Emergent Cosmology from the BFSS Matrix Model

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(in collaboration with R. Brandenberger and S. Laliberté, 2107.11512)

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Motivation

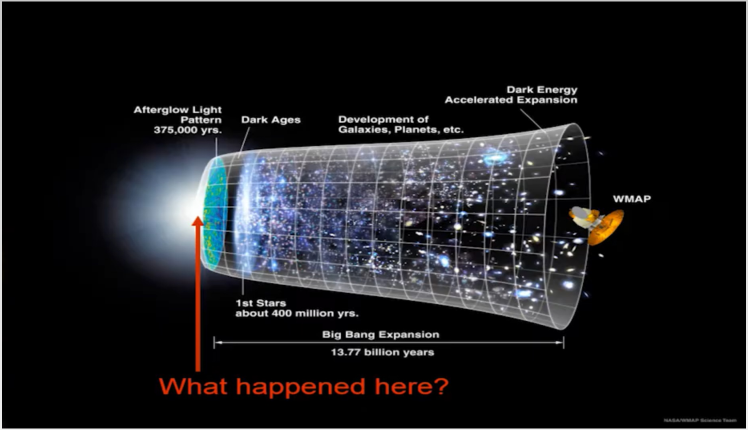

Photo credit: P. Adshead

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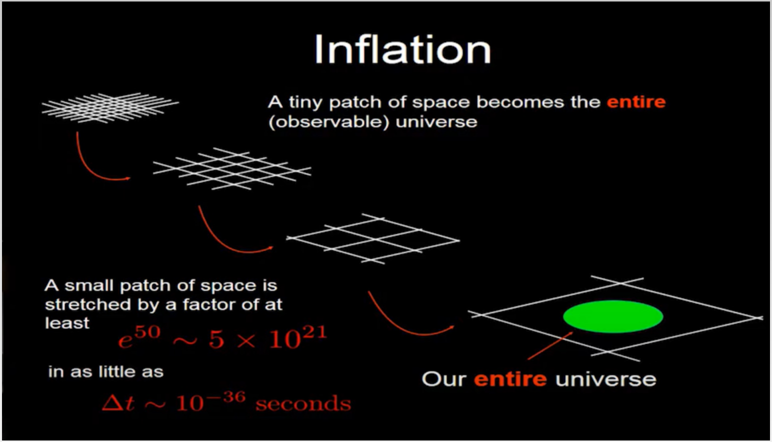

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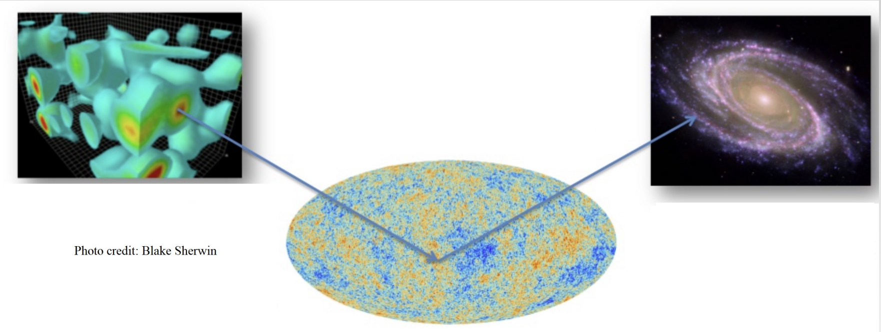

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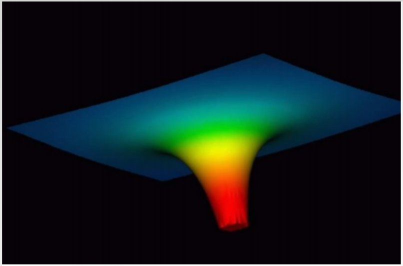
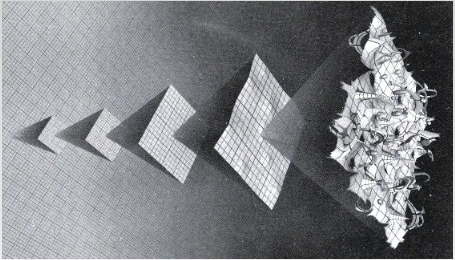


Credit: Pablo Laguna



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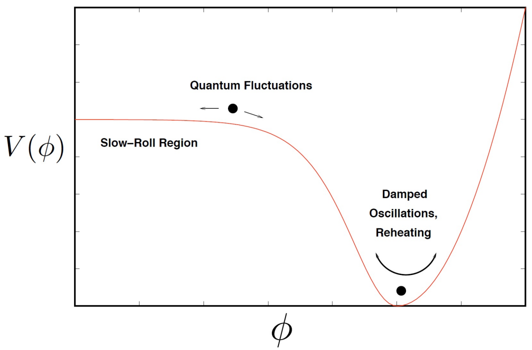

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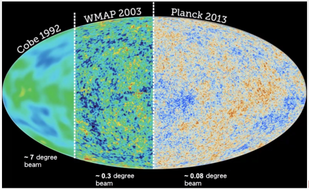

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Alternate description of the early-universe from *BFSS matrix theory*.

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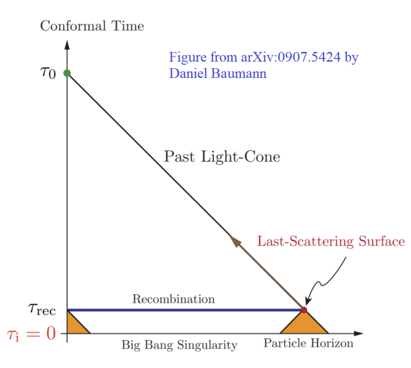

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- Solution to the standard horizon problem $\Leftarrow$ Hubble radius smaller than causal horizon is all that is needed. [Brandenberger, 2011]
- Origin of structure $\Leftarrow$ Scale invariant power spectrum of adiabatic perturbations. [Sunyaev & Zel'Dovich; Peebles & Yu, 1970]
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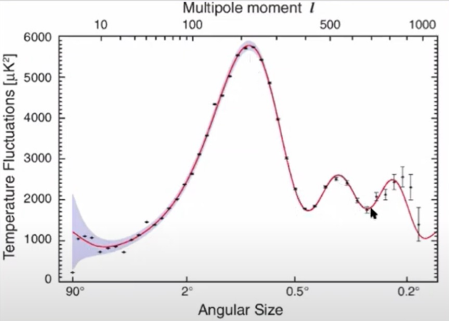

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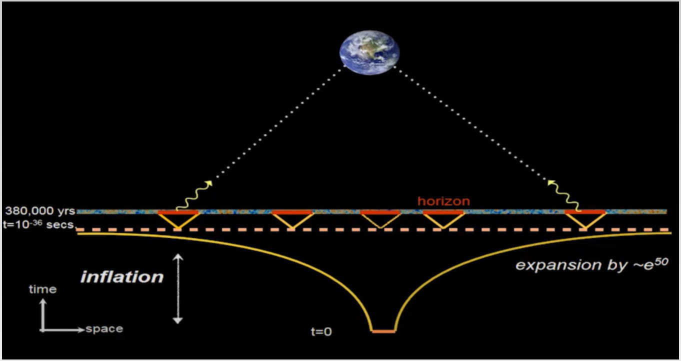

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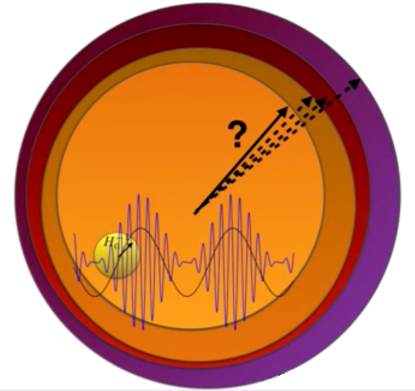

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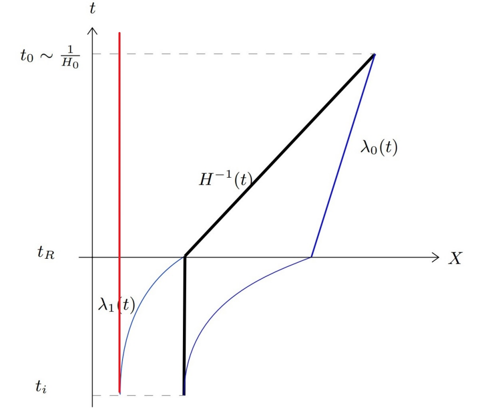

[Bedroya, Brandenberger, LoVerde, Vafa, 2019]

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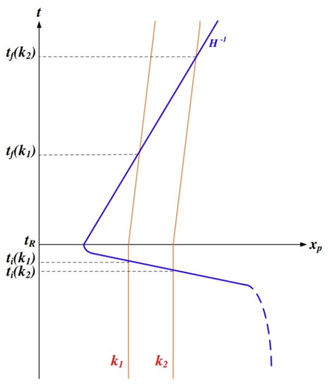
✓ Inflation as an EFT of simple scalar dofs with higher order terms added as one goes back in time might *not* be the final picture. Difficulty of embedding (quasi)-dS in String Theory ⇒ Need to go beyond EFT!

↪ Even if inflation needs to be realized, has to be derived from a UV-complete theory going beyond simple EFT!

Alternatives

↪ Alternate descriptions of early-universe cosmology:

- Examples: *String Gas Cosmology* [Brandenberger & Vafa, 1989], *Ekpyrotic bounce* [Khoury, Ovrut, Steinhardt & Turok, 2001], *Early phase of topological gravity* [Agrawal, Gukov, Obied & Vafa, 2020], ...



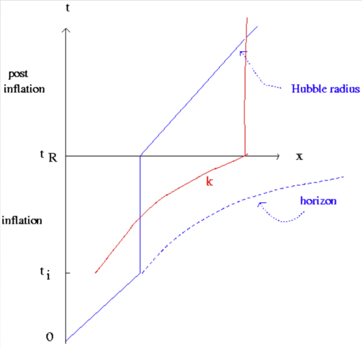


Figure Credit: R. Brandenberger

Matrix model descriptions in string theory

↪ The BFSS matrix model [Banks, Fischler, Shenker & Susskind, 1997]:

$$S_{\mathrm{BFSS}} = \frac{1}{g^2}\int \mathrm{d}t\mathrm{Tr}\left\{\frac{1}{2}\left(D_t X_i\right)^2 - \frac{1}{4}\left[X_i, X_j\right]^2 + \frac{1}{2}\psi_\alpha D_t \psi_\alpha - \frac{1}{2}\psi_\alpha \gamma^i_{\alpha\beta}\left[X_i, \psi_\beta\right]\right\}$$

where $D_t \equiv \partial_t - i\,[A_t, \cdot]$ and $N \times N$ bosonic matrices $A(t), X_i(t)$ $(i = 1, \ldots, d)$ and $\psi_\alpha(t)$ $(\alpha = 1, \ldots, p)$.

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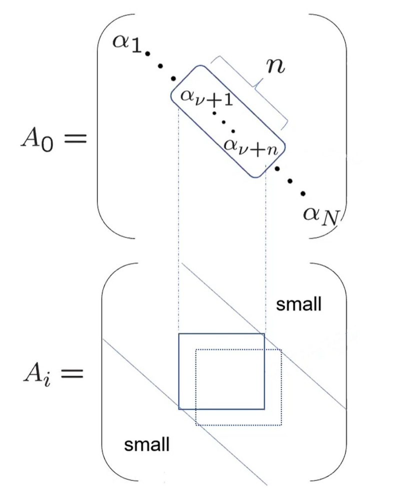
↪ Rich promise for UV-complete description of cosmology in a *top-down* approach from a non-perturbative description of String Theory.

Background dynamics from the IKKT model

[Aoki, Hirasawa, Ito, Kim, Nishimura, Tsuchiya, ...]

$\hookrightarrow$ Lorentzian IKKT model: $Z \sim \int \mathrm{d}A\, \mathrm{d}\Psi\, e^{iS_{\rm IKKT}}$



✓ Need IR cutoffs:
$\frac{1}{N}\mathrm{Tr}\,(A_0)^2 < \kappa L^2$; $\frac{1}{N}\mathrm{Tr}\,(A_i)^2 < L^2$

✓ Diagonalize A_0 : $\alpha_1 < \ldots < \alpha_N$.

✓ Define time via *coarse-graining*:

$$t(\nu) := \frac{1}{n}\sum_{i=1}^{n} \alpha_{\nu+i}, \quad \nu = 1, \ldots, N-n$$

✓ *Non-trivial* to obtain dynamical band-diagonal structure!
$\rightarrow$ Time-dep $n \times n$ spatial matrices:
$(\bar{A}_i)_{I,J}(t(\nu)) := (A_i)_{\nu+I,\nu+J}$

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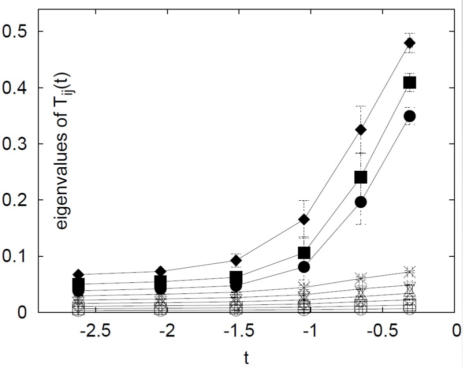
✓ Numerical results show SSB $SO(9) \to SO(3)$ at some t_c.

↪ *Emergence* of 3 large spatial dimensions:



✓ As order parameter, define moment of inertia tensor

$$T_{ij}(t) := \left\langle \frac{1}{n}\,\mathrm{Tr}\bar{A}_i(t)\bar{A}_j(t) \right\rangle$$

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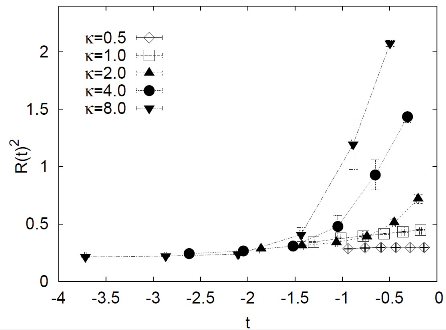

✓ Extent of a given spatial dimension parameter: $x_i^2(t) := \left\langle \frac{1}{n} \mathrm{Tr}\, \bar{A}_i(t)^2 \right\rangle$

→ Total extent of space parameter: $R^2(t) = \sum_{i=1}^{9} x_i^2(t)$

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- SSB *Mechanism*: $S_{\rm b} \sim -\left[A_0, A_i\right]^2 + \frac{1}{2}\left[A_i, A_j\right]^2$
- This naive picture glosses over subtleties such as having a *Pauli-matrix structure* for bosonic part alone.
- Smooth spacetime, as well as SSB, possible with additional deformation parameters in Wick rotation. Expansion is *typically weak* (not *exponential*)?
- Role of fermionic matrices crucial! Technical obstructions to overcome (CLM *vs.* MC)

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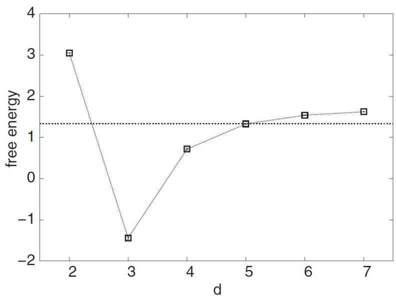
$\hookrightarrow$ SSB is a robust feature $\rightsquigarrow$ MC simulations (or even analytic Gaussian expansion methods) for Euclidean model:



- Can calculate Free Energy for the Euclidean IKKT model (no IR cutoffs needed).
- Once again, fermions are essential.
- SSB due to the phase of Pfaffian becoming more stationary as one goes to $d = 3$

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Takeaway: A $(3 + 1)$-d universe emerges *dynamically* from non-perturbative (matrix model) description of superstring theory

Formalism: Cosmo perturbations in thermal state

↪ To confront with observations, need cosmological perturbations: go *beyond* IKKT model.

↪ Consider a state in the BFSS model such that the background evolution is given by the IKKT model while the primordial perturbations are in a thermal state. Thermal state formalism: [Nayeri, Brandenberger & Vafa, 2005]

✓ Start with the Euclidean BFSS model and consider its compactification on a thermal circle: BFSS $\xrightarrow{T\to\infty}$ IKKT (natural to assume thermal state)

⇝ Scalar modes: $\langle|\Phi(k)|^2\rangle = M_{\rm Pl}^{-4}k^{-4}\langle\delta T^0_0(k)\delta T^0_0(k)\rangle$

⇝ Tensor modes: $\langle|h(k)|^2\rangle = M_{\rm Pl}^{-4}k^{-4}\langle\delta T^i_j(k)\delta T^i_j(k)\rangle,\ i\neq j.$

↪ For a thermal state, perturbations are sourced by (box of side R):

$$C^{00}{}_{00} = \frac{T^2}{R^6}C_V\,, \qquad C_V = \left(\frac{\partial E}{\partial T}\right)_V$$

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✓ Justified to use Einstein's equations since we are considering IR modes (as in SG). Operator interpretation of matrices as derivatives on curved spaces → Einstein's Eqn arise from classical EoMs. [Hanada, Kawai & Kimura]

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↪ Thermal fluctuations considered in *String gas cosmology* and *Warm Inflation*. Unlike in standard inflation or *ekpyrosis*, perturbations not sourced by quantum vacuum fluctuations.

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↪ $S_{\mathrm{BFSS}} = S_0 + S_{\mathrm{kin}} + S_{\mathrm{int}}$, where $S_0 =: S_{\mathrm{IKKT}}$ (zero-mode action).

↪ Free energy *next-to-leading* + corrections

$$\mathcal{F}(R,\beta) = \frac{3N^2}{4\beta}\left[\chi_2 \ln\beta - \frac{2}{3}\left(\frac{d-1}{12} - \frac{p}{8}\right)\left(N^2\chi_2 - \frac{N^2}{d}\chi_2 - 4\right)\chi_1\beta^{3/2}\right]$$

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✓ Use approximations to evaluate higher-order moments of zero-modes.

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↪ We have all the quantities required ${C^{00}}_{00}$, ${C^{ij}}_{ij}$ to calculate spectrum of cosmological perturbations in the BFSS thermal state. [Kawahara, Nishimura & Takeuchi, 2007; S.B., Brandenberger & Laliberté, 2107.11512]

Cosmological observables from the BFSS theory

We find scale-invariant spectrum for *IR modes* of observational interest
[S.B., Brandenberger & Laliberté, 2107.11512]

$P_\zeta \sim (\ell_s M_{\rm Pl})^{-4}\, \mathcal{O}(1), \quad P_h \sim \alpha\, (\ell_s M_{\rm Pl})^{-4}\, \mathcal{O}(1).$ SG: $\mathcal{A} \sim (\ell_s M_{\rm Pl})^{-4}$

$\hookrightarrow$ UV-modes for density perturbations have a Poisson spectrum ($\propto k^2$); *distinct* from inflation but not of (direct) observable consequence. Small tilt from next order corrections and due to the SSB phase transition.

$\hookrightarrow$ The *exact* time-dependent expansion of χ_1 *not* required for above result!

✓ Tensor-to-scalar ratio: $r = (8/3)\alpha$, where α cannot be *fine-tuned* to be very small $\Rightarrow$ Predicts observable primordial tensor modes! Different predictions from *topological gravity model* & *string gas*.

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[S.B., Brandenberger & Laliberté, 2107.11512]

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↪ UV-modes for density perturbations have a Poisson spectrum ($\propto k^2$); *distinct* from inflation but not of (direct) observable consequence. Small tilt from next order corrections and due to the SSB phase transition.

↪ The *exact* time-dependent expansion of χ_1 *not* required for above result!

✓ Tensor-to-scalar ratio: $r = (8/3)\alpha$, where α cannot be *fine-tuned* to be very small ⇒ Predicts observable primordial tensor modes!
Different predictions from *topological gravity model* & *string gas*.

↪ *Yet* to work out details of the SSB phase transition. Nevertheless can make clear predictions. Similar to reheating phase in inflation.

↪ Top-down derivation of UV-complete early-universe cosmology → Naturally free from swampland constraints.

Discussion & Looking ahead

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- M-theory consistency rules out large classes of bounce models. [Bernardo, S.B., Dasgupta Mir & Tatar, Phys. Rev. Lett. 2020]
- A new path towards a UV-complete paradigm for the early-universe: Ambitious, promising but a lot to be done:

✓ Details of non-geometric phase → Connection to non-commutative geometry emergent in the UV? [H. Steinacker; A. Chaney & A. Stern; ...]

✓ Details & physical explanation of the SSB phase? Connection with String Gas? Interestingly, non-geometric phase has $p = 0$ just as the quasi-static phase in SG!

✓ Other conceptual issues: *Matrix String Theory*? Start with BMN model instead of IR regulator?

✓ Observable consequences: NG, precise expression for r, ...

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