. global symmetries broken by instantons

$\longrightarrow$ suppression of proton decay $\quad \mathcal{O}_{\not B} \simeq e^{-S_{\rm inst}}/M_*^{\Delta-4}$

Comparison with type I models e.g. [Ibáñez, Quevedo '99]

Consistency Checks

- The expectation $\alpha_{sm}^{-1} = \mathscr{V}_6/g_s^2$ seems still safe using our anomaly cancellation condition

$$4\pi f_{\mathrm{YM}}^{(i)} = S + \gamma \frac{M_s^2}{8\pi^2}\int_X J \wedge \left(\mathrm{Tr}(F_i \wedge F_i) - \frac{1}{2}\mathrm{Tr}(R\wedge R)\right) + \mathcal{O}\left(e^{-2\pi T_k}\right) + \mathcal{O}\left(e^{-2\pi S}\right)$$

[Ibáñez, Nilles '85]

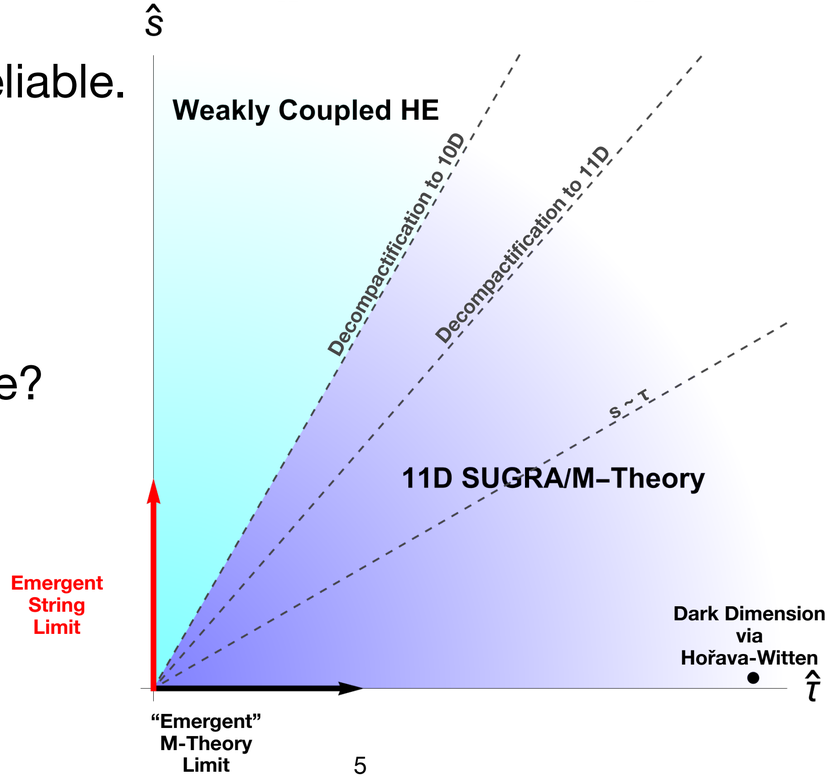
- The one-loop FI term also vanishes: $\xi_a^{(i)} \sim \frac{M_s^4}{g_s^2}\int_X J\wedge J\wedge c_1(L_a) - \int_X c_1(L_a)\wedge\left(\mathrm{Tr}(F_i\wedge F_i) - \frac{1}{2}\mathrm{Tr}(R\wedge R)\right) + \dots$.

[Blumenhagen, Honecker, Weigand '05, Blumenhagen, Moster, Weigand '06]

- Planck scale relation seems also reliable.

[Green, Rudra '16, Florakis '16]

Can we really work in this regime?



Limit seems not to be obstructed, at least not via

[Kaufmann, Weigand, Wiesner '26]

Emergence to the rescue?

M theory limit appearing in Emergence Proposal applications

[Blumenhagen, Cribiori, Gligovic, AP '24]^2

See also: [Artime, Blumenhagen, AP '25, Blumenhagen, Gligovic '25, Artime, Blumenhagen, Leivadaros '26]

Emergence Proposal: Integrating out light degrees of freedom ⟶ kinetic terms

[Palti '18]

Based on earlier results e.g.: [Grimm, Palti, Valenzuela '18]

Multiple applications e.g.: [Blumenhagen, Kläwer, Schlechter '19, Lee, Lerche, Weigand '21, Casas, Ibáñez, Marchesano '24, Calderón-Infante, Delgado, Li, Lüst, Uranga '25, Anastasi, Angius, Huertas, Uranga, Wang '25, Basile, Lüst '26]

M-Theoretic Refinement:

[Blumenhagen, Cribiori, Gligovic, AP '24]^2

In the isotropic decompactification limit to M-theory

$$M_{\mathrm{Pl},d} = \mathrm{const}$$

$$r_i = \mathrm{const}$$

⟶ full results
(Resolved) conifold prepotential,
R^4 terms,
F^4 terms
...

Emergence to the rescue?

For the scalar potential one would generally expect an expression of the form: $\rho \sim M_*^4 \int_0^\infty \frac{dt}{t^3} \mathrm{Str}_{\mathscr{H}_L} e^{-\pi t\, m^2}$.

We can **speculate** about some contributions:

$$m^2 = \left(\frac{n}{r_{11}}\right)^2 + \left(p\, r_{\rm CY}^2\right)^2$$

$$|M2, x_{11}, p_{11}\rangle + |\overline{M2}, -x_{11}, -p_{11}\rangle$$

$$\rho_{\rm KK} \sim M_*^4 \int_0^\infty \frac{dt}{t^3} \sum_{n\neq 0} e^{-\pi t \frac{n^2}{r_{11}^2}} \sim \frac{M_*^4}{r_{11}^4} \sim \frac{M_{\rm pl}^4}{\tau^6}$$

With $\tau = r_{11} r_{\rm CY}^2$

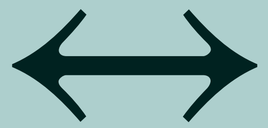
$$\rho_{\rm KK+M2} \sim M_*^4 \int_0^\infty \frac{dt}{t^3} \sum_{\substack{p\neq 0 \\ n\in\mathbb{Z}}} \alpha_p\, e^{-\pi t\left(\frac{n^2}{r_{11}^2} + (p\, r_{\rm CY}^2)^2\right)}$$

$$\sim \beta \frac{M_{\rm pl}^4}{\tau} + \frac{M_{\rm pl}^4}{\tau^4} e^{-2\pi\tau}\left(1 + \frac{3}{2\pi\tau} + \frac{3}{(2\pi\tau)^2}\right) + \mathcal{O}\left(e^{-4\pi\tau}\right)$$

How much information can be extracted from these contributions?

Cosmological aspects of such solutions? Relation with other swampland considerations? [Masias, Makridou, AP, wip]

Outlook

Dark Dimension Scenario ?  **M Theory**

Thank you!