

Three tales of Kination (in String Theory)

Based on 2207.00567, 2212.10293 + works in progress

with Fien Apers, Joe Conlon, Ed Copeland, Martin Mosny

See also Joe Conlon's plenary talk



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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][Rudelius '21][Conlon,FR '22]
[Calderon Infante,Ruiz,Valenzuela '22] [Apers,Conlon,Mosny,Revello '22]
[Shiu,Tonioni,Tran '23] x 2 [Cremonini,Gonzalo,Rajaguru,Tang,Wrane '23]
[Hebecker, Schreyer,Venken '23] [Freigang,Lust,Nian,Scalisi '23]

What is kination?

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

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

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

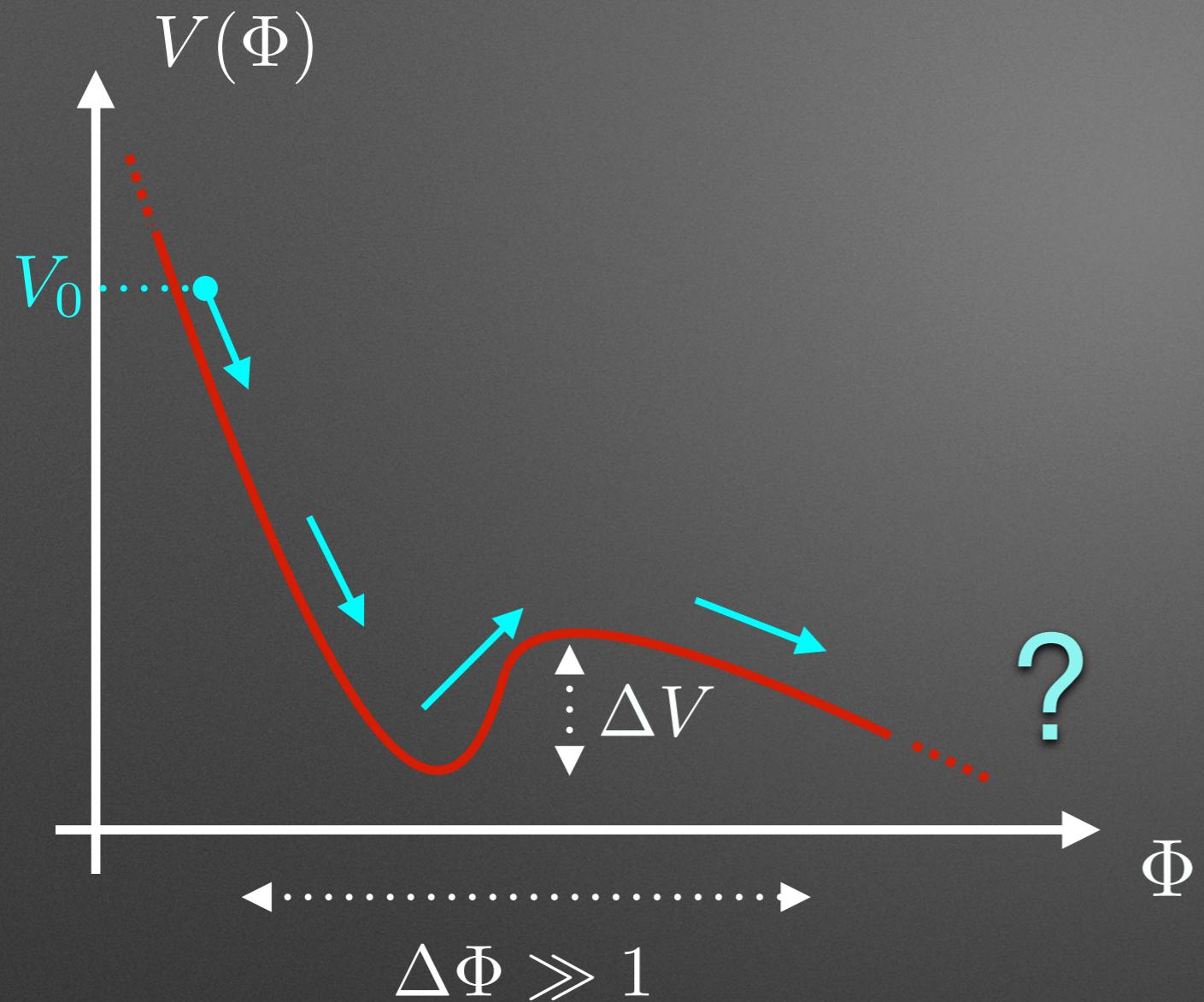
stiff fluid

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

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

$$\phi = \phi_0 + \sqrt{\frac{2}{3}}M_P \ln \left(\frac{t}{t_0} \right) \quad a(t) \sim t^{1/3}$$

Why care about Kination?



$\left. \begin{array}{l} \text{Energy sources \underline{diluted} after inflation} \\ + \\ \text{Potentials near boundaries of moduli space} \end{array} \right\}$

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

[Grimm,Li,Valenzuela '19]+...

Specific example: 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 $m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$

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]

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

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

No isotropic expansion/contraction (unlike FLRW)

#1 volume kination = Kasner

String to
Einstein frame

\mathcal{V}_{int}

$$ds_E^2 = t^2 \left(-dt^2 + \underbrace{\sum_{i=1}^3 t^{-2/3} dx_i^2}_{\mathcal{V}_{int}} + \underbrace{\sum_{j=1}^6 t^{2/3} dy_j^2}_{10d \text{ Kasner, solves vacuum EE}} \right)$$

10d Kasner, solves vacuum EE

$$ds_{4d,E}^2 = -dt_E^2 + (2t_E)^{2/3} (dx_1^2 + dx_2^2 + dx_3^2)$$

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

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

$$\left\{ \begin{array}{l} l_s \sim \frac{\sqrt{\mathcal{V}}}{M_P} \quad \text{grows faster than } a(t) \\ (\text{Planck mass fixed in Ein. frame}) \end{array} \right.$$



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

Kinematics

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

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



#2 Trackers and axions

Reformulate as a dynamical system

See also [Shiu,Tonioni,Tran '23] x 2

$$x = \frac{\dot{s}}{\sqrt{6}Hs}$$

$$y = \frac{\dot{b}}{\sqrt{6}Hs}$$

$$z = \frac{1}{H} \sqrt{\frac{V(s)}{3}}$$

$$T = s + ib$$

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

Matter/radiation + rolling scalar



Trackers

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

What about Axions? [Sonner, Townsend '06] [FR, WiP]

universal coupling through kint term

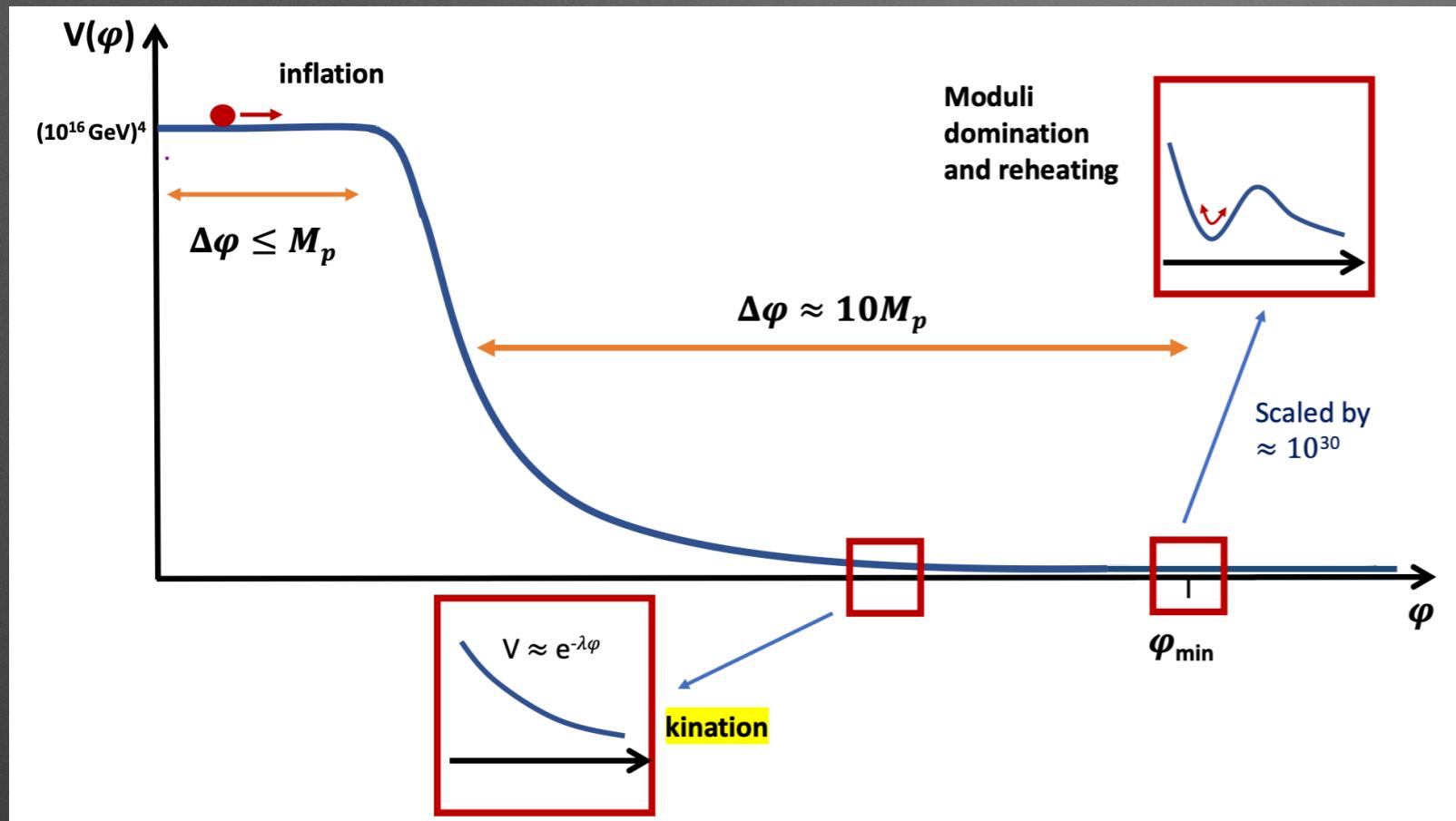
$$\mathcal{L} \supset \frac{(\partial s)^2 + (\partial b)^2}{s^2} + \frac{V_0}{s^\lambda}$$

Late time attractor

$$\dot{s}(t) \sim \dot{b}(t) \sim t^{2/\lambda - 1}$$

Fixed ratios $x^2 \sim y^2 \sim z^2$

#3 A non-standard picture



Scalar perturbations



Small scale structure?

[Apers,Conlon,Copeland,FR WiP]

$$\text{Ex. } \mathcal{R}_k \sim J_0(k\eta)$$

From [Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23]

Other Signatures/implications of kinflation/tracker epochs?

GWS [Muia,Schachner,Quevedo,Villa' 23] [Chowdhury,Parameswaran,Tasinato '23]

Axion kinflation

[Co,Harigaya '20] [Co,Hall,Harigaya '20]
[Gouttenoire,Servant,Simakachorn '21] x 2+...

Overshoot problem

[Conlon,Kallosh,Linde,Quevedo '08] [Conlon,FR '22]

A LOT
TO DO

Thank you for your attention!

Avoiding the catastrophe

- In a quantum universe: radiation will take over

$$\rho_{\text{kin}} \sim a^{-6}$$

vs

$$\rho_{\text{mat}} \sim a^{-3}$$

$$\rho_{\text{rad}} \sim a^{-4}$$

Tracker solutions!

See also [Conlon,FR '22]

10d interpret: Kasner is unstable to perturbations

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

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

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

$$\rho_{\text{kin}} \sim a^{-6}$$

vs

$$\rho_{\text{mat}} \sim a^{-3}$$

$$\rho_{\text{rad}} \sim a^{-4}$$

Attractor solution with

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

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

[Conlon,Kallosch,Linde,Quevedo '08]

In realistic models (LVS)

localising the
minimum



$$\Lambda_{\text{inf}} \gg \Lambda_{\text{EW}}$$

1od interpret:

Kasner is unstable to
perturbations

[Conlon,FR '22]

[Apers,Conlon,Mosny,FR '22]

The tracker solution w/ radiation (matter)

$$\left\{ \begin{array}{l} H^2 = \frac{1}{3M_P^2} \left(\rho_\gamma + \frac{1}{2} \dot{\Phi}^2 + V(\Phi) \right) \\ \dot{H} = -\frac{1}{2M_P^2} \left(\rho_\gamma + P_\gamma + \dot{\Phi}^2 \right) = -\frac{1}{2M_P^2} \left(\gamma \rho_\gamma + \dot{\Phi}^2 \right) \end{array} \right. \quad \text{Friedmann Equations}$$

$$+ \quad \dot{\rho}_\gamma = -3H(\rho_\gamma + P_\gamma) = -3H\gamma\rho_\gamma \quad \text{Energy conservation}$$

Attractor solution

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

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

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