Cosmology of generic features of string theory

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Based on recent papers in collaboration with:

Braun, Brunelli, Caraffi, Carta, Chauhan, Chinaia, Hassan, Krippendorf, Lin, Lorenzoni, Maharana, McDonough, Milioli, Piantadosi, Qoreishi, Padilla, Pedro, Schachner, Vagnoni, Valandro

See also: 'String cosmology: from the early universe to today'

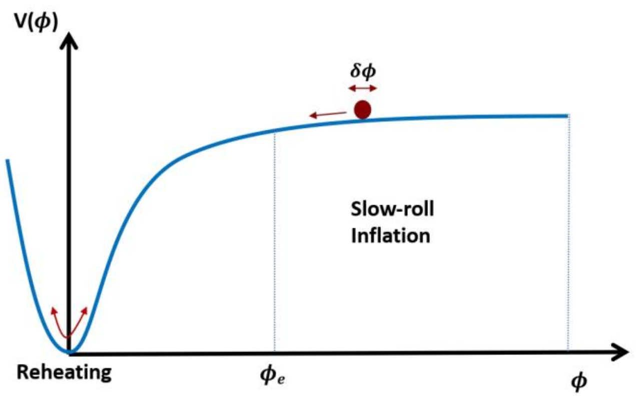
MC, Conlon, Maharana, Parameswaran, Quevedo, Zavala

Cosmology and string theory

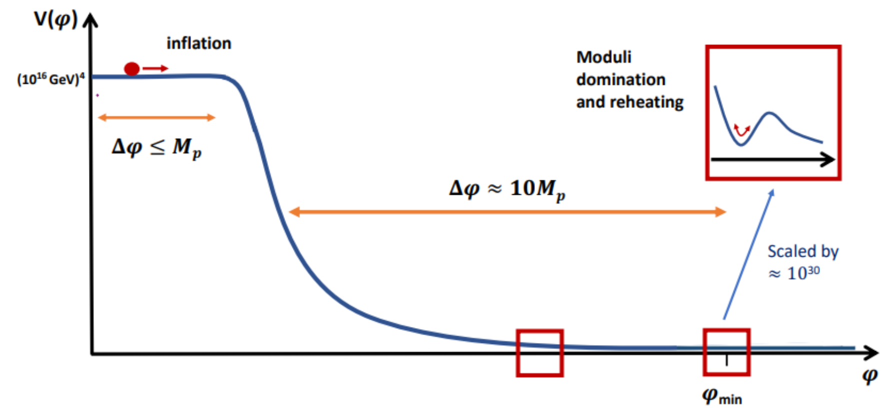
[MC,Conlon,Maharana,Parameswaran,Quevedo,Zavala]

- 4 cosmological epochs where string theory is needed to control Planck scale physics:

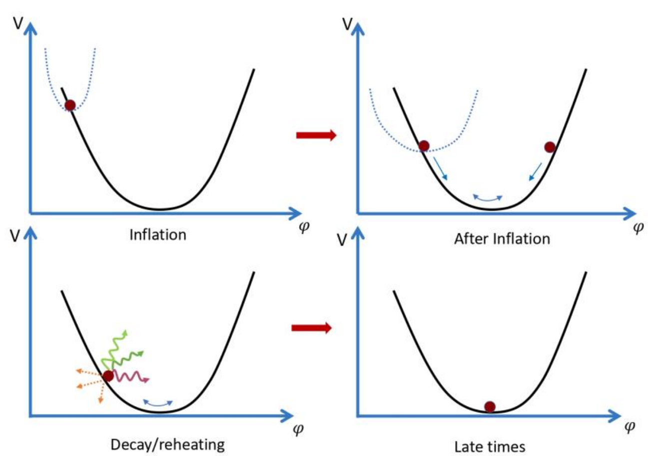
i) Small and large field inflation



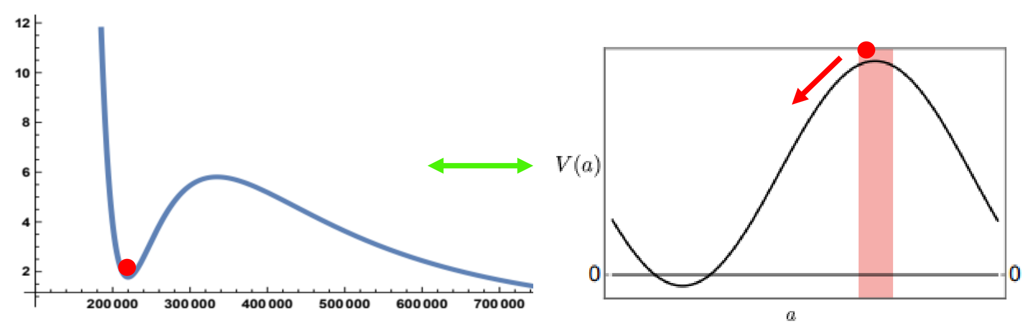
ii) Kination after inflation



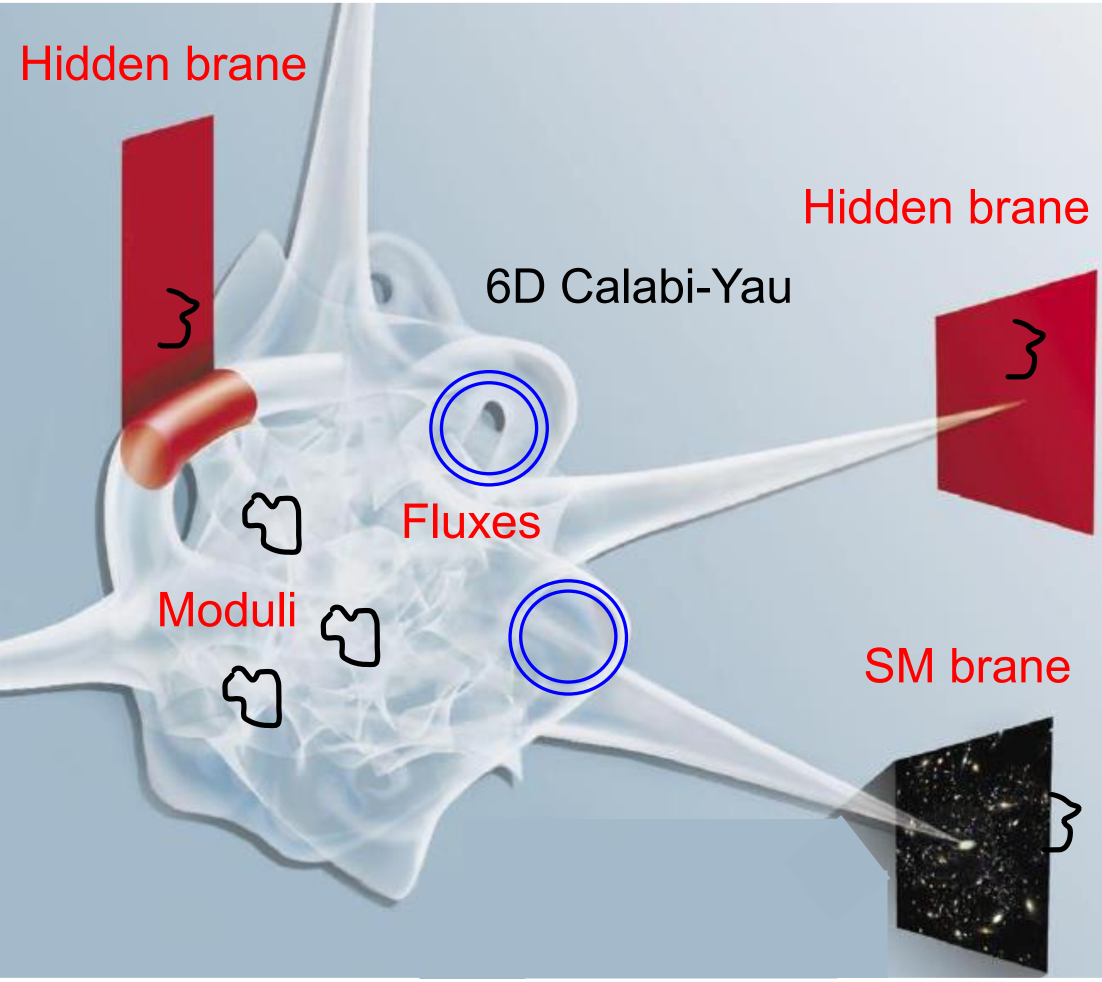
iii) Reheating



iv) Dark energy



4D string models

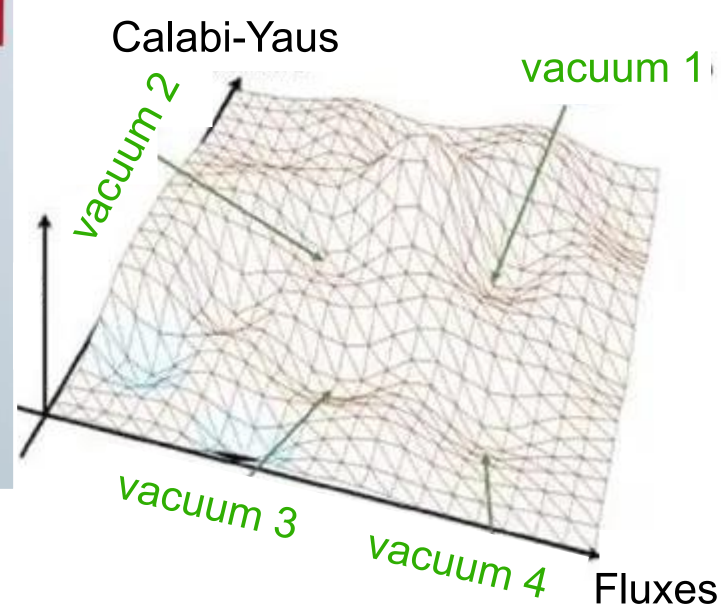


10D string theory compactified on 6D CY

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

Type IIB 4D EFT

- Focus on 4D EFT of type IIB flux compactification on CY orientifolds
- Closed string moduli:

  i) axio-dilaton $S = g_s^{-1} + iC_0$

  ii) complex structure (shape) moduli $z_\alpha \quad \alpha = 1, \dots, h^{1,2}$

  ii) Kaehler (size) moduli $T_i = \tau_i + i\theta_i \qquad i = 1, \dots, h^{1,1}$

- Tree-level Kahler potential and superpotential

$$K = -2\ln\mathcal{V}(\tau_i) - \ln(\mathrm{S}+\bar{\mathrm{S}}) - \ln\left(-i\int \Omega(\mathrm{z}_\alpha)\wedge\bar{\Omega}\right)$$

$$W = \int (F_3 + iSH_3)\wedge\Omega = W(S, z_\alpha)$$

- Tree-level F-term potential for $\partial_T W = 0$ and no-scale cancellation: $K^{T\bar{T}}K_T K_{\bar{T}} = 3$

$$V = e^K\left(|D_z W|^2 + |D_S W|^2\right) \geq 0$$

- Fix S and z-moduli at $|D_z W| = |D_S W| = 0$ $\longrightarrow$ $W_0 = \langle W(S, z_\alpha)\rangle \sim \mathrm{O}(1)$
- SUSY-breaking (due to $F^T \neq 0$) Minkowski minimum with flat T-moduli
- Mass spectrum: $m_z \sim m_S \sim m_{3/2} \sim \dfrac{|W_0| M_p}{\mathcal{V}} \gg m_T = 0$

Numerical flux vacua

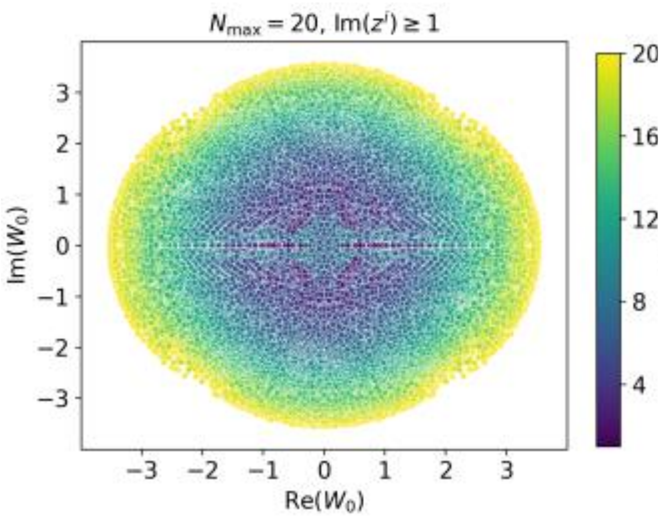
[Chauhan,MC,Krippendorf,Maharana,Piantadosi,Schachner]

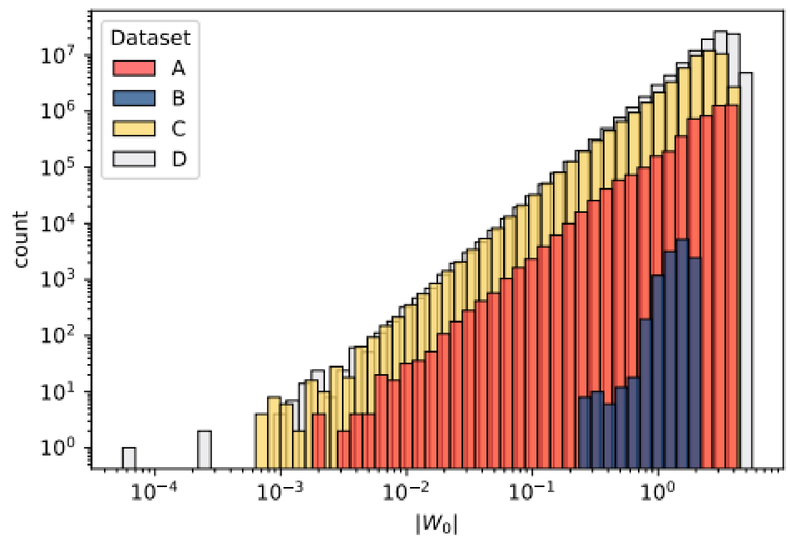
- Numerical searches of flux vacua using Machine Learning (JAXVacua)
- Exhaustive searches in targeted regions of moduli space of type IIB Calabi-Yau flux vacua
- Example with $h^{1,2} = 2$: $\mathbb{CP}^4_{[1,1,1,6,9]}$ at $\mathbb{Z}_6 \times \mathbb{Z}_{18}$ symmetric locus

Name	$\mathrm{Im}(z^i)$	s	$N_{\max}$	$\#h$	$\#f$	$\#(f,h)$	$\mathcal{N}_{\text{vac}}$	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

Compare with 15392 solutions of *Finding all flux vacua in an explicit example* [Martinez-Pedrera et al, 2012]

- Distribution of $|W_0|$





$$m_{mod} \propto m_{3/2}$$

$$m_{3/2} \sim \frac{|W_0| M_p}{\mathcal{V}}$$

- $|W_0| = 5.547 \times 10^{-5}$ for dataset D without perturbatively flat vacua

Numerical flux vacua

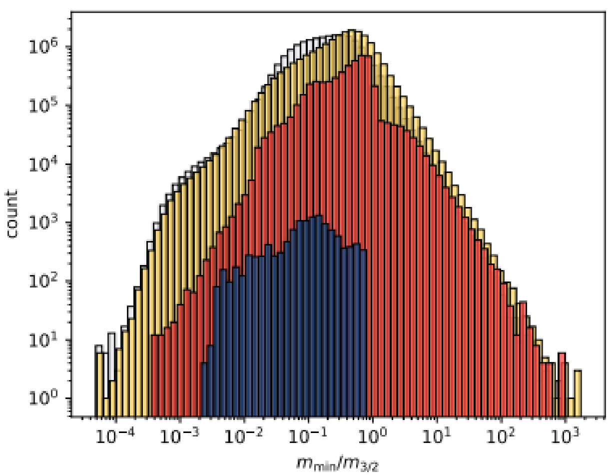
[Chauhan,MC,Krippendorf,Maharana,Piantadosi,Schachner]

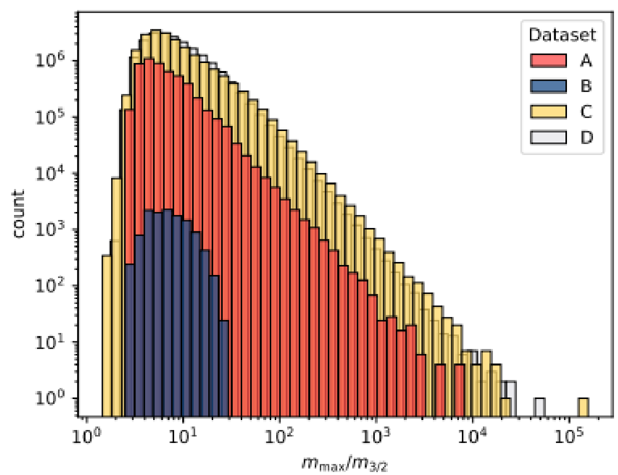
- No continuous flux approx. → distribution of actual flux vacua beyond [Denef,Douglas]

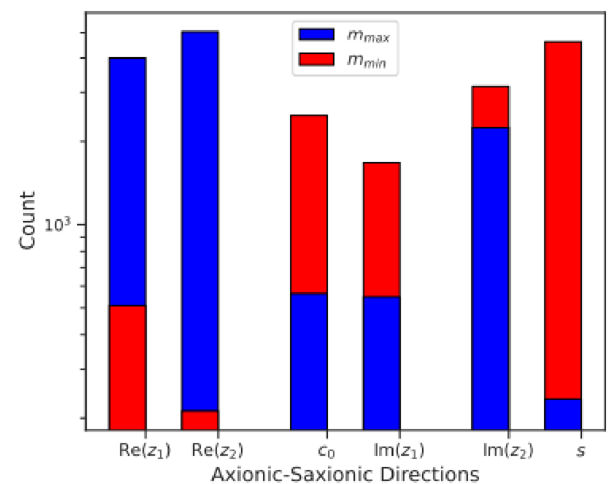
$$\mathcal{N}_{\text{vac}} = \begin{cases} (7.17 \pm 1.19) \times 10^{-3} \times (N_{\max})^{5.80\pm0.05} & \text{dataset A} \\ (7.00 \pm 4.19) \times 10^{-2} \times (N_{\max})^{4.91\pm0.34} & \text{dataset B} \\ (1.24 \pm 0.20) \times (N_{\max})^{5.05\pm0.06} & \text{dataset C} \\ (4.89 \pm 1.18) \times 10^{-2} \times (N_{\max})^{5.63\pm0.08} & \text{dataset D} \end{cases}$$

$$\mathcal{N}_{\text{stat}} = (N_{\max})^{6} \times \begin{cases} (0.00483 \pm 1.88 \times 10^{-6}) & \text{dataset A} \\ (0.01535 \pm 7.64 \times 10^{-6}) & \text{dataset B} \\ (0.17458 \pm 8.65 \times 10^{-5}) & \text{dataset C} \\ (0.02886 \pm 1.32 \times 10^{-5}) & \text{dataset D} \end{cases}$$

- Distribution of moduli masses







dataset B

→ axions heavier than saxions and dilaton lightest mode

Numerical flux vacua

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

- Principal Component Analysis to find patterns of variations of flux quanta:

  i) Diagonalise covariant matrix via orthogonal basis of principal components (eigenvectors)
  ii) Eigenvalues give variance along that direction in flux space

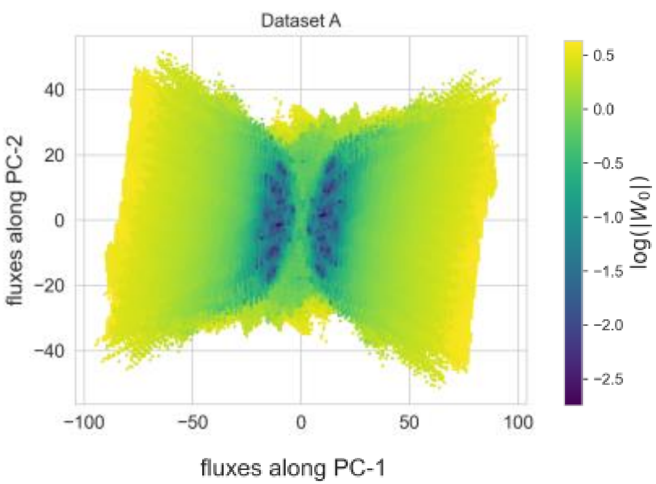
Dataset	PC1	PC2	PC3	PC4	PC5	PC6
A	0.740	0.095	0.077	0.055	0.025	0.006
B	0.638	0.187	0.087	0.043	0.031	0.011

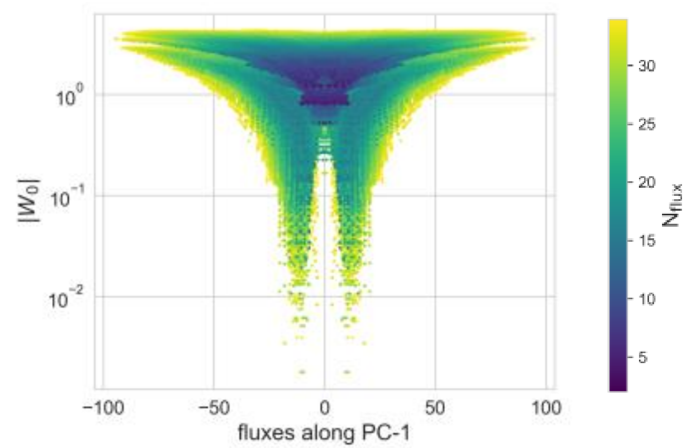
→ Parameter compression: 12D flux space effectively reduced to 5D!

PC	$(f_1)^1$	$(f_1)^2$	$(f_1)^3$	$(f_2)^1$	$(f_2)^2$	$(f_2)^3$	$(h_1)^1$	$(h_1)^2$	$(h_1)^3$	$(h_2)^1$	$(h_2)^2$	$(h_2)^3$
PC1	0.069	0.920	0.371	0.001	0.016	0.002	0.086	0.020	-0.009	0.000	0.007	0.056
PC2	0.280	-0.015	0.044	0.001	0.123	-0.148	-0.059	-0.926	-0.146	0.000	-0.005	-0.023
PC3	0.833	0.038	-0.247	0.001	-0.082	0.444	-0.039	0.174	-0.087	0.000	0.002	-0.029

dataset A

- Correlations between flux quanta and $|W_0|$





Inflating with Kaehler moduli

- Slow-roll inflation driven by Kaehler moduli τ with canonical inflaton ϕ

$$V(\phi) = V_0[1 - g(\phi)] \simeq V_0 \qquad \text{with} \qquad g(\phi) \ll 1 \quad \text{for} \quad \phi \gg 1$$

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

  $\longrightarrow$ no ϕ-independent plateau if $\phi \equiv \mathcal{V}$

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

- Each term in V depends on $\mathcal{V}$

  $\longrightarrow$ $V(\phi) \simeq V_0$ if leading dynamics fixes $\mathcal{V}$ but not τ_ϕ

  $\longrightarrow$ $\phi \equiv \tau_\phi$ 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 $V_{tree}(\tau_i) = 0$

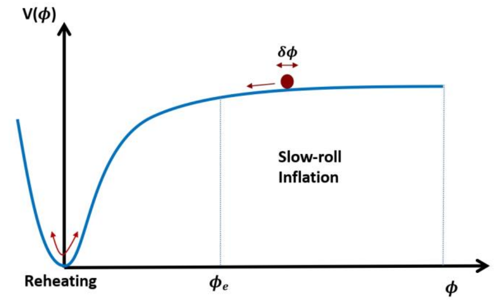
$O(\alpha'^2 g_s^2)$: extended no-scale cancellation $V_{\alpha'^2 g_s^2}(\tau_i) = 0$ [MC,Conlon,Quevedo]

$O(\alpha'^3)$: leading no-scale breaking effect lift only $\mathcal{V}$ $\quad V_{\alpha'^3}(\tau_i) \sim \mathcal{V}^{-3}$ [Becker et al]

$O(\alpha'^4 g_s^2)$ or $O(\alpha'^3 F^4)$: subleading quantum effects lift τ_ϕ which drives inflation

Plateau inflation with Kaehler moduli

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



- Non-perturbative Blow-up Inflation:

$$g(\phi) \propto e^{-a\,\mathcal{V}^{2/3}\,\phi^{4/3}} \quad \text{with} \quad r \sim 10^{-10} \quad \Delta\phi \ll M_p$$

[Conlon,Quevedo][Bond et al]

- Non-perturbative Fibre Inflation:

$$g(\phi) \propto e^{-b\,e^{c\phi}} \quad \text{with} \quad r \sim 10^{-5} \quad \Delta\phi \sim 0.1\,M_p$$

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

- Loop Fibre Inflation:

$$g(\phi) \propto e^{-p\phi} \quad \text{with} \quad r \sim 0.007 \quad \Delta\phi \sim 5\,M_p$$

[MC,Burgess,Quevedo][Broy et al]
[MC,Ciupke,deAlwis,Muia]
[MC,Grassi,Lacombe,Pedro]

Explicit CY example with branes and fluxes

- Loop Blow-up Inflation:

$$g(\phi) \propto \frac{1}{\mathcal{V}^{1/3}\,\phi^{2/3}} \quad \text{with} \quad r \sim 10^{-5} \quad \Delta\phi \sim 0.1\,M_p$$

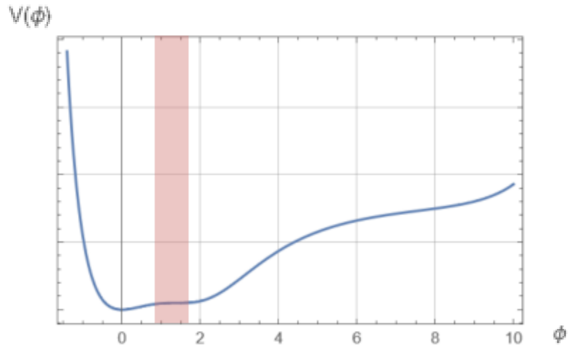
[Bansal,Brunelli,MC,Hebecker,Kuespert]

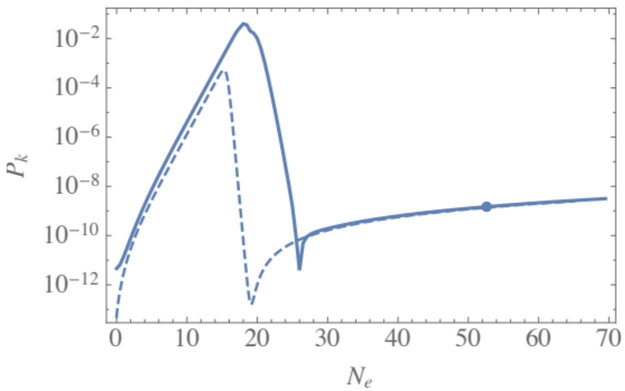
PBHs and secondary GWs in Fibre Inflation

- LVS in fibred CY: $V = V_{lead}(\mathcal{V}, \tau_{dP}, \theta_{dP}) + V_{inf}(\tau_{K3}) + V_{sub}(\theta_{P1}, \theta_{K3})$ $\qquad \mathcal{V} = t_{P1}\tau_{K3} - \tau_{dP}^{3/2}$
- Loop Fibre Inflation: [MC,Burgess,Quevedo]

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

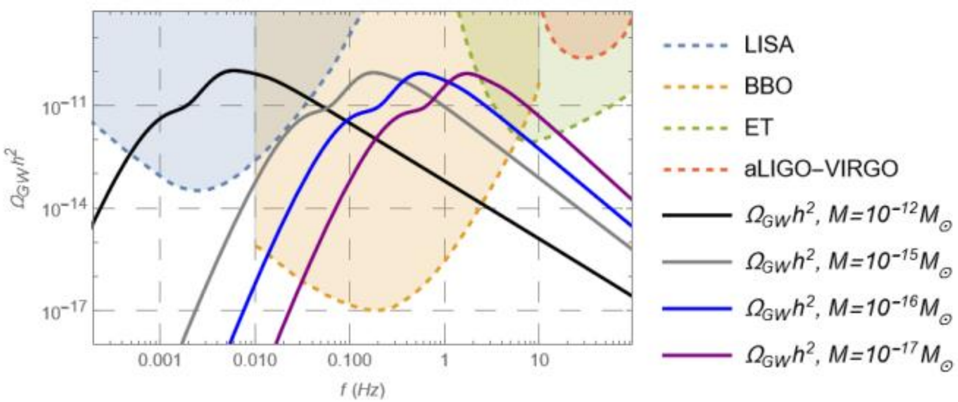
- PBHs with $10^{-17}M_\odot \lesssim M_{\rm PBH} \lesssim 10^{-11}M_\odot$ from ultra slow roll with θ_{P1} and θ_{K3} as spectators





[MC,Diaz,Pedro]

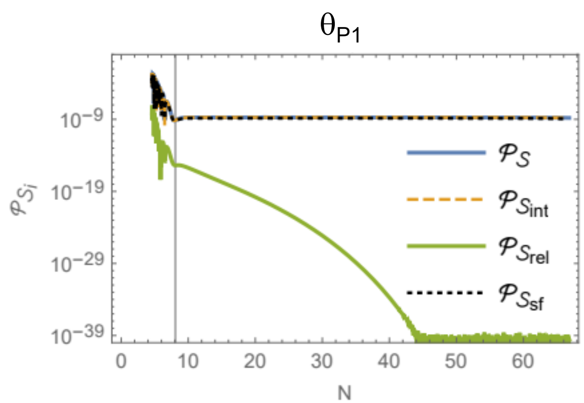
- Detectable secondary GWs:

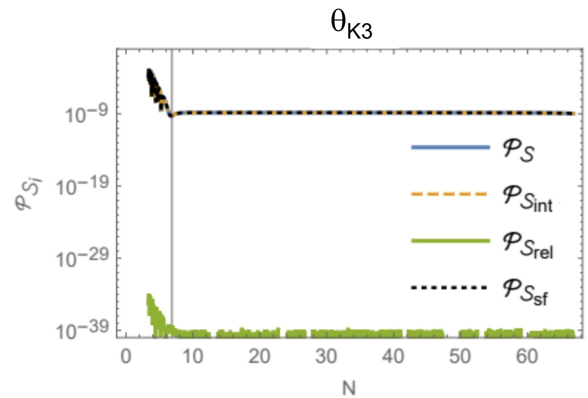


[MC,Pedro,Pedron]

Spectator axions and PBHs in Fibre Inflation

- Decaying isocurvature modes if θ_{P1} and θ_{K3} are ultra-light [MC,Guidetti,Muia,Pedro,Vacca]

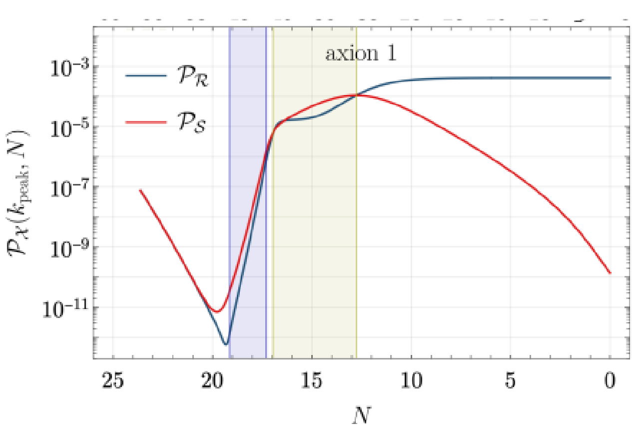


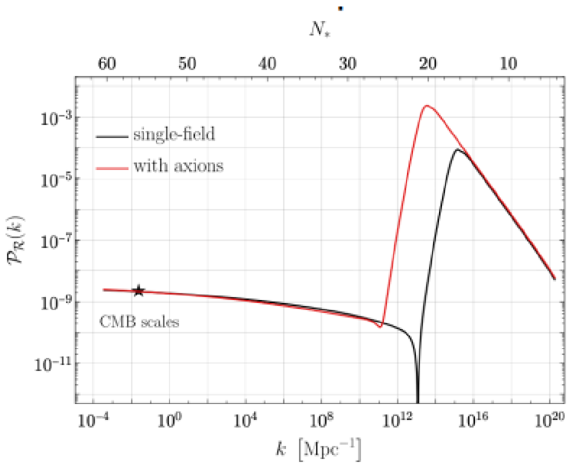


- Motion along θ_{K3} during ultra slow roll if $m_{\theta_{K3}} \sim 0.1\ H$

→ isocurvature modes source curvature modes due to non-zero turning rate

→ θ_{K3} helps reducing tuning on V to obtain PBHs



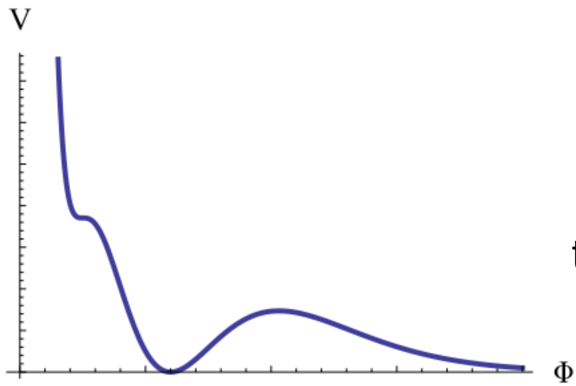


WIP: [MC,Lorenzoni, McDonough,Pedro]

Kination after volume inflation

- Modulus domination after inflation can be matter (Fibre Infl.) but also kination
- Example: Volume inflation around inflection point

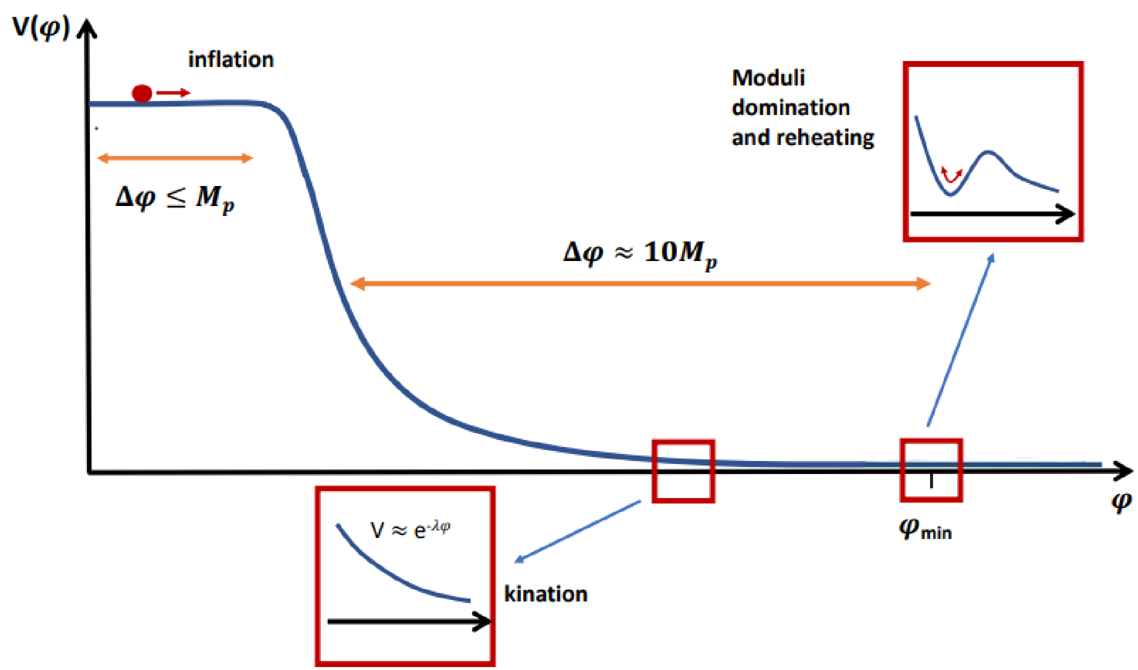
[Conlon,Kallosh,Linde,Quevedo] [MC,Muia,Pedro]



$$V(\Phi) = V_0\left[\left(1-\kappa_{\rm np}\Phi^{3/2}\right)e^{-\sqrt{\frac{27}{2}}\Phi}+\kappa_{g_s}\,e^{-\frac{10}{\sqrt{6}}\Phi}+\kappa_{F^4_{(b)}}\,e^{-\frac{11}{\sqrt{6}}\Phi}+\kappa_{\overline{D3}}\,e^{-\sqrt{6}\Phi}\right]$$

to get high scale inflation and low-energy SUSY as $m_{3/2} \sim \frac{W_0 M_p}{\mathcal{V}}$

zoom



Kination after brane-antibrane inflation

- Rolling moduli after brane-antibrane inflation

$$V(\phi) = C_0\left(1 - \frac{C_1}{\phi^4}\right) \qquad \phi = \sqrt{T_{D3}}\, r$$

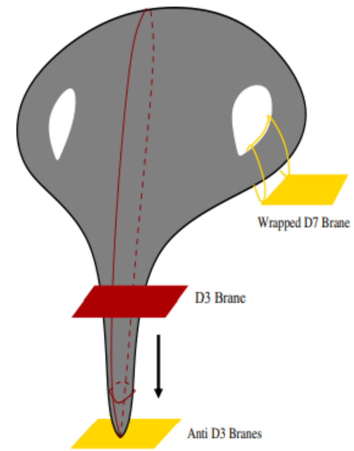
- D3-antiD3 inflation without η-problem due perturbative $\mathcal{V}$ fixing

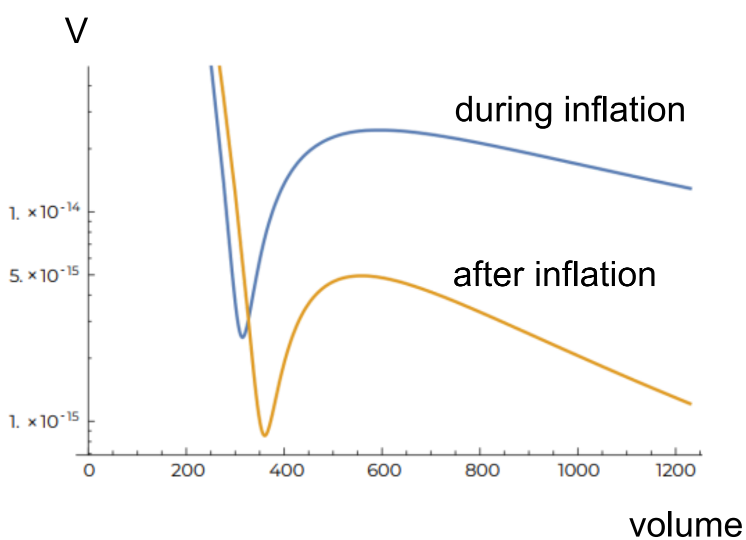
$$\mathcal{V}^{2/3} = \sigma = \tau - \frac{1}{6}(M_{KK} r)^2 \to \tau \quad \text{at end of inflation}$$

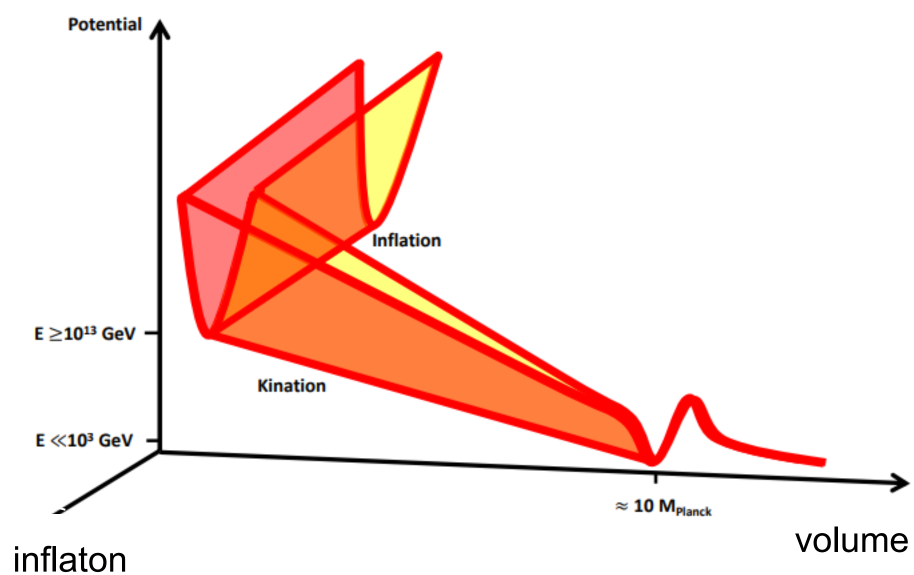
- During inflation: $V \simeq \frac{1}{3\sigma^2}\left(W_X - \frac{3g_s W_0}{\sigma}\right)^2 + \frac{3\xi W_0^2}{4 g_s^{3/2}\sigma^{9/2}}$ $\qquad W = W_0 + X\, W_X(r)$

- Brane annihilation after inflation: $W_X \to 0$ $\longrightarrow$ $\frac{V}{3W_0^2} \simeq \frac{\alpha}{\tau^4} - \frac{\xi\sqrt{g_s}}{4c\tau^{9/2}}\left(\ln\tau - \frac{c}{g_s^2}\right)$

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







A cosmic superstring network?

- Generic stringy features after inflation:

  i) Fundamental strings: initial population of string loops

  ii) Evolving moduli: kination due to rolling volume $\mathcal{V}$

  iii) Field-dependent scales: tension of F-strings controlled by $\mathcal{V}$

$$\mu \simeq M_s^2 \simeq \frac{M_p^2}{\mathcal{V}} = M_p^2\, e^{-\sqrt{6}\,\beta\,\phi/M_p} \qquad \beta = 1/2$$

- Volume increases ⟶ decreasing tension ⟶ $2H + \frac{\dot{\mu}}{\mu} < 0$

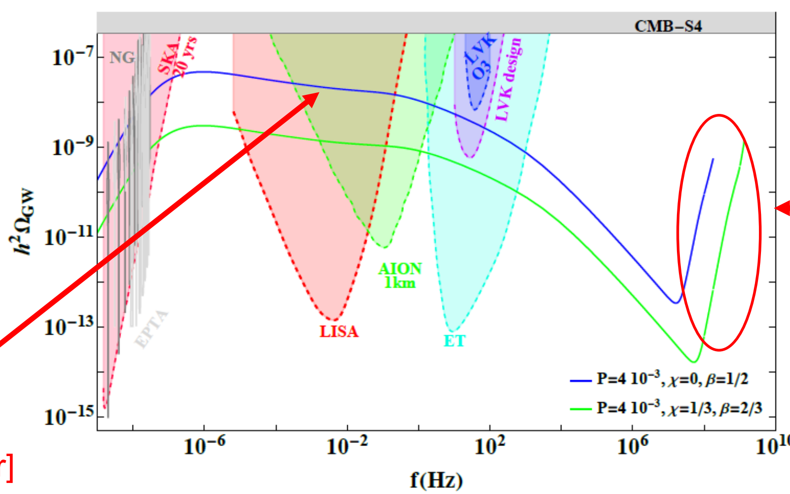
  ⟶ growth of comoving radius of cosmic strings [Conlon,Copeland,Hardy,Gonzales]

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

[Ghoshal,Revello,Villa]

enhanced $\mathcal{V}$ decay

[MC,Hebecker, Jaeckel,Wittner]



kination

Growth of cosmic strings

- 3 regimes for growth of comoving radius:

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

  ii) F-strings in scaling fixed points

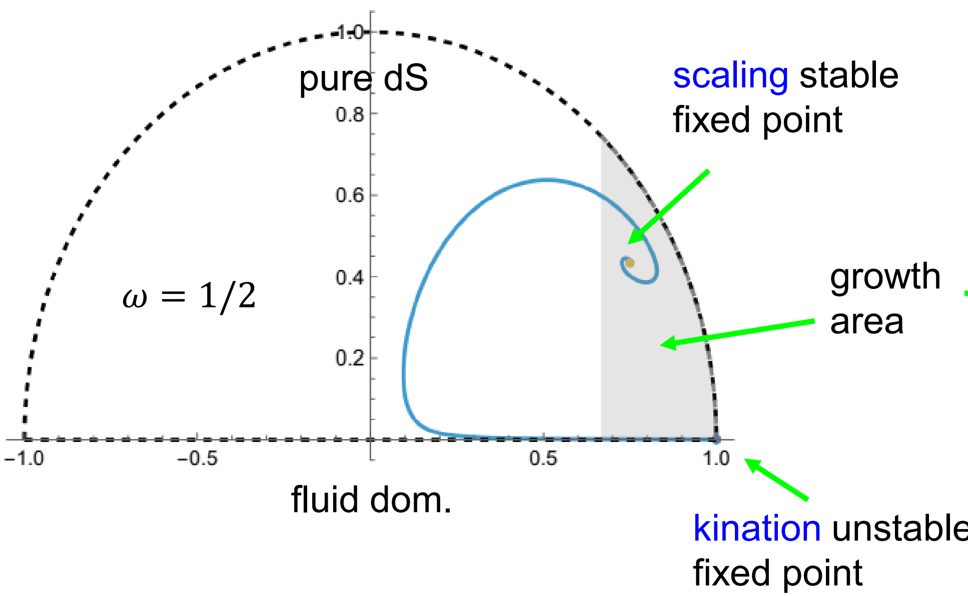
  iii) Effective strings from D3s or NS5s on fibration cycles

  [Brunelli,MC,Pedro]

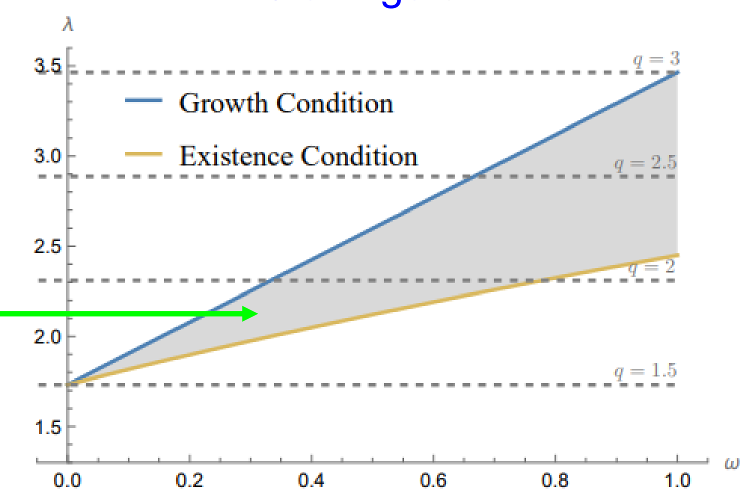
- Dynamical system:

  strings with ϕ-dependent μ and negligible ρ_{loop} + fluid + ϕ with $V(\phi) = V_0 e^{-\lambda\phi}$

F-strings

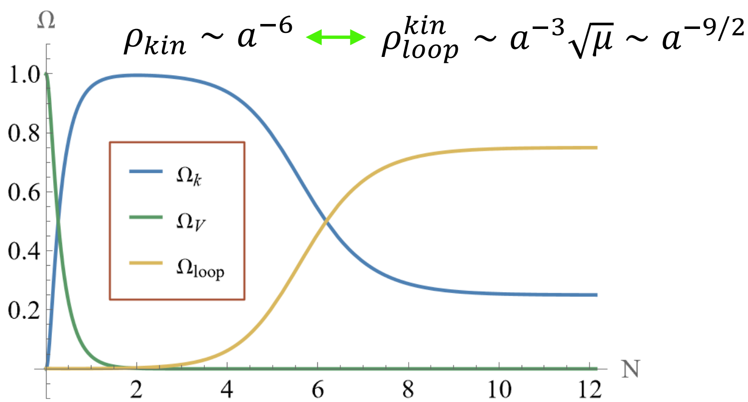


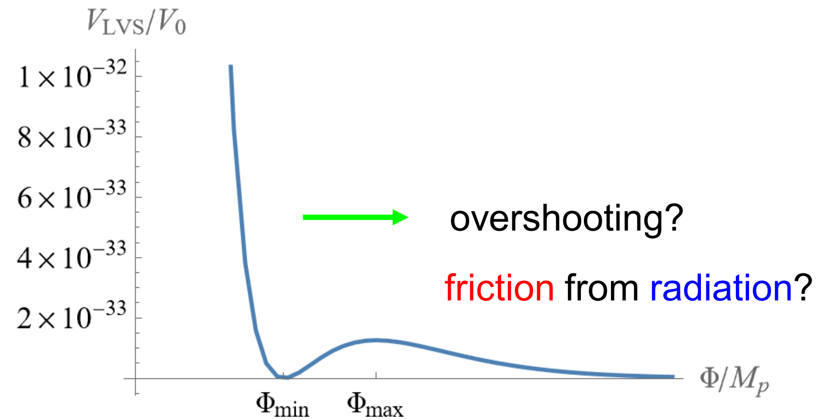
D3 strings on $\mathbb{P}^1$



Cosmic strings and overshooting

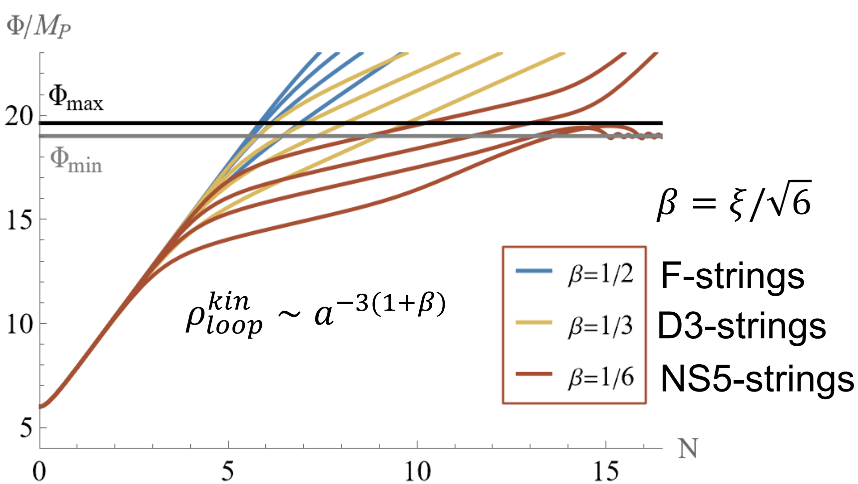
- If ρ_{loop} is not negligible, new loop tracker for F-strings [Gonzalez,Conlon,Copeland,Hardy]

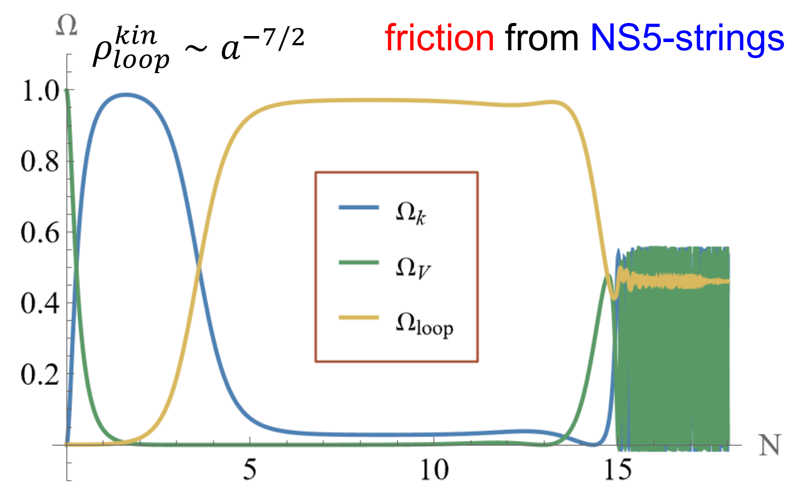




- No overshooting of LVS minimum for NS5-strings without radiation! [Brunelli,MC,Pedro]

$$V_{\text{LVS}}(\Phi) = V_0\left[\left(1-\epsilon\,\Phi^{3/2}\right)e^{-3\sqrt{\frac{3}{2}}\,\Phi} + \delta\,e^{-2\sqrt{\frac{3}{2}}\,\Phi}\right]$$





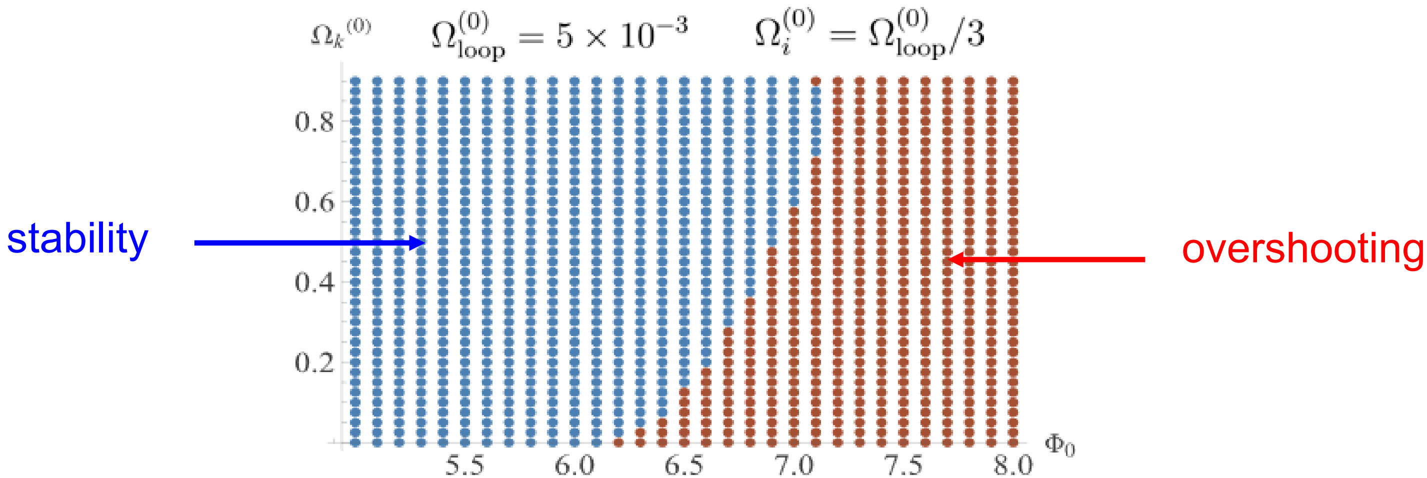
General case with all types of strings

WIP: [Brunelli,MC,Hassan,Pedro,Qoreishi]

- General case:

i) Non-zero initial velocity of ϕ $\longrightarrow$ $\Omega_k^{(0)} \neq 0$

ii) F-strings, D3-strings and NS5-strings $\longrightarrow$ $\Omega_F^{(0)} \neq 0$ $\quad \Omega_3^{(0)} \neq 0$ $\quad \Omega_5^{(0)} \neq 0$



- Larger initial velocities improve stability since kination is reached earlier

$\longrightarrow$ friction from NS5-strings acts sooner

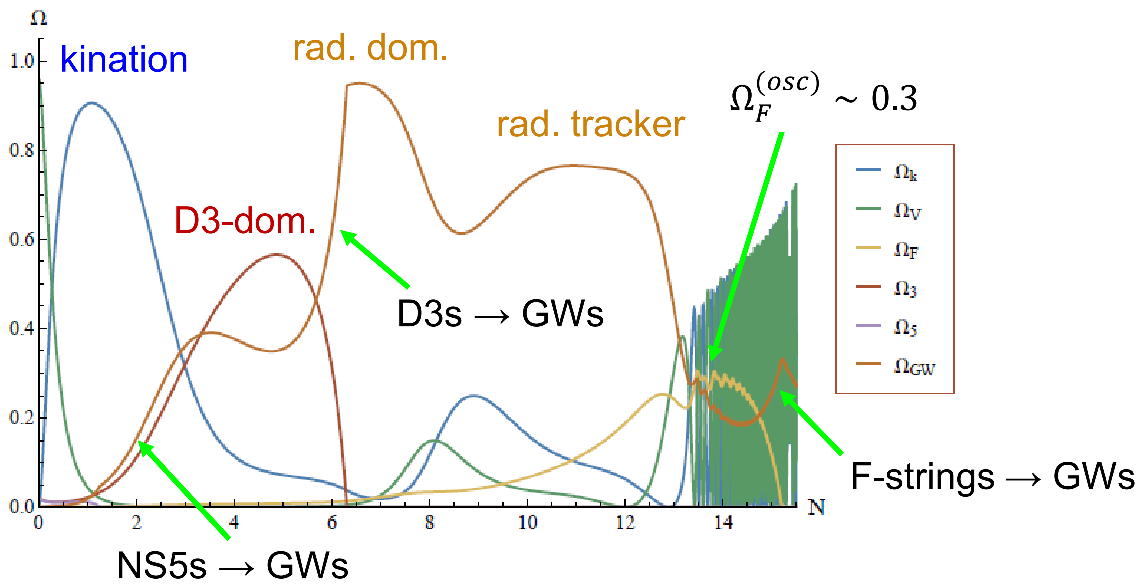
- Need to include GW production from string loop decays since: [Conlon,Copeland,Hardy,Gonzales]

$$\delta_i \equiv \frac{\Gamma_{GW,i}}{H} \sim \frac{\gamma\, \mu_i}{M_p^2 \ell_i H} \sim \frac{\gamma}{\mathcal{V}^{2\beta} \ell_i H} \qquad \text{for} \quad \left\{ \begin{array}{l} \gamma \sim 10 \\ \mathcal{V}_0 \sim 10^3 \\ \ell_0 H \sim 0.1 \end{array} \right. \longrightarrow \left\{ \begin{array}{l} \delta_{NS5}^{(0)} \sim 10 \\ \delta_{D3}^{(0)} \sim 10^{-1} \\ \delta_F^{(0)} \sim 10^{-3} \end{array} \right.$$

General case with all types of strings

WIP: [Brunelli,MC,Hassan,Pedro,Qoreishi]

- No overshooting due to friction from GW radiation from string loop decays:



$$\Phi_0 = 6$$

$$\Omega_k^{(0)} = \Omega_{GW}^{(0)} = 0$$

$$\Omega_{NS5}^{(0)} = \Omega_{D3}^{(0)} = 0.02$$

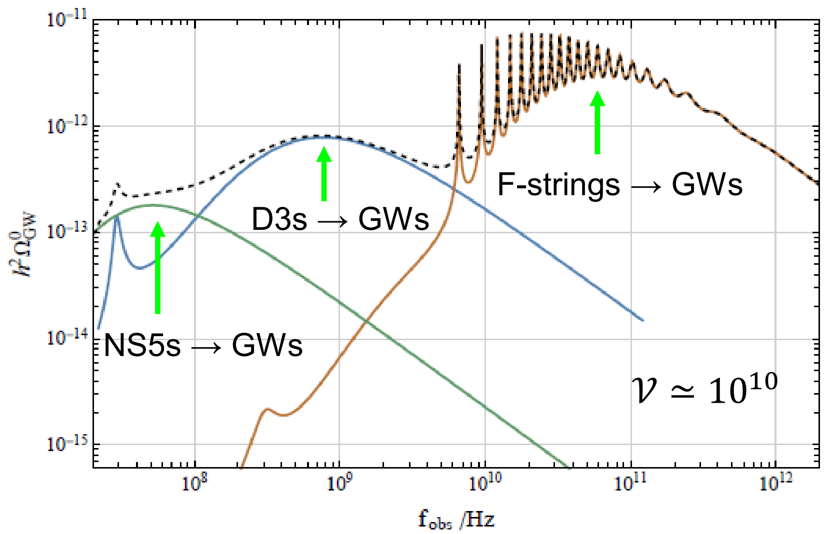
$$\Omega_F^{(0)} = 10^{-3}$$

- Multiple peaks of GWs at GHz range for loop-enhanced $\mathcal{V}$ decay

$$\Gamma_{\mathcal{V}\to hh} \sim c_{loop}^2 \left(\frac{M_{soft}}{m_{\mathcal{V}}}\right)^4 \frac{m_{\mathcal{V}}^3}{M_p^2}$$

$$M_{soft} \gg m_{\mathcal{V}} \longrightarrow \Gamma_{\mathcal{V}\to hh} \gg m_{\mathcal{V}}^3/M_p^2$$

[MC,Hebecker,Jaeckel,Wittner]



Reheating from volume decay

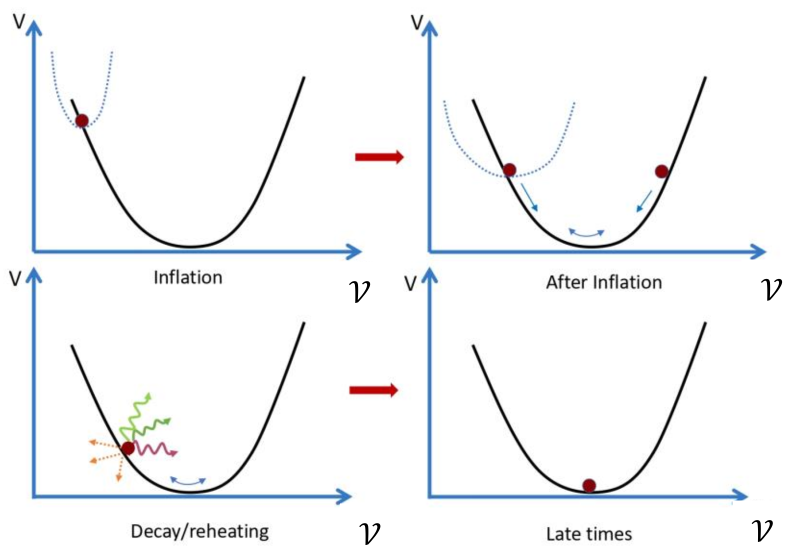
- Non-standard cosmology after inflation:

i) Inflation $\rightarrow$ matter dom. from inflaton ϕ oscillations $\rightarrow$ rad. dom. after ϕ decay
$\rightarrow$ matter dom. from volume $\mathcal{V}$ oscillations $\rightarrow$ reheating from $\mathcal{V}$ decay

ii) Inflation $\rightarrow$ kination from volume $\mathcal{V}$ rolling $\rightarrow$ rad. dom. after string loop decay
$\rightarrow$ matter dom. from volume $\mathcal{V}$ oscillations $\rightarrow$ reheating from $\mathcal{V}$ decay

$\longrightarrow$ Reheating from $\mathcal{V}$ decay in general

$\longrightarrow$ dark radiation, non-thermal dark matter, Affleck-Dine baryogenesis,…



$$N_e \simeq 57 + \frac{1}{4}\ln r - \frac{1}{4}N_\phi - \frac{1}{4}N_{\mathcal{V}} + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{end}}\right)$$

[MC,Conlon,Quevedo]

$$\mathcal{V}$$

$\Gamma_{\mathcal{V}\rightarrow SM}$: $\mathcal{V} \rightarrow$ SM dof

$\Gamma_{\mathcal{V}\rightarrow\theta_b\theta_b} \sim m_{\mathcal{V}}^3/M_p^2$

$\Gamma_{\mathcal{V}\rightarrow\gamma'\gamma'}$

$\mathcal{V} \rightarrow$ bulk axions θ_b, hidden photons γ'

$\downarrow$

$\Delta N_{\rm eff} \neq 0$

Dark radiation from bulk axions

- Bulk axions θ_b enjoy a perturbative shift symmetry $\longrightarrow$ K_{pert} depends just on $\mathcal{V} \sim \tau_b^{3/2}$

$$K_{pert} = -2\ln\mathcal{V} + K_{corr}(\mathcal{V}) = -3\ln\tau_b + \cdots \qquad T_b = \tau_b + i\theta_b$$

- Shift symmetry broken by non-perturbative effects $\longrightarrow$ θ_b is ultra-light

$$W_{non-pert} = e^{-a_b T_b} \propto e^{-a_b \mathcal{V}^{2/3}} \ll 1 \longrightarrow m_{\theta_b} \sim e^{-a_b\mathcal{V}^{2/3}} M_p \ll m_{\mathcal{V}} \sim \frac{W_0 M_p}{\mathcal{V}^{3/2}}$$

- $\mathcal{V}$-θ_b coupling from kinetic terms

$$\frac{1}{4}\frac{\partial^2 K}{\partial\tau_b^2}\left(\partial_\mu\tau_b\partial^\mu\tau_b + \partial_\mu\theta_b\partial^\mu\theta_b\right) = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}e^{-2\sqrt{2/3}\phi}\,\partial_\mu\vartheta_b\partial^\mu\vartheta_b \qquad \left\{\begin{array}{l} \tau_b = e^{\sqrt{2/3}\phi/M} \\ \theta_b = \sqrt{2/3}\vartheta_b \end{array}\right.$$

$$\longrightarrow \sqrt{\frac{2}{3}}\frac{\phi}{M_p}\partial_\mu\vartheta_b\partial^\mu\vartheta_b$$

- Model-independent $\mathcal{V} \to \theta_b\theta_b$ decay rate [MC,Conlon,Quevedo]

$$\Gamma_{\mathcal{V}\to\theta_b\theta_b} = \frac{1}{48\pi}\frac{m_{\mathcal{V}}^3}{M_p^2} \longrightarrow \Delta N_{\rm eff} \neq 0$$

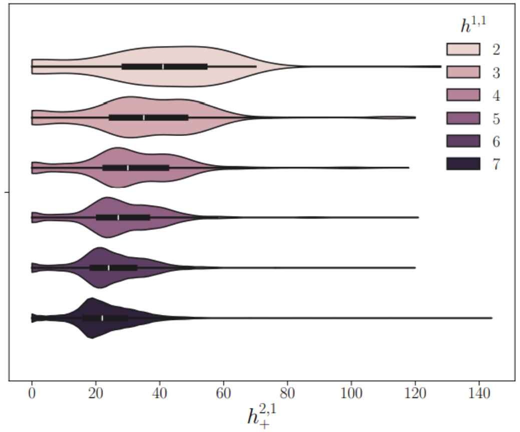
Bulk hidden photons

- Bulk hidden photons γ' from dimensional reduction of C_4

$$C_4 = D_2^i(x) \wedge \widehat{D}_i + V^\lambda(x) \wedge \alpha_\lambda + U^\lambda(x) \wedge \beta_\lambda + \rho_i(x)\widetilde{D}^i \qquad \lambda = 1, \dots, h_+^{1,2}$$

- $h_+^{1,2} \gg 1$ for CYs in Kreuzer-Skarke list with $2 \leq h^{1,1} \leq 7$

[Sheridan et al]



- Charged modes are D3s wrapping 3-cycle Σ_3 with mass

$$m_{D3} \simeq T_{D3} Vol(\Sigma_3) \gg M_s$$

→ no light charged modes → no Stueckelberg/Higgs mechanism → massless γ'

[$m_{\gamma'} \geq M_s$ for torsional cycles]

- Gauge kinetic function depends on cx str moduli z^a $\quad a = 1, \dots, h_-^{1,2}$

[Camara,Ibanez,Marchesano]

$$Re(f_{\lambda\kappa}) X_{\mu\nu}^\lambda X^{\mu\nu,\kappa} \qquad f_{\lambda\kappa} = \frac{i}{2} \partial_{\lambda\kappa}^2 F(z) \Big|_{z^\alpha = 0} \qquad \forall \alpha = 1, \dots, h_+^{1,2}$$

$$F(z) = -\frac{1}{6} k_{IJK} z^I z^J z^K + \cdots \quad I, J, K = 1, \dots, h^{1,2} \quad \longrightarrow \quad f_{\lambda\kappa}(z) \sim k_{\lambda\kappa a} z^a$$

- Kinetic mixing with SM photon on D7s wrapped on 4-cycle Σ_4 [Grimm,Louis][Jockers,Louis]

$$\chi X_{\mu\nu}^\lambda F^{\mu\nu} \qquad \chi \propto \int_{\Sigma_4} A \wedge i^* \alpha_\lambda \quad \longrightarrow \quad \chi = \chi(a_{\tilde{I}}, \zeta^A, z^a)$$

$a_{\tilde{I}}$ = Wilson lines

ζ^A = D7 deformations

Bulk hidden photons

- Lagrangian for photon and bulk hidden photon γ'

$$-Re(f_{vis})(T)\, F^{\mu\nu}F_{\mu\nu} - Re(f_{hid})(z)\, X^{\mu\nu}X_{\mu\nu} + \epsilon(z,a,\zeta)X^{\mu\nu}F_{\mu\nu} + J^{\mu}_{vis}A_{\mu} + \overset{\overset{0}{\shortparallel}}{J^{\mu}_{hid}}V_{\mu} - \frac{1}{2}\overset{\overset{0}{\shortparallel}}{m^2_{\gamma'}}V_{\mu}V^{\mu}$$

$$\longrightarrow \quad -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{\epsilon}{2}X^{\mu\nu}F_{\mu\nu} + g_{vis}\, J^{\mu}_{vis}A_{\mu} \qquad \epsilon \sim \frac{\chi}{\sqrt{Re(f_{vis})Re(f_{hid})}} \sim g_{vis}g_{hid}\chi \ll 1$$

- Non-unitary transformation

$$A_{\mu} = \frac{\hat{A}_{\mu}}{\sqrt{1-\epsilon^2}} \qquad\qquad V_{\mu} = \hat{V}_{\mu} + \frac{\epsilon}{\sqrt{1-\epsilon^2}}\,\hat{A}_{\mu}$$

$$\longrightarrow \quad \boxed{-\frac{1}{4}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} + \hat{g}_{vis}\, J^{\mu}_{vis}\hat{A}_{\mu}}$$

- Small correction to U(1)-charge: $\hat{g}_{vis} \simeq g_{vis}\left(1 + \frac{1}{2}\epsilon^2\right)$ $\longrightarrow$ tiny effect on GUT unification

$\longrightarrow$ bulk hidden photons are super-hidden

- Observations:

i) Collider signals for low-scale ~~SUSY~~ from hidden photini mixed with Bino [Arvanitaki et al]

ii) Dipole moments from γ' coupling to visible matter via dim 6 operators [Coudarchet et al]

- Gravitational production from $\mathcal{V} \to \gamma'\gamma'$ decay at reheating? $\longrightarrow$ $\Delta N_{\rm eff} \neq 0$

Dark radiation from bulk hidden photons

- Moduli coupling to γ' from gauge kinetic function

WIP: [Caraffi,Chinaia,MC,Lin]

$$Re(f_{hid}(z))\, X^{\mu\nu}X_{\mu\nu} \longrightarrow$$ only cx str moduli z couple directly to γ'

- Volume $\mathcal{V}$ coupling to γ' induced by kinetic mixing between $\mathcal{V}$ and z

$$K = -2\ln\mathcal{V} - 3\ln(z+\bar{z}) + \frac{f(z+\bar{z})}{\mathcal{V}^{2/3}} + \frac{c}{\mathcal{V}} + \ldots$$

- Canonical normalisation at minimum with $Re(z) \equiv u$

$$\frac{\hat{u}}{\langle u\rangle} \simeq O(\mathcal{V}^{-2/3})\phi + O(1)\chi$$

$\longrightarrow$ $\mathcal{V}$-suppressed $\mathcal{V}$-γ' coupling at $O(\alpha'^2)$ level: $g_{\mathcal{V}\gamma'}\dfrac{\phi}{M_p}X^{\mu\nu}X_{\mu\nu}$ $\quad g_{\mathcal{V}\gamma'} \sim \dfrac{1}{\mathcal{V}^{2/3}} \ll 1$

$\longrightarrow$ negligible contribution to $\Delta N_{\rm eff}$ since (for $\mathcal{V} \gtrsim 10^3 \quad N_{\gamma'} \sim 100$)

$$\Gamma_{\mathcal{V}\to\gamma'\gamma'} \sim g^2_{\mathcal{V}\gamma'}N_{\gamma'}\frac{m^3_{\mathcal{V}}}{M_p^2} \sim \mathcal{V}^{-4/3}N_{\gamma'}\Gamma_{\mathcal{V}\to\theta_b\theta_b} \lesssim 10^{-2}\Gamma_{\mathcal{V}\to\theta_b\theta_b} \ll \Gamma_{\mathcal{V}\to\theta_b\theta_b} \longrightarrow \Delta N_{\rm eff} \to 0$$

- $\Gamma_{z\to\gamma'\gamma'} \gg \Gamma_{\mathcal{V}\to\gamma'\gamma'}$ since $g_{z\gamma'} \sim 1$ but z-moduli are heavy $\longrightarrow$ tiny initial displacement

$\longrightarrow$ no z-moduli domination or dilution of γ' by $\mathcal{V}$ decay $\longrightarrow$ $\Delta N_{\rm eff} \to 0$

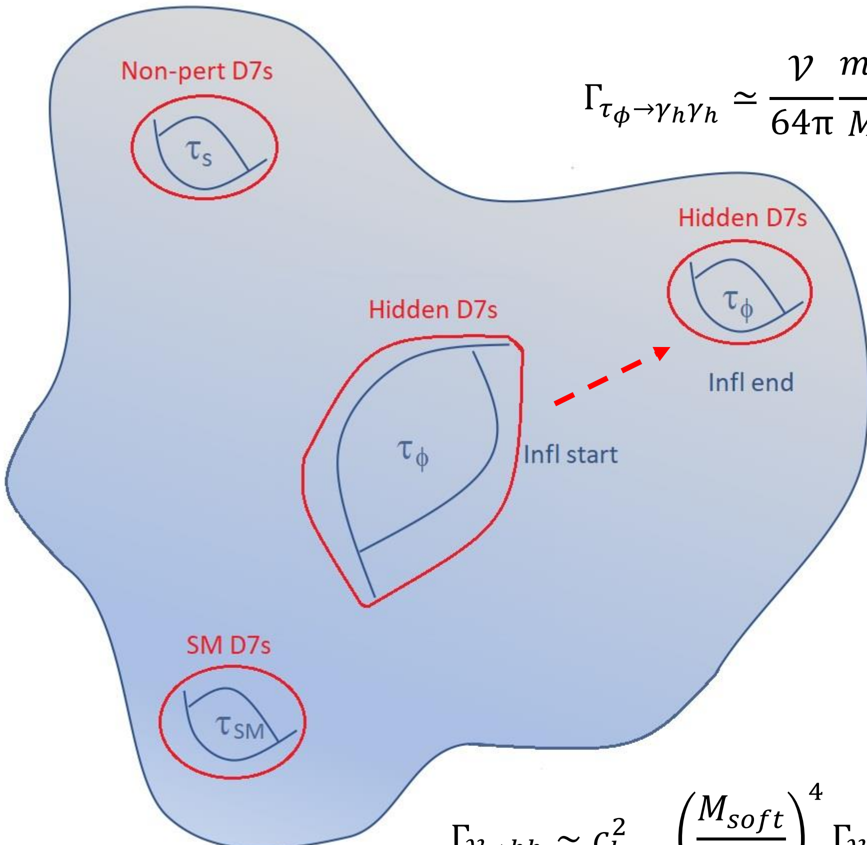
BUT big challenge if some z-moduli are light as predicted in general by tadpole conjecture

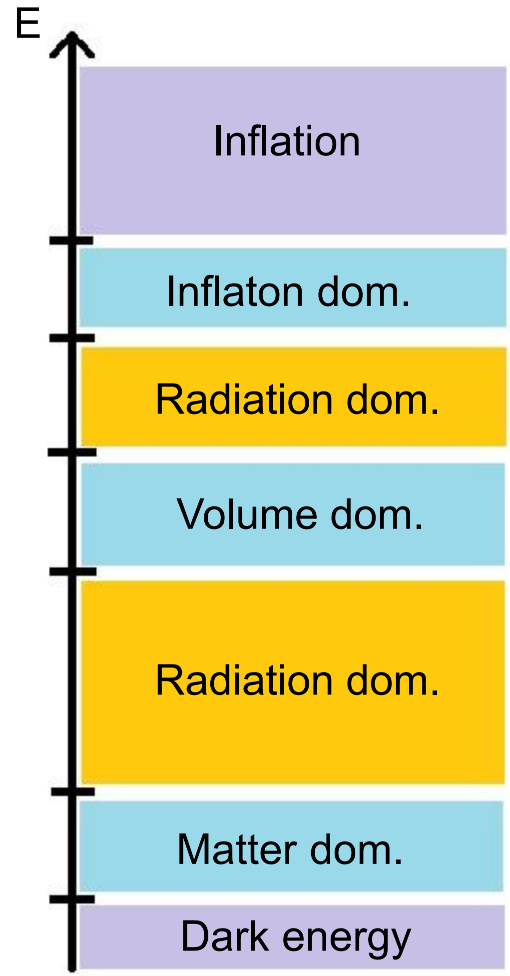
[Bena,Blaback,Grana,Lust]

Loop blowup inflation with SM on D7s

[Bansal,Brunelli,MC,Hebecker,Kuespert]

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





$N_e \simeq 53$

$N_{\tau_\phi} \simeq 1$

$\tau_\phi \to \gamma_h \gamma_h$

$N_{\mathcal{V}} \simeq 3$

$\mathcal{V} \to hh$

$$\Gamma_{\mathcal{V}\to hh} \sim c_{loop}^2 \left(\frac{M_{soft}}{m_{\mathcal{V}}}\right)^4 \Gamma_{\mathcal{V}\to\theta_b\theta_b}$$

$$M_{soft} \sim m_{3/2} \gg m_{\mathcal{V}} \longrightarrow \Gamma_{\mathcal{V}\to hh} \gg \Gamma_{\mathcal{V}\to\theta_b\theta_b}$$

[MC,Hebecker,Jaeckel,Wittner]

Predictions:

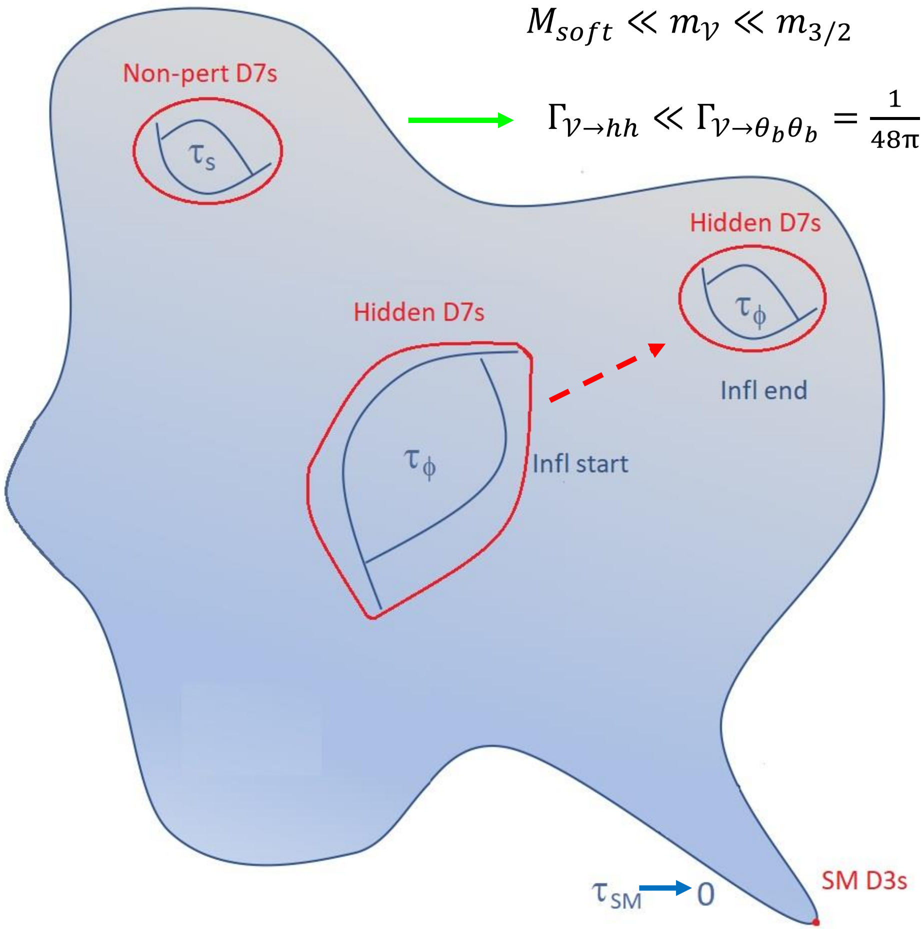
$n_s \simeq 0.9765$ $\quad r \simeq 1.7 \times 10^{-5}$ $\quad T_{\rm rh} \simeq 4 \times 10^{10}\,\mathrm{GeV}$ $\quad \Delta N_{\rm eff} \simeq 0$

Loop blowup inflation with SM on D3s

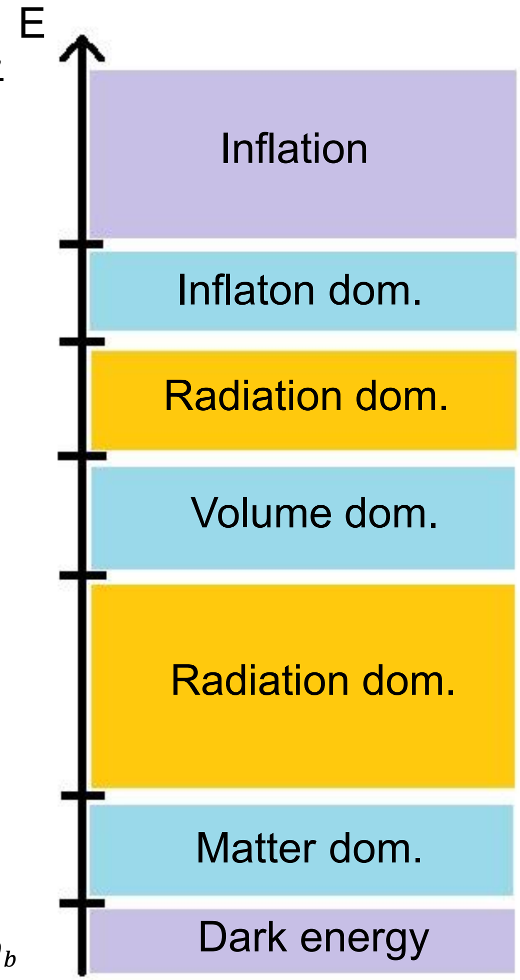
[Bansal,Brunelli,MC,Hebecker,Kuespert]

$$M_{soft} \ll m_{\mathcal{V}} \ll m_{3/2}$$

$$\Gamma_{\mathcal{V}\to hh} \ll \Gamma_{\mathcal{V}\to\theta_b\theta_b} = \frac{1}{48\pi}\frac{m_{\mathcal{V}}^3}{M_P^2}$$



$$K \supset Z\frac{H_u H_d}{\mathcal{V}^{2/3}} \qquad \Gamma_{\mathcal{V}\to H_u H_d} = 2Z^2\,\Gamma_{\mathcal{V}\to\theta_b\theta_b}$$



$N_e \simeq 51.5$

$N_{\tau_\phi} \simeq 1$

$\tau_\phi \to \gamma_h\gamma_h$

$N_{\mathcal{V}} \simeq 10.5$

$\mathcal{V} \to H_u H_d, \theta_b\theta_b$

Predictions:

$$n_s \simeq 0.9757 \qquad r \simeq 1.8\times 10^{-5} \qquad T_{\rm rh} \simeq 1\times 10^{8}\,\text{GeV} \qquad \Delta N_{\rm eff} \simeq \frac{1.43}{Z^2} \neq 0$$

Dark energy from axions

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

i) Hierarchy allows $V_{\rm sub} \sim 10^{-120} M_p^4$ for $M_s > M_{soft} \gtrsim 1\ \mathrm{TeV}$ and $m_{\mathcal{V}} \gtrsim 30\ \mathrm{TeV}$ $\longrightarrow$ no CMP

$$V_{\rm sub}(\phi,\mathcal{V}) \sim \underbrace{e^{-\sqrt{\frac{3}{2}}\frac{M_p}{f}}}_{10^{-120}} M_p^4 \left[1-\cos\left(\frac{\phi}{f}\right)\right] \qquad f = \sqrt{3/2}\,\frac{M_p}{a\mathcal{V}^{2/3}}$$

10^{-120} for $f \sim 0.003\, M_p \quad \Leftrightarrow \quad \mathcal{V} \sim 10^3$ natural + EFT under control

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

ii) Radiative stability due to perturbative shift symmetry

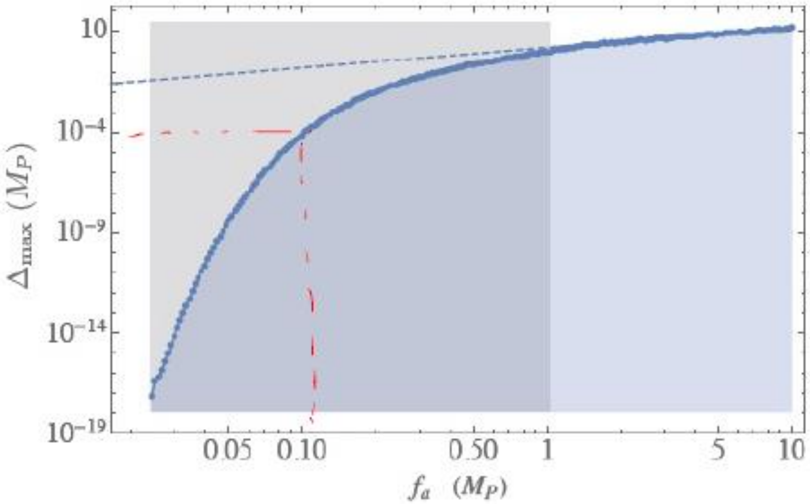
iii) No fifth-force problem

- But axion potential yields acceleration only for $f \gtrsim M_p$
- Never obtained in EFT + forbidden by WGC
- For $f < M_p$ can have axion hilltop quintessence

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 $H_{inf} \lesssim \Delta_{max}$

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

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

- In (i) use poly-instantons to generate axion potential with right DE scale [MC,Padilla,Pedro]
- 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: $\mathcal{V} = t_{P1}\tau_{K3} - \tau_{dP}^{3/2}$ [MC,Padilla,Pedro]

$$V = V_{lead}(\mathcal{V}, \tau_{dP}, \theta_{dP}) + V_{inf}(\tau_{K3}) + V_{sub}(\theta_{P1}, \theta_{K3})$$

- 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 ultra-light axions: θ_{P1} = spectator (0.2% of DM) + θ_{K3} = DE via poly-instantons

$$W = W_{LVS} + e^{-a\,T_{P1} + e^{-bT_{K3}}}$$

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

- Axion potential:

$$V_{sub} \sim e^{-a\tau_{P1}}\left[1 - \cos\left(\frac{\psi}{g}\right)\right] + e^{-a\tau_{P1} - b\tau_{K3}}\left[1 - \cos\left(\frac{\psi}{g} + \frac{\phi}{f}\right)\right]$$

fix $\psi = 0$ $\longrightarrow$ $V_{DE} \sim e^{-1/f - 1/g}\left[1 - \cos\left(\frac{\phi}{f}\right)\right]$

$$f = \frac{N}{2\sqrt{2}\pi\tau_{K3}} M_p \simeq 0.1\, M_p \quad \text{and} \quad g = \frac{M}{2\pi\tau_{P1}} M_p \simeq 0.005\, M_p$$

- Numerical results:

$$\tau_{K3} \sim O(5) \qquad \tau_{P1} \sim O(500) \qquad N \sim O(10) \qquad M \sim O(10)$$

$$m_{\theta_{P1}} \simeq 10^{-29}\ \text{eV} \qquad m_{\theta_{K3}} \simeq 10^{-32}\ \text{eV}$$

Quintessence from poly-instantons

- 2 challenges for model building:

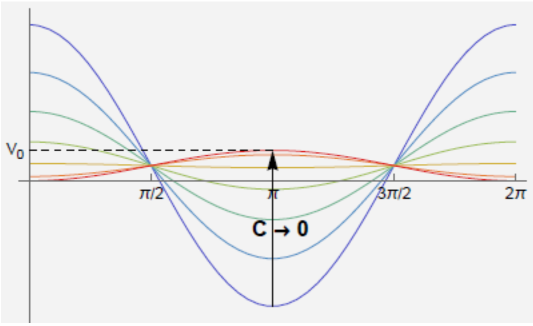
  i) $f \simeq 0.1\, M_p$ needs tuning of initial conditions $|\phi_0 - \pi f| \lesssim 10^{-4}\, M_p$ [MC,Cunillera,Padilla,Pedro]

  ii) Poly-instantons on Wilson divisors $(h_+^{10} = 1, h^{20} = 0)$, not on K3s $(h^{10} = h_+^{20} = 0, h_-^{20} = 1)$

  [Blumenhagen,Schmidt-Sommerfeld]

- To address (i) use dependence on open string C WIP: [MC,Vagnoni]

$$W = W_{LVS} + A(C)\, e^{-c\, T_{K3}} + e^{-a\, T_{P1} + e^{-bT_{K3}}} \qquad m_C < m_\phi(C) < H$$



Inflation → ϕ relaxes at $\phi_{min} = \pi f$

→ C moves to $C = 0$ where $A(C) = 0$ → ϕ sits at $\phi_{max} = \pi f$

- 2 options to address (ii):

  1) Poly-instantons on Wilson divisors with $\tau_W = \tau_{K3} - \tau_{dP} \simeq \tau_{K3}$ [Luest,Zhang]

  2) Poly-instantons on K3-like divisors for O3-planes [Caraffi,Carta,MC]

$$\chi^\sigma(D) = \sum_{i=0}^{2} (-1)^i (h_+^{i0} - h_-^{i0}) = -\frac{1}{4}\sum_i k_{DDO7_i} + \frac{1}{4} N_{O3}^D$$ [Cvetic,Garcia-Etxebarria,Halverson]

for K3-like D with $k_{DDO7_i} = 0\ \forall i$ ⟶ $\chi^\sigma = 1 + h_+^{20} - h_-^{20} = \frac{1}{4} N_{O3}^D$

if $N_{O3}^D = 0$ ⟶ $\chi^\sigma = 1 + h_+^{20} - h_-^{20} = 0$ ⟶ $h_+^{20} = 0, h_-^{20} = 1$ NO

if $N_{O3}^D = 8$ ⟶ $\chi^\sigma = 1 + h_+^{20} - h_-^{20} = 2$ ⟶ $h_+^{20} = 1, h_-^{20} = 0$ YES

ADD and the Dark Dimension

- Bound on large EDs: $M_{KK} \gtrsim meV$

  ia) ADD: 2 large EDs with $M_{KK}^{6D} \sim meV$ and $M_6 \sim TeV$ [Arkani-Hamed,Dimopoulos,Dvali]

  $\longrightarrow$ hierarchy problem

  ib) SLED: 2 large SUSY EDs with $M_{KK}^{6D} \sim m_{3/2} \sim meV$ and $V \sim \left(M_{KK}^{6D}\right)^2 m_{3/2}^2 \sim meV^4$

  $\longrightarrow$ hierarchy probl. + dark energy [Aghababaie,Burgess,Parameswaran,Quevedo]

  ii) DD: 1 large ED with $M_{KK}^{5D} \sim meV$ and $V \sim \left(M_{KK}^{5D}\right)^4 \sim meV^4$ [Montero,Vafa,Valenzuela]

  $\longrightarrow$ dark energy

- Challenges:

  i) Need string embedding to have quantitative control

  ii) No known accelerating solutions at boundary of moduli space

  iii) $V \sim \left(M_{KK}^{6D}\right)^2 m_{3/2}^2$ and $V \sim \left(M_{KK}^{5D}\right)^4$ ruined by larger loops of bulk/brane fields? SM loops?

  iv) Hard to fix moduli at anisotropic CY with 1 or 2 large EDs with $M_{KK} \sim meV$

  [first attempt at anisotropic LVS stabilisation [MC,Burgess,Quevedo]]

  v) Tension with pheno: low SUSY breaking, CMP, fifth-forces, moduli DM overprod., inflation

Moduli stabilisation for ADD and the Dark Dimension

[Braun,MC,Milioli,Valandro]

- Moduli stabilisation for anisotropic string compactifications with 1 (DD) or 2 (ADD) large EDs

  i) Large EDs: via type IIB LVS where $\mathcal{V}$ is exponentially large

  ii) Anisotropy: via CY = small 4D K3 fibre over large 2D $\mathbb{P}^1$ base
  ADD for isotropic $\mathbb{P}^1$ $\longleftrightarrow$ DD for anisotropic $\mathbb{P}^1$ (Tyurin degeneration)

- $\mathcal{V} \simeq t_{P1}\tau_{K3}$ where $t_{P1} = \ell_L\, R$ controls 2D $\mathbb{P}^1$ size while $\tau_{K3} = \ell_{K3}^4$ controls 4D K3 size

- Leading LVS order: $O(\alpha'^3)$ + non-pert. effects fix $\mathcal{V} \sim e^{c/g_s} \gg 1$ leaving τ_{K3} flat

- Subleading order: τ_{K3} lifted by $O(g_s^2\alpha'^4)$ loops and $O(\alpha'^3 F^4)$ corrections

$$V_{\rm sub} \simeq \frac{W_0^2}{\mathcal{V}^3}\left(-\frac{A}{\sqrt{\tau_{\rm K3}}} + \frac{B}{\tau_{\rm K3}}\right) \qquad A \equiv g_s\, c_{\rm loop} \qquad B \equiv \sqrt{g_s}\, c_{F^4}\, W_0^2$$

$$\Lambda^2 Str(M^2) \sim \left(M_{KK}^{10D}\right)^2 m_{3/2}^2 \qquad V_{F^2}\left(m_{3/2}/M_{KK}^{5D}\right)^2$$

- 2 cases depending on W_0:

1) $W_0 \sim O(10)$: AdS min at $\tau_{K3} \simeq \left(\frac{2B}{A}\right)^2 \sim O(5)$ with $\langle V_{\rm sub}\rangle \simeq -\frac{B\,W_0^2}{\mathcal{V}^3\langle\tau_{\rm K3}\rangle}$

ADD: $\langle V_{\rm sub}\rangle \sim -\left(M_{\rm KK}^{6D}\right)^3 M_p$

DD: $\langle V_{\rm sub}\rangle \sim -\left(M_{\rm KK}^{5D}\right)^2 M_p^2$

$\longrightarrow$ uplifting to dS min with $\langle V_{sub}\rangle \sim M_{KK}^4$

2) $W_0 \ll 1 \Rightarrow B \ll A$: quintessence with $V \simeq V_0\, e^{-c\phi}$ and $c = 1/\sqrt{3}$

$\longrightarrow$ tune $\tau_{K3} \sim O(5)$ and W_0 to get $V \sim meV^4$

ADD: $W_0 \sim 10^{-12}$

DD: $W_0 \sim 10^{-27}$

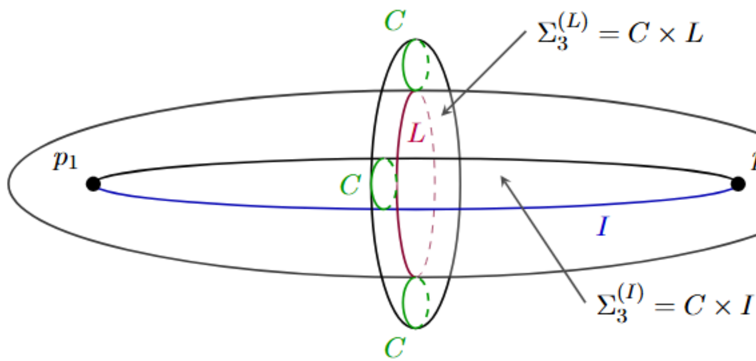
[no interacting DM−DE with $M_{KK}^{5D} \simeq M_{KK,0}^{5D}\, e^{+\phi/c}$ as ruled out]

Anisotropy and mass scales

[Braun,MC,Milioli,Valandro]

- Complex structure stabilisation fixes shape of $\mathbb{P}^1$ controlled by $u = \ell_L / R$

  i) ADD for isotropic $\mathbb{P}^1$ ($\ell_L \sim R$)
  ii) DD for anisotropic $\mathbb{P}^1$ ($\ell_L \ll R$) in Tyurin degeneration limit



$$\mathrm{Vol}(\Sigma_3^{(I)}) \simeq \int_{C\times I} \Omega_3 \gg \mathrm{Vol}(\Sigma_3^{(L)}) \simeq \int_{C\times L} \Omega_3$$

$$r \equiv \frac{\sqrt{\tau_{K3}}}{t_{P1}} \ll 1 \qquad u = \ell_\mathrm{L}/R \ll 1$$

- Relevant mass scales

$$M_s \simeq \frac{M_p}{\sqrt{\mathcal{V}}} \qquad M_{KK}^{10D} \simeq \frac{1}{\ell_{K3}} \simeq \frac{M_s}{\tau_{K3}^{1/4}} \qquad M_{KK}^{5D} \simeq \frac{1}{R} \simeq u\, M_{KK}^{5D} \qquad M_{KK}^{6D} \simeq \frac{1}{\ell_L} \simeq \frac{M_s^2}{M_p}\sqrt{\frac{\tau_{K3}}{u}} \qquad m_{3/2} \simeq \frac{M_p}{\mathcal{V}}$$

$$m_{dP} \simeq m_{\theta_{dP}} \simeq m_{3/2} \ln\left(\frac{M_p}{m_{3/2}}\right) \qquad m_{\mathcal{V}} \simeq m_{3/2}\sqrt{\frac{m_{3/2}}{M_p}} \qquad m_r \simeq \frac{m_{\mathcal{V}}}{\sqrt{\tau_{K3}}} \qquad m_{\theta_{P1}} \simeq m_{\theta_{K3}} \simeq 0$$

	$t_{\mathbb{P}^1}$	u	$\mathcal{V}$	ℓ_{K3}	ℓ_L	R	M_{KK}^{5D}	M_{KK}^{6D}	M_s	m_{dP}	$m_{3/2}$	$m_{\mathcal{V}}$	m_r
ADD	10^{30}	1	$5\cdot 10^{30}$	$1.5\,\ell_s$	$10^{15}\,\ell_s$	$10^{15}\,\ell_s$	-	$1\,\mathrm{meV}$	$10^3\,\mathrm{GeV}$	$100\,\mathrm{meV}$	$1\,\mathrm{meV}$	$10^{-18}\,\mathrm{eV}$	$10^{-18}\,\mathrm{eV}$
DD	10^{26}	10^{-8}	$5\cdot 10^{26}$	$1.5\,\ell_s$	$10^{9}\,\ell_s$	$10^{17}\,\ell_s$	$1\,\mathrm{meV}$	$0.1\,\mathrm{MeV}$	$10^5\,\mathrm{GeV}$	$10^3\,\mathrm{eV}$	$1\,\mathrm{eV}$	$10^{-12}\,\mathrm{eV}$	$10^{-12}\,\mathrm{eV}$
DD	10^{20}	10^{-20}	$5\cdot 10^{20}$	$1.5\,\ell_s$	$1.0\,\ell_s$	$10^{20}\,\ell_s$	$1\,\mathrm{meV}$	-	$10^8\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$10\,\mathrm{MeV}$	$1\,\mathrm{meV}$	$1\,\mathrm{meV}$

$$\tau_{K3} \sim W_0 \sim O(5)$$

- Explicit CY orientifold example with branes and fluxes

Theory and pheno challenges

[Braun,MC,Milioli,Valandro]

- Quantum corrections: absent at $O(g_s^n \alpha')$; extended no-scale at $O(g_s^n \alpha'^2)$ except possibly for

$$\tau_i^{new} = \tau_i + \beta_i \ln \mathcal{V}$$

$$\delta V_{K3} \sim \beta_{K3} \frac{W_0^2}{\mathcal{V}^2 \tau_{K3}}$$ bad: would fix τ_{K3} large

$$\delta V_{\mathbb{P}^1} \sim \beta_{\mathbb{P}^1} \frac{W_0^2 \sqrt{\tau_{K3}}}{\mathcal{V}^3}$$ good: could give dS!

- Stabilisation of u: fluxes should yield $O(10^{-3}) \lesssim u \lesssim 1$; instantons might give $u \gtrsim O(10^{-20})$
- Explicit uplifting: several possibilities from $F^U \neq 0$, anti-branes, T-branes,…
- SUSY breaking: $M_{soft} \lesssim m_{3/2} \lesssim 10\ MeV$ (gauge mediation is subdominant)
  - $\longrightarrow$ non-SUSY SM brane with $M_{soft} \sim M_s$
  - $\longrightarrow$ $V \sim M_s^4$ cancelled by brane backreaction?
- CMP: moduli decay after BBN for $m_{mod} \lesssim O(50)\ TeV$ $\longrightarrow$ issue for $m_{dP} \sim 1\ GeV$ in DD
  - $\longrightarrow$ dilution? models without dP?
- Dark matter overproduction: stable moduli for $m_{mod} \lesssim O(10)\ MeV$ $\longrightarrow$ issue for ADD and DD
  - $\longrightarrow$ tune ϕ_{in} to avoid $\Omega_\phi h^2 \gg 0.12$

$$\Omega_\phi h^2 \sim 5 \cdot 10^{13} \left(\frac{\phi_{in}}{M_p}\right)^2 \sqrt{\frac{m_\phi}{1\ MeV}}$$

- Fifth-forces: moduli mediate fifth-forces for $m_{mod} \lesssim O(1)\ meV$ $\longrightarrow$ issue for ADD
  - $\longrightarrow$ geometrical sequestering of SM?

[inflation ?]

Conclusions

- 4 epochs need string theory to control M_p-physics: inflation, kination, reheating, dark energy
- Machine Learning IIB flux vacua: new vacua, distributions, param. compression, correlations
- Inflation driven by Kaehler moduli due to approximate shift symmetries
- PBHs and secondary GWs from axion isocurvature modes in Fibre Inflation
- Kination from rolling $\mathcal{V}$ after volume inflation and brane-antibrane inflation
- Formation of cosmic superstring network in kination $\longrightarrow$ emission of high freq GWs
- Growth for F-strings in scaling regimes and for NS5 and D3-strings on fibration cycles
- No overshooting due to NS5 and D3-strings decays into GWs $\longrightarrow$ GW peaks at high freq
- Reheating and moduli domination from volume decay
- Negligible dark radiation from bulk axions for high scale SUSY or Giudice-Masiero decay
- Negligible dark radiation from bulk hidden photons if all cx str moduli are heavy
- Dark energy from axion hilltop quintessence via poly-instantons
- Initial conditions from min to max transition and K3-like poly-instantons with O3-planes
- Anisotropic moduli stabilisation for ADD and Dark Dimension
- Tuning to address dark energy + theory and pheno challenges