Landscape, swampland and extra dimensions

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Extra dimensions

important ingredient of theories of quantum gravity such as string theory

if they are large $\Rightarrow$

gravity becomes strong at energies lower than the Planck scale

M_*: higher dimensional Planck scale $<<$ M_p

with observable universe localised on a '3-brane'

I.A.-Arkani Hamed-Dimopoulos-Dvali '98

Dark dimension proposal for the dark energy Montero-Vafa-Valenzuela '22

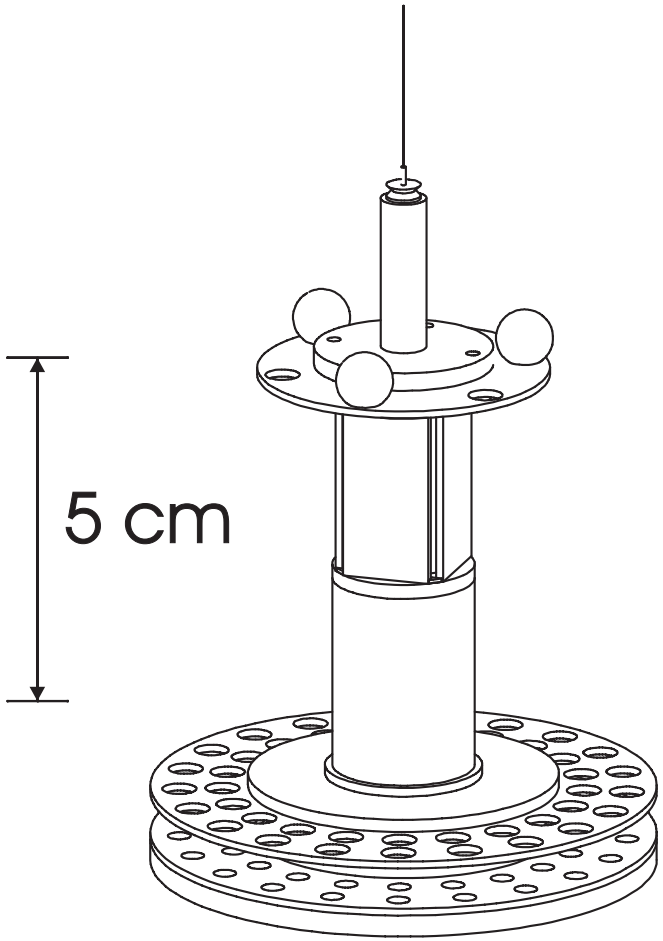
Swampland distance conjecture + observations $\Rightarrow$

one (or 2) extra dimension(s) of a micron size

strong gravity at $M_* \simeq 10^9$ GeV (10 TeV) / 10^{-22} cm

Newton's law is valid down to distances 30 μm

Adelberger et al. '06



Large hierarchies in particle physics and cosmology

Particle physics: why gravity appears so weak compared to other forces?

$$M_p/M_w \sim 10^{16}$$

Cosmology: why the Universe is so large compared to our causal horizon?

at least 10^{15} larger

Possible connection: through large extra dimensions

Horizon problem can be explained by a period of inflation

expansion rate faster than speed of light

Extra dimensions may obtain large size by higher-dim inflation

Anchordoqui-IA-Lust '22

Extra dimensions should expand from the fundamental length

to the size required for the present strength of gravity

Example: Dark Dimension and inflation

$R_0 \sim 1/M_* \simeq 10^{-22}$ cm to $R \sim \mu$m requires ~ 40 efolds!

$$ds_5^2 = -d\hat{t}^2 + \hat{a}^2(d\vec{x}^2 + R_0^2\, dy^2) \quad R_0 : \text{initial size}, \quad \hat{a} = e^{H\hat{t}}$$

$$\text{4D frame} = \frac{ds_4^2}{R/R_0} + R^2 dy^2 \quad ; \quad ds_4^2 = -dt^2 + a^2 d\vec{x}^2 \quad \Rightarrow a^2 = \hat{a}^3$$

$$\Rightarrow \quad R(t) \sim t^2 \quad ; \quad a(t) \sim t^3$$

After 5d inflation of $N = 40$-efolds $\quad \hat{a} \simeq e^{40}$

$\Rightarrow$ 60 e-folds in our 4D universe with $a = e^{3N/2} \simeq e^{60}$

- If 4d inflation occurs with fixed radius $\Rightarrow$ too low inflation scale

Higuchi bound: $H_I \lesssim 1/R \sim$ eV

Large extra dimensions from higher-dim inflation

Anchordoqui-IA '23

Question: can uniform $(4+d)$ inflation relate the 2 hierarchies?

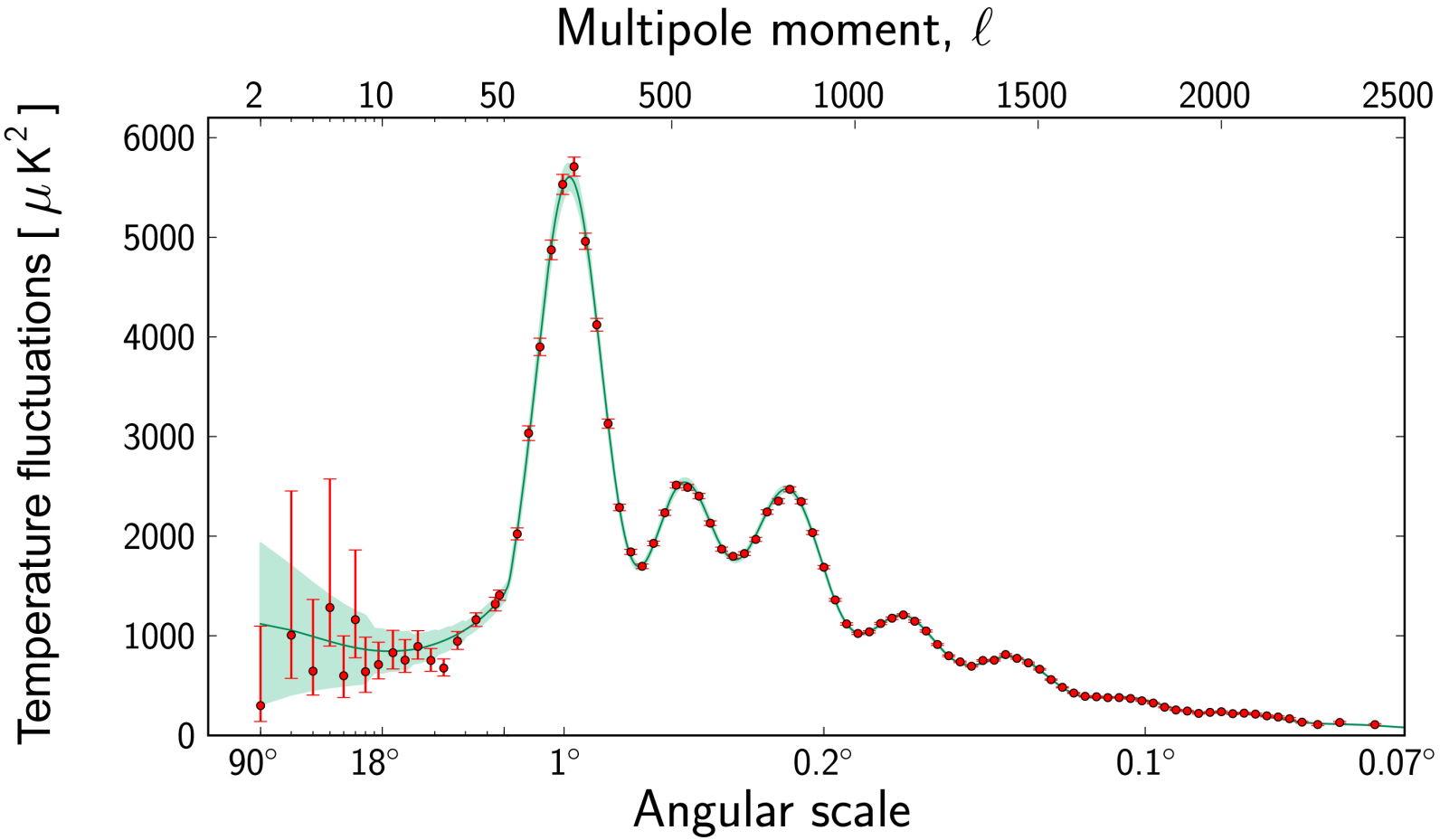
Answer: yes for any d

- $R(t) \sim t^{2/d}$, $a(t) \sim t^{1+2/d} \sim R^{1+d/2}$
- $\hat{N}$ e-folds in $(4+d)$-dims $\Rightarrow$ $N = (1+d/2)\hat{N}$ e-folds in 4D

Impose $M_* \gtrsim 10$ TeV and $R \lesssim 30\mu$m $\Rightarrow$

the horizon problem is solved for any d $\quad N \gtrsim 30 - 60$ $\left(N \gtrsim \ln \frac{M_I}{\mathrm{eV}}\right)$

Precision of CMB power spectrum measurement



CMB anomalies at large scales: preliminary evidence of scale invariance violation?

see e.g. Schwarz-Copi-Huterer-Starkman '16

Density perturbations from 5D inflation

inflaton (during inflation) $\simeq$ massless scalar in de Sitter spacetime

$\Rightarrow$ scale invariant fluctuations in any d

in momentum space at late cosmic time: $\langle \Phi^2(k) \rangle \sim 1/k^3$ (4D)

$$5\text{D}: \ \langle \Phi^2(\hat{k}) \rangle \simeq \frac{4}{\pi} \frac{H^3}{\hat{k}^4} \quad ; \quad \hat{k}^2 = k^2 + n^2/R_0^2$$

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

$$\sum_n \langle \Phi^2(\hat{k}) \rangle \simeq \frac{2R_0 H^3}{k^2} \left(\frac{1}{k} \coth(\pi k R_0) + \frac{\pi R_0}{\sinh^2(\pi k R_0)} \right) ; \quad k = 2\pi/\lambda$$

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

- $\pi k R_0 > 1$ ('small' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{H^3}{\pi^3}$ $\quad n_s \simeq 1$

  KK sum crucial for scale invariance [11]

- $\pi k R_0 < 1$ ('large' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{2H^3}{\pi^4 k R_0}$ $\quad n_s \simeq 0$

CMB power spectrum: scale of precision [13]

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

Mpc $\to 10^{15}$m at $T_N \sim$ MeV with radiation dominated expansion

$\times$ MeV$/T_R$ at a reheating temperature T_R

$\times \left(\frac{t_I}{t_R}\right)^{2/3(1+w)}$ for a period with $p = w\rho$

$\frac{t_I}{t_R} \sim \frac{H_R}{H} = \frac{T_R^2}{M_p H}$

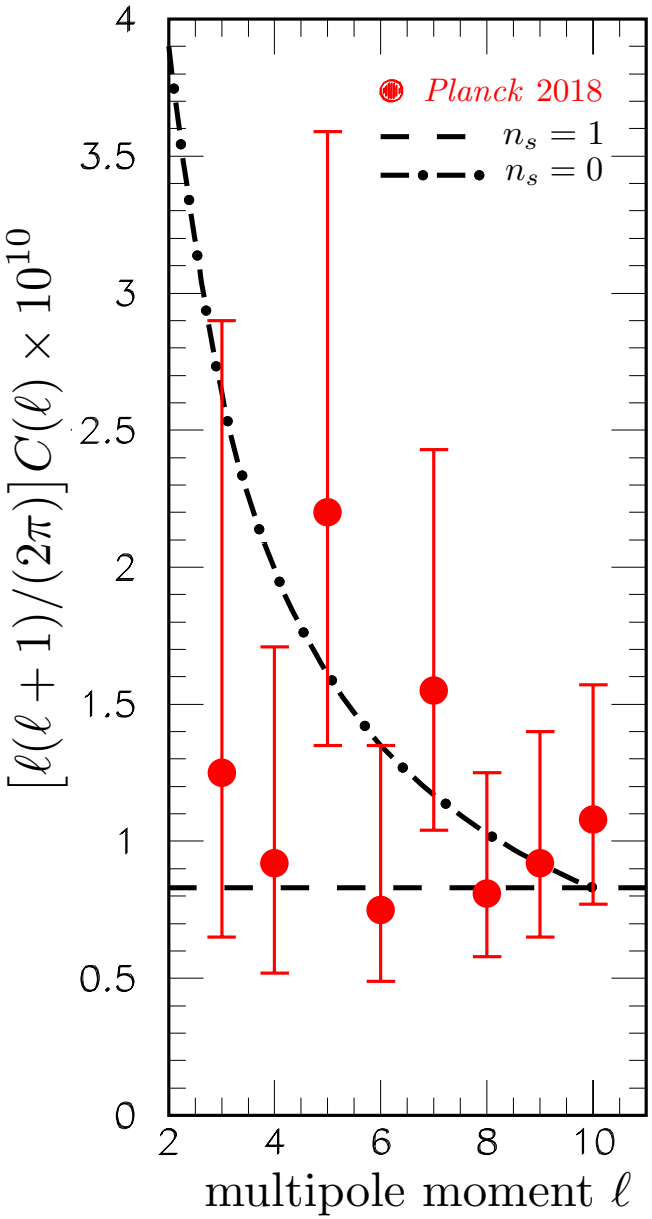
$\lesssim 10^{-3}$m (Newton's law bound) and $T_R \gtrsim$ MeV $\Rightarrow H \gtrsim$ TeV

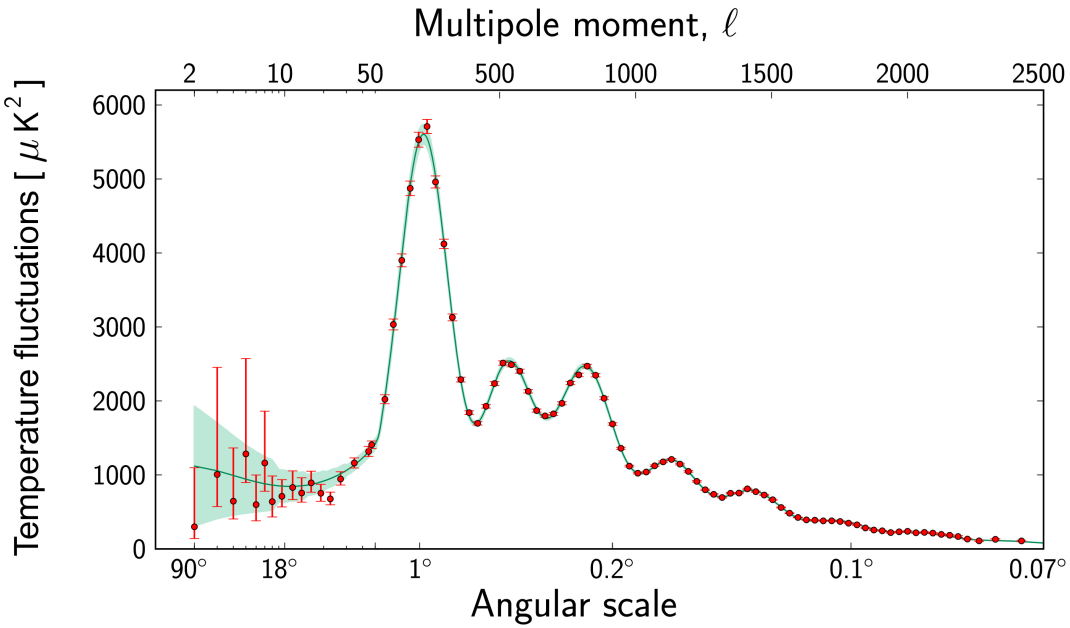
possible for a non accelerating phase from t_I to t_R with $w \geq -1/3$

Anchordoqui-I.A.-Cunat '26

$w = -1/3$: exact string solution

Large-angle CMB power spectrum





Detailed computation of primordial perturbations:

IA-Cunat-Guillen '23

5D: inflaton + metric (5 gauge invariant modes) $\Rightarrow$

4D: 2 scalar modes (inflaton + radion), 2 tensor modes, 2 vector modes

$$\mathcal{P}_{\mathcal{R}} \simeq \frac{1}{6\varepsilon}\mathcal{A}\left[\left(\frac{k}{\hat{a}H}\right)^{2\delta-5\varepsilon} + \varepsilon\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} \frac{5}{24} & R_0 k >> 1 \\ \frac{1}{3} & R_0 k << 1 \end{cases}\right] \text{[8]}$$

$$\mathcal{P}_{\mathcal{T}} \simeq \frac{4H^3}{\pi^3 M_*^3}\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} 1 & R_0 k >> 1 \\ \frac{2}{\pi k R_0} & R_0 k << 1 \end{cases} \qquad r = 24\varepsilon < 0.032 \,\text{exp}$$

$$\mathcal{P}_{\mathcal{V}} \simeq \frac{2H^3}{\pi^3 M_*^3}\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} 1 & R_0 k >> 1 \\ \frac{\pi^3}{45}(R_0 k)^3 & R_0 k << 1 \end{cases} \qquad S^1/Z_2\,(n \neq 0)$$

$$\mathcal{P}_{\mathcal{S}} \simeq \frac{9\varepsilon^2}{16}\mathcal{P}_{\mathcal{R}} \quad \text{entropy} \Rightarrow \beta_{\text{isocurvature}} = \frac{\mathcal{P}_{\mathcal{S}}}{\mathcal{P}_{\mathcal{R}} + \mathcal{P}_{\mathcal{S}}} \simeq \frac{9\varepsilon^2}{16} < 0.038 \,\text{exp}$$

slow-roll parameters: $\varepsilon = -\frac{\dot{H}}{H^2} \equiv \varepsilon_1$; $\quad \varepsilon_{n+1} = \frac{\dot{\varepsilon}_n}{H\varepsilon_n}$; $\quad \delta = \varepsilon - \varepsilon_2/2 \simeq \eta - \varepsilon$

Bispectrum from 5D inflation IA-Chatrabhuti-Cunat-Isono '25

$$f_{\rm NL} \underset{\substack{R_0 k_1 \gg 1 \\ R_0 k_2 \gg 1 \\ R_0 k_3 \gg 1}}{\simeq} \frac{5}{12}\left\{(\varepsilon_2-\varepsilon_1)+\frac{16\varepsilon_1}{k_1^3+k_2^3+k_3^3}\sum_{1\le a<b\le 3}\left(\frac{k_a^2 k_b^2}{k_t}+k_1k_2k_3\frac{k_a k_b}{k_t^2}\right)\right\}$$

$$f_{\rm NL}^{\rm 4D}=\frac{5}{12}\left\{(\varepsilon_2-\varepsilon_1)+\frac{\varepsilon_1}{k_1^3+k_2^3+k_3^3}\sum_{1\le a<b\le 3}\left(k_a k_b^2+k_a^2 k_b+\frac{8}{k_t}k_a^2k_b^2\right)\right\}$$

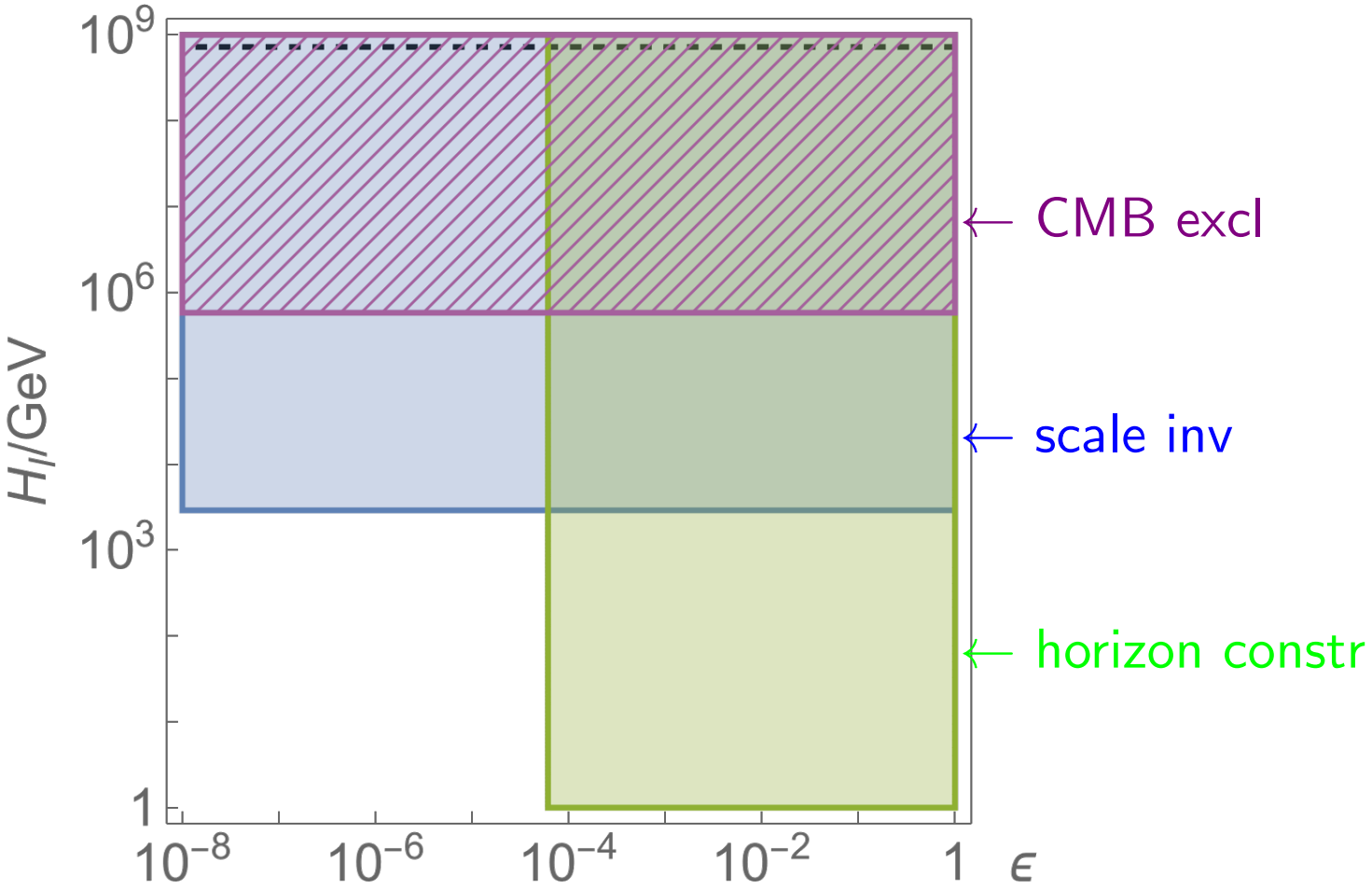
$f_{\rm NL}|_{R_0 k_a\gg 1} \neq f_{\rm NL}^{\rm 4D}$: global conformal invariance is broken

requirement of conformal invariance $\Rightarrow$ different prediction [9]

IA-Mazur-Mottola '96

Cosmological history after 5D inflation

parameters: H_I, inflaton mass m, $R_0 \to \epsilon \equiv 1/(R_0 M_*)$



$R_\perp = 1\mu\text{m},\ T_R = T_N = 1\ \text{GeV},\ m = 1\ \text{eV}$

Neutrino masses

natural explanation of neutrino masses introducing ν_R in the bulk

small masses due to ν_R wave function suppression

ν-oscillation data with 3 bulk neutrinos $\Rightarrow$ $m_{\rm KK} \gtrsim 2.5$ eV $(R \lesssim 0.4\,\mu{\rm m})$

Forero-Giunti-Ternes-Tyagi '22

$\Rightarrow$ $M_* \sim 10^9$ GeV

the bound can be relaxed in the presence of bulk ν_R masses

Lukas-Ramond-Romanino-Ross '00, Carena-Li-Machado^2-Wagner '17

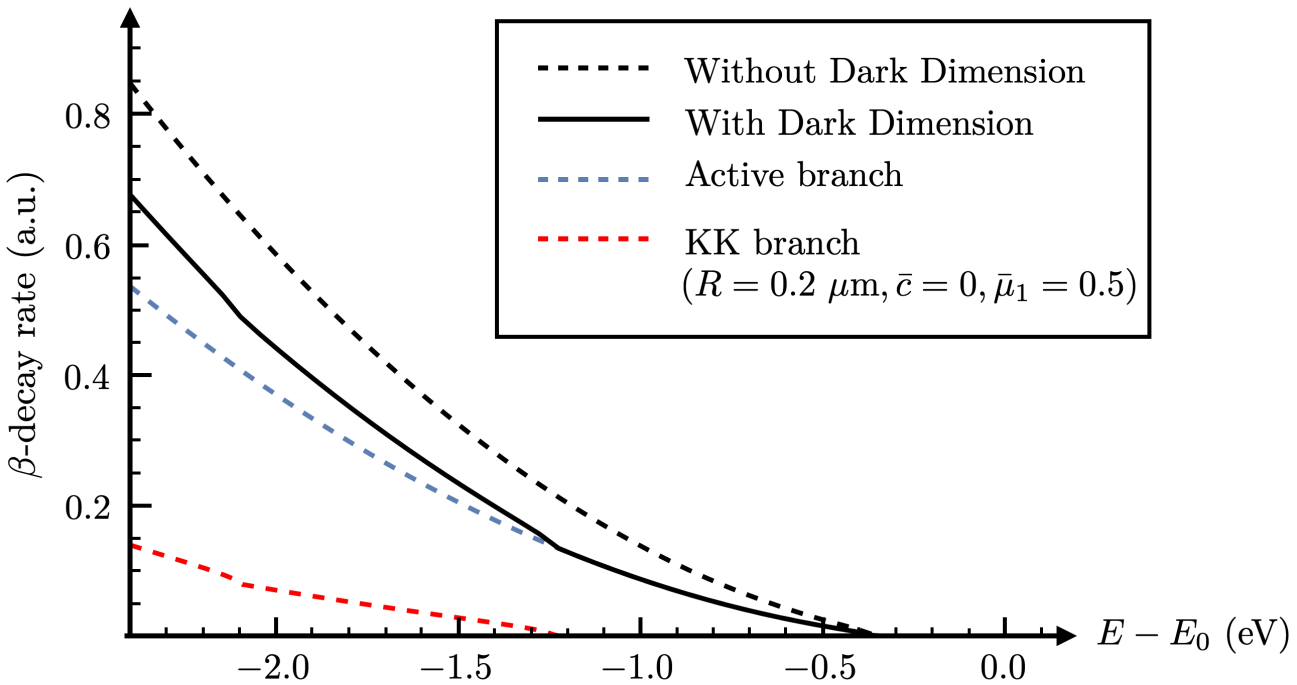
Main consequences:

- Towers of sterile KK excitations
- Dirac neutrino masses
- Bulk masses for ν_R states [16]

Sterile KK excitations in β-decay spectrum (KATRIN, PTOLEMY)

$$\mathcal{R}_\beta \sim \Delta E \sqrt{(\Delta E)^2 - m_\nu^2}\, \theta(\Delta E - m_\nu) \qquad \Delta E \equiv E_0 - E \qquad E_0 \approx 18.57 \text{ keV}$$

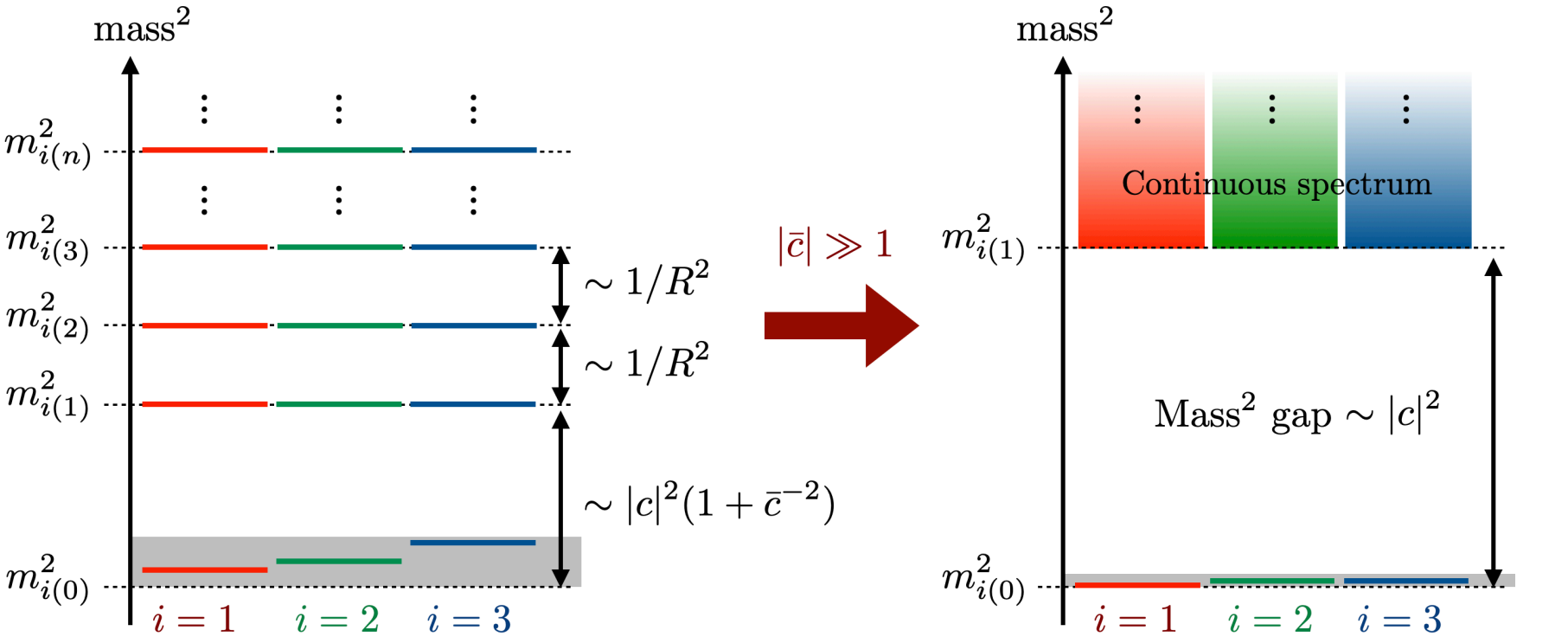
$\Rightarrow$ kinks at the energy spectrum $E_0 - E_n \equiv \Delta E \simeq m_n$



IA-Chatrabhuti-Isono '25

KATRIN sensitivity reach: $m_4 \lesssim 40$ eV and energy resolution $\delta E \gtrsim 0.4$ eV

Search of KK neutrino: large bulk mass $|c|R >> 1$

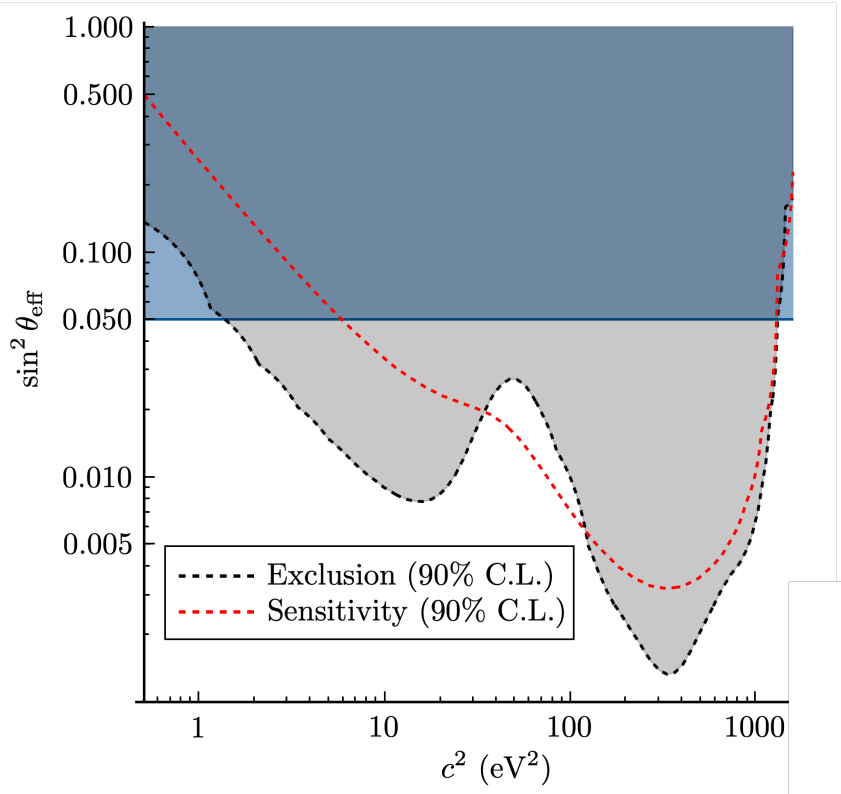


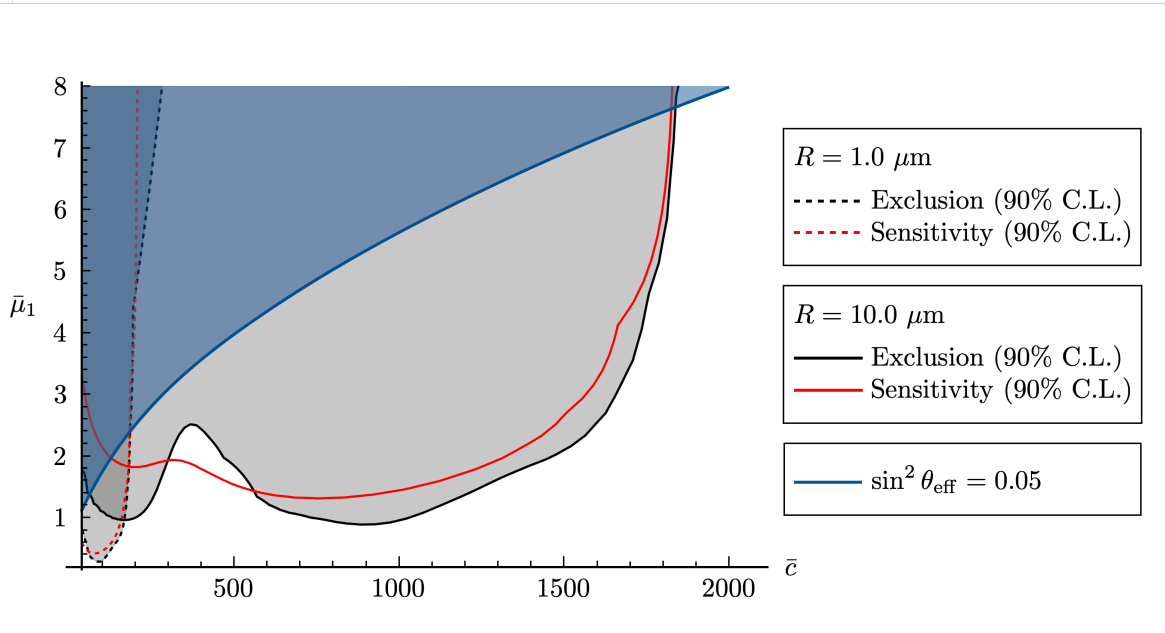
$\Rightarrow$ differential beta decay spectrum takes the 3+1 sterile form

with $m_4 = |c|$ and $\sin^2\theta_4 \equiv \sin^2_{\text{eff}} = \frac{\pi\bar{\mu}^2}{2|\bar{c}|}$ $\quad \Theta(x) = \begin{cases} 1 & \text{for } x > 0 \\ 0 & \text{for } x < 0 \end{cases}$

IA-Chatrabhuti-Isono '25

Search of KK neutrino: large bulk mass $|c|R >> 1$





Dark matter candidates

- 2 main new DM candidates:

  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)

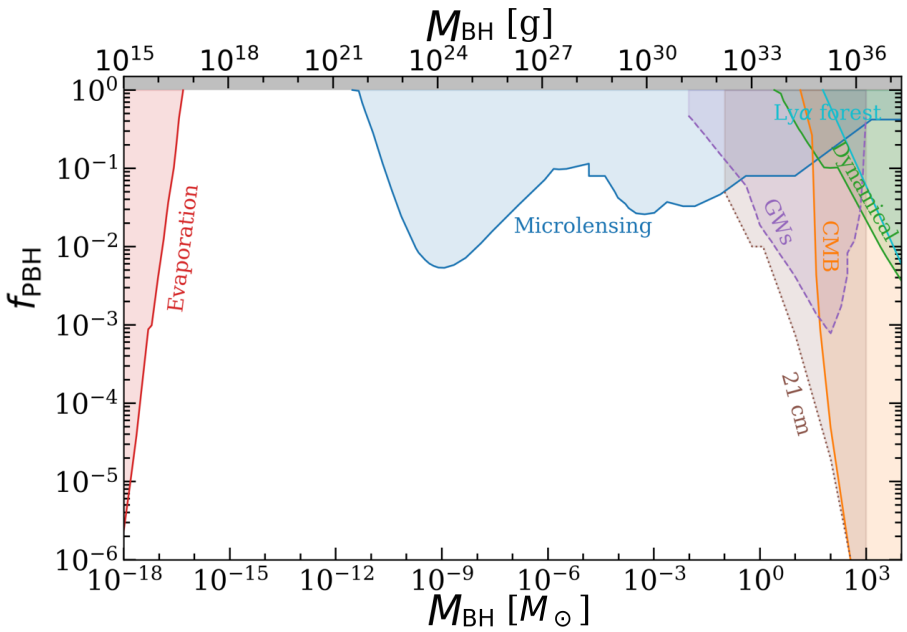
     from $\sim$ MeV at matter/radiation equality ($T \sim$ eV) to $\sim$ 50 keV today

     Gonzalo-Montero-Obied-Vafa '22

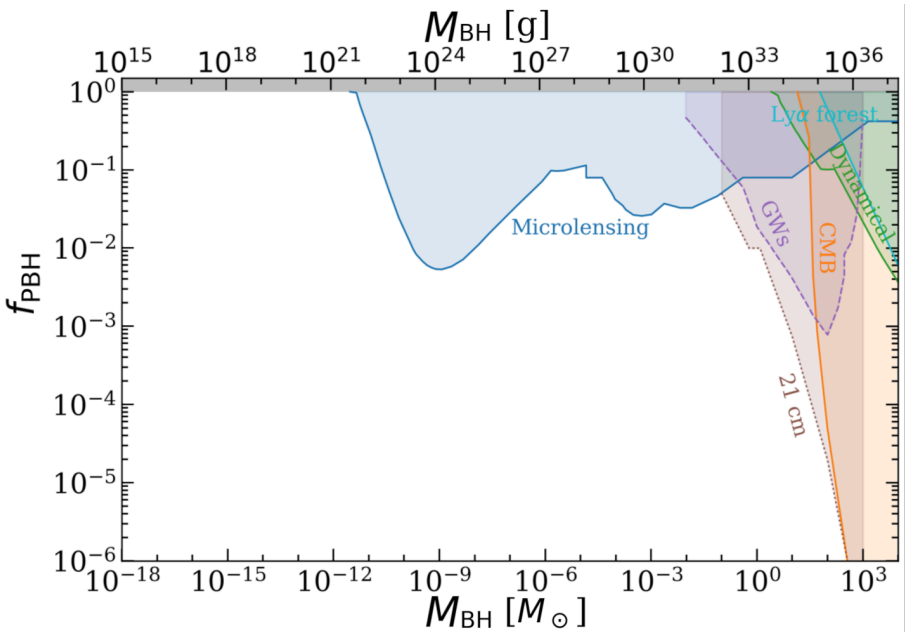
* $10^{8} - 10^{21}$g for 6D Anchordoqui-I.A.-Lust '25

Primordial Black Holes as Dark Matter

4d PBH



5d PBH



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

Conclusions

smallness of some physical parameters might signal

a large distance corner in the string landscape of vacua

$\Rightarrow$ large extra dimensions and low scale gravity

such parameters can be the scales of dark energy and SUSY breaking

mesoscopic dark dimension(s) proposal: interesting phenomenology

neutrino masses, dark matter, cosmology, SUSY breaking

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/6D inflation

neutrino physics: possible experimental window

to micron-size extra dimensions