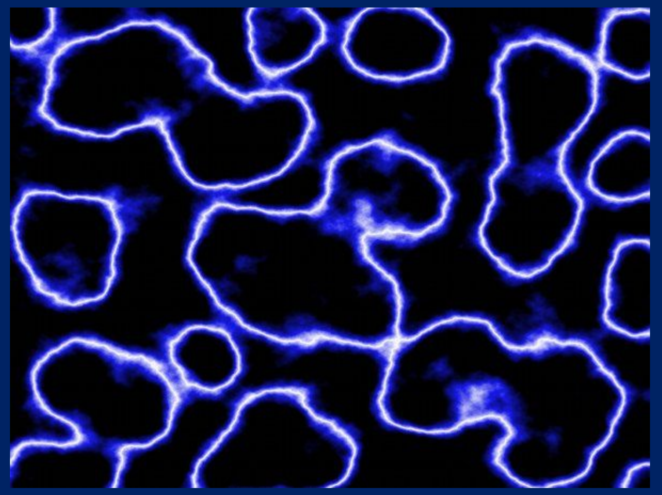
Progress in constructing KKLT de Sitter vacua

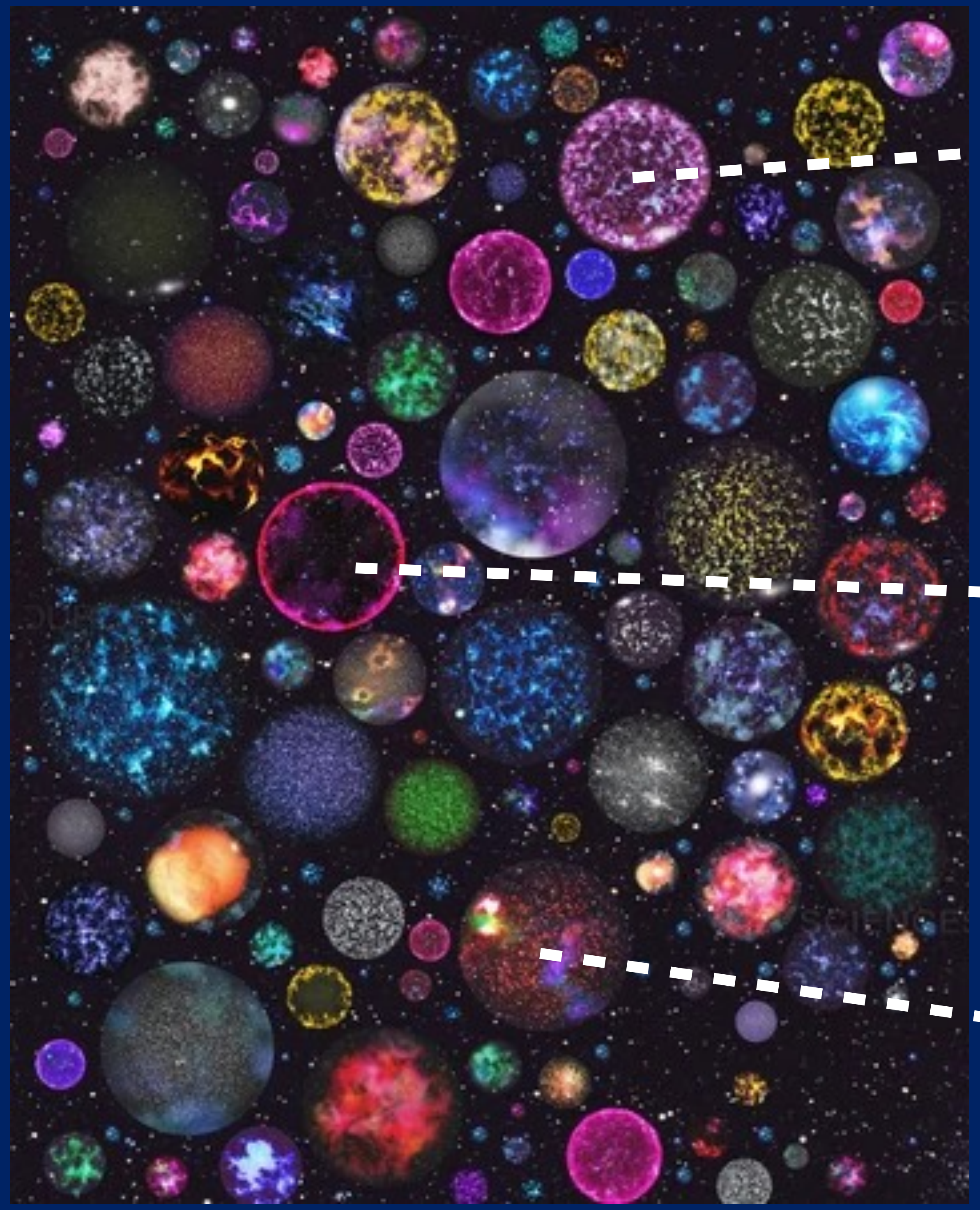
시작이 반이다

Based on work in progress with N. Gendler, L. McAllister, J. Moritz, R. Nally



Compactification

String Theory



String Landscape

Andreas Schachner

String Phenomenology Conference 2023

Institute for Basic Science, Daejeon, South Korea

July 6, 2023

Email: as3475@cornell.edu

Collaboration

Cornell University

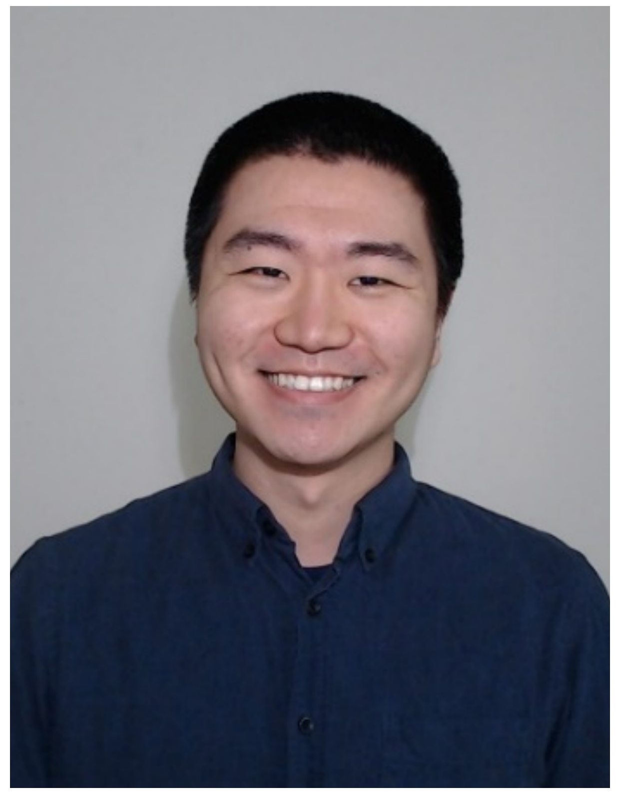
Naomi Gendler
(now at Harvard)

Liam McAllister

Jakob Moritz

Richard Nally
(applying this year)

MIT



Manki Kim
(applying this year)

LMU Munich

Sven Krippendorf

Julian Ebelt
(Master)

Abhishek Dubey
(Master)

JAXVacua - A framework for string vacua

Objective: Numerical framework to determine and evaluate EFT (e.g. scalar potential, Hessian etc.) with only minimal input by using auto-differentiation

Demirtas, Rios-Tascon, McAllister 2211.03823

CY data $\kappa_{ijk}\,, c_2\,, GVs$ → **Prepotential** F $\xrightarrow{\text{auto-diff}}$ **Periods** Π, K, W $\xrightarrow{\text{auto-diff}}$ **EFT properties** $V\,, \partial_I \partial_J V\,, M_{3/2}\,, \,\ldots$

Based on work with:

- A. Dubey, S. Krippendorf 2306.06160
- J. Ebelt, S. Krippendorf (to appear next week)
- S. Krippendorf (to appear next week)

See talk of Sven Krippendorf.

LMU Munich

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Julian Ebelt (Master)

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KKLT proposal: de Sitter vacua in Type IIB String Theory

Kachru, Kallosh, Linde, Trivedi hep-th/0301240

Claim 1:

Well-controlled SUSY AdS_4 exist in Type IIB flux compatifications with

$$\langle W_{flux} \rangle \ll 1$$

and non-perturbative D-brane instantons.

Achieved explicitly in Demirtas et al. [2107.09064, 2107.09065]

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- warped deformed conifold [Klebanov, Strassler hep-th/0007191]
- containing some anti-D3 branes [Kachru et al. hep-th/0112197]
- in a suitable parameter regime

there are metastable dS_4 vacua.

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Do there exist geometries that realise this idea?

Yes, we found explicit configurations that satisfy all requirements for KKLT de Sitter vacua **in the leading approximation.**

Important work in progress is checking effects of further corrections like:

- perturbative corrections to Kähler potential, beyond BBHL [hep-th/0204254], and
- α' corrections to anti-D3-brane action [Hebecker, 2x(Schreyer, Venken) 2208.02826, 2212.07437].

Gendler, McAllister, Moritz, Nally, Schachner 230X.XXXX

KKLT SUSY AdS_4 vacua with conifolds

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[Gukov et al. hep-th/9906070]

$$\boxed{W_{flux}(\tau, z^a) = W_{pert}(\tau, z^a) + W_{inst}(\tau, z^a) + W_{cf}(\tau, z^a)}$$

We work at **large complex structure** using mirror symmetry to compute W_{flux}.

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Stabilise $z^i = p^i \tau$
$i = 2, \ldots, h^{1,2}(X_3)$

Stabilise τ

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$$|W_0| = |\langle W_{inst} \rangle| \ll 1 \qquad z_{cf} \approx \frac{1}{2\pi} \exp\left(-\frac{2\pi K}{n_{cf} g_s M} \right)$$

[Demirtas et al. 2009.03312, Álvarez-García et al. 2009.03325]

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[Witten hep-th/9604030]

$$W_{np}(\tau, z^a, T_A) = \sum_A \mathscr{A}_A(\tau, z^a)\, e^{-2\pi T_A / c_A}$$

verified condition of
[Witten hep-th/9610234]

$\mathscr{A}_A(\tau, z^a) =$ const.

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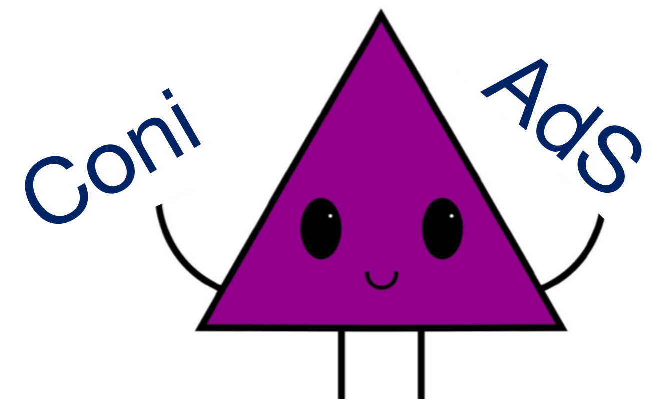
We solve $D_A W = 0$ for the Kähler moduli such that

$$T_A \approx \frac{c_A}{2\pi} \log\left(|W_0|^{-1} \right)$$

This leads to SUSY AdS_4 vacua with

$$g_s \sim \frac{2\pi}{\log(|W_0|^{-1})} \ll 1$$



(see talk L. McAllister string pheno 2022 for details)

[Demirtas et al. 2107.09064, 2107.09065]

Initial scan for vacua

We search for

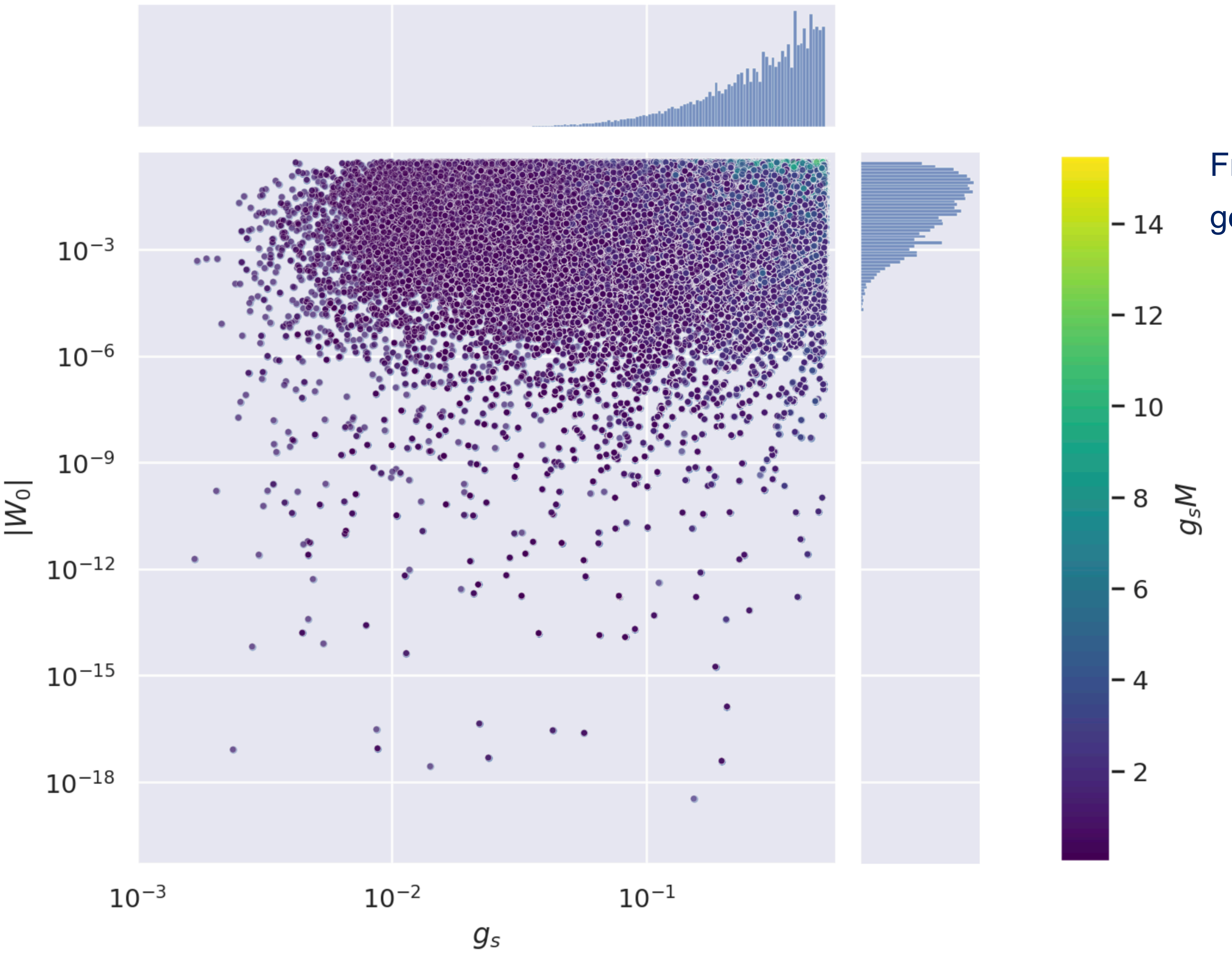
- CY_3 from 4D reflexive polytopes with $3 \leq h^{1,2} \leq 8$ [Kreuzer, Skarke hep-th/0002240]
- orientifolds with $h^{1,2}_+ = 0$ from $\mathbb{Z}_2$-involutions $x \to -x$ following [Moritz 2305.06363]
- conifold points by shrinking toric flop curves
- flux vacua with $|W_0| \ll 1$ together with stabilisation near conifold loci
- $\geq h^{1,1}$ rigid divisors supporting D-instantons and having constant Pfaffian [Jefferson, Kim 2211.00210]

Computations performed with

http://cy.tools

Demirtas, Rios-Tascon, McAllister 2211.03823

KKLT SUSY AdS_4 vacua with conifolds



From a scan over 36 polytopes and 300 CY geometries, we obtained 4,831,234 vacua with

- $g_s < 0.5$
- $|W_0| < 0.3$

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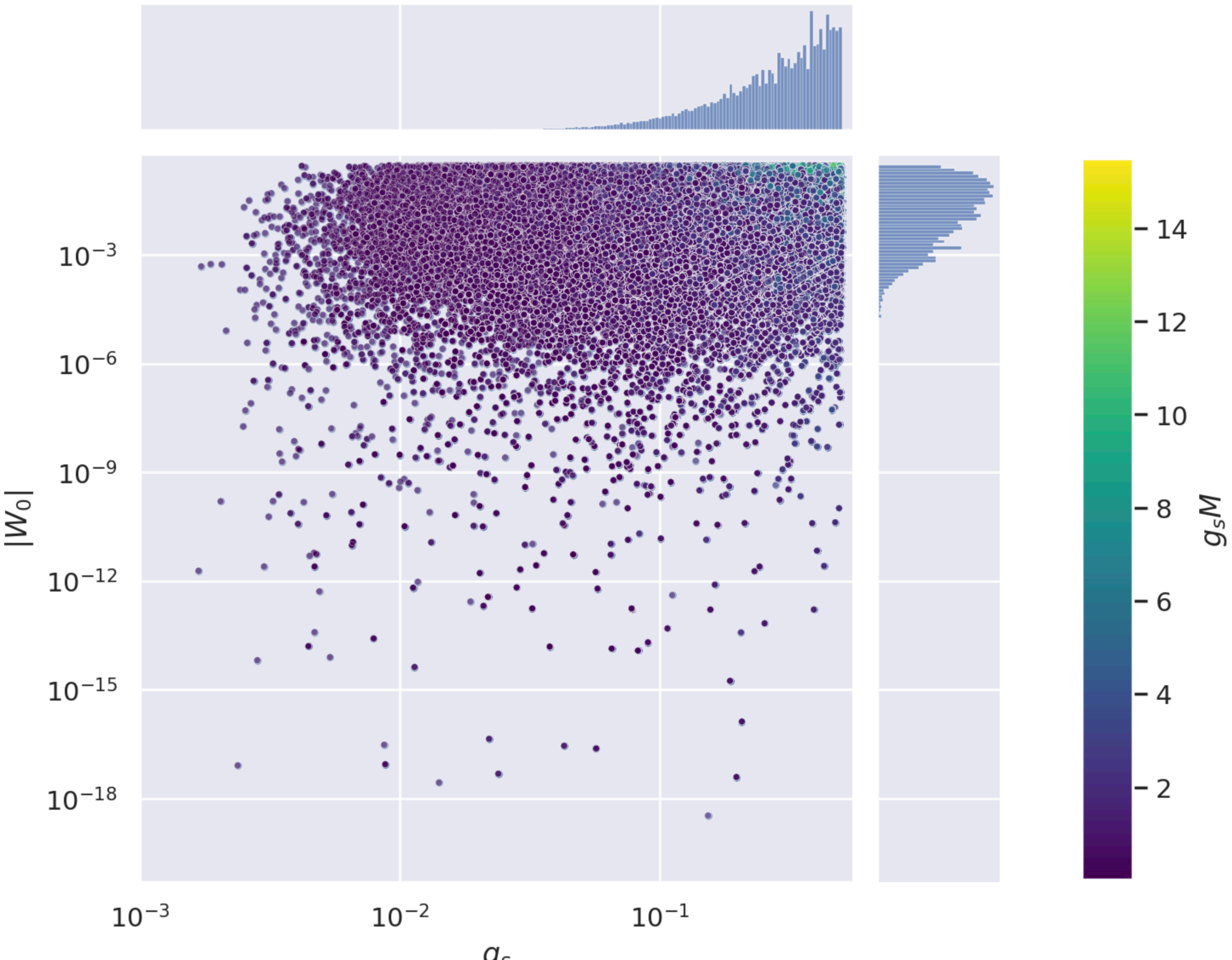

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In what follows, I will impose more and more cuts on this dataset to eventually satisfy all of the requirements in Claim 2 of KKLT!

Claim 2 checklist:

- warped throat
- anti-D3 branes
- suitable parameter regime

KKLT SUSY AdS_4 vacua with warped throats

Stabilisation near conifold point in moduli space leads to warped throat [GKP hep-th/0105097] with warp factor at the tip

$$e^{4A_{IR}} \approx e^{-8\pi K/3n_{cf} g_s M} \sim |z_{cf}|^{\frac{4}{3}}$$

M, K fluxes threading the S^3 at the tip

For $e^{4A_{IR}} \ll 1$, we obtain long warped throats that for $g_s M \gg 1$ is well approximated by the KS solution [hep-th/0007191]

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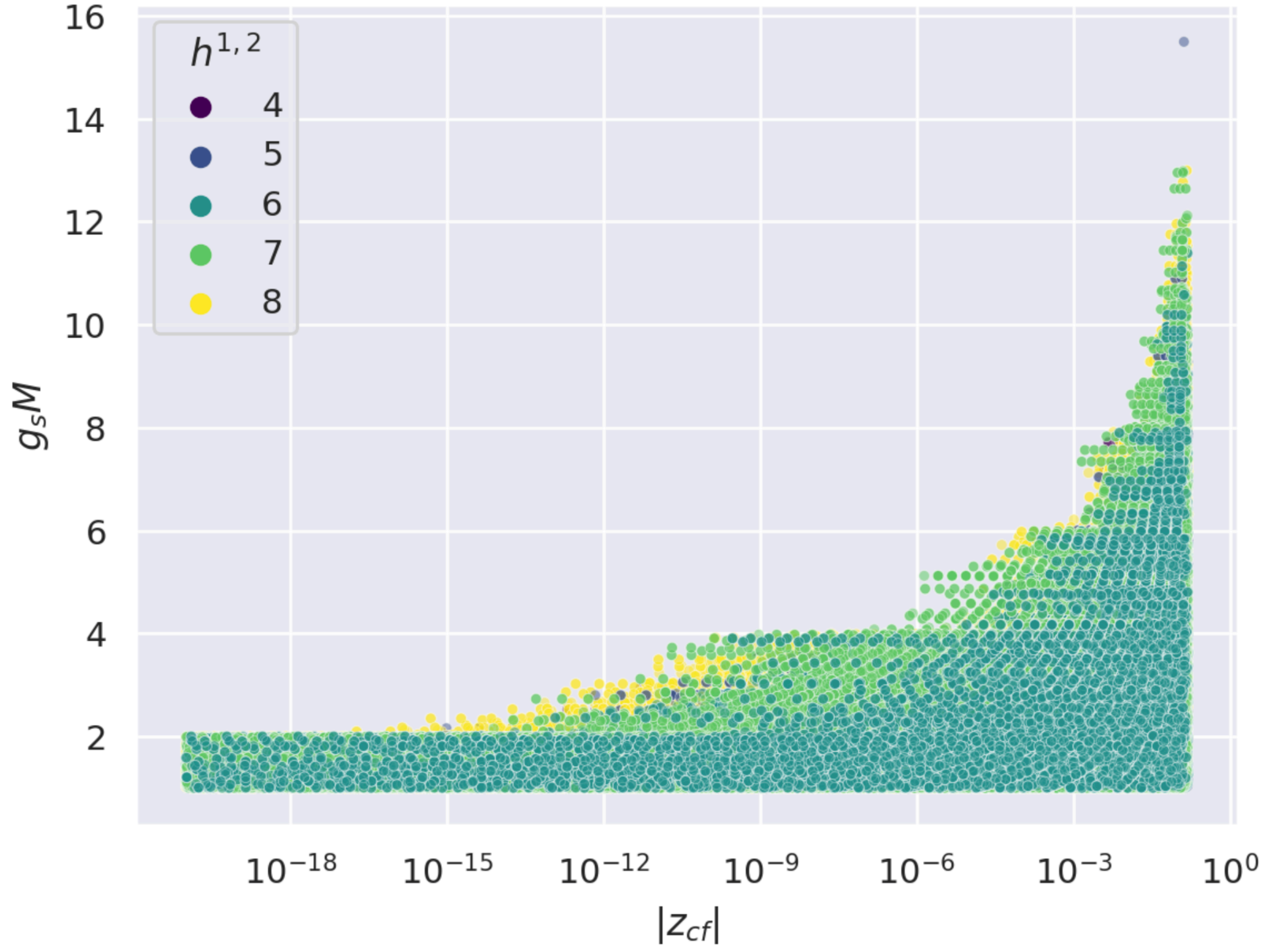

We find 3,801,168 vacua satisfying

- $g_s < 0.5$
- $|W_0| < 0.3$
- $g_sM > 1$

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Are there flux configurations that allow anti-D3 branes?

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Towards KKLT dS_4 vacua from a single anti-D3 brane

We consider flux choices allowing to add a single anti-D3 brane $N_{flux} = Q_{D3} + 1$.

There are roughly $1\,\% \sim 10^4$ vacua of this type.

Related LVS construction

[Crino et al. 2010.15903]

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Full potential

$$V(\tau, z^a, T_A) = V_{SUSY} + V_{uplift}$$

SUSY AdS contribution

$$V_{SUSY} = -3e^K |W|^2 = -\frac{3}{8\pi}\frac{g_s\, e^{K_{cs}}}{(\mathscr{V}_E)^2} |W_0|^2$$

Classical KPV potential

$$V_{uplift} \sim \frac{e^{-8\pi K/3n_{cf}g_sM}}{(\mathscr{V}_E)^{4/3}}$$

[KPV hep-th/0112197]

Balance condition for dS uplift

$$\frac{\kappa\, e^{K_{cs}/3}}{(g_sM)^2}\mathscr{V}_E^{2/3}\,|z_{cf}|^{4/3} \approx |W_0|^2$$

$\kappa = 179.1286...$

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Conditions on control:

- $M \gtrsim 12$: meta-stability of the throat configuration against brane-flux annihilation [KPV hep-th/0112197]
- $g_sM > 1$: small curvature at bottom of throat [Klebanov, Strassler hep-th/0007191]
- $z_{cf} \ll 1$: long throat
- $g_s < 0.5$ and $W_0 < 0.3$: perturbative control and Kähler moduli stabilisation

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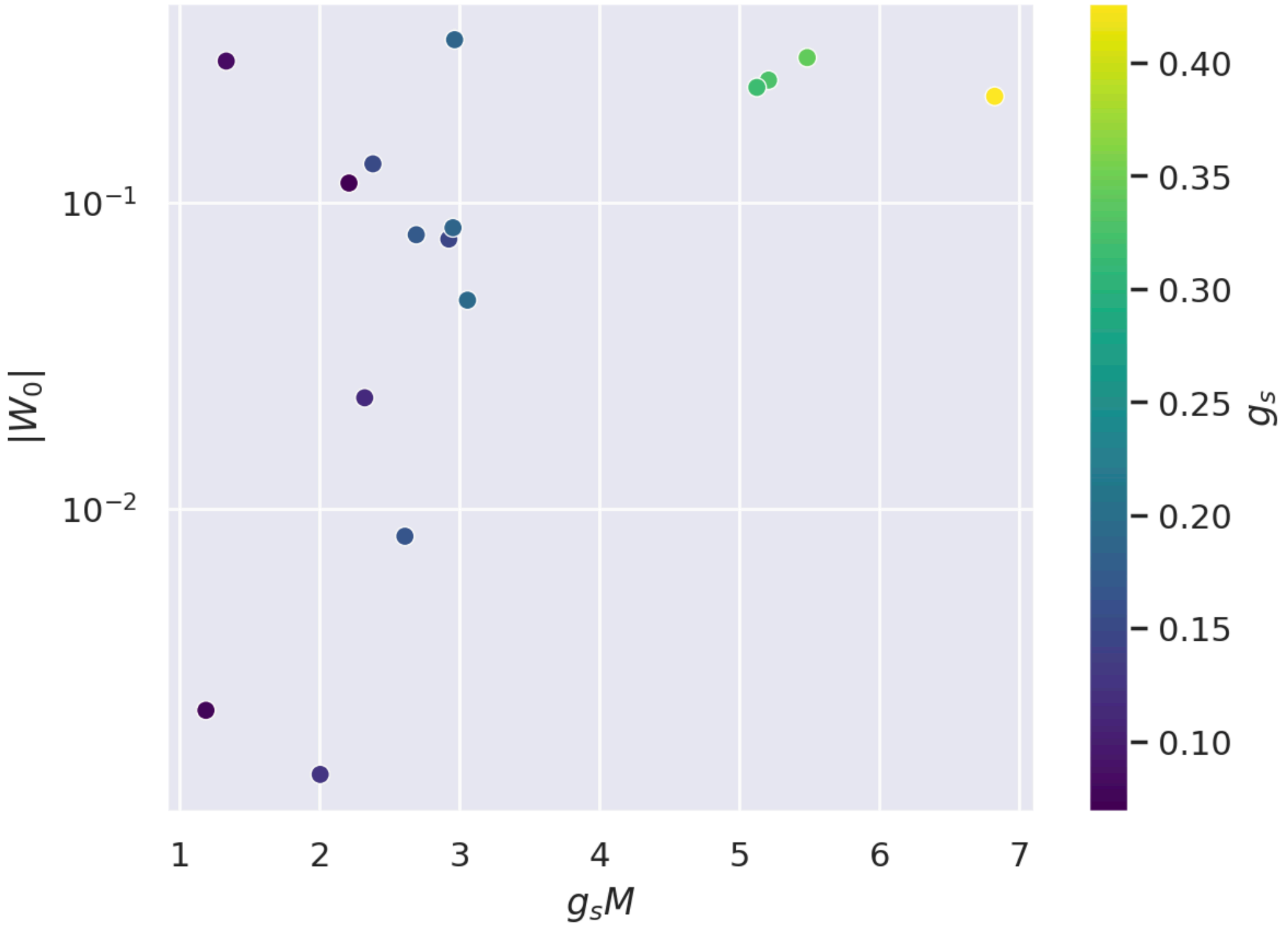

$h^{1,2}$	$h^{1,1}$	g_s	W_0	M	g_sM	g_sM^2	$\lvert z_{cf}\rvert$	$\mathcal{V}_E$	$Q/\mathcal{V}_E^{2/3}$
5	205	0.069	0.116	32	2.21	70.74	$7.61 \cdot 10^{-6}$	46464	0.080
7	219	0.146	0.076	20	2.92	58.48	$3.43 \cdot 10^{-6}$	32803	0.101
7	219	0.168	0.079	16	2.69	43.07	$4.36 \cdot 10^{-6}$	20613	0.138
7	219	0.149	0.134	16	2.38	38.11	$4.16 \cdot 10^{-6}$	10664	0.215
7	219	0.185	0.083	16	2.95	47.26	$3.83 \cdot 10^{-6}$	9009	0.240
8	198	0.125	0.001	16	2.00	32.08	$1.00 \cdot 10^{-8}$	10453	0.222
8	198	0.163	0.008	16	2.61	41.77	$1.60 \cdot 10^{-7}$	9266	0.240
8	198	0.191	0.048	16	3.06	48.92	$3.28 \cdot 10^{-6}$	75155	0.077
8	198	0.325	0.251	16	5.21	83.33	$2.09 \cdot 10^{-4}$	13751	0.185
8	198	0.185	0.341	16	2.97	47.45	$9.58 \cdot 10^{-5}$	33540	0.133
8	202	0.320	0.238	16	5.12	82.00	$1.02 \cdot 10^{-8}$	21262	0.149
8	202	0.074	0.002	16	1.19	19.02	$1.00 \cdot 10^{-8}$	21025	0.150
8	202	0.343	0.298	16	5.48	87.75	$1.65 \cdot 10^{-8}$	17226	0.171
8	202	0.083	0.289	16	1.33	21.34	$1.29 \cdot 10^{-8}$	9402	0.238
8	266	0.116	0.023	20	2.32	46.46	$2.10 \cdot 10^{-8}$	40986	0.089
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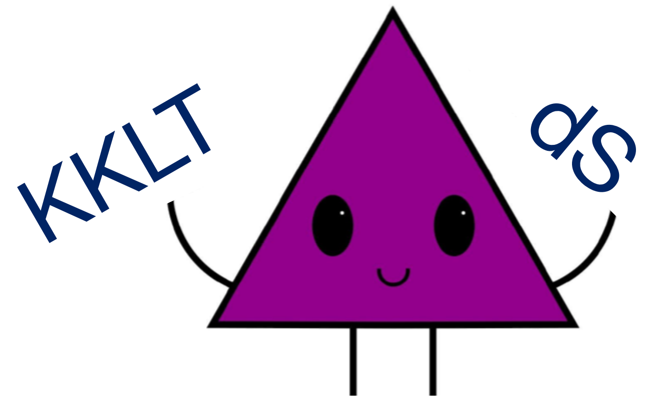
We find 16 dS_4 vacua satisfying the aforementioned conditions!



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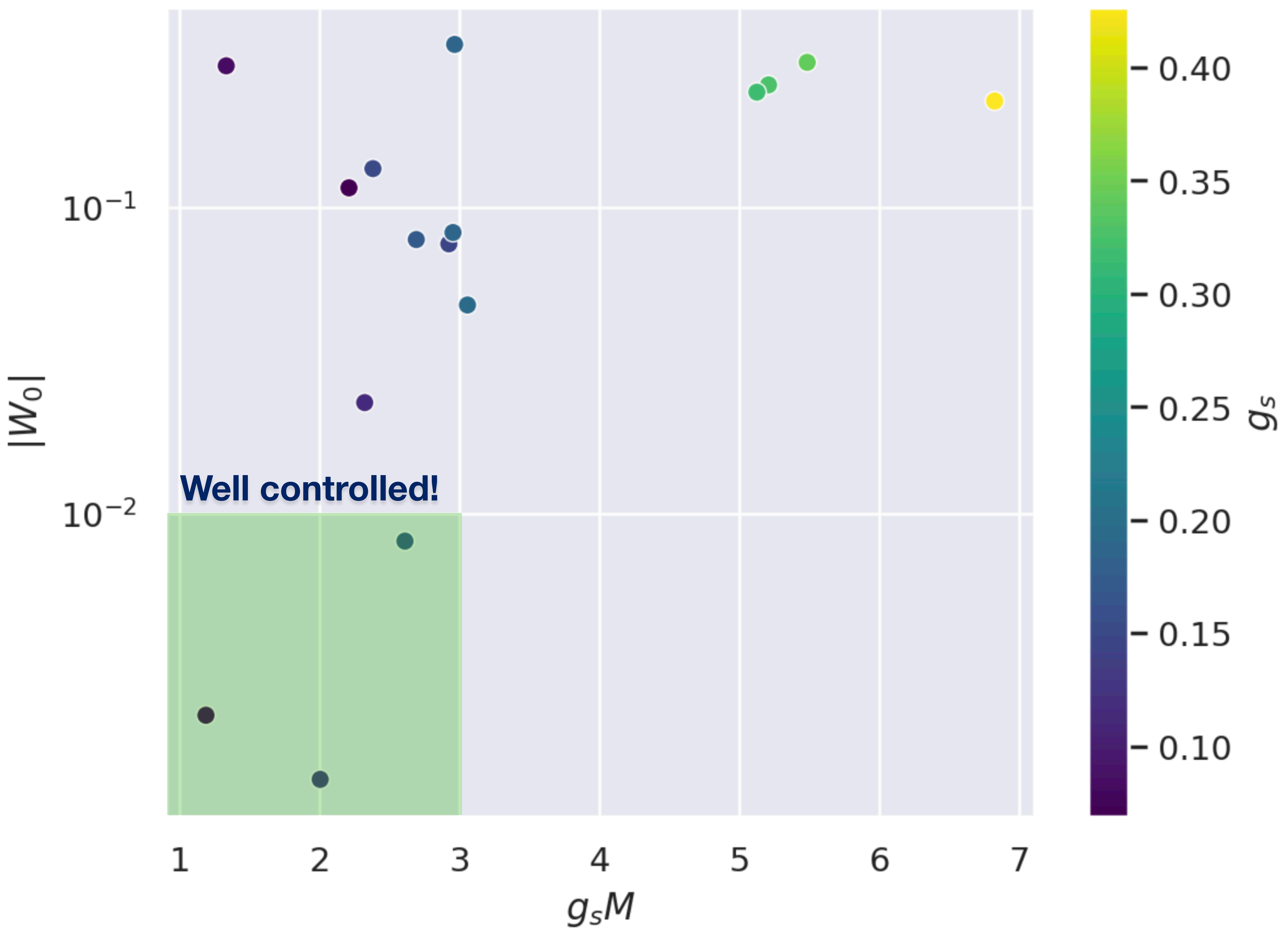

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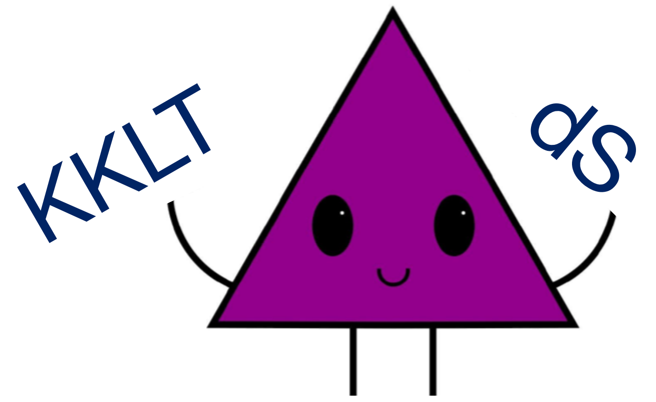

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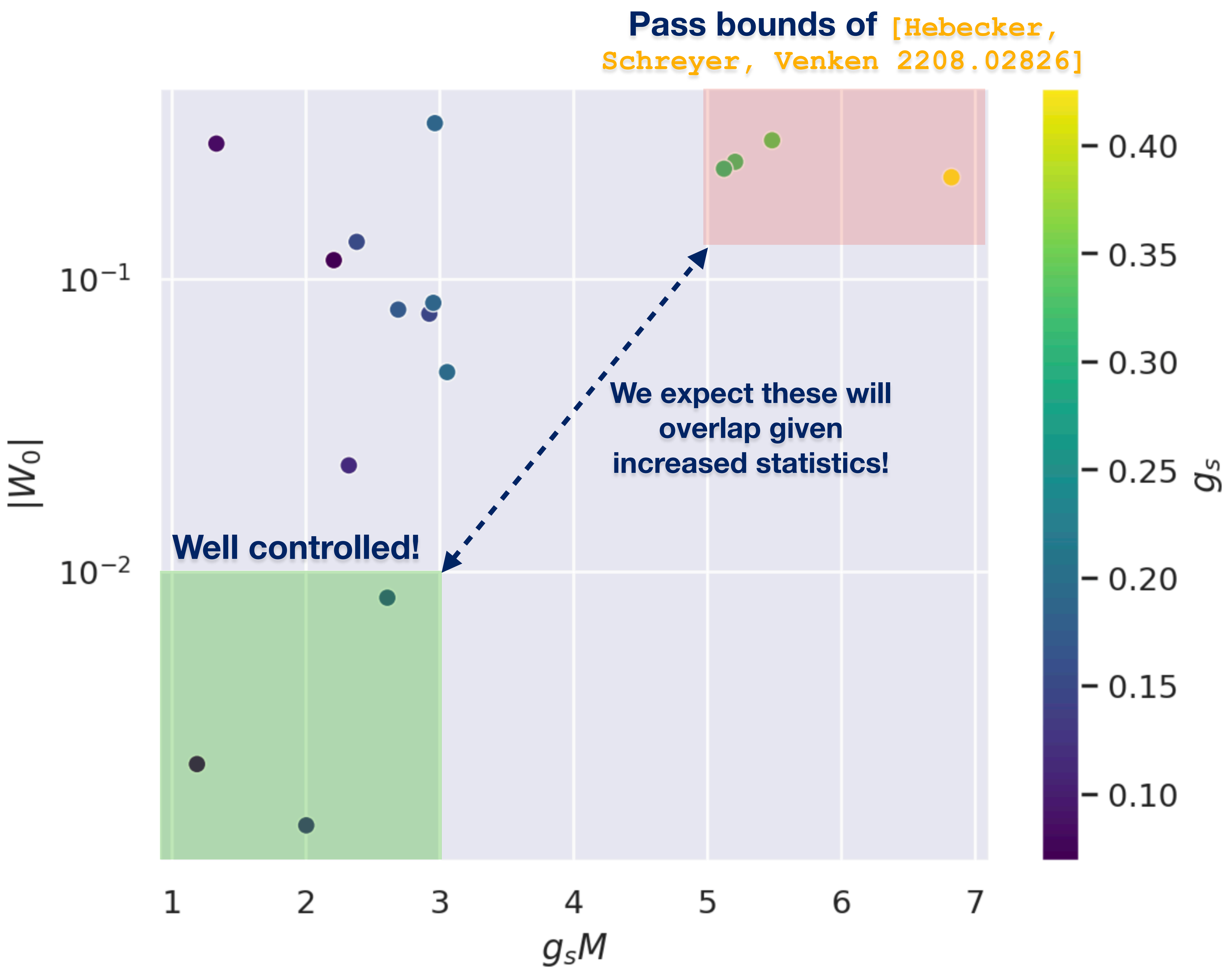

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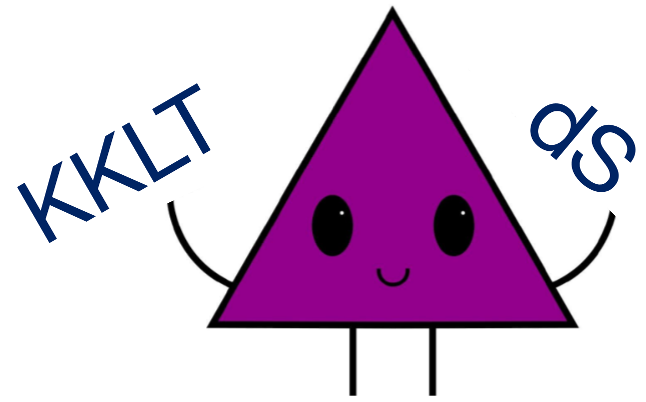
8	198	0.163	0.008	16	2.61	41.77	$1.60 \cdot 10^{-7}$	9266	0.240
8	198	0.191	0.048	16	3.06	48.92	$3.28 \cdot 10^{-6}$	75155	0.077
8	198	0.325	0.251	16	5.21	83.33	$2.09 \cdot 10^{-4}$	13751	0.185
8	198	0.185	0.341	16	2.97	47.45	$9.58 \cdot 10^{-5}$	33540	0.133
8	202	0.320	0.238	16	5.12	82.00	$1.02 \cdot 10^{-8}$	21262	0.149
8	202	0.074	0.002	16	1.19	19.02	$1.00 \cdot 10^{-8}$	21025	0.150
8	202	0.343	0.298	16	5.48	87.75	$1.65 \cdot 10^{-8}$	17226	0.171
8	202	0.083	0.289	16	1.33	21.34	$1.29 \cdot 10^{-8}$	9402	0.238
8	266	0.116	0.023	20	2.32	46.46	$2.10 \cdot 10^{-8}$	40986	0.089
8	266	0.426	0.222	16	6.82	109.18	$6.35 \cdot 10^{-8}$	20641	0.152

We find 16 dS_4 vacua satisfying the aforementioned conditions!



Control issues and further challenges

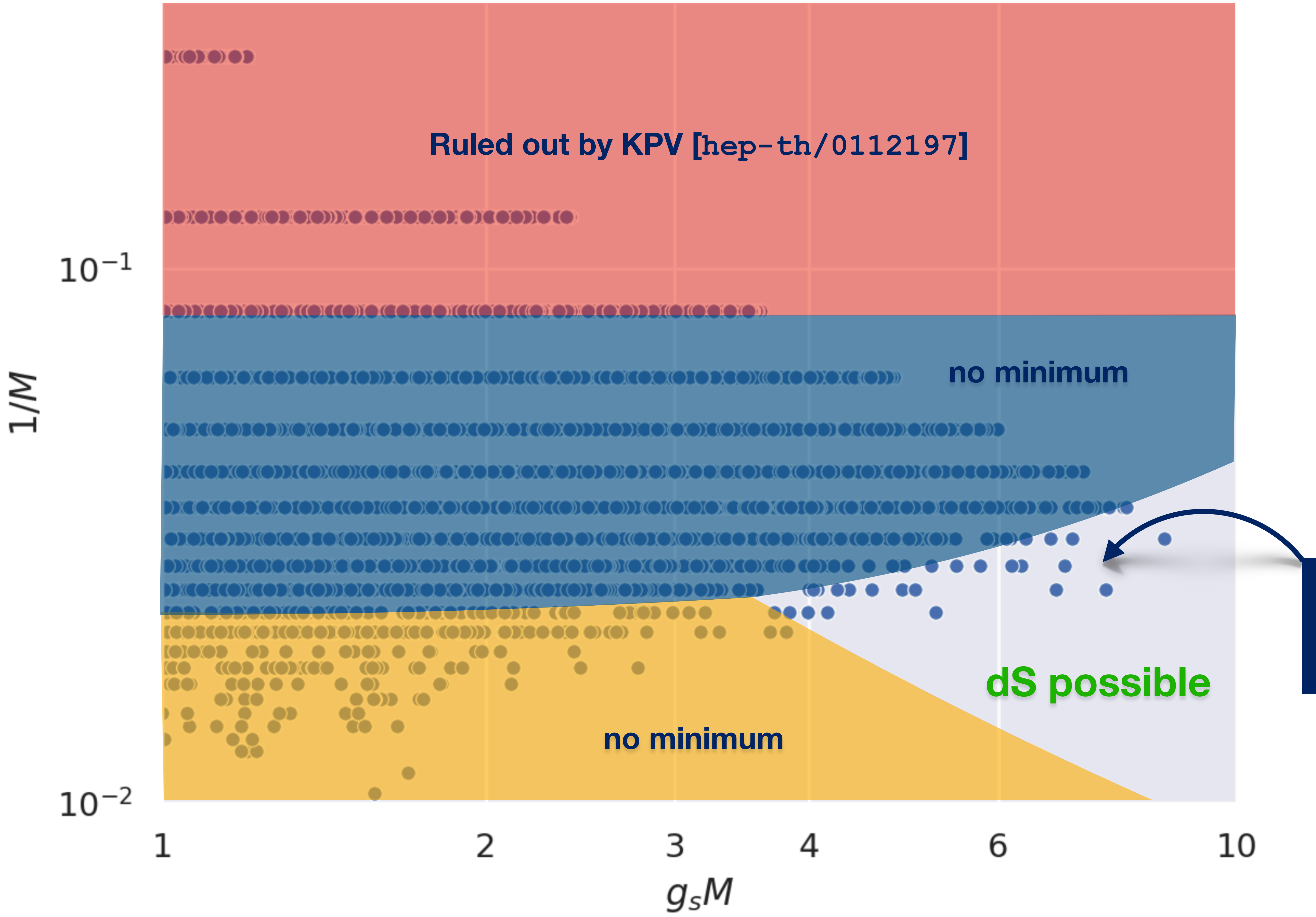
So far, we have been working in the **leading approximation**.

More work is required to understand the role of

- loop corrections to the Kähler potential, see [Kim 2301.03602, 2302.12117, 2305.08263] for recent progress
- the singular bulk problem [Gao, Hebecker, Junghans 2009.03914], but note that it is already rather well-controlled in our examples, cf. [Demirtas et al. 2107.09064] and also [Carta, Moritz 2101.05281]
- α' corrections to KPV such as computed by [Hebecker, 2x(Schreyer, Venken) 2208.02826, 2212.07437]

Coming back to the full dataset…

Contours from flux dependent α' corrections to the KPV potential as obtained by [Schreyer, Venken 2212.07437]



Warning, examples shown over-uplift! In particular, these are NOT the dS vacua shown before!

Surviving solutions have $N_{flux} \leq Q_{D3}$ requiring additional D3-branes which is potentially interesting for realising inflation (work in progress)

Conclusions

We have exhibited explicit examples of CY orientifold flux compactifications with

- **small W_0**
- **small g_s**
- **all moduli explicitly stabilised**
- **including a single anti-D3-brane in an explicit KS throat**

for which the KPV computation of the anti-brane energy predicts uplift to a KKLT de Sitter vacuum.

We think this is tremendously exciting, but we are not declaring the job done:

- We are still working to find examples in which the KS throat has large enough $g_s M$ so that upon including (the known) corrections to the KPV computation, one remains in de Sitter.
- This appears to us to be a matter of statistics, and will take more compute time.


매우 감사합니다

Contours from curvature corrections to the KPV potential as obtained by [Hebecker, Schreyer, Venken 2208.02826]