Cosmic strings and bulk hidden photons after string inflation

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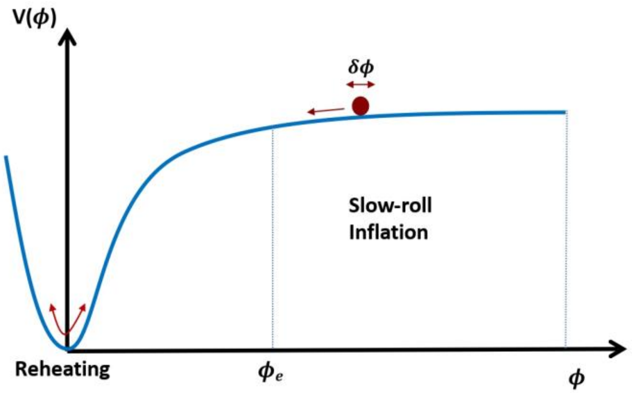
Based on recent papers in collaboration with:

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

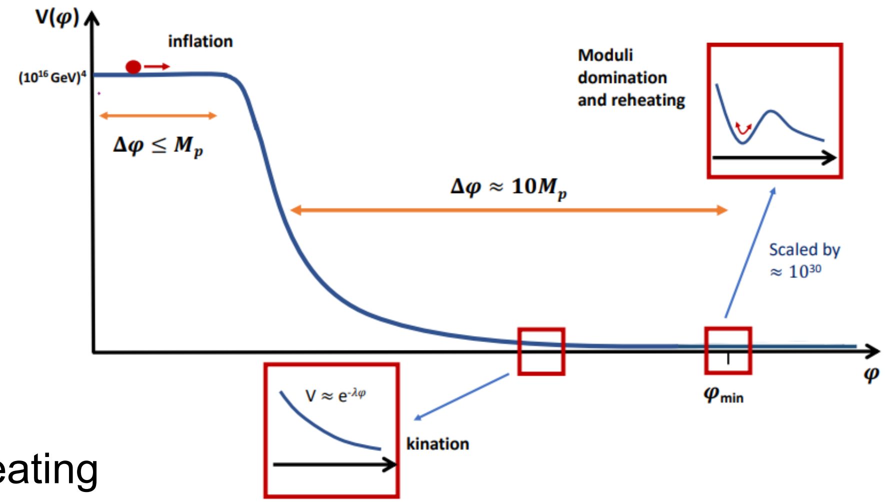
Cosmology and string theory

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

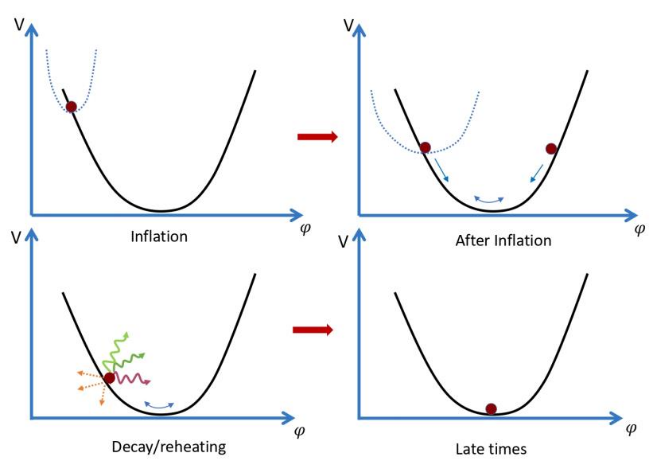
i) Small and large field inflation



ii) Kination after inflation



iii) Reheating



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_α $\alpha = 1, \ldots, h^{1,2}$

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

- Tree-level Kahler potential and superpotential

$$K = -2 \ln \mathcal{V}(\tau_i) - \ln(S + \bar{S}) - \ln(-i \int \Omega(z_\alpha) \wedge \bar{\Omega})$$

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

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

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

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

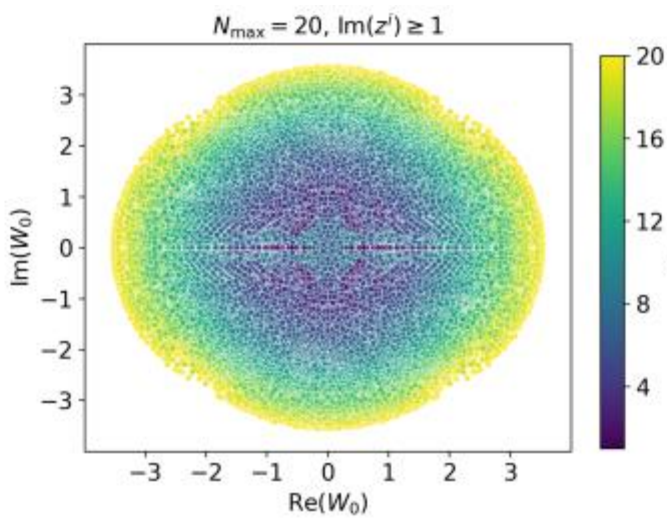
Numerical flux vacua

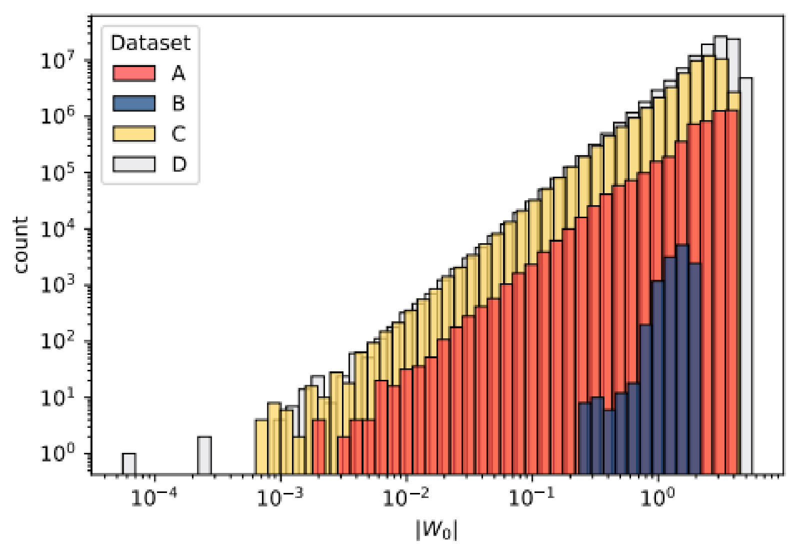
[Chauhan,MC,Krippendorf,Maharana,Piantadosi,Schachner]

- Numerical searches of flux vacua using Machine Learning (JAXVacua)
- Exhaustive searches in targeted regions of moduli space
- 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	$\text{Im}(z^i)$	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]





\+ distribution of g_s and moduli masses

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

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 $e^K = \mathcal{V}^{-2}$

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

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

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

  ⟶ $V(\phi) \simeq V_0$ 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 $V_{tree}(\tau_i) = 0$

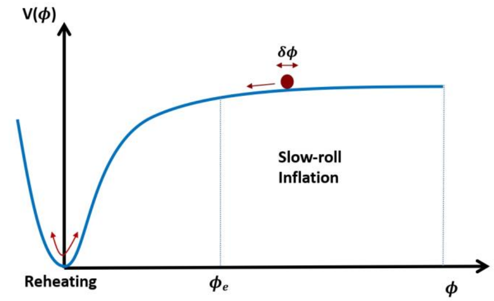
$O(\alpha'^2 g_s^2)$: extended no-scale cancellation $V_{\alpha'^2 g_s^2}(\tau_i) = 0$ [MC,Conlon,Quevedo]

$O(\alpha'^3)$: 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

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



- **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]

Explicit model: CY with $h^{1,1} = 4$ from toric geometry, O3/O7, D3 and D7-tadpole canc., chirality, moduli stab., dS from anti-D3, inflation inside Kaehler cone

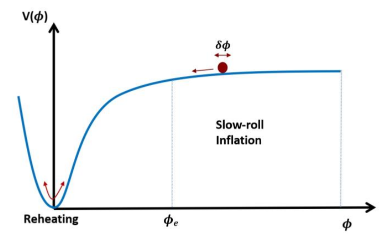
[MC,Grassi,Lacombe,Pedro]

- **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]

Reheating from volume decay



- Non-standard cosmology after inflation:

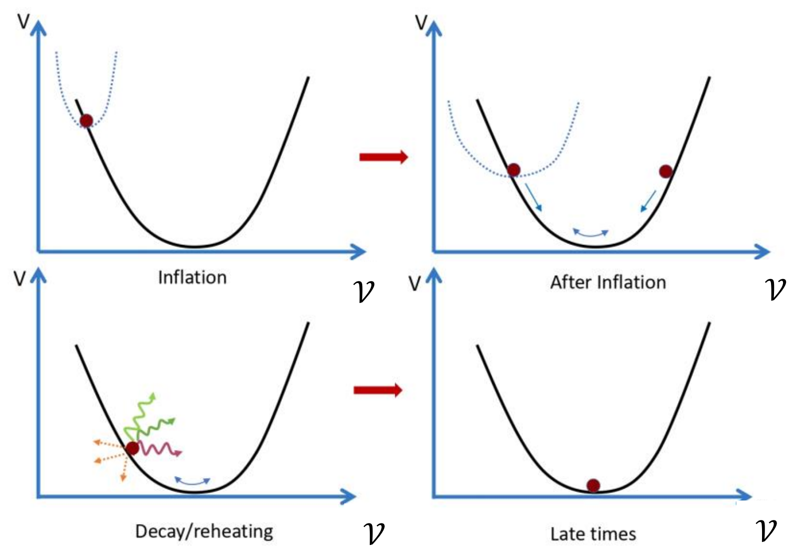
  i) N_ϕ efolds of matter dom. from inflaton ϕ oscillations

  ii) Radiation dom. after inflation decay

  iii) $N_\mathcal{V}$ efolds matter dom. from volume $\mathcal{V}$ oscillations

  iv) Reheating from $\mathcal{V}$ decay

  → dark radiation, non-thermal dark matter, Affleck-Dine baryogenesis,…



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

$\mathcal{V}$

$\Gamma_{\mathcal{V}\to SM}$ ↙ SM dof

$\Gamma_{\mathcal{V}\to\theta_b\theta_b}$, $\Gamma_{\mathcal{V}\to\gamma'\gamma'}$ ↘ bulk axions θ_b, hidden photons γ'

↓

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

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

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

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

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

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

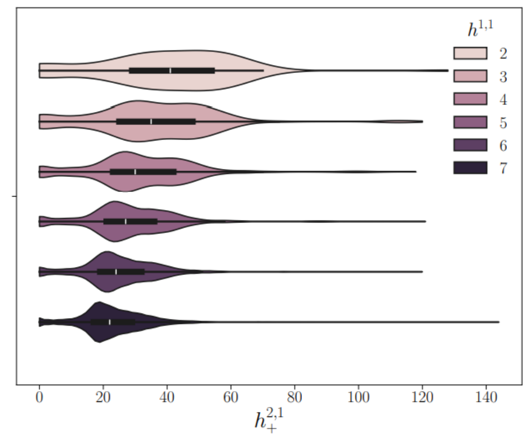
Bulk hidden photons

- 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 mode → no Stueckelberg/Higgs mechanism → massless γ'

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

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

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

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

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

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

ζ^A = D7 deformations

Bulk hidden photons

- Generic Lagrangian for photon and bulk hidden photon γ'

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

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

- Non-unitary transformation

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

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

- 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 [Caraffi,Chinaia,MC,Lin]

$$Re(f_{hid}(z))\, X^{\mu\nu}X_{\mu\nu}$$

→ 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 normalization around $\mathcal{V}^{2/3} = \tau = \langle\tau\rangle + \hat{\tau}$ and $Re(z) = u = \langle u\rangle + \hat{u}$

$$\frac{\hat{u}}{\langle u\rangle} \simeq O(\mathcal{V}^{-4/3})\phi + O(1)\chi \sim \chi \qquad \frac{\hat{\tau}}{\langle\tau\rangle} \simeq O(1)\phi + O(\mathcal{V}^{-2/3})\chi \sim \phi$$

→ $\mathcal{V}$-suppressed $\mathcal{V}$-γ' coupling at $O(\alpha'^4)$ level

$$g_{\mathcal{V}\gamma'}\frac{\phi}{M_p}X^{\mu\nu}X_{\mu\nu} \qquad g_{\mathcal{V}\gamma'} \sim \frac{1}{\mathcal{V}^{4/3}} \ll 1$$

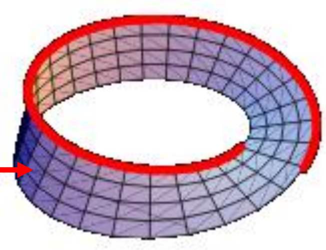
→ negligible contribution to $\Delta N_{\rm eff}$ since

$$\Gamma_{\mathcal{V}\to\gamma'\gamma'} \sim N_{\gamma'}g^2_{\mathcal{V}\gamma'}\frac{m^3_{\mathcal{V}}}{M_p^2} \sim \mathcal{V}^{-8/3}N_{\gamma'}\Gamma_{\mathcal{V}\to\theta_b\theta_b} \lesssim 10^{-6}\Gamma_{\mathcal{V}\to\theta_b\theta_b} \ll \Gamma_{\mathcal{V}\to\theta_b\theta_b} \quad \longrightarrow \quad \Delta N_{\rm eff}\to 0$$

$$\mathcal{V} \gtrsim 10^3 \quad N_{\gamma'} \sim 100$$

Massive bulk hidden photons from torsion

- A torsional 3-cycle $\tilde{\Sigma}_3$ of degree k is the boundary of a non-orientable 4-chain $\tilde{S}_4$



- Dimensional reduction of C_4 in presence of a torsional 3-cycle of degree k

$$C_4 \supset V(x) \wedge \tilde{\alpha}_3 + \rho(x)\tilde{\omega}_4 \qquad d\tilde{\alpha}_3 = k\tilde{\omega}_4$$

- Geometric Stueckelberg mechanism ⟶ massive γ' [Camara,Ibanez,Marchesano]

$$F_5 = dC_4 \supset dV \wedge \tilde{\alpha}_3 + (d\rho - kV)\tilde{\omega}_4$$

$$F_5 \wedge * F_5 \longrightarrow \frac{1}{2} m_{\gamma'}^2 \hat{V}_\mu \hat{V}^\mu \qquad \hat{V} = d\rho - kV$$

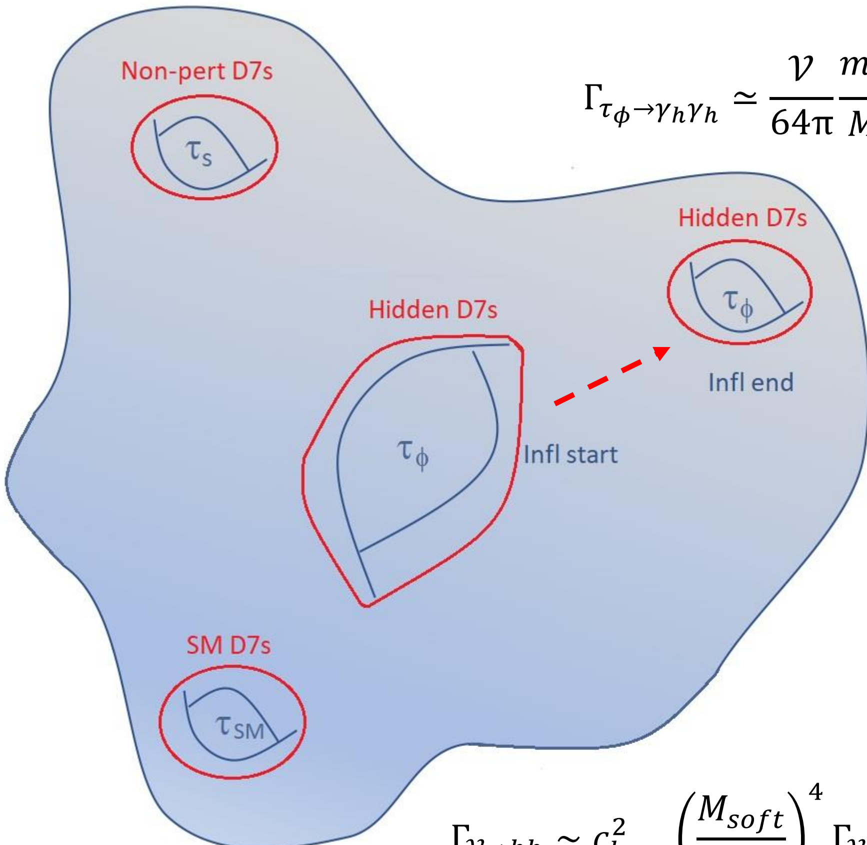
- Very large mass: $m_{\gamma'} \geq M_s$

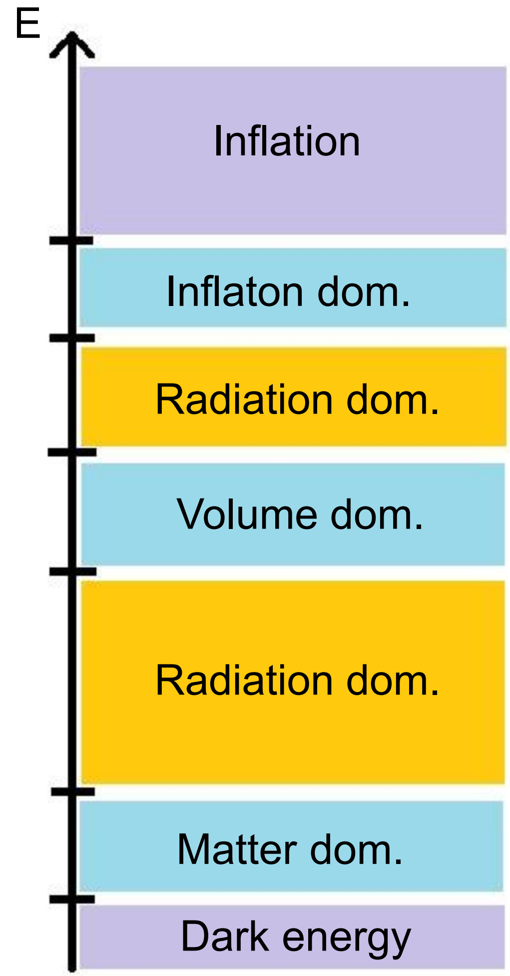
⟶ hidden photons from torsional cycles disappear from EFT

Loop blowup inflation with SM on D7s

[Bansal,Brunelli,MC,Hebecker,Kuespert]

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





$N_e \simeq 53$

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

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

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

$\mathcal{V} \to hh$

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

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

[MC,Hebecker,Jaeckel,Wittner]

Predictions:

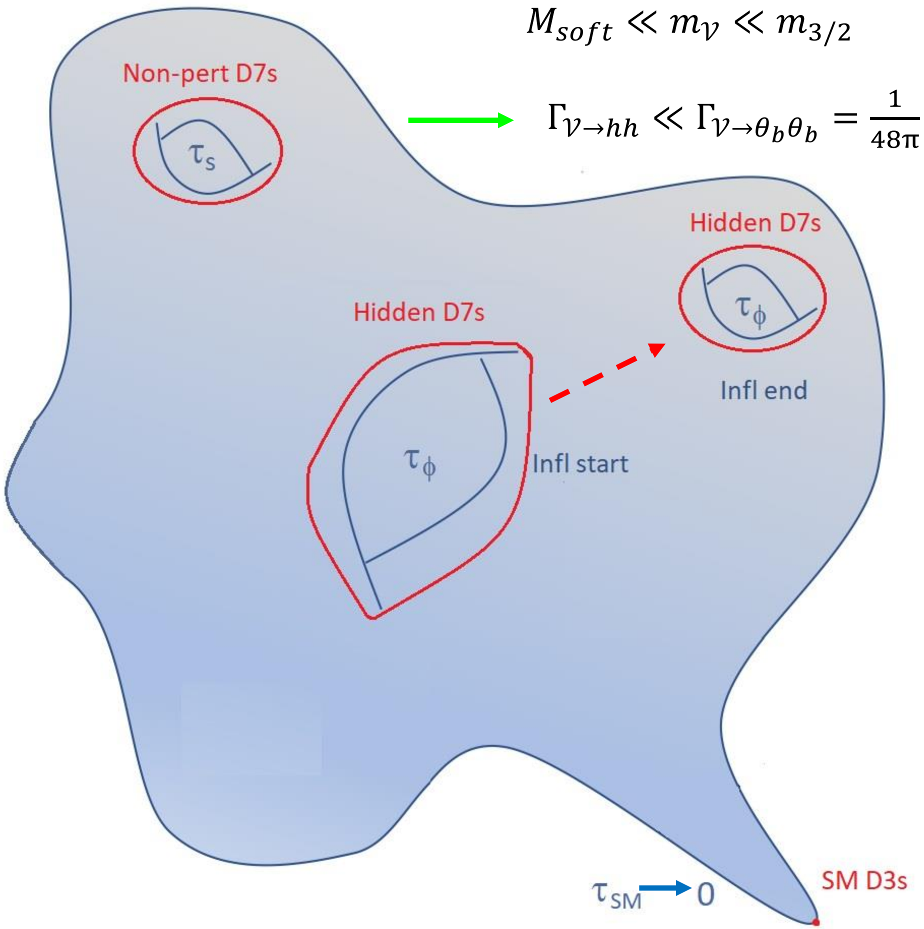
$n_s \simeq 0.9765$ $\quad r \simeq 1.7 \times 10^{-5}$ $\quad T_{\rm rh} \simeq 4 \times 10^{10}\,{\rm GeV}$ $\quad \Delta N_{\rm eff} \simeq 0$

Loop blowup inflation with SM on D3s

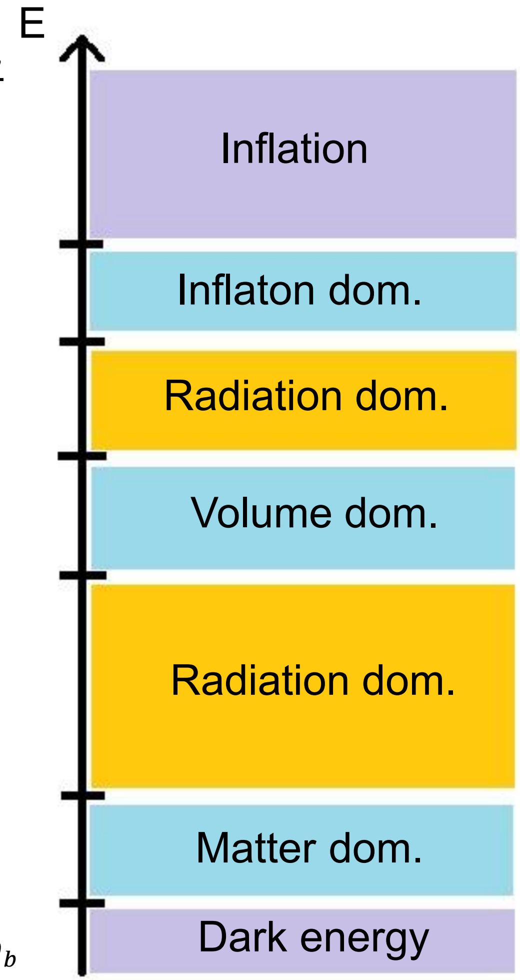
[Bansal,Brunelli,MC,Hebecker,Kuespert]

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

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



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



$N_e \simeq 51.5$

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

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

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

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

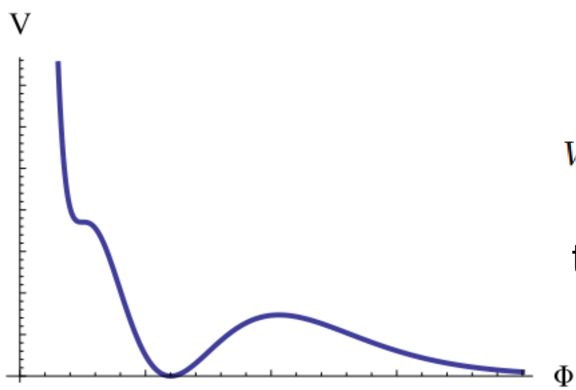
Predictions:

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

Kination after volume inflation

- 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]

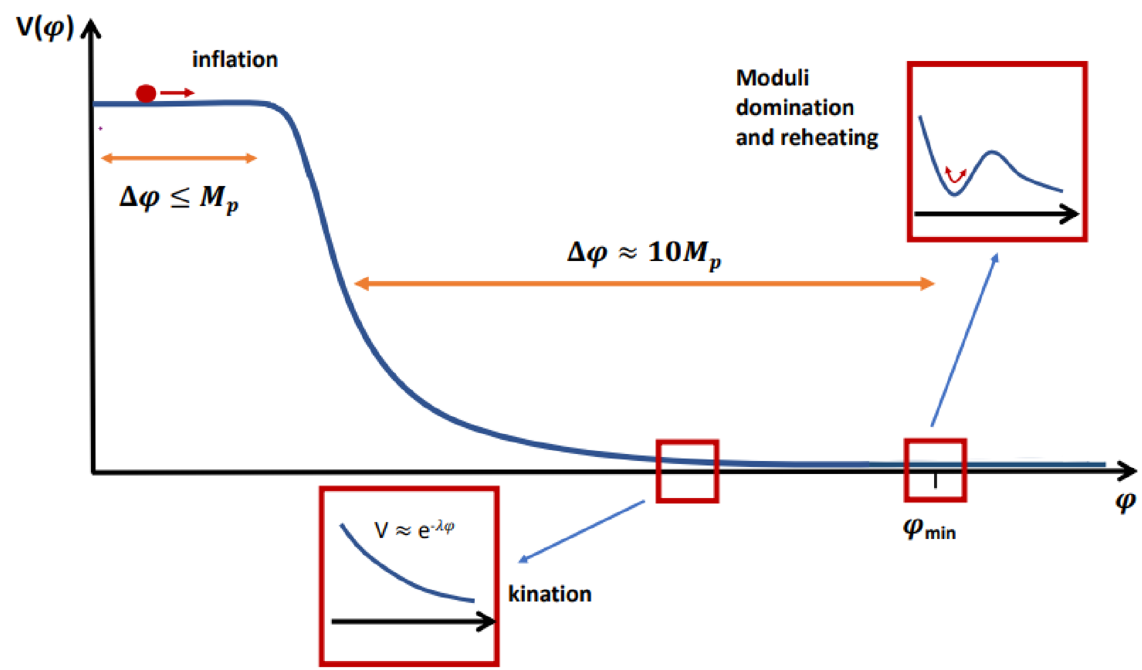


$$V(\Phi) = V_0\left[\left(1-\kappa_{\rm np}\Phi^{3/2}\right)e^{-\sqrt{\frac{27}{2}}\Phi} + \kappa_{g_s}\,e^{-\frac{10}{\sqrt{6}}\Phi} + \kappa_{F^4_{(b)}}\,e^{-\frac{11}{\sqrt{6}}\Phi} + \kappa_{\overline{D3}}\,e^{-\sqrt{6}\Phi}\right]$$

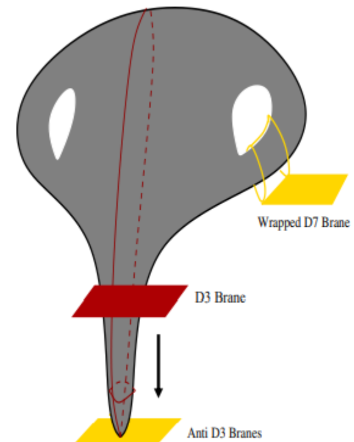
to have high scale inflation and low-energy SUSY since

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

zoom



Kination after brane-antibrane inflation



- Can have rolling moduli after brane-antibrane inflation

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

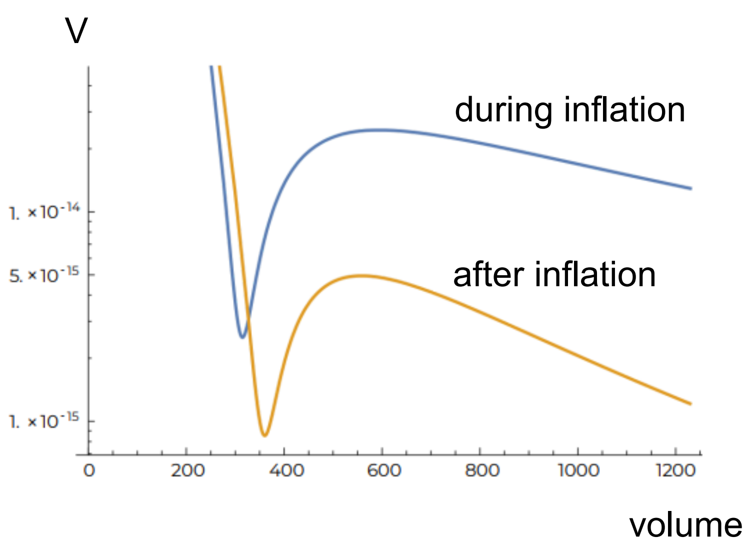
- D3-antiD3 inflation without η-problem due perturbative $\mathcal{V}$ fixing

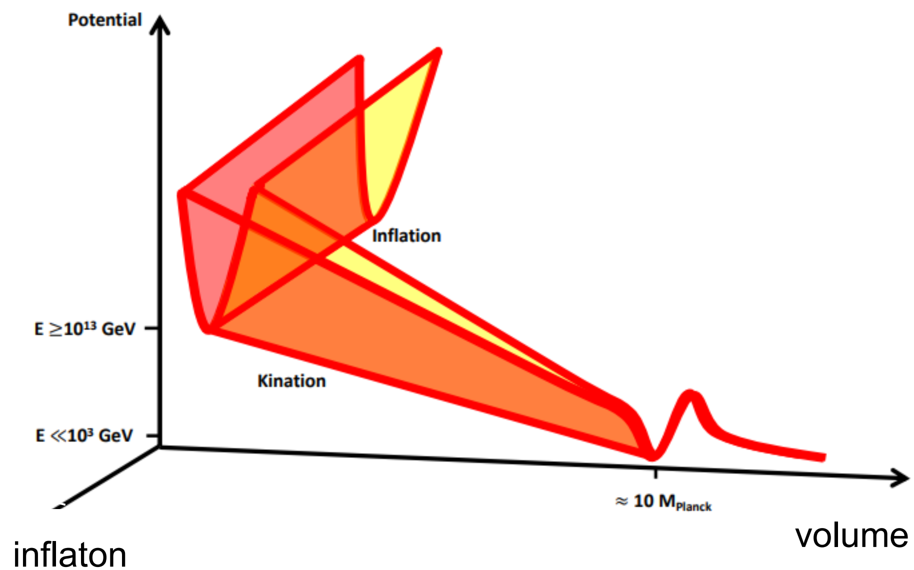
$$\mathcal{V}^{2/3} = \sigma = \tau - \frac{1}{6}(M_{KK} r)^2 \to \tau \quad \text{at end of inflation}$$

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

- After inflation branes annihilate: $W_X \to 0$ → $\frac{V}{3W_0^2} \simeq \frac{\alpha}{\tau^4} - \frac{\xi\sqrt{g_s}}{4c\tau^{9/2}}\left(\ln\tau - \frac{c}{g_s^2}\right)$

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





A cosmic superstring network?

- After D3-antiD3 inflation:

  i) initial population of string loops

  ii) rolling volume $\mathcal{V}$ ⟶ kination

- Tension of F-strings controlled by $\mathcal{V}$

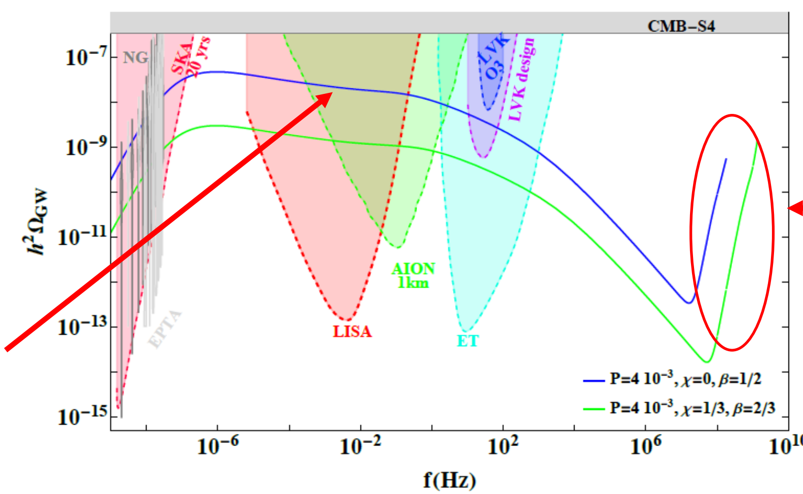
$$\mu \simeq M_s^2 \simeq \frac{M_p^2}{\mathcal{V}} = M_p^2\, e^{-\xi\phi/M_p} \qquad\qquad \xi = \sqrt{3/2}$$

- Volume increases ⟶ decreasing tension

- Comoving radius 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

[Ghoshal,Revello,Villa]



$\mathcal{V}$ decay

kination

⟶ see Revello's talk

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 beyond kination as in scaling fixed points

  iii) EFT strings from D3s or NS5s on fibration cycles

  (ii–iii) [Brunelli,MC,Pedro]

- Dynamical system:

  i) strings with field-dependent tension $\mu = M^2\, e^{-\xi\,\phi/M_p}$

  ii) flat universe with fluid and modulus with potential $V(\phi) = V_0\, e^{-\lambda\phi}$

  iii) ρ_{loop} is assumed to be negligible

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 $\sqrt{\omega+1} > \frac{2}{\sqrt{3}\lvert\xi\rvert}$

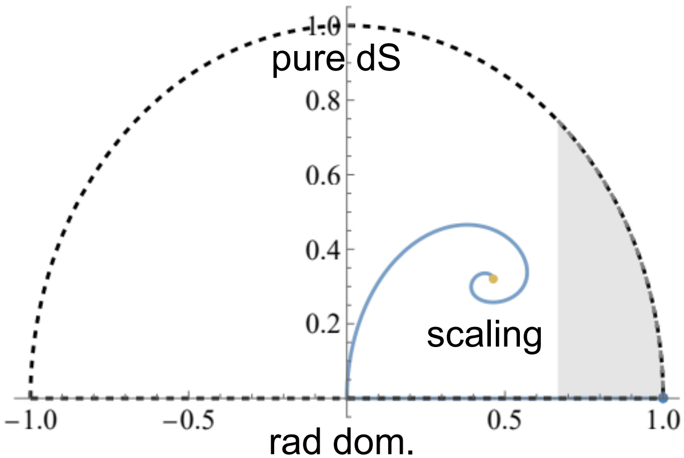
Growth of cosmic strings beyond kination

[Brunelli,MC,Pedro]

- F-strings with rolling $\mathcal{V}$:

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

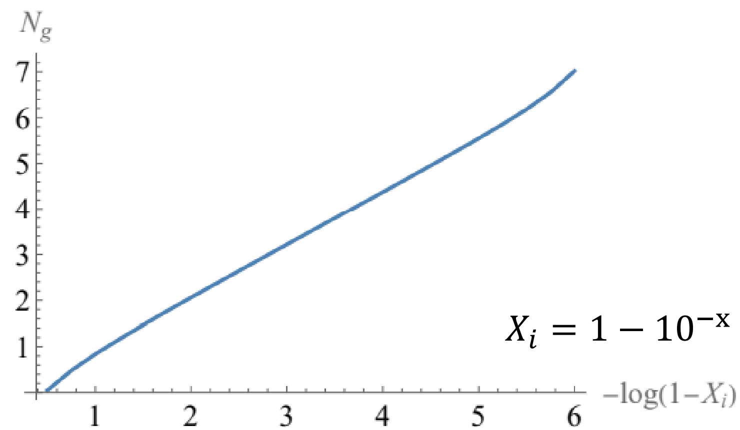
i) Kination is an unstable fixed point but can have enough efolds of growth N_g



kination

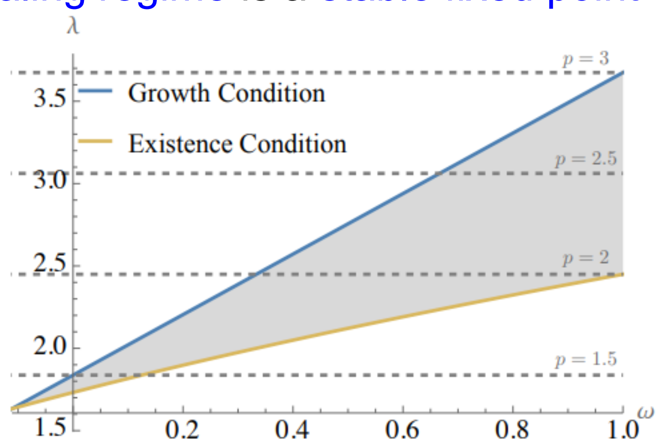
$p = 3$

$\omega = 1/3$



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

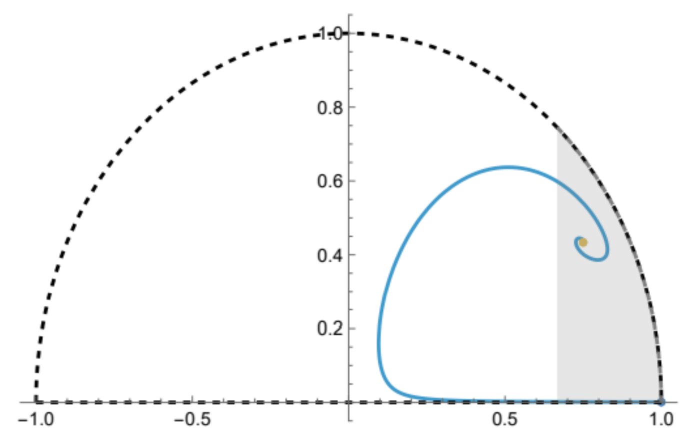
ii) Scaling regime is a stable fixed point



$\longrightarrow$

$p = 2$

$\omega = 1/2$



Growth of cosmic strings beyond kination

[Brunelli,MC,Pedro]

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

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

- D3 on 2-cycle with rolling $\mathcal{V}$: $\mu \simeq \frac{M_p^2}{\mathcal{V}^{2/3}} = M_p^2\, e^{-\xi\chi/M_p}$ $\quad \xi = \sqrt{2/3}$ → No growth

- NS5 on 4-cycle with rolling $\mathcal{V}$: $\mu \simeq \frac{M_p^2}{\mathcal{V}^{1/3}} = M_p^2\, e^{-\xi\chi/M_p}$ $\quad \xi < \sqrt{2/3}$ → No growth

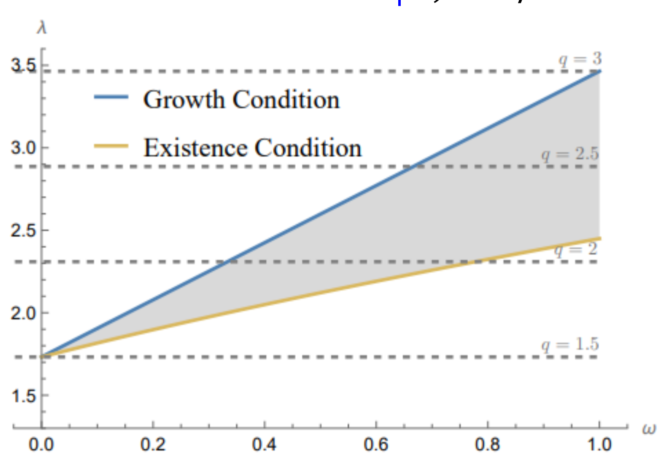
- Fix $\mathcal{V}$ and consider rolling fibration modulus for K3-fibred CY over P^1:

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

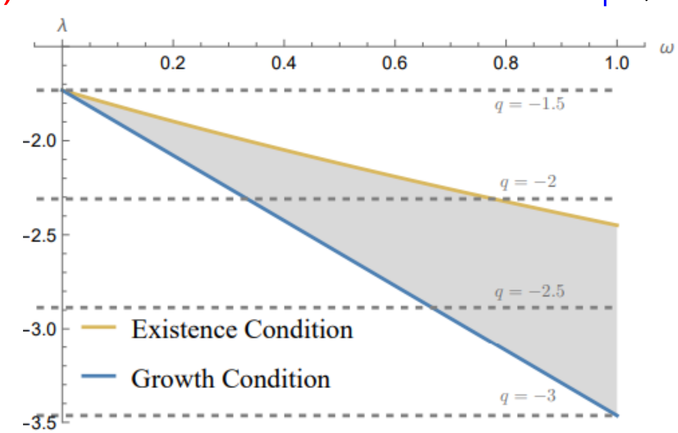
- EFT string growth for both kination and scaling: $V \propto \tau_1^{-q}$ → $\lambda = 2\, q/\sqrt{3}$

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

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



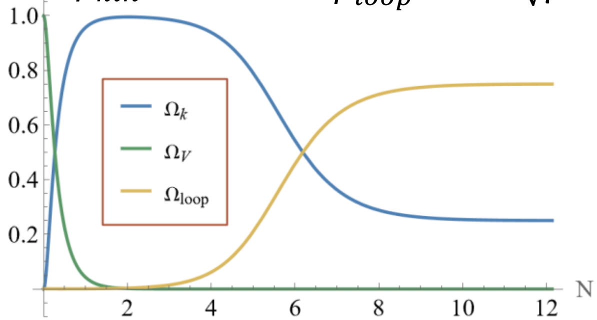
ii) NS5 on K3 fibre with volume τ_1: $\xi = -2/\sqrt{3}$

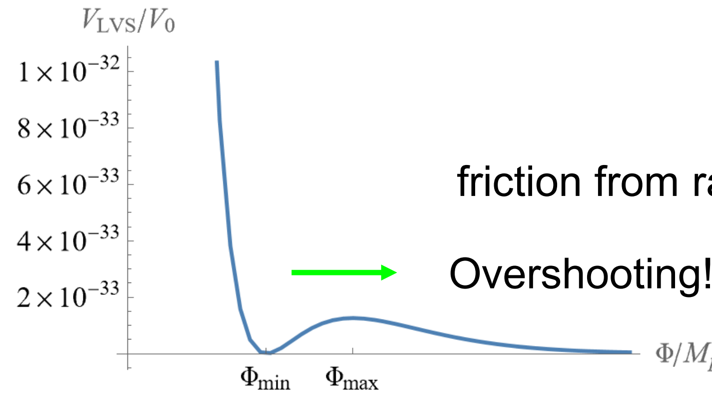


Cosmic strings and overshooting

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

$\rho_{kin} \sim a^{-6} \leftrightarrow \rho_{loop}^{kin} \sim a^{-3}\sqrt{\mu} \sim a^{-9/2}$

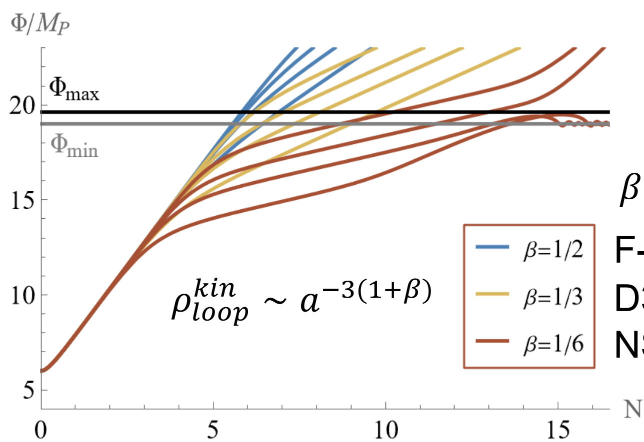




friction from radiation?

→ Overshooting!

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



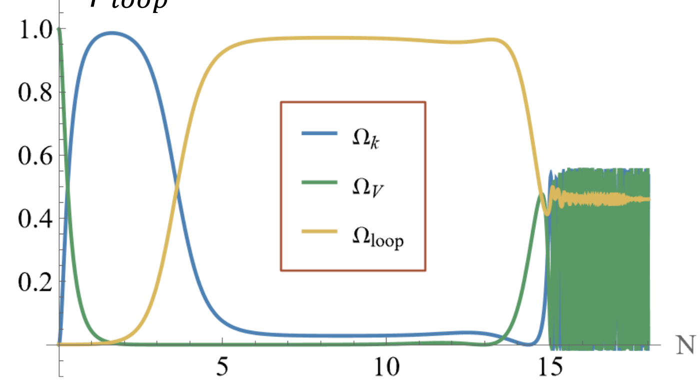
$\beta = \xi/\sqrt{6}$

F-strings

D3-strings

NS5-strings

$\rho_{loop}^{kin} \sim a^{-7/2}$



→ Potentially large GW signal around 10^9 Hz for isolated F-strings (not a network)

[Conlon,Copeland,Hardy,Gonzales]

Conclusions

- 3 epochs need string theory to control M_p-physics: inflation, kination, reheating
- Type IIB Kaehler moduli $\perp \mathcal{V}$ are good inflatons ϕ due to approximate shift symmetries
- $V(\phi)$ determined by no-scale breaking effects (pert/non-pert.) and topology (bulk/local cycle)

  $\longrightarrow$ several scenarios of small and large field inflation
- Post-inflation with moduli domination and reheating from volume decay
- Dark radiation from ultralight bulk axions
- SM on D7s: $\Delta N_{\text{eff}} \to 0$ $\longleftrightarrow$ SM on D3s: $\Delta N_{\text{eff}} \neq 0$
- Negligible dark radiation from bulk hidden photons
- Rolling $\mathcal{V}$ after volume inflation and brane-antibrane inflation
- Growth of physical size of cosmic strings in kination $\longrightarrow$ network emitting high freq GWs
- Growth for F-strings in scaling fixed points and for EFT strings on fibration cycles in kination
- Energy of F-strings dominates and causes overshooting in absence of radiation
- No overshooting for NS5-strings with potentially large high freq GW signal