Physics with Costas: exploring the string landscape

I. Antoniadis

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and

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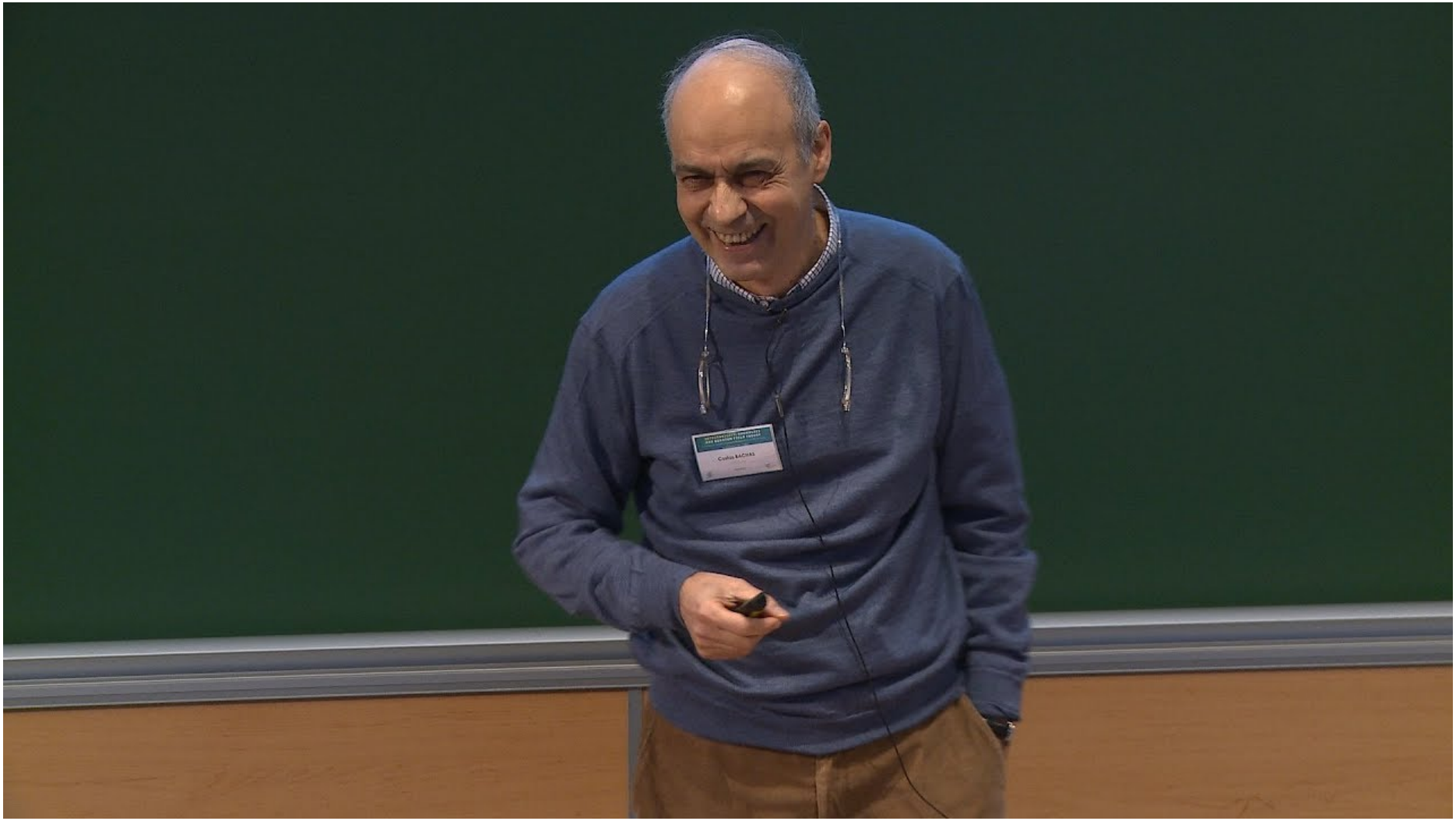
The road together started in 1984 at SLAC



Working with Costas

1984-86: SLAC - SLAC

1986-87: SLAC - CERN

1987-88: CPHT - CERN

1988-90: CERN - CPHT

1990-98: CPHT - CPHT $\leftarrow$ build string group

1998-00: ENS - CPHT & CERN

Working with Costas: 1990-98 CPHT

joint efforts to build an active group on string theory

PhD students: Marios Petropoulos, Pierre Vanhove, Cyrille Fabre, Karim Benakli, Boris Pioline, Hervé Partouche

European Networks

- "String Theories and their Phenomenological Applications" 1992-96
  EP, U Athens, ICTP, UA Madrid, Oxford, SISSA
- "Physics Beyond the Standard Model" 1996-00
  EP, U Lisbon, UA Madrid, U Munich, Oxford, U Thessaloniki, U Valencia, INFN Padova + Pisa, SISSA, CNRS LPTENS + LPTHE, CERN

Postdocs/Marie-Curie fellowships (institutional + individual)

Ioannis Rizos, Niels Obers, Nick Tsamis, Alberto Zaffaroni, Katrin Foerger, Carlo Angelantonj, Fawad Hassan, Adi Armoni, Damiano Anselmi

Summary of joint publications

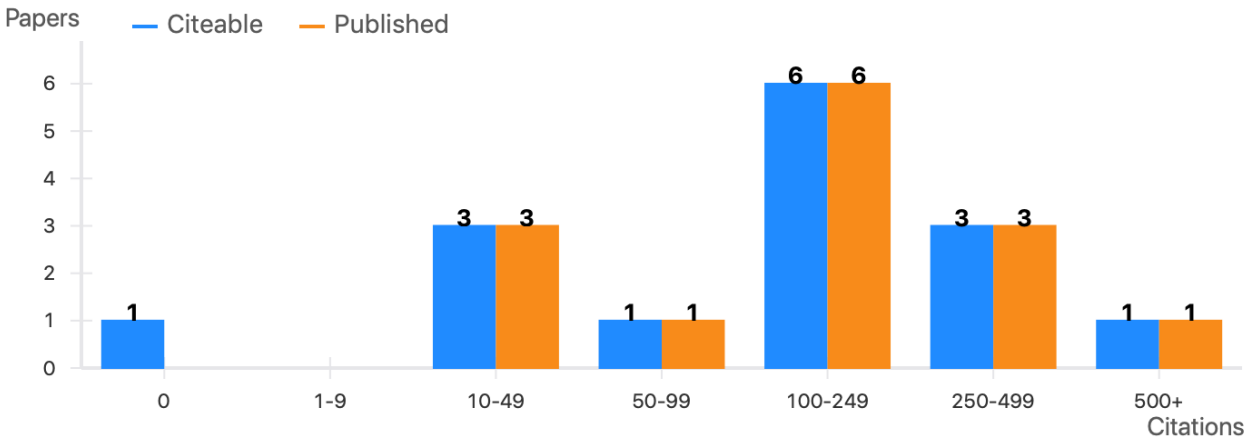
15 results | cite all

Citation Summary | Least Recent

Citation Summary

Exclude self-citations

	Citeable	Published
Papers	**15**	**14**
Citations	**3,020**	**3,020**
h-index	**14**	**14**
Citations/paper (avg)	**201.3**	**215.7**



Conformal Invariance and Parastatistics in Two-dimensions

#1

Ignatios Antoniadis (SLAC), Constantin Bachas (SLAC) (Apr, 1985)

Published in: *Nucl.Phys.B* 278 (1986) 343-352

pdf | links | DOI | cite | claim | reference search | 25 citations

Construction of 4d strings

SLAC - Berkeley collaboration

Supersymmetry Among Free Fermions and Superstrings #2

Ignatios Antoniadis (SLAC), Constantin Bachas (SLAC), C. Kounnas (UC, Berkeley and LBL, Berkeley), Paul Windey (UC, Berkeley and LBL, Berkeley) (Sep, 1985)

Published in: *Phys.Lett.B* 171 (1986) 51-56

pdf links DOI cite claim reference search 239 citations

Four-Dimensional Superstrings #3

Ignatios Antoniadis (CERN), C.P. Bachas (Ecole Polytechnique), C. Kounnas (LBL, Berkeley) (Dec, 1986)

Published in: *Nucl.Phys.B* 289 (1987) 87

DOI cite claim reference search 896 citations

4-D Fermionic Superstrings with Arbitrary Twists #4

Ignatios Antoniadis (CERN), C. Bachas (Ecole Polytechnique) (Jun, 1987)

Published in: *Nucl.Phys.B* 298 (1988) 586-612

DOI cite claim reference search 352 citations

Construction of 4d strings

Basic idea:

describe the compactification space by a (S)CFT of free 2d fermions

Heterotic string $c = (6 + 3, 22) \Rightarrow$ 18 L-moving and 44 R-moving

↑

with non-linear supersymmetry $SU(2)^6$

Parameters:

boundary conditions around the 2 cycles of the world-sheet torus

$\Rightarrow$ Hamiltonian and fermion number projection

Constraints: one-loop modular invariance and 2-loop factorisation

$\Rightarrow$ sum over several sectors of boundary conditions

Set of rules for constructing chiral models with interesting phenomenology

$N = 1$ SUSY, 3 generations, exact α'-calculability of effective SUGRA,

$SO(10)$ underlying structure: flipped $SU(5)$, Pati-Salam, Standard Model

Symmetry breaking

SLAC - CERN collaboration

Higgs Phenomenon in String Theories

#5

Ignatios Antoniadis (CERN), C. Bachas (Ecole Polytechnique), C. Kounnas (UC, Berkeley and LBL, Berkeley) (Oct, 1987)

Published in: *Phys.Lett.B* 200 (1988) 297-304

DOI cite claim reference search 48 citations

On Supersymmetry Breaking in Superstrings

#6

Ignatios Antoniadis (CERN), Constantin Bachas (SLAC), David C. Lewellen (SLAC), T.N. Tomaras (Ecole Normale Superieure) (Mar, 1988)

Published in: *Phys.Lett.B* 207 (1988) 441-446

pdf links DOI cite claim reference search 136 citations

The first example of the swampland distance conjecture

Theorem:

if 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 $\lambda_{3/2} = 1/2N$

String cosmological solutions

CERN - Ecole Polytechnique collaboration

Cosmological String Theories and Discrete Inflation #7

Ignatios Antoniadis (CERN), C. Bachas (CERN), John R. Ellis (CERN), Dimitri V. Nanopoulos (Wisconsin U., Madison) (May, 1988)

Published in: *Phys.Lett.B* 211 (1988) 393-399

DOI cite claim reference search 316 citations

An Expanding Universe in String Theory #8

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (Ecole Polytechnique), John R. Ellis (CERN), Dimitri V. Nanopoulos (Texas A-M) (Nov, 1988)

Published in: *Nucl.Phys.B* 328 (1989) 117-139

DOI cite claim reference search 329 citations

STRINGS IN AN EXPANDING UNIVERSE #9

Ignatios Antoniadis (Ecole Polytechnique and CERN), C. Bachas (Ecole Polytechnique) (Jun, 1989)

Published in: *Conf.Proc.C* 8903131 (1989) 391-402 • Contribution to: Strings 89, Trieste Conference on Recent Developments in Conformal Field Theories

Linear Dilaton background

Exact string solution: string frame dilaton linear in time and metric flat

$$\Phi = -2QX^0 \quad ; \quad G_{\mu\nu} = \eta_{\mu\nu}$$

The 3-space can also be a sphere of radius $\sqrt{k}$ ($SU(2)_k$ WZW model)

exact CFT with central charge $c = 4 - 12Q^2 - \frac{6}{k+2} + d_I$ $\leftarrow$internal space

$\Rightarrow$ Einstein frame: linearly expanding universe

$$ds^2 = -dt^2 + t^2\left[\frac{dr^2}{1-\kappa r^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \qquad \kappa^{-1} = 2Q^2k$$

$$\Phi = -2\ln(Qt) \quad ; \quad a = 2Q^2\sqrt{\kappa}t \leftarrow \text{ axion}$$

$c = 10$ (superstring) $\Rightarrow d_I > 6$ (critical dimension > 10) !

Other string vacua

Gauged Supergravity Vacua in String Theory #10

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (CERN), A. Sagnotti (Rome U., Tor Vergata and INFN, Rome) (Oct, 1989)

Published in: *Phys.Lett.B* 235 (1990) 255-260

DOI cite claim reference search 67 citations

$N = 2$ Superliouville and Noncritical Strings #11

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (CERN), C. Kounnas (Ecole Normale Superieure) (Mar, 1990)

Published in: *Phys.Lett.B* 242 (1990) 185-190

DOI cite claim reference search 21 citations

String dualities

Ecole Polytechnique collaboration

Aspects of type I - type II - heterotic triality in four-dimensions

#13

Ignatios Antoniadis (Ecole Polytechnique and CERN), C. Bachas (Ecole Polytechnique), C. Fabre (Ecole Polytechnique), H. Partouche (Ecole Polytechnique), T.R. Taylor (CERN and Northeastern U.) (Jul, 1996)

Published in: *Nucl.Phys.B* 489 (1997) 160-178 • e-Print: hep-th/9608012 [hep-th]

pdf DOI cite claim reference search 134 citations

Branes and the gauge hierarchy

#14

Ignatios Antoniadis (Ecole Polytechnique), Constantin Bachas (Ecole Normale Superieure) (Dec, 1998)

Published in: *Phys.Lett.B* 450 (1999) 83-91 • e-Print: hep-th/9812093 [hep-th]

pdf DOI cite claim reference search 157 citations

Gauge couplings in four-dimensional type I string orbifolds

#15

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (Ecole Normale Superieure), E. Dudas (Orsay, LPT) (Jun, 1999)

Published in: *Nucl.Phys.B* 560 (1999) 93-134 • e-Print: hep-th/9906039 [hep-th]

pdf DOI cite claim reference search 169 citations

UV sensitivity on D-branes

localised couplings + closed string propagation in $d \leq 2$

Effective propagation of massless bulk states in $d \leq 2 \Rightarrow$ IR divergences

$d = 1$: linear, $d = 2$: logarithmic

$\Rightarrow$ corrections to (brane) localised couplings

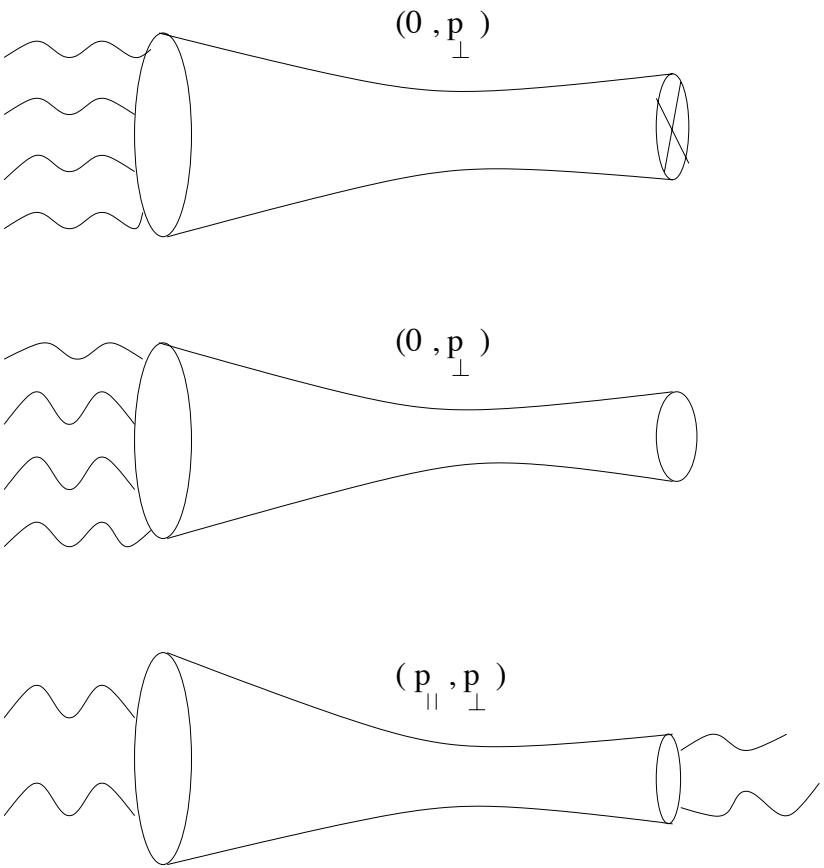
depending on the size of the bulk due to local closed string tadpoles

e.g. log running of the 4d gauge coupling

linear dilaton dependence on the 11th dim of M-theory

UV sensitivity on D-branes: local tadpoles in (a), (b)

decompactification limit in the presence of branes



$$\mathcal{A} \sim \frac{1}{V_\perp} \sum_{|p_\perp|<M_s} \frac{1}{p_\perp^2} F(\vec{p}_\perp)$$

$$V_\perp = R^d \quad \vec{p}_\perp = \vec{n}/R$$

$$R >> l_s \Rightarrow$$

$$\mathcal{A} \sim \begin{cases} \mathcal{O}(R) & for\ d{=}1 \\ \mathcal{O}(\log R) & for\ d{=}2 \\ \text{finite} & for\ \ \mathrm{d}{>}\ 2 \end{cases}$$

local tadpoles: $F(\vec{p}_\perp) \sim \left(2^{5-d} \prod_{i=1}^{d} (1+(-)^{n_i}) - 2\sum_{a=1}^{16} \cos(\vec{p}_\perp \vec{y}_a)\right)$ [23]

Landscape (25 years later)

Huge number of 4D string ground states with $N \leq 1$ SUSY

with all closed string moduli stabilised in terms of discrete fluxes

all physical couplings of the EFT fixed in terms of the moduli

Validity of the framework: weak string coupling and large volume

Identify physically relevant vacua:

need an extra input of guiding 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 $\Rightarrow$ 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: 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

$$M_* = M_P/\sqrt{N} \qquad \text{Dvali '07}$$

- 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 scales : large distance corner of lanscape?

Examples of small parameters

Scales of dark energy and supersymmetry breaking

Recent proposal: dark dimension at the micron scale with $M_* \sim 10^9$ GeV

Montero-Vafa-Valenzuela '22

$\Rightarrow$ interesting phenomenology

neutrino masses, dark matter, cosmology, SUSY breaking

3 candidates of dark matter:

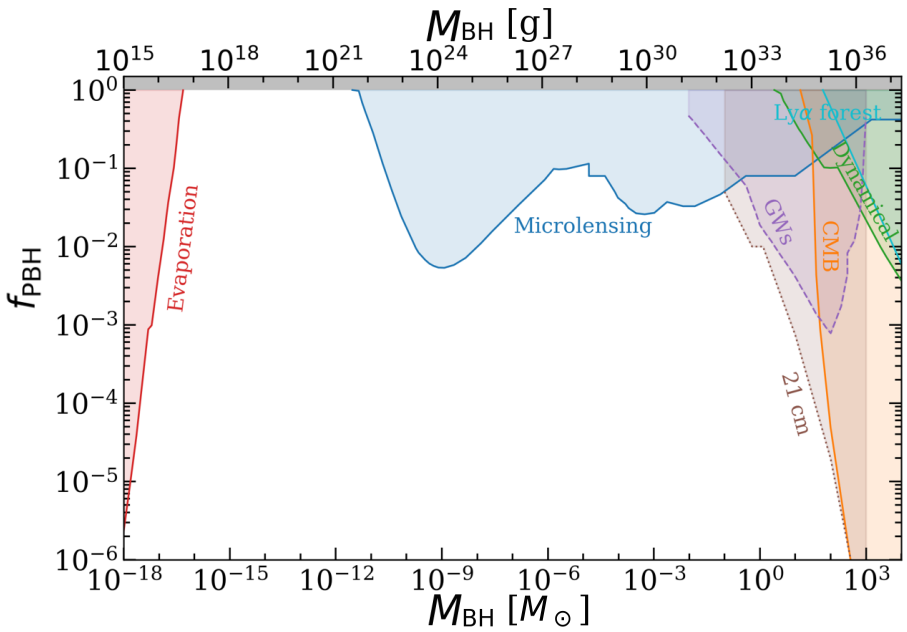
- 5D primordial black holes in the mass range $10^{15} - 10^{21}$g
  with Schwarzschild radius in the range $10^{-4} - 10^{-2}$ μm

  Anchordoqui-I.A.-Lust '22
- KK-gravitons of decreasing mass due to internal decays (dynamical DM)
  from $\sim$ MeV at matter/radiation equality to $\sim$ 50 keV today

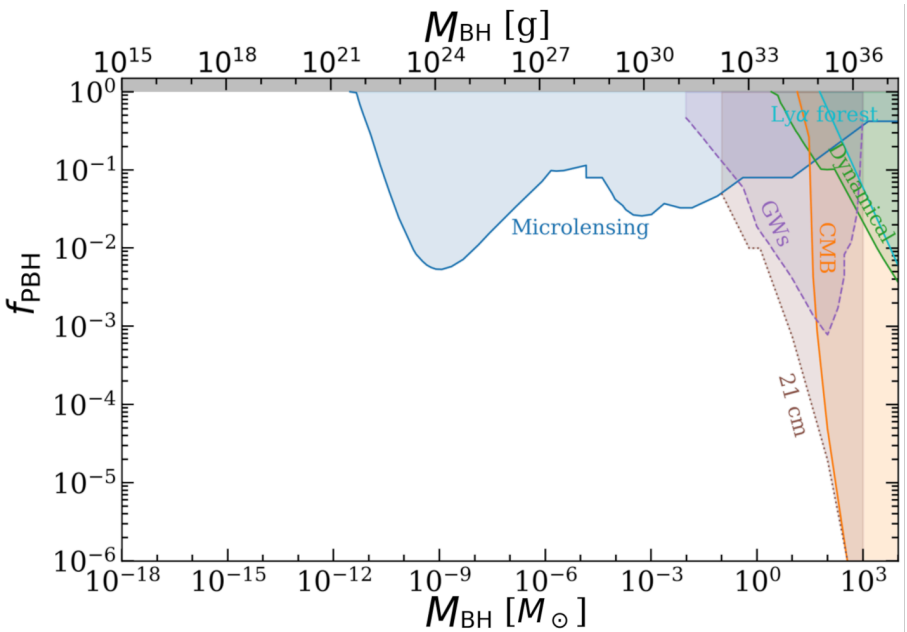
  Gonzalo-Montero-Obied-Vafa '22
- ultralight radion as a fuzzy dark matter Anchordoqui-I.A.-Lust '23

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) $H_I \lesssim m \sim \text{eV}$

Interesting possibility: the extra dimension expands with time

$R_0 \sim 1/M_*$ to $R \sim \mu$m requires ~ 40 efolds! Anchordoqui-I.A.-Lust '22

$$ds_5^2 = a_5^2(-d\tau^2 + d\vec{x}^2 + R_0^2\, dy^2) \quad R_0 : \text{initial size prior to inflation}$$

$$= \frac{ds_4^2}{R} + R^2 dy^2 \quad ; \quad ds_4^2 = a^2(-d\tau^2 + d\vec{x}^2) \quad \Rightarrow a^2 = R^3$$

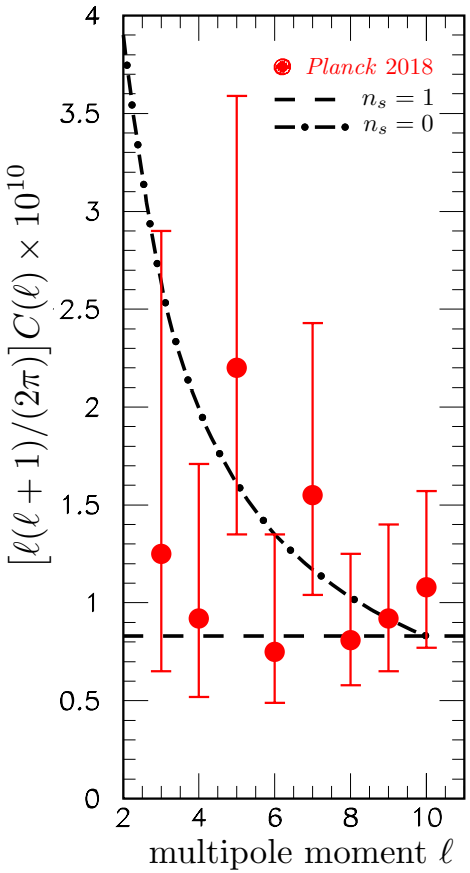
After 5d inflation of $N = 40$-efolds $\Rightarrow$ 60 e-folds in 4d with $a = e^{3N/2}$

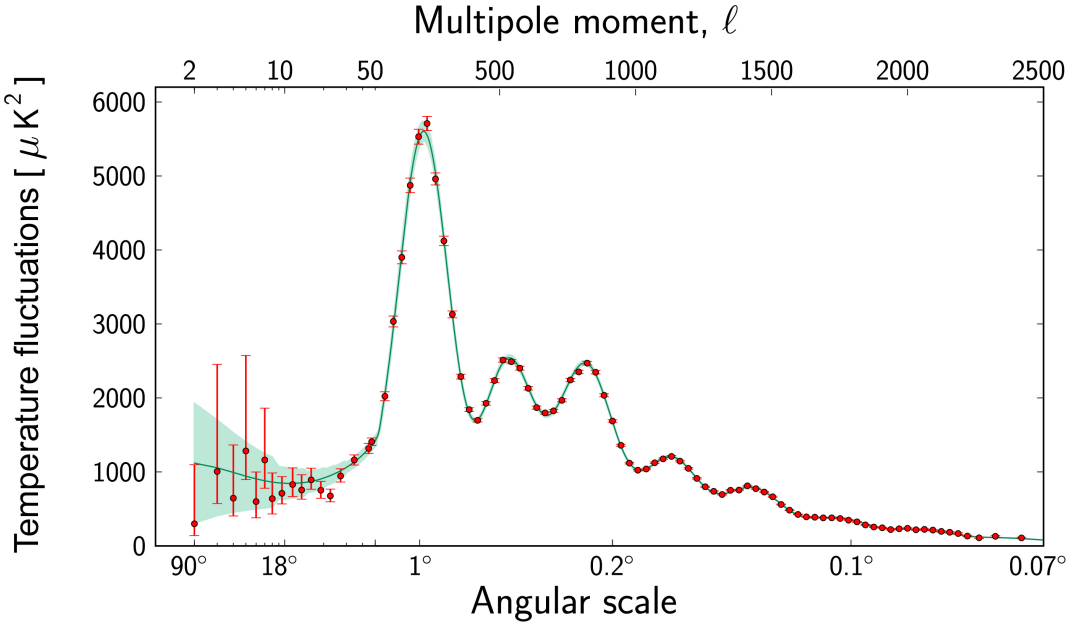
Large extra dimensions from inflation in higher dimensions

Anchordoqui-IA '23

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





Happy Retirement Costa

Have a new productive career ahead

Without duties and obligations

Welcome to the club!