Recent progress in string cosmology

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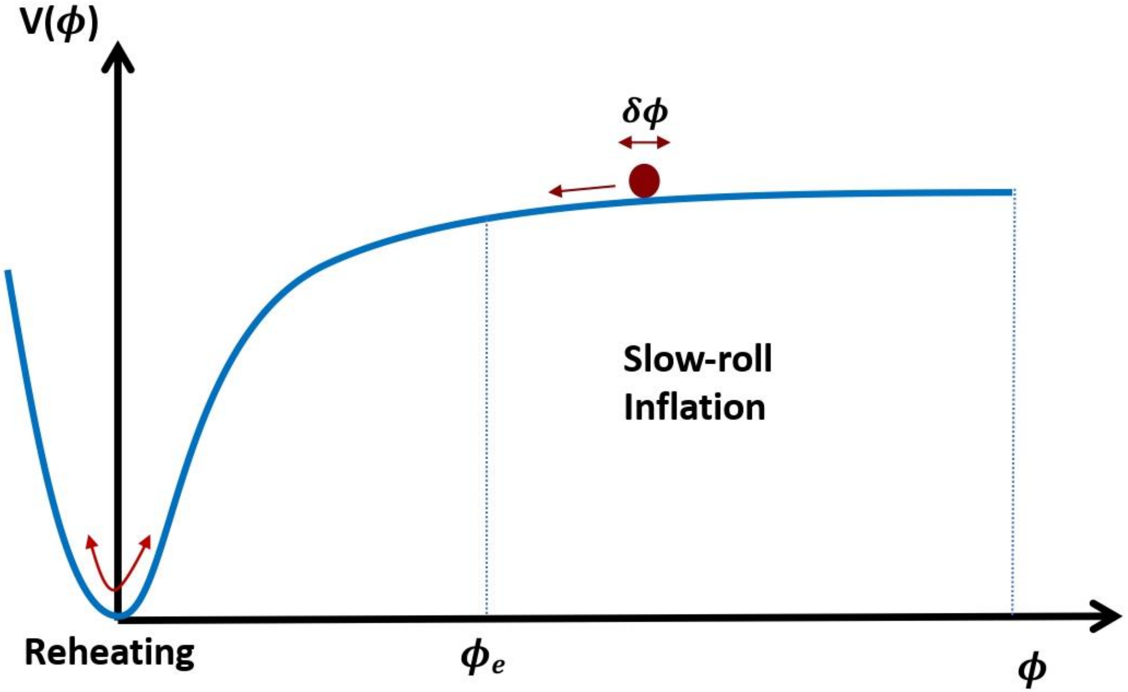
Based on recent papers in collaboration with:

Bansal, Brunelli, Chauhan, Cunillera, Grassi, Hebecker, Hughes, Kamal, Krippendorf, Kuespert, Lacombe, Maharana, Marino, Padilla, Piantadosi, Pedro, Quevedo, Ramos-Hamud, Schachner, Villa

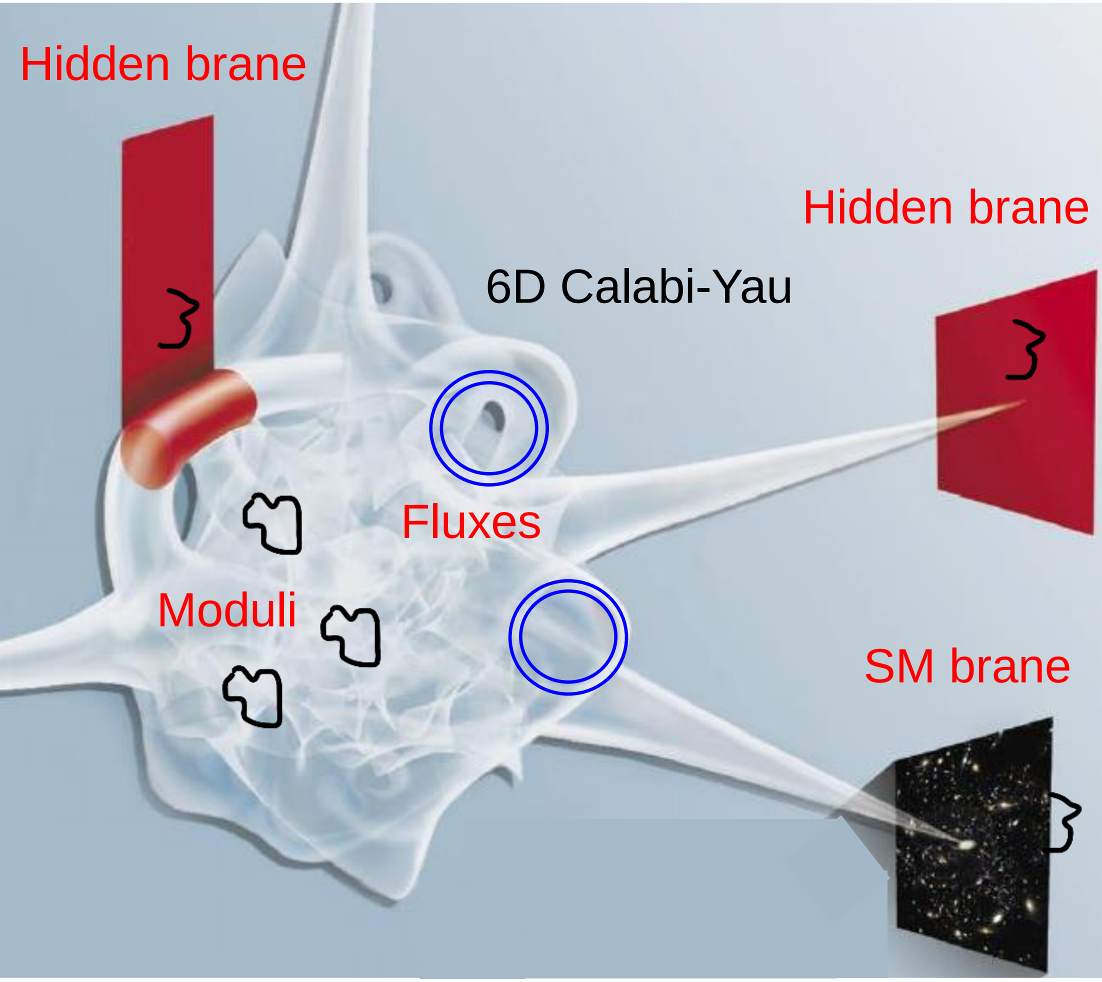
Inflation

Standard slow-roll



$$V(\phi) = V_0[1 - g(\phi)] \simeq V_0$$ since $g(\phi) \ll 1$ for $\phi \gg 1$

4D string models

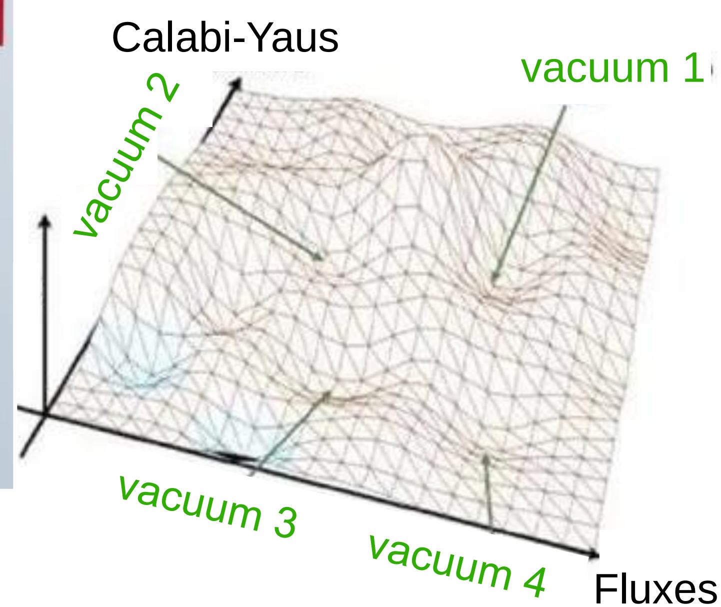


10D string theory compactified on 6D CY

KK 0-modes of 10D metric yield 4D moduli ϕ

ϕ-dependent EFT: $g_{YM}(\phi)$, $Y_{ijk}(\phi)$, $M_{SUSY}(\phi)$, $m_\phi(\phi)$, $H_{inf}(\phi)$, $\Lambda(\phi)$, …

Moduli stabilisation: generate $V(\phi)$ to fix $<\phi>$ at minimum



Landscape of string vacua ⟶ vacua which reproduce SM + slow-roll inflation driven by ϕ

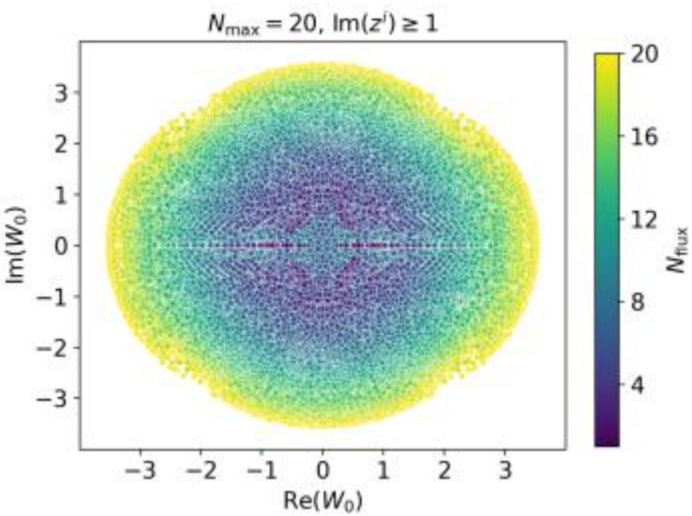
Numerical flux vacua

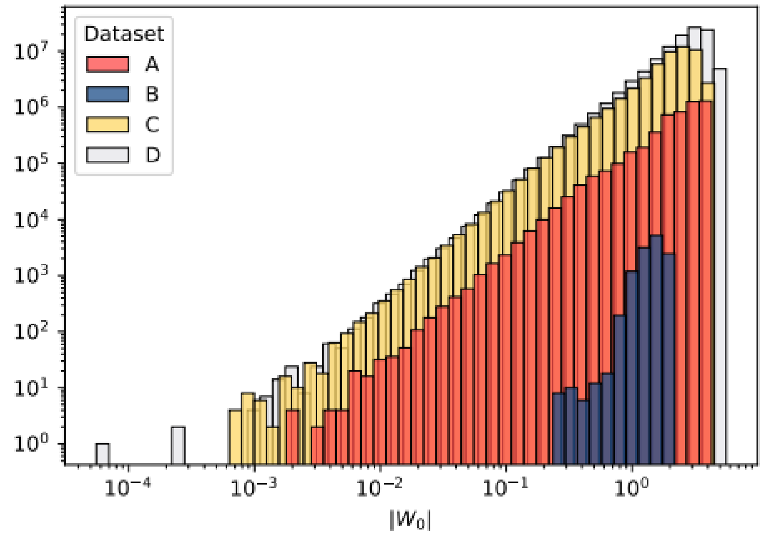
[Chauhan,MC,Krippendorf,Maharana,Piantadosi,Schachner]

- Numerical searches of flux vacua using Machine Learning (JAXVacua)
- Exhaustive searches in targeted regions of moduli space
- No continuous flux approx. ⟶ distribution of actual flux vacua beyond [Denef,Douglas]
- Example with $h^{1,2} = 2$:

Name	$\mathrm{Im}(z^i)$	s	$N_{\max}$	$\#h$	$\#f$	$\#(f,h)$	$\mathcal{N}_{\mathrm{vac}}$	exhaustive[7]
A	$[2,3]$	$[\frac{\sqrt{3}}{2},20]$	34	82,082	1,849,426	5,134,862	5,140,872	Yes
B	$[2,5]$	$[\frac{\sqrt{3}}{2},10]$	10	1,900	6,340	12,160	12,196	Yes
C	$[1,10]$	$[\frac{\sqrt{3}}{2},50]$	34	3,652,744	21,043,832	50,652,686	50,884,086	No
D	$[2,10]$	$[\frac{\sqrt{3}}{2},10]$	50	5,909,012	45,886,900	123,075,206	123,408,240	No

Dataset	$\min(\lvert W_0\rvert)_{\mathrm{obs}}$	$\min(\lvert W_0\rvert)_{\mathrm{stat}}$
A	1.789×10^{-3}	2.192×10^{-3}
B	2.354×10^{-1}	2.546×10^{-2}
C	6.305×10^{-4}	3.872×10^{-4}
D	5.547×10^{-5}	3.324×10^{-4}





+ distribution of g_s and moduli masses

Inflating with string moduli

- Slow-roll picture with inflaton ϕ reproduced with type IIB Kaehler moduli τ

- Volume mode $\mathcal{V}$ couples to all sources of energy due to $e^K = \mathcal{V}^{-2}$

  → cannot have a ϕ-independent plateau if $\phi \equiv \mathcal{V}$

  → ϕ should be a direction $\perp$ $\mathcal{V}$: $\phi \equiv \tau_\phi$

- Since each term in V depends on $\mathcal{V}$, $V(\phi) \simeq V_0$ only if leading dynamics fixes $\mathcal{V}$ but not τ_ϕ

  → $\phi \equiv \tau_\phi$ is a leading order flat direction with an approximate shift symmetry

  [Burgess,MC,Quevedo,Williams][Burgess,MC,deAlwis,Quevedo]

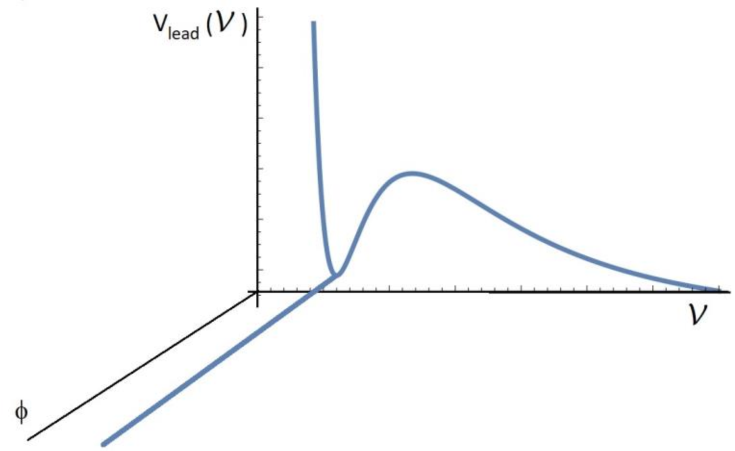
- Type IIB Kaehler sector: tree-level no-scale cancellation + 1-loop extended no-scale

  [MC,Conlon,Quevedo]

- Leading no-scale breaking $O(\alpha'^3)$ effects lift only $\mathcal{V}$

  → ϕ lifted by subdominant quantum effects can drive slow-roll inflation

Leading dynamics



- Total potential with 1 leading order flat direction τ_ϕ:

$$V_{tot}(\mathcal{V},\tau_\phi) = V_{lead}(\mathcal{V}) - V_{sub}(\mathcal{V},\tau_\phi)$$

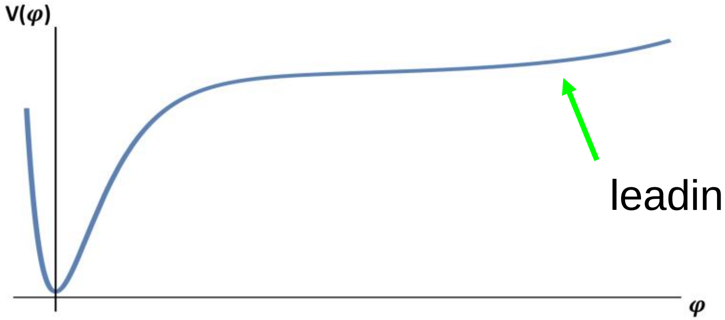
- Setting $\mathcal{V} = \langle\mathcal{V}\rangle$, $V_{tot}(\langle\mathcal{V}\rangle,\tau_\phi)$ becomes:

$$\boxed{V(\phi) = V_0[1-g(\phi)]}$$

with:

$$V_0 \equiv V_{sub}(\langle\mathcal{V}\rangle,\langle\tau_\phi\rangle) \qquad \text{and} \qquad g(\phi) \equiv \frac{V_{sub}\left(\langle\mathcal{V}\rangle,\tau_\phi(\phi)\right)}{V_{sub}(\langle\mathcal{V}\rangle,\langle\tau_\phi\rangle)} \ll 1 \quad \text{for} \quad \phi \gg 1$$

- $\tau_\phi(\phi)$ determined by canonical normalisation



String inflation potentials

Function $g(\phi)$ depends on 2 features:

1. Origin of effects which generate $V_{\rm sub}\left(\langle\mathcal{V}\rangle, \tau_\phi\right)$:

- Perturbative effects:

$$V_{\rm sub}\left(\langle\mathcal{V}\rangle, \tau_\phi\right) \propto \frac{1}{\tau_\phi^p} \longrightarrow 0 \quad \text{for} \quad \tau_\phi \to \infty \ \ \text{if} \ \ p > 0$$

- Non-perturbative effects:

$$V_{\rm sub}\left(\langle\mathcal{V}\rangle, \tau_\phi\right) \propto {\rm e}^{-{\rm k}\tau_\phi} \longrightarrow 0 \quad \text{for} \quad \tau_\phi \to \infty \ \ \text{if} \ \ {\rm k} > 0$$

2. Topology of τ_ϕ which determines $\tau_\phi(\phi)$ (canonical normalisation):

- Bulk (fibre) modulus:

$$\tau_\phi = e^{\lambda\phi} \qquad \text{with} \qquad \lambda \sim \mathcal{O}(1)$$

- Local (blow-up) modulus:

$$\tau_\phi = \mu\, \mathcal{V}^{2/3}\, \phi^{4/3} \qquad \text{with} \qquad \mu \sim \mathcal{O}(1)$$

String inflation potentials

$$V(\phi) = V_0[1 - g(\phi)]$$

- Non-perturbative Blow-up Inflation:

$$g(\phi) \propto e^{-k\mu \mathcal{V}^{2/3} \phi^{4/3}} \ll 1 \quad \text{for} \quad \phi > 0$$

[Conlon,Quevedo]
[Bond,Kofman,Prokushkin,Vaudrevange]

- Non-perturbative Fibre Inflation:

$$g(\phi) \propto e^{-k\, e^{\lambda\phi}} \ll 1 \qquad \text{for} \quad \phi > 0$$

[MC,Pedro,Tasinato][Luest,Zhang]

- Loop Fibre Inflation:

$$g(\phi) \propto e^{-p\lambda\phi} \ll 1 \qquad \text{for} \quad \phi > 0$$

[MC,Burgess,Quevedo]
[Broy,Ciupke,Pedro,Westphal]
[MC,Ciupke,deAlwis,Muia]

Explicit realisation: CY with $h^{1,1} = 4$ from toric geometry, O3/O7, D3 and D7-tadpole cancellation, chirality, moduli stabilisation, dS from anti-D3, inflation [MC,Grassi,Lacombe,Pedro]

- Loop Blow-up Inflation:

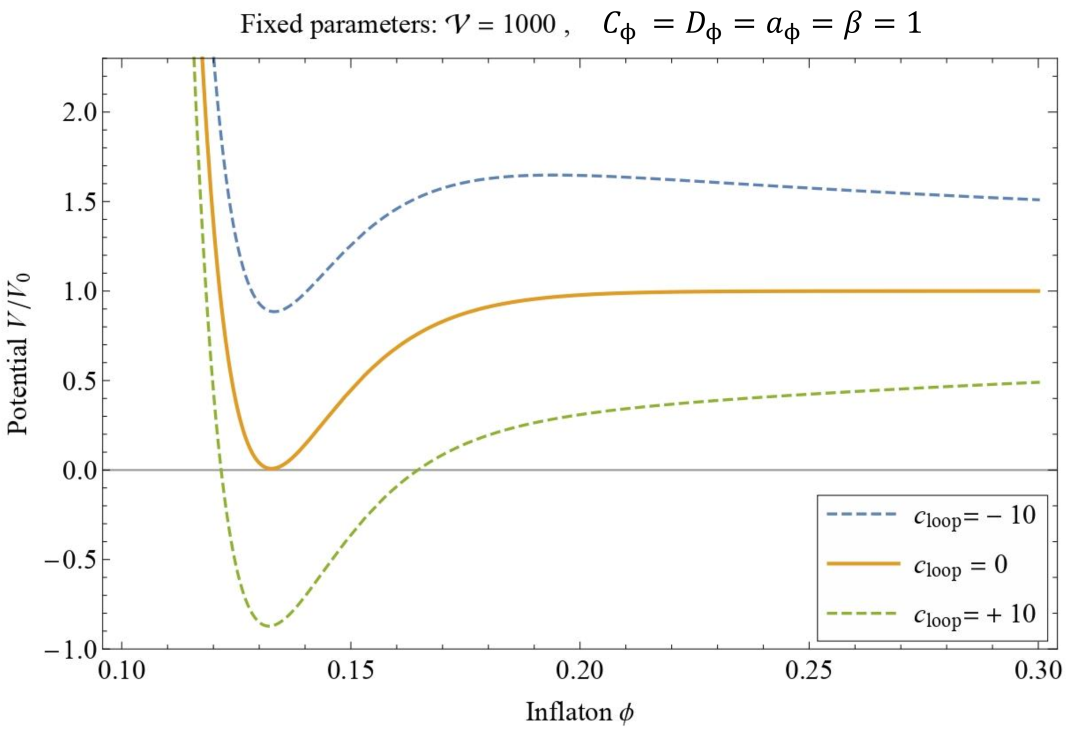
$$g(\phi) \propto \frac{1}{\mathcal{V}^{1/3}\, \phi^{2/3}} \ll 1 \quad \text{for} \quad \phi \lesssim 1$$

[Bansal,Brunelli,MC,Hebecker,Kuespert]

Blow-up Inflation

- Total potential including string loops: [Bansal,Brunelli,MC,Hebecker,Kuespert]

$$V(\tau_\phi) = C_0\left[\frac{\beta}{\mathcal{V}^3} + C_\phi\,\frac{\sqrt{\tau_\phi}\,e^{-2a_\phi\tau_\phi}}{\mathcal{V}} - D_\phi\,\frac{\tau_\phi\,e^{-a_\phi\tau_\phi}}{\mathcal{V}^2} - \frac{c_{loop}}{\mathcal{V}^3\sqrt{\tau_\phi}}\right] \qquad \phi = \sqrt{\frac{4}{3\mathcal{V}}}\,\tau_\phi^{3/4}$$



- Non-perturbative blow-up inflation [Conlon,Quevedo] requires $c_{loop} \ll 10^{-6}$
- For $c_{loop} \gtrsim 10^{-6}$ potential in inflationary region is:

$$V \simeq C_0\left(\frac{\beta}{\mathcal{V}^3} - \frac{c_{loop}}{\mathcal{V}^3\sqrt{\tau_\phi}}\right) = \boxed{V_0\left(1 - \frac{c_{loop}}{\mathcal{V}^{1/3}\phi^{2/3}}\right)}$$

Inflationary dynamics

- Slow-roll parameters:

$$\epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 \simeq \frac{2}{9}\frac{c_{\text{loop}}^2}{\mathcal{V}^{2/3}\phi^{10/3}}$$

$$\eta = \frac{V_{\phi\phi}}{V} \simeq -\frac{10}{9}\frac{c_{\text{loop}}}{\mathcal{V}^{1/3}\phi^{8/3}}$$

- Cosmological observables:

$$N_{\text{e}} = \int_{\phi_{\text{end}}}^{\phi_*} \frac{\text{V}}{\text{V}_\phi}\, d\phi \simeq \frac{9}{16}\frac{\mathcal{V}^{1/3}\phi_*^{8/3}}{c_{\text{loop}}}$$

$$\hat{A}_s = \frac{9V_0}{4}\frac{\mathcal{V}^{2/3}\phi_*^{10/3}}{c_{\text{loop}}^2} \simeq 2.5 \times 10^{-7}$$

$$\phi_* = 0.06\, N_e^{7/22}$$

$$\mathcal{V} = 1743\, N_e^{5/11}$$

$$c_{\text{loop}} \simeq \frac{1}{16\pi^2}$$

$$n_s = 1 + 2\eta - 6\epsilon \simeq 1 - \frac{20}{9}\frac{c_{\text{loop}}}{\mathcal{V}^{1/3}\phi_*^{8/3}}$$

$$r = 16\,\epsilon \simeq \frac{32}{9}\frac{c_{\text{loop}}^2}{\mathcal{V}^{2/3}\phi_*^{10/3}}$$

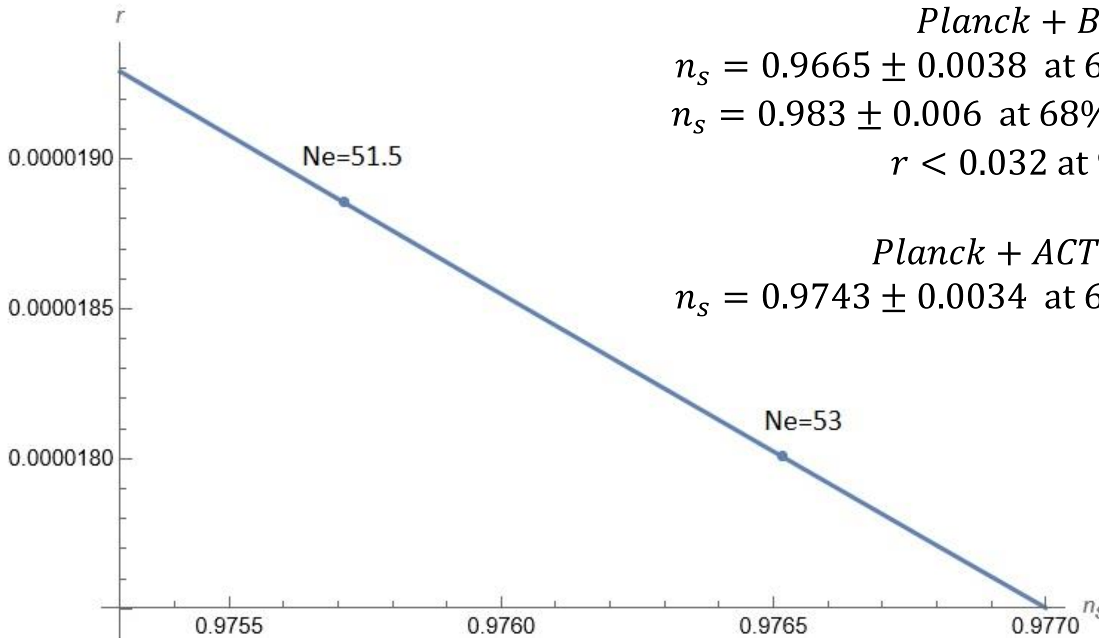
$$n_s \simeq 1 - \frac{1.25}{N_e} \qquad r \simeq \frac{0.004}{N_e^{15/11}}$$

→

$$r \simeq 0.003(1 - n_s)^{15/11}$$

Cosmological predictions

$$r \simeq 0.003(1-n_s)^{15/11}$$



$Planck + BICEP$:

$n_s = 0.9665 \pm 0.0038$ at 68% CL for $\Delta N_{eff} = 0$

$n_s = 0.983 \pm 0.006$ at 68% CL for $\Delta N_{eff} = 0.39$

$r < 0.032$ at 98% CL

$Planck + ACT + DESI$:

$n_s = 0.9743 \pm 0.0034$ at 68% CL for $\Delta N_{eff} = 0$

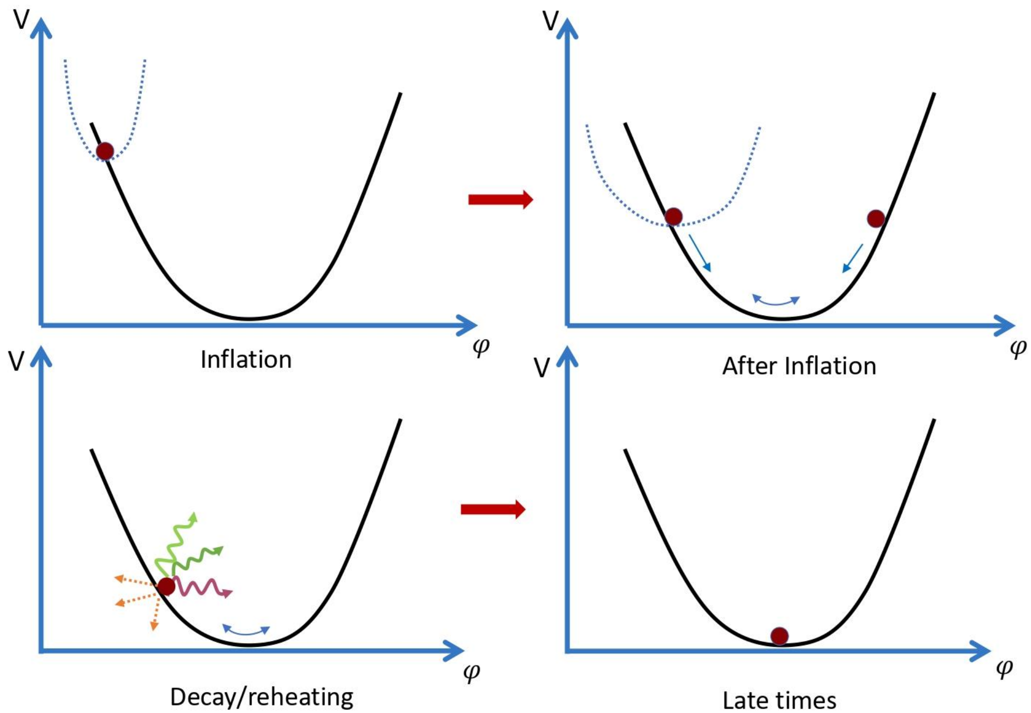
for $51.5 \lesssim N_e \lesssim 53$ $\quad$ n_s in agreement with CMB data $\quad$ $r \simeq 2 \times 10^{-5}$

determined by post-inflationary evolution

N_e from post-inflation

$$N_e \simeq 57 + \frac{1}{4}\ln r - \frac{1}{4}N_\phi - \frac{1}{4}N_\chi + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho(t_{\rm end})}\right)$$

τ_ϕ domin. $\mathcal{V}$ domin.



$\varphi \equiv \tau_\phi$ or $\mathcal{V}$

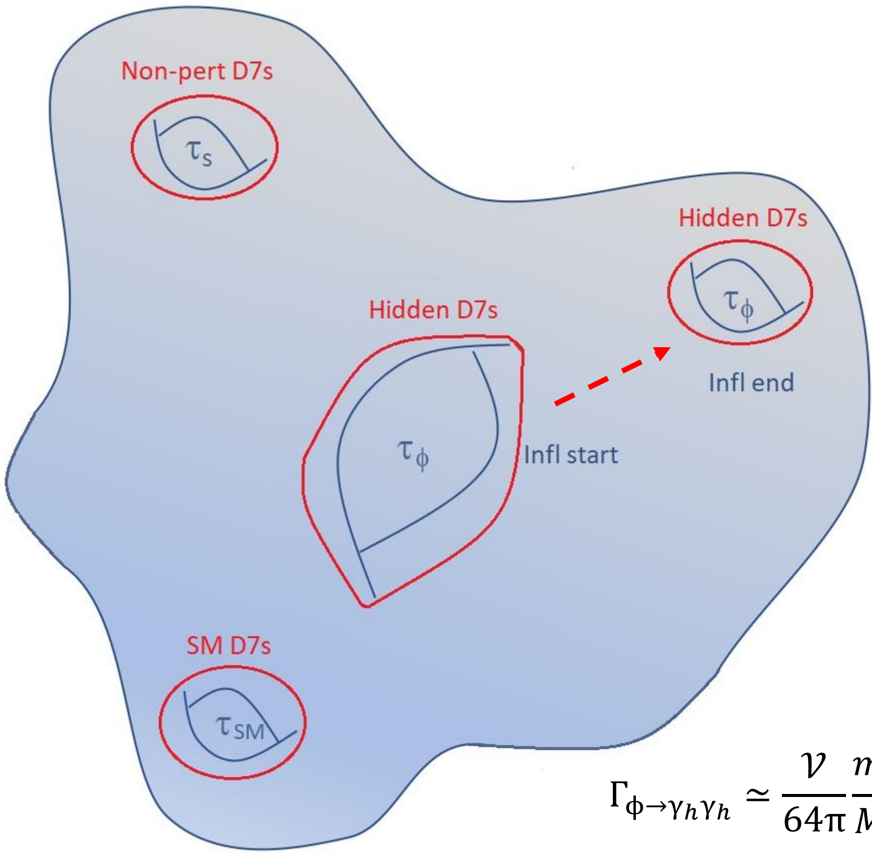
φ

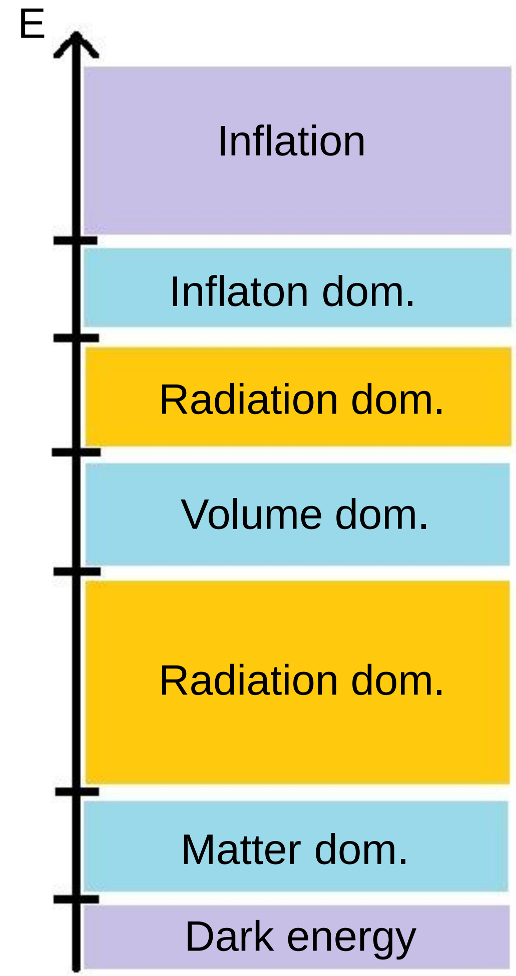
$\Gamma_{\varphi\to SM}$ $\Gamma_{\varphi\to\vartheta_b\vartheta_b}$

SM dof τ_b axions → $\Delta N_{\rm eff} \neq 0$

$\Delta N_{\rm eff} \lesssim 0.15 - 0.35$ at 95% CL

SM on D7s and inflaton wrapped by D7s





$N_e \simeq 53$

$N_\phi \simeq 1$

$\phi \to \gamma_h \gamma_h$

$N_\chi \simeq 3$

$\chi \to hh$

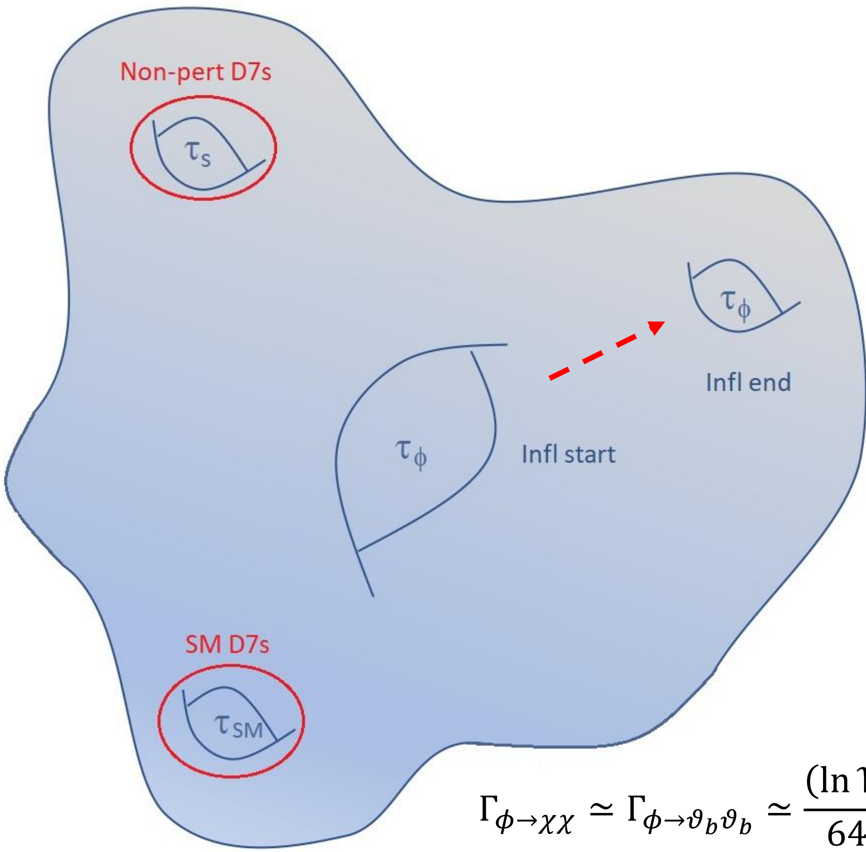
$$\Gamma_{\phi\to\gamma_h\gamma_h} \simeq \frac{\mathcal{V}}{64\pi}\frac{m_\phi^3}{M_p^2}$$

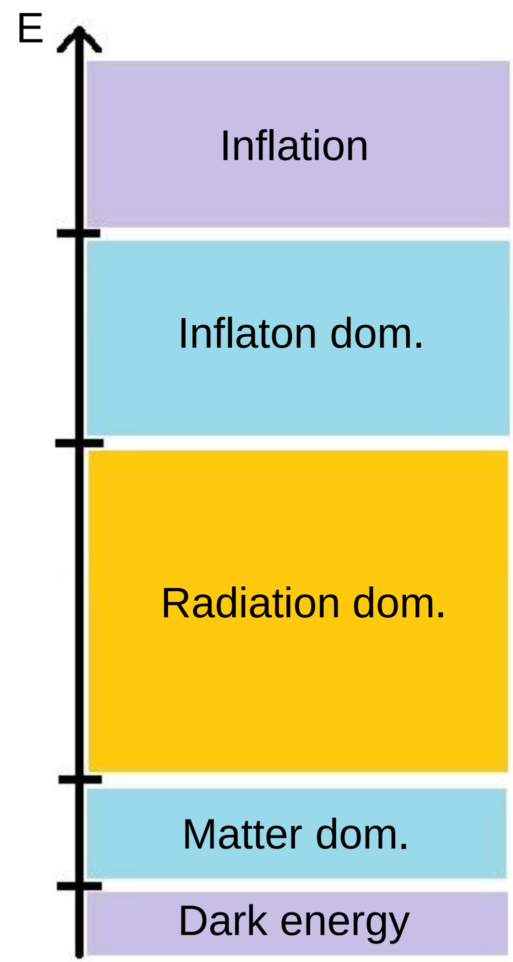
$$\Gamma_{\chi\to hh} = \frac{\left(c_{\rm loop}\mathcal{V}\ln\mathcal{V}\right)^2}{32\pi}\frac{m_\chi^3}{M_p^2}$$

Predictions:

$n_s \simeq 0.9765$ $\quad r \simeq 1.7\times 10^{-5}$ $\quad T_{\rm rh} \simeq 4\times 10^{10}\,\text{GeV}$ $\quad \Delta N_{\rm eff} \simeq 0$

SM on D7s and unwrapped inflaton





$N_e \simeq 52$

$N_\phi \simeq 8$

$\phi \to \gamma\gamma, \vartheta_b\vartheta_b$

$N_\chi = 0$

$$\Gamma_{\phi\to\chi\chi} \simeq \Gamma_{\phi\to\vartheta_b\vartheta_b} \simeq \frac{(\ln\mathcal{V})^{3/2}}{64\pi\,\mathcal{V}}\frac{m_\phi^3}{M_p^2}$$

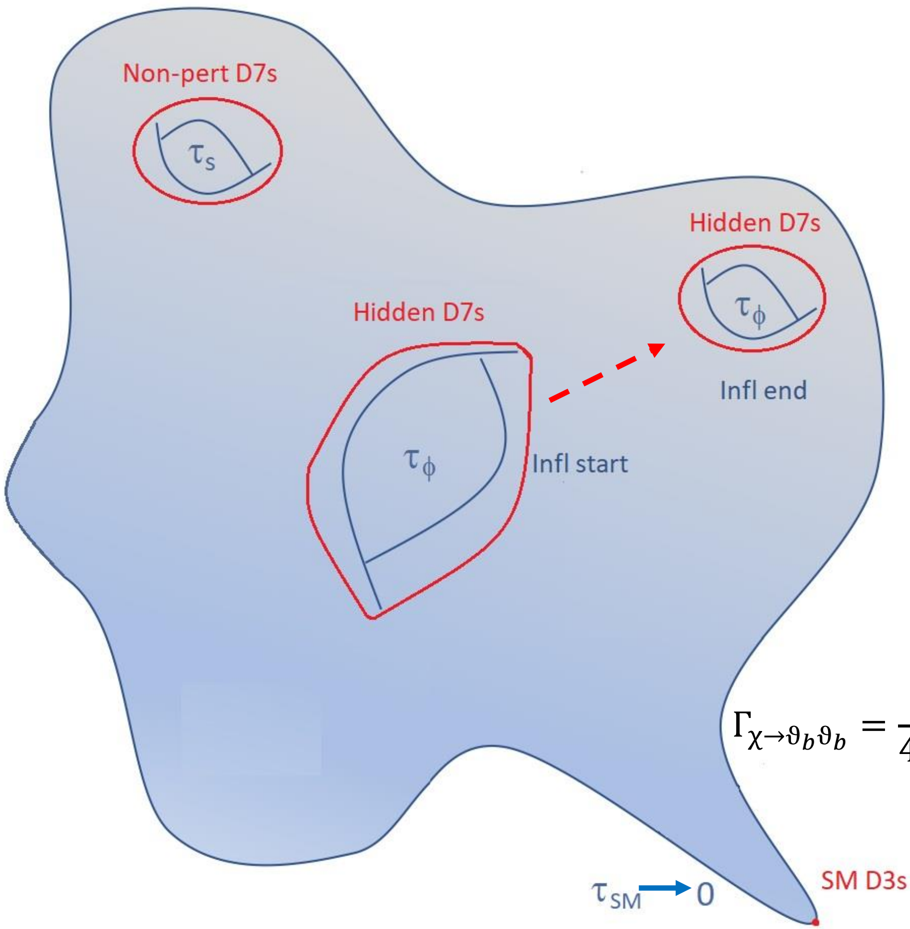
$$\Gamma_{\phi\to\gamma\gamma} \simeq 12\,\Gamma_{\phi\to\chi\chi}$$

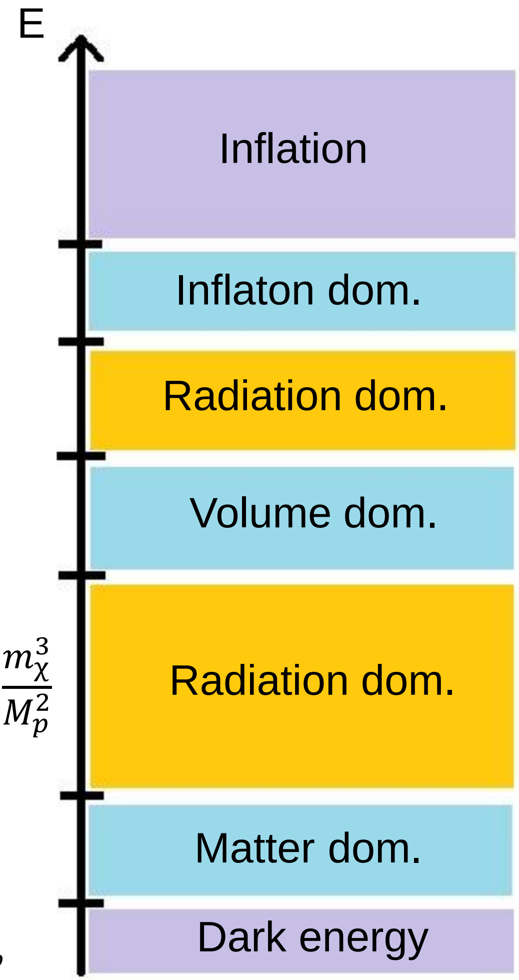
Predictions:

$n_s \simeq 0.9761$ $\quad r \simeq 1.7\times 10^{-5}$ $\quad T_{\rm rh} \simeq 3\times 10^{12}\,\text{GeV}$ $\quad \Delta N_{\rm eff} \simeq 0.14$

[MC,Hebecker,Jaeckel,Wittner]

SM on D3s and inflaton wrapped by D7s





$N_e \simeq 51.5$

$N_\phi \simeq 1$

$\phi \rightarrow \gamma_h \gamma_h$

$N_\chi \simeq 10.5$

$\chi \rightarrow H_u H_d, \vartheta_b \vartheta_b$

$$\Gamma_{\chi \rightarrow \vartheta_b \vartheta_b} = \frac{1}{48\pi} \frac{m_\chi^3}{M_p^2}$$

$$\Gamma_{\chi \rightarrow H_u H_d} = 2Z^2 \, \Gamma_{\chi \rightarrow \vartheta_b \vartheta_b}$$

Predictions:

$n_s \simeq 0.9757$ $\quad r \simeq 1.8 \times 10^{-5}$ $\quad T_{\rm rh} \simeq 1 \times 10^8 \text{ GeV}$ $\quad \Delta N_{\rm eff} \simeq \frac{1.43}{Z^2} \simeq 0.36 \quad Z = 2$

Conclusions on inflation

- Type IIB Kaehler moduli $\perp \mathcal{V}$ are good inflatons ϕ due to approximate shift symmetries

- $V(\phi)$ determined by breaking effects (pert/non-pert.) and topology (bulk/local cycle)

  → several scenarios

- New model: Loop Blow-up Inflation [Bansal,Brunelli,MC,Hebecker,Kuespert]

- Inflation driven by a blow-up mode with $V(\phi)$ generated by loops

$$V(\phi) = V_0\left(1 - \frac{c}{\mathcal{V}^{1/3}\phi^{2/3}}\right)$$

- EFT under control with large volume and weak string coupling

- Predictions: $0.9757 \lesssim n_s \lesssim 0.9765$ and $r \simeq 2 \times 10^{-5}$

- Post-inflation with moduli domination and reheating from moduli decay

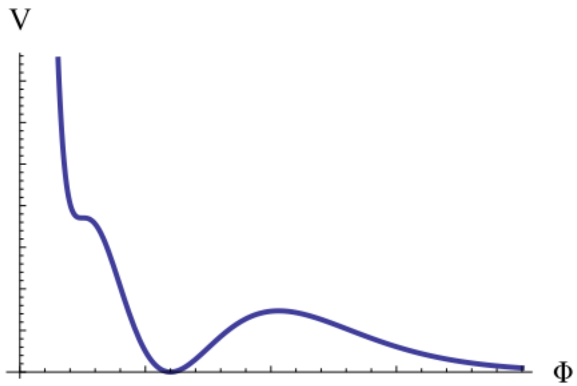
- Depending on SM realisation: $51.5 \lesssim N_{\mathrm{e}} \lesssim 53$ and $0 \lesssim \Delta N_{\mathrm{eff}} \lesssim 0.36$

Post-inflation

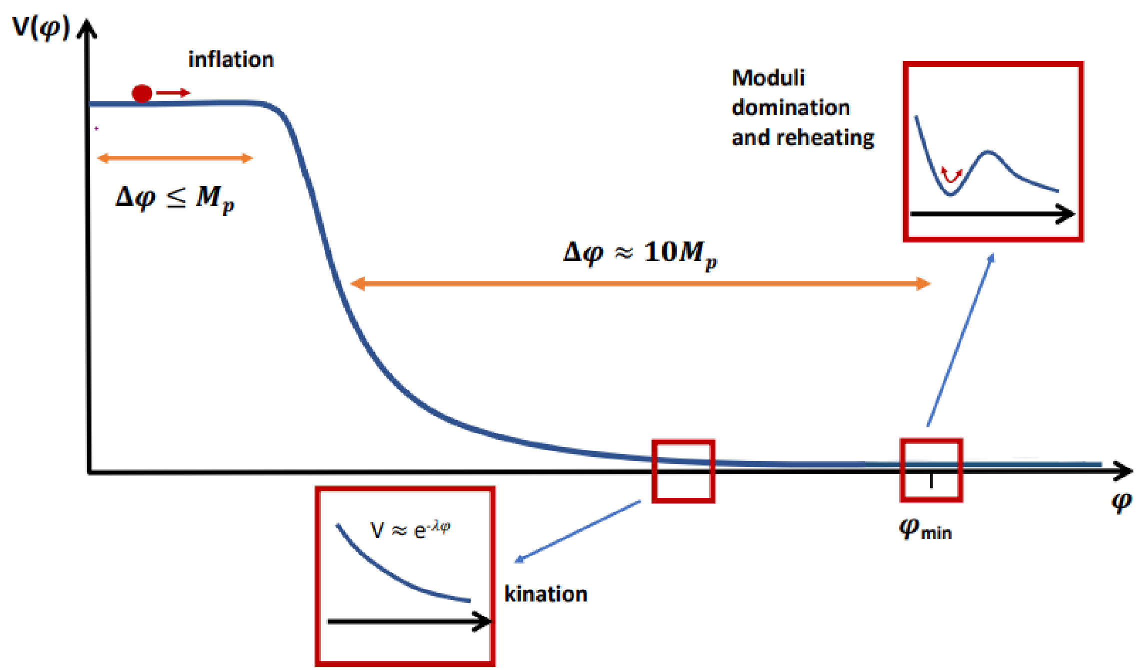
Kination

- Modulus domination after inflation can be matter with $\omega \simeq 0$ but also kination with $\omega \simeq 1$
- Example: Volume modulus inflation around an inflection point

[Conlon,Kallosh,Linde,Quevedo] [MC,Muia,Pedro]



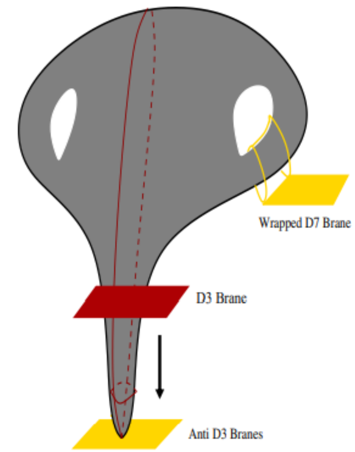
zoom



Rolling moduli in brane-antibrane inflation

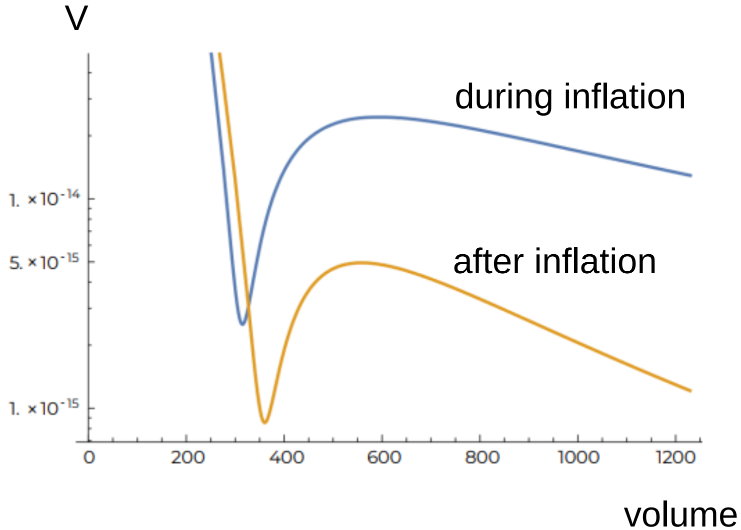
- Can have rolling moduli after brane-antibrane inflation

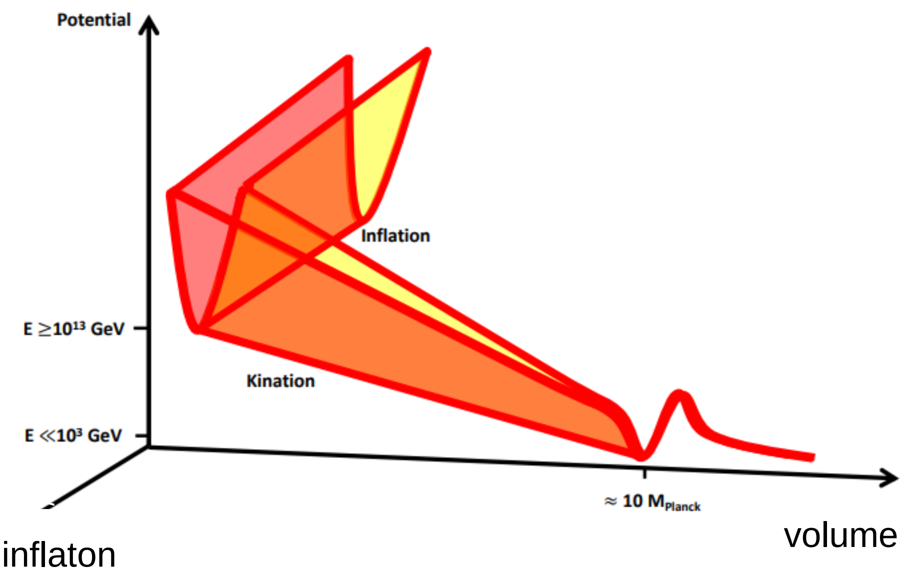
$$V(\phi) = C_0\left(1 - \frac{C_1}{\phi^4}\right)$$



- D3-antiD3 inflation without η-problem due perturbative stabilisation of volume mode

[MC,Hughes,Kamal,Marino,Quevedo,Ramos,Villa]





Growth of cosmic strings

- Physical size of cosmic strings with time-varying tension μ grows if:

$$2H + \frac{\dot{\mu}}{\mu} < 0$$

→ strings can percolate and form a network with emission of high freq GWs

- 3 cases for growth:

i) Fundamental strings during kination [Conlon,Copeland,Hardy,Gonzales][Revello,Villa]

ii) Fundamental strings in scaling fixed points

iii) EFT strings from D3s or NS5s on fibration cycles

[Brunelli,MC,Pedro] (cases ii and iii)

- Dynamical system:
strings with $\mu = M^2 \, e^{-\xi \, \phi/M_p}$ in a flat universe with fluid and modulus with $V(\phi) = V_0 \, e^{-\lambda\phi}$

FP	X	Y	Existence	Existence and Growth when $\lvert\xi\rvert > \sqrt{2/3}$
$\mathcal{K}_+$	1	0	$\forall\lambda$ and $\forall\omega$	$\forall\lambda$ and $\forall\omega$
$\mathcal{K}_-$	-1	0	$\forall\lambda$ and $\forall\omega$	$\forall\lambda$ and $\forall\omega$
$\mathcal{F}$	0	0	$\forall\lambda$ and $\forall\omega$	never
$\mathcal{M}$	$\frac{\lambda}{\sqrt{6}}$	$\sqrt{1-\frac{\lambda^2}{6}}$	$\lvert\lambda\rvert < \sqrt{6}$	$\frac{2}{\lvert\xi\rvert} < \lvert\lambda\rvert < \sqrt{6}$
$\mathcal{S}$	$\sqrt{\frac{3}{2}}\frac{\omega+1}{\lambda}$	$\sqrt{\frac{3(1-\omega^2)}{2\lambda^2}}$	$\lambda^2 > 3(\omega+1)$	$\sqrt{3(\omega+1)} < \lvert\lambda\rvert < \frac{3}{2}(\omega+1)\lvert\xi\rvert$ with $\sqrt{\omega+1} > \frac{2}{\sqrt{3}\lvert\xi\rvert}$

if ρ_{loop} is not negligible new tracker solutions can exist [Gonzales,Conlon,Copeland,Hardy]

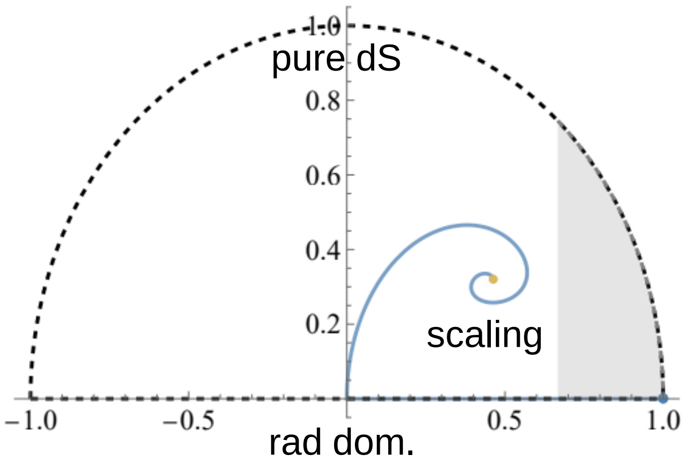
Growth of cosmic strings beyond kination

[Brunelli,MC,Pedro]

- Fundamental strings with rolling volume mode:

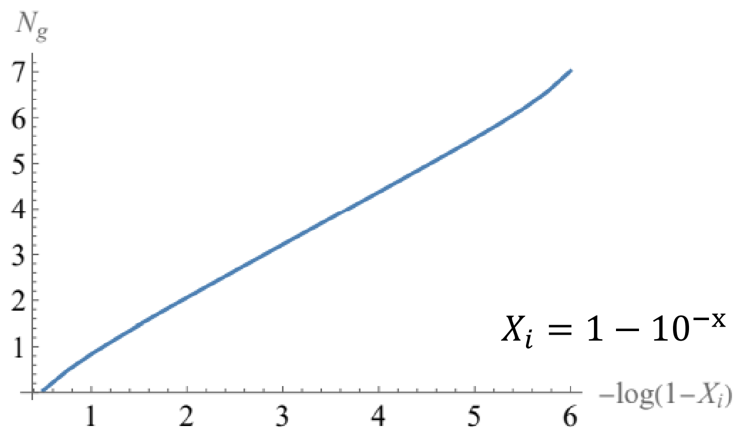
$$\mu \simeq M_s^2 \simeq \frac{M_p^2}{\mathcal{V}} = M_p^2\, e^{-\xi\chi/M_p} \qquad \xi = \sqrt{3/2} > \sqrt{2/3} \qquad V \simeq \frac{V_0}{\mathcal{V}^p} \longrightarrow \lambda = p\sqrt{3/2}$$

i) Kination is an unstable fixed point but can have enough efolds of growth N_g



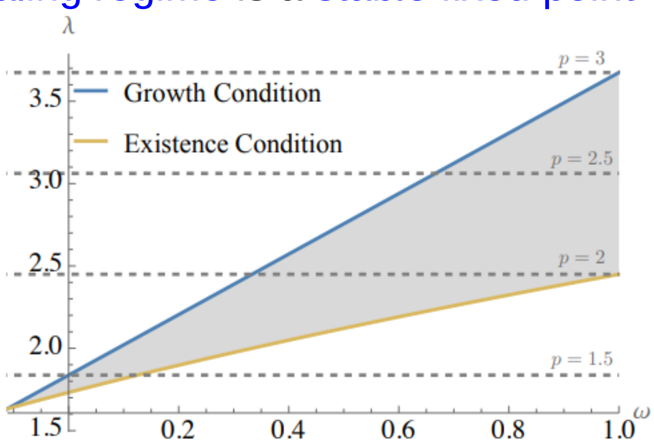
$p = 3$

$\omega = 1/3$



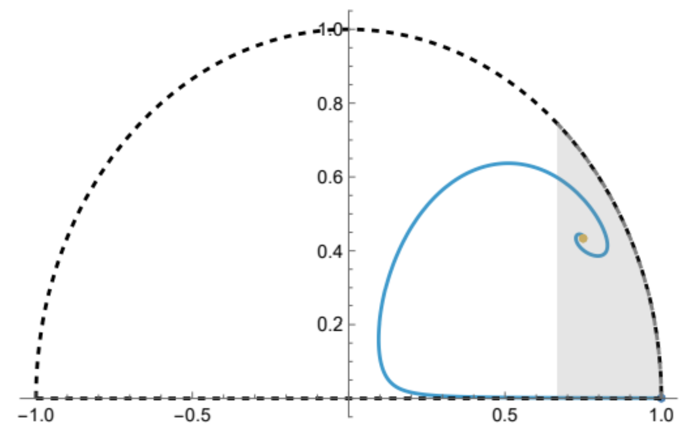
$X_i = 1 - 10^{-x}$

ii) Scaling regime is a stable fixed point



$p = 2$

$\omega = 1/2$



Growth of cosmic strings beyond kination

[Brunelli,MC,Pedro]

- EFT strings from p-branes wrapped on (p-1)-cycles Σ_{p-1}

  $\longrightarrow \quad \mu \simeq \mathrm{Vol}\left(\Sigma_{p-1}\right) M_s^{p+1}$

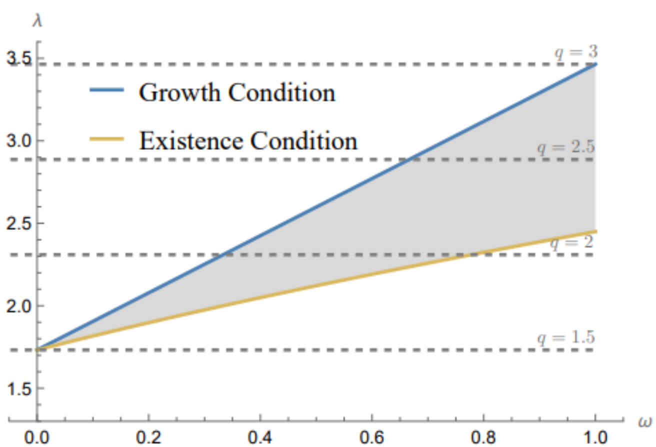
- D3 on 2-cycle with rolling $\mathcal{V}$: $\quad \mu \simeq \frac{M_p^2}{\mathcal{V}^{2/3}} = M_p^2\, e^{-\xi\chi/M_p} \qquad \xi = \sqrt{2/3} \longrightarrow$ No growth
- NS5 on 4-cycle with rolling $\mathcal{V}$: $\quad \mu \simeq \frac{M_p^2}{\mathcal{V}^{1/3}} = M_p^2\, e^{-\xi\chi/M_p} \qquad \xi < \sqrt{2/3} \longrightarrow$ No growth
- Fix $\mathcal{V}$ and consider rolling fibration modulus for K3-fibred CY over P^1:

$$\mathcal{V} \simeq t_1\tau_1 \longrightarrow \tau_1 = \mathcal{V}^{2/3} e^{\frac{2}{\sqrt{3}}\phi/M_p} \qquad t_1 \simeq \mathcal{V}^{1/3} e^{-\frac{2}{\sqrt{3}}\phi/M_p}$$

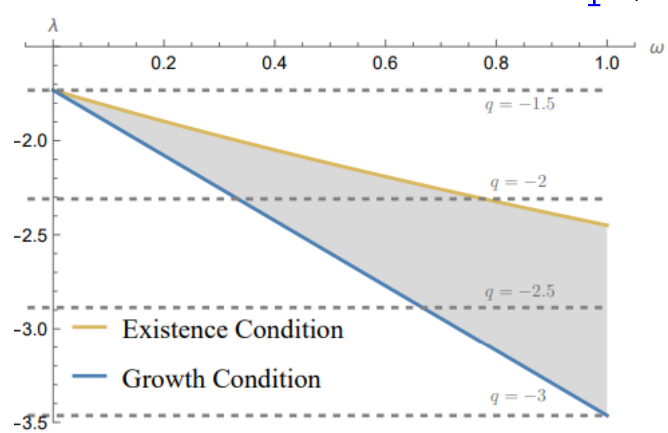
- EFT string growth for both kination and scaling: $\quad V \propto \tau_1^{-q} \longrightarrow \lambda = 2\,q/\sqrt{3}$

$$\mu \simeq M_s^2\, e^{-\xi\phi/M_p}$$

i) D3 on P^1 with volume t_1: $\xi = 2/\sqrt{3}$



ii) NS5 on K3 fibre with volume τ_1: $\xi = -2/\sqrt{3}$



Dark energy

dS from string theory?

- Stable dS does not exist
- Difficulty to get dS with EFT under control
- Extreme view: metastable dS incompatible with QG

  → No dS conjectures [Obied,Ooguri,Spodyneiko,Vafa]

  → DE has to be quintessence

- Conservative view: no dS conjecture at boundary of moduli space (no parametric control)

  → metastable dS in interior of moduli space [MC,de Alwis,Maharana,Muia,Quevedo]

  → dS with numerical control via $W_0 \ll 1$ in KKLT and $\mathcal{V}^{-1} \sim e^{-1/g_s} \ll 1$ in LVS

- Several uplifts: antibranes, D-terms, T-branes, α' effects, $F^z \neq 0$, non-pert. effects at sing

- Progress in computing and classifying α' and g_s corrections using 10D symmetries

  [Burgess,MC,Ciupke,Krippendorf,Quevedo]

- Explicit dS: global CY models with chirality on D3s, mod stab: cx str and dilaton by 3-form flux, Kaehler mod a la LVS, open string mod by 2-form + 3-form fluxes, dS from T-branes

  [MC,Klevers,Krippendorf,Mayrhofer,Quevedo,Valandro]

No quintessence at boundary of moduli space

- Focus on type IIB volume (similar results for type IIA and heterotic) [MC,Cunillera,Padilla,Pedro] [Shiu,Tonioni,Tran]

$$K = -3\ln\tau \qquad \Rightarrow \qquad \mathcal{L}_{kin} = \frac{3}{4\tau^2}\partial_\mu\tau\partial^\mu\tau = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \qquad \tau = e^{\sqrt{2/3}\phi}$$

- Potential for $\partial_\tau W = 0$ and $\tau \to \infty$ (α' expansion under control)

$$V = e^K(|D_U W|^2 + |D_S W|^2) = \frac{V_0}{\tau^3}$$

- If $|D_U W| = |D_S W| = 0$, quantum corrections give a larger suppression for $\tau \to \infty$

$$V = \frac{V_0}{\tau^{3+p}} = V_0\, e^{-\lambda\phi} \qquad \lambda = \sqrt{6}\,(1+p) \qquad p > 0$$

$$\longrightarrow \qquad \epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 = \frac{\lambda^2}{2} = 3\,(1+p)^2 > 1$$

No acceleration

- Similar results for dilaton $s \to \infty$ (g_s expansion under control)

Multifield quintessence?

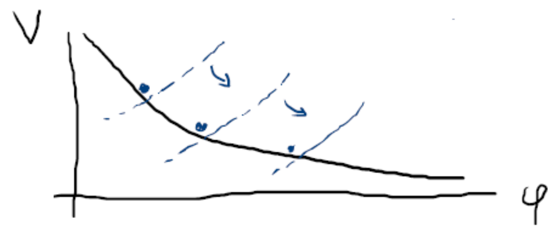
- Quintessence due to kinetic coupling with axion
  → non-geodesic motion in curved field space gives acceleration   [MC,Dibitetto,Pedro]

- Idea: $T = \tau + i\theta \quad \Rightarrow \quad \mathcal{L}_{kin} \supset \frac{3}{4\tau^2}\partial_\mu\theta\partial^\mu\theta = \frac{3}{4}e^{-2\sqrt{\frac{2}{3}}\phi}\dot{\theta}^2$

  gives effective time-dependent contribution to $V(\phi)$ if $\dot{\theta} \neq 0$ for $m_\theta \simeq 0$

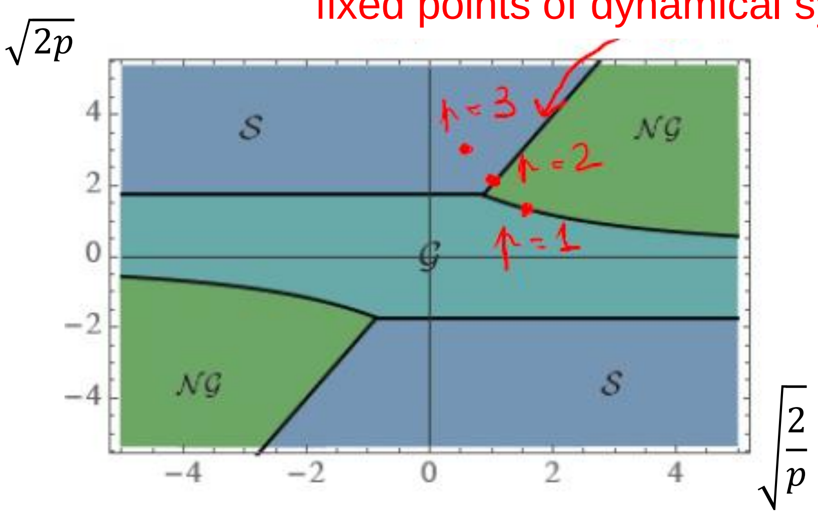
$$\pi_\theta = \frac{3}{2}a^3 e^{-2\sqrt{\frac{2}{3}}\phi}\dot{\theta} \simeq const$$

$$\longrightarrow \quad V_{\rm eff} = V_0\, e^{-\lambda\phi} + \frac{\pi_\theta^2}{3\,a^6}\, e^{+2\sqrt{\frac{2}{3}}\phi}$$

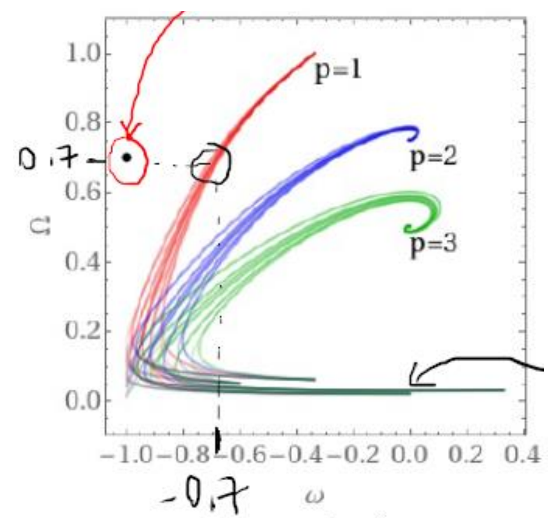


- However it does not work in string theory: $K = -p\,\ln(X + \bar{X}) \qquad V_{\rm eff} = V_0\, e^{-\sqrt{2p}\,\phi} + \frac{\pi_\theta^2}{3\,a^6}e^{+2\sqrt{\frac{2}{p}}\phi}$

fixed points of dynamical system



today



matter dom. initial cond.

[Brinkmann,MC, Dibitetto,Pedro]

Challenges for quintessence

- Quintessence, as dS, has to be in bulk of moduli space

- Same control issue as dS + extra challenges:

  i) Ultra-light quintessence field

$$m_\phi \lesssim H_0 \sim 10^{-60}\, M_p \qquad \text{from} \qquad \eta = \frac{V_{\phi\phi}}{V} \lesssim 1$$

radiatively stable?
fifth-forces?

  ii) String and SUSY scale above 1 TeV

$$M_s \simeq \frac{M_p}{\sqrt{\mathcal{V}}} \gtrsim 1\,\text{TeV} \qquad \Leftrightarrow \qquad \mathcal{V} \lesssim 10^{30}$$

  iii) Heavy volume mode

$m_{\mathcal{V}} \gtrsim 1\,\text{meV} \simeq 10^{-30}\, M_p$ from fifth-forces (screening/sequestering hard to work)

$$\Rightarrow \qquad m_{\mathcal{V}} \gg m_\phi$$

- Leading order: $\mathcal{V}$ is lifted while ϕ is flat: $V = \mathrm{V}_{\text{lead}}(\mathcal{V}) + \mathrm{V}_{\text{sub}}(\mathcal{V}, \phi)$

$$\frac{\mathrm{V}_{\text{lead}}}{\mathrm{V}_{\text{sub}}} \sim \left(\frac{m_\phi}{m_{\mathcal{V}}}\right)^2 \lesssim 10^{-60}$$

cannot be obtained with perturbative corrections

since $$\frac{\mathrm{V}_{g_s^2 \alpha'^4}}{\mathrm{V}_{\alpha'^3}} \sim \frac{1}{\mathcal{V}^{1/3}} \lesssim 10^{-60} \qquad \Leftrightarrow \qquad \mathcal{V} \gtrsim 10^{180} \qquad \Rightarrow \qquad M_s \ll 1\,\text{TeV}$$

Quintessence model building

- Quintessence as hard as dS + extra challenges (fifth forces, right scales, stability)
- Metastable dS seems easier to build [MC,Cunillera,Padilla,Pedro]
- But what if quintessence is preferred by data? (DESI? Euclid?)
- Best candidate: axion quintessence
- $V_{\text{lead}}(\mathcal{V})$ has a SUSY breaking Minkowski vacuum and axion ϕ is flat
- $V_{\text{sub}}(\phi, \mathcal{V})$ generated by non-perturbative effects

  i) Right hierarchy: $V_{\text{sub}}(\phi, \mathcal{V}) \ll V_{\text{lead}}(\mathcal{V})$

  $$V_{\text{sub}} \sim e^{-a\tau} \sim e^{-a\mathcal{V}^{2/3}} \longrightarrow \frac{V_{\text{lead}}}{V_{\text{sub}}} \sim \frac{e^{a\mathcal{V}^{2/3}}}{\mathcal{V}^3} \gtrsim 10^{60} \quad \text{for} \quad \mathcal{V} \lesssim 10^{30} \quad \text{and} \quad M_s \gtrsim 1\,\text{TeV}$$

  ii) Radiative stability due to perturbative shift symmetry

  iii) No fifth-force problem
- But axion potential yields acceleration only for $f \gtrsim M_p$

$$V_{\text{sub}}(\phi, \mathcal{V}) = \Lambda(\mathcal{V})\left[1 - \cos\left(\frac{\phi}{f(\mathcal{V})}\right)\right]$$

- Never obtained in EFT + forbidden by WGC
- For $f < M_p$ can have quintessence from axion hilltop

LVS axion hilltop

[MC,Cunillera,Padilla,Pedro]

- Type IIB LVS compactification on CY with volume:

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} \simeq \tau_b^{3/2} \qquad T_i = \tau_i + i\theta_i$$

- Kaehler potential (tree-level + α'^3)

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right)$$

- Superpotential (tree-level + non-pert.):

$$W = W_0 + e^{-a_s T_s} + e^{-a_b T_b}$$

- Scalar potential:

$$V = V_{\rm lead}(\mathcal{V},\tau_s,\theta_s) + V_{\rm sub}(\theta_b)$$

$$V_{\rm lead}(\mathcal{V},\tau_s,\theta_s) = \frac{C_{up}}{\mathcal{V}^2} + C_s\,\frac{\sqrt{\tau_s}\,e^{-2a_s\tau_s}}{\mathcal{V}} - D_s\,\frac{\tau_s\,e^{-a_s\tau_s}}{\mathcal{V}^2}\cos(a_s\theta_s) + \frac{C_{\alpha'}}{g_s^{3/2}\mathcal{V}^3}$$

$$V_{\rm sub}(\theta_b) = -D_b\,\frac{\tau_b\,e^{-a_b\tau_b}}{\mathcal{V}^2}\cos(a_b\theta_b)$$

Axion hilltop

[MC,Cunillera,Padilla,Pedro]

- Leading order stabilisation: SUSY breaking Minkowski vacuum at

$$\theta_s = 0 \qquad \tau_s \sim g_s^{-1} \gg 1 \qquad \mathcal{V} \sim e^{a_s \tau_s} \gg 1 \qquad \theta_b \text{ is flat}$$

$$\mathrm{V_{lead}}(\mathcal{V}_{max}) \sim m_{\mathcal{V}}$$

Canonical normalisation for volume axion

$$\mathcal{L}_{kin} \supset \frac{3}{4\tau_b^2} \partial_\mu \theta_b \partial^\mu \theta_b = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi$$

$$\longrightarrow \qquad \theta_b = \sqrt{\frac{2}{3}} \tau_b \frac{\phi}{M_p}$$

- Subleading order:

$$\mathrm{V_{sub}}(\phi, \mathcal{V}) \sim e^{-\sqrt{\frac{3}{2}} \frac{M_p}{f}} M_p^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] \qquad f = \sqrt{\frac{3}{2}} \frac{M_p}{a_b \tau_b}$$

$$10^{-120} \text{ for } f \sim 0.003\, M_p \quad \Leftrightarrow \quad \mathcal{V} \simeq \tau_b^{3/2} \sim 10^3$$

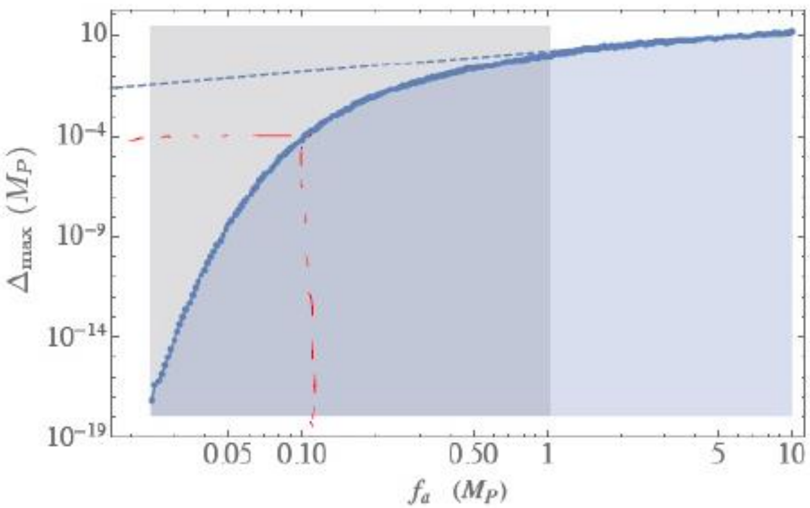
natural + EFT under control

$$m_{\mathcal{V}} \sim 10^{13}\ \mathrm{GeV}$$

Hilltop and initial conditions

- How close should ϕ be to the maximum to get acceleration with $\omega_\phi \simeq -1$ and $\Omega_\phi \simeq 0.7$?

[MC,Cunillera,Padilla,Pedro]



- Quantum diffusion during inflation causes fluctuations $\Delta\phi \sim H_{inf}$
- Need to require $H_{inf} \lesssim \Delta_{max}$

i) $f \simeq 0.1\, M_p$ ⟶ $H_{inf} \lesssim 10^{-4}\ \mathrm{M_p} \sim 10^{14}\ \mathrm{GeV}$ but can get DE scale for $f \simeq 0.1\, M_p$?

ii) $f \simeq 0.02\, M_p$ ⟶ $H_{inf} \lesssim 10^{-18}\ \mathrm{M_p} \sim 1\ \mathrm{GeV}$ tiny and even lower for $f \simeq 0.003\, M_p$

- In (i) use poly-instantons to generate axion potential with right DE scale
- In (ii) use axion alignment [Kim,Nilles,Peloso] to get an effective $f \simeq 0.1\, M_p$

Quintessence from poly-instantons

- LVS in fibred CY: $\mathcal{V} = \sqrt{\tau_f}\tau_b - \tau_s^{3/2}$ [MC,Cunillera,Padilla,Pedro]
- Potential:

$$V = V_{lead}(\mathcal{V}, \tau_s, \theta_s) + V_{inf}(\tau_f) + V_{sub}(\theta_b, \theta_f)$$

- Loop Fibre Inflation: [MC,Burgess,Quevedo]

$$V_{inf} \simeq V_0\left(1 - \frac{4}{3}e^{-\phi/\sqrt{3}}\right) \quad \text{and} \quad H_{inf} \simeq 10^{-5} M_p$$

- 2 light bulk axions: θ_b = spectator (0.2% of DM) and θ_f = DE via poly-instantons

$$W = W_{LVS} + e^{-a_b T_b + e^{-a_f T_f}}$$

[Blumenhagen,Schmidt-Sommerfeld]
[Luest,Zhang]

- Axion potential:

$$V_{sub} \sim e^{-a_b\tau_b}\left[1 - \cos\left(\frac{\phi_b}{f_b}\right)\right] + e^{-a_b\tau_b - a_f\tau_f}\left[1 - \cos\left(\frac{\phi_b}{f_b} + \frac{\phi_f}{f_f}\right)\right]$$

fix $\phi_b = 0$ $\longrightarrow$ $V_{DE} \sim e^{-f_f^{-1} - f_b^{-1}}\left[1 - \cos\left(\frac{\phi_f}{f_f}\right)\right]$

$$f_f = \frac{N_f}{2\sqrt{2}\pi\tau_f} M_p \simeq 0.1\, M_p \quad \text{and} \quad f_b = \frac{N_b}{2\pi\tau_b} M_p \simeq 0.005\, M_p$$

- Numerical results:

$$\tau_f \sim O(5) \quad \tau_b \sim O(500) \quad N_1 \sim O(5) \quad N_2 \sim O(10)$$

$$m_{\theta_b} \simeq 10^{-29}\ \text{eV} \qquad m_{\theta_f} \simeq 10^{-32}\ \text{eV}$$

Conclusions on dark energy

- No quintessence at boundary of moduli space
- Multifield string models give acceleration but without $\omega_\phi \simeq -1$ and $\Omega_\phi \simeq 0.7$
- Quintessence as hard as dS + extra challenges (fifth forces, right scales, stability)
- dS models seem easier to build
- If quintessence is preferred by data (DESI?), axions are the best candidates to drive DE
- But simplest axion potential does not yield acceleration
- Need to rely on axion hilltop:

  i) $f \simeq 0.1\, M_p$ ⟶ $H_{inf} \lesssim 10^{-4}\, \mathrm{M_p} \sim 10^{14}\, \mathrm{GeV}$

  ii) $f \simeq 0.02\, M_p$ ⟶ $H_{inf} \lesssim 10^{-18}\, \mathrm{M_p} \sim 1\, \mathrm{GeV}$

- In (i) do not get right DE scale for a single axion

  ⟶ poly-instantons, not tuned but need an explicit CY example

- In (ii) need alignment to get an effective $f \simeq 0.1\, M_p$ but contrived and tuned