

Recent Advances in pre Big Bang String Cosmology: Bouncing solutions in non-perturbative String Theory

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Cosmological Challenges and String Theory

- Consistent theory of Quantum Gravity
- Avoid the Classical Big Bang Singularity
- Go beyond EFT approach to Inflation
- No need for ad-hoc fields to drive Inflation

What does String Theory suggest?

- The existence of a low energy massless multiplet $\{\varphi, g_{\mu\nu}, B_{\mu\nu}\}\$
- Pre Big-Bang scenario instead of Slow-Roll (Bouncing Cosmology)
- Higher order curvature corrections (α' expansion)
- Higher order string coupling expansion $g_s^2 = exp(\phi)$ (Genus Expansion)
- Additional simmetry in cosmological space-time with d abelian isometries, O(d,d) invariance in the field space (Continuous generalisation of T-duality)

Main Topics

• General criteria to have bouncing solutions using Hohm Zwiebach (HZ) action (all order α' action) starting from perturbative vacuum of String Theory

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- General criteria to have bouncing solutions using Hohm Zwiebach (HZ) action (all order α' action) starting from perturbative vacuum of String Theory
- Dilaton stabilisation, FLRW and de-Sitter attractor from non-perturbative dilaton potential
- Isotropisation mechanism via α' corrections and Dilaton potential

All order α' O(d,d) invariant HZ String Action in a **anisotropic cosmology (Bianchi-I)** (*ds*² ⁼ *^N*²(*t*)*dt*² ^P *divice* a *divident invariant in diring Action in d*

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S = \int Ldt = -\frac{1}{2} \int dtN e^{-\bar{\phi}} \left(N^{-2} \dot{\bar{\phi}}^2 + F(N^{-1} \dot{\beta}_i) + 2(\alpha')^{(d-1)/2} V(\phi) \right)
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 $F = -N^{-2} \sum_i \dot{\beta}_i + O(\alpha') = -\sum_i H_i + O(\alpha')$ Fyen function of the Hubble function $\bar{\phi} = \phi - \sum_i \beta_i$ Shifted Dilaton that acts on the scale factors as *^ai*(*t*) ! ¹ $\phi = \phi - \sum_i \beta_i$ Shifted Dilaton t^2 \sum \sum \sum \sum \sum σ_{ij} e $x^i dx^j$ $\sum_i P_i + \sum_j \beta_i + \sum_j (\alpha_j) = \sum_i P_i + \sum_j (\alpha_j)$ Even factor of the Habbie factor of α $\phi = \phi$ -

LOW ENERY ISOU OPIC $\psi = (1 + \nu a) \ln(\nu b)$ (Asymptotic Past Triviality) $H = \beta = \frac{1}{\sqrt{d}(-t)}$ [6] in the case of *V* ()=0. The core of the formalism is to perform a Legendre transform on a subset of the called a "partial Hamiltonian" formalism, that we better contained in a subsequent paper as a Routhian formalism, that we better contained in a subsequent paper as a Routhian formalism, the subsequent paper as a Routhian f (Asymptotic Past invidity) $\sqrt{a(-t)}$ $\frac{1}{2}$ partial Hamiltonian formalism, that we be $\left(\frac{1}{2} + \frac{1}{2} \right)$ and $\left(\frac{1}{2} + \frac{1}{2} \right)$ $\begin{array}{ccc} \text{SOLUTION} \ \text{(a)} & \text{if } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \end{array}$ (Asymptotic Past Triviality) $T = \mu - \sqrt{d}(-t)$ solution
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(Asymptotic Past Triviality) $H = \dot{\beta}$

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\textsf{Low Energy isotropic} \qquad \phi \sim -\left(1+\sqrt{d}\right)\ln\left(-t\right)
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 $\text{Low energy isotropic}$ wave $\begin{pmatrix} 1 + \sqrt{\alpha} & \mu & \mu \\ \mu & \mu & \mu \end{pmatrix}$ in what they are the solution collection: $H = \beta = \frac{1}{\sqrt{d}(-t)}$ for a subset of the paper and the subsequent paper as a Routhian formalism, $H = \beta = \frac{1}{\sqrt{d}(-t)}$ called a "partial Hamiltonian" for the that we better control in a subsequent paper as a Routhian formalism, that we better control in a subsequent paper as a Routhian formalism of \mathbb{R} [6] in the case of *V* ()=0. The core of the formalism is to perform a Legendre transform on a subset of the $\frac{1}{2}$ partial Hamiltonian formalism, that we be $\left(\frac{1}{2} + \frac{1}{2} \right)$ and $\left(\frac{1}{2} + \frac{1}{2} \right)$ $\begin{array}{ccc} \text{SOLUTION} \ \text{(a)} & \text{if } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \text{ is } \mathsf{S} \end{array}$ solution $H = \left| \dot{\beta} \right| = \frac{1}{\sqrt{2\pi}}$ solution
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10

The Routhian formalism and the all order α' Hamiltonian. \mathbf{r} @˙ *i* a \mathbf{a} @*Hⁱ* $\frac{1}{2}$ **C** α ^{*l*} **Lomitonian** @˙ *i* m and the all order α' Hamiltonian. \blacksquare

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\mathcal{R}(N,\bar{\phi},\pi_i) = \sum_i \pi_i \dot{\beta}_i - L = Ne^{\bar{\phi}} \left[\frac{1}{2} N^{-2} \dot{\bar{\phi}}^2 + h(z_i) + V(\bar{\phi} + \sum_i \beta_i) \right]
$$

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h(z_i) \equiv \frac{1}{2} \left(F - \sum_i \dot{\beta}_i \frac{\partial F}{\partial H_i} \right) = \frac{1}{2} \sum z_i^2 + \mathcal{O}(\alpha') + \dots \qquad \frac{\partial h}{\partial z_i} = H_i
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^R(*N,* ¯*,* ⇡*i*) = ^P

ⁱ ⇡*i*˙

The Routhian formalism and the all order α' Hamiltonian. \mathbf{r} @˙ *i* a \mathbf{a} @*Hⁱ* $\frac{1}{2}$ **C** \mathbf{r} and the all erder α' Hamiltonian @˙ *R*_(*N*) \mathbf{R} and \mathbf{R} and \mathbf{R} \mathbf{R} and \mathbf{R} \mathbf{R} and \mathbf{R} a m and the all order α' Hamiltonian. \blacksquare

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\nEoM
\n
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$$
\nAdvantages:
\n
$$
\dot{\bar{\phi}} = \sum_i \dot{z}_i \frac{\partial h}{\partial z_i} + \frac{\partial V}{\partial \phi}
$$

2 Advantages:

- *x* two functions to have a non-perturbative description zify only two functions to have a non-perturbative description of the system. tion of the system. Advantages:
• Specify only two functions to have a non-perturbative description of the system. (c) Two dimensional parametric plot of *H* = *H*() (d) its three-dimensional version with explicit time evolution, • Specity only two functions to have a non-*R*
R(*i*) \overline{A} \overline{B} \overline{B}
- have another zero except the trivial one. In general they come from non-holomorphic F. In the isotropic case we used: $d_{(2,2)}$ z^4 ship the first manneonians tapture and toncellons and generate bounting solutions in they
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 $h(z) = \frac{d}{dz}(z^2 - \alpha' \frac{z^4}{z})$ a corrections are
vial one. In genera @*zⁱ* have another zero except the trivial one. In general they come from non-holomorphic F. In
the isotropic case we used: • Simple 'hamiltonians' capture all α' corrections and generate bouncing solutions if they າo \overline{P} in-holomorphic F. II

The isotropic case we used:
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The phenomenological non-perturbative dilaton potential

Dilaton Potential with Istantonic behaviour not captured by string coupling expansion (Non-perturbative Potential)

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The phenomenological non-perturbative dilaton potential

evolutions ienomenological non-perturbative We thus considered an effective dilaton potential which has a local minimum *V* = *V*0, needed to stabilise the large values, and obtained from (16) with *q* = 0. The black curves show an example of "runaway" potential, asymptotically going to zero for *q* = 1 and stabilising to a non-vanishing constant value for 0 *<q<* 1. Solid curves are plotted with **by a local minimum** *V* \sim 0. Dotted curves corresponding by a local minimum \sim to the same potential plotted however for = 0, and with a local minimum *V*⁰ = 0. All curves are plotted for

Dilaton Potential with Istantonic behaviour not captured by string coupling expansion (Non-perturbative Potential) where

$$
V(\phi) = A e^{-B(\phi)/\beta} \left[\left(c^2 - B(\phi) \right)^2 + \delta B(\phi) \right] \left[1 - q B^{-1}(\phi) \right]
$$

$$
B(\phi) = \frac{1 + \alpha g_s^2}{\alpha g_s^2} = \frac{1 + \alpha e^{\phi}}{\alpha e^{\phi}}
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The phenomenological non-perturbative dilaton potential

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 \mathbb{N} is it possible to reach a final state with a frozen dilaton?

-
- What is the final geometry?
- the dilaton keeps monotonically growing both before and after the bounce, and we recovered a regular transition

Dilaton Stabilisation and FLRW attractor With an appropriate choice of the parameters the potential can produce *i*) the stabilisation of the dilaton at a pilaton Stabilisation and FLRW attractor

Asymptotic Matter FLRW geometry δ=0 λ superiotic λ start from Γ $D\lambda l$ consectrus S Ω **Example conditions to the gravital conditions of the gravitations**

 $V_0 = 0$

Dilaton Stabilisation and FLRW attractor With an appropriate choice of the parameters the potential can produce *i*) the stabilisation of the dilaton at a pilaton stabilisation and FLRW attractor \overline{a}

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Dilaton Stabilisation and de-Sitter attractor The cosmic geometry Cosmic properties duality duality duality duality duality duality duality duality of the in interested, in particular, in a "realistic" post-bounce scenario with the dilaton stabilized at a final constant value the continue continue of the cosmic duality of the initial lowinterested, in particular, in a stabilized at a final constant value of the distortion stabilized at a final c

 ρ er use ntationale Citter geometry δ + ρ $\overline{}$ the displace direction potential $\overline{}$ of $\overline{}$ Asymptotic de-Sitter geometry $\delta \neq 0$

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V_0 = V(\phi_m) > 0
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Dilaton Stabilisation and de-Sitter attractor The cosmic geometry Cosmic properties duality duality duality duality duality duality duality duality of the in interested, in particular, in a "realistic" post-bounce scenario with the dilaton stabilized at a final constant value the cosmic geometry (no longer necessarily duality-related to that of the initial low-energy solution). We were 3.2 de-Sitter attractor and isotropization mechanism interested, in particular, in a stabilized at a final constant value of the distortion stabilized at a final c Dilaton Stabilisation and de-S

Asymptotic de-Sitter geometry $\delta \neq 0$

$$
V_0 = V(\phi_m) > 0
$$

Dilaton Stabilisation and de-Sitter attractor p^{rel} written in the E-frame where the dilaton is a minimally coupled scalar. We also is a minimally coupled scalar coupled scalar. We also discuss a minimally coupled scalar. We also discuss a minimally coupled analy the difference between $\frac{1}{\sqrt{d}}$ and de-sittle attractor $\frac{1}{\sqrt{d}}$ **Dilaton Stabilisation and de-Sitter attractor The cosmic geometry Cosmic properties** duality duality duality duality duality duality duality duality of the in interested, in particular, in a "realistic" post-bounce scenario with the dilaton stabilized at a final constant value the cosmic geometry (no longer necessarily duality-related to that of the initial low-energy solution). We were 3.2 de-Sitter attractor and isotropization mechanism interested, in particular, in a stabilized at a final constant value of the distortion stabilized at a final c Dilaton Stabilisation and de-S

⇣ *^V* ²

 $\sqrt{2}$ *m*⁴

 p_{e} () p_{e} () results at the first order in *V*0*/m*² = *^c*² 2(*c*21)² ⁺ *^O*(²): Asymptotic de-Sitter geometry $\delta \neq 0$

$$
V_0 = V(\phi_m) > 0
$$

\n
$$
\phi_0 \simeq \phi_m - \frac{2V_0}{m^2(d-1)}
$$

\n
$$
H_0 \simeq \left[\frac{2V_0}{d(d-1)}\right]^{1/2}
$$

Dilaton Stabilisation and de-Sitter attractor p^{rel} written in the E-frame where the dilaton is a minimally coupled scalar. We also is a minimally coupled scalar coupled scalar. We also discuss a minimally coupled scalar. We also discuss a minimally coupled analy the difference between $\frac{1}{\sqrt{d}}$ and de-sittle attractor $\frac{1}{\sqrt{d}}$ **Dilaton Stabilisation and de-Sitter attractor The cosmic geometry Cosmic properties** duality duality duality duality duality duality duality duality of the in interested, in particular, in a "realistic" post-bounce scenario with the dilaton stabilized at a final constant value the cosmic geometry (no longer necessarily duality-related to that of the initial low-energy solution). We were 3.2 de-Sitter attractor and isotropization mechanism interested, in particular, in a stabilized at a final constant value of the distortion stabilized at a final c Dilaton Stabilisation and de-S

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⇣ *^V* ²

 $\sqrt{2}$ *m*⁴

 -2

-1

1

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Sand Subsets 15 and 15 assets the Subset of August 25 and 10 and 10 Hon a stable attractor? The assumption of \mathcal{B} $\mathsf{\mathsf{R}}$ $\mathsf{\math$ (c) Time evolution of H(t) for the same numerical solution . The final asymptotic regime is characterised by a (a) (b) (b) (b) (b) (b) (b) (b) (b) **Is this solution a stable attractor?** ²⁵

 -2

-1

1

Numerical analysis of the attraction basin: Isotropic case

Variation of the height of the first peak (β) and the amplitude A

β controls the height of the first peak.

• Conserved quantity from the EoM used to fix the initial condition of the dilaton.

 $e^{-\phi}z = \kappa^{-1}$

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- **q** controls the asymptotic behaviour of the dilaton potential.
- **q**=1: Asymptotically vanishing potential

: de Sitter, stabilised dilaton

: Growing dilaton, Runaway

: Time-reversal post Bounce,

decreasing dilaton

• 0 ≤ **q** < 1: Asymptotically constant potential

Variation of the height of the first peak (β) and the amplitude A

Whenever there is a late-time attractor with constant ϕ and z_i the attractor must be isotropic, i.e $z_i = z = z_0$, and consequently $H_i = H = H_0$.

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Case study: Bianchi I geometry with two isotropic *d* and *n* dimensional subspaces

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h(z_i) = \frac{1}{2} \sum_i z_i^2 - \frac{\alpha'}{4} \sum_i z_i^4
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Past-asymptotic low curvature solutions.

• Scale factors:

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a_i \sim (-t)^{-\gamma_i}
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• Hubble functions:

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• Kasner condition

 $\sum_{i} \gamma_i^2 = 1$

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de Sitter attraction basin in the $\{\epsilon, \kappa\}$ **space**

Take-home messages

• Regular bounce if the reduced hamiltonian has another non trivial zero

- Non-perturbative potential to stabilize the dilaton
- FLRW or de-Sitter are attractors
- Isotropisation of the final geometry

Thanks for your attention!

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This presentation was based on:

P. Conzinu, G.Fanizza, M.Gasperini, E. Pavone, L. Tedesco, G. Veneziano, *From the string vacuum to FLRW or de Sitter via α' corrections* ,JCAP **12**, 019 (2023).