Discriminating Between Theories of the Very Early Universe

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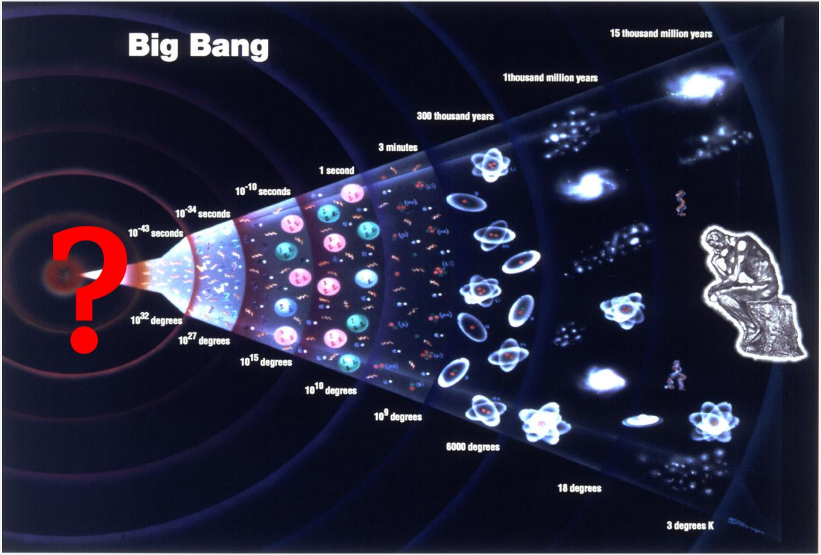
Big Bang Cosmology

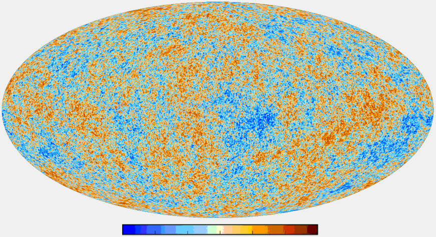


Adapted from `https://www.universetoday.com/54756/what-is-the-big-bang-theory/`

The relic of the ‘big bang’ (thanks Peebles!)

Adapted from Planck Collaboration [arXiv:1502.01582,1807.06211]

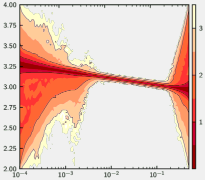
Cosmic Microwave Background $\sim 300{,}000$ yr after the ‘big bang’



temperature fluctuations $\sim 10^{-4}$

primordial power spectrum $\sim 10^{-32}$ sec after the ‘big bang’
(variance of spacetime curvature perturbations)

$\log\langle\zeta_k\zeta_k\rangle'$



standard deviation

Fourier wavenumber k [Mpc^{-1}]

$$\langle\zeta_k\zeta_k\rangle' = (2.10 \pm 0.03) \times 10^{-9} \left(\frac{k}{0.05\,\mathrm{Mpc}^{-1}}\right)^{-0.0351 \pm 0.0042}$$

$\Rightarrow$ Nearly scale-invariant, Gaussian, scalar fluctuations

$\Rightarrow$ Currently no (statistically significant) sign of anything else!
(e.g., primordial gravitational waves, non-Gaussianities, running of the spectrum, features, etc.)

$\Rightarrow$ Incredibly rich and complex, yet very simple

How can this be explained?

ASSUME initial conditions: quantum vacuum on small scales $\xrightarrow[? \ ? \ ?]{\text{Evolve}}$ MEASURE 'final conditions': $\langle\zeta_k\zeta_k\rangle' \sim k^0$ on large scales

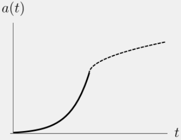
$$\text{perturbed Einstein equations} \Rightarrow \ddot{\zeta}_k + \left(3\frac{\dot{a}}{a} + \frac{\dot{\epsilon}}{\epsilon}\right)\dot{\zeta}_k + \frac{k^2}{a^2}\zeta_k = 0$$

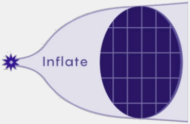
$a(t) =$ scale factor of the universe

$\epsilon(t) =$ characterizes the equation of state of the matter content

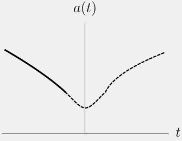
- E.g., $\epsilon \approx$ const., $a(t) \sim |t|^{1/\epsilon}$
  - $\Rightarrow$ Accelerated expansion ($t > 0$): $\epsilon \ll 1$ (negative pressure vacuum EoS)
  - $\Rightarrow$ Fast contraction ($t < 0$): $\epsilon \approx 3/2$ (pressureless matter)
  - $\Rightarrow$ Slow contraction (a.k.a. ekpyrosis; $t < 0$): $\epsilon > 3$ (ultra-stiff EoS)
- **Can all be made consistent with the measured $\langle\zeta_k\zeta_k\rangle'$**
- A few more scenarios are also possible, but let's keep it simple for today

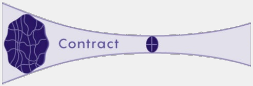
- Inflation (standard paradigm)



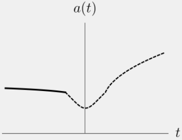


- Fast contraction (alternative)





- Slow contraction (alternative)



Images adapted from `https://www.wired.com/story/what-if-the-big-bang-was-actually-a-big-bounce/`

Some pros and cons

- Inflation:
  - The universe starts with a **big bang** (geodesically incomplete)
  - The universe may be eternally inflating
  - Needs new field to drive inflation, e.g., scalar field with sufficiently flat potential
  - Hard to get such potentials in ultraviolet-complete theories
- Fast contraction:
  - The universe must undergo a **bounce** (geodesically complete)
  - Standard matter is sufficient
  - Somewhat unstable (to anisotropies, inhomogeneities, other matter contents, etc.)
- Slow contraction:
  - The universe must undergo a **bounce** (geodesically complete)
  - Originally proposed as a string theory construction
  - Generally requires more than one field
  - Very stable background

But are there ways of discriminating between those theories, in a model-independent way, both theoretically and observationally?

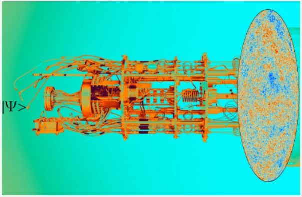
We need to invent new approaches!

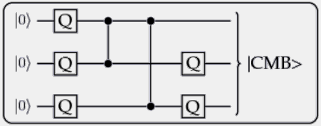
Let me propose a few avenues in that direction for the rest of this talk:

(1) Primordial quantum complexity
(2) Primordial quantum amplitudes
(3) Primordial standard clocks

(1) Primordial quantum complexity

- How **complex** are the various scenarios? If we did a quantum simulation of the early universe, **how many quantum gates** would it require?





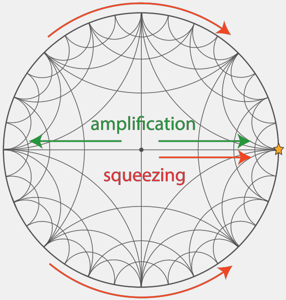
$$\left|\Psi_{\mathrm{Ref}}\right\rangle \xrightarrow{\left|\Psi_{\mathrm{Target}}\right\rangle = \hat{U}\left|\Psi_{\mathrm{Ref}}\right\rangle} \left|\Psi_{\mathrm{Target}}\right\rangle$$

- How many elementary quantum gates to construct $\hat{U}$? $\implies$ complexity
- The general idea is that a circuit can have a continuous differential-geometry description
  $\Rightarrow$ optimal quantum simulation $\equiv$ smallest number of gates $\equiv$ geodesic in the geometry of quantum gates

  Nielsen [quant-ph/0502070], Jefferson & Myers [1707.08570], Camargo+ [1807.07075], Ali+ [1810.02734], Chapman+ [1810.05151], Bhattacharyya+ [2001.08664,2005.10854], Lehners & JQ [2012.04911]

Quantum circuit complexity

- A convenient geometry is the hyperbolic one [it naturally arises when representing the Gaussian wavefunctions as covariance matrices, where elementary gates are elements of $\mathrm{Sp}(2,\mathbb{R})$] Camargo+ [1807.07075]

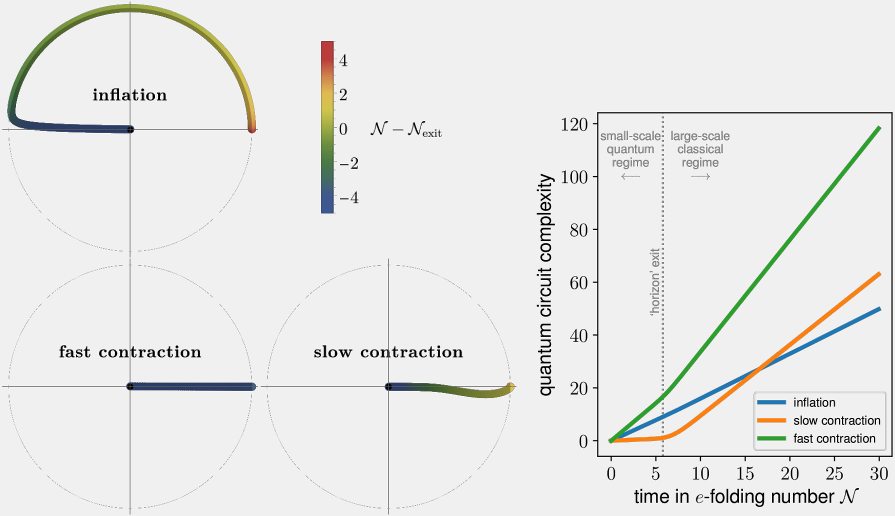


Lehners & JQ, Phys. Rev. D (2021)

- **amplification** $\leftrightarrow$ growth of $\langle\zeta_k\zeta_k\rangle'$
- **squeezing** $\leftrightarrow$ classicalization in the WKB sense

Complexity of early universe perturbations

Lehners & JQ, Phys. Rev. D (2021)



⇒ inflation acts as a 'simple' quantum computer compared to its alternatives

⇒ very modest dependence on specific model realizations

(2) Primordial quantum amplitudes

Jonas, Lehners & JQ, Phys. Rev. D (2021)

$$\mathcal{A}(\Phi_\mathrm{i} \to \Phi_\mathrm{f}) = \int_{\Phi_\mathrm{i}}^{\Phi_\mathrm{f}} \mathcal{D}\Phi \, e^{\frac{i}{\hbar} S[\Phi]} \simeq \sum \mathcal{N} e^{\frac{i}{\hbar} S_\mathrm{cl}[\Phi_\mathrm{i} \to \Phi_\mathrm{f}]} \,, \quad \Phi = \{g_{\alpha\beta}, \phi, A_\mu, \ldots\}$$

→ this only yields a well-defined amplitude if the relevant saddle points have finite classical on-shell action

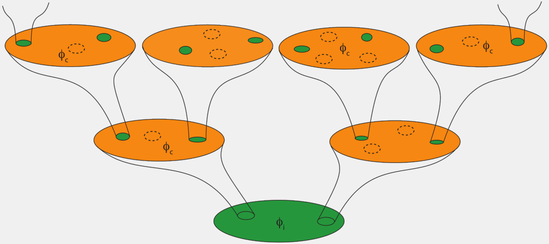
→ E.g., in cosmology,

$$S_\text{on-shell} \sim \int_{t(\Phi_\mathrm{i})}^{t(\Phi_\mathrm{f})} \mathrm{d}t \, a\dot{a}^2 \overset{a \sim |t|^{1/\epsilon}}{\sim} \begin{cases} t^{\frac{3-\epsilon}{\epsilon}} \Big|_0^{t(\Phi_\mathrm{f})} & \text{inflation with } \epsilon \ll 1 \\ (-t)^{\frac{3-\epsilon}{\epsilon}} \Big|_{-\infty}^{t(\Phi_\mathrm{f})} & \text{contraction with } \epsilon > 1 \end{cases}$$

→ Inflation appears to be fine, but contraction converges only if $\epsilon > 3$ (only slow contraction!)

But the story is not that simple for inflation

- If inflation really goes all the way back to the big bang singularity ($a = 0$), instabilities in the perturbations arise (interference among different saddle points) $\Rightarrow$ unviable Di Tucci *et al.* [1906.09007]
- If inflation is eternal (potential is so flat that field stochastically jumps up the potential and keeps inflating), action is divergent Jonas, Lehners & JQ [2102.05550]

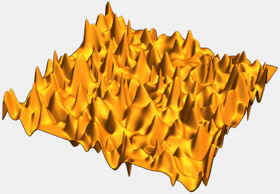
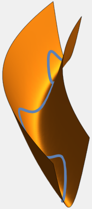
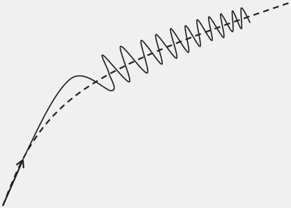


$$S \sim \int_0^\infty \mathrm{d}t\, a^3\, V(\phi)\, \underbrace{\mathrm{Prob}[\phi \text{ is inflating at time } t]}_{\text{sol. to Fokker-Planck equation}} \to \infty \quad \text{if} \ \frac{|V_{,\phi}|}{V^{3/2}} < \frac{1}{\sqrt{2}\pi}$$

$\rightarrow$ Reminiscent of swampland criteria

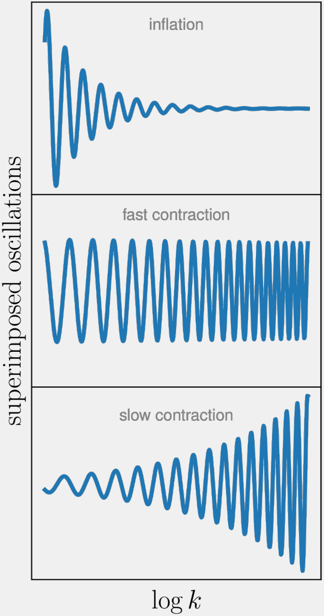
(3) Primordial standard clocks

- One generally expects a wealth of heavy spectator fields in the early universe

- These oscillating heavy fields are expected to leave oscillatory signals in the observations
- And the frequency dependence is expected to mainly depend on the background evolution Chen [1104.1323]

$$a(t) \sim |t|^{1/\epsilon} \quad \longrightarrow \quad \frac{\Delta\langle\zeta_k\zeta_k\rangle'}{\langle\zeta_k\zeta_k\rangle'_{\text{no oscil.}}} \sim A(k,\epsilon)\sin(k^{\epsilon}) \quad \longrightarrow \quad \text{standard clock}$$



→ Oscillations superimposed on top of the nearly scale-invariant power spectrum **could tell us about $a(t)$ in the very early universe!**

→ Expected signals in other windows as well (3-pt function, GWs, etc.)

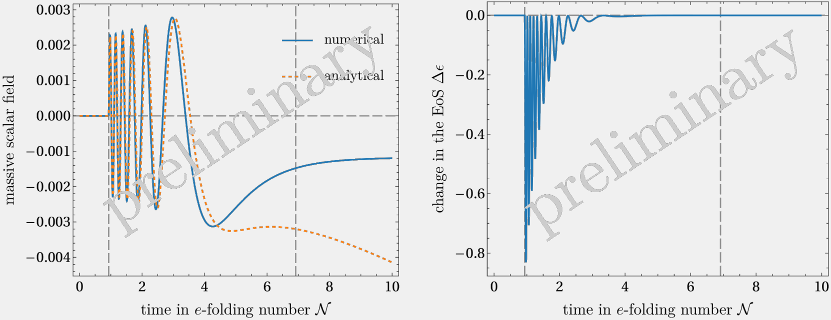
→ Potentially observable with next generation of telescopes!

→ Explicit particle physics models have been constructed for inflation and the corresponding signals are currently extensively studied

→ Barely any exploration of the alternatives!

First classical standard clock model in ekpyrosis

(slow contraction)



$\rightarrow$ **Predicted signals in the observations currently under investigation, so stay tuned!**

Conclusions and future directions

- Very different realizations of the very early universe can degenerately predict the same simple nearly scale-invariant primordial spectrum
- We need new ways of discriminating between theories, in the most model-independent way:
  - $\rightarrow$ quantum circuit complexity:
    - ✓ nice description of the quantum-to-classical transition
    - ✓ very modest model dependence
    - ✗ limited applicability?
  - $\rightarrow$ finite quantum cosmological amplitudes:
    - ✓ strong theoretical constraint on allowed models
    - ✗ more model dependent
  - $\rightarrow$ standard clocks (heavy spectator fields):
    - ✓ strong potential observational constraints on allowed models
    - ✓ quite model independent
    - ✗ a lot more work to be done on the alternatives!
- Other constructions of the very early universe are worth paying attention to (e.g., string gas, topological gravity, and more)

Thank you for your attention!

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