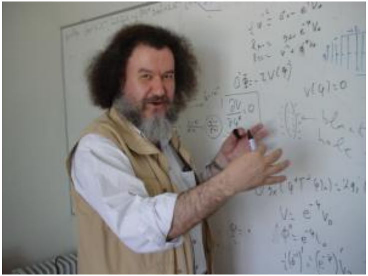
Swampland program, extra dimensions and supersymmetry breaking

I. Antoniadis

LPTHE, Sorbonne University, CNRS, Paris

Workshop on the Standard Model and Beyond

Corfu, Greece, September 2023



Co-founder of Corfu meetings since 1982

1st Hellenic School on Elementary Particle Physics

Bibliographic information

Title	Proceedings of the 1st Hellenic School on Elementary Particle Physics, Corfu, Greece, 12-30 September 1982
Contributors	Th Papadopoulou, N. D. Tracas
Publisher	World Scientific, 1983
Original from	the University of California
Digitized	Sep 20, 2008
ISBN	9971950995, 9789971950996
s, Length	689 pages

STRONG CP VIOLATION AND AXION MECHANISM

Ignatios Antoniadis (Ecole Polytechnique)
1982

19 pages
Contribution to: 1st Hellenic School on Elementary Particle Physics, 613-631

then 1998 as a lecturer and regularly since 2005

Since 2004: European networks funded & organised Corfu meetings:

- "Quest for Unification" 2004-08
  EP, U Lisbon, UA Madrid, U Bonn, Oxford, U Thessaloniki, U Valencia, U Warsaw, INFN, SISSA, CEA-Saclay, CERN
- "Unification in the LHC era" 2009-13
- Also an ERC advanced grant
  "Mass Hierarchy and Particle Physics at the TeV Scale" 2008-14

The European Institute for Sciences and their Applications (EISA) is a big step forward promoting science and fundamental research in Corfu island and Greece in general

THANK YOU GEORGE

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 $\phi \Rightarrow$ 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?

An early example

I.A.-Bachas-Lewellen-Tomaras '88 [8]

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 $\quad m^2_{\text{spin}-2} \geq 2H^2 \sim \Lambda$ 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

Gravitino Mass Conjecture [6]

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

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

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

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

However Standard Model soft terms depend on the mediation mechanism

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

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

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 $n = 3/2$

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

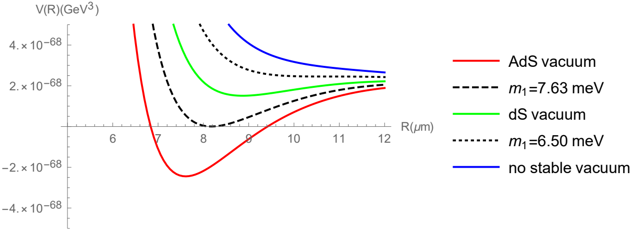
radion stabilisation: 4d cosmological constant versus Casimir energy

Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07

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

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:

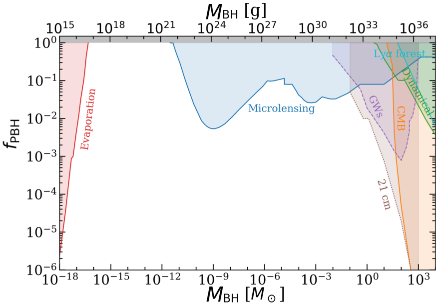
  1. 5D primordial black holes in the mass range $10^{15} - 10^{21}$g
     with Schwarzschild radius in the range $10^{-4} - 10^{-2}$ μm
     Anchordoqui-I.A.-Lust '22
  2. KK-gravitons of decreasing mass due to internal decays (dynamical DM)
     from $\sim$ MeV at matter/radiation equality ($T \sim$ eV) to $\sim$ 50 keV today
     Gonzalo-Montero-Obied-Vafa '22

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

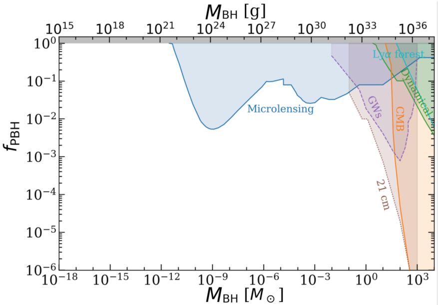
- ultralight radion as a fuzzy dark matter — Anchordoqui-I.A.-Lust '23

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

Anchordoqui-IA-Lust '23

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

Mohapatra, Nussinov, Perez-Lorenzana

$$\Gamma_R^{\mathrm{KK}} = \sum_{l'<l} \Gamma^l_{Rl'} \sim \frac{1}{2\pi}\frac{m_l\, m_{KK}^3}{m\ M_p^2}\langle\varphi_{l'}\rangle \simeq \frac{1}{2\pi}\frac{m_l\ \ m_{KK}^3(RM_*)}{m\ M_p^2}$$

$$= \frac{1}{2\pi}\frac{m_l m_{KK}^3}{m\ M_*^2} \sim 10^6\,\mathrm{s}^{-1} \quad m_{KK} = 10\,\mathrm{eV}$$

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

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

$\delta S_{\mathrm{radion}}^{\mathrm{localised}} = \zeta \int [d^4x] \left(\frac{\partial R}{R}\right)^2$ ζ : VEV of a brane field

also Albrecht-Burgess-Ravndal-Skordis '01

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