Axions from Kähler Moduli

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Motivation – the Cosmological Constant Dark Matter?

- Dynamic mechanism for small CC
  - Anthropic argument not sufficient

[Weinberg ’89]

- Anthropic suggestion requires $N_{\text{vac}} \gtrsim M_{\text{Pl}}^4/\rho_{\text{DE}} \sim 10^{120}$
  - But need to track Cosmic history for structure formation
  - Tracking this is NP hard

[Bachlechner et al. 1810.02822]

$$\mathcal{L}_{\text{axion}} = \frac{1}{2}\partial\boldsymbol{\theta}^{\top}\boldsymbol{K}\partial\boldsymbol{\theta} - \sum_{I=1}^{P}\Lambda_I^4\left[1-\cos\left(\boldsymbol{\mathcal{Q}}^I\boldsymbol{\theta}\right)\right] - V_0\,.$$

- Potential solution: Theories of many axions?

[Bachlechner et al. 1902.05952]

Motivation – the Cosmological Constant Dark Matter?

- The lightest axion (~10^{-22} eV) resemble dark matter distribution

[Bachlechner et al. 1703.00453]

- Clearly promising but can we find a stringy origin?
  - Axions candidates arise in string theory when compactifying

[Svrcek Witten hep-th/0605206]

- Many examples contain the O(100) axions required
  - The simplest example has 15 from 2 forms alone

[Douglas Kachru hep-th/0610102]
[March-Russell Tillim 2109.14637]

Goal

- Find axions that survive compactification that could source these Cosmological models

Outline

- Axions and moduli stabilisation in IIB
- Analytic Setup
- Numerical results & Explicit examples
- Future Directions

Moduli in IIB

- Compactify on $\mathbb{R}^{1,3} \times X_3$
  - The number of forms on X is given by the dimension of the cohomology groups.

$$h^{p,q} = dim\left[H^{p,q}(X_3)\right]$$

[Greene hep-th/9702155]

- The moduli coming from this are
  - We need to stabilize the moduli else we contradict experiment

$$U^i = v^i + iu^i$$

$$S = C_0 + ie^{-\phi} = C_0 + is$$

$$G^a = c^a + Sb^a$$

$$T_\alpha = \left(\rho_\alpha + \hat{k}_{\alpha ab}c^a c^b + \frac{1}{2}S\hat{k}_{\alpha ab}b^a b^b\right) - \frac{i}{2}k_{\alpha\beta\gamma}t^\beta t^\gamma$$

[Benmachiche Grimm hep-th/0602241]

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axions

Moduli in IIB

- We focus on the Kahler moduli T_a
  - S^i & U can be stabilsed with 3 form fluxes
  - We assume there are no G^a

[Greene hep-th/9702155]

$$V_F = e^{\mathcal{K}} \left(\mathcal{K}^{A\bar{B}} D_A \mathcal{W} D_{\bar{B}} \bar{\mathcal{W}} - 3|\mathcal{W}|^2 \right)$$

$$\mathcal{W} = W_0 + \sum_{\alpha}^{N \leq h_+^{1,1}} A_\alpha e^{-i a_\alpha T_\alpha}$$

$$D_S W_0 = 0 = D_{\bar{S}} \bar{W}_0 \quad , \quad D_i W_0 = 0 = D_{\bar{i}} \bar{W}_0$$

Analytic Setup

- Now can write simply as a function of just T[a]

$$V = \lambda_0(\tau) + \sum_{\alpha=1}^{N} \lambda_\alpha(\tau)\cos(a_\alpha b_\alpha) + \sum_{\alpha=1}^{N}\sum_{\beta=\alpha+1}^{N} \lambda_{\alpha\beta}(\tau)\cos(a_\alpha \rho_\alpha - a_\beta \rho_\beta)$$

- Seemingly straightforward to now minimize this for $T^a=\rho^a - i\tau^a$
  - Difficulty is in the implicit dependance on τ of terms in $\lambda_{\alpha\beta}(\tau)$
  - Solution is to work in 2 cycle moduli

$$\tau_\alpha = \frac{\partial \mathcal{V}}{\partial t^\alpha} = \frac{1}{2} k_{\alpha\beta\gamma} t^\alpha t^\beta$$

Analytic Setup

- Thus far only trivially minimized axion directions by setting
  - We will show that this does not explore the full landscape

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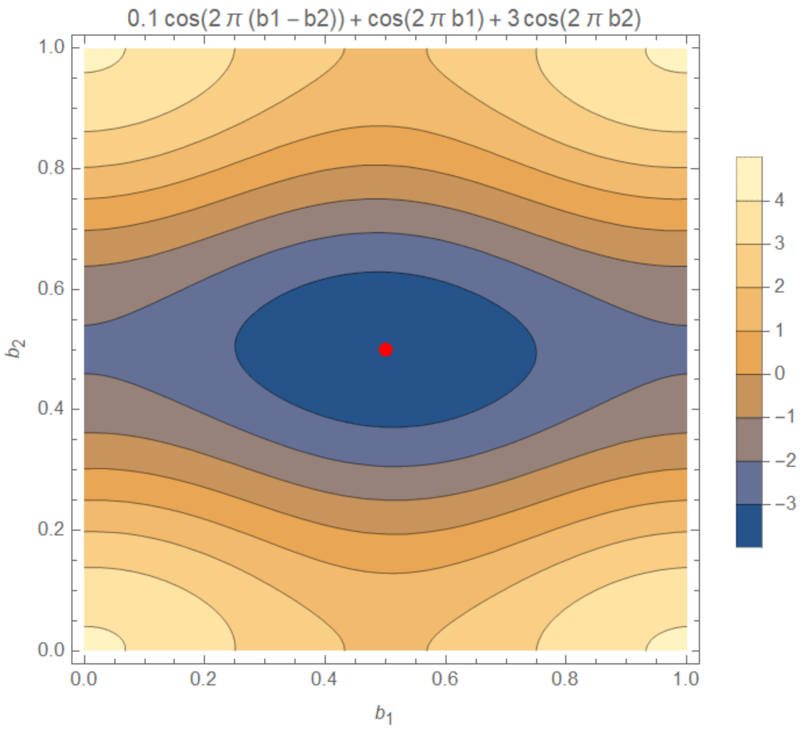
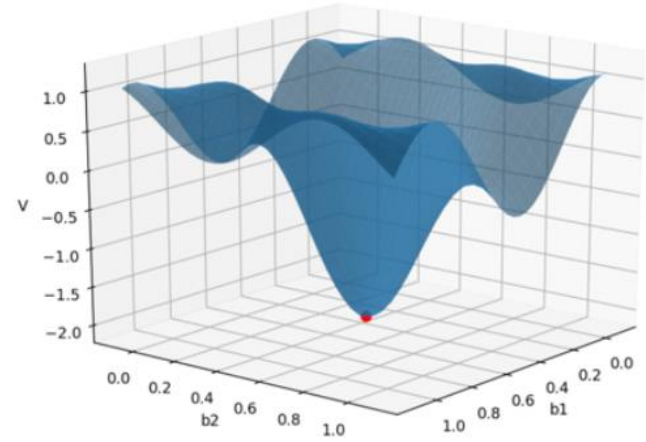
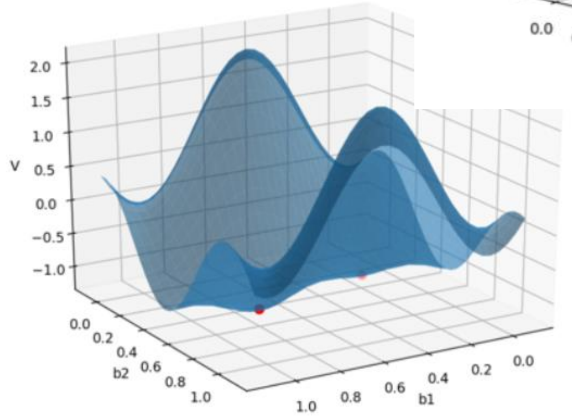


Numeric Results

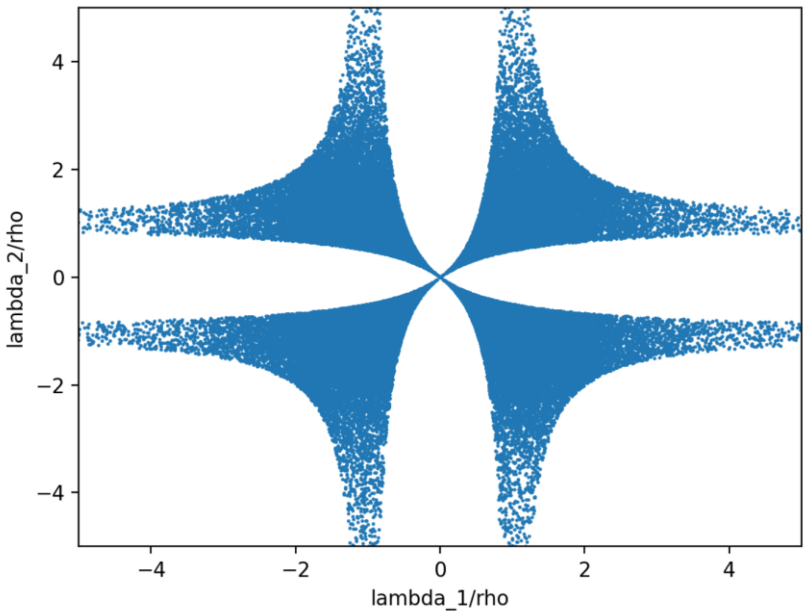
- Can obtain an analytic expression for the gradient and Hessian but analytically solving for a min is not feasible.
  - Instead construct a script that can minimize an arbitrary number of moduli on a specified X.

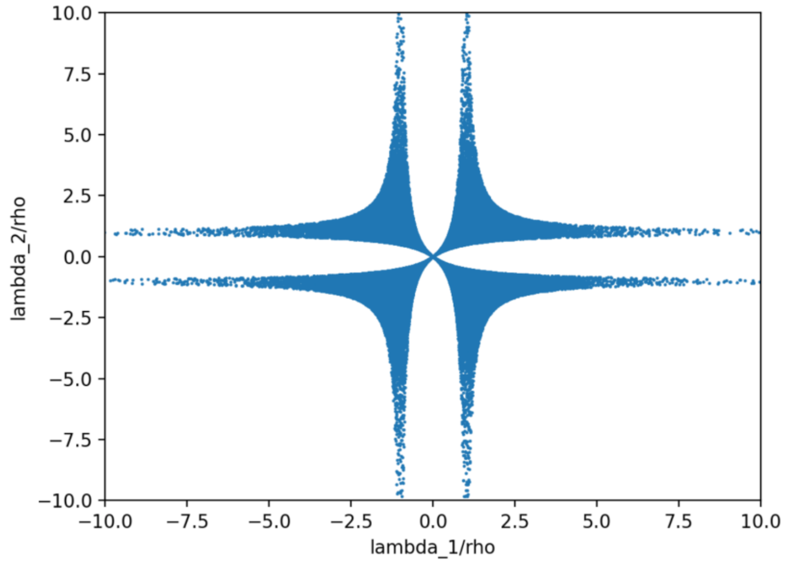




Numeric Results

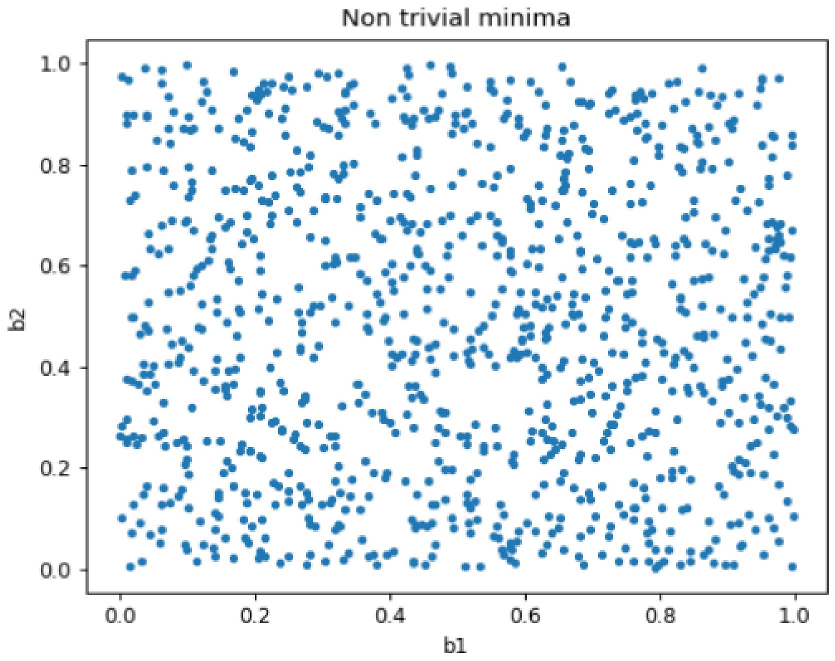
- First a simple check for the non trivial solutions in axion directions





Numeric Results

- Now revisit know solutions and search for extra solutions



Numeric Results

- Need to check physical conditions
  - Positive 4 cycles
  - Large volumes would also be desirable

	g_s	$\hat{\xi}$	W_0	$\{A_i\}$	$\{t_i, b_i\}$	$\{\tau_i\}$	$\mathcal{V}$	Trivial
0	0.15	22.54937	1.000000e-29	[1, 1]	[68.424, -1.055, 0.871, 0.577]	[83840.6206, 13973.344]	1.907323e+06	0
1	0.15	22.54937	1.000000e-29	[1, 1]	[33.377, -2.855, 0.439, 0.626]	[19484.7618, 3246.7811]	2.136911e+05	0
2	0.15	22.54937	1.000000e-29	[1, 1]	[94.775, -1.674, 0.01, 0.882]	[160730.8923, 26788.2485]	5.062809e+06	0
3	0.15	22.54937	1.000000e-29	[1, 1]	[55.174, -2.968, 0.917, 0.217]	[53816.9309, 8968.7544]	9.808920e+05	0
4	0.15	22.54937	1.000000e-29	[1, 1]	[19.035, -1.218, 0.578, 0.629]	[6383.596, 1063.809]	4.007201e+04	0
5	0.15	22.54937	1.000000e-29	[1, 1]	[56.628, -1.015, 0.719, 0.344]	[57376.7975, 9562.7137]	1.079809e+06	0
6	0.15	22.54937	1.000000e-29	[1, 1]	[47.685, -2.561, 0.536, 0.762]	[40200.0177, 6699.4564]	6.332602e+05	0
7	0.15	22.54937	1.000000e-29	[1, 1]	[6.189, -1.181, 0.814, 0.074]	[646.3091, 107.602]	1.290976e+03	0
8	0.15	22.54937	1.000000e-29	[1, 1]	[57.572, -1.311, 0.602, 0.428]	[59209.6313, 9868.1287]	1.131960e+06	0
9	0.15	22.54937	1.000000e-29	[1, 1]	[7.761, -2.767, 0.821, 0.404]	[959.1762, 159.2247]	2.334531e+03	0
10	0.15	22.54937	1.000000e-29	[1, 1]	[13.947, -2.417, 0.453, 0.007]	[3302.0001, 549.8465]	1.490801e+04	0

2 axion Racetrack

	g_s	$\hat{\xi}$	W_0	$\{A_i\}$	$\{t_i, b_i\}$	$\{\tau_i\}$	$\mathcal{V}$	Trivial
0	0.15	5.255198	-1	[1, 1, 0]	[19.517, -2.981, -2.853, 0.45, 0.341, 0.051]	[190.4566, 5.2309, 3.2985]	1230.712829	0
1	0.15	5.255198	-1	[1, 1, 0]	[13.589, -1.008, -2.805, 0.421, 0.132, 0.101]	[92.3305, 1.7291, 5.9422]	412.089314	0
2	0.15	5.255198	-1	[1, 1, 0]	[8.17, -2.857, -2.586, 0.076, 0.753, 0.445]	[33.3744, 5.7399, 1.7585]	83.907660	0
3	0.15	5.255198	-1	[1, 1, 0]	[7.937, -2.811, -2.691, 0.96, 0.035, 0.386]	[31.498, 4.6471, 2.9389]	76.342641	0
4	0.15	5.255198	-1	[1, 1, 0]	[11.208, -2.823, -2.567, 0.783, 0.228, 0.817]	[62.8096, 5.5283, 1.8166]	227.900208	0
5	0.15	5.255198	-1	[1, 1, 0]	[10.349, -2.98, -2.719, 0.868, 0.923, 0.445]	[53.5509, 6.0979, 2.1069]	176.765950	0
6	0.15	5.255198	-1	[1, 1, 0]	[7.37, -1.078, -2.863, 0.233, 0.369, 0.985]	[27.1584, 1.5119, 6.3537]	60.112398	0
7	0.15	5.255198	-1	[1, 1, 0]	[13.023, -2.773, -2.572, 0.378, 0.186, 0.919]	[84.7993, 5.0201, 2.1726]	361.610669	0
8	0.15	5.255198	-1	[1, 1, 0]	[8.666, -2.621, -2.976, 0.548, 0.682, 0.156]	[37.5498, 1.7629, 6.2262]	100.752187	0
9	0.15	5.255198	-1	[1, 1, 0]	[7.842, -1.114, -2.929, 0.785, 0.423, 0.631]	[30.7485, 1.518, 6.6862]	73.284855	0
10	0.15	5.255198	-1	[1, 1, 0]	[9.279, -2.59, -2.781, 0.039, 0.036, 0.904]	[43.0499, 2.4194, 4.8381]	126.579726	0

3 axion LVS

Next steps

- Further exploration of Kreuzer Skarke database
  - Ultimately want O(100) axion solutions
- Add uplift term and check survival
- Introduce axions from beyond the Kähler sector

Thank You

Any questions?