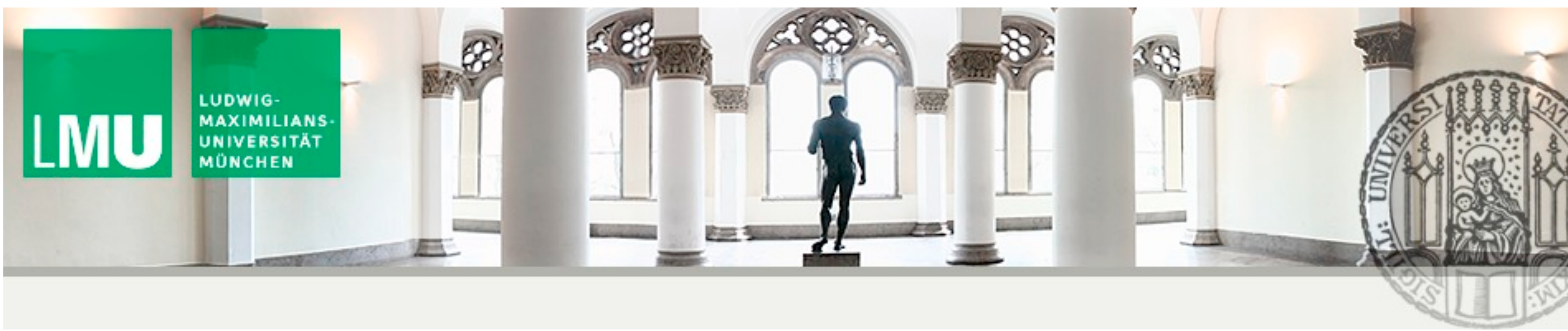
Distance Conjectures and Primordial Black Holes as Dark Matter

DIETER LÜST (LMU, MPP)



StringPheno 2022, Liverpool, 5th. July 2022

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Joint work with Luis Anchordoqui and Ignatios Antoniadis, arXiv:2206.07071

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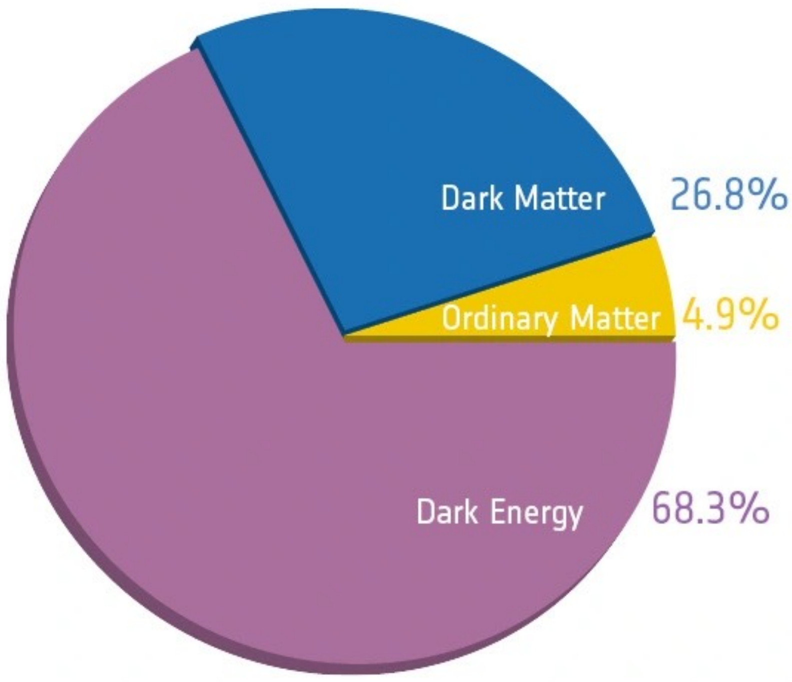
I) Introduction

Energy budget of the universe (cosmic pie):



Cosmological constant: $\Lambda_{cc} \simeq 10^{-122}\ M_p^4$

Dark matter density:

$$\rho_{DM} \simeq 2.2 \times 10^{-27} kg/m^3 \simeq 3.2 \times 10^{-8}\ M_{sun}/pc^3$$

Cosmological constant:

Statistical, anthropic „explanation“ via string landscape

[S. Weinberg (1987); R. Bousso, J. Polchinski (2000), …]

Dark matter:

Cold , hot, WIMPS, axions, …..

Primordial black holes: hard to accommodate 100% DM

[G. Chapline (1974)]

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Large extra dimensions: SM Hierarchy problem

[I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998)]

Dark dimension: Cosmological Hierarchy problem

[M. Montero, C. Vafa, I. Valenzuela, arXiv:2205.12293]

Outline:

II) AdS Distance Conjecture

III) Cosmological constant distance conjecture - Dark Universe

IV) Primordial BHs and the Dark Universe

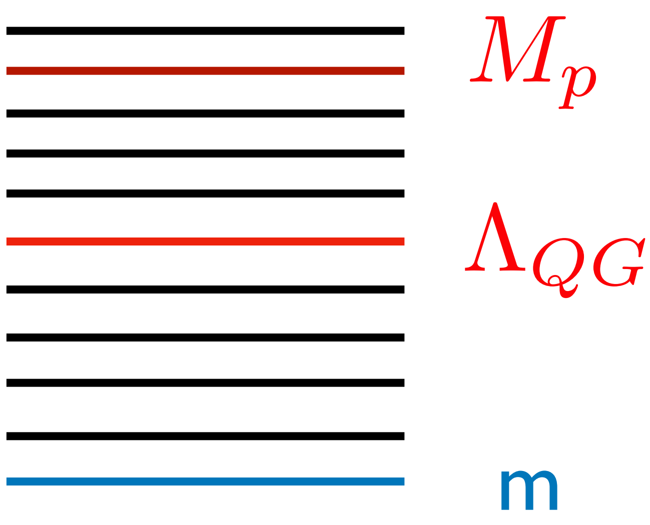
V) Conclusions

II) AdS Distance conjecture

EFT of quantum gravity typically breaks down above a certain cut-off, where gravity becomes strong:

Species scale: $$\Lambda_{QG} = \frac{M_p}{\sqrt{N}}$$ [G. Dvali (2007)]

Often there is an (infinite) tower of states with characteristic mass scale m related to the cut-off scale Λ_{QG} :



Swampland distance conjecture:

At large distance Δ directions in the parameter space of string vacua there must be an infinite tower of states with mass scale m.

SDC:

$$m = M_p e^{-\alpha\Delta}$$

[H. Ooguri, C. Vafa (2006)]

$m << M_p$ when $\Delta \to \infty$

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In this limit, typically also the species scale becomes small and there is the following hierarchy of scales:

$$m << \Lambda_{QG} << M_p \quad \text{when} \quad \Delta \rightarrow \infty$$

For (string) compactifications the SDC is often due to the higher dimensional nature of theory:

At the KK mass scale a new dimension is opening up.

For a compact circle of radius R, the relevant tower are the KK particles with mass scale

$$m = m_{KK} = 1/R\,, \quad \Delta_{KK}(R) = \log R$$

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For KK modes, related to n extra dimensions, the 4D species scale is given as:

$$\Lambda_{QG} = m^{n/(n+2)} M_p^{2/(n+2)}$$

This is nothing else than the higher dimensional Planck mass $M_{p,n}$.

We are now interested in the limit where the cosmological constant becomes small.

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Consider AdS_d vacua in quantum gravity with varying negative cosmological constant Λ_{cc}.

AdS Distance conjecture (ADC):

[D.L. , E. Palti, C. Vafa (2019)]

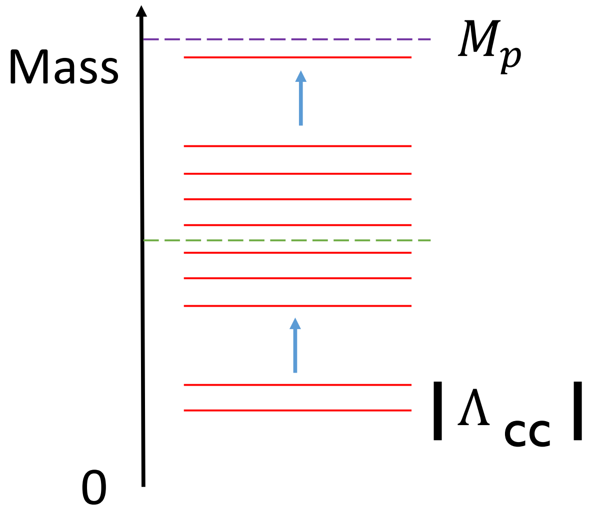
In the limit of small $|\boldsymbol{\Lambda_{cc}}|$ there exist an infinite tower of states with mass scale m, which behaves as

ADC: $$m \sim |\Lambda_{cc}|^{\alpha} \quad \text{with} \quad \alpha \geq \frac{1}{2}$$

$$\Delta = -\log |\Lambda_{cc}| \to \infty \qquad \text{for} \qquad \Lambda_{cc} \to 0$$

Strong AdS distance conjecture (SADC):

The bound $\alpha = 1/2$ is saturated for supersymmetric AdS vacua.



Infinite tower of states above Λ_{cc}

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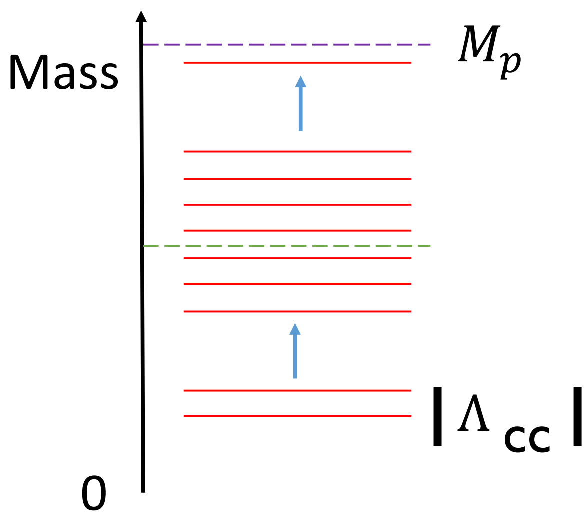

Infinite tower of states above Λ_{cc}

The conjecture is satisfied for many known AdS string backgrounds via the tower of KK modes.

AdS_d alone cannot exits alone as consistent background.

(Interesting implications for dual CFT description!)

[L. Alday, E- Perlmutter (2019), E. Perlmutter, L. Rastelli, C. Vafa, I. Valenzuela (2020)]

[S. Lüst, C. Vafa, M. Wiesner, K. Xu(2022)]

III) CC distance conjecture - The Dark Universe

Consider (meta-stable) vacua with positive cosmological constant and assume that the ADC is still valid :

ADC ⟶ Cosmological Constant distance conjecture:

The limit of small positive cosmological constant leads to a light tower of states with mass scale m:

[D.L. , E. Palti, C.Vafa (2019), P.Agrawal, G. Obied, C.Vafa (2019); M. Montero, C.Vafa, I.Valenzuela (2022)]

CCDC:

$$m \sim \lambda^{-1}\ \Lambda_{cc}^{\alpha}\ M_p^{1-4\alpha} \sim \lambda^{-1}\ 10^{-122\alpha}\ M_p$$

with $\frac{1}{4} \leq \alpha \leq \frac{1}{2}$

Dark Universe: the tower of states is given by the KK modes of n large, dark dimensions.

Note that there is a close relative of the ADC and of the CCDC:

Gravitino mass conjecture (GMC):

[N. Cribiori, M. Scalisi, D.L. ; A. Castellano, A. Font. A. Harraez, L. Ibanez (2021)]

In the limit of small gravitino mass there exist an infinite tower of states with mass scale m, which behaves as:

$$m \sim (m_{3/2})^{\beta} \quad \text{with} \quad \beta > 0$$

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For supersymmetric AdS spaces one has that

$$(m_{3/2})^2 = -\frac{\Lambda_{cc}}{3}$$

and the ADC and the GMC are equivalent to each other.

But in case of broken supersymmetry one has that

$$(m_{3/2})^2 > -\frac{\Lambda_{cc}}{3}$$

and the CCDC and the GMC lead to different conclusions.

In particular the GMC allows for

$$|\Lambda_{cc}| \to 0 \quad \text{and} \quad m_{3/2} \text{ finite}$$

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But it can be that there is parametric link of the form

$$(m_{3/2})^2 \sim |\Lambda_{cc}|^\gamma$$

Let us return to the CCDC and the dark universe:

Three parameters: $n\,,\ \alpha\,,\ \lambda$

Experimental bounds on Newton law: $\alpha = 1/4$

Neutron star reheating: $n = 1$

Cosmic ray spectrum: $\lambda \sim 10^{-3}$

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Radius of dark dimension: $R \sim \lambda \Lambda_{cc}^{-1/4} \sim 1\mu m$

$(\Lambda_{cc}^{1/4} \sim 2.31 meV)$

Related species scale: $\Lambda_{QG} \simeq 10^{10}\ Gev$

IV) Primordial BHs in the dark universe

[L. Anchordoqui, I. Antoniadis, D.L., arXiv:2206.07071]

Three possible regimes for black holes with horizon r_s :

(i) $\quad r_s > R \longrightarrow$ 4D black hole

(ii) $\quad l_s < r_s < R \longrightarrow$ 5D black hole

$(l_s \sim \Lambda_{QG}^{-1})$

(iii) $\quad r_s < l_s \longrightarrow$ BH becomes string state.

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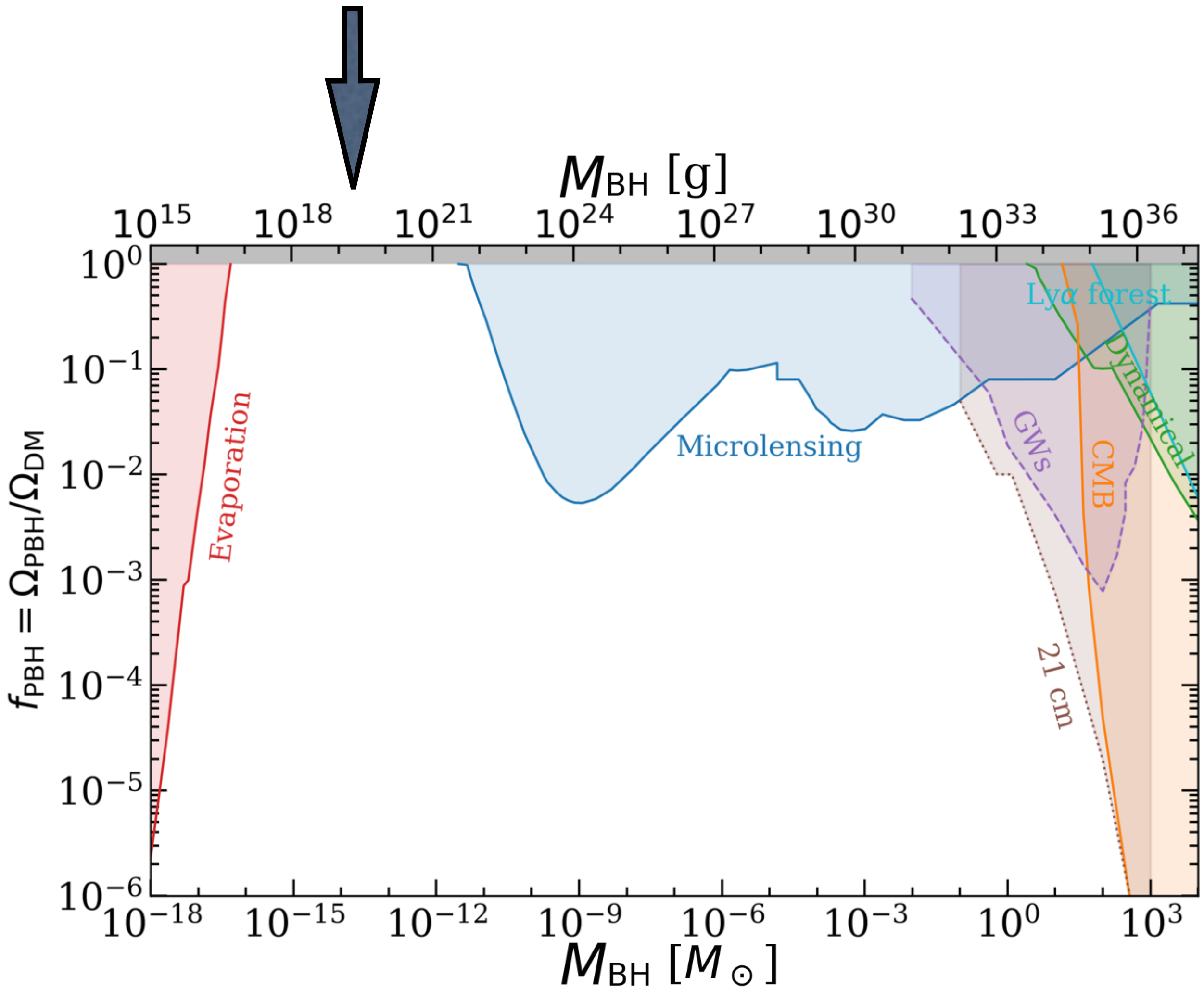
As we now discuss, these 5D BHs are good

all dark matter candidates.

Experimental status of 4D PBHs as dark matter:

In this window, 4D PBHs can be still all dark matter candidates - however there are further model dependent bounds that can also exclude this window.



P. Villanueva-Domingo, O. Mena, S. Palomares-Ruiz (2021)

We derived:

(i) Nice conspiracy of numbers for the dark universe:

$$M_{BH} \sim 10^{21}\ g \quad \Longleftrightarrow \quad r_s \sim 2\mu m \sim R$$

$\longrightarrow$ BHs in window are 5 - dimensional

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(iii) Even if window gets closed for 4D BHs, the 5D PBHs are still viable all dark matter candidates

Reason: longer life time for 5D BH due to dark dimension.

BH decay rate in 4+n dimensions:

(Assume semiclassical Hawking radiation.)

Hawking temperatur: $$T_{\rm BH} = \frac{n+1}{4\pi r_s}$$

Entropy: $$S = \frac{4\pi M_{BH} r_s}{n+2}$$

Horizon size:

$$r_s(M_{BH}) = \frac{1}{M_{p,n}} \left[\frac{M_{BH}}{M_{p,n}} \, \frac{2^n \pi^{(n-3)/2} \Gamma(\frac{n+3}{2})}{n+2} \right]^{1/(1+n)}$$

Number of emitted particles of energy Q:

$$\frac{d\dot{N}_i}{dQ} = \frac{\sigma_s}{8\,\pi^2}\, Q^2 \left[\exp\left(\frac{Q}{T_{\rm BH}} \right) - (-1)^{2s} \right]^{-1}$$

Decrease in mass:

$$\dot{M}_{\rm BH} = -\sum_i c_i \,\tilde{f}\, \frac{\Gamma_s}{32\,\pi^3}\, \frac{(n+3)^{(n+3)/(n+1)}(n+1)}{2^{2/(n+1)}}\, \Gamma(4)\,\zeta(4)\, T_{\rm BH}^2,$$

Results:

Temperatur:

(i) 4D BH (n=0):

$$T_{\rm BH}^{n=0} \simeq 1.05 \left(\frac{M_{\rm BH}}{10^{16}\ {\rm g}} \right)^{-1}\ {\rm MeV}$$

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$$T_{\rm BH}^{n=1} \sim \left(\frac{M_{\rm BH}}{10^{12}\ \rm g} \right)^{-1/2} \ \rm MeV$$

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$$\tau_{\rm BH}^{n=0} \simeq 1.6 \times 10^{-35} \; (M_{\rm BH}/{\rm g})^3 \; {\rm yr}$$

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The 5D PBHs are bigger, colder and longer lived than the 4D black holes !

V) Summary:

The dark universe opens the elegant possibility that all dark matter is given in terms of Primordial Black Holes !

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Comparing our calculations with the limits for the 4D BHs we can conclude that an all dark matter interpretation in terms of PBHs in the dark universe should be feasible for

$$10^{14}\ g \leq M_{BH} \leq 10^{21}\ g$$

Lighter PBHs as all dark matter candidates are excluded since their decays into photons and cosmic rays are not observed.

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$$\Longrightarrow \qquad T_{BH} \sim 1\ MeV$$

This BH can nicely explain the 511 keV gamma ray signal observed from the Galactic Center by the INTEGRAL satellite.

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Thank you !