Swampland program, extra dimensions and supersymmetry breaking

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problem of scales: challenge for a fundamental theory

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_W and M_{Planck} :

Strings and extra dimensions

- consistency of the theory ⇒ extra dimensions

  string coupling g_s can be treated as en extra dimension in M-theory

- matter and gauge interactions may be localized on lower dim branes

  transverse dimensions can be large

⇒ **string scale M_s can be lower than the 4d Planck mass!**

opening a new way to address physics problems and scales

M_s low (multi-TeV) ⇒ electroweak hierarchy

M_s at intermediate energies $\sim 10^{11}$ GeV ($M_s^2/M_P \sim$ TeV)

⇒ SUSY breaking, strong CP axion, see-saw neutrino scale

- compactification ⇒ parameters: moduli fields + discrete fluxes
- moduli stabilization ⇒ huge landscape of vacua

Swampland Program

Vafa '05, Ooguri-Vafa '06

$\Rightarrow$ **need an extra input of guidance principle**

Swampland Program

Not all effective field theories can consistently coupled to gravity

- anomaly cancellation is not sufficient

- consistent ultraviolet completion can bring non-trivial constraints

those which do not, form the 'swampland'

criteria $\Rrightarrow$ conjectures

supported by arguments based on string theory and black-hole physics

Distance/duality conjecture:

At large distance in field space $\phi \Rrightarrow$ tower of exponentially light states

$m \sim e^{-\alpha\phi}$ with $\alpha \sim \mathcal{O}(1)$ parameter in Planck units

Distance/duality conjecture

Tower of states

- provides a weakly coupled dual description up to the species scale

$$M_* = M_P/\sqrt{N}$$ Dvali '07

- can be either

1. a Kaluza-Klein tower (decompactification of d extra dimensions)

$$M_* = M_P^{(4+d)} = (m^d M_P^2)^{1/(d+2)} \quad ; \quad m \sim 1/R\,, \quad \phi = \ln R$$

2. a tower of string excitations

$$M_* = m \sim \text{the associated string scale} \quad ; \quad \phi = -\ln g_s$$

emergent string conjecture Lee-Lerche-Weigand '19

smallness of physical parameters : large distance corner of lanscape?

An early example

I.A.-Bachas-Lewellen-Tomaras '88 [11]

Theorem:

assuming a light gravitino (or gaugino) present in the string spectrum

$$M_{3/2} << M_P$$

$\Rightarrow \exists$ a tower of states with the same quantum numbers and masses

$$M_k = (2Nk + 1)M_{3/2}\,; \quad k = 1, 2, \ldots\,; \quad N \text{ integer (not too large)}$$

Proof:

2D free-fermionic constructions $\Rightarrow N \lesssim 10$

2D bosonic lattices $\Rightarrow N \lesssim 10^3$

$\Rightarrow$ compactification scale $m = \lambda_{3/2}^{-1} M_{3/2}$ with $\lambda_{3/2} = 1/2N$

Dark dimension proposal for the dark energy

$m = \lambda^{-1}\Lambda^{a}$ $\quad (M_P = 1) \quad ; \quad 1/4 \leq a \leq 1/2$ Montero-Vafa-Valenzuela '22

- distance $\phi = -\ln\Lambda$ Lust-Palti-Vafa '19
- $a \leq 1/2$: unitarity bound $\quad m^2_{\rm spin-2} \geq 2H^2 \sim \Lambda$ Higuchi '87
- $a \geq 1/4$: estimate of 1-loop contribution $\Lambda \gtrsim m^4$

observations: $\Lambda \sim 10^{-120}$ and $m \gtrsim 0.01$ eV (Newton's law) $\Rightarrow a = 1/4$

astrophysical constraints $\Rightarrow d = 1$ extra dimension

$\Rightarrow$ species scale (5d Planck mass) $M_* \simeq \lambda^{-1/3}\, 10^8$ GeV

$10^{-4} \lesssim \lambda \lesssim 10^{-1}$

Obviously such a low m cannot correspond to a string tower

More physics implications of the dark dimension

- natural explanation of neutrino masses introducing ν_R in the bulk

  recent analysis of ν-oscillation data with 3 bulk neutrinos $\Rightarrow$

  $m \gtrsim 2.5$ eV $\quad (R \lesssim 0.4\,\mu\text{m})$ Forero-Giunti-Ternes-Tyagi '22

  $\Rightarrow \lambda \lesssim 10^{-3}$ and $M_* \sim 10^9$ GeV

- 2 candidates of dark matter:

  1. 5D primordial black holes in the mass range $10^{15} - 10^{21}$g

     with Schwarzschild radius in the range $10^{-4} - 10^{-2}$ μm

     Anchordoqui-I.A.-Lust '22

  2. KK-gravitons of decreasing mass due to internal decays (dynamical DM)

     from $\sim$ MeV at matter/radiation equality ($T \sim$ eV) to $\sim$ 50 keV today

     Gonzalo-Montero-Obied-Vafa '22

  possible equivalence between the two Anchordoqui-I.A.-Lust '22

Dark Dimension Radion stabilization and inflation

Inflation scale $M_I = \Lambda_I^{1/4} \simeq \sqrt{M_*^I H_I}$ with $M_*^I = M_P/\sqrt{N_I}$

M_*^I: the strength of gravity at M_I $(N_I = M_*^I/m)$ I.A.-Patil '14

Also $H_I/M_*^I \simeq 10^{-4}\sqrt{r} \leftarrow$ tensor-to-scalar ratio of primordial fluctuations

$m \sim$ eV $\Rightarrow M_*^I \sim 10^9$ GeV and $M_I \lesssim 10^7$ GeV

However, if 4d inflation occurs with fixed DD radius $\Rightarrow$

(Higuchi bound) $H_I \lesssim m \sim$ eV $\Rightarrow M_I \lesssim 100$ GeV

Interesting possibility: the extra dimension expands with time

$R_0 \sim 1/M_*$ to $R \sim \mu$m requires ~ 42 efolds! Anchordoqui-I.A.-Lust '22

Dark Dimension hierarchy from inflation

$$ds_5^2 = \frac{ds_4^2}{R} + R^2 dy^2 \qquad ; \qquad ds_4^2 = a^2(-d\tau^2 + d\vec{x}^2)$$

$$= a_5^2(-d\tau^2 + d\vec{x}^2 + R_0^2\ dy^2)$$ R_0 : initial size prior to inflation

After 5d inflation of $N = 42$-efolds $\Rightarrow$ 63 e-folds in 4d with $a = e^{3N/2}$

Inflaton: 5D field φ with a coupling to the brane to produce SM matter

e.g. via a 'Yukawa' coupling suppressed by the bulk volume $y \sim 1/(RM_*)^{1/2}$

Its decay to KK gravitons should be suppressed to ensure $\Delta N_{\rm eff} < 0.2$

Anchordoqui '20

$$\left(\Gamma^{\varphi}_{\rm SM} \sim \frac{m}{M_*} m_\varphi\right) > \left(\Gamma^{\varphi}_{\rm grav} \sim \frac{m_\varphi^4}{M_*^3}\right) \Rightarrow m_\varphi < 1\,{\rm TeV}$$

Gravitino Mass Conjecture [6]

Cribiori-Lust-Scalisi, Castellano-Font-Herraez-Ibanez '21

$$m_2 = \lambda_{3/2}^{-1} M_{3/2}^n \quad (M_P = 1) \quad n > 0$$

supergravity in flat space: $M_{3/2} = \varkappa M_{\rm SUSY}^2 \leftarrow$ VEV of F (or D) auxiliary

Low energy SUSY (linear or non-linear) $\Rightarrow M_{3/2} < M_{\rm SUSY} \leq M_*$

However Standard Model soft terms depend on the mediation mechanism

- gravity mediation: $M_{\rm soft} \sim M_{\rm SUSY}^2 \sim M_{3/2}$
- gauge mediation: $M_{\rm soft} \sim \alpha M_{\rm SUSY}^2 / M_{\rm mess} \leftarrow$ messenger mass $\gtrsim M_{\rm SUSY}$
  ($\nwarrow$ loop factor)

Combine GMC with Dark Dimension proposal $\Rightarrow$ two possibilities:

1. one KK tower: $m_2 = m$
2. two different towers: $m = m_1$ for DE and m_2 for SUSY breaking

Anchordoqui-I.A.-Cribiori-Lust-Scalisi '23

scenario 1: single KK tower

$$\Lambda = (\lambda/\lambda_{3/2})^4 \, M_{3/2}^{4n}$$

identified as leading non-vanishing power of $\mathrm{Str}\mathcal{M}^{2k} \Rightarrow 2n$ is integer ≥ 1

requiring $M_{\mathrm{SUSY}} \leq M_* \Rightarrow n \leq 2$ while $M_{\mathrm{SUSY}} \gtrsim 10$ TeV $\Rightarrow n \geq 1$

n	$M_{3/2} \times (\lambda_{3/2})^{-\frac{1}{n}}$ GeV^{-1}	$M_{\mathrm{SUSY}} \times \varkappa^{\frac{1}{2}} (\lambda_{3/2})^{-\frac{1}{2n}}$ GeV^{-1}
1	2.5×10^{-9}	7.8×10^{4}
3/2	2.5×10^{0}	2.5×10^{9}
2	7.8×10^{4}	4.4×10^{11}

$n = 1$ requires gauge mediation

while $n = 2$ (with tuning of $\varkappa(\lambda_{3/2})^{-\frac{1}{2n}}$) gravity mediation

also $n = 3/2$

scenario 2: two KK towers

Dark Radius $R_1 = \lambda\Lambda^{-1/4}$; SUSY Radius $R_2 = 1/m_2 = \lambda_{3/2} M_{3/2}^{-n}$

species scale = $(5+p)$-dim Planck mass

$M_* = M_P/\sqrt{N}$ with $N = N_1 N_2 = R_1 R_2 M_*^{1+p}$ for p extra SUSY dims

$\Rightarrow M_* = (m_1 m_2^p)^{1/(3+p)}$ while $m_2 = (\varkappa^n/\lambda_{3/2})\, M_{\rm SUSY}^{2n}$

experimental bounds: $m_2 \gtrsim 10$ MeV (supernova), $M_{\rm SUSY} \gtrsim 10$ TeV (LHC)

- $n = 1/2$: $m_2 \sim M_{\rm SUSY} \Rightarrow M_{3/2} \gtrsim 0.1$ eV

  for $M_{\rm SUSY} = 10$ TeV $\Rightarrow M_* \sim 10^{7-8}$ GeV $(1 \leq p \leq 5)$

- $n > 1$ and $n = 1, p > 1$: excluded

- $n = 1 = p$: $M_{\rm SUSY} \sim M_* \simeq 10^7$ GeV, $m_2 \sim 10$ MeV, $M_{3/2} \simeq \lambda_{3/2} m_2$

  tuning $\lambda_{3/2}/\varkappa \sim \mathcal{O}(10^{-5})$

string realizations

5 viable solutions:

- $n = 1$ for $M_{3/2} \sim 1/R$ for $R = R_1$ or R_2
- $n = 1/2$ for scenario 2 with $M_{\rm SUSY} \sim 1/R_2$
- $n = 3/2$ or 2 for scenario 1 with $M_{\rm SUSY} \sim M_*$

First 3 can be realized by imposing Scherk-Schwarz boundary conditions

higher-dim fields periodic up to an $\mathcal{R}$-symmetry transf. that breaks SUSY

$\Rightarrow$ shift of KK-momentum by a parameter $\propto \mathcal{R}$-charge

gravitino 0-mode gets a mass $M_{3/2} = q/R$ $\quad (\lambda_{3/2} = q)$

simplest example: temperature breaking ($T = 1/R$):

fermions antiperiodic $\Rightarrow$ 1/2-integer frequencies $q = 1/2$

effective supergravity description: I.A.-Kounnas '91

string realizations

Minimal and attractive scenario 1 with $n = 1$

moreover vacuum energy: $\Lambda \sim 1/R^4$ consistent with $a = 1/4$

Generalization of Scherk-Schwarz in the presence of branes:

transverse (bulk) direction $\Rightarrow$ no tree-level effect on the brane

I.A.-Dudas-Sagnotti '99

open problem: string construction implementing $M_{\rm SUSY} \sim M_{3/2}^{1/2}$

Last 2 solutions with $M_{\rm SUSY} \sim M_*$

can be realized in the framework of Brane Supersymmetry Breaking

only non-linear SUSY on the brane I.A.-Dudas-Sagnotti '99, Uranga '00

effective supergravity

supergravity realization of $n = 4a$:

no scale models with 1-loop (or α'^3) correction

Kähler potential: $K = -\ln\left(i\prod_{I=1}^{3}(\Phi_I - \bar{\Phi}_I) + \xi\right)$

constant superpotential W

$$M_{3/2} = \frac{W}{\prod_{I=1}^{3}(2\mathrm{Im}\Phi_I)^{1/2}} + \mathcal{O}(\xi)$$

$$V = 6\xi \frac{|W|^2}{\prod_{I=1}^{3}(2\mathrm{Im}\Phi_I)^2} + \mathcal{O}(\xi^2) = \frac{6\xi}{|W^2|} M_{3/2}^4 + \mathcal{O}(\xi^2)$$

Scherk-Schwarz STU models with $T = U$ realize $n = 1$

$\mathrm{Im}S = \mathrm{Im}\,T = r$ in string units $\Rightarrow$

$$M_{3/2} \sim \frac{M_P}{r^{3/2}} \simeq \frac{M_s}{r} \quad ; \quad V \sim \xi \frac{M_P^4}{r^6} \simeq \xi \frac{M_s^4}{r^4}$$

Conclusions

smallness of some physical parameters might signal

a large distance corner in the string landscape of vacua

such parameters can be the scales of dark energy and SUSY breaking

$\Rightarrow$ generalization of the dark dimension proposal

- minimal scenario very attractive

  $M_{3/2} \sim$ eV, $M_{\rm SUSY} \sim$ ten's of TeV, require gauge mediation

- 2 more cases are possible: $M_{3/2} \sim (1/R)^{1/n}$ for $n = 3/2, 2$

  $M_{\rm SUSY} \sim M_* \sim 10^9$ GeV with $M_{3/2} \sim \mathcal{O}$(GeV-TeV)

- a separate SUSY tower is also possible but very restrictive

  $n = 1/2 \Rightarrow M_{\rm SUSY} \sim 1/R_2 > 10$ TeV and $M_{3/2} > 0.1$ eV

  $n = 1 \Rightarrow M_{\rm SUSY} \sim M_* \sim 10^7$ GeV and $m_2 \sim M_{3/2} \sim 10$ MeV

- possible string realizations and supergravity descriptions