On de Sitter Space in String Theory

Fernando Quevedo
ICTP + Cambridge

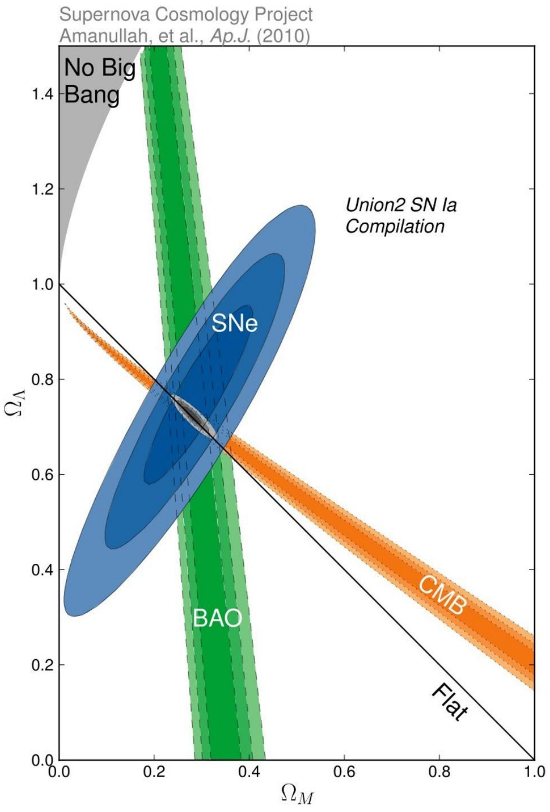
UK Annual Meeting

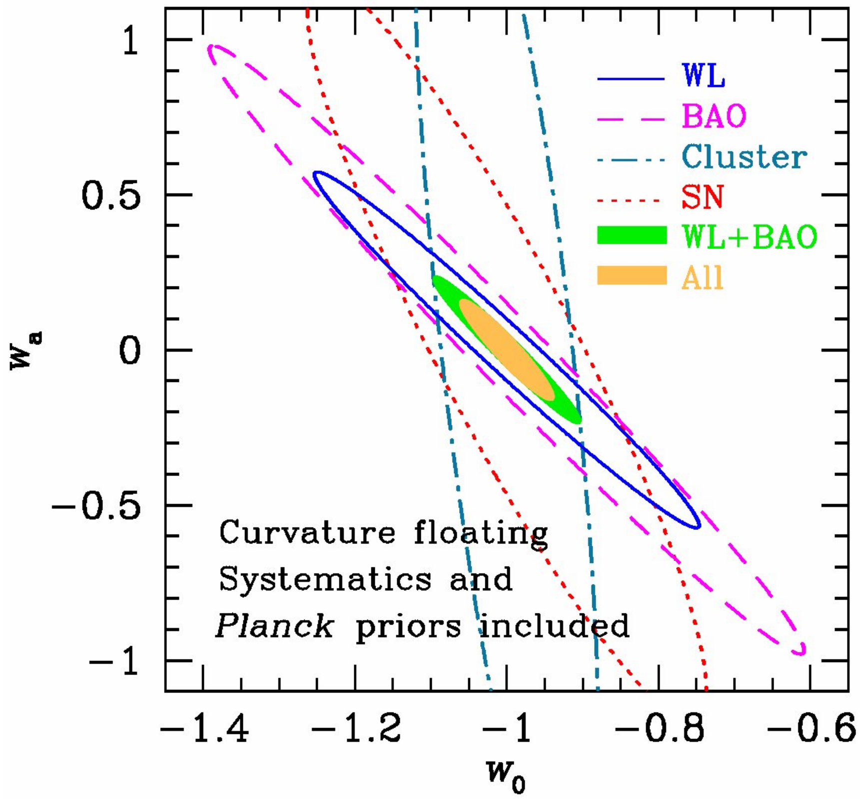
Durham, 2018

Outline

- Why de Sitter
- de Sitter from String Theory (difficulties)
- de Sitter Moduli Stabilisation (KKLT, LVS)
- Concrete mechanisms (anti-branes, T-branes, etc.)
- Progress over the years
- Challenges (Swampland conjectures)
- de Sitter and Quintessence

Why de Sitter? (Dark Energy)





$$w = p/\rho$$

$w_0 = -1.028 \pm 0.032\,.$ ~ de Sitter !

Also inflation ~ de Sitter !

de Sitter from String Theory?

Massless Spectrum of String/M Theories

Theory	Dimensions	Supercharges	Bosonic Spectrum	
Heterotic $E_8 \times E_8$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}	
Heterotic $SO(32)$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}	
Type I $SO(32)$	10	16	NS-NS R-R	g_{MN}, ϕ, A_M^{ij} C_{MN}
Type IIA	10	32	NS-NS R-R	g_{MN}, B_{MN}, ϕ C_M, C_{MNP}
Type IIB	10	32	NS-NS R-R	g_{MN}, B_{MN}, ϕ C, C_{MN}, C_{MNPQ}
11D Supergravity	11	32	g_{MN}, C_{MNP}	

de Sitter Challenges

- Define S-matrix (resonance?)
- Classical no-go theorems (Gibbons; Maldacena-Nuñez,...)
- Supersymmetry: Minkowski or AdS (e.g. $AdS_5 \times S^5$)
- No dS solution of string theory under full calculational control (KKLT, LVS,...?)

Moduli Stabilisation

String Scenarios

- IIB (+F-theory)

  KKLT
  LVS

  Moduli Stabilisation

- IIA

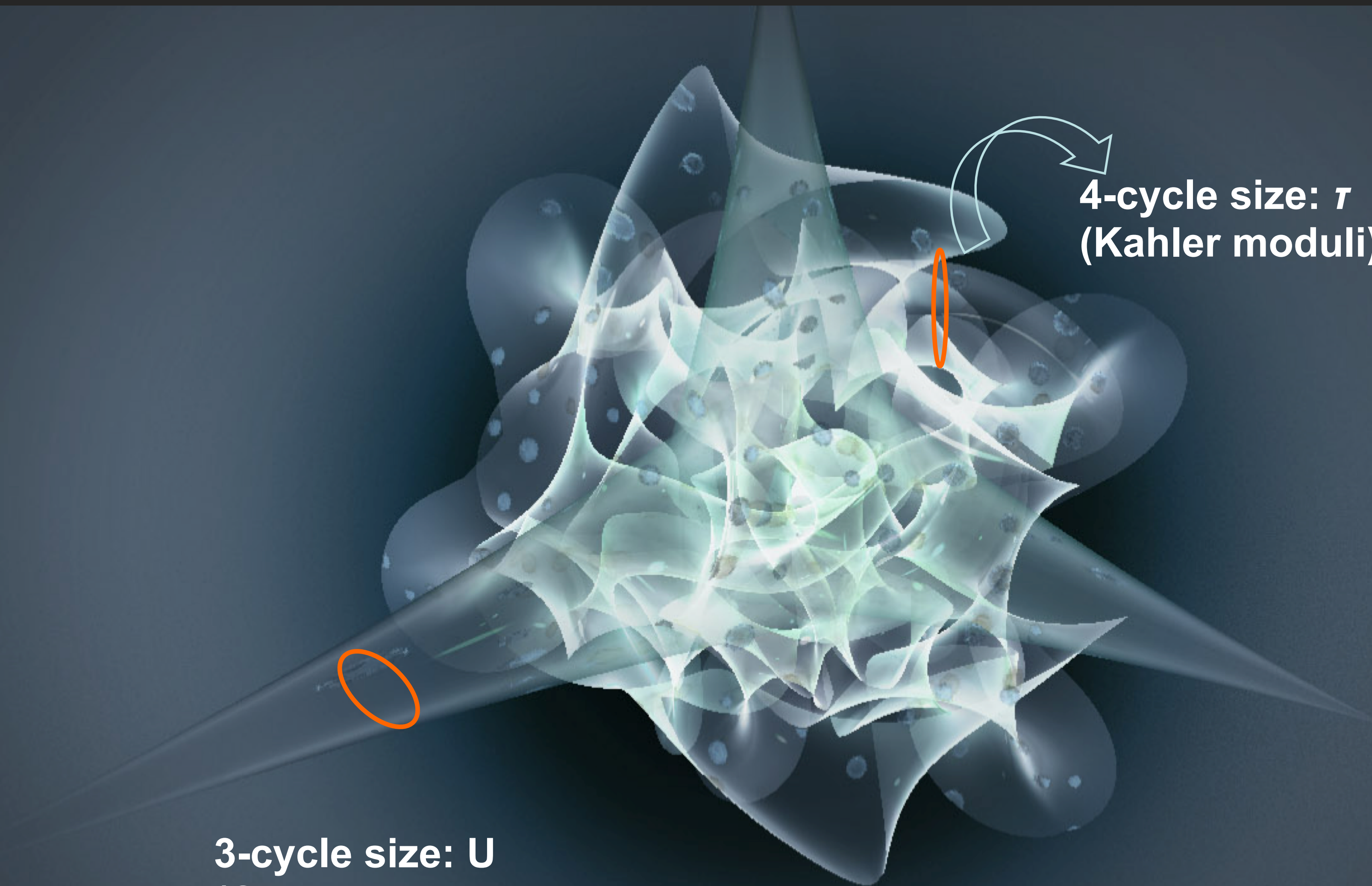
- Heterotic

- G2 manifolds

IIB Advantages

- Fluxes backreaction (warped) Calabi-Yau
- No-scale structure
- Scales $m_{3/2} << M_s << M_p$
- Two sets of 3-fluxes F_3, H_3 (allows `tuning')
- GVW Superpotential W(S,U) not renormalised!
- Many loop (g_s) and α' corrections to K computed
- Kahler moduli gauge couplings $W_{np}(T)$

IIB MODULI STABILISATION



Moduli Stabilisation in IIB

- Moduli S, T_i, U_a

$$V_F = e^K \left(K^{-1}_{M\overline{N}} D_M W \overline{D_{\overline{M}} W} - 3|W|^2 \right)$$

$$W_{\rm tree} = W_{\rm flux}(U,S) \qquad K^{-1}_{i\bar{\jmath}} K_i K_{\bar{\jmath}} = 3$$

No-scale

$$V_F = e^K \left(K^{-1}_{a\bar{b}} D_a W D_{\bar{b}} W \right) \geq 0$$

Fix S,U but T arbitrary

- Quantum corrections $\delta V \propto W_0^2 \delta K + W_0 \delta W$
- Three options: $W_0 \gg \delta W$ $\quad \delta K \gg \delta W$ Runaway: Dine-Seiberg problem

$$W_0 \sim \delta W = W_{\rm np}.$$
$$W_0 \ll 1$$

Fix T-modulus: KKLT

$$\delta K \sim W_0 \delta W$$
$$\delta K \sim 1/\mathcal{V} \text{ and } \delta W \sim e^{-a\tau}$$

Fix T-moduli: LVS

N=1, 4D Effective Field Theory

$$K = -2\log(\mathcal{V}_{\rm CY}) - \log(S+\bar{S}) - \log\left(\int \Omega\wedge\bar{\Omega}\right)$$

$$W = W_0 + Ae^{-aT_i} \qquad W_0 = \int G_3 \wedge \Omega$$

e.g. KKLT

$$V/M_{\rm Pl}^4 = \frac{e^{K_{\rm cs}}}{6\tau^2}\left(aA^2(3+a\tau)e^{-2a\tau} - 3aAe^{-a\tau}W_0\right) \qquad V_{\rm up} \simeq \left(\frac{T+\overline{T}}{2}\right)^{-2}$$

e.g. LVS

$$V_F \propto \left(\frac{K^{S\bar{S}}|D_SW|^2 + K^{a\bar{b}}D_aW\bar{D}_{\bar{b}}\bar{W}}{\mathcal{V}^2}\right) + \left(\frac{Ae^{-2a\tau}}{\mathcal{V}} - \frac{Be^{-a\tau}W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\boxed{\mathcal{V} \sim e^{a_s\tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.}$$

Anti-Brane 'Uplift' (KKLT)

- Nonperturbative effects: $W_{np} = \sum A_i e^{-a_i T_i}$

SUSY AdS Vacua: DW=0

- Anti D3 brane (SUSY breaking+uplift)

$$V_{\rm uplift} = \frac{D^2}{(T+T^*)^\alpha} = \frac{D^2}{\mathcal{V}^{2\alpha/3}} \qquad \begin{cases} \alpha = 3 & \text{KKLT} \\ \alpha = 2 & \text{KKLMMT} \end{cases}$$

LARGE Volume Scenario

Fluxes determine superpotential W_0 (U,S) (GKP 2002)

Perturbative corrections to K: $K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right)$

Nonperturbative contributions to W: $\boxed{W_{np} = \sum_i A_i e^{-a_i T_i}}$

$$V_F \propto \left(\frac{K^{S\bar{S}}|D_S W|^2 + K^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W}}{\mathcal{V}^2}\right) + \left(\frac{Ae^{-2a\tau}}{\mathcal{V}} - \frac{Be^{-a\tau}W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\boxed{\mathcal{V} \sim e^{a\tau}} \quad \text{with} \quad \tau \sim \mathrm{Re\ S} \sim 1/\mathrm{g_s} > 1.$$

BBCQ, CQS 2005

Exponentially large volume for weak coupling
(SUSY broken,Uplift as in KKLT but more options)

e.g. T- Branes

4D EFT: F and D terms

$$V_{\rm tot} = V_D^{\rm bulk} + V_F = \frac{1}{\tau_b}\left(q_{D7}|\phi_{\rm dS}|^2 - \xi_{D7}\right)^2 + m_{3/2}^2|\phi_{\rm dS}|^2 + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$$V_{\rm tot} = V_{D,0}^{\rm bulk} + V_F = \frac{m_{3/2}^4\tau_b}{4q_{D7}^2} + \underbrace{m_{3/2}^2\frac{\xi_{D7}}{q_{D7}}}_{\mathcal{V}^{-8/3}} + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$$\langle V_{\rm tot}\rangle = \frac{3W_0^2}{4a_s^{3/2}\mathcal{V}^3}\left[\delta\mathcal{V}^{1/3} - \sqrt{\ln\left(\frac{\mathcal{V}}{W_0}\right)}\right] \quad \text{with} \quad \delta \simeq 0.01\left(\frac{a_s^{3/2}}{q_{D7}}\right)$$

10D: T-branes

$$J\wedge\mathcal{F}_{D7} + \left[\Phi, \bar{\Phi}\right] d{\rm vol}_4 = 0, \qquad \langle\Phi\rangle = \begin{pmatrix} 0 & \phi_{\mathbf{6}_{+2}} \\ 0 & 0 \end{pmatrix}$$

dS Kahler Moduli Stabilisation

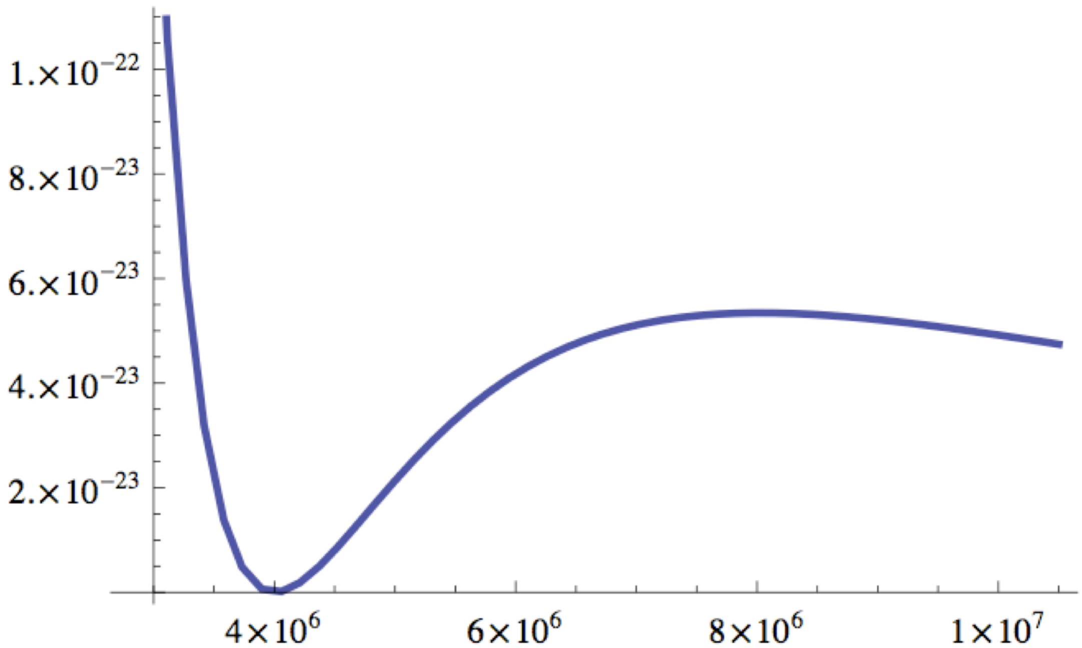
$$\boxed{V_F^{\rm tot} = V_{\rm np} + V_{\alpha'} + V_{\rm uplift}}$$

$$V_{\rm np} = \frac{8}{3\lambda}(a_s A_s)^2 \sqrt{\tau_s}\,\frac{e^{-2\,a_s\tau_s}}{\mathcal{V}} - 4\,a_s A_s |W_0| \tau_s \frac{e^{-a_s\tau_s}}{\mathcal{V}^2}$$

$$V_{\alpha'} = \frac{3}{4}\frac{\zeta |W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

$$V_{\rm uplift} = A/\mathcal{V}^{a}$$

$1<a<3$

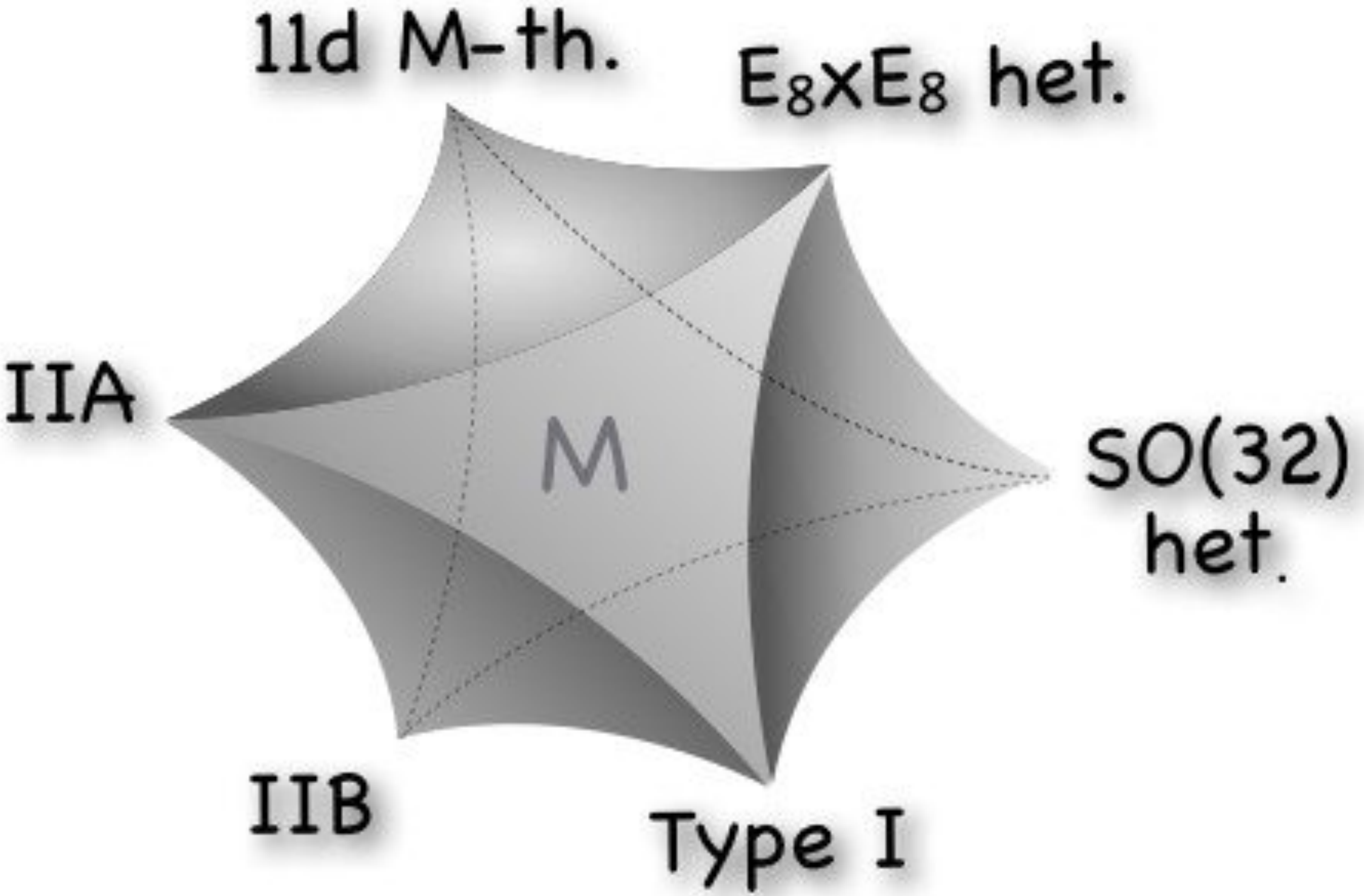


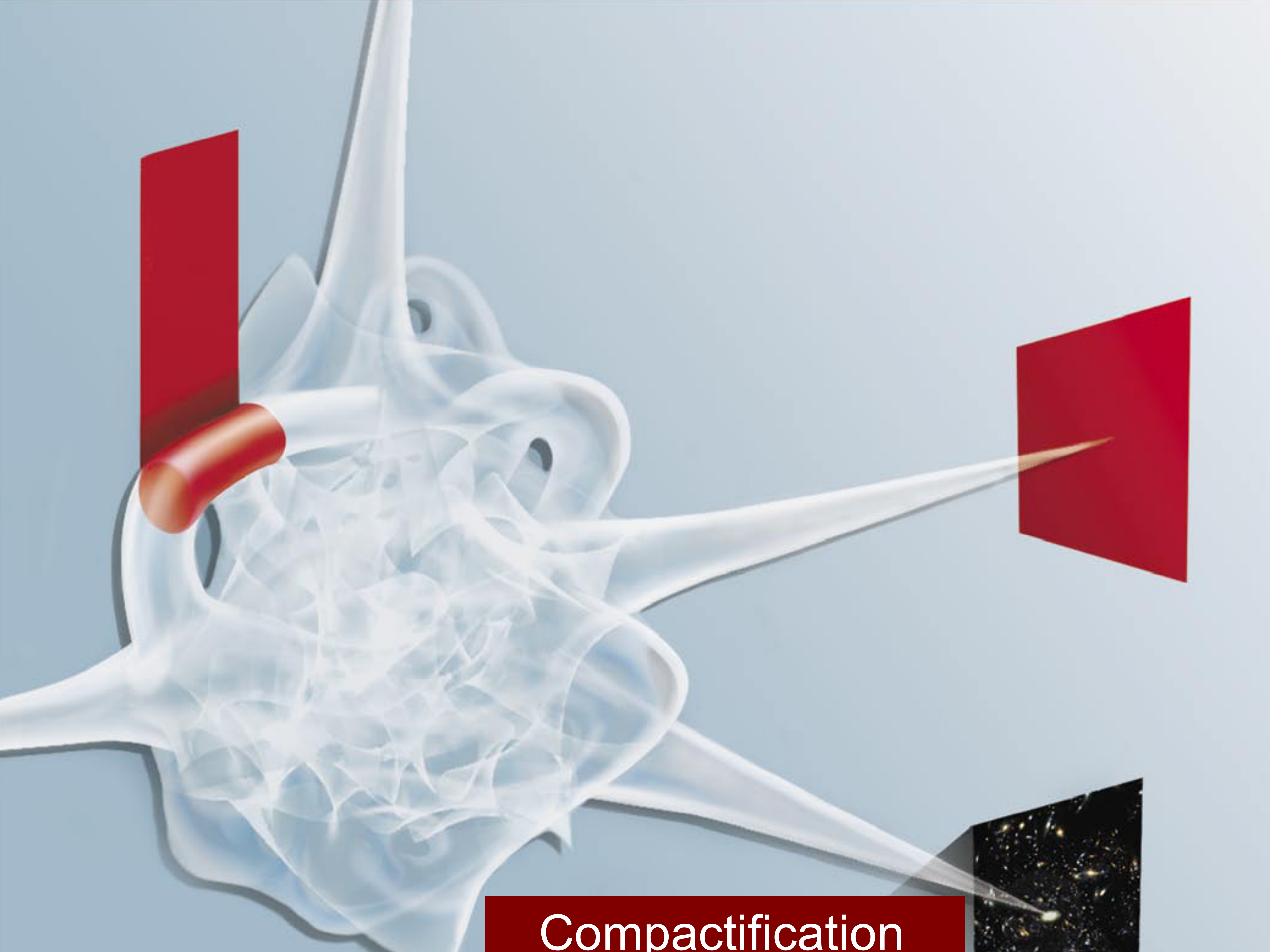
Other de Sitter proposals

- Anti D3 brane
- D+F terms in EFT or T-branes
- Complex structure/Dilaton uplift $(D_U W \neq 0,\ D_S W \neq 0)$
- Non critical strings, negative curvature compactifications, Kahler uplift, nonperturbative effects on D3 branes, ...

String Landscape

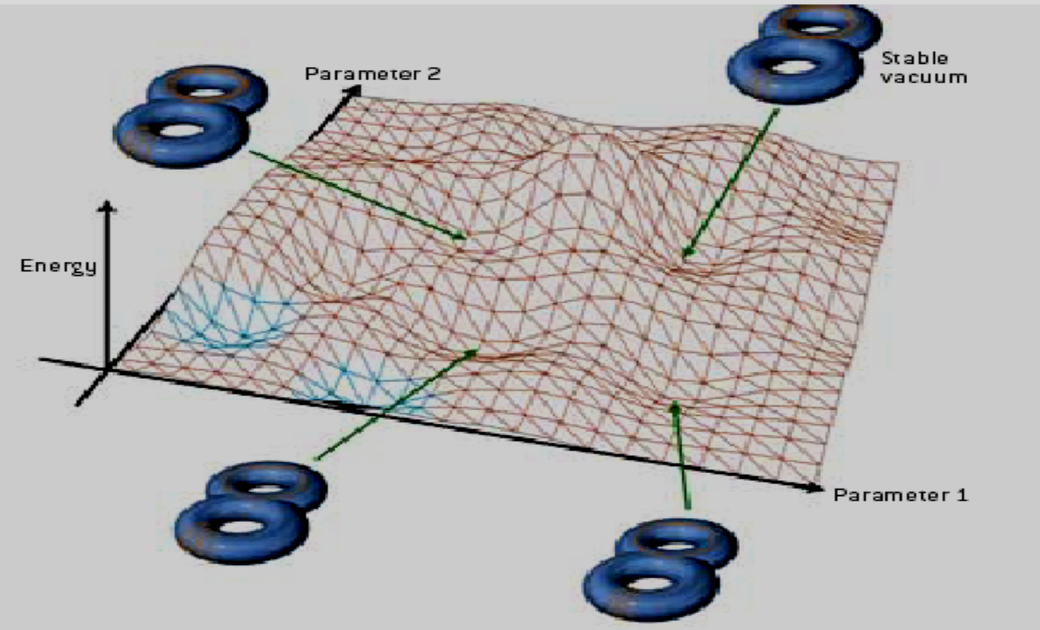
One single theory (+ no free parameters) but MANY solutions





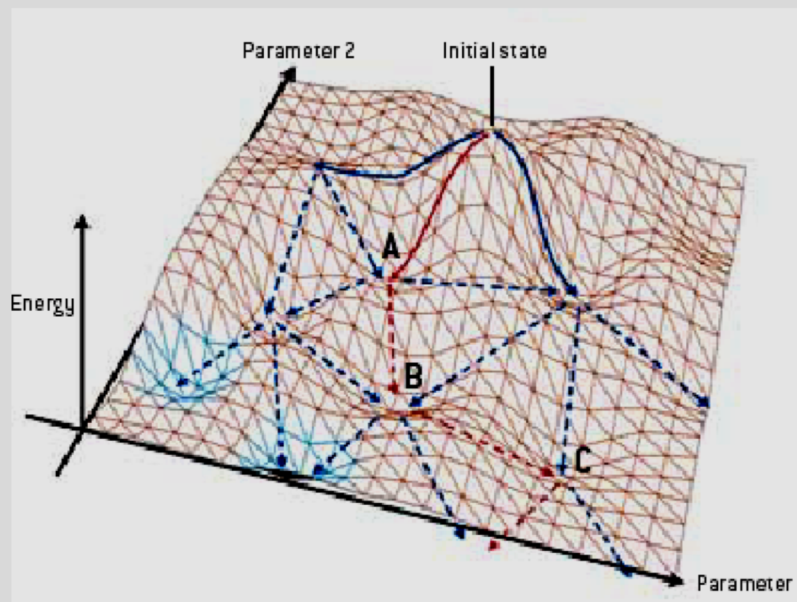
Compactification

The String Landscape

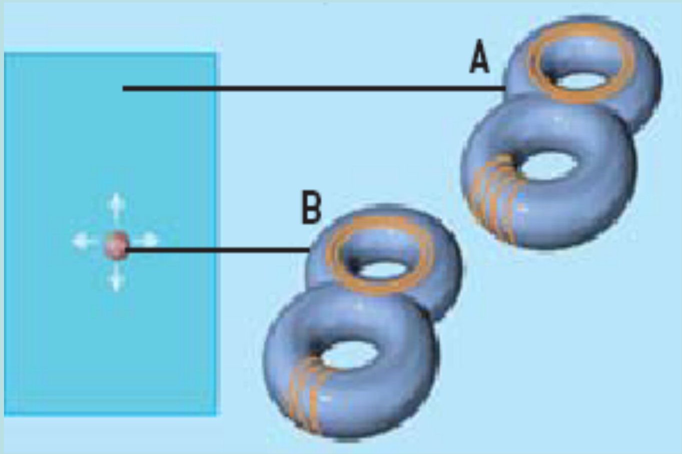


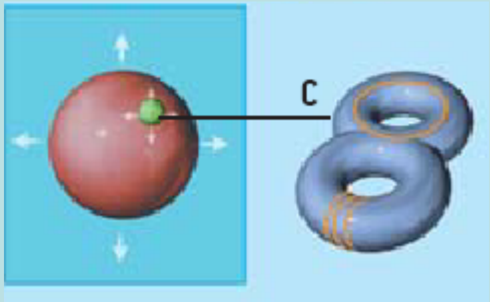
Classical Solutions

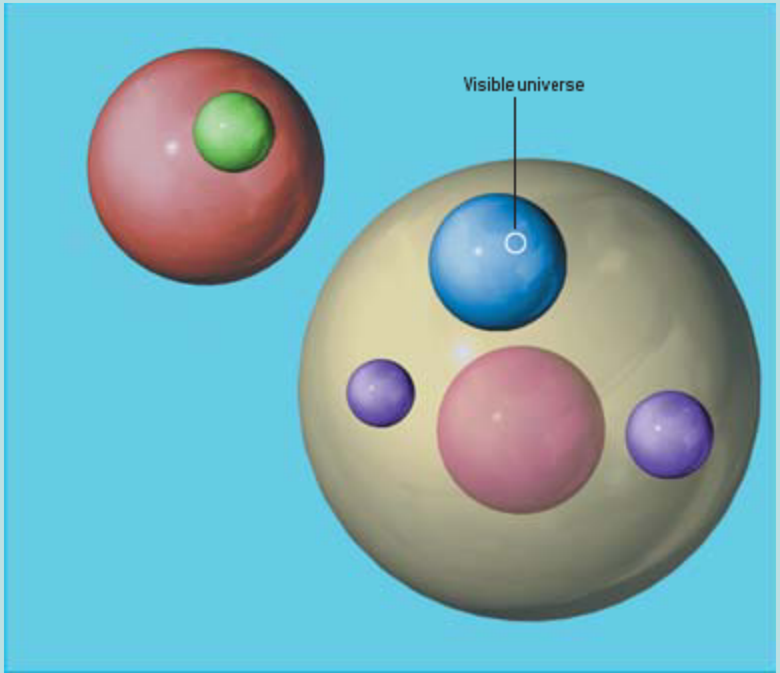
Quantum Decay
(tunnel effect)



Multiverse







MANY solutions (>10^{1000}!): Anthropic 'explanation' of dark energy!!?????

The Landscape

- **Good:** A `solution' of dark energy and allows for the first time to trust calculations for low-energy SUSY breaking.

- **Bad:** missed opportunity to have new physics at low energies from small Λ.

- **Ugly:** It may also be used to `solve' other problems (Split SUSY, High-energy SUSY) in unnatural ways.

Achievements over the years

- Remarkable: well defined prescription exists that includes all stringy ingredients: branes, orientifolds, warping, anti (T)-branes, perturbative, non-perturbative effects, etc.
- IIB with fluxes~ Calabi-Yau (moduli space understood).
- W_0<<1 is plausible (not achieved yet)
- Concrete compact CY examples
- Perturbative effects computed so far harmless.
- Antibrane: nonlinearly realised SUSY

$$X^2 = 0$$
$$\Delta W = c\,X\,, \qquad \Delta K = \beta\, X\bar{X}\,.$$

- Hierarchies:

$$E \ll M_{\mathrm{KK}} = \frac{M_s}{\mathcal{V}^{1/6}} \ll M_s \equiv \frac{1}{\ell_s} \equiv \frac{1}{2\pi\sqrt{\alpha'}} = g_s^{1/4}\frac{M_p}{\sqrt{4\pi\mathcal{V}}}\,.$$

$$m_{3/2} \simeq W_0 M_P/\mathcal{V} \qquad m_{3/2}/M_{KK} \ll 1$$

e.g. Nilpotent Super fields

Kallosh et al 2013-2015
(Also: Bergshoeff, van Proeyen, Wrase, Dudas, D’allagata, Zwirner, Ferrara, etc.)

Nilpotent Superfields EFT

$$X = X_0(y) + \sqrt{2}\psi(y)\theta + F(y)\theta\bar{\theta}$$

$$\boxed{X^2 = 0} \qquad X_0 = \frac{\psi\psi}{2F}$$

$$K = K_0 X X^* \qquad W = \rho X + W_0$$

$$V = K_0^{-1} \left\| \frac{\partial W}{\partial X} \right\|^2 = \frac{|\rho|^2}{K_0} \geq 0$$

$$\mathcal{L} = -\rho^2 + i\partial_a\bar{\psi}\bar{\sigma}^a\psi + \frac{1}{4\rho^2}\bar{\psi}^2\partial^2\psi^2 - \frac{1}{16\rho^6}\psi^2\bar{\psi}^2\partial^2\psi^2\partial^2\bar{\psi}^2$$

~ Volkov-Akulov !

Nilpotent Superfields and KKLT

Goldstino: Nilpotent chiral superfield

$$X^2(x,\theta) = 0.$$

Rocek,...,Komargodski, Seiberg,...

KKLT $K = -3\log(T+T^*) + c\,(T+T^*)^n\; XX^* + ZCC^* + \cdots$

$$Z = (T+T^*)^m + b\,(T+T^*)^k\, XX^*$$

$$W = W_0 + W_{\rm matter} + W_{np} + \boxed{\rho X}$$

Plug into SUGRA expression for V, V= V_{KKLT} + V_{uplift} :

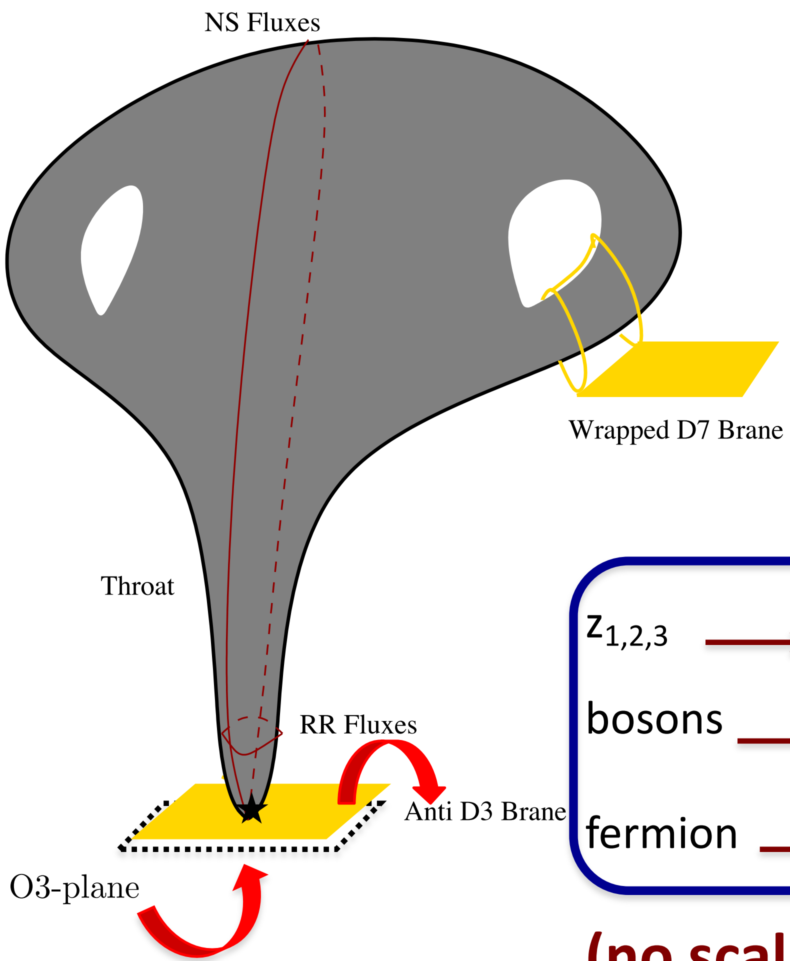
$$V_{\rm uplift} = \frac{|\rho|^2}{c(T+T^*)^{n+3}}$$

(like KKLT, KKLMMT)

Kallosh et al. 2013-15
see also Polchinski
@ SUSY 2015

Antibrane uplift from manifestly SUSY EFT!

Anti D3 Brane/O3$^-$ Spectrum



Kallosh, Uranga, FQ
arXiv:1507.07556

$z_{1,2,3}$	$\longrightarrow$	$-z_{1,2,3}$
bosons	$\longrightarrow$	-bosons
fermion	$\longrightarrow$	fermion

Massless spectrum:
Fermion=Goldstino

(no scalars, no gauge fields)

Spectrum on (anti) D3 brane

Field	$SO(3,1)$	$SO(6)$	$U(N)$	
Gauge boson	vector	$\mathbf{1}$	Adj	
Scalar	$\mathbf{1}$	$\mathbf{6}$	Adj	
Fermion	spinor	$\mathbf{4}$	Adj	$\bar{4}$ **for anti D3 brane**

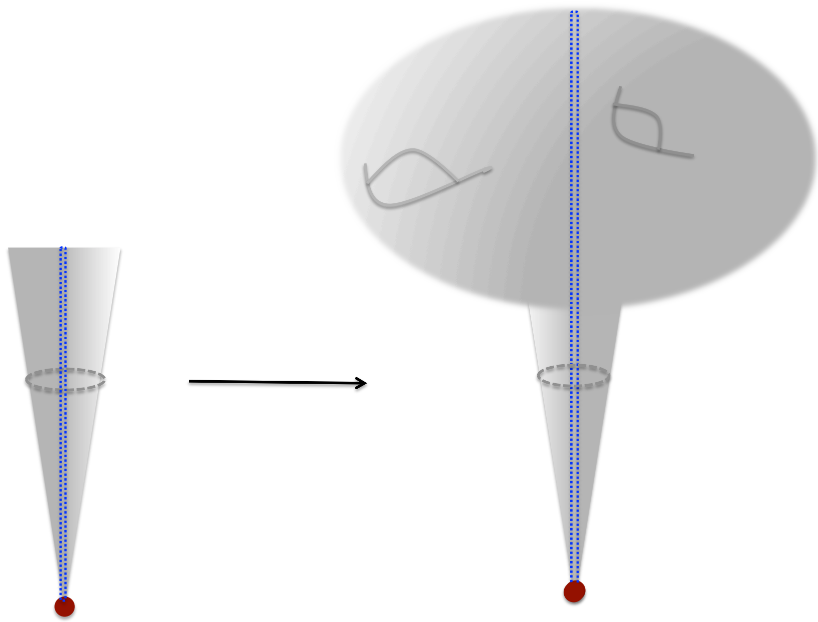
Masses from fluxes $G_3\,\lambda\lambda$

G3=10 (ISD) + $\overline{10}$ (IASD)

Mass term $\bar{4}\cdot\bar{4}\cdot 10$ **(10=6+3+1 and 4=3+1 of SU(3))**

3 massive 1 massless fermion (N=1 goldstino)

Local to Global Throats



Garcia-Etxebarria, FQ, Valandro
arXiv:1512.06926

e.g.

	W_1	W_2	W_3	W_4	W_5	Z	X	Y	D_{H}
$\mathbb{C}_1^*$	0	0	0	0	0	1	2	3	6
$\mathbb{C}_2^*$	1	1	1	0	0	0	6	9	18
$\mathbb{C}_3^*$	0	1	0	1	0	0	4	6	12
$\mathbb{C}_4^*$	0	0	1	0	1	0	4	6	12

,

First concrete realisation of warped throats in compact CY?

Potential Problems

- To EFT
- To fluxes
- To perturbative effects
- To nonperturbative effects
- To de Sitter

Challenges to KKLT, LVS,...

e.g. Danielson, Van Riet

- Fluxes under control only in SUSY 10D   Sethi
- All SUSY breaking part is 4D EFT (with string inputs). Trust EFT?
- Tuning $W_0 << 1$? in KKLT
- Higher correction in LVS?
- Antibranes (by hand, non susy, singularity?)
- T-branes in a controlled region?   Bena et al.
- Antibranes and non-perturbative effects?

Moritz et al.

Open Questions

- Full control of quantum corrections
- EFT of branes at singularities
- Realistic phenomenology (de Sitter but no SM?)
- F-theory moduli stabilisation
- Populating the landscape (large # of U moduli + vacuum transitions)
- ...

Partly full Partly empty

Quintessence

Swampland conjectures

- Swampland: Quantum gravity vs EFT !

Vafa et al.

- Weak gravity conjecture
- Distance conjecture
- New ('anti' de Sitter?) conjecture: $M_p \frac{|\nabla V|}{V} \gtrsim c \,,$

Obied et al

(It would imply quintessence and no de Sitter

and hard to have inflation!).

Challenges for the de Sitter conjecture

- Higgs potential with quintessence field? (at the <H>=0 point.

Denef et al.

- If V asymptotes to infinity from above even supersymmetric AdS forbidden.

Conlon

- Both addressed if modify conjecture (allow saddle points for V>0).

see e.g. Andriot, Ooguri et al.

$$A(\varphi)|H|^4 + C(\varphi)|H|^2 + B(\varphi)$$

$$V(H,\varphi) = A(\varphi)\left(|H|^2 - \alpha^2(\varphi)\right)^2 + B(\varphi)$$

$$H = H_0 + h.$$

$$V_H = 0 \quad ; \quad H = 0, \; |H| = \alpha(\varphi)$$

$$V_\varphi = A'\left(H^2 - \alpha^2\right)^2 + 2A(\quad)(-2\alpha\alpha') + B'$$

$$H = 0 \; : \; V_\varphi = A'\alpha^4 + 4A\alpha^3\alpha' + B' \geq c\left(A\alpha^4 + B\right)$$

$$H = \alpha \; : \; V_\varphi = B' \qquad \geq c\,(B)$$

Higgs and Quintessence

- Higgs as quintessence??

$$V = \Lambda^4 + C^4\, e^{-k\,h/M_{\rm p}} \qquad C \simeq 10^{-52} e^{2.5\cdot 10^{71}} M_{\rm p} \qquad k = 10^{88}$$

- Higgs-quintessence coupling?

$$V = f(\chi)\,\tilde{V}(h) + \hat{V}(\chi) \qquad \text{with} \qquad f(\chi) = e^{-\chi} \qquad \frac{f_\chi(\chi)\,\tilde{V}(h) + \hat{V}_\chi(\chi)}{f(\chi)\,\tilde{V}(h) + \hat{V}(\chi)} \simeq \frac{f_\chi(\chi)}{f(\chi)} \simeq 1$$

- Several fields?

$$V = f(\phi)\,\tilde{V}(h) + g(\phi) + \hat{V}(\chi)$$

Couplings to SM?, Supergravity?

See Hebecker's talk

de Sitter vs Quintessence

M. Cicoli, S. de Alwis, A. Maharana, F. Muia and FQ [arXiv:1808.08967]

Quintessence from Strings?

- Need stabilise all moduli except for quintessence field: as difficult as getting de Sitter
- Or have many fields rolling but slower than quintessence. Difficult.
- Fifth force and varying couplings constraints (e.g. volume modulus or dilaton problematic)

e.g. Banks, Dine, Douglas ‘00

Yukawa’s

$$\hat{Y}_{ijk} = e^{K/2}\,\frac{Y_{ijk}(U)}{\sqrt{\tilde{K}_i\tilde{K}_j\tilde{K}_k}}\,,$$

Quintessence Candidates

- Modulus (fibre, blow-up) that does not couple directly to SM. It also would require a very small string scale (e.g. Ms~TeV)

Cicoli, et al ‘12

- Axions

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\theta\partial_\mu\theta - \mu^4\left(1-\cos\left(\frac{\theta}{f}\right)\right) \,,$$

K. Choi ’99
Panda et al ‘11
Kaloper et al. ’08
Kamionkowski et al ‘13

de Sitter and Quintessence

Axion Quintessence in LVS

$$m_a \simeq \sqrt{\frac{g_s}{8\pi}}\,\frac{M_p}{\mathcal{V}^{2/3}}\,e^{-\frac{\pi}{N}\mathcal{V}^{2/3}}M_p\,,$$

Naturally very small!

$$\boxed{V = \Lambda^4 - \sum_{i=1}^{N_{\rm ULA}} \Lambda_i^4 \cos\left(\frac{a_i}{f_i}\right) + \cdots\,,}$$

Minimum not necessarily at zero

$$\epsilon = \frac{1}{2}\left[\left(\frac{\Lambda_\ell}{\Lambda}\right)^4 \frac{M_p}{f_\ell}\right]^2 \frac{\sin^2\left(a_\ell/f_\ell\right)}{\left(1-\left(\Lambda_\ell/\Lambda\right)^4\cos\left(a_\ell/f_\ell\right)\right)^2} < 1\,.$$

Slow-roll

$$f_\ell \gtrsim M_p.$$

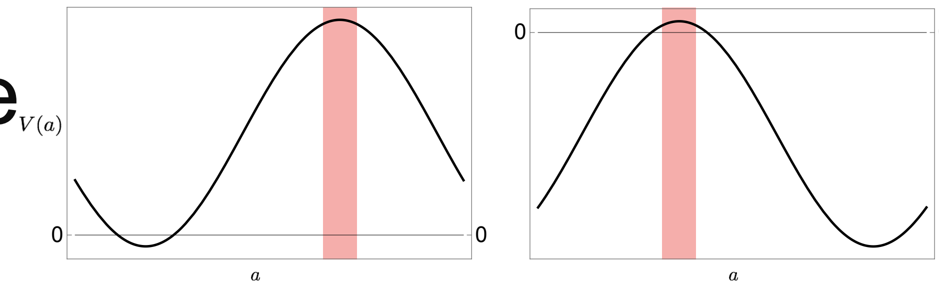
Not necessarily

ULA: (fuzzy) dark matter and dark radiation or dark energy and dark radiation?

(A)dS and Axion Quintessence

- Hilltop Quintessence

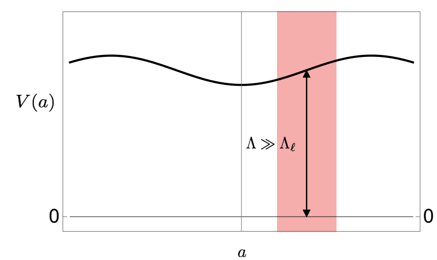
$$\Lambda^4 + \Lambda_i^4 > 0$$



- Quasi-natural quintessence

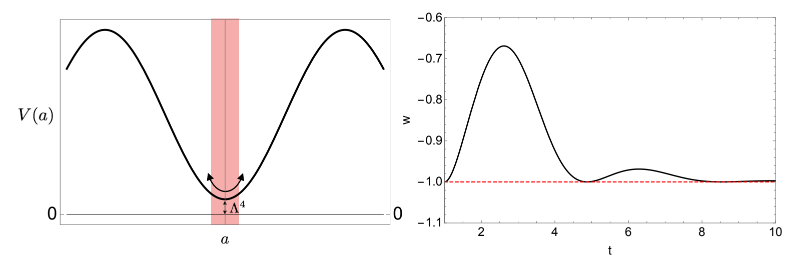
$$f_\ell \gtrsim \left(\frac{\Lambda_\ell}{\Lambda}\right)^4 M_p$$

$$f_\ell < M_p \qquad \Lambda \gg \Lambda_\ell.$$



$$w = \frac{p}{\rho} = \frac{\frac{\dot{a}^2}{2} - V}{\frac{\dot{a}^2}{2} + V} \sim -\frac{1 - \frac{1}{3}\epsilon}{1 + \frac{1}{3}\epsilon} \sim -1 + \frac{2}{3}\epsilon\,.$$

- Oscillating quintessence



Conclusions

- de Sitter and Quintessence: Many achievements, challenges, open questions

- Observational challenges for both!
  ($w<-1$ and varying??)

Maths Webmail Service

Message | Mailbox | Folders | Compose | Addressbook | Manage | Help | Logout

Reminder: Logout when you have finished.

User currently logged into Maths : fq201

From: Joseph Polchinski <joep@kitp.ucsb.edu>
To: fq201@damtp.cam.ac.uk
Cc: Senarath de Alwis <dealwiss@gmail.com>
Date: Mon, 7 Aug 2017 17:01:48 -0700
Subject: Re: Question on: Hartle-Hawking

By the way, I have a new principle: if we have a seemingly powerful no-go theorem, then we will find a powerful exception just beyond the limit of validity of the theorem.

Example:

No stable atoms in classical electrodynamics.

No symmetries beyond Coleman-Mandula.

No composite graviton in field theory.

No de Sitter in classical GR (including branes).

(are there others?)

So [redacted] the no-go argument [redacted] is just a red flag that it is irrelevant.

Best,
Joe