Landscape, swampland and extra dimensions

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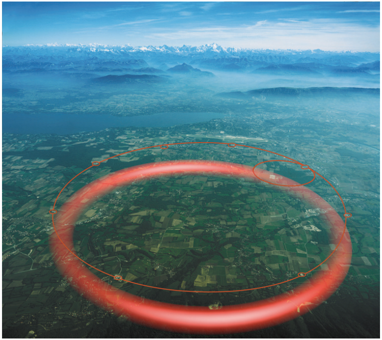
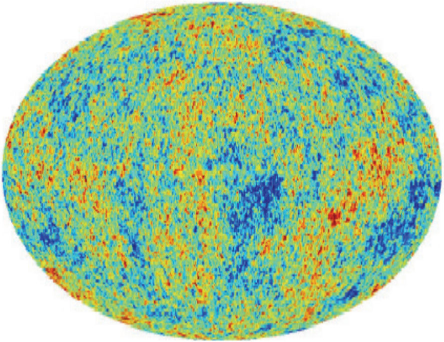
Challenge for a fundamental theory of Nature

describe both particle physics and cosmology



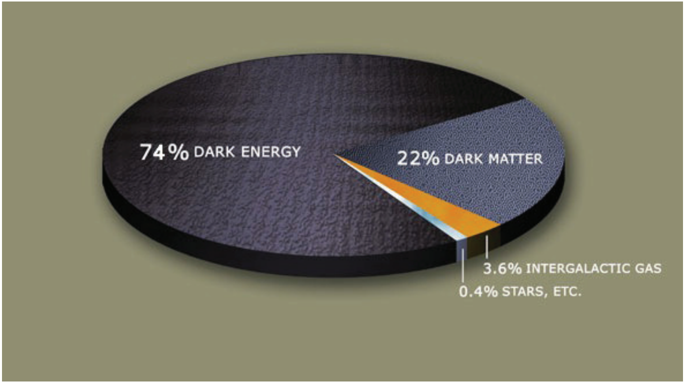


Accelerator experiments and cosmological observations:

complementary information for the same fundamental theory

Content of the Universe vs Standard Model

- Ordinary matter: only a tiny fraction $\lesssim 5\%$
- Non-luminous (dark) matter: $\sim 25\%$



Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho \;\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

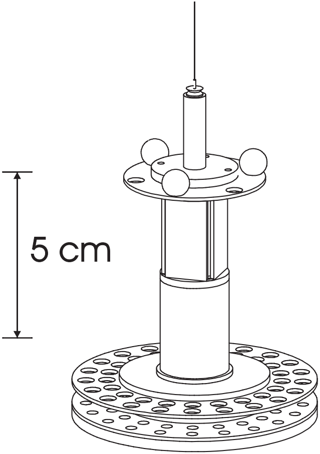
  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  $\nwarrow$ Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

Newton's law is valid down to distances 30 μm

Adelberger et al. '06



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

⇒ **need an extra input of guidance principle**

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 $\Rrightarrow$ 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: gravity is the weakest force

  $\Rrightarrow$ 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?

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 $m^2_{\rm spin-2} \geq 2H^2 \sim \Lambda$ 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 $\quad (R \lesssim 0.4\,\mu$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

More physics implications of the dark dimension

- 3 candidates of dark matter:

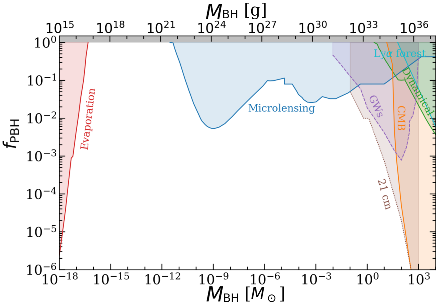
  1. 5D primordial black holes in the mass range $10^{15} - 10^{21}$g
     with Schwarzschild radius in the range $10^{-4} - 10^{-2}$ μm
     Anchordoqui-I.A.-Lust '22
  2. KK-gravitons of decreasing mass due to internal decays (dynamical DM)
     from $\sim$ MeV at matter/radiation equality ($T \sim$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

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

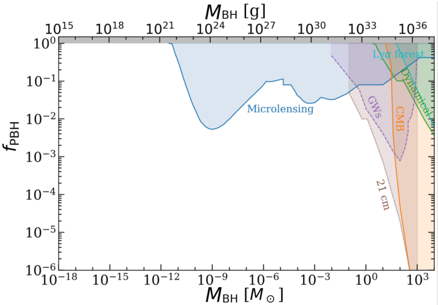
- ultralight radion as a fuzzy dark matter Anchordoqui-I.A.-Lust '23

Primordial Black Holes as Dark Matter

4d PBH



5d PBH



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

Dark Dimension Radion stabilization and inflation

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

(Higuchi bound) $H_I \lesssim m \sim \text{eV} \Rightarrow M_I \lesssim 100$ 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 ~ 42 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 $N = 42$-efolds $\Rightarrow$ 63 e-folds in 4d with $a = e^{3N/2}$

Large extra dimensions from inflation in higher dimensions

Anchordoqui-IA-Arkani-Hamed to appear

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 $\Delta N_{\text{eff}} < 0.2$

Anchordoqui '20

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

5D cosmological constant at the minimum of the inflaton potential

$\Rightarrow$ runaway radion potential:

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

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

$\Rightarrow$ 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

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 FDG 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: $m_\phi \sim \sqrt{V_{\phi\phi}} \sim \sqrt{\Lambda}_4/M_p$ $\quad f = \omega/(2\pi) = m/\pi$
- radion production: 5D inflaton decay via unstable KK gravitons

Mohapatra, Nussinov, Perez-Lorenzana

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

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

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

Gravitino Mass Conjecture [10]

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: $M_{3/2} = \varkappa M_{\rm SUSY}^2 \leftarrow$ 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 $n = 3/2$

Large extra dimensions from higher-dim inflation

Anchordoqui-IA-Arkani-Hamed to appear

$$ds^2_{4+d} = \left(\frac{r}{R}\right)^d ds^2_4 + R^2 dy^2 \qquad ; \qquad ds^2_4 = a^2(\tau)(-d\tau^2 + d\vec{x}^2)$$

$$= \hat{a}^2_{4+d}(\tau)(-d\tau^2 + d\vec{x}^2 + R_0^2\ dy^2) \qquad r \equiv \langle R \rangle_{\text{end of inflation}}$$

- exponential expansion in higher-dims $\Rightarrow$ power low inflation in 4D

  FRW coordinates: $e^{H\hat{t}} \sim (Ht)^{2/d} \Rightarrow R(t) \sim t^{2/d}$, $a(t) \sim t^{1+2/d}$

- $\hat{N}$ e-folds in $(4+d)$-dims $\Rightarrow$ $N = (1 + d/2)\hat{N}$ e-folds in 4D

Impose $M_* = M_p e^{-dN/(2+d)} \gtrsim 10$ TeV

$\gtrsim 10^8$ GeV for $d = 1$ $(r \lesssim 30\mu\text{m})$

$\gtrsim 10^6$ GeV for $d = 2$ $(r^{-1} \gtrsim 10$ keV$)$

$\Rightarrow$ the horizon problem is solved for any d $\quad N \gtrsim 30 - 60$ $(N \gtrsim \ln \frac{M_I}{\text{eV}})$ [27]

CMB power spectrum from higher-dim inflation

Physical distances change from higher to 4 dims

equal time distance between two points in 3-space

$$d_{\rm phys}(x,x') = d(x,x')\, a(\tau) = d(x,x')\, \hat{a}(\tau) \left(\frac{R}{R_0}\right)^{d/2} = \hat{d}_{\rm phys}(x,x') \frac{M_p}{M_*}$$

co-moving distance

precision of CMB data: angles $\lesssim 10$ degrees, distances $\lesssim$ Mpc (Gpc today)

Mpc $\to$ Mkm at $M_I \sim$ TeV with radiation dominated expansion

$\times$ TeV$/M_*$ at a higher inflation scale $M_I \sim M_*$

$\times M_*/M_P$ conversion to higher-dim distances

$\simeq$ micron scale $\Rightarrow d = 1$ is singled out!

$d > 1$: needs a period of 4D inflation for generating scale invariant density perturbations

Density perturbations from 5D inflation

inflaton (during inflation) $\simeq$ massless minimally coupled scalar in dS space

$\Rightarrow$ logarithmic growth at large distances (compared to the horizon H^{-1})

equal time 2-point function in momentum space at late cosmic time

$$\langle \Phi^2(\hat{k},\tau)\rangle_{\tau\to 0} \simeq \frac{4}{\pi}\frac{H^3}{(\hat{k}^2)^2} \quad ; \quad \hat{k}^2 = k^2 + n^2/R^2$$

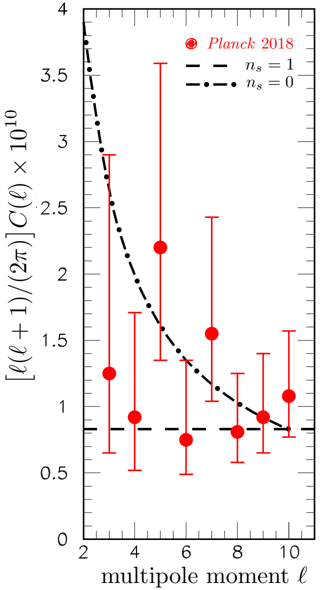
2-point function on the Standard Model brane (located at $y=0$):

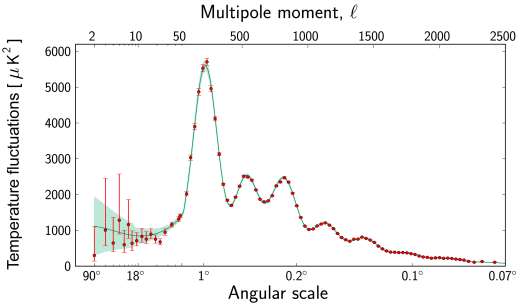
$$\sum_n \langle \Phi^2(\hat{k},\tau)\rangle_{\tau\to 0} \simeq \frac{2RH^3}{k^2}\left(\frac{1}{k}\coth(\pi kR) + \frac{\pi R}{\sinh^2(\pi kR)}\right) \; ; \quad k = \pi/\lambda$$

Amplitude of the power spectrum: $\mathcal{A} = \frac{k^3}{2\pi^2}\langle \Phi^2(k,\tau)\rangle_{y=0}$

- $\pi kR > 1$ ('small' wave lengths) $\Rightarrow \mathcal{A} \sim \frac{H^2}{\pi^2}$ $\quad n_s \simeq 1$
- $\pi kR < 1$ ('large' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{2H^3}{\pi^3 k}$ $\quad n_s \simeq 0$

Large-angle CMB power spectrum





Radion stabilisation at the end of 5D inflation

Potential contributions stabilising the radion:

$$V = \left(\frac{r}{R}\right)^2 \hat{V} + V_C \quad ; \quad \hat{V} = 2\pi R \Lambda_5^{\min} + T_4 + 2\pi \frac{K}{R}$$

T_4: 3-branes tension, K: kinetic gradients, V_C: Casimir energy

↑Arkani-Hamed, Hall, Tucker-Smith, Weiner '99

$$V_C = 2\pi R \left(\frac{r}{R}\right)^2 \mathrm{Tr}(-)^F \rho(R,m) \;;\; \rho(R,m) = -\sum_{n=1}^{\infty} \frac{2m^5}{(2\pi)^{5/2}} \frac{K_{5/2}(2\pi Rmn)}{(2\pi Rmn)^{5/2}} \begin{cases} mR \to \infty & \text{exp suppressed} \\ mR \to 0 & 1/R^5 \end{cases}$$

Radion mass m_R: $\sim$ eV (m_{KK}) to 10^{-30} eV (m_{KK}^2/M_p) depending on K

- $K \sim M_*$, all 3 terms of $\hat{V}$ of the same order, V_C negligible

  tune $\Lambda_4 \sim 0_+ \Rightarrow m_R \lesssim m_{KK} \sim$ eV

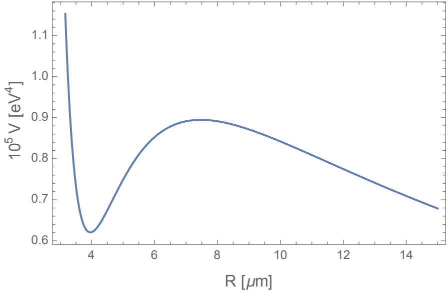
- K negligible, all 3 remaining terms of the same order

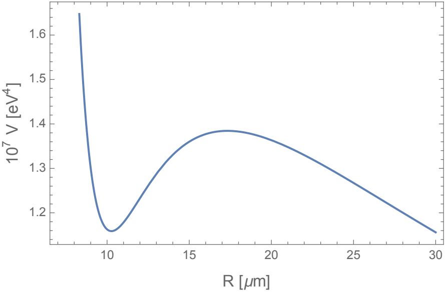
- $\Rightarrow$ minimum is driven by a +ve $V_C = \frac{2\pi r^2}{32\pi^7 R^6}(N_F - N_B)$

Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07

need light bulk fermions: 3 (2) R-neutrinos $\rightarrow N_F = 12\,(8),\ N_B = 3$

$\Rightarrow m_R \sim 10^{-28} - 10^{-30}$ eV





$(\Lambda_5^{\min})^{1/5} = 70$ meV, $|T_4|^{1/4} = 76$ meV, $N_F - N_B = 9$ (left)

$(\Lambda_5^{\min})^{1/5} = 25$ meV, $|T_4|^{1/4} = 26$ meV, $N_F - N_B = 5$ (right)

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
- scale invariant density fluctuations from 5D inflation
- radion stabilization