de Sitter vacua in string theory

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Cornell

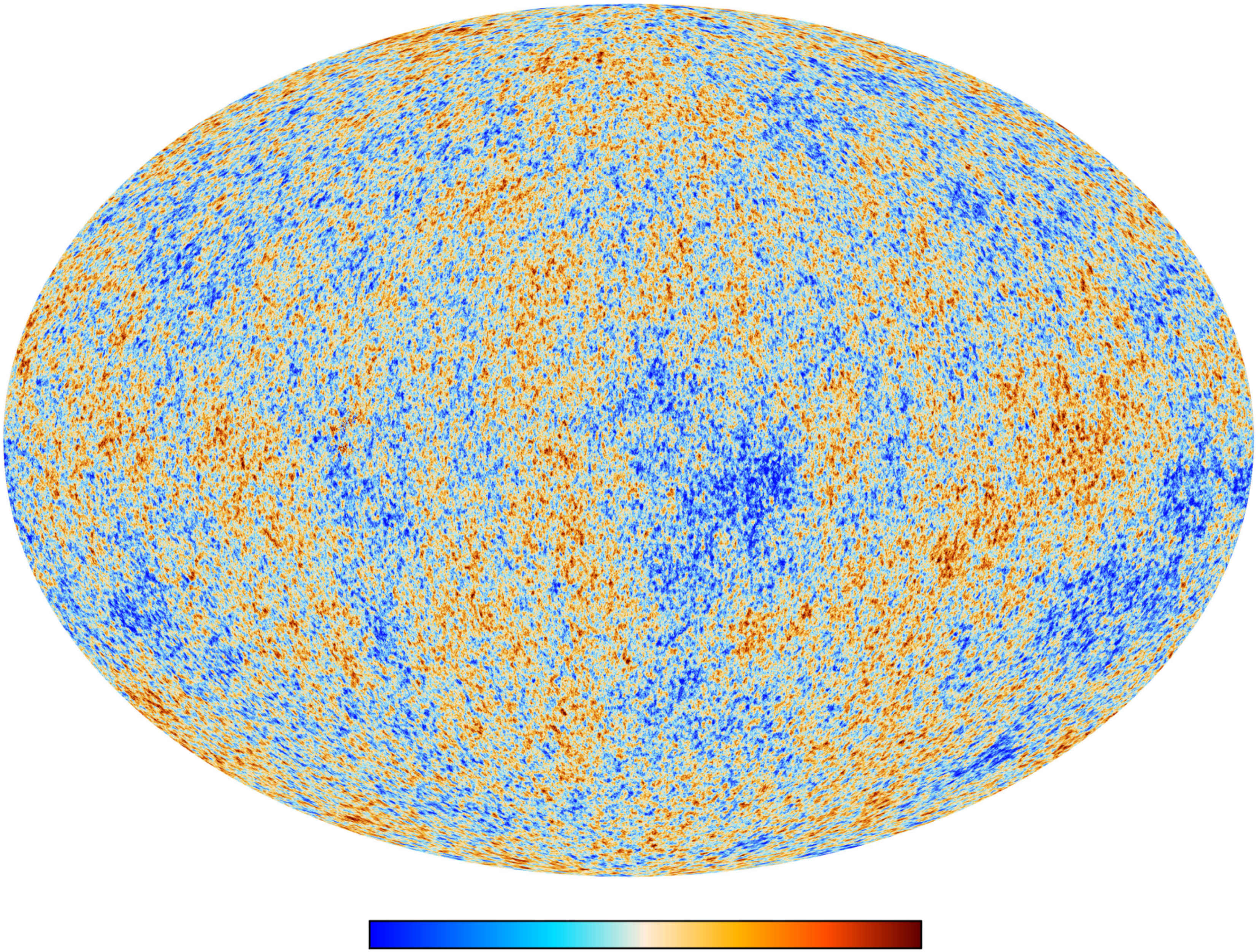
Strings 2019, Brussels

Why de Sitter space?

Simplest explanation for cosmological observations.

Foundation of concordance model of cosmology.


SN 2011fe
Byrne Observatory at Sedgwick Reserve and the Palomar Transient Factory | LCOGT.net | BJ FULTON



Planck collaboration

Reidar Hahn, Fermilab

Why de Sitter space?

Measurements of supernovae,
the cosmic microwave background,
and large-scale structure
give overwhelming evidence for

two stages of accelerated expansion:

early: $t \ll 1\,s$ Inflation
late: $t \gtrsim 10^{17}\,s$ Dark energy

Simplest explanation: (quasi) de Sitter space

ΛCDM + inflation consistent with all observations.

Evidence goes far beyond homogeneous expansion.

Why in string theory?

Is string theory compatible with the concordance cosmology?

Why in string theory?

Dark energy:

Cosmological constant problem.

Does string theory have enough de Sitter vacua, $\gg 10^{120}$, to accommodate anthropic "solution"?

Does it admit a better solution?

Inflation:

CMB signatures depend on Planck-scale physics.

Dramatic for primordial tensors, but holds generally.

Understanding inflation requires quantum gravity.

Powerful link from string theory to observations.

Plan

I. Overview of task

II. KKLT scenario   Kachru, Kallosh, Linde, Trivedi 03

III. Other constructions

Focus: constructions of dS_4

Quantum gravity in de Sitter space is challenging.

Today: review status of constructions of dS_4
in EFTs derived from compactifications of superstrings.

Require $\mathcal{R}_4\,\alpha' \ll 1$, derive and use EFT below string scale.

Possible worry: are EFTs meaningful in quantum gravity?
Banks 00, 03 Banks, Dine, Gorbatov 03

Will assume that vacua of an EFT derived from string theory descend from vacua of full string theory.

Focus: constructions of dS_4

Quantum gravity in de Sitter space is challenging.

Today: review status of constructions of dS_4
in EFTs derived from compactifications of superstrings.

Require $\mathcal{R}_4\,\alpha' \ll 1$, derive and use EFT below string scale.

10d supergravity + localized sources $\Rightarrow$ 4d (super)gravity

$$S_{10} = \frac{1}{2\kappa_{10}^2}\int \mathrm{d}^{10}x\sqrt{G}\Big(\mathcal{R}_{10} + \ldots\Big)$$

$$\Rightarrow S_4 = \int \mathrm{d}^4x\sqrt{g}\Big(\tfrac{M_{\rm pl}^2}{2}\mathcal{R}_4 + \mathcal{L}(\phi)\Big)$$

Task: derive $\mathcal{L}(\phi)$.

Strategy for finding de Sitter

Conceptually easy, impractical at present:

Find solution preserving $\mathcal{N} = 1$ SUSY, e.g. type II on CY_3-$\mathcal{O}$.

Directly compute 4d EFT to $\mathrm{N^kLO}$, in α' and g_s .

Exhibit de Sitter solutions in EFT at $\mathrm{N^{k-1}LO}$,

show that $\mathrm{N^kLO}$ negligible.

Practical: apply further approximations.

Look under special lampposts.

e.g. parameter regimes where sectors decouple

into 'modules' that interact weakly.

Analyze modules in isolation, then weakly couple them.

At present, many such modules well-understood.

Final 'assembly' is the key challenge.

Status of constructions

Many scenarios for constructing de Sitter vacua
in EFTs derived in compactifications of string theory.

No incontrovertible example to date.
But, many highly nontrivial tests already passed,
and remaining difficulties appear purely technical.

Challenge is not unique to de Sitter vacua.

e.g., no derivation of Standard Model + Einstein gravity
(with no light moduli) to standard demanded for de Sitter.

Non-supersymmetric compactifications are hard,
but this does not imply they do not exist.

KKLT de Sitter vacua

Compactification of type IIB on an orientifold X of a CY_3, including:

three-form flux $G_3 = F_3 - \tau H_3 \in H_3(X, \mathbb{Z})$

an $\mathcal{N} = 1$ pure SYM sector on $N_c > 1$ D7-branes

a warped deformed conifold region Klebanov, Strassler 00

containing one or more anti-D3-branes

Claim [KKLT]: in a suitable parameter regime,

these sources can yield metastable dS_4,

and corrections to approximations are small.

Kachru, Kallosh, Linde, Trivedi 03

Large Volume Scenario (LVS): different parameter regime,

crucially including $\alpha'^3 \mathcal{R}^4$ correction to $\mathcal{K}$

Balasubramanian, Berglund, Conlon, Quevedo 05

Setup

Type IIB string theory compactified on O3/O7 orientifold, X, of a CY_3.

$$ds^2 = G_{AB} dX^A dX^B = e^{-6u(x)+2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{2u(x)-2A(y)} g_{ab} dy^a dy^b$$

Take $h^{1,1}_+ = 1,\ \Sigma \in H_4(X, \mathbb{Z})$. Choose $G_3 = F_3 - \tau H_3 \in H_3(X, \mathbb{Z})$.

Moduli: axiodilaton $\tau := C_0 + i e^{-\phi}$

complex structure $\zeta_a, \quad a = 1, \ldots h^{2,1}$

Kähler: $T = e^{4u} + i \int_\Sigma C_4$.

$4d\ \mathcal{N} = 1$ supergravity:

$$W_{\text{classical}} = \int_X G_3 \wedge \Omega$$

Gukov, Vafa, Witten 99

$$\mathcal{K} = -3 \log\left(T + \overline{T}\right) - \log\left(-i(\tau - \bar{\tau})\right) - \log\left(-i \int_X \Omega \wedge \Omega\right)$$

For generic G_3, solutions of $D_\tau W = D_{\zeta_a} W = 0$ are isolated $\Rightarrow \tau, \zeta_a$ fixed.

Giddings, Kachru, Polchinski 01 Kachru, Kallosh, Linde, Trivedi 03

Setup

Below the scale $m_{\zeta_a} \sim \frac{\alpha'}{\sqrt{\mathrm{Vol}(X)}}$ of the complex structure moduli masses,

$$\mathcal{K} = -3\log(T+\overline{T}) \qquad W \to \left\langle \int_X G_3 \wedge \Omega \right\rangle =: W_0$$

$$D_T W = K_T W_0 = -\frac{3}{T+\overline{T}} W_0 \neq 0$$

$$V_F = e^{\mathcal{K}}\left(K^{T\overline{T}} D_T W_0 \overline{D_T W_0} - 3W_0\overline{W_0}\right) = 0$$

SUSY broken, but $V_F = 0$ and T unfixed.

Consider a stack of D7-branes on Σ that support pure $SU(N_c)$ SYM.

[or, ED3 on Σ]

Witten 96

$$W_{\mathrm{np}} = -\frac{N_c}{32\pi^2}\langle\lambda\lambda\rangle = \mathcal{A}\, e^{-\frac{2\pi}{N_c}T} \qquad W = W_0 + \mathcal{A}\, e^{-\frac{2\pi}{N_c}T}$$

This supergravity theory has a SUSY AdS_4 minimum. KKLT

If $W_0 \ll 1$, the minimum is at large volume, and $m_T \ll m_{\zeta_a}$.

$W_0 \ll 1$ occurs for some of the $\mathcal{O}(e^{2b_3})$ choices of G_3.

Ashok, Douglas 03 Giryavets, Kachru, Tripathy, Trivedi 03 Denef, Douglas 04

Setup

Introduce p anti-D3-branes at the tip of a Klebanov-Strassler throat.

$$S_{\text{DBI+CS}} \Rightarrow V_{\overline{D3}} = 2p\,T_3 e^{4A} e^{-8u}$$

Kachru, Pearson, Verlinde 01

In a noncompact throat, this gives a metastable SUSY-breaking state.

In a compact throat, anti-D3-branes affect EOM of T.

and *can* affect D7-brane $\langle\lambda\lambda\rangle$.

To the extent that the antibranes affect the gaugino condensate

only by contributing to the EOM for T,

it follows that $V_{\text{tot}} \approx V_{\overline{D3}} + V_F$.

This theory has a metastable dS_4 minimum.

KKLT

One should ask:

MODULI STABILIZATION

Do there exist consistent global models with:

i. Quantized fluxes giving small classical superpotential W_0

ii. D7-brane stack(s) supporting gaugino condensate

iii. Klebanov-Strassler throat region

ANTIBRANE UPLIFTING

Can anti-D3-branes be described with a SUSY action?

Is decompactification the only important instability from anti-D3-branes?

Do anti-D3-branes and D7-brane $\langle\lambda\lambda\rangle$ interact weakly?

Can the de Sitter solution be described in ten-dimensional supergravity?

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Can the de Sitter solution be described in ten-dimensional supergravity? yes

Can one exhibit an explicit and fully-controlled compactification that unifies all necessary components? TBD

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Denef, Douglas, Florea 04
Denef, Douglas, Florea, Grassi, Kachru 05

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ii. D7-brane stack(s) supporting gaugino condensate yes

Hulsey 19

Explicit CY_3 orientifolds:

e.g., $h^{2,1} = 3,\ h^{1,1} = 51:$ resolution of $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$

12 D7/O7 stacks, pure $\mathcal{N} = 1$ SYM, gauge group $SO(8)^{12}$

48 exceptional divisors $D_\alpha \cong \mathbb{P}^1 \times \mathbb{P}^1, h^{0,i} = 0.$

each unique in homology class, and $h^3(\widehat{D}_\alpha) = 0 \Rightarrow W_{\mathrm{np}} \neq 0$

$$W = W_0 + \sum_{i=1}^{12} e^{-2\pi T_i/6} + \sum_{\alpha=1}^{48} e^{-2\pi T_\alpha}$$

Corrections: higher instantons in W, $\lesssim 10^{-3}$; in K, $\lesssim 10^{-2}$

$\alpha'^3 \mathcal{R}^4$, $\lesssim 10^{-2}$

One should ask:

ANTIBRANE UPLIFTING

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Ferrara, Kallosh, Linde 14
Kallosh, Wrase 14
Kallosh, Quevedo, Uranga 15
Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase 15
Bandos, Heller, Kuzenko, Martucci, Sorokin 16
Vercnocke, Wrase 16
Dall'Agata, Dudas, Farakos 16
Kallosh, Vercnocke, Wrase 16
Aalsma, Van Der Schaar, Vercnocke 17
Garcia del Moral, Parameswaran, Quiroz, Zavala 17
Aalsma, Tournoy, Van Der Schaar, Vercnocke 18

Using constrained multiplets, can write complete supergravity action.

Volkov, Akulov 72
Komargodski, Seiberg 09

Cribiori, Roupec, Wrase, Yamada 19

SUSY spontaneously broken.

One should ask:

ANTIBRANE UPLIFTING

Kachru, Pearson, Verlinde 01

Is decompactification the only important instability from anti-D3-branes? yes

Bena, Graña, Halmagyi 09
Bena, Giecold, Graña, Halmagyi, Massai 11
Dymarsky 11
Bena, Graña, Kuperstein, Massai 12
Bena, Graña, Kuperstein, Massai 14
Michel, Mintun, Polchinski, Puhm, Saad 14
Blåbäck, Danielsson, Junghans, Van Riet, Vargas 14

Singularities in fluxes near anti-D3-branes?

Yes, if ansatz too restrictive and excludes puffing up into NS5.

Cohen-Maldonado, Diaz, Van Riet, Vercnocke 15

Study beyond probe, and at finite temperature, matches KPV.

Armas, Nguyen, Niarchos, Obers, Van Riet 18

"We regard this as very strong evidence for the existence of the meta-stable states, since by now they have been argued in rather complementary ways.

Armas, Nguyen, Niarchos, Obers, Van Riet 18

de Sitter vacua from 10d

Can the de Sitter solution be described in ten-dimensional supergravity? yes

KKLT: after dimensional reduction of $\overline{\text{D3}}$-branes and D7-brane $\langle\lambda\lambda\rangle$,
the EOM of the 4d EFT lead to a dS_4 vacuum.

Possible complaint: "this is not a 10d construction" Maldacena, Núñez 00

So we ask: does the same vacuum follow from the 10d EOM?

$$\frac{1}{4}M_{\text{pl}}^2\mathcal{R}_4[g] = \underbrace{2T_3 e^{-12u} e^{4A}(z_{\overline{D3}})}_{V_{\overline{D3}}} - \frac{1}{4}\int_X \sqrt{g_6}\, e^{-4A} g^{\mu\nu} T^{\lambda\lambda}_{\mu\nu}$$

Task: compute $T^{\lambda\lambda}_{\mu\nu}$ in 10d. Is it such that $\mathcal{R}_4[g] \to \mathcal{R}_4[g]\Big|_{\text{KKLT}}$?

Moritz, Retolaza, Westphal 17, 18; Hamada, Hebecker, Shiu, Soler 18, 19; Gautason, Van Hemelryck, Van Riet 18
Gautason, Van Hemelryck, Van Riet, Venken 19; Carta, Moritz, Westphal 19; Kachru, Kim, L.M., Zimet 19

Stress-energy of gaugino condensate

Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

$$S_{G\lambda\lambda} = -\frac{i}{(4\pi^2\alpha')^2}\int\sqrt{g}e^{-4A}e^{\phi}G_3\cdot\Omega\frac{\bar{\lambda}\bar{\lambda}}{16\pi}\delta^{(0)} + c.c.$$

Cámara, Ibáñez, Uranga 03

G_3 causes D7-brane gaugino mass $\Leftrightarrow$ $\langle\lambda\lambda\rangle$ sources G_3.

Strong consistency check: potential for position z of a D3-brane.

Ganor 96
DeWolfe, Giddings 02
Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi 03
Berg, Haack, Körs 04
Baumann, Dymarsky, Klebanov, Maldacena, L.M., Murugan 06
Koerber, Martucci 07
Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Heidenreich, L.M, Torroba 10
Dymarsky, Martucci 10

$$4d: \quad V_F\Big[\mathcal{K}(T,\overline{T},z,\bar{z}),W_{\rm np}(T,z)\Big]$$

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G_3 causes D7-brane gaugino mass $\Leftrightarrow$ $\langle\lambda\lambda\rangle$ sources G_3.

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$$V_{\rm DBI+CS}\Big|_{G_3} = V_F\left[\mathcal{K}(T,\overline{T},z,\bar{z}),W_{\rm np}(T,z)\right]$$

Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Dymarsky, Martucci 10
Kachru, Kim, L.M., Zimet

The 4d F-term potential due to $W_{\rm np}(T,z)$
matches
the 10d DBI+CS potential due to G_3 sourced by $\langle\lambda\lambda\rangle$.

Compelling evidence that gaugino condensation sources flux via $S_{G\lambda\lambda}$.

We can compute the associated 10d stress-energy $T^{\lambda\lambda}_{\mu\nu}$.

Stress-energy of gaugino condensate

Stress-energy $T^{\lambda\lambda}_{\mu\nu}$ due to

$$S_{G\lambda\lambda} = -\frac{i}{(4\pi^2\alpha')^2}\int \sqrt{g}e^{-4A}e^{\phi}G_3 \cdot \Omega \frac{\bar{\lambda}\bar{\lambda}}{16\pi}\delta^{(0)} + c.c.$$

is such that

$$\frac{1}{4}M_{\rm pl}^2\mathcal{R}_4[g] = -3e^{\mathcal{K}}|W|^2 = V_{\rm KKLT}^{\rm AdS}$$

without anti-D3-branes

$$\frac{1}{4}M_{\rm pl}^2\mathcal{R}_4[g] = V_{\overline{D3}} + V_F = V_{\rm KKLT}^{\rm dS}$$

with anti-D3-branes

Match is exact.

Hamada, Hebecker, Shiu, Soler 19
Gautason, Van Hemelryck, Van Riet, Venken 19
Carta, Moritz, Westphal 19
Kachru, Kim, L.M., Zimet

Upshot: consistency between 10d and 4d calculations.

Stress-energy of gaugino condensate

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Match is exact.

Manki Kim

Upshot: consistency between 10d and 4d calculations.

KKLT status summary

No evidence of obstructions or inconsistencies.

Still awaiting complete explicit compactifications.

Heterotic string

Complete moduli stabilization at weak coupling difficult.

$$W = \int H \wedge \Omega + \mathcal{A}\, e^{-S}$$

Dine, Rohm, Seiberg, Witten 85

Issue: flux quantization.

Gukov, Kachru, Liu, L.M. 03
Anderson, Gray, Lukas, Ovrut 11
Cicoli, de Alwis, Westphal 13
Apruzzi, Gautason, Parameswaran, Zagermann 14
Anderson, Gray, Lukas, Wang

Constructions global $\Rightarrow$ non-modular.

No module for metastable SUSY breaking in de Sitter.

Type IIA

Classical flux compactifications already interesting.

Grimm, Louis 04
DeWolfe, Giryavets, Kachru, Taylor 05
Villadoro, Zwirner 05

CY_3 with $H_3, F_p\ (p = 0, 2, 4, 6), \mathrm{D6}, \mathrm{O6}:$ no-go. Hertzberg, Kachru, Taylor, Tegmark 07

Negative curvature $\Rightarrow$ no no-go, dS critical points.

Flauger, Paban, Robbins, Wrase 08
Caviezel, Koerber, Kors, Lust, Wrase, Zagermann 08
Danielsson, Haque, Shiu, Van Riet 09
Wrase, Zagermann 10
Danielsson, Haque, Koerber, Shiu, Van Riet, Wrase 11
Andriot 18

Obied, Ooguri, Spodyneiko, Vafa 18
Ooguri, Palti, Shiu, Vafa 18

Nilmanifolds with fluxes, O-planes, KK-monopoles: dS vacuum. Silverstein 07

Problematic simplification: smearing of O-planes.
Do solutions with localized (i.e. not smeared) O-planes exist?

Córdova, De Luca, Tomasiello 18
Cribiori, Junghans 19

See talk by Tomasiello

Conclusion

Considerable promise for exhibiting controlled de Sitter vacua in EFTs derived in solutions of string theory.

Steady progress, increasingly precise and explicit computations.
Many highly nontrivial tests already passed.

No incontrovertible example to date.
Little prospect of de Sitter at *arbitrarily* weak coupling.

Learning to control non-SUSY solutions a central challenge.

Thanks!