Cosmology vs Equilibrium

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PPCC, IGC Penn State
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Outline

1) Intro

2) Toy model 1: (related to “Eternal Inflation) Atypical is typical (non-ergodic behavior)... strange relationship to $\infty$.

3) Toy model 2: (related to de Sitter Eqm cosmology) Typical is typical (ergodic model consistent with cosmology).

4) de Sitter Eqm cosmology

5) Concluding comments
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• The 2nd law tells us that the early universe was dynamically “unusual” (low entropy, past hypothesis)
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• Inflation is supposed to teach us that the early universe was dynamically “typical”
• Perhaps thanks to inflation ideas, may cosmologists expect to “explain” the “initial state”.
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See also Wald, Unruh, Gibbons, Turok, and others
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Assume something about initial state

Don’t assume something about initial state
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Dyson et al, AA & Sorbo
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ILLUSTRATION: The “failure” of ergodic/state counting (eqm) arguments
Eqm system with fluctuating entropy
Very rare fluctuation

Us in the Universe
Very rare fluctuation

Us in the Universe

The “past hypothesis”
Us in the Universe
Us in the Universe
Competing fluctuations

Us in the Universe
Competing fluctuations
Us in the Universe
Boltzmann Brains
No Past hypothesis
and why are we not up here, anyway?
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Options

- Assume something about initial state
  - Terminal vacua and initial states
  - Put arrow of time in equilibrium, explain AoT?
- Don’t assume something about initial state
If you can have this

See recent papers by Bousso (’11), Susskind (’12) (Harlow et al.)
Why not this?

Departures Terminal Vacua

Arrivals Terminal Vacua
Why not this?

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Arrivals Terminal Vacua

Arrivals terminal vacua can derail approach to attractors

See recent papers by Bousso ('11), Susskind ('12)

✿ Arrow of time assumed in initial state

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⟵ Arrow of time assumed in initial state
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 направленность времени предполагается в начальном состоянии (так что ненаркитурально?)
Why not this?

Departures Terminal Vacua

Arrivals Terminal Vacua

See recent papers by Bousso ('11), Susskind ('12) 🔄 But see later

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Consider the upside-down Harmonic Oscillator

\[ V(q) = -\frac{q^2}{2} \]
Phase space trajectories of Upside-down Harmonic Oscillator
At $t = 0$, $f_{s-} = 0.24$, $f_{s+} = 0.08$, and $P = 11$. 
$t = 0.5 \quad f_{s-} = 1.29 \quad f_{s+} = 0.06 \quad P = 11$
\[ t = 1 \quad f_{s^-} = 5.87 \quad f_{s^+} = 0.04 \quad P = 11 \]
$t = 1.5 \quad f_{s-} = 26.38 \quad f_{s+} = 0.02 \quad P = 11$
t = 1.8  \ f_{s-} = 64.89  \ f_{s+} = 0.02  \ P = 11
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t = 0.5 \quad f_{s^-} = 0.50 \quad f_{s^+} = 0.04 \quad P = 12
\[ t = 1 \quad f_{s^-} = 2.31 \quad f_{s^+} = 0.02 \quad P = 12 \]
\[ t = 1.5 \quad f_{s-} = 10.41 \quad f_{s+} = 0.01 \quad P = 12 \]
\[ t = 2 \quad f_{s-} = 0.01 \quad f_{s+} = 17.10 \quad P = 12 \]
$t = 2 \quad f_{s^-} = 0.01 \quad f_{s^+} = 17.10 \quad P = 12$
$t = 2.3 \quad f_{s-} = 0.02 \quad f_{s+} = 6.95 \quad P = 12$
I’ve put a barrier in the USHO to make a finite system
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$t = 3 \quad f_{s-} = 0.03 \quad f_{s+} = 0.84 \quad P = 12$
$t = 4 \quad f_{s-} = 0.09 \quad f_{s+} = 0.04 \quad P = 12$
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t = 4, \( f_{s^-} = 0.09 \), \( f_{s^+} = 0.04 \), \( P = 12 \)
At $t = 0$, $f_{s-} = 0.03$, $f_{s+} = 0.02$, and $P = 14$. 

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\text{t} = 1.2 \quad f_{s-} = 0.07 \quad f_{s+} = 0.01 \quad P = 14
$t = 1.4 \quad f_{s-} = 0.01 \quad f_{s+} = 1.15 \quad P = 14$
\( t = 2.5 \quad f_{s^-} = 0.01 \quad f_{s^+} = 0.01 \quad P = 14 \)
\( t = 5 \quad f_{s-} = 0.02 \quad f_{s+} = 0.04 \quad P = 14 \)
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$t = 48.08 \quad f_{s^-} = 0.01 \quad f_{s^+} = 0.01 \quad P = 14$
For finite case (no matter how large), most regions of phase space never get squeezed.
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The unbounded (infinite) case is not the limit of the large but infinite case.
USHO toy model for eternal inflation:
• Illustrates how a special part of phase space can be “typical”
• Non-ergoidc
• Very special role of $\infty$... phenomenon cannot be reproduced in an (arbitrarily large) finite system.
• For finite system, need bias on initial conditions.

(A. Hernley, AA, & T. Dray in prep.)
USHO toy model for eternal inflation:

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(de Sitter) Equilibrium cosmology:

- An eqm. system has no initial state $\rightarrow$ state of the universe fully dictated by the laws of physics
- Eqm state for cosmology realized by de Sitter space (realized by $\Lambda$ as for cosmic acceleration)
- But what about the past hypothesis, BB problem, etc?
(de Sitter) Equilibrium cosmology:
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Address this using toy model illustration
(de Sitter) Equilibrium cosmology:

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- But what about the past hypothesis, BB problem, etc?

See also Bousso, ‘11
Toy model 2a: State machine with “normal” behavior.

- Ergodic at micro level
- At macro (coarse grained) level, large fluctuations are less frequent than small ones (=> Boltzmann Brains, no “past hypothesis”)
Toy model 2b: State machine with cosmological behavior.

- The state space is larger than “micro”
- “Trans Micro” represents full fundamental theory
- Ergodicity only at Trans Micro level
- Micro is now itself a “coarse graining” of the fundamental Trans Micro states. Macro is a further coarse graining.
- *not* ergodic at Micro level (this is needed anyway for past hypothesis!)
- Correlation between Macrofluctuations and micro states is unchanged from model 2a
- At the Macro level, large fluctuation are more frequent than small ones. This due to specific relationship chosen between Micro and Trans Micro. A realistic theory that realizes this sort of relationship can be in equilibrium at the fundamental level and exhibit good cosmological properties (past hypothesis valid, no Boltzmann Brains). dSE is an example of this
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Implications of the de Sitter horizon

- Maximum entropy
  \[ S_\Lambda \propto A = H_\Lambda^2 = \left( \frac{\Lambda}{3} \right)^{-1} \]

- Gibbons-Hawking Temperature
  \[ T_{GH} = H_\Lambda = \sqrt{\frac{8\pi G}{3}} \rho_\Lambda \]

Gibbons & Hawking 1977
“De Sitter Space: The ultimate equilibrium for the universe?

\[ S \propto A = H^{-2} = \Lambda^{-1} \]

\[ T_{\text{ch}} = H_\Lambda = \sqrt{\frac{8\pi G}{3}} \rho_\Lambda \]
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- Only a finite volume ever observed

- If \( \Lambda \) is truly constant: Cosmology as fluctuating Eqm.

- Maximum entropy \( N = e^{S_\Lambda} \) \( \rightarrow \) finite Hilbert space of dimension

\[ \text{Banks & Fischler & Dyson et al.} \]
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- Maximum entropy leads to finite Hilbert space of dimension
  \[ N = e^{S_\Lambda} \]

Assembly whatever needed for successful cosmology...

“Bohr Atom”

Banks & Fischler & Dyson et al.
Equilibrium Cosmology
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An eqm. theory does not require any theory of initial conditions. The probability of appearing in a given state is given entirely by stat mech, and is thus “given by the dynamics”.

If you know the Hamiltonian you know how to assign probabilities to different states without any special theory of initial conditions.
Rare Fluctuation
Rare Fluctuation
Concept:

Realization:

“de Sitter Space”
Fluctuating from dSE to inflation:

• The process of an inflaton fluctuating from late time de Sitter to an inflating state is dominated by the “Guth-Farhi process”
• A “seed” is formed from the Gibbons-Hawking radiation that can then tunnel via the Guth-Farhi instanton.
• Rate is well approximated by the rate of seed formation:
  \[ \frac{m}{T_{GH}} = e^{\frac{m}{H_\Lambda}} \]
• Seed mass:
  \[ m_s = H(d_H)^3 \frac{\epsilon_{1000} \left( \frac{\Omega_{DM}^4}{\rho} \right)^{1/2}}{P} \]
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m_s = \frac{(15.6\text{GeV})^4}{\rho}
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• Seed mass:

\[
\frac{m_s}{H(H)}^3 = \left(\frac{\rho}{\rho_c}\right)^{\frac{3}{4}}
\]

Small seed can produce an entire universe ➔ Evade “Boltzmann Brain” problem
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- Rate is well approximated by the rate of seed formation:
  \[ \frac{m_i}{T_{GH}} \approx e^{\frac{m_i}{H_\Lambda}} \]
- Seed mass:
  \[ m_s \approx \sqrt[3]{\frac{10^{16} \text{GeV}^4}{\rho}} \]
degrees of freedom temporarily break off to form baby universe:

- Eqm.
- Seed Fluctuation
- Tunneling
- Evolution
- Evolution
- Evolution
- Recombination

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Implications of finite Hilbert space $N = e^{S_A}$

- Recurrences
- Eqm.
- Breakdown of continuum field theory
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Implications of finite Hilbert space \( N = e^{S_A} \)

- Recurrences
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- Breakdown of continuum field theory
A variety of inflation models, all saturating the dSE bound

Evolution of curvature radius

Curvature radius set by initial curvature $\Omega_k^B$

Holographic bound equivalent to Banks & Fischler
$$\log \left( \frac{L}{c H_0} \right)$$

$\log(a/a_0)$

AA: arXiv:1104.3315
dSE Cosmology and cosmic curvature

• The Guth-Farhi process starts inflation with an initial curvature set by the curvature of the Guth-Farhi bubble $\Omega^B_k$

• Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation

$$\Omega_k = \frac{1}{g^2} \frac{\Omega^B_k}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1\right)}$$

where

$$g\left(\frac{\rho_m^0}{\rho_\Lambda}, \frac{\rho_k^0}{\rho_\Lambda}\right) \equiv \int_0^\infty \frac{dx}{x^2 \sqrt{x^3 - 3\frac{\rho_m^0}{\rho_\Lambda} + x^{-2} \frac{\rho_k^0}{\rho_\Lambda} + 1}}$$
Predicted $\Omega_k$ from dSE cosmology is:
- Independent of almost all details of the cosmology
- Just consistent with current observations
- Will easily be detected by future observations
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Work in progress on expected values of $\Omega_k^B$ (Andrew Ulvestad & AA)
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• Perhaps unnecessary (or impossible): But then SBB plus correct initial conditions is a complete theory.
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  o No Boltzmann brain problem (solved by inflation).
Dynamical explanations of initial state of standard big bang (SBB):

- Perhaps unnecessary (or impossible): But then SBB plus correct initial conditions is a complete theory.
- Eternal inflation, as represented here by upside-down SHO:
  - Deeply dependent on $\infty$, picture cannot be reproduced in an (arbitrarily large) finite system.
- de Sitter Eqm. cosmology, represented here by the state machine.
  - Eqm. $\rightarrow$ no initial state!
  - Ergodicity is fine!
  - No Boltzmann brain problem (solved by inflation).