Swampland program, extra dimensions and susy breaking

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Swampland Program

Vafa '05, Ooguri-Vafa '06

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 $\Rightarrow$ conjectures

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

Some well established examples:

- No exact global symmetries in Nature
- Weak Gravity Conjecture (WGC): gravity is the weakest force

  $\Rightarrow$ minimal non-trivial charge: $q \geq m$ in Planck units $8\pi G = \kappa^2 = 1$

  Arkani-Hamed, Motl, Nicolis, Vafa '06

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

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

$$M_* = M_P/\sqrt{N}$$

Dvali '07

- tower 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

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

emergent string conjecture

Lee-Lerche-Weigand '19

smallness of physical parameters : large distance corner of lanscape?

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

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

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

$R \lesssim 30\mu$m

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

Gravitino Mass Conjecture [4]

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

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

4d supergravity in flat space: $M_{3/2} = \varkappa M^2_{\rm SUSY}$ ← VEV of F (or D) auxiliary

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

However Standard Model soft terms depend on the mediation mechanism

- gravity mediation: $M_{\rm soft} \sim M^2_{\rm SUSY} \sim M_{3/2}$
- gauge mediation: $M_{\rm soft} \sim \alpha M^2_{\rm SUSY} / M_{\rm mess}$ ← messenger mass $\gtrsim M_{\rm SUSY}$
  ↖loop factor

Combine GMC with Dark Dimension proposal ⇒ 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 $m_2 = (\varkappa^n/\lambda_{3/2})\, M_{\mathrm{SUSY}}^{2n}$

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

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

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

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

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

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

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

  the bound can be relaxed in the presence of bulk ν_R-neutrino masses

  Lukas-Ramond-Romanino-Ross '00, Carena-Li-Machado^2-Wagner '17

support on Dirac neutrinos by the sharpened WGC

non-SUSY AdS vacua (flux supported) are unstable   Ooguri-Vafa '16

avoid 3d AdS vacuum of the Standard Model with Majorana neutrinos

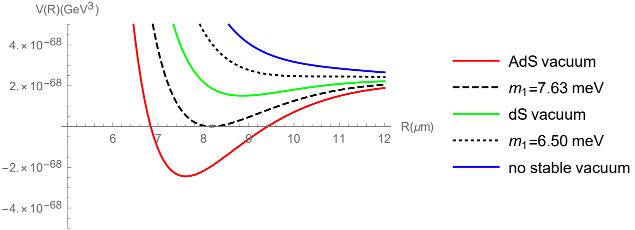
radion stabilisation: 4d cosmological constant versus Casimir energy

Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07

$\Rightarrow$ Dirac neutrinos with a lightest mass $\lesssim$ few meV

Ibanez, Martin-Lozano, Valenzuela '17

or a light gravitino in the meV range   Anchordoqui-I.A.-Cunat '23



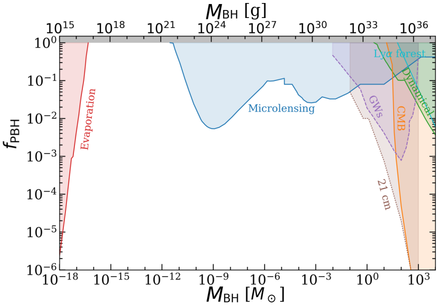
More physics implications of the dark dimension

- 3 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 $\Rightarrow$
     Dynamical DM for small violation of KK-momentum conservation [14]
     from $\sim$ MeV at matter/radiation equality ($T \sim$ eV) to $\sim$ 50 keV today
     Gonzalo-Montero-Obied-Vafa '22

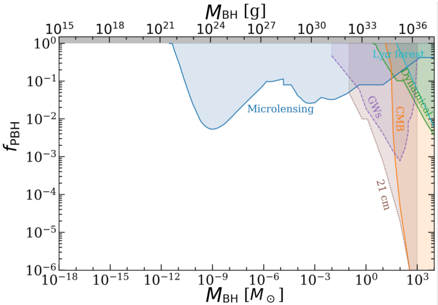
  possible equivalence between the two Anchordoqui-I.A.-Lust '22
- ultralight radion as a fuzzy dark matter Anchordoqui-I.A.-Lust '23

Primordial Black Holes as Dark Matter

4d PBH



5d PBH



5D BHs live longer than 4D BHs of the same mass

Fuzzy dark matter & the Pulsar Timing Array signal

Anchordoqui-IA-Lust '23

FDM: ultralight bosonic particles with wave-like behavior at galactic scales

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 4.8 \ {\rm kpc} \left(\frac{10^{-23} \ {\rm eV}}{m}\right) \left(\frac{250 \ {\rm km/s}}{v}\right)$$

$\Rightarrow$ at larger distances FDM behaves as CDM

PTA signal: time arrival stochastic sinusoidal oscillations

of amplitude $\mathcal{A} \sim 10^{-15}$ at frequency $f \sim$ a few nHz

Similar signal can be produced by FDM

of mass $m \sim 10^{-23}$ eV using $\rho_{\rm DM} \sim 0.4 \ {\rm GeV/cm^3}$

oscillations generate fluctuations in metric perturbations

$\Rightarrow$ (quasi) stabilised **radion as fuzzy dark matter**

Dark dimension radion as fuzzy dark matter

- radion mass: $m_\phi \sim \sqrt{V_{\phi\phi}} \sim \sqrt{\Lambda}_4 / M_p$ $\quad f = \omega/(2\pi) = m/\pi$
- radion production: (inflaton decay) via unstable KK gravitons [11]

5D coupling $\searrow$ (→ λ^2) Mohapatra-Nussinov-Perez Lorenzana '03 (↓ $\langle\varphi_{l-l'}\rangle$)

$$\Gamma^l_{\rm tot} = \sum_{l'<l} \Gamma^l_{Rl'} = \frac{1}{8\pi}\frac{\lambda^2}{m_l^2}\frac{1}{(2\pi R M_*)^2}\sum_{l'<l}(m_l - m_{l'})\,\langle\varphi_{l-l'}\rangle^2$$

$$= \frac{\lambda^2}{64\pi^3}\left(m_{\rm KK} + \frac{m_{\rm KK}^2}{m_l}\right)\left(\frac{\langle\varphi\rangle}{M_*}\right)^2$$

$$\sim\ 10^{13}\text{-}10^2\,{\rm s}^{-1} \quad \text{for } \frac{\langle\varphi\rangle}{M_*} \sim 1\text{-}10^{-5} \text{ and } m_{KK} = 10\,{\rm eV}$$

$\Rightarrow$ (KK-tower $\rightarrow$ radion) well before the QCD phase transition ($\sim 20\mu$s)

- suppress radion coupling to matter: add a localised kinetic term

$$\delta S^{\rm localised}_{\rm radion} = \zeta \int [d^4x] \left(\frac{\partial R}{R}\right)^2 \qquad \zeta : \text{VEV of a brane field}$$

also Albrecht-Burgess-Ravndal-Skordis '01

Dark Dimension Radion stabilization and inflation

If 4d inflation occurs with fixed DD radius $\Rightarrow$

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

Inflation scale $M_I = \Lambda_I^{1/4} \simeq \sqrt{M_P H_I}$

Interesting possibility: the extra dimension expands with time

$R_0 \sim 1/M_*$ to $R \sim \mu$m requires ~ 40 efolds! Anchordoqui-I.A.-Lust '22

$$ds_5^2 = a_5^2(-d\tau^2 + d\vec{x}^2 + R_0^2\, dy^2) \quad R_0 : \text{ initial size prior to inflation}$$

$$= \frac{ds_4^2}{R} + R^2 dy^2 \quad ; \quad ds_4^2 = a^2(-d\tau^2 + d\vec{x}^2) \quad \Rightarrow a^2 = R^3$$

After 5d inflation of $N = 40$-efolds $\Rightarrow$ 60 e-folds in 4d with $a = e^{3N/2}$

Large extra dimensions from inflation in higher dimensions

Anchordoqui-IA '23

Dark Dimension hierarchy from inflation

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

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

5D cosmological constant at the minimum of the inflaton potential

$\Rightarrow$ runaway radion potential:

$$V_0 \sim \frac{\Lambda_5^{\rm min}}{R}\,; \qquad (\Lambda_5^{\rm min})^{1/5} \lesssim 100\,{\rm GeV} \quad \text{(Higuchi bound)}$$

canonically normalised radion: $\phi = \sqrt{3/2}\,\ln(R/r) \qquad r \equiv \langle R \rangle_{\text{end of inflation}}$

$\Rightarrow$ exponential quintessence-like form $V_0 \sim e^{-\alpha\phi}$ with $\alpha \simeq 0.8$

just at the allowed upper bound: Barreiro-Copeland-Nunes '00

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

mesoscopic dark dimension proposal: interesting phenomenology

neutrino masses, dark matter, cosmology, SUSY breaking

- minimal scenario for SUSY breaking 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)

Large extra dimensions from higher dim inflation

- connect the weakness of gravity to the size of the observable universe