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# The Swampland Criteria from the Perspective of String Gas Cosmology

Robert Brandenberger Physics Department, McGill University

APCTP, Nov. 29, 2018

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### Swampland Criteria

H. Ooguri and C. Vafa, hep-th/0605264; G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, arXiv:1806.08362; H. Ooguri, E. Palti, G. Shiu and C. Vafa, arXiv:1810.05506.

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Swampland conditions: Scalar fields  $\varphi$  emerging from an **effective field theory** approximation of string theory must satisfy the following conditions:

 The effective field theory is only valid for Δφ < d (field range condition).

The potential of  $\varphi$  obeys

 $|V'| \geq c_1 V$  or  $V'' \leq -c_2 V$ 

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Conclusions

### • Large field inflation is in the swamp.

- Slow roll inflation is in the swamp.
- No local or global de Sitter minima.
- $\rightarrow$  inflation does not naturally fit into string theory [R.B. and C. Vafa, 1989].
- Dark Energy cannot be a cosmological constant.
- Quintessence as an explanation of Dark Energy is constrained and may be ruled out by upcoming observations [L. Heisenberg et al, arXiv:1809.00154].
- $\rightarrow$  we need radically new ideas to explain Dark Energy.

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### Current Constraints on Quintessence

L. Heisenberg, M. Bartelman, RB and A. Refregier, arXiv:1809.00154.



### Euclid Constraints on Quintessence

L. Heisenberg, M. Bartelman, RB and A. Refregier, arXiv:1809.00154.



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# Which Early Universe Scenario Emerges Naturally from Superstring Theory?

### **Criteria**:

- Explains the problems of Standard Big Bang Cosmology (e.g. Horizon Problem).
- Produces an almost scale-invariant and nearly
   Gaussian spectrum of cosmological perturbations with a small red tilt.

## Question

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# Map of the Cosmic Microwave Background (CMB)



### Angular Power Spectrum of CMB Anisotropies



### Criteria



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### Key Realization

R. Sunyaev and Y. Zel'dovich, Astrophys. and Space Science **7**, 3 (1970); P. Peebles and J. Yu, Ap. J. **162**, 815 (1970).

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- Given a scale-invariant power spectrum of adiabatic fluctuations on "super-horizon" scales before *t<sub>eq</sub>*, i.e. standing waves.
- $\bullet \rightarrow$  "correct" power spectrum of galaxies.
- → acoustic oscillations in CMB angular power spectrum.

### Angular Power Spectrum of CMB Anisotropies



Conclusio

### Early Work

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Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line  $M_2(t)$ ; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.





R. Sunyaev & Ya. Zeldovich, Astrophysics and Space Science 7 © Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System 3-14 (1970

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## Predictions from 1970

R. Sunyaev and Y. Zel'dovich, Astrophys. and Space Science **7**, 3 (1970); P. Peebles and J. Yu, Ap. J. **162**, 815 (1970).

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- $\bullet \rightarrow$  "correct" power spectrum of galaxies.
- → acoustic oscillations in CMB angular power spectrum.
- → baryon acoustic oscillations in matter power spectrum.

# Key Challenge

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### How does one obtain such a spectrum?

- Inflationary Cosmology is the first scenario based on causal physics which yields such a spectrum.
- But it is not the only one.

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## Hubble Radius vs. Horizon

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- Horizon: Forward light cone of a point on the initial Cauchy surface.
- Horizon: region of causal contact.
- Hubble radius:  $I_H(t) = H^{-1}(t)$  inverse expansion rate.
- Hubble radius: local concept, relevant for dynamics of cosmological fluctuations.
- In Standard Big Bang Cosmology: Hubble radius = horizon.
- In any theory which can provide a mechanism for the origin of structure: Hubble radius ≠ horizon.

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- Horizon ≫ Hubble radius in order for the scenario to solve the "horizon problem" of Standard Big Bang Cosmology.
- Scales of cosmological interest today originate inside the Hubble radius at early times in order for a causal generation mechanism of fluctuations to be possible.
- Squeezing of fluctuations on super-Hubble scales in order to obtain the acoustic oscillations in the CMB angular power spectrum.
- Mechanism for producing a scale-invariant spectrum of curvature fluctuations on super-Hubble scales.

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## Inflation as a Solution



### Matter Bounce as a Solution

F. Finelli and R.B., *Phys. Rev. D65*, 103522 (2002), D. Wands, *Phys. Rev. D60* (1999)



## Emergent Universe

R.B. and C. Vafa, Nucl. Phys. B316:391 (1989)



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### Emergent Universe as a Solution

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)* 



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### Which paradigm arises from string theory?

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### Assumption: All spatial dimensions toroidal, radius R.

### String states:

- momentum modes:  $E_n = n/R$
- winding modes:  $E_m = mR$
- oscillatory modes: E independent of R

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### **T-Duality**

- Momentum modes:  $E_n = n/R$
- Winding modes:  $E_m = mR$
- Duality:  $R \rightarrow 1/R$   $(n,m) \rightarrow (m,n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level  $\rightarrow$  existence of D-branes

## **Position Operators**

R.B. and C. Vafa, Nucl. Phys. B316:391 (1989)

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### Position operators (dual to momenta)

$$|x> = \sum_{p} \exp(ix \cdot p)|p>$$

Dual position operators (dual to windings)

$$|\tilde{x}\rangle = \sum_{w} \exp(i\tilde{x}\cdot w)|w\rangle$$

Note

$$|x> = |x+2\pi R>, |\tilde{x}> = |\tilde{x}+2\pi \frac{1}{R}>$$

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### • $R \gg 1$ : momentum modes light.

•  $R \ll 1$ : winding modes light.

•  $R \gg 1$ : length measured in terms of |x>.

 $ho \,\, {m R} \ll$  1: length measured in terms of  $| ilde{x}>$ 

•  $R \sim 1$ : both |x > and  $|\tilde{x} >$  important.

**Conclusion:** At string scale densities usual effective field theory (EFT) based on supergravity will break down.

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## Physical length operator

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## Physical length



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### String Gas Cosmology R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

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Idea: make use of the new symmetries and new degrees of freedom which string theory provides to construct a new theory of the very early universe.

Assumption: Matter is a gas of fundamental strings.

Assumption:  $g_s \ll 1$ .

### Key points:

- New degrees of freedom: string oscillatory modes
- Leads to a maximal temperature for a gas of strings, the Hagedorn temperature
- New degrees of freedom: string winding modes
- Leads to a new symmetry: physics at large *R* is equivalent to physics at small *R*

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### Absence of a Temperature Singularity in String Cosmology R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

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### Temperature-size relation in string gas cosmology



# Singularity Problem in Standard and Inflationary Cosmology



## Dynamics



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## Dynamics



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- Begin with all 9 spatial dimensions small, initial temperature close to *T<sub>H</sub>* → winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



Decay only possible in three large spatial dimensions.
 → dynamical explanation of why there are exactly three large spatial dimensions.

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Conclusions

- Begin with all 9 spatial dimensions small, initial temperature close to  $T_H \rightarrow$  winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



- Decay only possible in three large spatial dimensions.
- $\bullet \to$  dynamical explanation of why there are exactly three large spatial dimensions.

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## Moduli Stabilization in SGC

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### Size Moduli [S. Watson, 2004; S. Patil and R.B., 2004, 2005]

- winding modes prevent expansion
- momentum modes prevent contraction
  - $ho 
    ightarrow V_{eff}(R)$  has a minimum at a finite value of  $R, 
    ightarrow R_{min}$
- in heterotic string theory there are enhanced symmetry states containing both momentum and winding which are massless at *R<sub>min</sub>* 
  - $0 
    ightarrow V_{eff}({m R}_{min}) = 0$
- ullet o size moduli stabilized in Einstein gravity background
- Shape Moduli [E. Cheung, S. Watson and R.B., 2005]
  - enhanced symmetry states
  - ullet o harmonic oscillator potential for heta
  - ho 
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  - $\rightarrow$  harmonic oscillator potential for  $\theta$
  - $\rightarrow$  shape moduli stabilized

## Dilaton stabilization in SGC

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- The only remaining modulus is the dilaton.
- Make use of gaugino condensation to give the dilaton a potential with a unique minimum.
- $\bullet \rightarrow$  diltaton is stabilized.
- Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008].
- Gaugino condensation induces (high scale) supersymmetry breaking [S. Mishra, W. Xue, R.B. and U. Yajnik, 2012].

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## Theory of Cosmological Perturbations: Basics

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Cosmological fluctuations connect early universe theories with observations

- Fluctuations of matter  $\rightarrow$  large-scale structure
- Fluctuations of  $\ensuremath{\textit{metric}}\xspace \to \ensuremath{\mathsf{CMB}}\xspace$  anisotropies
- N.B.: Matter and metric fluctuations are coupled

### Key facts:

- 1. Fluctuations are small today on large scales
- ullet ightarrow fluctuations were very small in the early universe
- ullet
  ightarrow  $\operatorname{can}$  use linear perturbation theory
- 2. Sub-Hubble scales: matter fluctuations dominate
- Super-Hubble scales: metric fluctuations dominate

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## Quantum Theory of Linearized Fluctuations

/. Mukhanov, H. Feldman and R.B., *Phys. Rep. 215:203 (1992)* 

Step 1: Metric including fluctuations

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$$ds^2 = a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2]$$
  
$$\varphi = \varphi_0 + \delta\varphi$$

Note:  $\Phi$  and  $\delta \varphi$  related by Einstein constraint equations Step 2: Expand the action for matter and gravity to second order about the cosmological background:

$$S^{(2)} = \frac{1}{2} \int d^4 x ((v')^2 - v_{,i}v^{,i} + \frac{z''}{z}v^2)$$
$$v = a(\delta\varphi + \frac{z}{a}\Phi)$$
$$z = a\frac{\varphi'_0}{\mathcal{H}}$$

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## $ds^{2} = a^{2}[(1+2\Phi)d\eta^{2} - (1-2\Phi)d\mathbf{x}^{2}]$ $\varphi = \varphi_{0} + \delta\varphi$

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### Step 3: Resulting equation of motion (Fourier space)

$$V_k'' + (k^2 - \frac{z''}{z})v_k = 0$$

#### Eeatures:

oscillations on sub-Hubble scales
squeezing on super-Hubble scales v<sub>k</sub> ~ 2

Quantum vacuum initial conditions:

 $v_k(\eta_i) = (\sqrt{2k})^{-1}$
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$$v_k(\eta_i) = (\sqrt{2k})^{-1}$$

## Structure formation in inflationary cosmology



# N.B. Perturbations originate as quantum vacuum fluctuations.

## Background for string gas cosmology



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# Structure formation in string gas cosmology

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)* 



## Method

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Conclusions

- Calculate matter correlation functions in the Hagedorn phase (neglecting the metric fluctuations)
- For fixed *k*, convert the matter fluctuations to metric fluctuations at Hubble radius crossing *t* = *t<sub>i</sub>*(*k*)
- Evolve the metric fluctuations for *t* > *t<sub>i</sub>*(*k*) using the usual theory of cosmological perturbations

## Extracting the Metric Fluctuations

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Conclusions

Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^2 = a^2(\eta) ((1+2\Phi)d\eta^2 - [(1-2\Phi)\delta_{ij} + h_{ij}]dx^i dx^j).$$

Inserting into the perturbed Einstein equations yields

$$\langle |\Phi(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0_0(k) \delta T^0_0(k) \rangle,$$

 $\langle |\mathbf{h}(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i_{j}(k) \delta T^i_{j}(k) \rangle.$ 

## Power Spectrum of Cosmological Perturbations

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Key ingredient: For thermal fluctuations:

$$\langle \delta \rho^2 \rangle = \frac{T^2}{R^6} C_V.$$

Key ingredient: For string thermodynamics in a compact space

$$C_V pprox 2 rac{R^2/\ell_s^3}{T\left(1-T/T_H
ight)}$$
 .

## Power Spectrum of Cosmological Perturbations

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### Power spectrum of cosmological fluctuations

$$P_{\Phi}(k) = 8G^{2}k^{-1} < |\delta\rho(k)|^{2} >$$

$$= 8G^{2}k^{2} < (\delta M)^{2} >_{R}$$

$$= 8G^{2}k^{-4} < (\delta\rho)^{2} >_{R}$$

$$= 8G^{2}\frac{T}{\ell_{s}^{3}}\frac{1}{1 - T/T_{H}}$$

Key features:

- scale-invariant like for inflation
- slight red tilt like for inflation

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## Comments

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Conclusions

- Evolution for t > t<sub>i</sub>(k): Φ ≃ const since the equation of state parameter 1 + w stays the same order of magnitude unlike in inflationary cosmology.
- Squeezing of the fluctuation modes takes place on super-Hubble scales like in inflationary cosmology → acoustic oscillations in the CMB angular power spectrum
- In a dilaton gravity background the dilaton fluctuations dominate → different spectrum [R.B. et al, 2006; Kaloper, Kofman, Linde and Mukhanov, 2006]

## Prediction: Spectrum of Gravitational Waves

R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett. (2007*)

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$$egin{array}{rcl} {\cal P}_h(k)&=&16\pi^2G^2k^{-1}<|T_{ij}(k)|^2>\ &=&16\pi^2G^2k^{-4}<|T_{ij}(R)|^2>\ &\sim&16\pi^2G^2rac{T}{\ell_s^3}(1-T/T_H) \end{array}$$

## Key ingredient for string thermodynamics

$$||<|T_{ij}(R)|^2>\sim rac{T}{l_s^3R^4}(1-T/T_H)$$

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## **BICEP-2** Results



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## Requirements

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- Static Hagedorn phase (including static dilaton)  $\rightarrow$  new physics required.
- C<sub>V</sub>(R) ~ R<sup>2</sup> obtained from a thermal gas of strings provided there are winding modes which dominate.
- Cosmological fluctuations in the IR are described by Einstein gravity.

# Prediction: Running of the Spectrum of Cosmological Perturbations

R.B., G. Franzmann and Q. Liang, arXiv:1708.06793 [hep-th]

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## Running

$$\alpha_s \equiv \frac{d^2 \ln P_{\Phi}(k)}{d \ln k^2}|_{k=aH}$$

For Inflation: 
$$\alpha_s \sim (1 - n_s)^2$$

• For String Gas Cosmology:  $\alpha_s \sim (1 - n_s)$ 

 $\rightarrow$  String Gas Cosmology predicts a parametrically larger running.

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### Action S. Patil and RB, hep-th/0502069

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Action: Dilaton gravity plus string gas matter

$$egin{aligned} S &= rac{1}{\kappa} \left( S_g + S_\phi 
ight) + S_{SG} \,, \ S_{SG} &= -\int d^{10} x \sqrt{-g} \sum_lpha \mu_lpha \epsilon_lpha \,, \end{aligned}$$

#### where

μ<sub>α</sub>: number density of strings in the state α
ϵ<sub>α</sub>: energy of the state α.

Introduce comoving number density:

$$\mu_lpha \ = \ rac{\mu_{0,lpha}(t)}{\sqrt{g_s}} \, ,$$

### Action S. Patil and RB, hep-th/0502069

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#### where

•  $\mu_{\alpha}$ : number density of strings in the state  $\alpha$ 

•  $\epsilon_{\alpha}$ : energy of the state  $\alpha$ .

Introduce comoving number density:

$$\mu_{lpha} \,=\, rac{\mu_{0,lpha}(t)}{\sqrt{g_s}}\,,$$

## **Energy-Momentum Tensor**

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Ansatz for the metric:

$$ds^{2} = -dt^{2} + a(t)^{2}d\vec{x}^{2} + \sum_{a=1}^{6} b_{a}(t)^{2}dy_{a}^{2},$$

Contributions to the energy-momentum tensor

$$ho_{lpha} = rac{\mu_{\mathbf{0},lpha}}{\epsilon_{lpha}\sqrt{-g}}\epsilon_{lpha}^2\,,$$

$$p^{i}_{lpha} = rac{\mu_{0,lpha}}{\epsilon_{lpha}\sqrt{-g}}rac{p^{2}_{d}}{3}\,,$$

$$p_{\alpha}^{a} = rac{\mu_{0,\alpha}}{\epsilon_{lpha}\sqrt{-g}lpha'} \left(rac{n_{a}^{2}}{b_{a}^{2}} - w_{a}^{2}b_{a}^{2}
ight)$$

## **Energy-Momentum Tensor**

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#### Contributions to the energy-momentum tensor

$$\rho_{\alpha} = \frac{\mu_{0,\alpha}}{\epsilon_{\alpha}\sqrt{-g}}\epsilon_{\alpha}^{2},$$

$$p^i_lpha \,=\, rac{\mu_{0,lpha}}{\epsilon_lpha \sqrt{-g}} rac{p^2_d}{3}\,,$$

$$p_{\alpha}^{a} = \frac{\mu_{0,\alpha}}{\epsilon_{\alpha}\sqrt{-g}\alpha'} \left(\frac{n_{a}^{2}}{b_{a}^{2}} - w_{a}^{2}b_{a}^{2}\right)$$

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# Single string energy

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 $\epsilon_{\alpha}$  is the energy of the string state  $\alpha$ :

$$\epsilon_{\alpha} = \frac{1}{\sqrt{\alpha'}} \left[ \alpha' p_d^2 + b^{-2}(n,n) + b^2(w,w) + 2(n,w) + 4(N-1) \right]^{1/2},$$

#### where

- *n* and *w*: momentum and winding number vectors in the internal space
- $\vec{p}_d$ : momentum in the large space

## Background equations of motion

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### Radion equation:

$$\dot{b} + \dot{b}(3\frac{\dot{a}}{a} + 5\frac{\dot{b}}{b}) = \frac{8\pi G\mu_{0,\alpha}}{\alpha'\sqrt{\hat{G}_a}\epsilon_\alpha}$$
$$\times \left[\frac{n_a^2}{b^2} - w_a^2b^2 + \frac{2}{(D-1)}[b^2(w,w) + (n,w) + 2(N-1)]\right]$$

Scale factor equation:

ä

$$\begin{aligned} a &+ \dot{a}(2\frac{\dot{a}}{a}+6\frac{\dot{b}}{b}) = \frac{8\pi G\mu_{0,\alpha}}{\sqrt{\hat{G}_i}\epsilon_{\alpha}} \\ &\times \left[\frac{p_d^2}{3}+\frac{2}{\alpha'(D-1)}[b^2(w,w)+(n,w)+2(N-1)]\right], \end{aligned}$$

## Special states

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### Enhanced symmetry states

$$b^{2}(w,w) + (n,w) + 2(N-1) = 0$$

Stable radion fixed point:

$$\frac{n_a^2}{b^2} - w_a^2 b^2 = 0.$$

## Connection with the Swampland Criteria

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Conclusions

The scalar field associated with *b* is

 $\varphi = m_s e^b$ 

The effective potential for  $\varphi$  can be read off from the radion equation:

 $V_{eff}(arphi) \sim arphi^2$ 

#### and hence

 $m_{pl} \frac{V'}{V} \sim \frac{m_{pl}}{m_{p} e^b} \gg 1$ .

## Connection with the Swampland Criteria II

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**Note**: If  $\delta b \sim 1$  then a new set of string gas states becomes massless and the effective potential derived from the self-dual radius breaks down.

# Shape Moduli Stabilization

Y-K. Cheung, S. Watson and RB, hep-th/0501032

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Conclusions

Consider an internal toroidal manifold with angle  $\theta$  and radius *R*, i.e.

 $G_{xy} = R^2 \sin\theta(t)$ 

and antisymmetric tensor field (flux) given by

$$B_{xy} = b^2(t).$$

Couple the background to string gas matter.

## **Resulting Equation of Motion**

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Conclusions

- $\theta = b = 0$  is a stable solution for constant dilaton and constant *R*.
- Equation of motion for θ is that of a damped oscillator, the damping given by the expansion of the large dimensions.
- Linearized about  $\theta = 0$ , the equation of motion is

$$\ddot{ heta} + 4(1+b^2)K^{-1/2}e^{-2\phi} heta \,=\,0\,,$$

with

$$K = 4 + 2b^2 + 2N.$$

• The effective potential obeys the swampland criterium.

# Dilaton Stabilization from Gaugino condensation

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Add a single non-perturbative ingredient - gaugino condensation - in order to fix the remaining modulus, the dilaton Kähler potential: (standard)

 $\mathcal{K}(S) = -\ln(S+\bar{S}), S = e^{-\Phi} + ia.$ 

where  $\Phi = 2\phi - 6 \ln b$  is the 4-d dilaton, *b* is the radion and *a* is the axion. Non-perturbative superpotential (from gaugino condensation):

$$W = M_P^3 \left( C - A e^{-a_0 S} 
ight)$$

## Dilaton potential I

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## Yields a potential for the dilaton (and radion)

$$= \frac{M_P^4}{4} b^{-6} e^{-\Phi} \left[ \frac{C^2}{4} e^{2\Phi} + AC e^{\Phi} \left( a_0 + \frac{1}{2} e^{\Phi} \right) e^{-a_0 e^{-\Phi}} \right.$$
$$+ A^2 \left( a_0 + \frac{1}{2} e^{\Phi} \right)^2 e^{-2a_0 e^{-\Phi}} \right].$$

Expand the potential about its minimum:

$$\begin{array}{ll} \prime & = & \displaystyle \frac{M_{P}^{4}}{4} b^{-6} e^{-\Phi_{0}} a_{0}^{2} A^{2} \left(a_{0} - \frac{3}{2} e^{\Phi_{0}}\right)^{2} e^{-2a_{0} e^{-\Phi_{0}}} \\ & & \times \left(e^{-\Phi} - e^{-\Phi_{0}}\right)^{2} \ . \end{array}$$

## Dilaton potential II

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Conclusions

# Lift the potential to 10-d, redefining *b* to be in the Einstein frame.

$$V(b,\phi) = \frac{M_{10}^{16}\hat{V}}{4}e^{-\Phi_0}a_0^2A^2\left(a_0-\frac{3}{2}e^{\Phi_0}\right)^2e^{-2a_0e^{-\Phi_0}} \times e^{-3\phi/2}\left(b^6e^{-\phi/2}-e^{-\Phi_0}\right)^2.$$

Dilaton potential in 10d Einstein frame

$$V \simeq n_1 e^{-3\phi/2} \left( b^6 e^{-\phi/2} - n_2 
ight)^2$$

# Analysis including both string matter and dilaton potential I

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Conclusions

## Worry: adding this potential will mess up radion stablilization

Thus: consider dilaton and radion equations resulting from he action including both the dilaton potential and string gas natter.

Step 1: convert the string gas matter contributions to the IO-d Einstein frame

$$egin{array}{rcl} g^E_{\mu
u} &=& e^{-\phi/2}g^s_{\mu
u}\ b_s &=& e^{\phi/4}b_E\ T^E_{\mu
u} &=& e^{2\phi}T^s_{\mu
u}\,. \end{array}$$

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Worry: adding this potential will mess up radion stablilization

Thus: consider dilaton and radion equations resulting from the action including both the dilaton potential and string gas matter.

Step 1: convert the string gas matter contributions to the 10-d Einstein frame

$$egin{array}{rcl} g^{E}_{\mu
u} &=& e^{-\phi/2}g^{s}_{\mu
u}\ b_{s} &=& e^{\phi/4}b_{E}\ T^{E}_{\mu
u} &=& e^{2\phi}T^{s}_{\mu
u}\,. \end{array}$$

## Joint analysis II

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Step 2: Consider both dilaton and radion equations:

$$- \frac{M_{10}^{8}}{2} \left( 3a^{2}\dot{a}b^{6}\dot{\phi} + 6a^{3}b^{5}\dot{b}\dot{\phi} + a^{3}b^{6}\ddot{\phi} \right) \\ + \frac{3}{2}n_{1}a^{3}b^{6}e^{-3\phi/2} \left( b^{6}e^{-\phi/2} - n_{2} \right)^{2} \\ + a^{3}b^{12}n_{1}e^{-2\phi} \left( b^{6}e^{-\phi/2} - n_{2} \right) \\ + \frac{1}{2\epsilon}e^{\phi/4} \left( -\mu_{0}\epsilon^{2} + \mu_{0}|p_{d}|^{2} \\ + 6\mu_{0} \left[ \frac{n_{a}^{2}}{\alpha'}e^{-\phi/2}b^{-2} - \frac{w^{2}}{\alpha'}e^{\phi/2}b^{2} \right] \right) \\ = 0,$$
### Joint analysis III

b

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$$+ 3\frac{\dot{a}}{a}\dot{b} + 5\frac{\dot{b}^{2}}{b} = -\frac{n_{1}b}{M_{10}^{8}}e^{-3\phi/2}\left(b^{6}e^{-\phi/2} - n_{2}\right)^{2}$$
$$-\frac{2n_{1}}{M_{10}^{8}}b^{7}e^{-2\phi}\left(b^{6}e^{-\phi/2} - n_{2}\right)$$
$$+\frac{1}{2-D}\left[-\frac{10b}{M_{10}^{8}}n_{1}e^{-3\phi/2}\left(b^{6}e^{-\phi/2} - n_{2}\right)^{2}\right]$$
$$-\frac{12n_{1}}{M_{10}^{8}}b^{7}e^{-2\phi}\left(b^{6}e^{-\phi/2} - n_{2}\right)\right]$$
$$+\frac{8\pi G_{D}\mu_{0}}{\alpha'\sqrt{\hat{G}_{a}\epsilon}}e^{2\phi}\left[n_{a}^{2}b^{-2}e^{-\phi/2} - w_{a}^{2}b^{2}e^{\phi/2}\right]$$
$$+\frac{2}{D-1}\left(e^{\phi/2}b^{2}w^{2} + n \cdot w + 2(N-1)\right)$$

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# Joint analysis IV

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#### Step 3: Identifying extremum

- Dilaton at the minimum of its potential and
- Radion at the enhanced symmetry state

Step 4: Stability analysis

- Consider small fluctuations about the extremum
- show stability (tedious but straightforward)

**Result**: Dilaton and radion stabilized simultaneously at the enhanced symmetry point.

Result: Effective potentials obey the swampland criteria.

### Plan

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Double Field Theory as a Background for String Gas Cosmology

# Double Field Theory (DFT) as a Background for String Gas Cosmology

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**Idea** Describe the low-energy degrees of freedom with an action in doubled space in which the T-duality symmetry is manifest.

Candidate for dynamics in the Hagedorn phase: Double Field Theory [W. Siegel, 1993, C. Hull and B. Zwiebach, 2009], L. Freidel et al., 2017]

$$S = \int dx d\tilde{x} e^{-2d} \mathcal{R},$$

$$= \frac{1}{8} \mathcal{H}^{MN} \partial_{M} \mathcal{H}^{KL} \partial_{N} \mathcal{H}_{KL} - \frac{1}{2} \mathcal{H}^{MN} \partial_{M} \mathcal{H}^{KL} \partial_{K} \mathcal{H}_{NL} + 4 \mathcal{H}^{MN} \partial_{M} \partial_{N} d - \partial_{M} \partial_{N} \mathcal{H}^{MN} - 4 \mathcal{H}^{MN} \partial_{M} d \partial_{N} d + 4 \partial_{M} \mathcal{H}^{MN} \partial_{N} d + \frac{1}{2} \eta^{MN} \eta^{KL} \partial_{M} \mathcal{E}^{A}_{K} \partial_{N} \mathcal{E}^{B}_{L} \mathcal{H}_{AB}.$$

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$$\begin{aligned} \mathcal{H}_{MN} &= \begin{bmatrix} g^{ij} & -g^{ik}b_{kj} \\ b_{ik}g^{kj} & g_{ij} - b_{ik}g^{kl}b_{lj} \end{bmatrix} \\ \mathcal{X}^{M} &= (\tilde{x}_{i}, x^{i}), \\ \eta^{MN} &= \begin{bmatrix} 0 & \delta_{i}^{\ j} \\ \delta^{i}_{\ j} & 0 \end{bmatrix}. \end{aligned}$$

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# Nonsingular String Cosmology from the DFT Perspective

R.B., R. Costa, G. Franzmann and A. Weltman, arXiv:1805.06321 [hep-th]

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Conclusions

#### **Consider Dilaton gravity**

$$\left(\dot{\phi} - dH\right)^2 - dH^2 = e^{\phi}\rho$$
$$\dot{H} - H\left(\dot{\phi} - dH\right) = \frac{1}{2}e^{\phi}p$$
$$2\left(\ddot{\phi} - d\dot{H}\right) - \left(\dot{\phi} - dH\right)^2 - dH^2 = 0$$

coupled to string gas matter.

$$w(a) = \frac{2}{\pi d} \arctan\left(\beta \ln\left(\frac{a}{a_0}\right)\right),$$

# Limiting Solutions

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Conclusions

### Large radius limit:

$$ho\left(a ext{ large}
ight) 
ightarrow 
ho_0 \left(a/a_0
ight)^{-(d+1)},$$
radius limit:

 $\rho$  (a small)  $\rightarrow \rho_0 (a/a_0)^{-d+1}$ 

Ansatz:

Small

$$\begin{array}{ll} \textbf{a}(t) & \sim & \big(\frac{t}{t_0}\big)^{\alpha} \\ \bar{\phi}(t) & \sim & \beta \ln(t/t_0) \,, \end{array}$$

 $ar{\phi} \equiv \phi - d \ln(a)^{- + \sigma + + z + + z + - z} = \frac{\sigma_{SS}}{77/82}$ 

# Limiting Solutions

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Ansatz:

Where

Small

$$\begin{array}{ll} \textbf{a}(t) & \sim & \big(\frac{t}{t_0}\big)^{\alpha} \\ \bar{\phi}(t) & \sim & \beta \ln(t/t_0) \,, \end{array}$$

 $ar{\phi} \equiv \phi - d \ln(a)$ 

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Hagedorn phase, w = 0:

$$(\alpha,\beta) = (0,2).$$

Note: Static in string frame.

Large *a* phase, w = 1/d:

$$(lpha,eta) = \left(rac{2}{D},rac{2}{D}(D-1)
ight).$$

Note: constant dilaton.

Small *a* phase, w = -1/d:

$$(\alpha, \beta) = \left(-\frac{2}{D}, \frac{2}{D}(D-1)\right).$$

#### String Cosmology

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Conclusions

#### • Bouncing cosmology in the string frame $\rightarrow$ nonsingular.

- Contracting cosmology for  $t \rightarrow 0$  in the Einstein frame.
- As t → 0 the energy of the string gas drifts to winding modes.
- Physical space is measured in terms of winding modes.
- In terms of winding modes the contraction as  $t \rightarrow 0$  corresponds to expansion.

•  $t 
ightarrow 0 \equiv t_d 
ightarrow \infty$ 

- In terms of physical variables: bouncing cosmology.
- Conclusion: nonsingular cosmology.

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Conclusions

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•  $t \to 0 \equiv t_d \to \infty$ 

In terms of physical variables: bouncing cosmology.
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DFT

- **Cosmology of string theory** must take into account the key symmetries of string theory, in particular the T-duality symmetry.
- Standard effective field theory of supergravity will break down in the very early universe.
- Hence it is not surprising that inflationary models are in the swamp.
- String Gas Cosmology appears to emerge naturally from string theory.
- String Gas Cosmology provides a way to understand the second swampland criterium.

# Conclusions I

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#### String Cosmology

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DFT

- String Gas Cosmology provides an alternative to inflation for producing the spectrum of cosmological perturbations.
- Cosmological evolution is **nonsingular**.
- Our universe emerges from an early Hagedorn phase.
- Thermal string fluctuations in the Hagedorn phase yield an almost scale-invariant spectrum of cosmological fluctuations.
- Characteristic signal: blue tilt in the spectrum of gravitational waves.