

# The Dark Dimension: Particle Physics & Cosmology

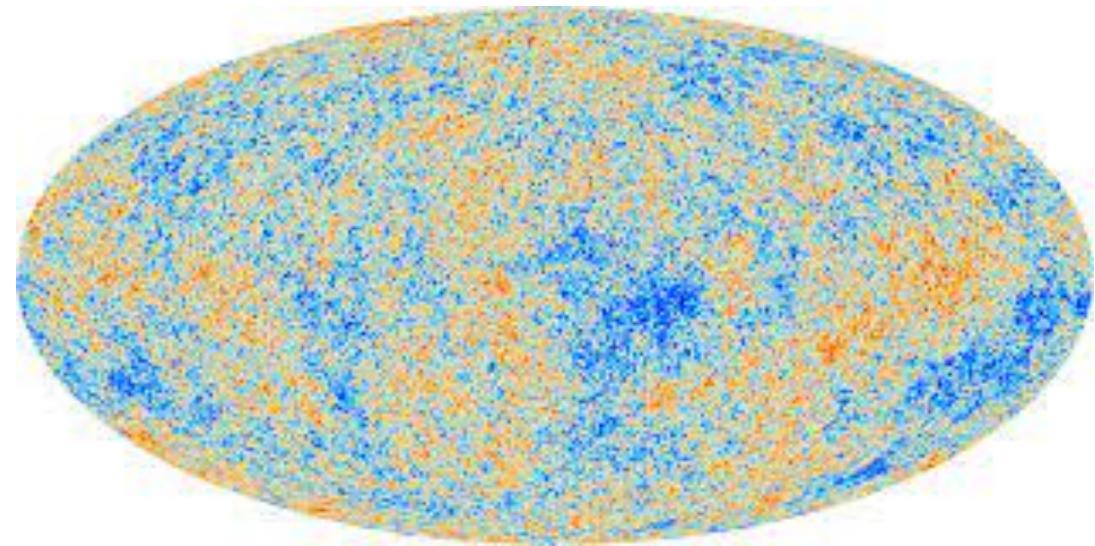
**DIETER LÜST (LMU, MPP)**

Joint work with Luis Anchordoqui, Ignatios Antoniadis,  
Niccolo Cribiori, Marco Scalisi

Montpellier, 2nd. March 2023

# Challenge for a fundamental theory of nature

that describes both physics at short and at long distances !

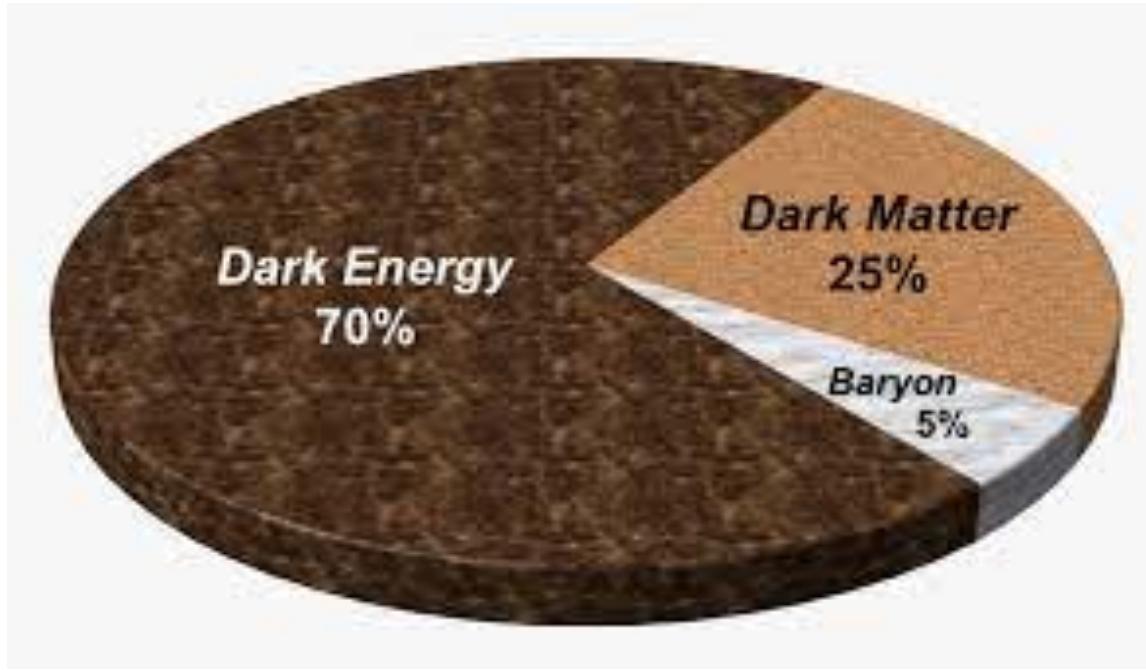


Short distances → particles physics

Long distances → cosmology

Is there a connection between physics in the **UV** and in the **IR** ?

# Energy budget of the universe (cosmic pie):



Dark energy:

$$\Lambda_{cc} \simeq 10^{-122} M_p^4 \simeq (2.31 \text{ meV})^4$$

Dark matter density:

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

## Fundamental IR length scale :

Two related IR length scales:

Size of the observable universe:

$$(\Lambda_{cc})^{1/2} = [L]^{-2} \simeq 3H_0^2 \simeq (10^{26} \text{m})^{-2}$$

Dark energy length:

$$(\Lambda_{cc})^{1/4} = [L]^{-1} \simeq (85 \mu\text{m})^{-1}$$

# Small cosmological constant:

**Anthropic „explanation“:**

[S. Weinberg (1987)]

**String landscape: Statistical „explanation“**

[R. Bousso, J. Polchinski (2000); M. Douglas (2001), KKLT (2001), ...]

General quantum gravity arguments against de Sitter vacua

[G. Dvali, C. Gomez (2014);  
G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa (2018)]

Stability and other issues for KKLT in string theory

[I. Bena, G. Giecold, M. Graña, N. Halmagyi (2011);  
I. Bena, E. Dudas, M. Graña, S. Lüst (2018);  
I. Bena, J. Blabäck, M. Graña, S. Lüst (2020);  
S. Lüst, L. Randall (2022)]

**Small cosmological constant:**

**Anthropic „explanation“:**

[S. Weinberg (1987)]

**String landscape: Statistical „explanation“**

[R. Bousso, J. Polchinski (2000); M. Douglas (2001), KKLT (2001), ...]

General quantum gravity arguments against de Sitter vacua

[G. Dvali, C. Gomez (2014);  
G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa (2018)]

Stability and other issues for KKLT in string theory

[I. Bena, G. Giecold, M. Graña, N. Halmagyi (2011);  
I. Bena, E. Dudas, M. Graña, S. Lüst (2018);  
I. Bena, J. Blabäck, M. Graña, S. Lüst (2020);  
S. Lüst, L. Randall (2022)]

**Dark matter:**

**Cold , hot, WIMPS, axions, .....**

**Primordial black holes: hard to accommodate 100% DM**

[G. Chapline (1974)]

**Small cosmological constant:**

**Anthropic „explanation“:**

[S. Weinberg (1987)]

**String landscape: Statistical „explanation“**

[R. Bousso, J. Polchinski (2000); M. Douglas (2001), KKLT (2001), ...]

General quantum gravity arguments against de Sitter vacua

[G. Dvali, C. Gomez (2014);  
G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa (2018)]

Stability and other issues for KKLT in string theory

[I. Bena, G. Giecold, M. Graña, N. Halmagyi (2011);  
I. Bena, E. Dudas, M. Graña, S. Lüst (2018);  
I. Bena, J. Blabäck, M. Graña, S. Lüst (2020);  
S. Lüst, L. Randall (2022)]

**Dark matter:**

**Cold , hot, WIMPS, axions, .....**

**Primordial black holes: hard to accommodate 100% DM**

[G. Chapline (1974)]

Can one relate **Dark Matter** to  $\Lambda_{cc}$ ?

# UV length scales in particle physics :

Weak scale:

$$\Lambda_{weak} \simeq 100 \text{ GeV}$$

Supersymmetry breaking scale:

$$\Lambda_{SUSY} \geq 1 \text{ TeV}$$

Quantum gravity mass scale:

$$\Lambda_{QG}$$

# Generic Features in Quantum Gravity :

# Generic Features in Quantum Gravity :

- All mass scales depend on scalar fields:  $\Lambda = \Lambda(\phi)$

# Generic Features in Quantum Gravity :

- All mass scales depend on scalar fields:  $\Lambda = \Lambda(\phi)$
- There is UV - IR mixing:  $\Lambda_{UV} \longleftrightarrow \Lambda_{IR}$

# Generic Features in Quantum Gravity :

- All mass scales depend on scalar fields:  $\Lambda = \Lambda(\phi)$

- There is UV - IR mixing:

$$\Lambda_{UV} \longleftrightarrow \Lambda_{IR}$$

- UV cut-off: Species scale:

$$\Lambda_{QG} = \frac{M_p}{\sqrt{N}} \leq M_p \simeq 10^{19} \text{GeV}$$

[G. Dvali (2007)]

N: Number of particles below  $\Lambda_{QG}$ .

.... it depends on scalar fields:  $N = N(\phi)$

Outline :

**I) Swampland Program**

**II) The Dark Universe**

**III) The Dark Universe and SUSY Breaking**

**IV) Primordial Black Holes & Dark Matter**

# I) Swampland Program

[C.Vafa (2005)]

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

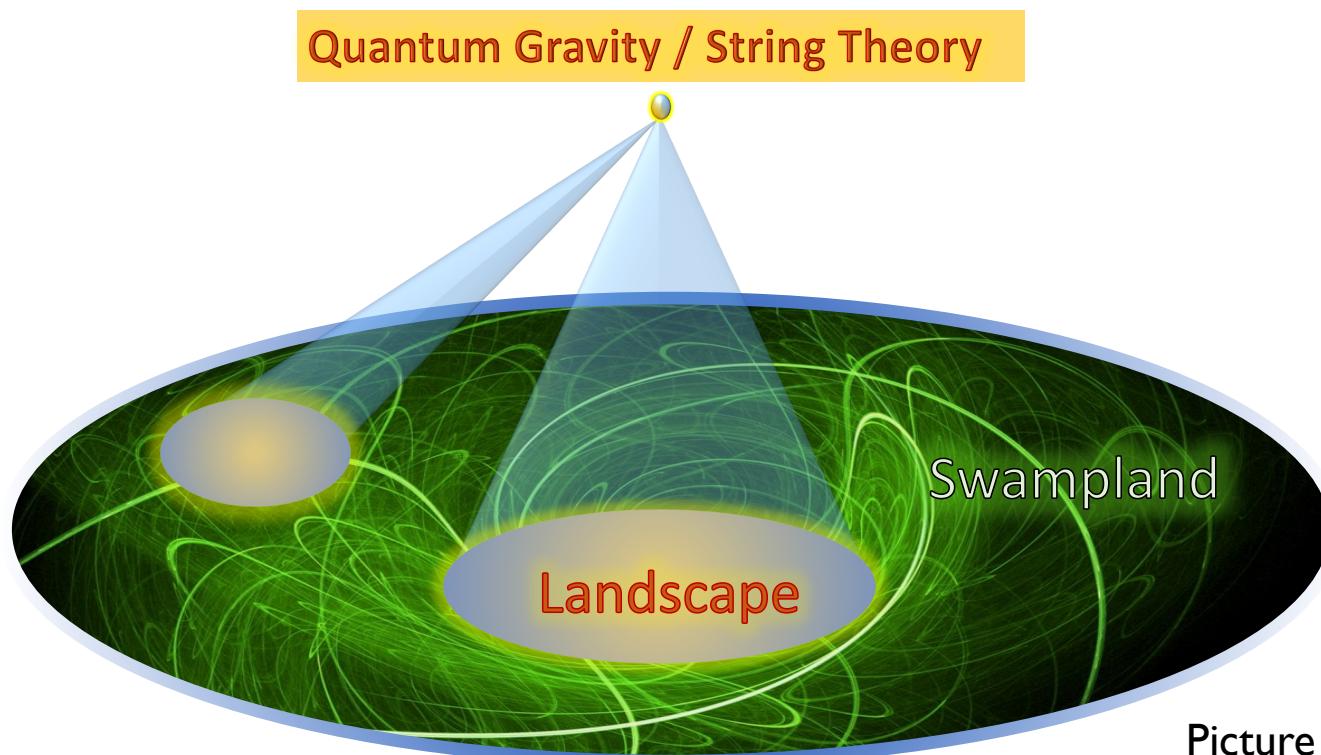
Which IR consistent quantum field theories  
cannot be embedded into a UV complete  
quantum gravity theory?

# I) Swampland Program

[C.Vafa (2005)]

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

Which IR consistent quantum field theories  
cannot be embedded into a UV complete  
quantum gravity theory?



Picture thanks to Eran Palti

## Swampland conjectures:

**General conjectures** about the boarder line between the landscape and the swampland.

## Swampland conjectures:

**General conjectures** about the boarder line between the landscape and the swampland.

- rigorous and also less rigorous
- less useful and useful in phenomenology
- often motivated from general black hole properties
- often tested in string theory

# Swampland Distance Conjecture:

Quantum gravity exhibits very interesting physics and mathematics features at boundaries of the moduli space.

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

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

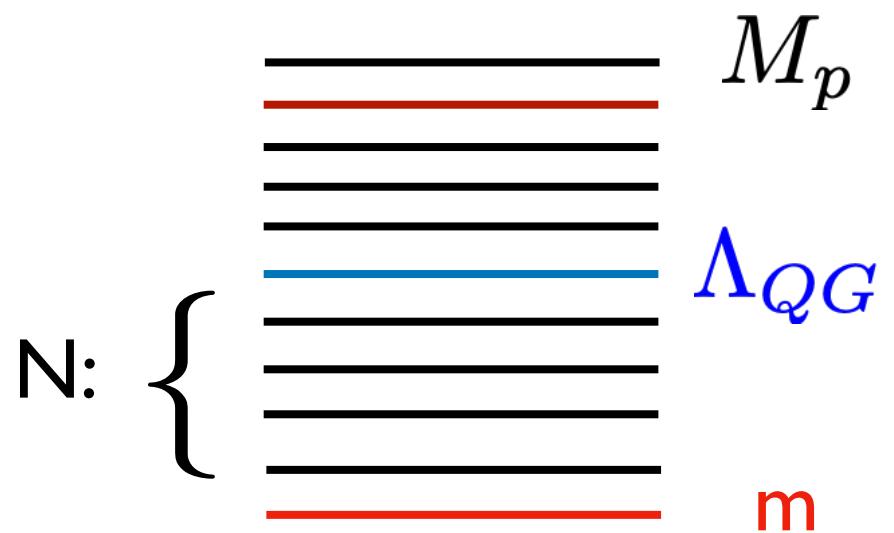
[H. Ooguri, C.Vafa (2006)]

$$m \ll M_p \quad \text{when} \quad \Delta \rightarrow \infty$$

The distance conjecture leads to ...



UV scale: species scale:



IR scale: tower mass scale  $m$

N: Number of particles between  $m$  and  $\Lambda_{QG}$ .

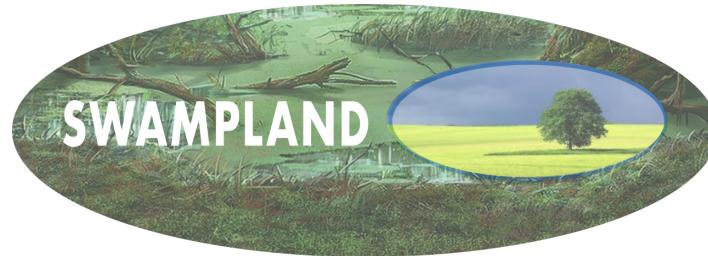
# KK compactification with n large extra dimensions of radius R

Tower mass scale:  $m_{KK} = 1/R$        $\Delta = \log R$

Number of KK states:  $N = \left( \frac{\Lambda_{QG}}{m_{KK}} \right)^n = (\Lambda_{QG} R)^n$

UV scale:  $\Lambda_{QG} = (M_p)^{\frac{2}{n+2}} (m_{KK})^{\frac{n}{n+2}}$   
 $= \frac{(M_p)^{\frac{2}{n+2}}}{(R)^{\frac{n}{n+2}}}$

# Some Generalized Distance Conjectures:



# Some Generalized Distance Conjectures:

Anti-de Sitter  
Conjecture

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

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

$$\uparrow \quad \Lambda_{cc} \rightarrow 0$$



# Some Generalized Distance Conjectures

$$M_{3/2} \rightarrow 0$$

Gravitino conjecture



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

# Some Generalized Distance Conjectures



$S \rightarrow \infty, T_{BH} \rightarrow 0$

BH entropy/temperature conjecture

$$m \sim \left(\frac{1}{S}\right)^\gamma \text{ or } (T_{BH})^\gamma \text{ with } \gamma > 0$$

[Q. Bonnefoy, L. Ciambelli, S. Lust, D.L. (2019);  
N. Cribiori, M. Dierigl, A. Gnechi, M. Scalisi, D.L. (2019)]

## II) The Dark Universe

[M. Montero, C.Vafa, I.Valenzuela (2022)]

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  $m$ :

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

## Bounds on the tower mass scale $m$ :

Lowest possible mass from the Higuchi bound (unitarity):

$$m \geq (\Lambda_{cc})^{1/2} / M_p$$

Highest possible mass from one-loop potential in string theory  
(contribution from light modes):

$$m \leq (\Lambda_{cc})^{1/4}$$

So we get:

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

## Bounds on the tower mass scale $m$ :

Lowest possible mass from the Higuchi bound (unitarity):

$$m \geq (\Lambda_{cc})^{1/2} / M_p$$

Highest possible mass from one-loop potential in string theory  
(contribution from light modes):

$$m \leq (\Lambda_{cc})^{1/4}$$

So we get:

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

Species scale in terms of  $\Lambda_{cc}$  (UV-IR mixing):

$$\Lambda_{QG} = (M_p)^{\frac{2+n-4\alpha n}{n+2}} [\lambda^{-1} (\Lambda_{cc})^\alpha]^{\frac{n}{n+2}}$$

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

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

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

Neutron star reheating:  $n = 1$

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

[L.Anchordoqui, arXiv:2205.13931]

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

KK mass scale:  $m_{KK} \simeq \lambda^{-1} \Lambda_{cc}^{1/4} \sim 10^{-1} eV$

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

### III) The Dark Universe and SUSY Breaking

Supergravity scalar potential:

$$V = M_P^2 e^K (|DW|^2 - 3|W|^2), \quad M_{3/2}^2 = e^K |W|^2$$

Spontaneous SUSY Breaking  $F_\phi = e^{K/2} DW \simeq M_{SUSY}^2 / M_P$

$$\Lambda_{cc} = V \approx 0 \Rightarrow M_{SUSY} \simeq \sqrt{M_P \ M_{3/2}}$$

### III) The Dark Universe and SUSY Breaking

Supergravity scalar potential:

$$V = M_P^2 e^K (|DW|^2 - 3|W|^2), \quad M_{3/2}^2 = e^K |W|^2$$

Spontaneous SUSY Breaking  $F_\phi = e^{K/2} DW \simeq M_{SUSY}^2 / M_P$

$$\Lambda_{cc} = V \approx 0 \Rightarrow M_{SUSY} \simeq \sqrt{M_P M_{3/2}}$$

Gauge mediation:  $M_{\text{soft}} \simeq M_{SUSY} \geq \mathcal{O}(\text{TeV})$

$$M_{3/2} \geq \mathcal{O}(10^{-3} \text{eV})$$

### III) The Dark Universe and SUSY Breaking

Supergravity scalar potential:

$$V = M_P^2 e^K (|DW|^2 - 3|W|^2), \quad M_{3/2}^2 = e^K |W|^2$$

Spontaneous SUSY Breaking  $F_\phi = e^{K/2} DW \simeq M_{SUSY}^2 / M_P$

$$\Lambda_{cc} = V \approx 0 \Rightarrow M_{SUSY} \simeq \sqrt{M_P M_{3/2}}$$

Gauge mediation:  $M_{\text{soft}} \simeq M_{SUSY} \geq \mathcal{O}(\text{TeV})$

$$M_{3/2} \geq \mathcal{O}(10^{-3} \text{eV})$$

Gravity mediation:  $M_{\text{soft}} \simeq M_{SUSY}^2 / M_P \geq \mathcal{O}(\text{TeV})$

$$M_{3/2} \geq \mathcal{O}(\text{TeV})$$

# Gravitino conjecture :

$$m = \lambda_{3/2}^{-1} \left( \frac{M_{3/2}}{M_P} \right)^\beta M_P \quad \left( \frac{1}{4} \leq \beta \leq 2 \right)$$

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

# Gravitino conjecture :

$$m = \lambda_{3/2}^{-1} \left( \frac{M_{3/2}}{M_P} \right)^\beta M_P \quad (\frac{1}{4} \leq \beta \leq 2)$$

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

Combine with the dark dimension: assume one common KK tower with  $\alpha = 1/4$

$$\Lambda_{cc} = \left( \frac{\lambda}{\lambda_{3/2}} \right)^4 \left( \frac{M_{3/2}}{M_P} \right)^{4\beta} M_P^4 \quad \text{or}$$

$$\Lambda_{cc} = \left( \frac{\lambda}{\lambda_{3/2}} \right)^4 \left( \frac{M_{\text{SUSY}}}{M_P} \right)^{8\beta} M_P^4$$

# Gravitino conjecture :

$$m = \lambda_{3/2}^{-1} \left( \frac{M_{3/2}}{M_P} \right)^\beta M_P \quad \left( \frac{1}{4} \leq \beta \leq 2 \right)$$

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

Combine with the dark dimension: assume one common KK tower with  $\alpha = 1/4$

$$\Lambda_{cc} = \left( \frac{\lambda}{\lambda_{3/2}} \right)^4 \left( \frac{M_{3/2}}{M_P} \right)^{4\beta} M_P^4 \quad \text{or}$$

$$\Lambda_{cc} = \left( \frac{\lambda}{\lambda_{3/2}} \right)^4 \left( \frac{M_{\text{SUSY}}}{M_P} \right)^{8\beta} M_P^4$$

This can be viewed as the leading term of a more general power series expansion:

$$\Lambda_{cc} = M_P^4 \sum_{k=1}^{\infty} c'_k \left( \frac{M_{\text{SUSY}}}{M_P} \right)^{2k}$$

$\beta$	$M_{3/2} \times (\lambda_{3/2})^{-\frac{1}{\beta}} \text{ GeV}^{-1}$	$M_{\text{SUSY}} \times (\lambda_{3/2})^{-\frac{1}{2\beta}} \text{ GeV}^{-1}$
1/2	$2.5 \times 10^{-36}$	$2.5 \times 10^{-9}$
1	$2.5 \times 10^{-9}$	$7.8 \times 10^4$
3/2	$2.5 \times 10^0$	$2.5 \times 10^9$
2	$7.8 \times 10^4$	$4.4 \times 10^{11}$

$$\beta = 1 : \quad M_{\text{SUSY}} = \mathcal{O}(\Lambda_{cc}^{1/8}) = \mathcal{O}(1 - 10 \text{ TeV})$$

This is the relevant case for gauge mediation.

$$\beta = 2 : \quad M_{3/2} = \mathcal{O}(\Lambda_{cc}^{1/8}) = \mathcal{O}(1 - 10 \text{ TeV})$$

This is the relevant case for gravity mediation.

# Microscopic realisation: String compactification on an anisotropic two-torus with Scherk-Schwarz boundary conditions:

$$V = M_P^2 e^K (|DW|^2 - 3|W|^2), \quad M_{3/2}^2 = e^K |W|^2$$

$$W = \text{const} \quad , \quad K = -\log ((-i(\phi - \bar{\phi}))^3 + \xi)$$

$$M_{3/2} = \frac{|W|}{\sqrt{(2\text{Im } \phi)^3 + \xi}} = \frac{|W|}{(2\text{Im } \phi)^{\frac{3}{2}}} + \mathcal{O}(\xi)$$

$$V = 6M_P^2 \xi \frac{|W|^2}{(2\text{Im } \phi)^6} + \mathcal{O}(\xi^2) = \frac{6M_P^2 \xi}{|W|^2} (M_{3/2})^4 + \mathcal{O}(\xi^2)$$

$$m_{KK} = 1/R \quad (\text{In 4D Planck units})$$

Two-torus:  $\text{Im } \phi = R^{2/3} \Rightarrow \alpha = 1/4, \beta = 1$

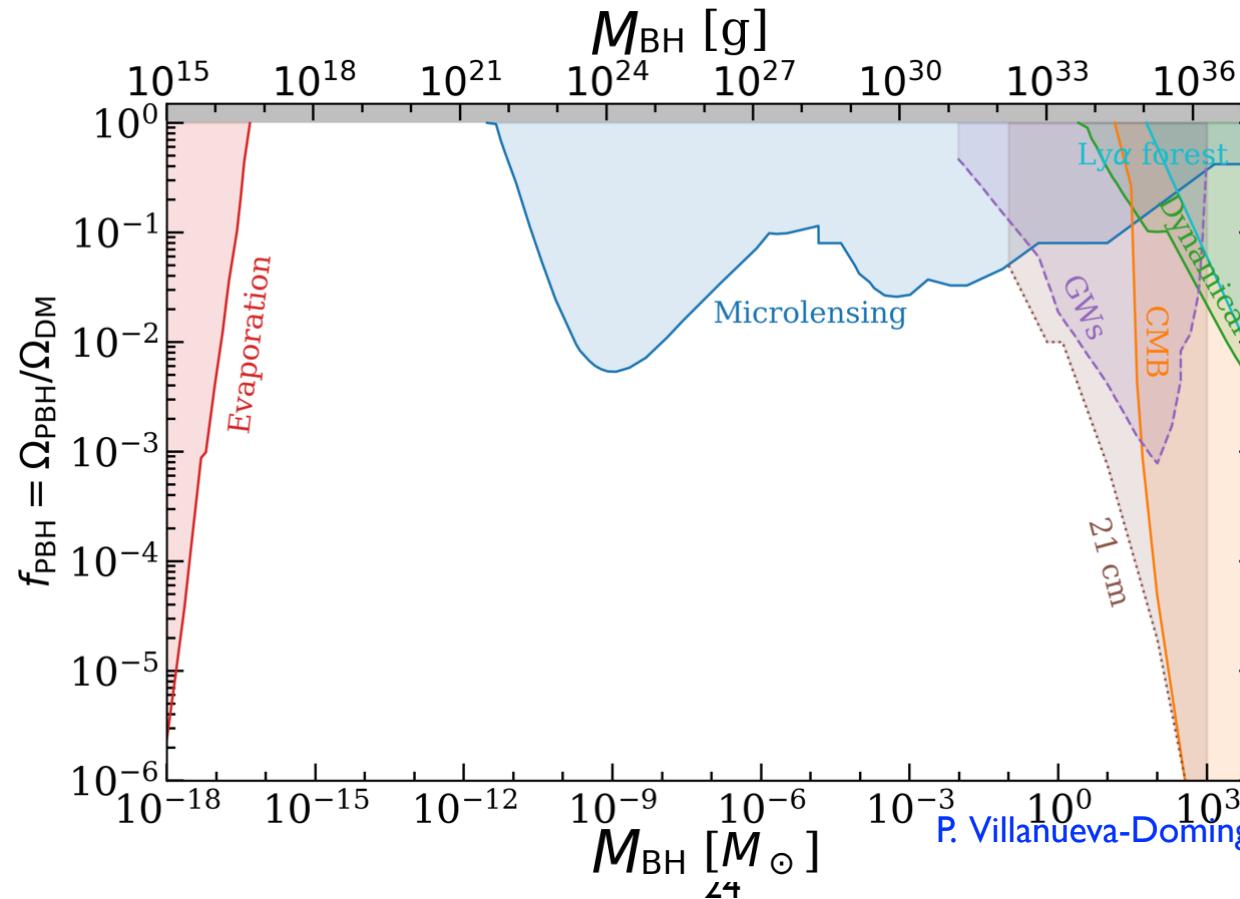
# IV) Primordial Black Holes & Dark Matter

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

## IV) Primordial Black Holes & Dark Matter

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

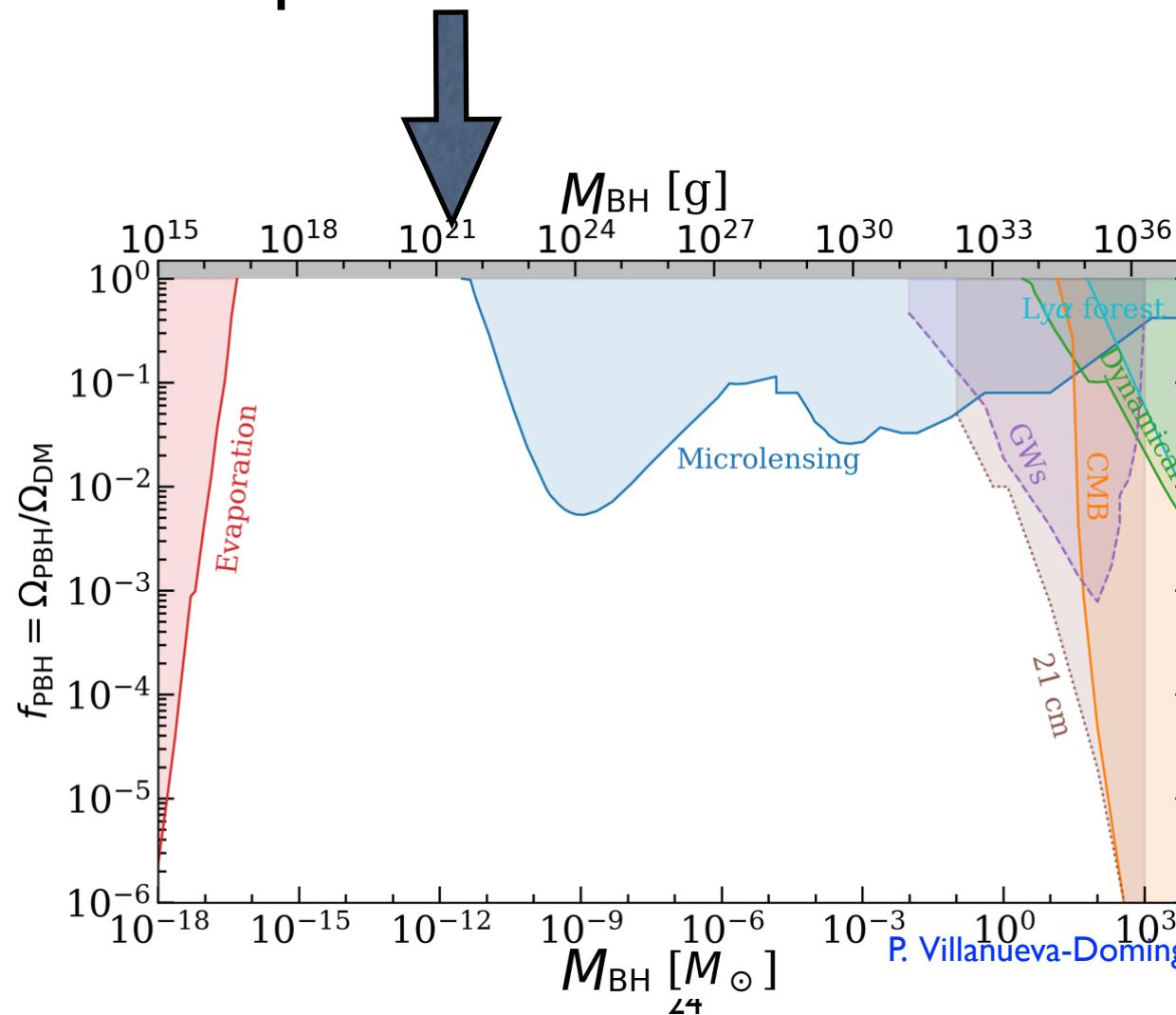
From observations there is a window, in which 4D PBHs can be still all dark matter candidates - however there are further model dependent bounds that can also exclude this window.



## IV) Primordial Black Holes & Dark Matter

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

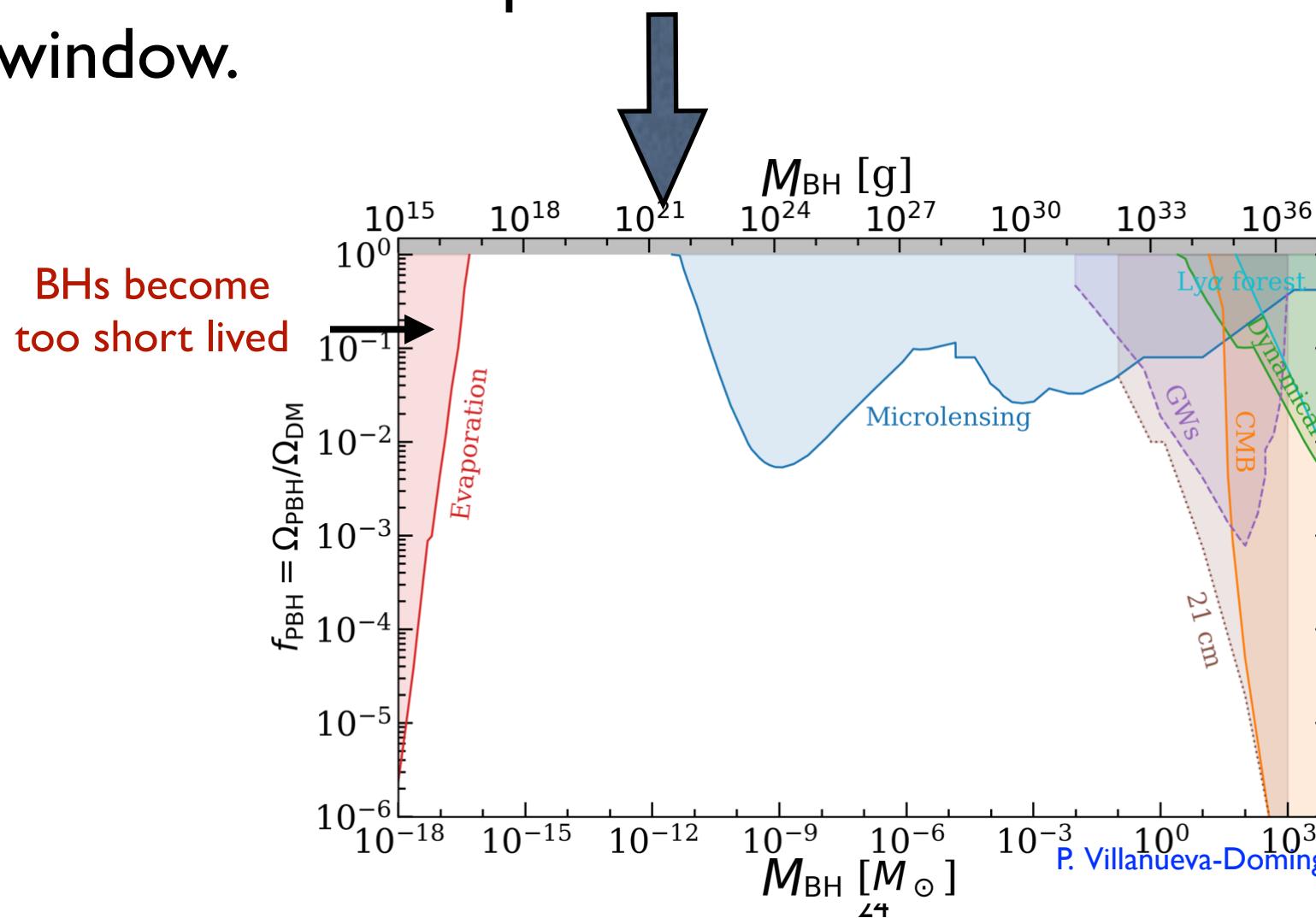
From observations there is a window, in which 4D PBHs can be still all dark matter candidates - however there are further model dependent bounds that can also exclude this window.



## IV) Primordial Black Holes & Dark Matter

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

From observations there is a window, in which 4D PBHs can be still all dark matter candidates - however there are further model dependent bounds that can also exclude this window.



Dark universe with  $R \simeq (\Lambda_{cc})^{-1/4} \simeq 1\mu\text{m}$

Three possible regimes for black holes with horizon  $r_s$  :

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

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

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

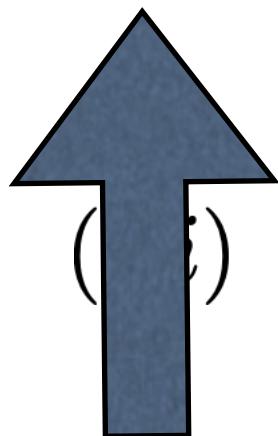
(iii)  $r_s < l_s \longrightarrow$  BH becomes string state.

Dark universe with  $R \simeq (\Lambda_{cc})^{-1/4} \simeq 1\mu\text{m}$

Three possible regimes for black holes with horizon  $r_s$  :

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

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



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

$r_s < l_s \longrightarrow$  BH becomes string state.

As we now discuss, these 5D BHs are good  
all dark matter candidates.

## Horizon size of BH in 4+n dimensions:

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

## Horizon size of BH in 4+n dimensions:

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

Dark Universe:  $n = 1, R \simeq (\Lambda_{cc})^{-1/4}$

$$\begin{aligned} r_s(M_{BH}, \Lambda_{cc}) &\simeq \frac{(M_{BH})^{1/2}}{M_p} (\Lambda_{cc})^{-1/8} \\ &= \frac{(M_{BH})^{1/2} (\Lambda_{cc})^{1/8}}{M_p} (\Lambda_{cc})^{-1/4} \end{aligned}$$

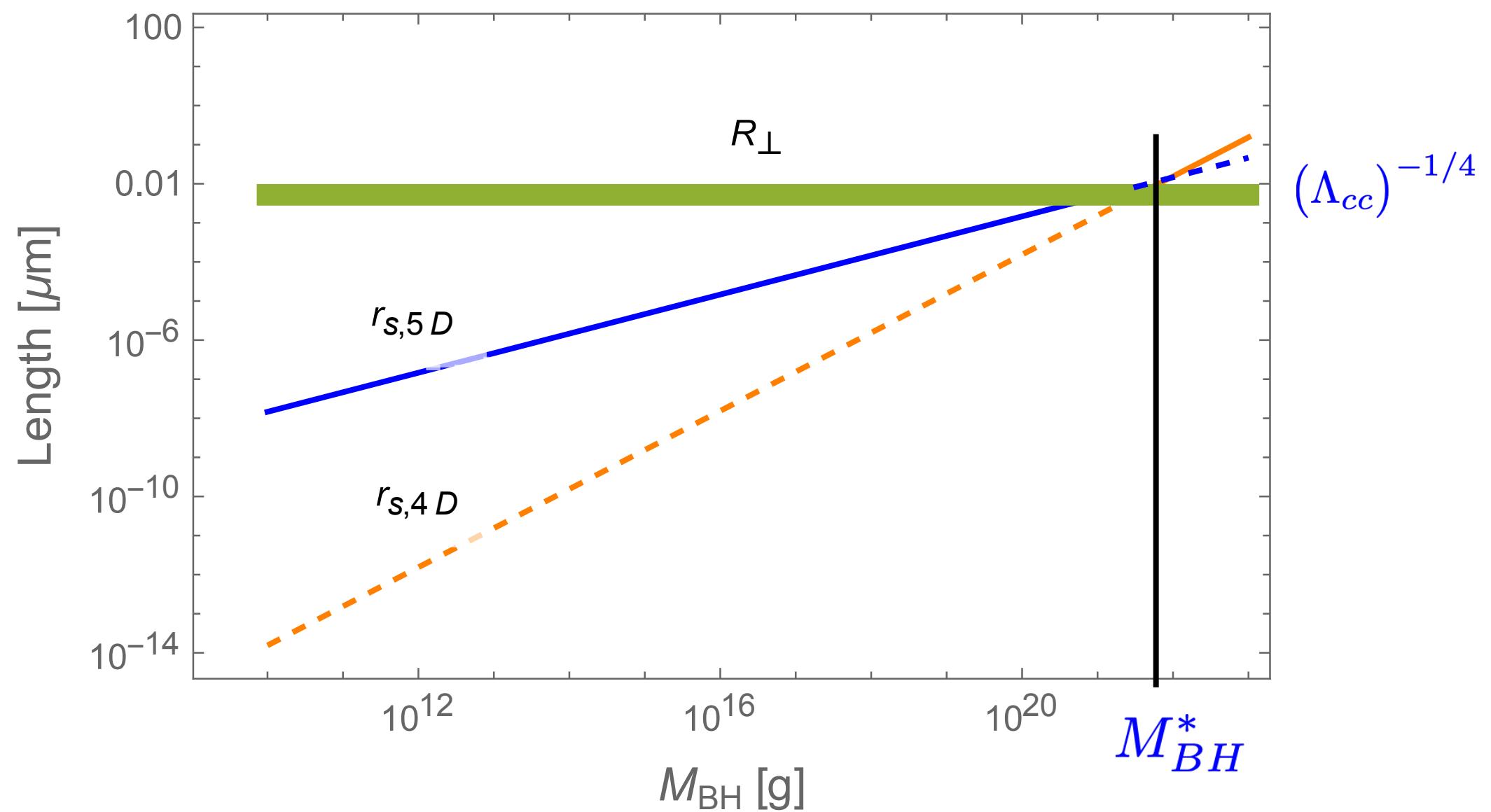
# Horizon size of BH in 4+n dimensions:

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

Dark Universe:  $n = 1, R \simeq (\Lambda_{cc})^{-1/4}$

$$\begin{aligned} r_s(M_{BH}, \Lambda_{cc}) &\simeq \frac{(M_{BH})^{1/2}}{M_p} (\Lambda_{cc})^{-1/8} \\ &= \frac{(M_{BH})^{1/2} (\Lambda_{cc})^{1/8}}{M_p} (\Lambda_{cc})^{-1/4} \end{aligned}$$

$r_s \stackrel{!}{=} R \simeq (\Lambda_{cc})^{-1/4} \Rightarrow M_{BH}^* \simeq \frac{M_p^2}{(\Lambda_{cc})^{1/4}} \simeq 10^{21} \text{ g}$



BH evaporation goes by Hawking radiation:

$$\left. \frac{dM_{\text{BH}}}{dt} \right|_{\text{evap}} \sim T_{BH}^2$$

Hawking temperatur:  $T_{\text{BH}} = \frac{n+1}{4\pi r_s} \sim \frac{M_p}{(M_{BH})^{1/2}} (\Lambda_{cc})^{1/8}$

Entropy:

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

## Numerical results:

Temperatur:

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

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

(ii) 5D BH (n=1):

$$T_{\text{BH}} \simeq \left( \frac{M_{\text{BH}}}{5 \times 10^{10} \text{ g}} \right)^{-1/2} \text{ MeV}$$

## Life time and age of the universe:

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

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

Black hole with  $5 \times 10^{14} \text{ g}$  has lifetime comparable to the age of the universe.

## Life time and age of the universe:

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

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

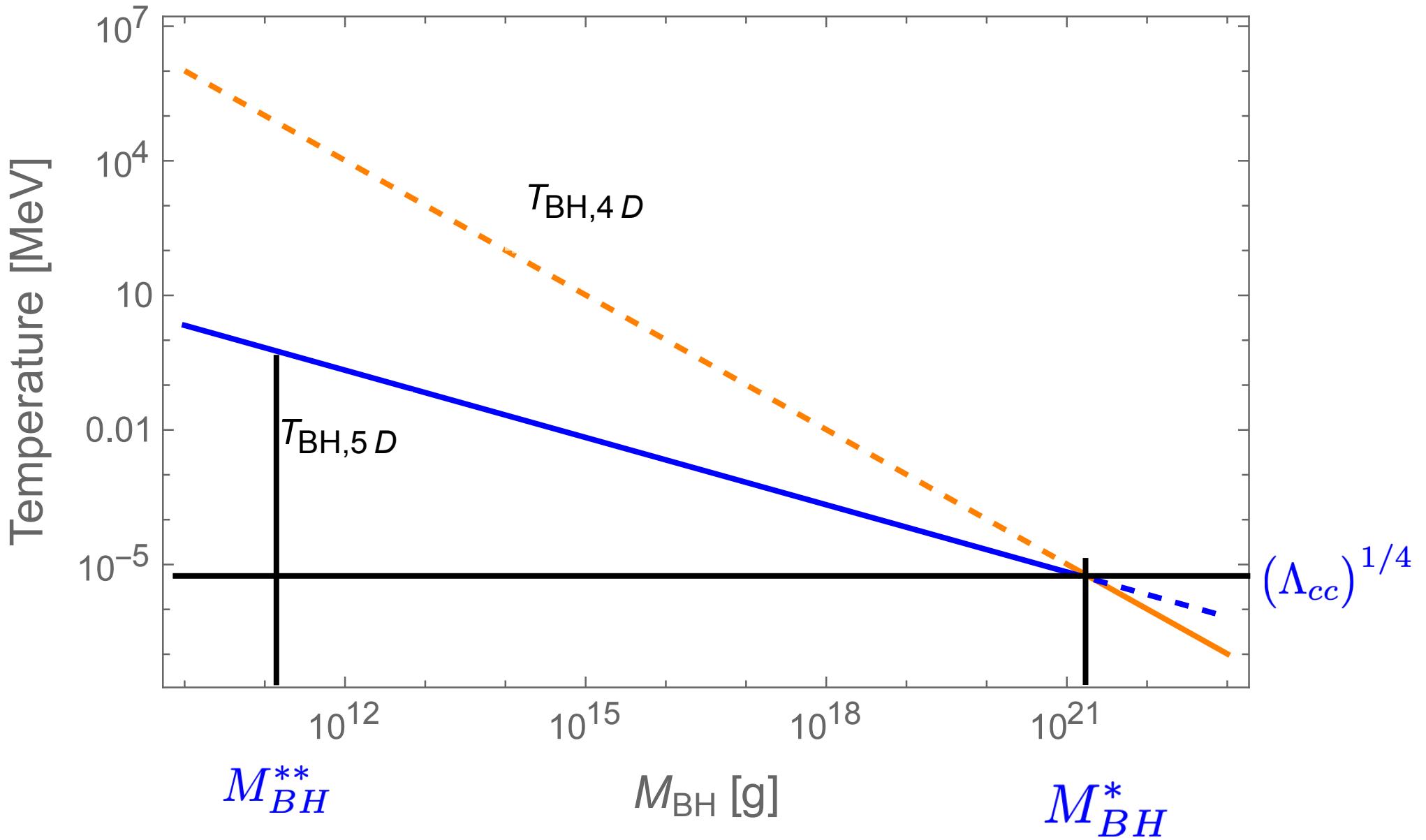
Black hole with  $5 \times 10^{14} \text{ g}$  has lifetime comparable to the age of the universe.

(ii) 5D BH ( $n=1$ ):

$$\tau_{\text{BH}}^{n=1} \simeq 9 \times 10^{-15} (M_{\text{BH}}/\text{g})^2 \text{ yr}$$

Black hole with  $M_{\text{BH}}^{**} \simeq 2 \times 10^{11} \text{ g}$  has lifetime comparable to the age of the universe.

This sets the lower mass end of the viable window.



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

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

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

→ BHs in window are 5 - dimensional

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

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

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

→ BHs in window are 5 - dimensional

(ii) Viable window for 5D primordial black holes:

$$2 \times 10^{11} \text{ g} \leq M_{BH} \leq 10^{21} \text{ g}$$
$$2 \times 10^{-11} \text{ m} \leq r_S \leq 2 \mu \text{m}$$

$$500 \text{ keV} \geq T_{BH} \geq 10 \text{ eV}$$

## V) Summary of Dark Universe

## V) Summary of Dark Universe

- It relates  $\Lambda_{cc}$  to an extra dimension of micron size:

$$1/R \sim \mathcal{O}(\Lambda_{cc}^{1/4}) \simeq 10^{-1}\text{eV} \simeq (1\mu\text{m})^{-1}$$

## V) Summary of Dark Universe

- It relates  $\Lambda_{cc}$  to an extra dimension of micron size:  
$$1/R \sim \mathcal{O}(\Lambda_{cc}^{1/4}) \simeq 10^{-1} \text{eV} \simeq (1\mu\text{m})^{-1}$$
- It relates  $\Lambda_{cc}$  to the scale of supersymmetry breaking:  
$$M_{SUSY} \sim \mathcal{O}(\Lambda_{cc}^{1/8}) M_P^{1/2} \simeq 1 \text{TeV}$$

## V) Summary of Dark Universe

- It relates  $\Lambda_{cc}$  to an extra dimension of micron size:

$$1/R \sim \mathcal{O}(\Lambda_{cc}^{1/4}) \simeq 10^{-1} \text{eV} \simeq (1\mu\text{m})^{-1}$$

- It relates  $\Lambda_{cc}$  to the scale of supersymmetry breaking:

$$M_{SUSY} \sim \mathcal{O}(\Lambda_{cc}^{1/8}) M_P^{1/2} \simeq 1 \text{TeV}$$

- It relates  $\Lambda_{cc}$  to the scale of quantum gravity:

$$M_{QG} \sim \mathcal{O}(\Lambda_{cc}^{1/12}) M_P^{2/3} \simeq 10^{10} \text{GeV}$$

## V) Summary of Dark Universe

- It relates  $\Lambda_{cc}$  to an extra dimension of micron size:

$$1/R \sim \mathcal{O}(\Lambda_{cc}^{1/4}) \simeq 10^{-1} \text{eV} \simeq (1\mu\text{m})^{-1}$$

- It relates  $\Lambda_{cc}$  to the scale of supersymmetry breaking:

$$M_{SUSY} \sim \mathcal{O}(\Lambda_{cc}^{1/8}) M_P^{1/2} \simeq 1 \text{TeV}$$

- It relates  $\Lambda_{cc}$  to the scale of quantum gravity:

$$M_{QG} \sim \mathcal{O}(\Lambda_{cc}^{1/12}) M_P^{2/3} \simeq 10^{10} \text{GeV}$$

- It relates  $\Lambda_{cc}$  to the mass of primordial black holes:

$$M_{BH} \sim \mathcal{O}(\Lambda_{cc}^{-1/4}) M_P^2 \simeq 10^{21} \text{g}$$

Alternative and possibly related proposal for dark matter:

## Dark KK Gravitons as Dark matter candidates.

[E. Gonzalo, M. Montero, G. Obied, C.Vafa (2022)]

[L.Anchordoqui, I.Antoniadis, D.L., arXiv:2210.02475]

Alternative and possibly related proposal for dark matter:

## Dark KK Gravitons as Dark matter candidates.

[E. Gonzalo, M. Montero, G. Obied, C.Vafa (2022)]

[L.Anchordoqui, I.Antoniadis, D.L., arXiv:2210.02475]

Also masses of elementary particles can be related to the cosmological constant by swampland arguments:

Neutrino mass:

$$m_\nu \simeq (\Lambda_{cc})^{1/4}$$

[E. Gonzalo, L. Ibanez, I.Valenzuela (2021)]

But still question big questions about dark energy:

Can there be a de Sitter vacuum in quantum gravity?

Stabilization of dark radius?

Time dependent dark energy - quintessence models?

But still question big questions about dark energy:

Can there be a de Sitter vacuum in quantum gravity?

Stabilization of dark radius?

Time dependent dark energy - quintessence models?

**Thank you !**