Distance Conjectures and Primordial Black Holes as Dark Matter

DIETER LÜST (LMU, MPP)

Back to the Swamp, IFT Autonoma University, Madrid, 26th. September 2022

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

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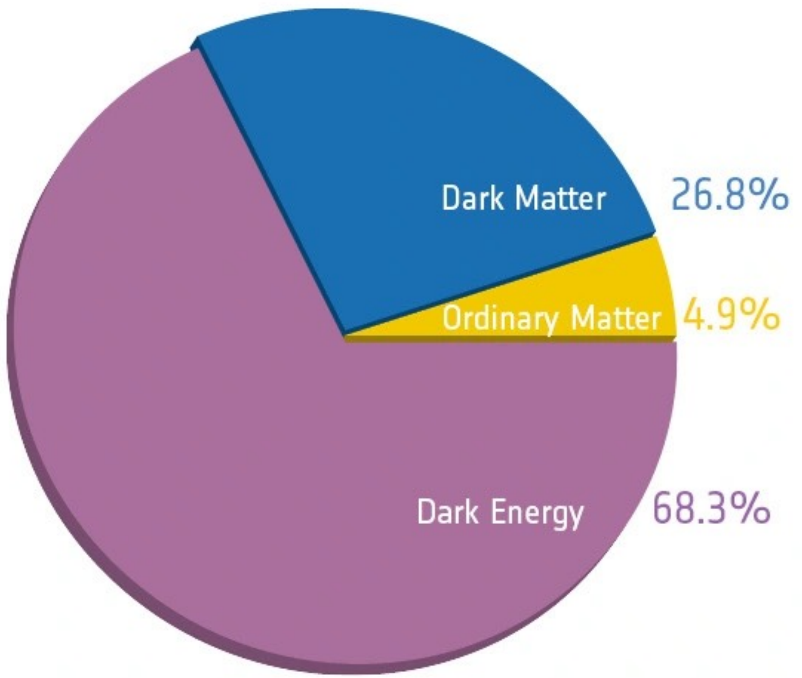
I) Introduction

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) Some Distance Conjectures

III) Cosmological constant distance conjecture - Dark Universe

IV) Primordial BHs and the Dark Universe

V) Conclusions

Swampland Distance Conjectures

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

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

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

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

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)]

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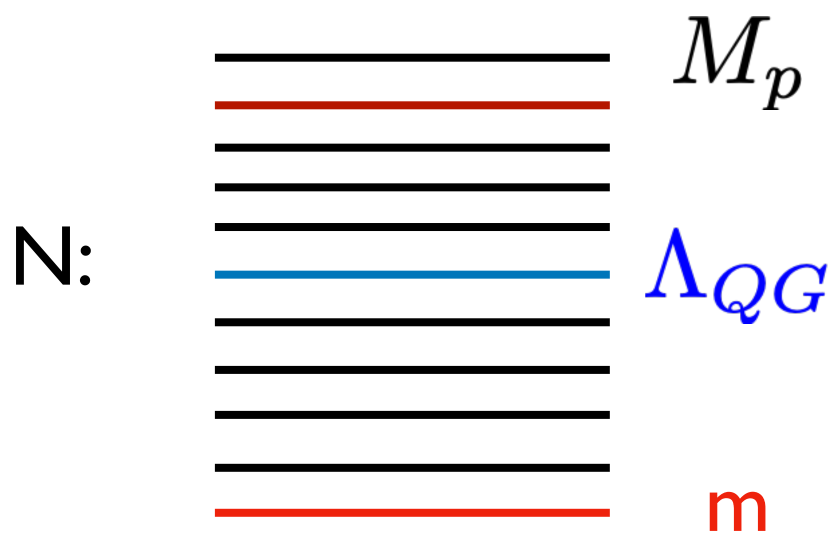

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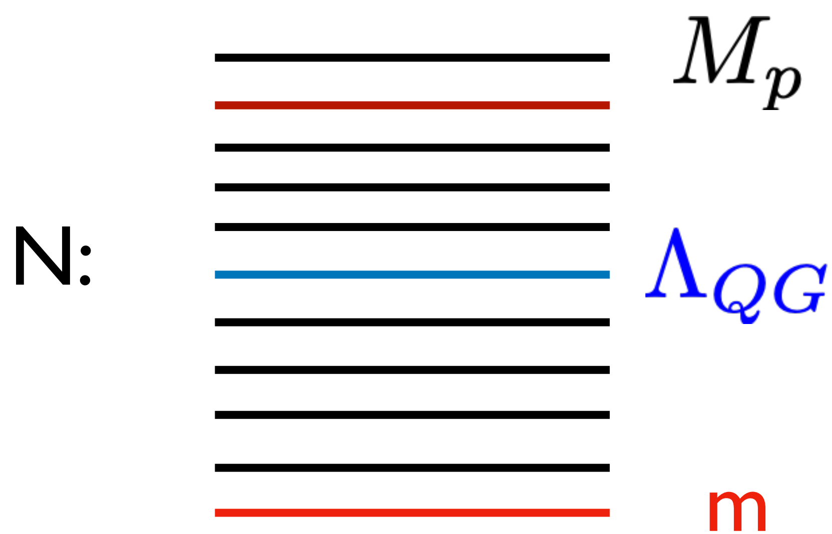

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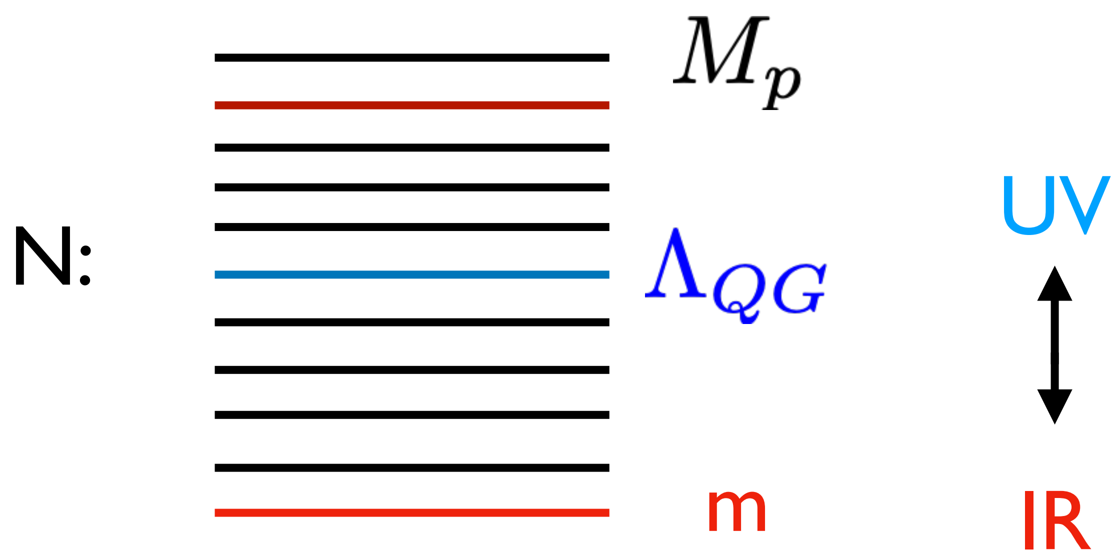

[A.Castellano, A.Herraez, L. Ibanez (2012)]

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Some 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)]

Some Distance Conjectures

Gravitino conjecture

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

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

Some Distance Conjectures

BH entropy conjecture

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

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

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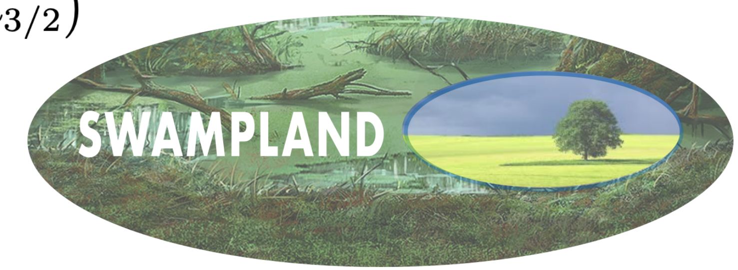
$$\Lambda_{cc} = |DW|^2 - 3\left(m_{3/2}\right)^2$$



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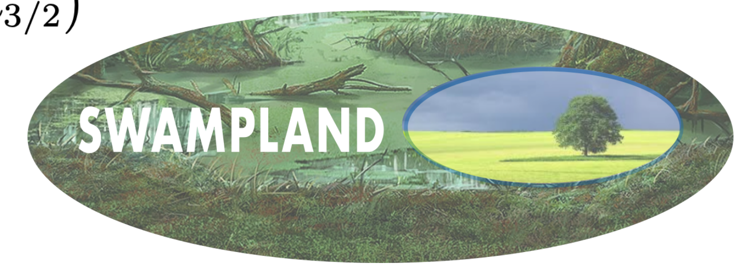

BH - flux - domain wall correspondence

$$\mathcal{S} = |DZ|^2 + |Z|^2$$

[to appear]

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Emergent string conjecture:

[S.-J. Lee, W. Lerche, T. Weigand (2019)]

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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

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

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 $M_{p,n}$.

CC Distance Conjectures - 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.

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]

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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: $\Lambda_{QG} \simeq 10^{10}\;Gev$

Concrete implementation of the dark universe scenario?

F - theory ? [M. Montero, C. Vafa, I. Valenzuela (2022)]

KKLT with uplift ?

Dark dimension in a warped throat

$$\longrightarrow \quad \alpha = 1/4$$

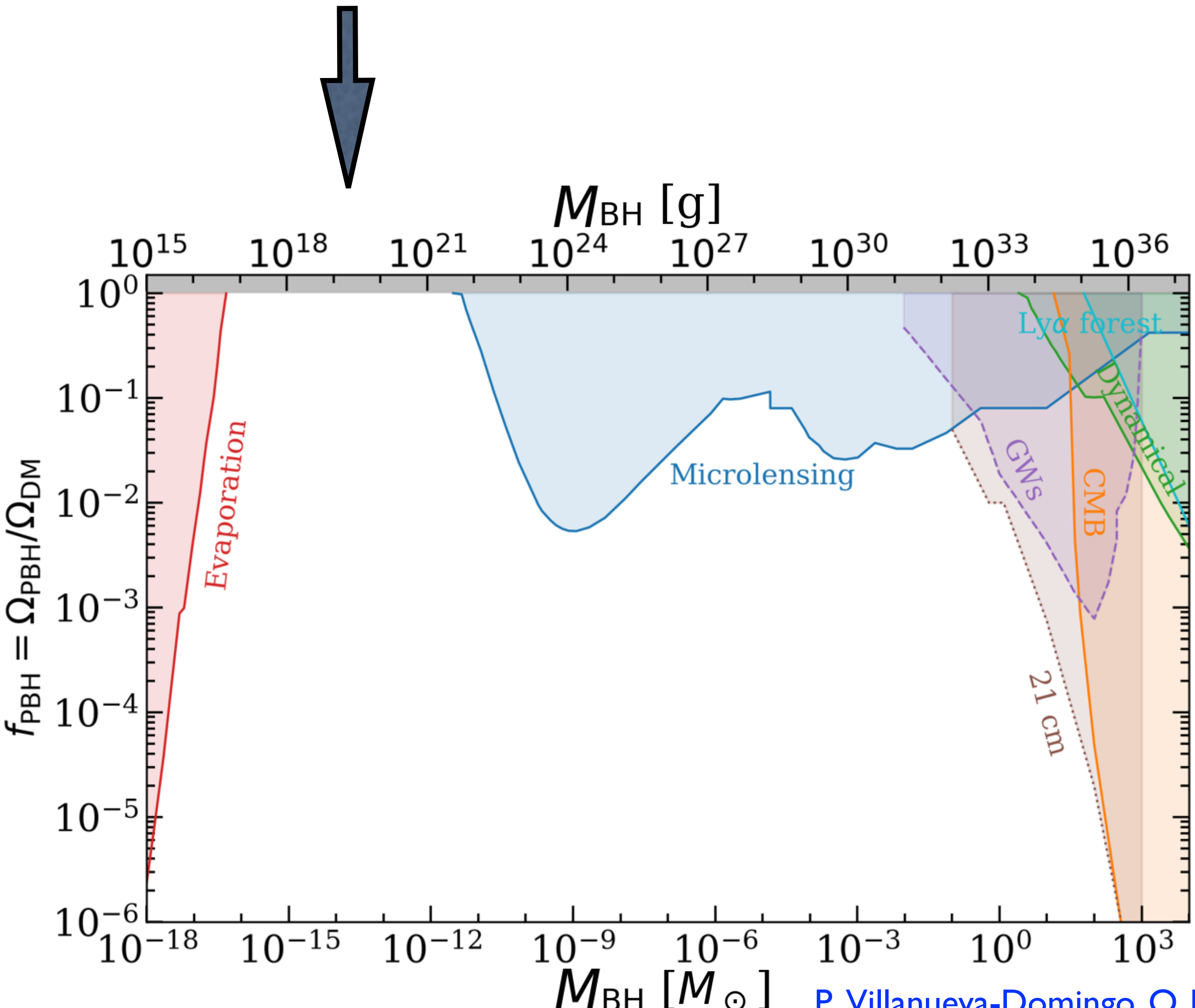
[R. Blumenhagen, M. Brinkmann, A. Makridou (2022)]

Primordial Black Hole in the Dark Universe

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

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)

Three possible regimes for black holes with horizon r_s :

(i) $r_s > R$ ⟶ 4D black hole

(ii) $l_s < r_s < R$ ⟶ 5D black hole

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

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

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

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

We derived:

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

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

⟶ BHs in window are 5 - dimensional

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

The net change of the black hole mass is given by

$$\frac{dM_{\rm BH}}{dt} = \left.\frac{dM_{\rm BH}}{dt}\right|_{\rm accr} + \left.\frac{dM_{\rm BH}}{dt}\right|_{\rm evap}$$

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Black hole production by accretion:

$$\left.\frac{dM_{\rm BH}}{dt}\right|_{\rm accr} \approx \pi \left(\frac{n+3}{2}\right)^{2/(n+1)} \frac{n+3}{n+1}\, r_s^2\, \varepsilon$$

ε ….. energy density of hot plasma around horizon.

Primordial black holes will be produced after inflation but before the reheating temperature.

BH evaporation goes by Hawking radiation.

BH decay rate in 4+n dimensions:

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

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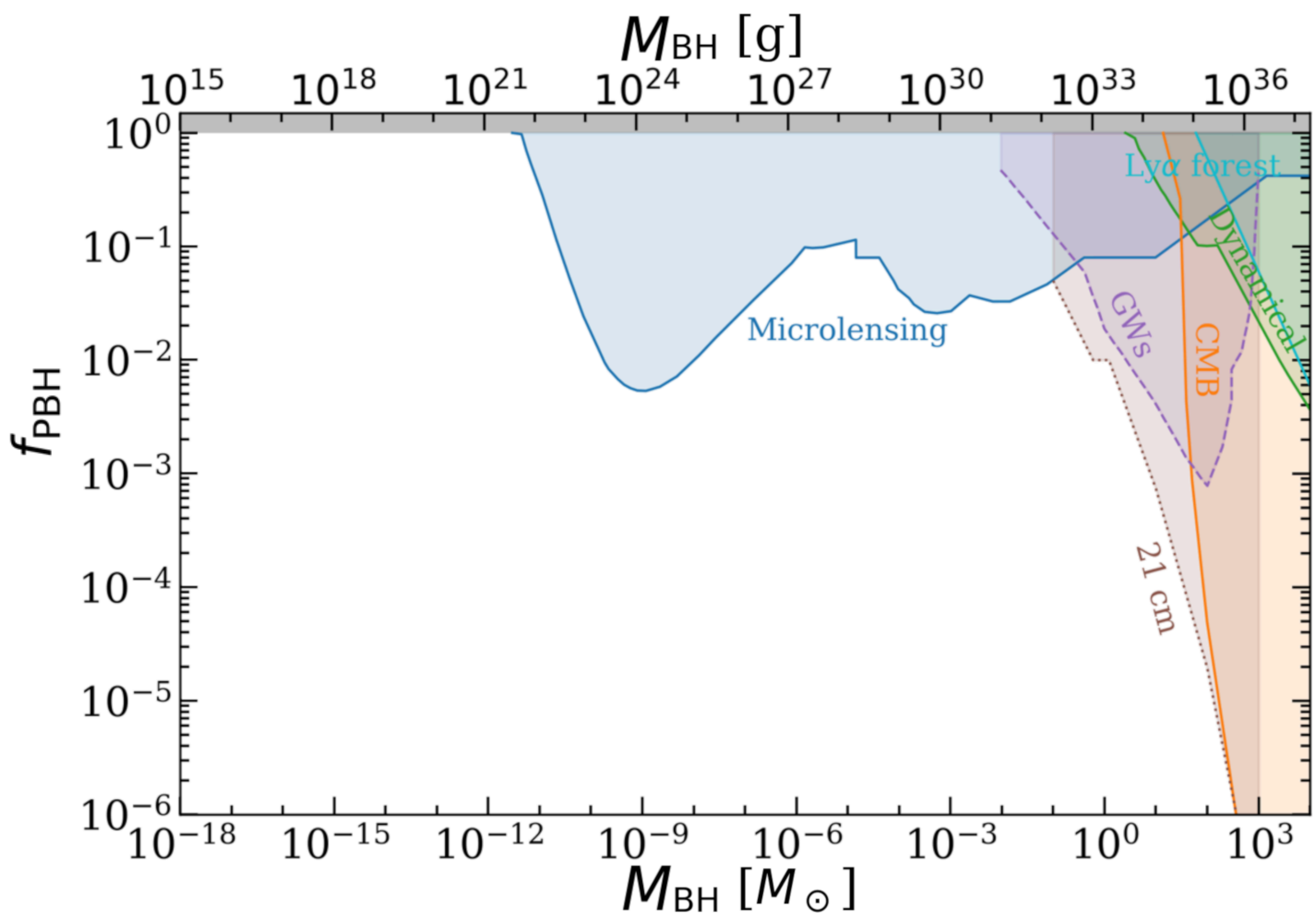
The 5D PBHs are bigger, colder and longer lived than the 4D black holes !

5D primordial black holes:



Summary and Outlook

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

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5D black holes in the dark universe emit less particles than the 4D black holes, so the limits from photon background can be relaxed.

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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However assume the existence of a 5D PBH with

$$M_{BH} \sim 10^{12}\ g \quad \text{and} \quad f_{PBH} \sim 10^{-7}$$

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

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

Alternative proposal for dark matter in the dark universe:

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.. KK tower of dark gravitons, i.e. 5D gravitons

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

Being produced at temperature

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They decay down to lighter gravitons of mass

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Is there a relation between BHs and gravitons as dark matter?

BH as being bound states of gravitons.

[G. Dvali, C. Gomez (2011)]

Thank you !