Origin of probabilities and their application to the multiverse

Andreas Albrecht
UC Davis

2015: THE SPACETIME ODYSSEY CONTINUES
Stockholm
June 4, 2015

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AA & D. Phillips (PRD Dec 2014)
Thank you Katie!!!
Origin of probabilities and their application to the multiverse

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AA & D. Phillips (PRD Dec 2014)
Cosmic Inflation:

Consumers & Producers

The multiverse of eternal inflation with multiple classical rolling directions

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)
Cosmic Inflation:

Consumers & Producers

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(Blue Monster by Simon Richards)
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Eternal Inflation

The multiverse of eternal inflation with multiple classical rolling directions

Classically Rolling A

Classically Rolling B

Classically Rolling C

Classically Rolling D

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc.)

(Blue Monster by Simon Richards)
My history with this topic

AA: All randomness/probabilities are quantum (coin flip, card choice etc)
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AA: All randomness/probabilities are quantum (coin flip, card choice etc). Hartle, Srednicki, Aguirre, Tegmark, ...
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A potential issue even for finite models
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Perhaps this type of discipline can help resolve the measure problems of the multiverse/eternal inflation
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Apparently this type of discipline can help resolve the measure problems of the multiverse/eternal inflation
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
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NB: Very different subject from “make probabilities precise” in “Stanford sense”.
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

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4) Implications for multiverse/eternal inflation
Planck Data
--- Cosmic Inflation theory
Slow rolling of inflaton

Observable physics generated here
Slow rolling of inflaton

Observable physics generated here

Extrapolating back
Slow rolling of inflaton

“Self-reproducing regime”
(dominated by quantum fluctuations): Eternal inflation/Multiverse

Observable physics generated here

Extrapolating back

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others
Slow rolling of inflaton

“Self-reproducing regime” (dominated by quantum fluctuations): Eternal inflation/Multiverse

Observable physics generated here

Alternatively, perhaps something (such as holography) cuts off this extrapolation

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others
Slow rolling of inflaton

"Self-reproducing regime" (dominated by quantum fluctuations): Eternal inflation/Multiverse

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The multiverse of eternal inflation with multiple classical rolling directions

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)
The multiverse of eternal inflation with multiple classical rolling directions

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“Where are we?” ➔ Expect the theory to give you a probability distribution in this space... hopefully with some sharp predictions
The multiverse of eternal inflation with multiple classical rolling directions

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“Anything that can happen will happen infinitely many times” (A. Guth)

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String theory landscape even more complicated (e.g. many types of eternal inflation).

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“Anything that can happen will happen infinitely many times” (A. Guth)
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

\[ U = A \otimes B \]

\[ A : \{ |1^A\rangle, |2^A\rangle \} \quad B : \{ |1^B\rangle, |2^B\rangle \} \]

\[ U : \{ |11\rangle, |12\rangle, |21\rangle, |22\rangle \} \]

\[ |ij\rangle \equiv |i^A\rangle |j^B\rangle \]

Page, 2009; These slides follow AA & Phillips 2014
Quantum vs Non-Quantum probabilities

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\[ U : \{ |11, 12, 21, 22 \} \quad |ij \rangle \equiv |i^A \rangle |j^B \rangle \]

Possible Measurements \( \leftrightarrow \) Projection operators:

Measure A only: \[ \hat{P}_i^A = \left( |i^A \rangle A \langle i | \right) \otimes 1^B = \left[ |i1 \rangle \langle i1 | + |i2 \rangle \langle i2 | \right] \]

Measure B only: \[ \hat{P}_i^B = \left( |i^B \rangle B \langle i | \right) \otimes 1^A = \left[ |1i \rangle \langle 1i | + |2i \rangle \langle 2i | \right] \]

Measure entire \( U \): \[ \hat{P}_{ij} = |ij \rangle \langle ij | \]
Quantum vs Non-Quantum probabilities

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Possible Measurements \(\leftrightarrow\) Projection operators:

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Measure entire \(U\):
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\hat{P}_{ij} = |ij\rangle\langle ij|
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BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

\[ U = A \otimes B \]

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Measure A only: \[ \hat{P}_i^A = (|i\rangle^A \langle i|) \otimes 1^B = [|i1\rangle\langle i1| + |i2\rangle\langle i2|] \]

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Could Write

\[ \hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B \]

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Albrecht @ Stockholm 6/4/15
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Quantum vs Non-Quantum probabilities

\[ \hat{P}_i = p_A \hat{P}^A_i + p_B \hat{P}^B_i \]

\[ \hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j \]

\[ \hat{P}^A_i = (|i\rangle^A \langle i|) \otimes 1^B = [|i1\rangle\langle i1| + |i2\rangle\langle i2|] \]

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Measure entire \( U \): \[ \hat{P}_{ij} = |ij\rangle\langle ij| \]

Non-Quantum probabilities in a toy model:

\[ U_A \otimes U_B \]

Possible Measurements ⇔ Projection operators:

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Albrecht @ Stockholm 6/4/15
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Could Write

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Classical Probabilities to measure A, B

Page: The multiverse requires this (are you in pocket universe A or B?)

Does not represent a quantum measurement

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Albrecht @ Stockholm 6/4/15
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Possible Measurements ↔

\[ \hat{P}_i^A = (|i\rangle^A) \]
\[ \hat{P}_i^B = (|i\rangle^B) \]

\[ \hat{P}_{ij} = |ij\rangle \langle ij| \]

Does not represent a quantum measurement

Measure entire \( U \):

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Non-Quantum probabilities in a toy model:

\[ U_A B \]

\{ 1, 2 \}

\{ 1, 2 \}

\{ 11, 12, 21, 22 \}

\( U \)

\( A \)

\( B \)

\( \| j \rangle^B \)

Classical Probabilities to measure \( A, B \)

Page: The multiverse requires this (are you in pocket universe A or B?)

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• All everyday probabilities are quantum probabilities
• All everyday probabilities are quantum probabilities

Our *only* experiences with successful practical applications of probabilities are with quantum probabilities
• All everyday probabilities are quantum probabilities

• One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin
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AA & D. Phillips 2014
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

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Possible Measurements

Measures \( A \) only:

Measures \( B \) only:

Measures entire \( U \):

Could Write

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Classical Probabilities to measure A, B

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Does not represent a quantum measurement.
Quantum vs Non-Quantum probabilities

$U = A \otimes B$

Non-Quantum probabilities in a toy model:

$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$

Can write

$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$

Possible Measurements $\leftrightarrow$ Probabilities

Measure entire $U$: $\hat{P}_{ij} = |ij\rangle \langle ij|$
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

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Outline

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Quantum effects in a billiard gas
Quantum effects in a billiard gas

Quantum Uncertainties
Quantum effects in a billiard gas

\[ \Delta b = \delta x \perp + \frac{\delta p \perp}{m} \Delta t \]
Quantum effects in a billiard gas

\[ \Delta b = \delta x_\perp + \frac{\delta p_\perp}{m} \Delta t = \sqrt{2} \left( a + \frac{\hbar}{2a} \frac{l}{m\bar{v}} \right) \]

\[ \psi \propto \exp \left( \frac{-x^2}{2a^2} \right) \]
Quantum effects in a billiard gas

\[ \Delta b = \delta x_\perp + \frac{\delta p_\perp}{m} \Delta t = \sqrt{2} \left( a + \frac{\hbar}{2a} \frac{l}{m\overline{v}} \right) \]

\[ \psi \propto \exp \left( \frac{-x^2}{2a^2} \right) \]

\[ \min \rightarrow 2^{3/2} \left( \frac{\hbar l}{2m\overline{v}} \right) \equiv \sqrt{\frac{l}{\hbar dB}} / 2 \]
Quantum effects in a billiard gas

\[ \Delta b = \delta x_1 \]

Minimizing \( \Rightarrow \) conservative estimates for my purposes (also motivated by decoherence in some cases)
Quantum effects in a billiard gas

Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)
Quantum effects in a billiard gas

After $n$ collisions:

\[ \Delta b_n = \Delta b \left(1 + \frac{2l}{r}\right)^n \]
Quantum effects in a billiard gas

\( n_Q \) is the number of collisions so that

\[
\Delta b_{n_Q} = r
\]

(full quantum uncertainty as to which is the next collision)

\[
n_Q = - \frac{\log \left( \frac{\Delta b}{r} \right)}{\log \left( 1 + \frac{2l}{r} \right)}
\]
\( n_Q \) for a number of physical systems

(All units MKS)

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**$n_Q$ for a number of physical systems**

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</tr>
<tr>
<td>Billiards</td>
<td>0.029</td>
<td>1</td>
<td>0.16</td>
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<td>$6.6 \times 10^{-34}$</td>
<td>5.4</td>
</tr>
<tr>
<td>Bumper Car</td>
<td>1</td>
<td>2</td>
<td>150</td>
<td>0.5</td>
<td>$1.4 \times 10^{-36}$</td>
<td>3.6</td>
</tr>
</tbody>
</table>
$n_Q$ for a number of physical systems

(all units MKS)

<table>
<thead>
<tr>
<th></th>
<th>$r$</th>
<th>$l$</th>
<th>$m$</th>
<th>$\bar{v}$</th>
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Quantum at every collision

$(n_Q < 1 \rightarrow$ breakdown of formula, but conclusion robust)
For a number of physical systems

<table>
<thead>
<tr>
<th></th>
<th>( r )</th>
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<tr>
<td>Billiards</td>
<td>( 8.4 \times 10^{-7} )</td>
<td>( 3 \times 10^{-26} )</td>
<td>( 2 \times 10^{-25} )</td>
<td>75</td>
<td>( 6.6 \times 10^{-34} )</td>
<td>( 5.1 \times 10^{-32} )</td>
<td>(0.5)</td>
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<tr>
<td>Bumper Car</td>
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<td>( 1.5 \times 10^{-34} )</td>
<td>( 1.5 \times 10^{-35} )</td>
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(all units MKS)

Quantum at every collision

Every Brownian Motion is a “Schrödinger Cat”
\( n_Q \) for a number of physical systems

(all units MKS)

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Quantum at every collision

Every Brownian Motion is a “Schrödinger Cat” (independent of “interpretation”)
$n_Q$ for a number of physical systems

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This result is at the root of our claim that all everyday probabilities are quantum.

Every Brownian Motion is a “Schrödinger Cat”

Quantum at every collision
An important role for Brownian motion: Uncertainty in neuron transmission times

Brownian motion of polypeptides determines exactly how many of them are blocking ion channels in neurons at any given time. This is believed to be the dominant source of neuron transmission time uncertainties $\delta t_n \approx 1ms$.
Analysis of coin flip

\[
\delta t_f = \delta t_n \times \left( \frac{v_h}{v_h + v_f} \right)
\]

\[
\delta t_t = \sqrt{2}\delta t_f
\]

\[
f = \frac{4v_f}{\pi d}
\]

\[
\delta N = f\delta t_t = 0.5
\]

Using:

\[
\delta t_n \approx 1\text{ms} \quad v_h = v_f = 5\text{m/s}
\]

\[
d = 0.01\text{m}
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Analysis of coin flip

\[ \Delta t_f = \Delta t_n \times \left( \frac{v_h}{v_h + v_f} \right) \]

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50-50 coin flip probabilities are a derivable quantum result
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50-50 coin flip probabilities are a derivable quantum result

Using: Without reference to “principle of indifference” etc. etc.
Analysis of coin flip

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NB: Coin flip is “at the margin” of deterministic vs random: Increasing \(d\) or deceasing \(v_h\) can reduce \(\delta N\) substantially.
Analysis of coin flip

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Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.
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Using:

Coin diameter \( = d \)

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Physical probabilities vs “probabilities of belief”

Bayes:

\[
P(\text{Theory} \mid \text{Data}) = \frac{P(\text{Data} \mid \text{Theory})}{P(\text{Data})} P(\text{Theory})
\]

Physical probability: To do with physical properties of detector etc
Physical probabilities vs “probabilities of belief”

Bayes:

$$P(\text{Theory} \mid \text{Data}) = \frac{P(\text{Data} \mid \text{Theory})}{P(\text{Data})} P(\text{Theory})$$

Probabilities of belief:
• Which data you trust most
• Which theory you like best
Physical probabilities vs “probabilities of belief”

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Physical probabilities vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

\[
P_4(T \mid D_4) = \frac{P(D_4 \mid T)}{P(D_4)} P_3(T)
\]

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Physical probabilities vs “probabilities of belief”

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All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
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• Which theories really do require classical probabilities not yet resolved rigorously (symmetry?... simplicity? See below)

Some further thoughts:
Some further thoughts:

- Special relationship to cosmic structure from inflation: “probability censorship”
- A counterexample: Betting on the digits of Pi (Not!)
- Compare with classical computer
- Compare with color:
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
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1) Quantum vs non-quantum probabilities (toy model/multiverse)
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Central message:

• “Randomness is (quantum) physics”
• Counting may or MAY NOT have a role in inferring or representing physical randomness
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Central message:

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Counts of red & green balls here can be related in very concrete terms to the probability of heads vs tails.
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?
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NB: “Sleeping Beauty problem”
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In a multiverse with many copies of you, there simply is *no* physical completion for the question “which observer am I?”. Future data may address this, but not in time to make predictions.
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This is where things go wrong in the standard treatment of the multiverse.

In many cases counting observers has no predictive value.

No point in counting for these cases.
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

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Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

Pocket $A$ with $p_A$

Pocket $B$ with $p_B$
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

Pocket $A$ with $p_A$ (from quantum branching ratio)

Pocket $B$ with $p_B$
One semiclassical universe having many more possible observers in it than another (often counted by volume), does *not* give that universe greater statistical weight. Quantum branching ratio into one vs the other ($p_A / p_B$) \textbf{does} count.
Implications for eternal inflation

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Implications for eternal inflation

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This model has no “Boltzmann Brain” problem as long as $p_A / p_B$ is not too small

Pocket A with $p_A$

Pocket B with $p_B$
Implications for eternal inflation

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This model has no "Boltzmann Brain" problem as long as $\frac{p_A}{p_B}$ is not too small

Pocket A with $p_A$

Pocket B with $p_B$

Boltzmann brains are observers which look good vs current data but which quickly go bad
Implications for eternal inflation

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More pocket universes produced later vs earlier (due to more inflation)
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
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More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff

Time cutoff regulator
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See also Guth & Vanchurin
Implications for eternal inflation

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2) Boltzmann Brain problem reduced
3) No “younghness/end of time” problem

More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff

- Wavefunction cannot give probabilities for which pocket you are in.
- Time cutoff only there as (wrong) attempt to determine which pocket
- The younghness/end of time problem is asking a question the theory cannot answer
Conclusions

1) All practically applicable probabilities are of physics (quantum) origin.
2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities.
3) Standard discussions of probabilities in cosmology often make errors re 2).
4) 1) and care about 2) allow us to introduce better discipline into cosmological discussions (just say “no”). Implications so far:
   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time problem
   d) Measure problems apparently resolved?
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Conclusions

⇒ I still have other concerns about eternal inflation that makes me prefer finite theories,
⇒ but this “probability discipline” may resolve what I used to think was the most troubling issue.

⇒ Perhaps related to work by Nomura and Garriga & Vilenkin and collaborators.

⇒ In a systematic treatment the classical probabilities will reappear as “priors”. Same math but very different role.

Landscape OK too
1) All practically applicable probabilities are of physics (quantum) origin.

2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities.

3) Standard discussions of probabilities in cosmology often make errors re 2) and care about 2) allow us to introduce better discipline into cosmological discussions (just say “no”).

Implications so far:

a) No (counting based) volume factors
b) Reduced Boltzmann Brain problem
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d) Measure problems apparently resolved? (perhaps)

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Conclusions

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→ I still have other concerns about eternal inflation that makes me prefer finite theories,
→ but this “probability discipline” may resolve what I used to think was the most troubling issue.

Landscape OK too

Clashes with my work on the “clock ambiguity”

Perhaps related to work by Nomura and Garriga & Vilenkin and collaborators.
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Additional Slides
Cosmic structure

Cosmic structure originates “superhorizon” in Standard Big Bag (why would they be quantum?)

Here

\[ \frac{\delta \rho}{\rho} \]

\[ \log(a/a_0) \]

\[ \log(R_H/R_{H0}) \]

Cosmic length scale

Scale factor (measures expansion, time)

A note on “probability censorship”
Cosmic structure originates in quantum ground state in inflationary cosmology.

Cosmic structure "superhorizon" in Standard Big Bag (why would they be quantum?)

Scale factor (measures expansion, time)
Proof by exhaustion not realistic
One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
Can still invent classical probabilities just to do multiverse cosmology
Not a problem for many finite theories (AA, Banks & Fischler)
Which theories really do require classical probabilities not yet resolved rigorously (symmetry?.. simplicity? See Cooperman 2011)

All everyday probabilities are quantum probabilities

Compare with identical particle statistics
Further discussion

Bet on the millionth digit of $\pi$

3.14159265358979323846264338327950288419716939937510582097494459230781640628620899862803482534211706798214808651328230664709384460955058223172535940812848111745028410270193852110555964466229489549303819644288109756659334461284756482337867831652712019091456485669234603486104543266482133936072602491141273724587006606315588174881520920962829254091715364367892590360011330530548820466521384146951941511609433005727036575959195309218611738193261179310511185480744623799627245673518857527248912279381803119491298336733624065664308602139494639522473719070217986094370277059392171762931765238467481846766940513200056812714152635608278757134275778960917363717872146844090122495343014654958537105079227968925892354201995611121290219608640344181598136297747713099605187072113499999983729780499510597317328160963185950244594553469083026425223082533446850385261931188171010003137838752886586575332083814206171776691473035982534904287554687311595626838823537875937519577818577805323171226806613001927876611195909216420198938095257201605485863278865936153381827968230301952035301852968995773622599413891249721775283479131515574857242454150695950829533116861727855889075098381754637466993931925506040092770167113900984882401285836160356370767601047101819429559619894676783744494482553797747268471040475346462608046684259069491293313677028989152104752162059660240580381501935112533824300355876402474964732639141192727604269922796782354781636009341721641219924586315030328618297455570674983850549458858692969956909272107975093029553211653449872027559602364806654991198818347977535663698074265252786255181841757467289097772793800081647060016145249192173217214772350141441973568548161361573525521334757418494684838523232907394143334547762416862518983569485562099219222184272550254256887671790494601653466804988627232791786085784383279679766814541009538837836095060680462251252051173929849860841284886269456042419652850222106611863067442786220391949450471237137876960956364371917287467764657573962413890865832645995813390478027590099465764078951269468398352595709825822620522489407726719478268482601476990902640136394437455305068203496

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Further discussion

Bet on the millionth digit of $\pi$

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3.141592653589793238462643383279502884197169399375105820974944592307816406286
208998628034825342117067982148086513282306647093844609550582231725359408128481
11745028410270193852110559644622948954930381964428810975665933446128475648233
786783165271201909145648566923460348610454326648213393607260249141273724587006
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9519411560943305720365675959195309218611738193261117931051118548074462379962749
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70217986094370277059321717629317652384674818467669405132000568127145263560827
875771342757789609173637178271468440901224953430146549585371050792279689258923
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283479131515574857242454150659595082953311686172785588907509838175463746939319
2550604009277016717139009848824012858361603563707660147071018194295596198946767
837449448255379774726847104047534646208046684259069491293313677028989151204752
162056966024058083185019351125338230035857640247496473263914199272604269922796
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69092721079750930295532116534498720275596023648066549919881834797753566369807
4265425278625625181841757467282090777279380081647060016145249192173217214772350
14144197356854816136115735255213347574184946848385232323907394143334547762416862
518983569485562099212221848272550254256887617790494601653466804988627232791786
0857843832796797668145410095388378360950680064225125205117392984896084128488
6269456042419652850222106611863067442786220391949450471237137876960956364371917
2874677646575739624138908658326459958133904780275909994657640789512694683938352
595709825822620522489407726719478268482601476990902640136394437455305068203496
Further discussion

Bet on the millionth digit of π

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- Fairness is about lack of correlation between digit choice and digit value
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Payout:

$$P_\pi = \lim_{N_{tot} \to \infty} \frac{1}{N_{tot}} \sum_{\{i\}} (N_i^\pi - 4.5) = 0$$
Classical Computer: The “computational degrees of freedom” of a classical computer are very classical: Engineered to be well isolated from the quantum fluctuations that are everywhere

→

• Computations are deterministic
• “Random” is artificial
• Model a classical billiard gas on a computer:
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Our ideas about probability are like our ideas about color:

• Quantum physics gives the correct foundation to our understanding
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