Abstract: The discovery of cosmic acceleration has generated tremendous excitement among researchers in fundamental physics and cosmology. Most experts agree that nothing short of a revolution will be required to fully integrate the observed cosmic acceleration (which many attribute to a mysterious "dark energy") with established physics. Currently this discovery is driving very exciting research in both the theoretical and observational domain. I will present two of these topics that particularly interest me: 1) Dark Energy and Cosmic Equilibrium: How a cosmological constant could make the universe look like a box of gas (and what this could mean for cosmology). 2) Probes of Dark Energy: A host of new probes promise to tell us more about dark energy, but what do we really want to know?
Fun With Dark Energy

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Outline

Intro

Part I
   Cosmic equilibrium
   Equilibrium & Cosmology
   Boltzmann’s Brain

Part II Probing “Dark Energy”
Introduction
Evidence for cosmic acceleration

The diagram illustrates the evidence for cosmic acceleration, with the axes labeled as $\Omega_\Lambda$ and $\Omega_M$. The preferred region is marked by the blue arrow, indicating the amount of accelerating matter. The red arrow points to the supernova observations, which support the idea of cosmic acceleration. The dark red line represents the preferred by modern data, which is consistent with the observations of supernovae and other cosmological data.

The diagram also shows different regions representing different cosmological scenarios, such as no Big Bang, clusters, and CMB expansions. The open and closed models are indicated, with the former suggesting an expanding universe and the latter a recollapsing universe.
Mass-Energy of the a Universe made only matter we know form the lab ("standard model matter")

Need to add dark matter here

Preferred by modern data

Need to add "dark energy" here

Amount of accelerating matter

(Dark Energy)

Amount of gravitating matter

Red line: No accelerating matter
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.
Dark Matter:

- Plausible Candidates in modern particle theories

Dark Energy:

- Many theories, NONE are compelling
Dark Matter:

- Plausible Candidates in modern particle theories

Dark Energy:

- Many theories, NONE are compelling

Ego test: Number of people who are not authors on their favorite explanation of acceleration $\sim 0$
The Numbers

\[ \rho_{DE} \approx 10^{-120} M_P^4 \approx (10^{-3} \text{ eV})^4 \]

or

\[ \rho_{DE} \approx M^2 \phi^2 \approx M^2 M_P^2 \quad \Rightarrow \quad M \approx 10^{-32} \text{ eV} \]
Great unsolved problem in physics:
Why is $\rho_\Lambda \leq 10^{-120} \rho_\Lambda^{QFT}$

$\rho_\Lambda^{QFT} \approx 10^{120} \rho_\Lambda$

$\Lambda \equiv 0$?
Issues

1) Where do these strange numbers come from?
2) How are they protected from quantum corrections?
3) How do unresolved quantum vacuum/quantum gravity problems impact your explanation.
4) Why Now?
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Most experts expect nothing short of a revolution in our understanding of fundamental physics is required to really understand the cosmic acceleration.
Issues

1) Where do these strange numbers come from?
2) How are they protected from quantum corrections?
3) How do unresolved quantum vacuum/quantum your explanation
4) Why Now?

Most experts expect nothing short of a revolution in our understanding of fundamental physics is required to really understand the cosmic acceleration

Not there yet, but we’re having a lot of fun
4) Why Now?

Most experts expect nothing short of a revolution in our understanding of fundamental physics is required to really understand the cosmic acceleration.
Part I

Some implications for physics and cosmology
Cosmic equilibrium
An interesting property of some types of dark energy (including a \( w = -1 \) cosmological constant): Formation of an event horizon:

Black Hole Event Horizon (schematic):

Outside observer sees in-falling object take infinite time to reach the horizon ("never reaches the horizon")
Cosmic equilibrium
An interesting property of some types of dark energy (including a $w=-1$ cosmological constant): Formation of an event horizon:

**Black Hole Event Horizon (schematic):**

Outside observer sees in-falling object take infinite time to reach the horizon ("never reaches the horizon")
An interesting property of some types of dark energy (including the cosmological constant): Formation of an event horizon:

Dark Energy Event Horizon (schematic):

INSIDE observer sees OUT-flying object take infinite time to reach the horizon ("never reaches the horizon")

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

"de Sitter Space"
"De Sitter Space: The ultimate equilibrium for the universe?"

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

Quantum effects: Hawking Temperature

\[ T = H = \sqrt{\frac{8\pi G}{3}} \rho_{DE} \approx 10^{-28} K \]

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

One consequence: If \[ S_{\text{deS}} = S_{\text{MAX}} \geq S = \ln N \]

Should \( N \) be finite? Does this mean we must abandon all known fundamental theories? 

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

Quantum effects: Hawking Temperature

\[ T = H = \sqrt{\frac{8\pi G}{3}} \rho_{DE} \approx 10^{-28} K \]
Equilibrium & Cosmology
Darwinian Cosmology

Two approaches to the state of the universe (initial conditions for the observed FRW universe)

1. State what the initial condition “must be” (play god)

2. Darwinian: Let all possible states compete. Most probable = your prediction
"De Sitter Space: The ultimate equilibrium for the universe?"

One consequence: If 

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Quantum effects: Hawking Temperature

\[ T = H = \sqrt{\frac{8\pi G}{3}} \rho_{\text{DE}} \approx 10^{-28} \, K \]

Banks & Fischler

Gibbons & Hawking
Equilibrium & Cosmology
Equilibrium & Cosmology
Darwinian Cosmology

Two approaches to the state of the universe (initial conditions for the observed FRW universe)

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Darwinian Cosmology

Two approaches to the state of the universe (initial conditions for the observed FRW universe)

1. State what the initial condition “must be” (play god)

2. Darwinian: Let all possible states be assigned probabilities. Most probable = your prediction. Needs a scheme for assigning probabilities (back to 1)?
Darwinian Cosmology

Two approaches to the state of the universe (initial conditions for the observed FRW universe)

1. State what the initial condition “must be” (play god)

2. Darwinian: Let all possible states be equally probable
   Most probable = your prediction

Only way out: In Eqm, nature tells you how to assign probabilities.

Needs a scheme for assigning probabilities (back to 1)?
Problems with 1.
(State what the initial conditions “must be”)
Problems with 1.
(State what the initial
the universe
you)
Problems with 1.
(State what the initial
the universe
Is the universe listening?
you)
de Sitter equilibrium gives the one chance I know to use eqm as a basis for cosmology
"Equilibrium Cosmology"

Rare Fluctuation
"Equilibrium Cosmology"

Rare Fluctuation

The only way to let physics teach you about "initial" conditions
Concept:

Realization:

"de Sitter Space"
Boltzmann’s Brain
Boltzmann’s Brain paradox:

- The most likely fluctuation consistent with everything you know is your world (actually just your brain) fluctuating out of chaos and immediately re-equilibrating.

- Only inflation has an answer to this paradox. With inflation, most probable way to create one brain (or planet) comes packaged with a huge flat universe (+body, fellow creatures etc)

- This is as least as important as the other successes of inflation!
But
Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
- Inflation much more likely than the whole universe “fluctuating directly”
- Solve “Boltzmann’s Brain” problem and have predictive power in cosmology

Version 2

- Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) fluctuating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann’s brain problem not resolved)
Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
- Inflation much more likely than the whole universe “fluctuating directly”
- Solve “Boltzmann’s Brain” problem and have predictive power in cosmology

Version 2

- Initial fluctuations that start inflation are much more “expensive” than universe (or fluctuation) directly bang
  - It is LESS likely than other junk
  - Boltzmann’s brain problem not resolved

Ruled Out
Two versions of the story

Version 1

• Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
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• Solve “Boltzmann’s Brain” problem and have predictive power in cosmology

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• Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) fluctuating directly.
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Version 1

• Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.

• Inflation much more likely than the whole universe “fluctuating directly”

• Solve “Boltzmann’s Brain” problem and have predictive power in

AA & Sorbo

Version 2

• Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) fluctuating directly.

• AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann’s brain problem not resolved)

Dyson Kleban & Susskind
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Dyson Kleban & Susskind
\[ A_n \to A_{n-\sqrt{A_nA_n}} \]
\[ e^{-S_p} \]

\[ S \rightarrow A_n \rightarrow A_{n+1} - \sqrt{A_n A_{n+1}} \]

\[ S_n \rightarrow S_{n+1} - \sqrt{S_n S_{n+1}} \]
$s_p \rightarrow s_{p'}$  

$A \rightarrow A' - \sqrt{A.A'}$  

$s_{p'} \rightarrow s_{p''} - \sqrt{s.p \cdot s.p}$
\[ S_p \rightarrow S_p \]

\[ A \rightarrow A_\wedge = \sqrt{A A_\wedge} \]

\[ S_{\wedge} \rightarrow S_{\wedge} = \sqrt{S_{\wedge} S_p} \]

\[ P_p = \frac{s_p \cdot s_p}{e_s e_s} \]
\[ P_p = \frac{e_s}{e_s} \]

\[ A_\lambda \rightarrow A_\lambda - \sqrt{A_\lambda A_\lambda} \]

\[ S_\Omega \rightarrow S_\Omega - \sqrt{S_\Omega S_\Omega} \]

\[ \frac{e_s}{e_s} = \frac{e_s}{e_s} = -\frac{e_s}{e_s} = -e \]
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Dyson Kleban & Susskind
\[ P_\sigma = \frac{e^{S_\sigma}}{e^{S_{\sigma}}} = \frac{e^{S_\sigma}}{e^{S_{\sigma}}} = -e \]
\[ \text{OKE: } S_{\text{uni}}(\text{inflation}) = A_1 \approx 10^{10} \]
OKS: \[ S_{\text{Uni.}}(\text{inflation}) = A_I \sim 10^{10} \]

\[ p_I \sim e^{10^{10}} \]

\[ p_{\text{BB}} \sim e \]
Oks, $S_{\text{univ}}(\text{inflation}) = c A_{\gamma} \approx 10^{10}$

$p_{\gamma} \sim e^{-10^{10}}$

$p_{\text{B}} \sim e^{-85} \gg p_{\gamma}$
Two versions of the story

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AA & Sorbo

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Dyson Kleban & Susskind
Discuss calculations at blackboard here
Version 1

Inflation requires only a small fluctuation “out of the bath” to get started. It is much easier to start inflation than start the whole big bang directly.

Version 2

Because of the horizon (similar to the de Sitter horizon) during inflation, there is no “bath”. The entropy of the entire universe must reduce down to $10^{10}$ to start inflation. Much more expensive than going directly to the big bang with entropy of $10^{85}$. 
\[ A \rightarrow A_\alpha - \sqrt{A_A} \]

\[ S_\alpha \rightarrow S_{1\alpha} - \sqrt{S_\alpha S_{1\alpha}} \]

\[ P_\alpha = e^{S_\alpha} = e^{S_{1\alpha} - \sqrt{S_\alpha S_{1\alpha}}} - e^{\frac{-\sqrt{S_\alpha S_{1\alpha}}}{10^{12}}} \]

\[ P_\alpha \sim e^{10^{12}} \]

\[ P_{\text{ee}} \sim e^{-\delta} \]

\[ P_{\text{ee}} \gg P_1 \]
\[ P_{\text{p}} = \frac{e^S}{e^S} - \frac{e^S}{e^S} - e^{-\sqrt{S}} \Rightarrow P_z = e^{\frac{\sqrt{S}}{2}} \]

\[ \text{OKS: } S_{\text{inf}}(\text{inflation}) = m^2 A_z = 10^{10} \]

\[ P_e \sim e^{10^{10}} \]

\[ P_{\text{sub}} \sim e^{85} \Rightarrow P \]
Version 1

Inflation requires only a small fluctuation “out of the bath” to get started.

It is much easier to start inflation than start the whole big bang directly.

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Important:

If the entire universe has an entropy of $10^{10}$ during inflation, the problems with version 2 are NOT resolved by

1) Eternal Inflation

2) String theory landscape
Important:

If the entire universe has an entropy of $10^{10}$ during inflation, the problems with version 2 are NOT resolved by

1) Eternal Inflation

2) String theory landscape
Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
- Inflation much more likely than the whole universe “fluctuating directly”.
- Solve “Brain” problem by making predictive power come from higher levels.

Version 2

- Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) fluctuating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann’s brain problem not resolved)

Hertog & Horowitz

Blau Farhi Guth Guendelman Gueven

Fischler Morgan & Polchinski

Dyson Kleban & Susskind

Banks

AA & Sorbo
Important:

If the entire universe has an entropy of $10^{10}$ during inflation, the problems with version 2 are NOT resolved by

1) Eternal Inflation

2) String theory landscape
Two versions of the story

**Version 1**

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
- Inflation much more likely than the whole universe “fluctuating directly”.
- Solve “Bell–Kibble Brain” problem and make predictive predictions.

**Version 2**

- Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) fluctuating directly.
- AND standard big bang as we know it is LESS LIKELY than other junk (Boltzmann’s brain problem not resolved)

**Contributors**

- Hertog & Horowitz
- Blau Farhi Guth Guendelman Gueven
- AA & Sorbo
- Fischler Morgan & Polchinski
- Dyson Kleban & Susskind
- Banks
Two versions of the story

Version 1

- Initial fluctuations that start inflation are a small perturbation on Eqm and are thus “cheap”.
- Inflation much more likely than current universe (or a brain) existing directly.
- Solve “Brain” problem, predictive power.

Version 2

- Initial fluctuations that start inflation are much more “expensive” the universe (or a brain) existing directly.
- Inflation much more likely than current universe (or a brain) existing directly.
- Solve “Brain” problem, predictive power.

Hertog &

Aguirre and Johnson Dec 05

Guendelman
Gueven

AA & Sorbo

Dyson Kleban
& Susskind

Fischler Morgan
& Polchinski

Banks
Conclusions of Part I

Taking a fundamental cosmological constant seriously:

- suggests radical changes to how we do fundamental physics and cosmology

- could form the basis for “equilibrium cosmology”. A much stronger way of doing cosmology than “stating the state of the Universe”.

- The depending on (deep) unresolved questions from quantum gravity, the eqm cosmology either puts the status quo on stronger footing or sends us back to the drawing board.
Part II

Probing “Dark Energy”
**Dark Energy Task Force**

Full report to appear soon

Key points already released (slides available):

- Quantitative figure of merit chosen
- "order of magnitude" progress only possibly through combinations of different data
- Major projects (i.e., Joint Dark Energy Mission or LST) required to achieve order of magnitude progress (mid-term projects critical to major projects).

- Combining "dark energy" data leads to extremely tight constraints on cosmological parameters such as $H_0, \Omega_k, \Omega_m$
Conclusions

- Science Magazine #1 question in science!
- A revolution is needed to understand the cosmic acceleration
- Already driving very exciting ideas in physics and cosmology
- A whole new level of high-impact data is within reach