Accelerating cosmology from qubit?

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It From Qubit

quantum information provides deeper origin for spacetime, gravity, black holes,...
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→ quantum information provides deeper origin for spacetime, gravity, black holes, ...

- what about cosmological spacetimes?

from qubit?
Holographic models work for $\Lambda < 0$ spacetimes that are asymptotically empty AdS.
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big bang $\rightarrow$ expansion (accelerated)
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Can we come up with a holographic model of 4D big bang cosmology?
String theory community: a lot of focus on $\Lambda > 0$

- simplest way to explain acceleration from EFT point of view
- explain small $\Lambda$ via anthropic principle in bubbling multiverse
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- simplest way to explain acceleration from EFT point of view
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**BUT**
- Seems v. difficult to construct $\Lambda > 0$ solutions/show existence
- Difficult to see what non-perturbative description of a bubbling multiverse could be
String theory community: a lot of focus on $\Lambda > 0$

- simplest way to explain acceleration from EFT point of view
- explain small $\Lambda$ via anthropic principle in bubbling multiverse

**BUT**: Seems very difficult to demonstrate $\Lambda > 0$ vacua exist

- Difficult to see what non-perturbative description could be

This talk: consider $\Lambda < 0$ cosmologies → novel perspective on naturalness problems

- possible non-perturbative description via holography
  can naturally give rise to accelerating cosmology (!)
- via time-dependent scalars
Starting point: certain 3D CFTs are associated with consistent $\Lambda < 0$ gravitational effective field theories.

CFT states $\leftrightarrow$ asymptotically AdS solutions.
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CFT states $\leftrightarrow$ asymptotically AdS solutions

* These effective field theories also have cosmological solutions*
\( \Lambda < 0 \) cosmologies:

With matter and/or radiation, get big bang/big crunch:

Can we come up with a holographic description?
Challenge: $\Lambda < 0$ big-bang/big crunch spacetimes are not asymptotically AdS.

conformal diagram:

bang

crunch
Challenge: $\Lambda < 0$ big-bang/big crunch spacetimes are not asymptotically AdS.

One idea: embed a bubble into asymptotically AdS spacetime like "Inflation in AdS/CFT"

Conformal diagram:

- FRW
- Schwarzschild AdS
- SAdS

Special CFT black hole microstates include bubbles of cosmology?

Domain wall

Enclidean preparation?

P. Leung
A. Saha
P. Simidzija
MVR
work in progress
Challenge: \( \Lambda < 0 \) big-bang/big crunch spacetimes are not asymptotically AdS.

**BUT:** analytic continuation is asymptotically AdS for any matter/radiation/\( \Lambda < 0 \) cosmology!

\[
ds^2 = d\tau^2 + \cosh\left(\frac{\xi}{L}\right)d\vec{x}^2
\]

**Example:**

\[
ds^2 = -dt^2 + \cos\left(\frac{t}{L}\right)d\vec{x}^2
\]
In QFT: Euclidean theory on analytic cont. often used to define natural state of the Lorentzian theory.

\[ \mathbb{R}^n \to \text{vacuum} \quad \mathbb{R}^{n-1} \times S^1 \to \text{thermal} \]

Gravity example: Hartle & Hawking wavefunction of universe

\[ \Psi[g] = \sum e^{-\text{gravitational action}} \]

4D Euclidean geometries with boundary \( g \)
In QFT: Euclidian theory on analytic cont. often used to define natural state of the Lorentzian theory.

Suggests:

1. Find holographic description of analytically continued spacetime

2. Use this to define holographic description of special state for cosmology
Time dependent scalars are generic.

- 2 asymptotically AdS boundaries suggest pair of Euclidean CFTs.
- These typically have relevant operators
- Dual gravitational EFT has $m^2 < 0$ scalars $m^2 L^2 = \Delta (\Delta - 3)$
- These turn on in most generic asympt. AdS solutions, vary on cosmological time scales.
A typical potential

\[ V(\phi) \]

\[ \phi \]

- **AdS extremum**
- **\( m^2 < 0 \) (dual of relevant operator)**
- Interaction terms make \( V(\phi) \) increasing for large \( \phi \)
Scalar evolution

\( \phi = 0 \)

- crunch
- \( \phi = \phi_0 \)
- AdS
- bang
- t
- \( \tau \)

\( V(\phi) \)

- \( \phi_0 \)
- wormhole
- Cosmology

Feynman diagram with AdS and crunch regions.
Acceleration is generic

In simple examples, find accelerating phase in significant region of parameters

\[ V(\phi) \]

\[ \phi_0 \]

\[ \phi \]

\[ V = -1 - \frac{3}{2} \phi^2 + V_{\text{int}}(\phi) \]

\[ V_{\text{int}} = e^{g\phi^2} - q_{\text{quad}}. \]
Doesn’t the data suggest $\Lambda$-CDM?

$5 \ln \left( \frac{d_L}{10 \text{pc}} \right)$

brightness

$\Lambda$CDM best fit

red shift

type IA supernova observations, Pantheon+ sample

$\ln(z)$
Many $[V(\phi), \Omega_m]$ combinations give very similar $a(t)$:

\[ \varphi(s) = \int_0^s ds_1 \sqrt{-\frac{2}{3} \frac{d\tilde{H}}{ds} - \frac{\Omega_m}{a^3}} \]

\[ V(s) = \frac{1}{3} \frac{d\tilde{H}}{ds} + \tilde{H}^2 - \frac{\Omega_m}{2a^3} \]

$\leftrightarrow V(\phi)$
Many \([V(\phi), \Omega M]\) combinations give very similar \(a(t)\):

\[
\varphi(s) = \int_0^s ds_1 \sqrt{-\frac{2}{3} \frac{dH}{ds_1} - \frac{\Omega M}{a^3}}
\]

\[
V(s) = \frac{1}{3} \frac{dH}{ds} + \frac{H^2}{2} - \frac{\Omega M}{2a^3}
\]

\(\rightsquigarrow V(\phi)\)

Not hard to come up w. potentials with AdS minima to realistic scale factor evolution.
$\Lambda$CDM model with Planck best fit params.

$\Omega_m = 0.315$

$H_0 = 67.4 \frac{\text{km}}{\text{s} \cdot \text{Mpc}}$

fits rather badly...

Hubble tension
Summary so far:

- $\Lambda < 0$ cosmologies suggest a possible holographic description via Euclidean 3D CFTs (will discuss).

AND

- if the 3D CFTs have relevant operators, generic solutions will have time-dependent scalars that can give realistic acceleration.
Interesting implications for observables...
- Observables in cosmology related via analytic continuation to observables in static wormhole geometry \(\rightarrow\) vacuum observables in weakly curved spacetime.

- "Initial" state for cosmology is at time symmetric slice. Naturalness questions should be asked here.

- Cosmological coincidence is naturally explained. \(\Lambda \sim \rho_m\)
How do we holographically describe the wormhole?

2 asymptotically AdS boundaries suggest pair of Euclidean CFTs.

- Connected Euclidean wormhole geometry suggests ensemble Maldacena, Maoz

- for flat cosmology, can perform another analytic continuation to traversable wormhole

\[ ds^2 = d\tau^2 + \cosh(\tau) d\tau d\tau^\mu \]

* holographic description of this should have CFTs interacting via auxiliary degrees of freedom*
Specific suggestion:

- Couple 2 CFTs by small N 4D CFT

RG flow → confining 3D theory in IR w. large entanglement/correlations between two 3D CFTs
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Higher dimensional picture: brane-antibrane physics.
Specific suggestion:

- Couple 2 CFTs by small $N$ 4D CFT
  RG flow $\rightarrow$ confining 3D theory in IR w. large entanglement/correlations between 3D CFTs.

Higher dimensional picture: brane-antibrane physics.
Puzzle: what is the effective field theory description of the Lovelzian wormhole? (Lin, Maldacena)

\[ ds^2 = d\tau^2 + a^2(\tau) d\mathbf{x}^\mu d\mathbf{x}^\nu \]

++ component of Einst. eq. at middle gives:

\[ T_{++} = -\frac{1}{4\pi G} \frac{a''}{a} \approx -\frac{1}{G L^2} \]

We need large negative null energy.
Is there a limit to the Casimir energy density in a QFT on a space with two boundaries?

* Holographic model suggests negative null energy for QFT on strip of fixed width can be made arbitrarily large by appropriate coupling to another QFT. May/Simidzija/MVR

→ Free 3+1 Dirac fermion can have arbitrarily large uniform energy density on a slab. Swingle/MVR.
Cosmology as an Island

EFT picture: slice path integral to define state of cosmology

(proposed) microscopic picture:

more precisely:

- sliced path integral defines state of 4D auxiliary CFT (not necessarily holographic)

C.f. Hartman, Jiang, Shagonian, Chen, Gorbenko, Maldacena
- $\Lambda < 0$ cosmologies suggest a possible holographic description via Euclidean 3D CFTs.

- If the 3D CFTs have relevant operators, generic solutions will have time-dependent scalars that can give realistic acceleration.

- Euclidean picture gives specific state for cosmology: observables from weakly curved EFT physics of wormhole.

- Ongoing work to understand possible microscopic constructions, perturbations.