Cosmological Implications of the LARGE Volume String Scenario

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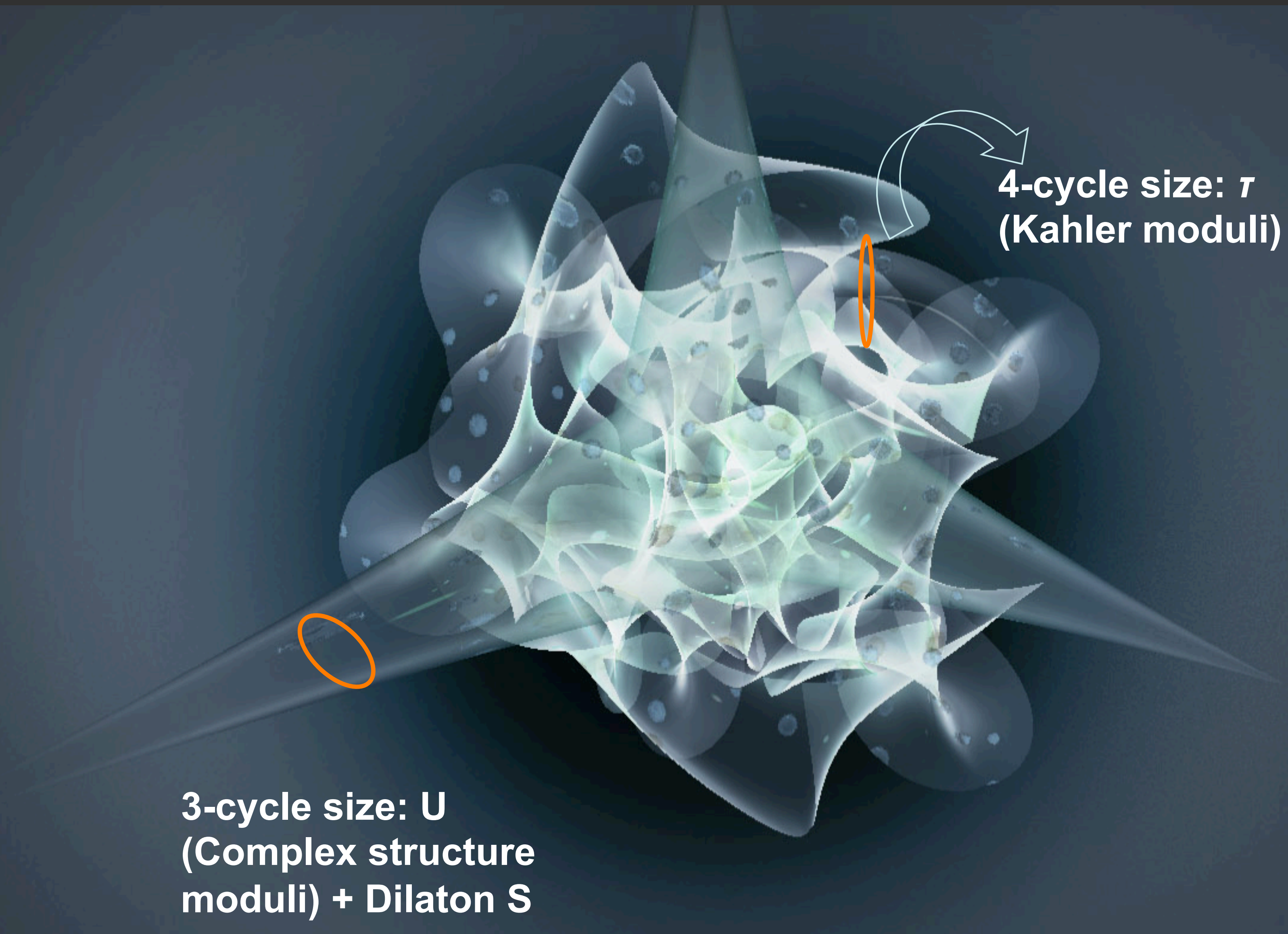
String Scenarios: Some cosmology challenges

- Big-bang singularity ✗
- Cosmological inflation or alternatives
- After inflation
- Current acceleration
- Consistency with low energy phenomenology

MODULI STABILISATION



String Scenarios

- IIB (+F-theory)

  KKLT
  LVS
  } ⟸ Moduli Stabilisation

- IIA

- Heterotic

- G2 manifolds

GKP Overview

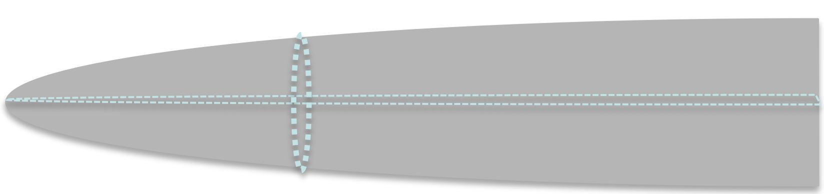
1. Fluxes: GVW $W_0 = \int G \wedge \Omega$

$$G_3 = F_3 - iSH_3, \int F_3 = 2\pi M, \int H_3 = -2\pi K$$

Fix CS moduli: z and dilaton: S

2. Warped throats

$$z^{1/3} = e^A = e^{-\frac{2\pi K}{3g_s M}} \equiv e^{-\alpha}$$



KKLT Overview

- 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

Perturbative corrections to K:

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

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

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

Exponentially large volume for weak coupling

(SUSY broken by Fluxes, AdS)

Other de Sitter 'Uplift'

- From F/D terms, hidden matter Burgess et al, Dudas et al, Villadoro-Zwirner, Cicoli et al, T-branes (Cicoli, FQ, Valandro arXiv:1512.04558)

- From non-perturbative effects on hidden brane at singularities

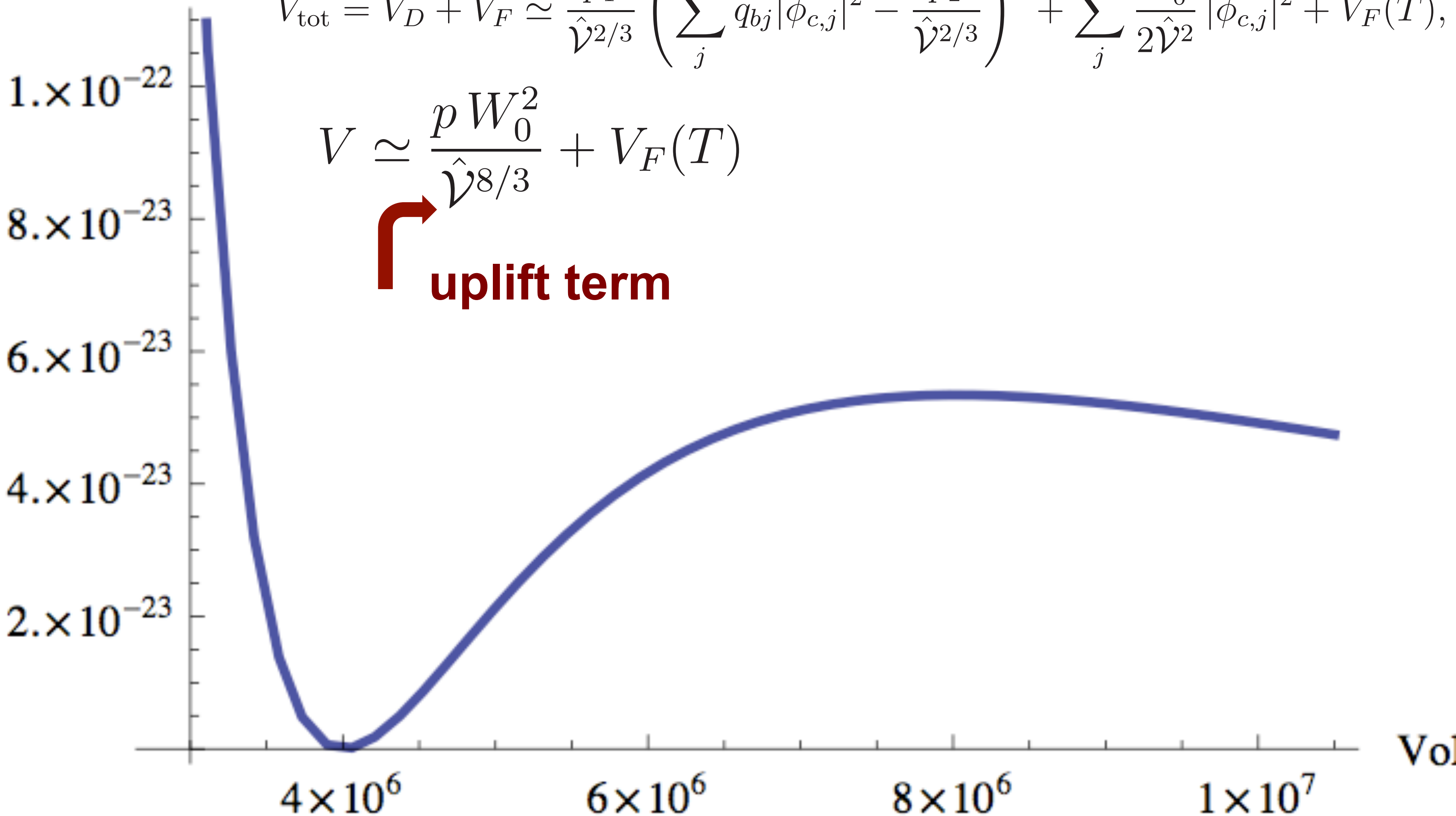
- …

dS Moduli Stabilisation

$$V_{\rm tot} = V_D + V_F \simeq \frac{p_1}{\hat{\mathcal{V}}^{2/3}} \left(\sum_j q_{bj} |\phi_{c,j}|^2 - \frac{p_2}{\hat{\mathcal{V}}^{2/3}} \right)^2 + \sum_j \frac{W_0^2}{2\hat{\mathcal{V}}^2} |\phi_{c,j}|^2 + V_F(T),$$

$$V \simeq \frac{p\, W_0^2}{\hat{\mathcal{V}}^{8/3}} + V_F(T)$$

uplift term



Relevant Scales

String Scale

$$M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi\mathcal{V}}},$$

Kaluza Klein Scale

$$M_{KK} \simeq \frac{M_P}{\sqrt{4\pi}\mathcal{V}^{2/3}},$$

Gravitino mass

$$m_{3/2} \simeq \left(\frac{g_s^2}{2\sqrt{2\pi}}\right)\frac{W_0 M_P}{\mathcal{V}}.$$

Volume modulus mass

$$m_{\mathcal{V}} \simeq m_{3/2}/\sqrt{\mathcal{V}}.$$

Vacuum decay rates

$$\Gamma \sim e^{-\mathcal{V}^3}$$

Constraints on the volume

- Validity of EFT ($m_{3/2} << M_{kk}$) : $V >> 10^3$
- CMP ($m_{volume} > 30$ TeV): $V < 10^9$

Ranges of relevant scales (GeV)

$$10^{17} > M_s > 10^{14}$$
$$10^{15} > m_{3/2} > 10^{10}$$
$$10^{12} > M_{1/2} > 10^2$$
$$10^7 > T_{RH} > 1$$

LVS vs KKLT

- W_0~0.1-100
- AdS non SUSY
- Minimum: perturbative in big cycle vs non-perturb. in small cycle
- Uplift:anti D3 branes, D-terms...
- Small parameter = 1/V
- SUSY broken by fluxes
- Many moduli: need $h_{21}>h_{11}>1$ + one blow up, the rest by loop effects/D-terms

- W_0<<1
- AdS SUSY
- Minimum: tree-level vs non-perturbative
- Uplift: anti D3 branes...(no D-terms)
- Small parameter W0
- SUSY broken by uplifting mechanism
- Many moduli: non-perturbative effects for each of them or ...

Revisiting Anti D3 Brane Uplift

Nilpotent Superfields EFT

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

Rocek, Komargodski-Seiberg, Dudas et al, Kallosh et al, D'allagata et al...

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

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

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

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

~ Volkov-Akulov !

Nilpotent Superfields and KKLT

Goldstino: Nilpotent chiral superfield

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

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

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

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

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

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

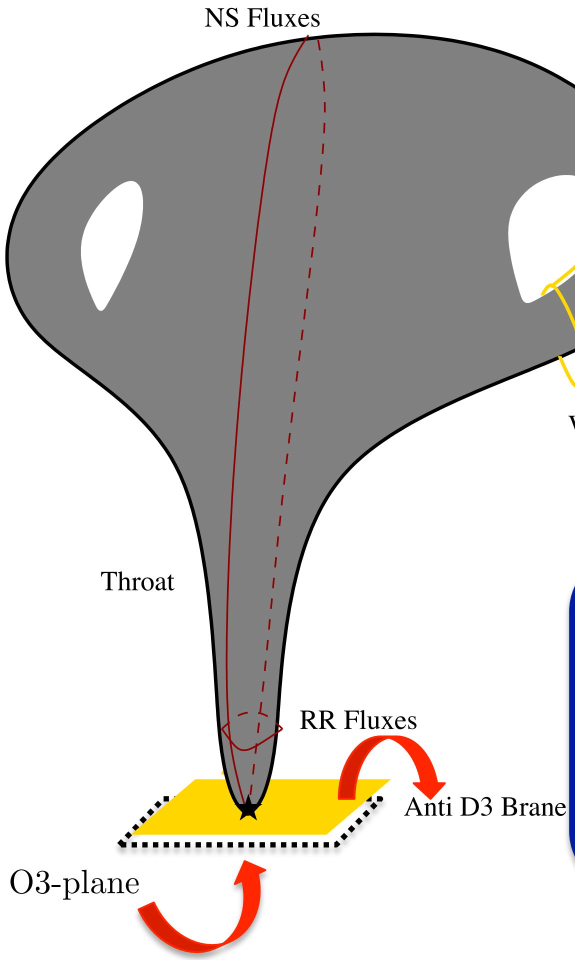
(like KKLT, KKLMMT)

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



$z_{1,2,3}$ →	$-z_{1,2,3}$
bosons →	-bosons
fermion →	fermion

⇒ **Massless spectrum: Fermion=Goldstino**

(no scalars, no gauge fields)

Metastability of dS LVS minima

- Brown-Teitelboim (+CdL) D5/NS5 brane nucleation
- AdS: Brane tension>upper bound, so stable in EFT
- dS: Decay rate ~ $\exp(-V^3)$

$P_{dS}/P_{AdS} \sim e^{-V}$ (The larger the volume, more stable!)

$P_{dS}/P_{dec} \sim e^{V^2}$

(Also: no evidence for bubble of nothing decay)

S. de Alwis, R. Gupta, E. Hatefi, FQ arXiv:1308.1222

Inflation

(moduli as inflatons)

e.g. 1: Swiss Cheese Calabi-Yau's

$$\mathcal{V} \sim \tau_l^{\frac{3}{2}} - \sum_{s=1}^{h^{1,1}-1} \tau_s^{\frac{3}{2}} .$$

e.g.

$\mathbb{P}_{[1,3,3,3,5]}[15]$ $\mathbb{P}^4_{1,2,2,10,15}(30)$ $\mathbb{P}^4_{1,1,2,2,6}(12)/\mathbb{Z}_2$ $\mathbf{M}_{\mathbf{n}}^{(\mathrm{dP}_8)^{\mathbf{n}}}$

Blumenhagen, et al., Grimm et al., Kreuzer et al. 08

Kähler Moduli Inflation (Blow-up)

$$V = \sum_i \frac{8(a_i A_i)^2 \sqrt{\tau_i}}{3\mathcal{V}\lambda_i \alpha} e^{-2a_i\tau_i} - \sum_i 4\frac{a_i A_i}{\mathcal{V}^2} W_0 \tau_i e^{-a_i\tau_i} + \frac{3\xi W_0^2}{4\mathcal{V}^3}.$$

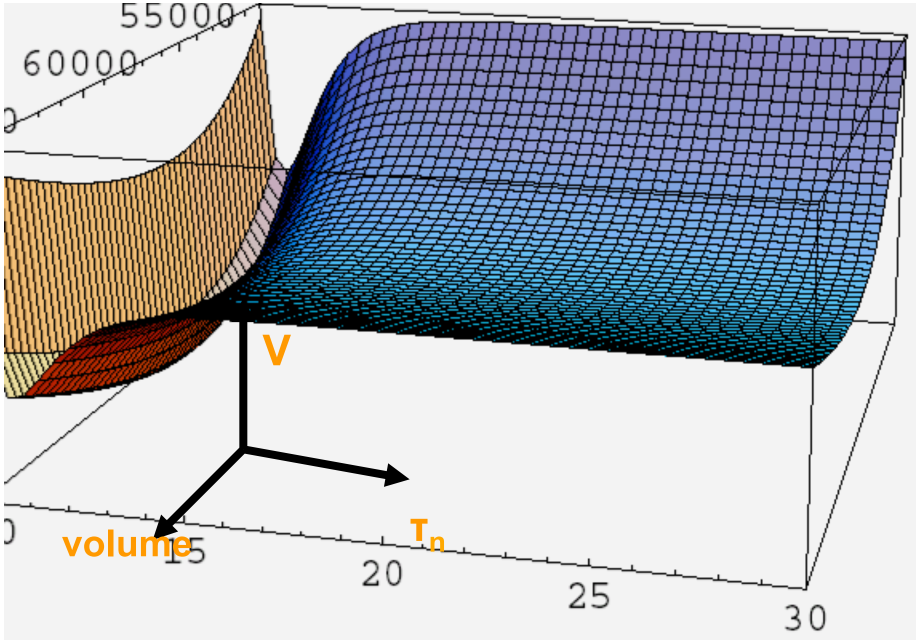
Conlon-FQ

Bond et al.

…

$$V \cong V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3} (\tau_n^c)^{4/3} \exp\left[-a_n \left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3} (\tau_n^c)^{4/3}\right].$$

Calabi-Yau: $h_{21} > h_{11} > 2$



Small field inflation (r<<<1)

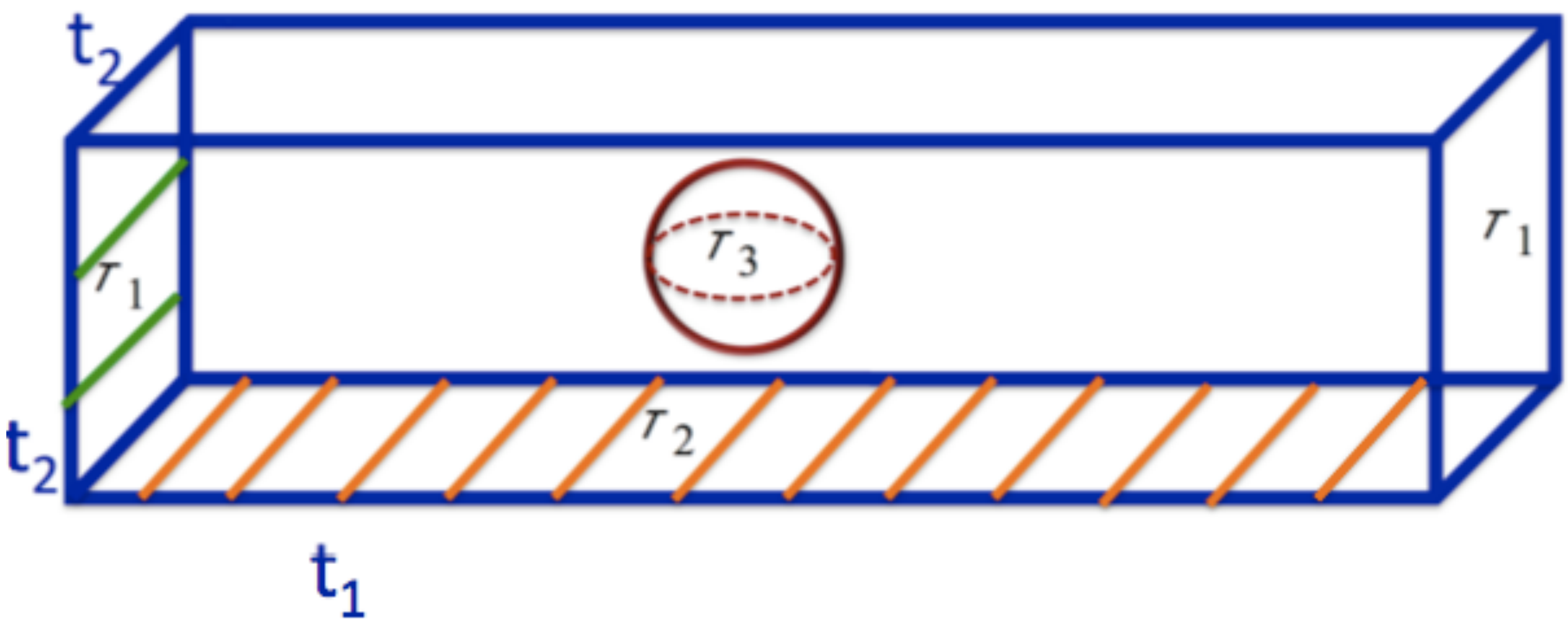
0.960<n<0.967

Loop corrections??

e.g. 2: Fibre Calabi-Yau

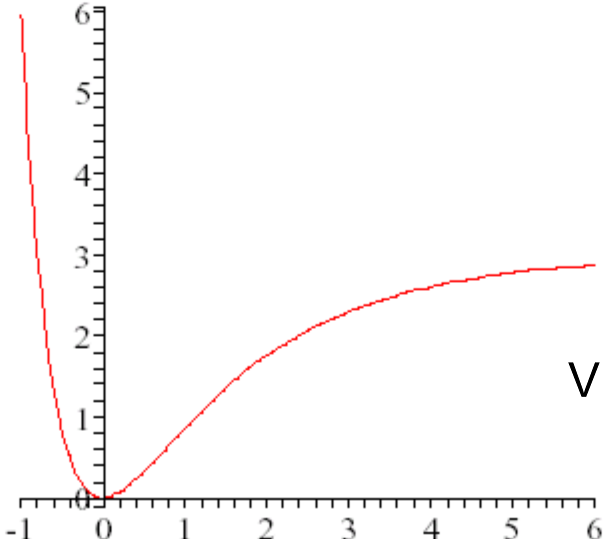
e.g.

$$\mathcal{V} = \lambda_1 t_1 t_2^2 + \lambda_2 t_3^3,$$
$$\tau_i = \partial\mathcal{V}/\partial t_i,$$



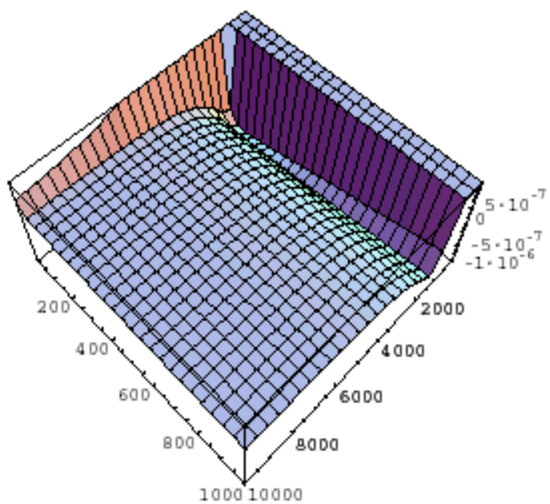
Fibre Inflatons

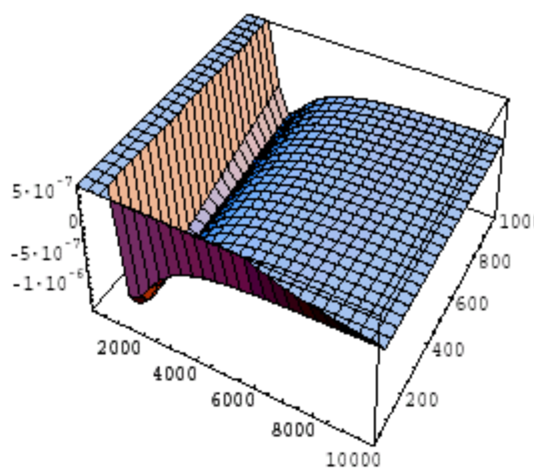
Burgess, Cicoli, FQ



$$\mathcal{V} = \alpha\left[\sqrt{\tau_1}(\tau_2 - \beta\tau_1) - \gamma\tau_3^{3/2}\right],$$

$$V = \frac{m_\varphi^2}{4}\left(3 - 4\,e^{-\kappa\hat{\varphi}/2} + e^{-2\kappa\hat{\varphi}}\right) \qquad \kappa = \frac{2}{\sqrt{3}}\,.$$





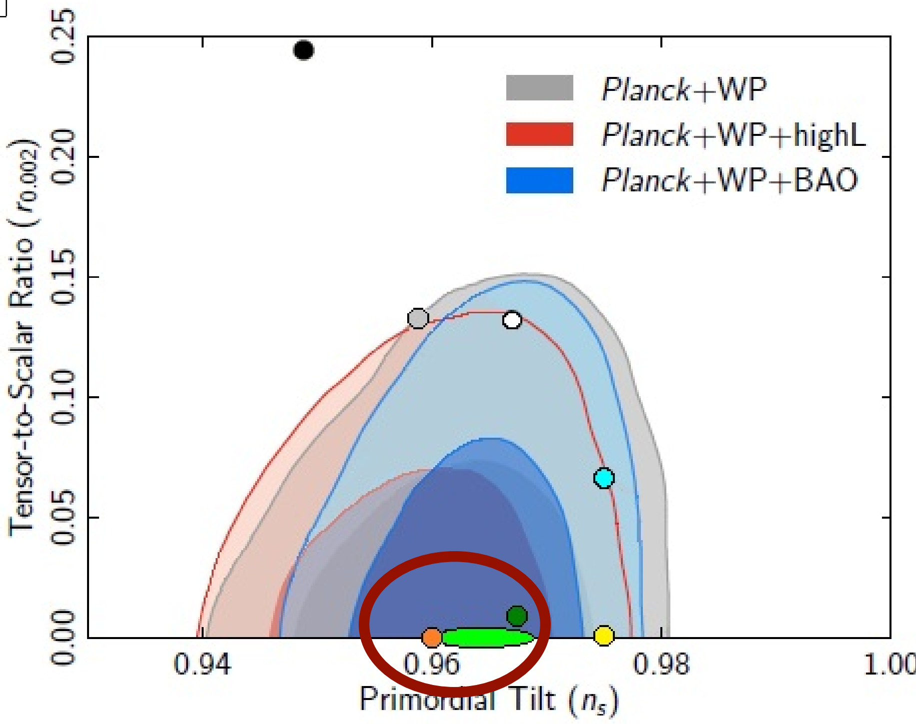
$$\varepsilon \simeq \frac{8}{3\left[3\,e^{\kappa\hat{\varphi}/2} - 4\right]^2},$$

$$\eta \simeq -\frac{4}{3\left[3\,e^{\kappa\hat{\varphi}/2} - 4\right]},$$

$$\varepsilon \simeq \frac{3\,\eta^2}{2}\,.$$

String Scenario	n_s	r
D3/$\overline{\text{D3}}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
Racetrack Inflation	$0.95 \leq n_s \leq 0.96$	$r \leq 10^{-8}$
N − flation	$0.93 \leq n_s \leq 0.95$	$r \leq 10^{-3}$
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$
Poly − instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

Overall, string inflation models in good shape after Planck 2013-2015



C. Burgess, M. Cicoli, FQ arXiv:1306.3512

Fibre vs Starobinsky Inflation

- Starobinsky α=1, Fibre α=2.

- Starobinsky from strings?

$$f(R) = R + \frac{a_2}{M^2}R^2 + \frac{a_3}{M^4}R^3 + \frac{a_4}{M^6}R^4 + \ldots.$$

$$V(\phi) = \frac{M^2}{2\kappa^2} e^{-2\sqrt{\frac{2}{3}}\phi}\left(U_0 + U_1 e^{\sqrt{\frac{2}{3}}\phi} + U_2 e^{2\sqrt{\frac{2}{3}}\phi} + U_3 e^{3\sqrt{\frac{2}{3}}\phi} + \ldots\right.$$

- Fibre very generic: Most known CY are fibrations (Anderson, Gray, et al 2015)

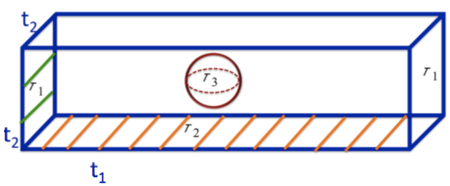
Summary of Fibre Inflation

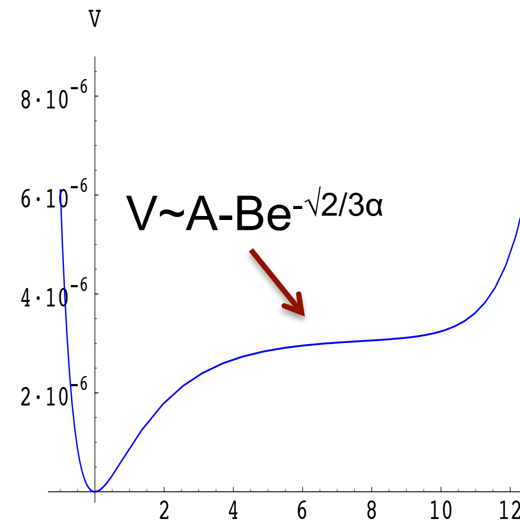
- String model of inflation with moduli stabilisation incorporated.
- Similar physics but much better rooted than Starobinsky duals (UV completion, tuning, etc.)
- Multi field generalisations (but only small non-gaussianities, Burgess et al 2010, 2012)
- Low l effects, α' inflation, global realisation (Cicoli et al. 2016)

Kahler+Fibre Inflation

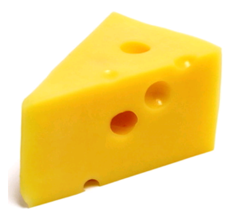
Stringy realisation of α-attractors

- $\alpha=2$ (fibre inflation) Burgess, Cicoli, FQ (2007)



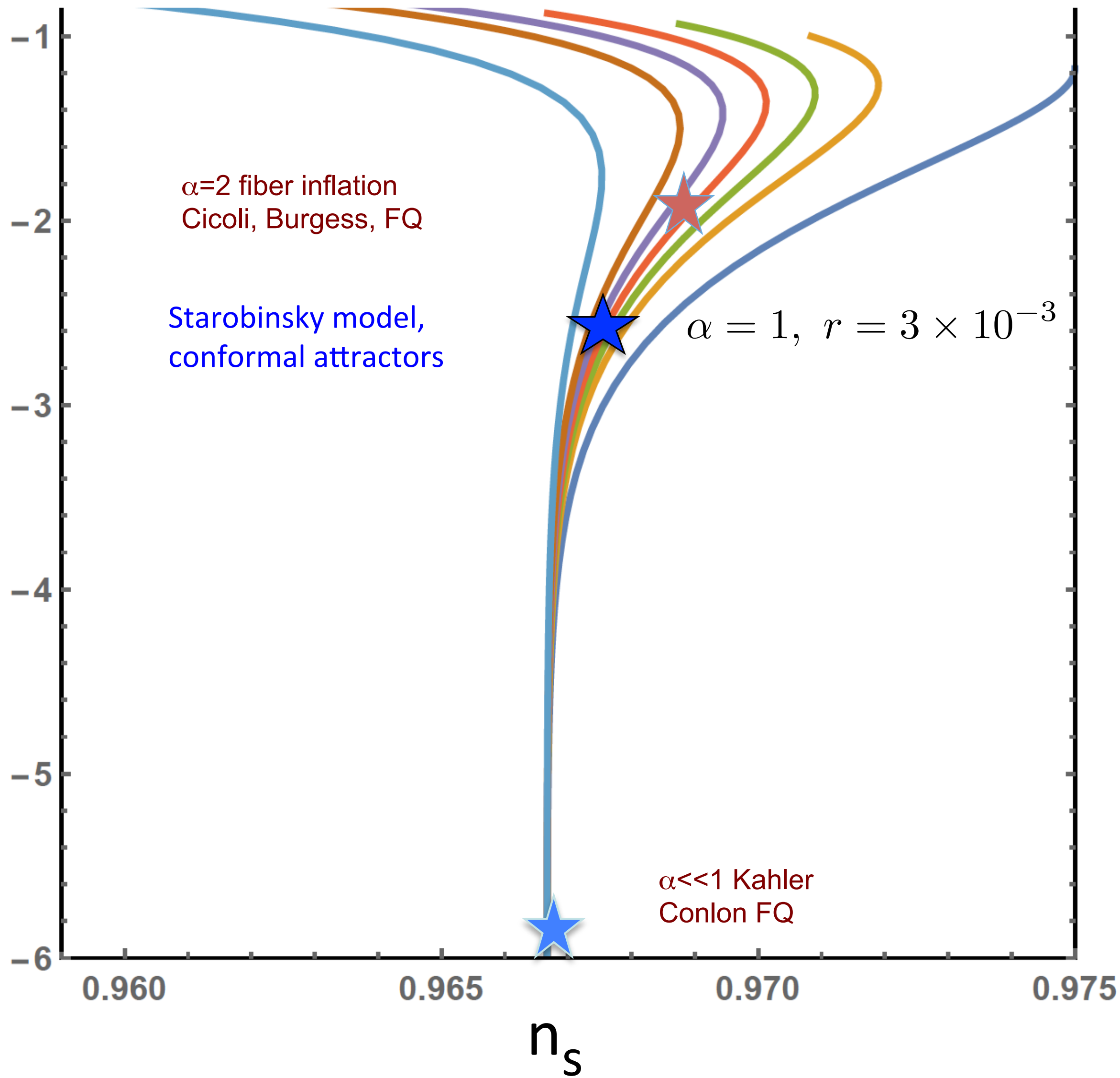


- $\alpha=(V\ln V)^{-1}$ (Kahler blow-up inflation)
- Conlon, FQ (2006)



- ...$\alpha=(\ln V)^{-1}$ (polyinstanton inflation) Cicoli, Pedro, Tasinato (2011)

Inflation: Fibre+Kahler

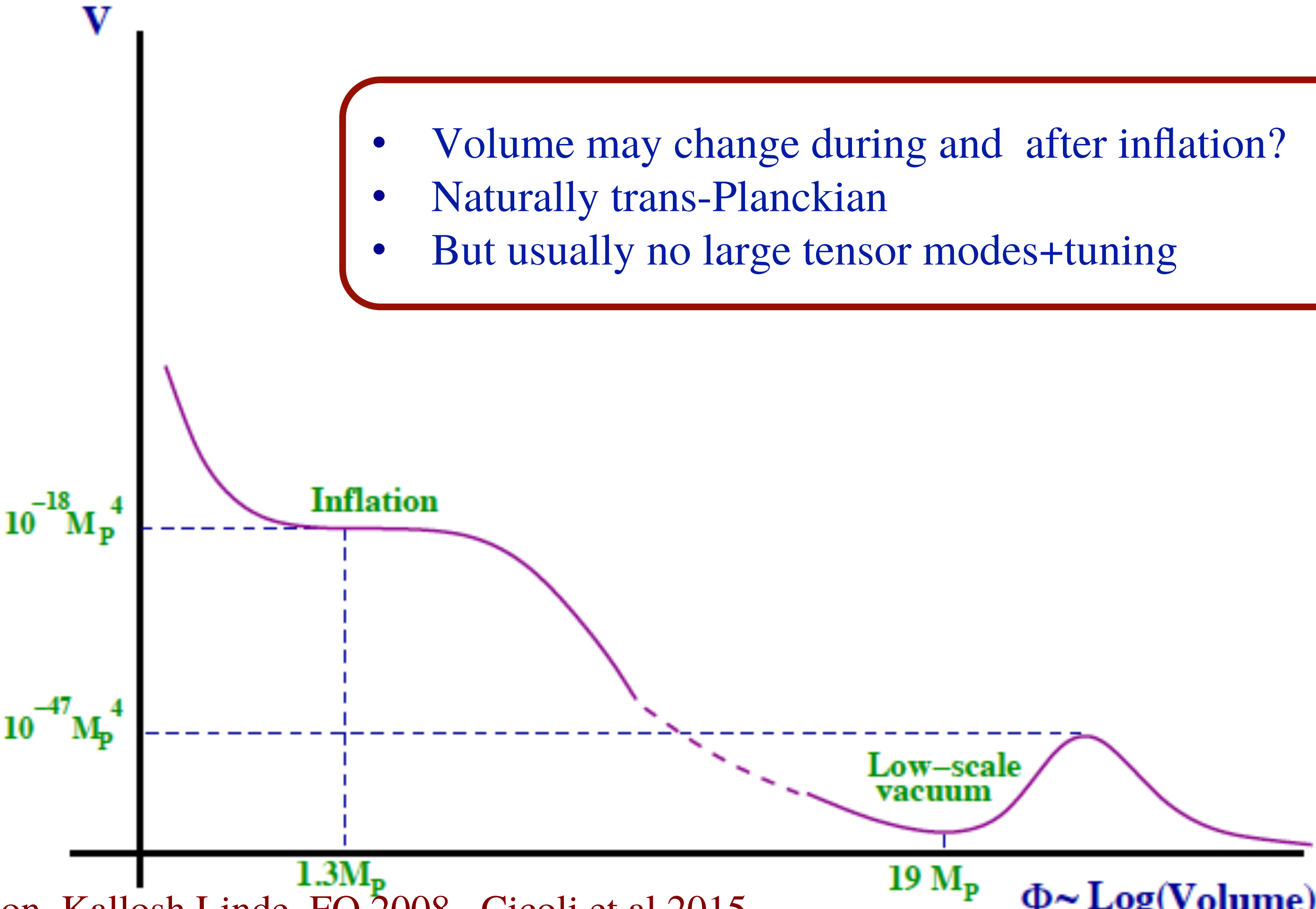


From Kallosh

Volume inflation?

(Inflation + ~~SUSY~~ Scales)

- Volume may change during and after inflation?
- Naturally trans-Planckian
- But usually no large tensor modes+tuning



Conlon, Kallosh,Linde, FQ 2008, Cicoli et al 2015

After Inflation

General prediction

Axion partner of the volume:
mass < exp(-volume) < 10^{-22} eV
Dark energy or matter and dark radiation

Cosmological Moduli Problem

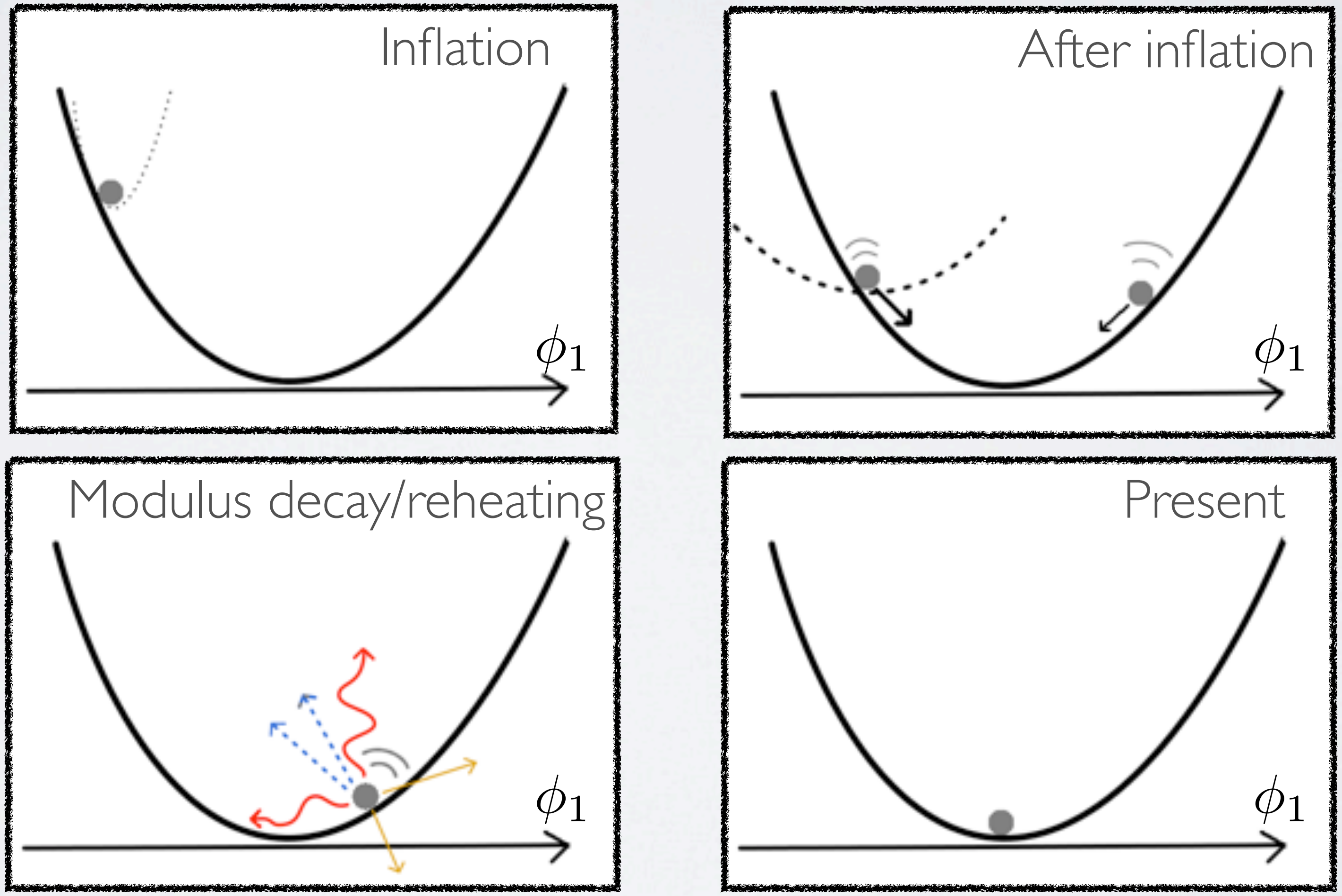
- Usually moduli masses = $m_{3/2}$

  (de Carlos et al 1993, Scrucca-Gomez-Reino 2008)
- And assume soft terms = $m_{3/2}$
- Identify $m_{3/2}$=1 TeV

But LVS is nongeneric scenario

- Volume modulus mass<<$m_{3/2}$
- So CMP more acute than expected!
- Unless $m_{3/2}$>> 1TeV

Cosmological Moduli ‘Problem’



$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$$

$T > O(1\ \text{MeV})$, so $m_\phi \gtrsim 3 \cdot 10^4\ \text{GeV}$

Coughlan et al 1983, Banks et al, de Carlos et al 1993

e.g. After Kahler Inflation

Explicit computation of Vacuum misalignement

$$Y = \frac{\delta\varphi}{M_{\rm pl}} = \sqrt{\frac{2}{3}}\delta\phi \simeq 2\sqrt{\frac{2}{3}}R\phi_* \simeq 0.1 - 1$$

M.Cicoli, K. Dutta, A. Maharana, FQ
arXiv:1604.08512

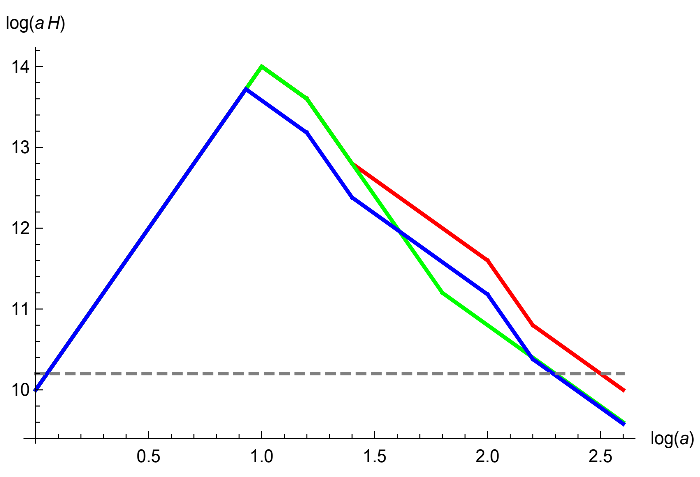
Number of efoldings:

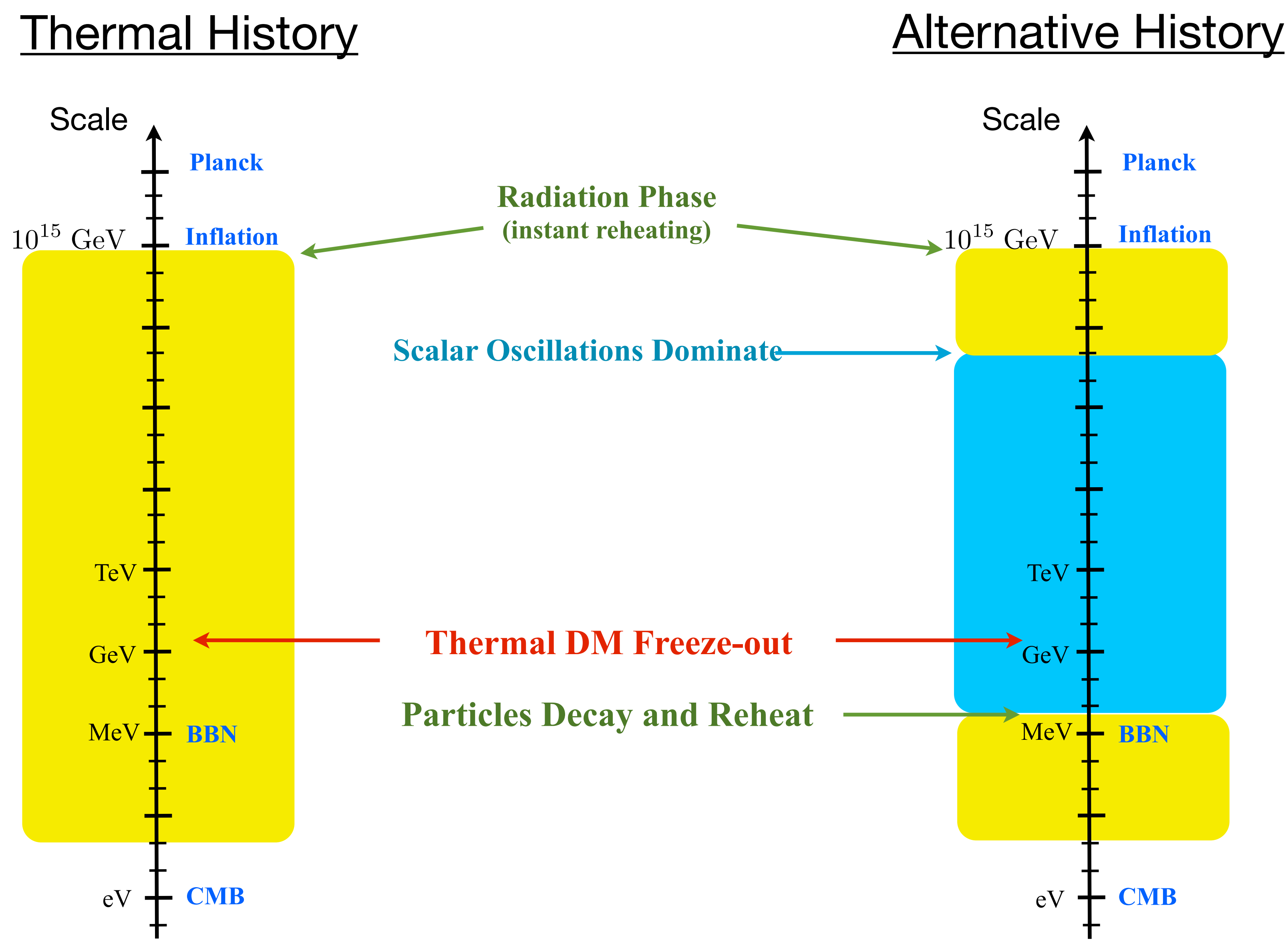
$$N_e + \frac{1}{4}N_{\rm mod} + \frac{1}{4}(1-3w_{\rm re})N_{\rm re} \approx 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{\rm end}}\right)$$

$$\left(55 - \frac{1}{4}N_{\rm mod}\right) \pm 5$$

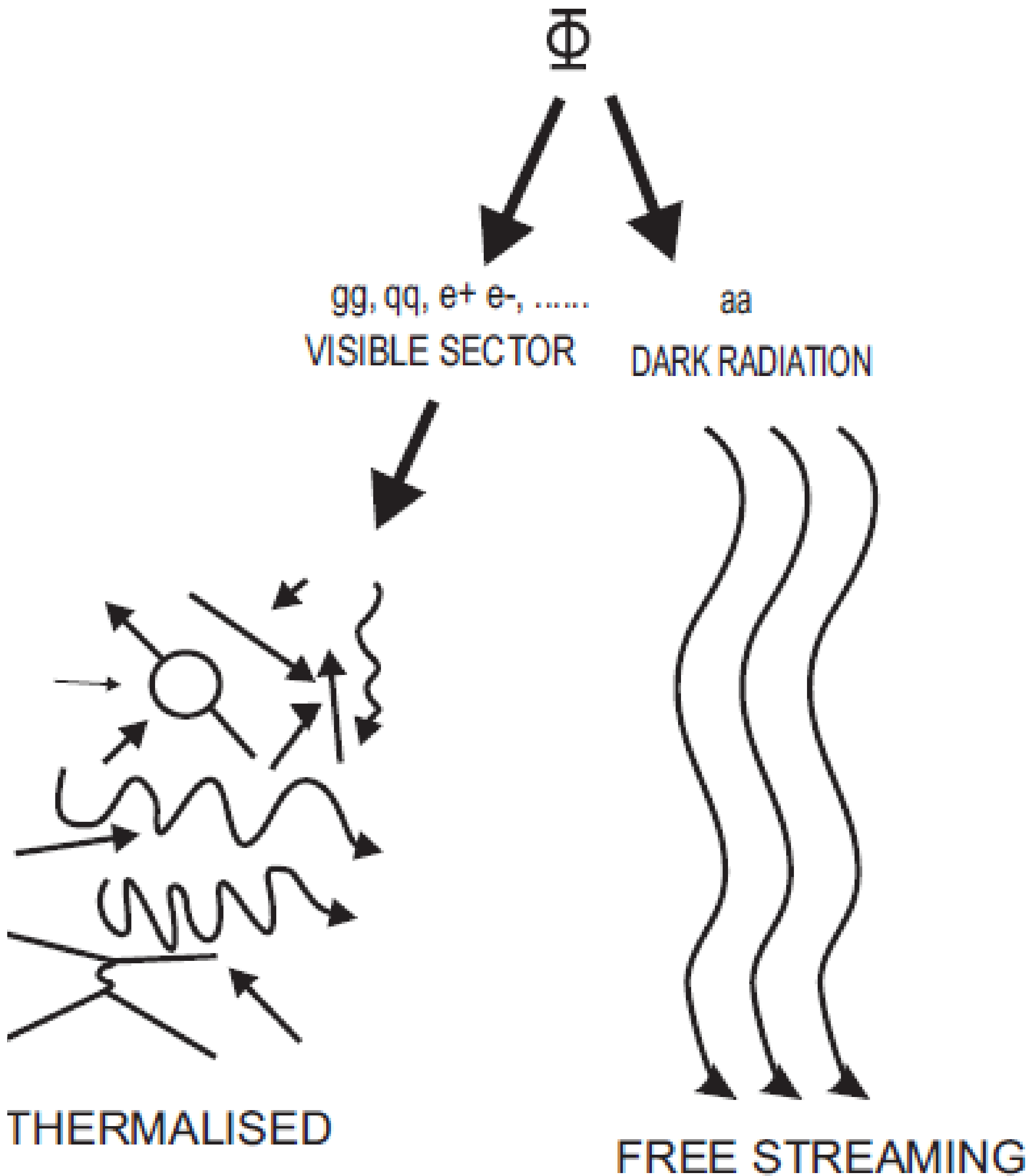
$$N_{\rm mod2} \approx \frac{2}{3}\ln\left(\frac{16\pi\mathcal{V}^{5/2}(\ln\mathcal{V})^{5/2}Y^4}{10\beta^2}\right)$$

$$N_e \simeq 44.65 + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{\rm end}}\right) \simeq 45 \qquad n_s \simeq 0.955\,.$$





From S. Watson, SUSY 2013


Φ
gg, qq, e+ e-, ...
VISIBLE SECTOR
aa
DARK RADIATION
THERMALISED
FREE STREAMING

Volume Reheating*

*Sequestered scenarios

M.Cicoli, J.P. Conlon, FQ arXiv:1208.3562
T. Higaki, F.Takahashi arXiv:1208.3563

$$\Gamma_{\Phi\to a_b a_b} = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}.$$

Volume axion a_b

$$\Gamma_{\Phi\to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}.$$

Higgses

$$\Gamma_{\Phi\to BB} = \left(\frac{\lambda}{3/2}\right)^2 \frac{9}{16}\frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Closed string axions

$$\Gamma_{\Phi\to C\bar{C}} \sim \frac{m_0^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

Matter scalars C

$$T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_{Pl}^{1/2}} \sim 0.6 \text{ GeV} \left(\frac{m_\Phi}{10^6 \text{GeV}}\right)^{3/2}.$$

Dark Radiation

Energy density:

$$\rho_{total} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right).$$

Standard Model N_{eff}=3.04

At CMB: WMAP, ACT, SPT

$$3.12\,\kappa \le \Delta N_{eff} \le 3.48\,\kappa$$
$$\kappa = (1 + 9n_a/16)/n_H Z^2$$

Simplest Z=1:

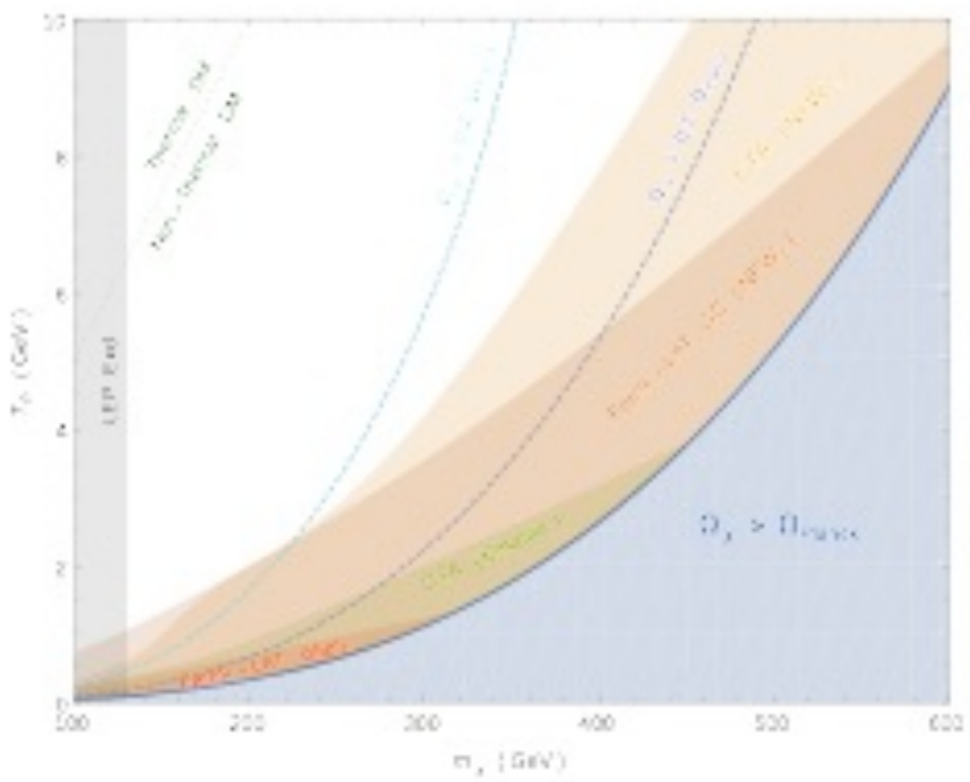
$$1.56 \le \Delta N_{eff} \le 1.74$$

General: Strong constraints on matter and couplings!

$$0.14 \lesssim \Delta N_{\rm eff} \lesssim 1.6$$

Cicoli+Muia 2016

MSSM: Non-thermal Higgsino DM



Model independent indirect search 300-600 GeV Higgsinos
all others multi TeV

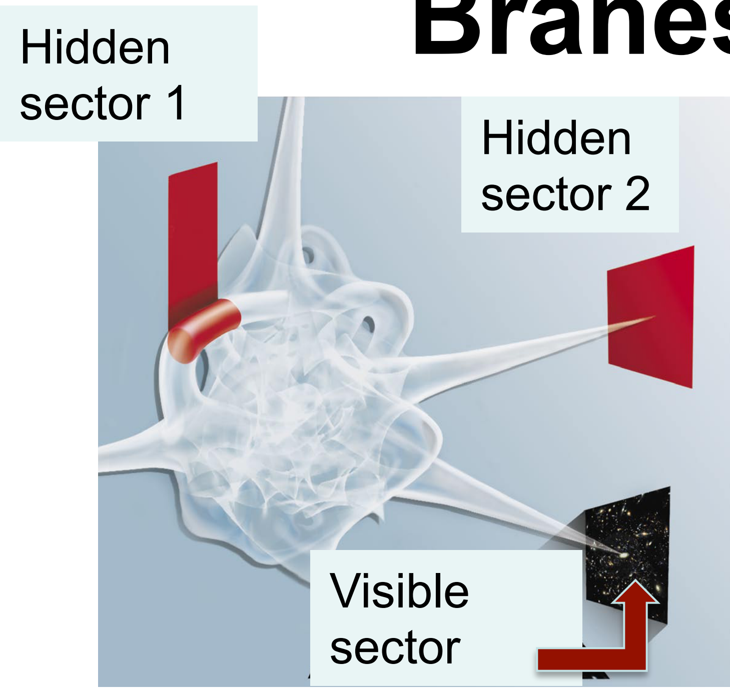
CONCLUSIONS

- Several stringy (EFT) de Sitter scenarios
- Several inflationary scenarios with concrete predictions (blow-up: r<<1, low-energyy SUSY, loops? Fibre: r<0.01, too large SUSY scale)
- CMP: after inflation signature of strings (e.g. dark radiation, non-thermal MSSM,...)
- Most known ingredients used (stringy vs simplicity): geometry, fluxes, branes, perturbative, non-perturbative effects

De Sitter 3:

DILATON DEPENDENT NON-PERTURBATIVE EFFECTS (ON LVS)

Hidden Sector on Branes@Singularities



Burgess, Cicoli, Maharana, FQ 2012

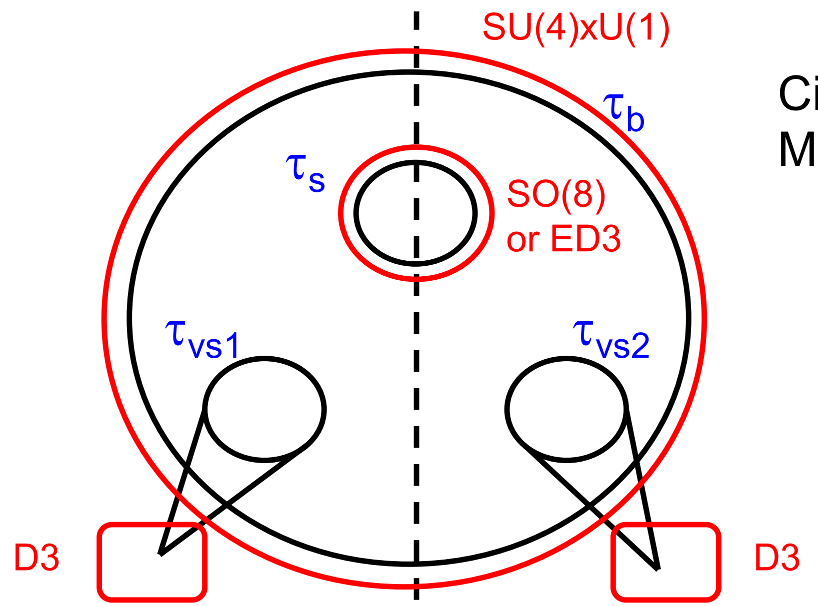
$$W_{\rm np} = A\, e^{-\,a\,T} + B\, e^{-\,b\,(S+hQ)}$$

$$V = V_{\rm LVS} + V_{\rm up}$$

$$V_{\rm up} \propto h^2\, \frac{e^{-2b\langle s\rangle}}{\mathcal{V}}\,,$$

Not explicit CY realisation yet

CONCRETE COMPACT CY



Cicoli, Klevers, Krippendorf, Mayhofer, FQ, Valandro 2013

$$V_{\rm tot} = V_D + V_F = \frac{1}{2\mathcal{V}^{2/3}}\left(\frac{q_\phi}{s}|\phi_{\rm ds}|^2 - \frac{3q_b}{8\pi\mathcal{V}^{2/3}}\right)^2 + \frac{1}{s}m_{3/2}^2|\phi_{\rm ds}|^2 + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

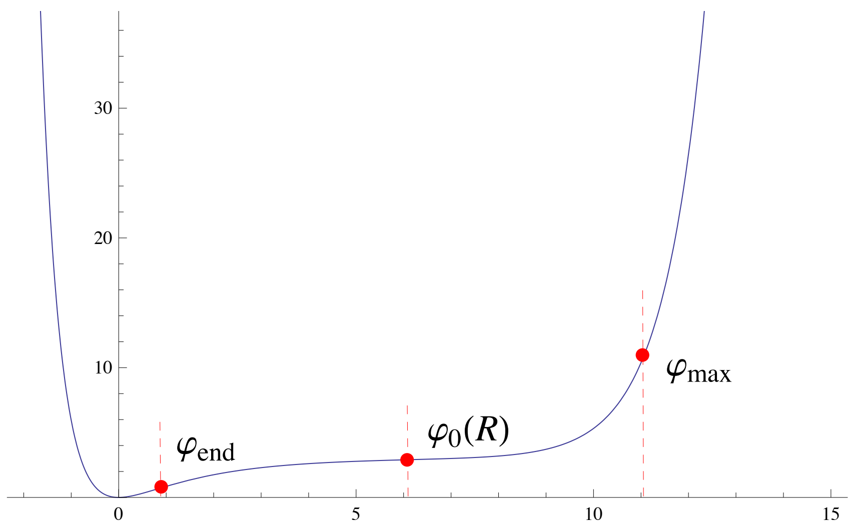
$$V_{\rm tot} = V_{D,0} + \frac{3q_b}{16\pi q_\phi}\frac{W_0^2}{s\mathcal{V}^{8/3}} + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$\mathbf{V_{uplift}}$

Also from T-Branes (M. Cicoli, FQ, R. Valandro)

Enhancing the value of r?

$$V \simeq \frac{\mathcal{C}_2}{\langle \mathcal{V} \rangle^{10/3}} \left[(3-R) - 4\left(1+\frac{1}{6}R\right) e^{-\kappa\hat{\varphi}/2} + \left(1+\frac{2}{3}R\right) e^{-2\kappa\hat{\varphi}} + R\, e^{\kappa\hat{\varphi}} \right]$$



R<<1

- $n_s = 0.98$ and r=0.01 for $N_e \simeq 50$
- $n_s = 0.99$ and r=0.01 for $N_e \simeq 60$

May need Neff>3.04?

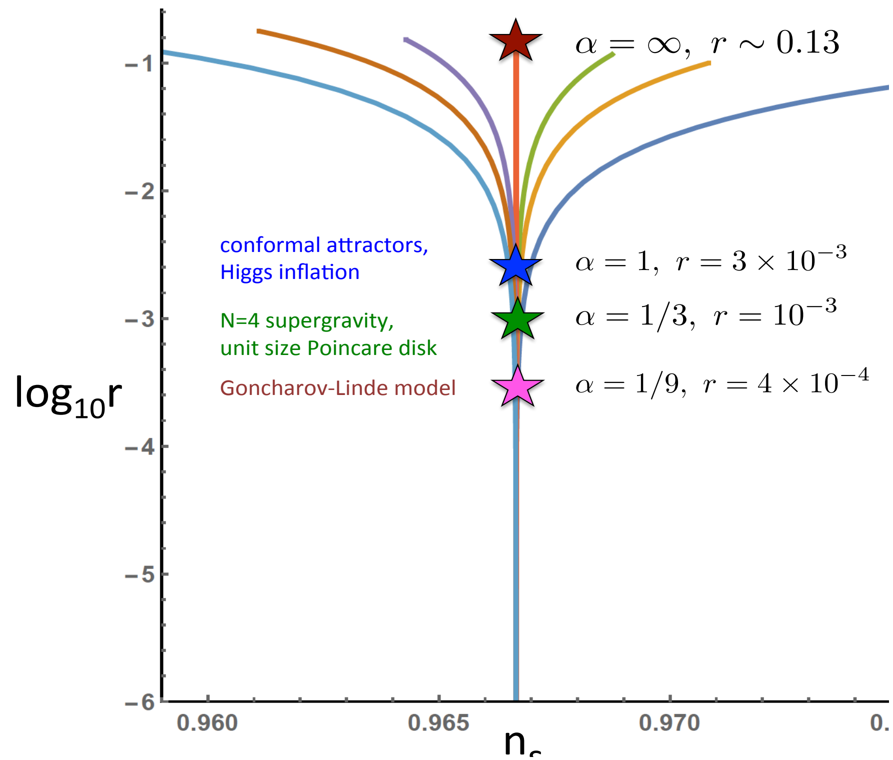
Comments on α-attractors

Kallosh and Linde

$$K = -3\alpha \ln(T + \bar{T}) \qquad \mathcal{R}_K = -\frac{2}{3\alpha}$$

Moduli space curvature

$$n_s = 1 - \frac{2}{N}\,, \qquad r = \alpha \frac{12}{N^2}\,, \qquad r \approx 3\,\alpha \times 10^{-3}$$



Questions:

Quantum corrections?

Stringy realisation?

e.g. Non-Thermal Dark-Matter (MSSM)

- KKLT: gravitino decay
- KKLT: D7 Higgsino overproduction
- KKLT:D3 small region allowed Higgsino DM

- LVS: Volume decay
- LVS:D7 Higgsino overproduction
- LVS: D3: allowed region to be constrained by 1Ton (Xenon, CTA) and 100TeV (not LHC).

L. Aparicio, M. Cicoli, B Dutta, F. Muia + FQ

arXiv:1607.00004