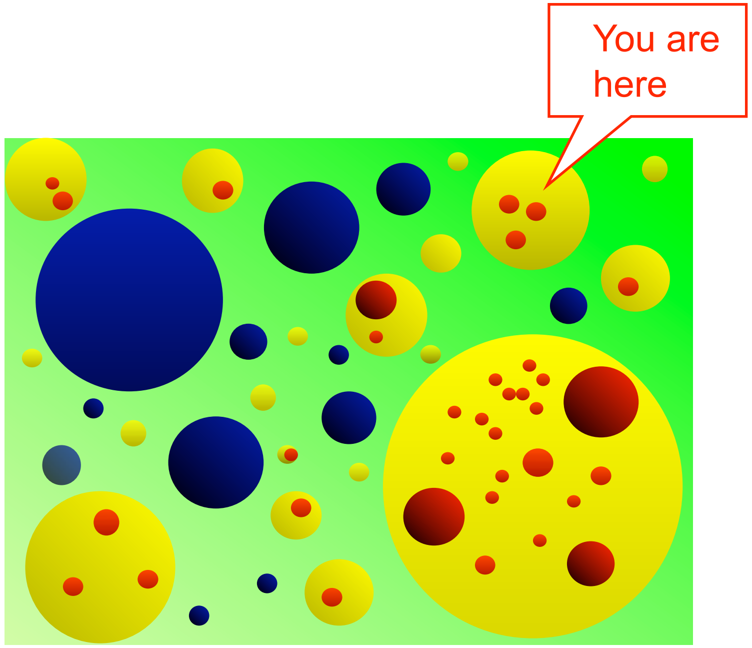
PROBABILITIES IN THE MULTIVERSE

Alex Vilenkin

Tufts Institute of Cosmology

Oxford, September 2009

Eternally inflating multiverse



- Bubbles with different constants of Nature nucleate and expand, approaching the speed of light.
- An unlimited number of bubbles of each kind is formed in the course of eternal inflation.
- We want to find probabilities for us to observe different values of the constants.

Given a theory of the multiverse, how can we find probabilities?

Self-sampling assumption:

N. Bostrom, "Anthropic bias" (2002).

Assume that we are typical (randomly picked) in our reference class of observers (*C*).

Probability of outcome *j*

$$P_j = \frac{N_j}{N} \equiv f_j$$

Fraction of observers in *C* who find *j*

However…

- How should we choose the reference class *C*?
- Should it include all intelligent observers? If so, how do we define intelligence? Should chimpanzees be included?
- Whatever the choice of *C*, how do we know that we are typical?

Note: this problem exists even if the physics of the multiverse is fully understood.

⇒ *Widespread belief that probabilities in the multiverse are inherently ambiguous.*

I will argue that this is not so.

J. Garriga & A.V. , "Prediction and explanation in the multiverse" Phys. Rev. D77, 043526 (2008).

An important feature of the multiverse:

Any event that has a non-zero probability
will occur an infinite number of times.

Each of us has an infinite number of exact duplicates.

G. Ellis & G. Brundrit, "Life in the infinite universe"
Q. Jl. R. Astr. Soc. (1979).

In the context of open FRW, assuming some "randomizer".

Bubbles are formed in all possible quantum states ⟹ randomness.

An important feature of the multiverse:

Any event that has a non-zero probability
will occur an infinite number of times.

Each of us has an infinite number of exact duplicates.

G. Ellis & G. Brundrit, "Life in the infinite universe"
Q. Jl. R. Astr. Soc. (1979).

In the context of open FRW, assuming some "randomizer".

Bubbles are formed in all possible quantum states $\Rightarrow$ randomness.

The measure problem:

Probabilities depend on how we regulate the infinities.

This is a separate problem;
I will not discuss it here.

Significant progress in the last few years.

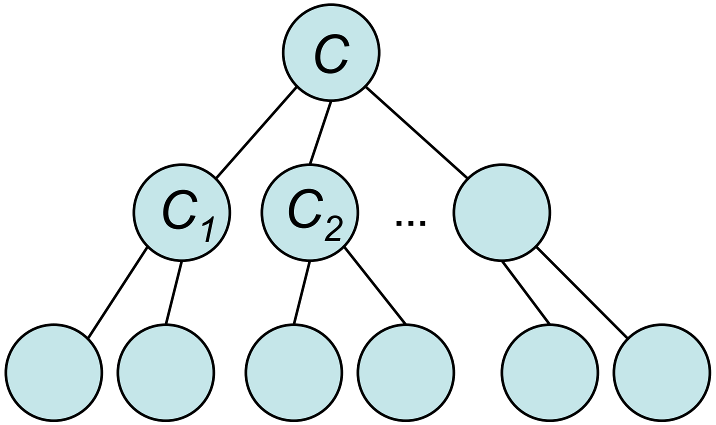
The "ideal" reference class

Consider an observer *O* in the multiverse who wants to predict the outcome of some measurement *M*.

The observer can be characterized by his information content.

(The results of all previous measurements, his address, name of his dog, etc.)

The "ideal" reference class C: class of observers with the same information content.



Branching tree of reference classes. (Similar to many worlds interpretation of QM.)

Observers in *C* cannot distinguish between one another $\Longrightarrow$ *O* is typical in *C*.

Once the measurement is made, *C* splits into subclasses C_j corresponding to different outcomes of *M*.

$$P_j = f_j$$

Branching ratios

Wider reference classes

In practice, we define the reference class using only a small subset of all available information. Much of the omitted information is irrelevant, but some may be relevant (correlated with the measurement). *Why should we then think of ourselves as typical in that class?*

Suppose we want to predict the value of the sum of the neutrino masses, m_ν .

We can consider the reference class $C^{(\nu)}$ of all observers who measured the same values for all constants except m_ν. Omitted information includes our galaxy mass, the Hubble expansion rate, observational constraints on m_ν , etc. – which may all be relevant.

J. Hartle & M. Srednicki, "Are we typical?"
Phys. Rev. D75, 123523 (2007):

We should never assume ourselves to be typical in some class, unless we have evidence to back up that assumption.

I disagree.

The principle of mediocrity:

We should assume ourselves to be typical in any class C that we belong to, unless there is some evidence to the contrary.

- Even though some relevant information may be missing, the distribution P_j for C can be used to make predictions.

  Some observers will guess incorrectly, but there will be more winners than losers. This justifies the use of POM.

- When more information becomes available, we get a narrower reference class and more accurate predictions.

- We can also use POM to explain the values of the constants which have already been measured. E.g., to explain the observed value of some constant α , we can consider the reference class of observers who measured the same values for the constants as we did, except for α .

  Evidence for the underlying theory: $E(T \mid D) = P(D \mid T)$.

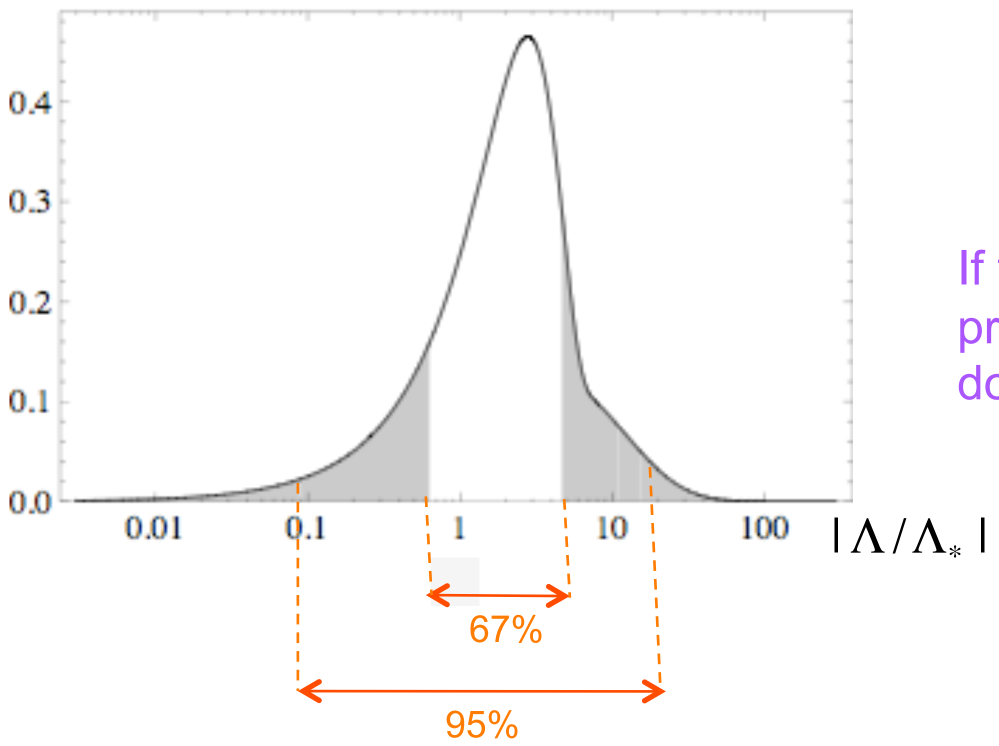
Is it meaningful to talk about probabilities when we can only observe a single bubble?

Suppose we found *P(X)* for some constant of Nature *X*. How can we test this distribution?

Is it meaningful to talk about probabilities when we can only observe a single bubble?

Suppose we found *P(X)* for some constant of Nature *X*. How can we test this distribution?

Make a prediction for a range of X at specified confidence level.



A. De Simone, A. Guth, B. M. Salem & A.V. (2008)

If the measured value is outside the predicted range, the theory is downgraded accordingly.

Conclusion:

Probabilities in the multiverse can be well defined and can be used to make predictions and to evaluate different models.

The principle of mediocrity is widely used in physics:

- Cosmologists think of the CMB fluctuations as randomly drawn from a Gaussian distribution.
- Whenever we represent measurement result as $x \pm \delta x$, we think of the data as a random sample drawn from a Gaussian distribution.