Kination in String Theory

Based on 2212.10293 + works in progress

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Introduction

String cosmology [Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23]

Desiderata:
inflation, QCD axion,
quintessence, CC → Embed in ST

This Talk

What are typical dynamics induced by moduli potentials?

Steep potentials → Kination

"Asymptotic" cosmology

[Cicoli,Cunillera,Padilla,Pedro '21]
[Calderon Infante,Ruiz,Valenzuela '22] [Apers,Conlon,Mosny,Revello '22]
[Shiu,Tonioni,Tran '23] x 2 [Cremonini,Gonzalo,Rajaguru,Tang,Wrase '23]
[Hebecker, Schreyer,Venken '23]

What is kination?

Scalar rolling down a steep potential: 'kination' [Joyce '97]

$$\frac{1}{2}\dot{\phi}^2 \gg V(\phi)$$

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \simeq 1$$

Stiff fluid

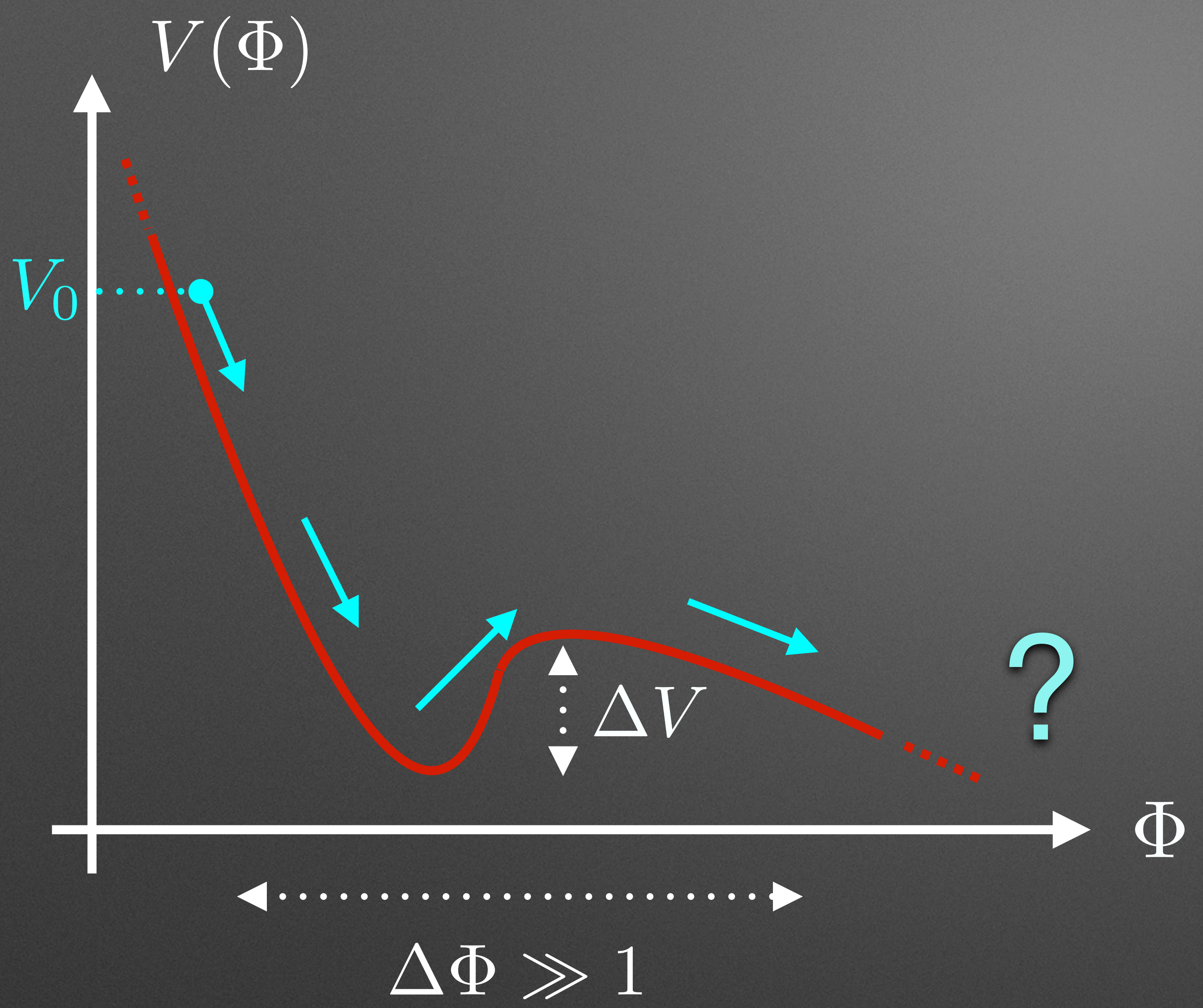
$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\partial V}{\partial \phi},$$

$$H^2 = \frac{1}{3M_P^2}\left(V(\phi) + \frac{\dot{\phi}^2}{2}\right)$$

$$\phi = \phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

$$a(t) \sim t^{1/3}$$

Why care about Kination?



Potentials near boundaries of moduli space

$$V(\Phi) \sim e^{-\lambda_i \Phi_i}$$

[Grimm,Li,Valenzuela '19]+…

<u>Specific example:</u> LVS (GKP) [Conlon,Quevedo,Suruliz '05] [Balasubramanian,Berglund,Conlon,Quevedo '05]

$$\Phi = \sqrt{\frac{2}{3}} \ln \mathcal{V}$$

V_0 high after inflation as $m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$

#1 Volume kination = Kasner

String to Einstein frame

$\mathcal{V}_{int}$

10d Kasner, solves vacuum EE

$$ds_E^2 = t^2 \left(-dt^2 + \sum_{i=1}^{3} t^{-2/3} dx_i{}^2 + \sum_{j=1}^{6} t^{2/3} dy_j{}^2 \right)$$

$$ds^2_{4d,E} = -dt_E^2 + (2t_E)^{2/3} \left(dx_1{}^2 + dx_2{}^2 + dx_3{}^2 \right)$$

$$\phi = \sqrt{\frac{2}{3}} \log \mathcal{V} \sim \sqrt{\frac{2}{3}} \log t \qquad a(t) \sim t^{1/3}$$

→ Kination

Big crunch: $ds^2 = -dt^2 + t^{-2/3}(dx_1^2 + dx_2^2 + dx_3^2)$

A dynamical Swampland?

"Big Crunch" of the non-compact dimensions

4d picture

$$l_s \sim \frac{\sqrt{\mathcal{V}}}{M_P}$$ grows faster than $a(t)$

(Planck mass fixed in Ein. frame)

↓

Assumes knowledge of UV physics

No apparent issues with EFT approach
or "kinematic" Swampland constraints

→ Motivates a dynamical Swampland?

Constraints on the cosmological evolution

What about the distance conjecture?

Distance conjecture:

[Ooguri, Vafa '06]
[Ooguri,Palti,Shiu,Vafa '19]

$\Delta\phi \gg 1$ ⟷ towers of light states

↓

Invalidate the EFT

"Static"

KK modes become light, but so do m_ϕ, Λ_ϕ ✓

Dynamics

KK modes above Hubble $m_{KK}(t) \gg H(t)$ ✓

Cutoff is adiabatic $\left|\frac{d\Lambda(t)_{KK}}{dt}\right| \ll \Lambda(t)^2_{KK}$ ✓

#2 Trackers and axions

Reformulate as a dynamical system   See also [Shiu,Tonioni,Tran '23] x 2

$$x = \frac{\dot{s}}{\sqrt{6}Hs} \quad y = \frac{\dot{b}}{\sqrt{6}Hs} \quad z = \frac{1}{H}\sqrt{\frac{V(s)}{3}}$$

$$\begin{cases} \dot{x} = f_x(x,y,z) \\ \dot{y} = f_y(x,y,z) \\ \dot{z} = f_z(x,y,z) \end{cases}$$

$$T = s + ib$$

Matter/radiation + rolling scalar → Trackers

[Wetterich '88] [Ferreira,Joyce '98]
[Copeland,Liddle,Wands'98]

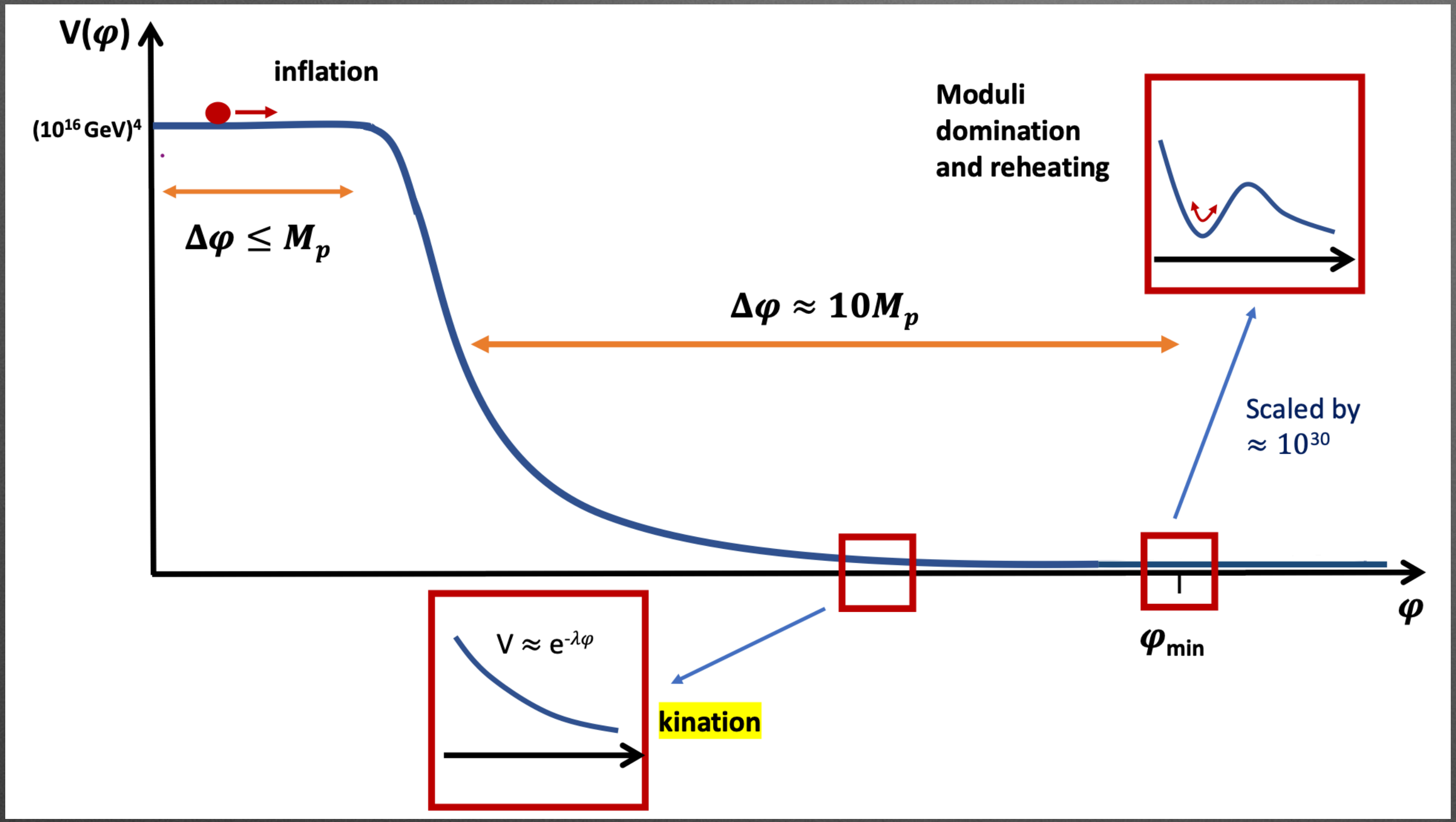
What about Axions? [FR, WiP]
[Russo, Townsend '22]

Universal coupling through kin term

$$\mathcal{L} \supset \frac{(\partial s)^2 + (\partial b)^2}{s^2} + \frac{V_0}{s^\lambda}$$

Late time attractor $\dot{s}(t) \sim \dot{b}(t) \sim t^{2/\lambda - 1}$ Fixed ratios $x \sim y \sim z$

#3 A non-standard picture



Scalar perturbations

small scale structure?

[Apers,Conlon,Copeland,FR WIP]

Figure taken from [Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23]

Other signatures of kination/tracker epochs?

Gravitational waves [Muia,Schachner,Quevedo,Villa '23]

Axion kination [Co,Harigaya'20] [Co,Hall,Harigaya'20]
[Gouttenoire,Servant,Simakachorn '21] x 2+…

Thank you for your attention!

Kasner metric

Sourceless solution to Einstein Equations

$$ds^2 = -dt^2 + \sum_{i=1}^{d} t^{2p_i} dx_i{}^2 + \sum_{j=1}^{D-d-1} t^{2q_j} dy_j{}^2$$

"external" "internal"

One of the oldest solutions to GR! [Kasner 1921]

$$\sum_{i=1}^{d} p_i + \sum_{j=1}^{D-d-1} q_j = 1 \qquad \sum_{i=1}^{d} p_i{}^2 + \sum_{j=1}^{D-d-1} q_j{}^2 = 1$$

No isotropic expansion/contraction (unlike FLRW)

Avoiding the catastrophe

- In a quantum universe: radiation will take over

$\rho_{\rm kin} \sim a^{-6}$ vs $\rho_{\rm mat} \sim a^{-3}$ $\rho_{\rm rad} \sim a^{-4}$

Tracker solutions!

See also [Conlon,FR '22]

10d interpret: Kasner is unstable to perturbations

$$ds^2 = ds^2_{\rm kasner} + \frac{2\epsilon t^{2/3}}{\sqrt{6}} \sum_{\substack{i=1,2,3 \\ j=4,\dots,9}} h_{ij}(t) dx_i dy_{j-3}$$

$$+ 2\epsilon^2 t^{2/3} \sum_{\substack{i,j=1,2,3 \\ i<j}} h^2_{ij}(t) dx_i dx_j + \epsilon^2 t^{2/3} \sum_{i=1,2,3} h^2_{ii}(t) dx_i^2$$

Solves EE at first order if $h'_{ij} = 1$ Exact solution if $h_{ij} = 1$

Radiation-like: $\rho \sim a^{-6} + \epsilon^2 a^{-4}$

P.S. Avoiding the catastrophe

- In a quantum universe: radiation will take over

$\rho_{\rm kin} \sim a^{-6}$ vs $\underbrace{\rho_{\rm mat} \sim a^{-3} \qquad \rho_{\rm rad} \sim a^{-4}}$

Attractor solution with $\Omega_\phi \sim \Omega_\gamma \sim \mathcal{O}(1)$

[Wetterich '88; Copeland,Liddle,Wands '98; Ferreira,Joyce '98]
[Conlon,Kallosh,Linde,Quevedo '08]

In realistic models (LVS)

localising the minimum ⟷ $\Lambda_{\rm inf} \gg \Lambda_{\rm EW}$

[Conlon,FR '22]

10d interpret:

Kasner is unstable to perturbations

[Apers,Conlon,Mosny,FR '22]

The tracker solution

$$\begin{cases} H^2 = \frac{1}{3M_P^2}\left(\rho_\gamma + \frac{1}{2}\dot{\Phi}^2 + V(\Phi)\right) \\ \dot{H} = -\frac{1}{2M_P^2}\left(\rho_\gamma + P_\gamma + \dot{\Phi}^2\right) = -\frac{1}{2M_P^2}\left(\gamma\rho_\gamma + \dot{\Phi}^2\right) \end{cases}$$

Friedmann Equations

$+$

$$\dot{\rho}_\gamma = -3H\left(\rho_\gamma + P_\gamma\right) = -3H\gamma\rho_\gamma$$

Energy conservation

Attractor solution

$$V = V_0 e^{-\frac{\lambda\Phi}{M_P}}$$

$$\Omega_{\rm kin} = \frac{3}{2}\frac{\gamma^2}{\lambda^2} \qquad \Omega_{\rm pot} = \frac{3(2-\gamma)\gamma}{2\lambda^2} \qquad \Omega_\gamma = 1 - \Omega_{\rm kin} - \Omega_{\rm pot} = 1 - \frac{3\gamma}{\lambda^2}$$

[Wetterich ’88; Copeland,Liddle,Wands ’98; Ferreira,Joyce ’98]