The Bubble Multiverses of the No Boundary Quantum State

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Hawking75, Cambridge, July 3, 2016

A Quantum Universe

If the universe is a quantum mechanical system it has a quantum state.
What is it?

$$\Psi$$

A theory of the quantum state is the objective of Quantum Cosmology.

No State --- No Predictions

- The probability p at time t of an alternative represented by a projection P(t) (e.g a range of position) in a state $|\Psi\rangle$ is:

$$p = ||P(t)|\Psi\rangle||^2$$

$$P(t) = e^{iHt/\hbar} P(0) e^{-iHt/\hbar}$$

- If we don't have the operator P and H and the state $|\Psi\rangle$ there are no probabilities and no predictions.

Contemporary Final Theories Have Two Parts

$$H \qquad \Psi$$

Which regularities of the universe come mostly from H and which from ψ ?

An unfinished task of unification?

H

- classical dynamics
- laboratory experiment eg CERN.

Ψ

- classical spacetime
- early homo/iso +inflation
- fluctuations in ground state
- arrows of time
- CMB, large scale structure
- isolated systems
- topology of spacetime
- num. of large and small dims.
- num. of time dimensions
- coupling consts. eff. theories

Third and First Person Probabilities

- The theory (H,Ψ) predicts third person probabilities for which history of the universe occurs.
- First person probabilities for what we observe are third person probabilities conditioned on a description D of our observational situation --- including us. All we know is that there is at least one instance of D. In a large universe D might be replicated.

$$p(\mathcal{O}|D^{\geq 1})$$

- We test the theory by its first person predictions for what we observe.

(H, Ψ) supply a probabilistic measure on cosmological histories.

Anthropic Reasoning is Automatic in Quantum Cosmology

We won't observe what is where D cannot exist

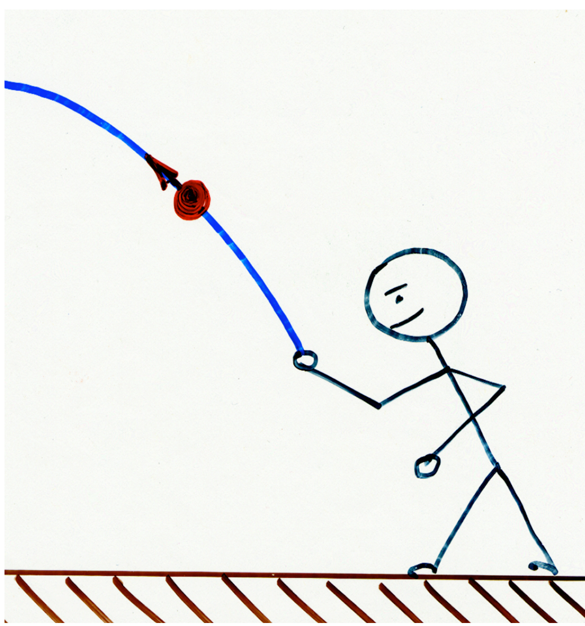
$$p(\mathcal{O}|D)) \propto p(D|\mathcal{O})$$

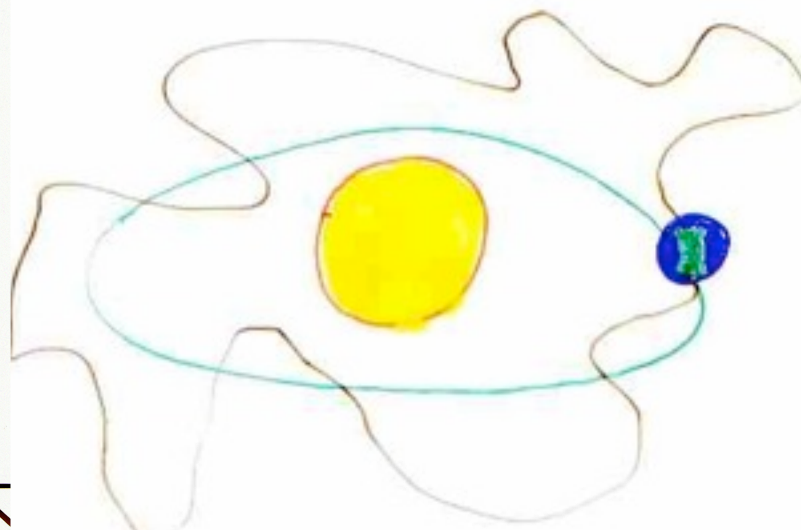
Anthropic reasoning follows from treating observers as physical systems within the universe.

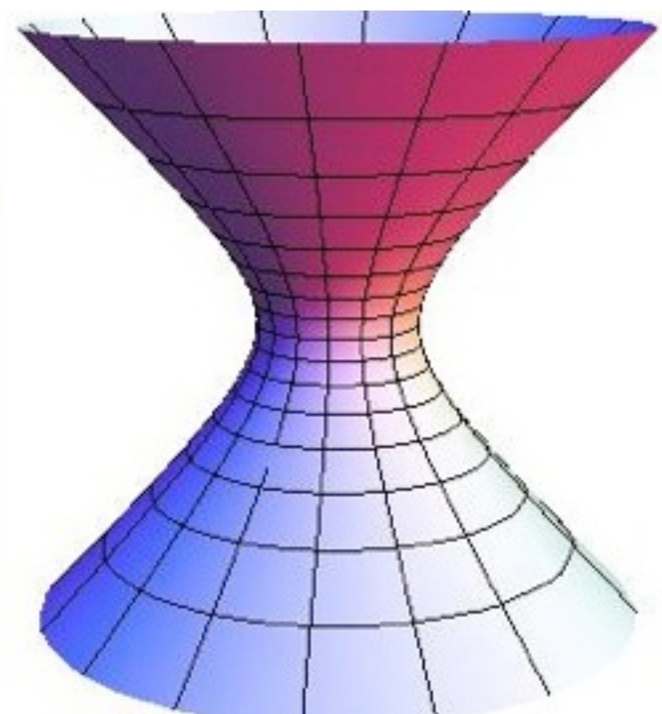
- Does not require a principle.
- Is not an option.
- Is not subjective choice.

Most of our observations of the universe are of its classical history.

Quantum systems behave classically when the 3rd person probabilities are high for histories with correlations in time governed by deterministic laws .







Classical Spacetime
is an Approximation
to the
Quantum Mechanics
of Gravity
in a given state.

Simple State, Complex Histories

A simple, managable, discoverable theory of the quantum state of the universe can't predict just one classical spacetime. Because it would then have to predict all of present complexity.

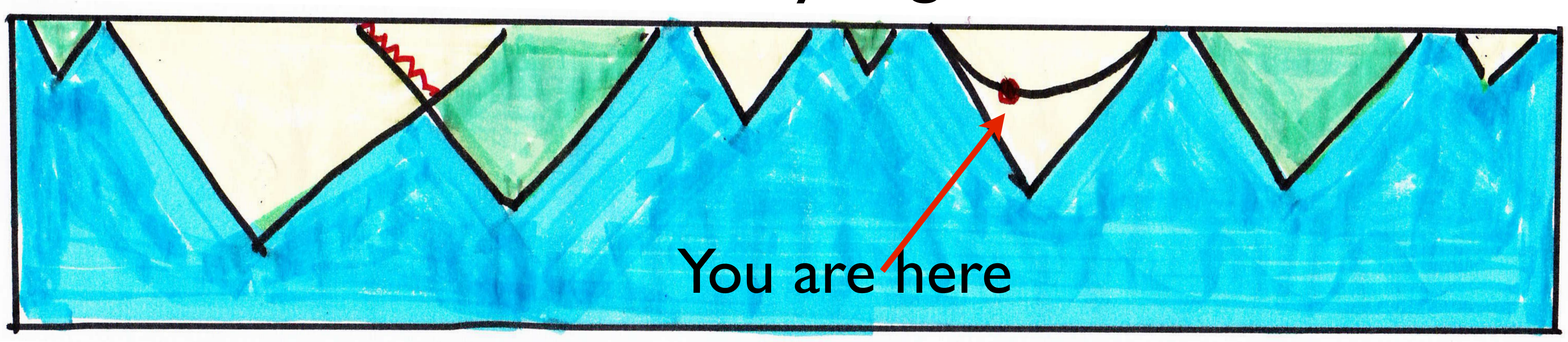
Rather a quantum state predicts an ensemble of possible classical spacetimes with probabilities for the quantum accidents that take place within them.

The state is can be simple but the individual histories in the ensemble can be very complex.

Example: Our own universe today at a sufficiently fine-grained level of description.

Quasiclassical Spacetimes of False Vacuum Eternal Inflation

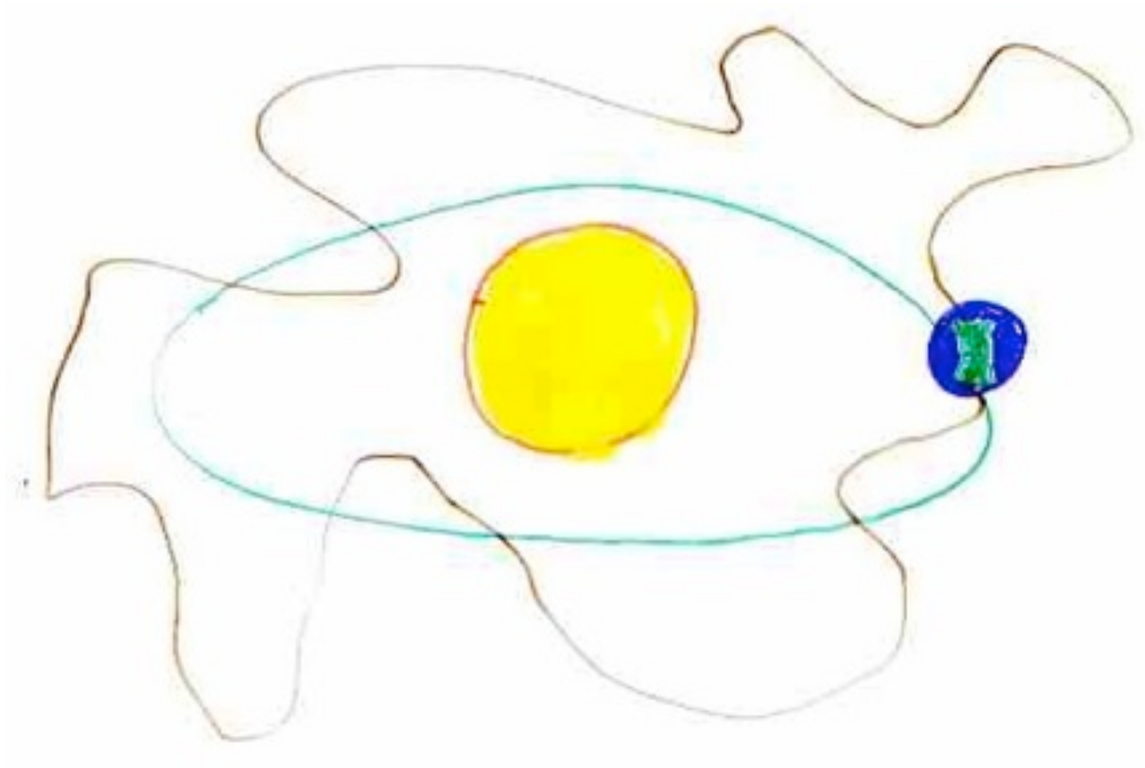
At a fine grained level these are a complex mosaic of true vacuum nucleated bubbles separated by inflationary regions.



We only observe the inside of our bubble. We can therefore coarse grain over all the structure outside

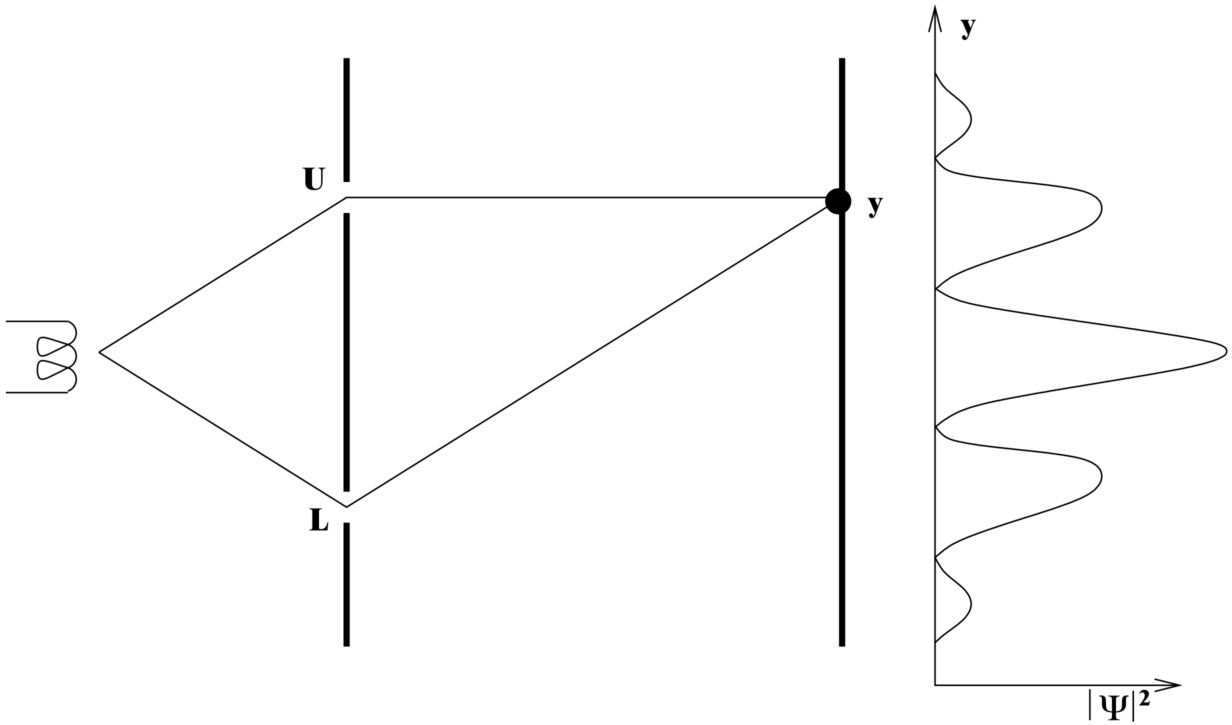
QM supplies a manageable way to coarse grain.

The most general objective of a quantum theory is the prediction of probabilities for histories.



In cosmology these are the histories of the universe --- cosmological histories of spacetime geometry and fields.

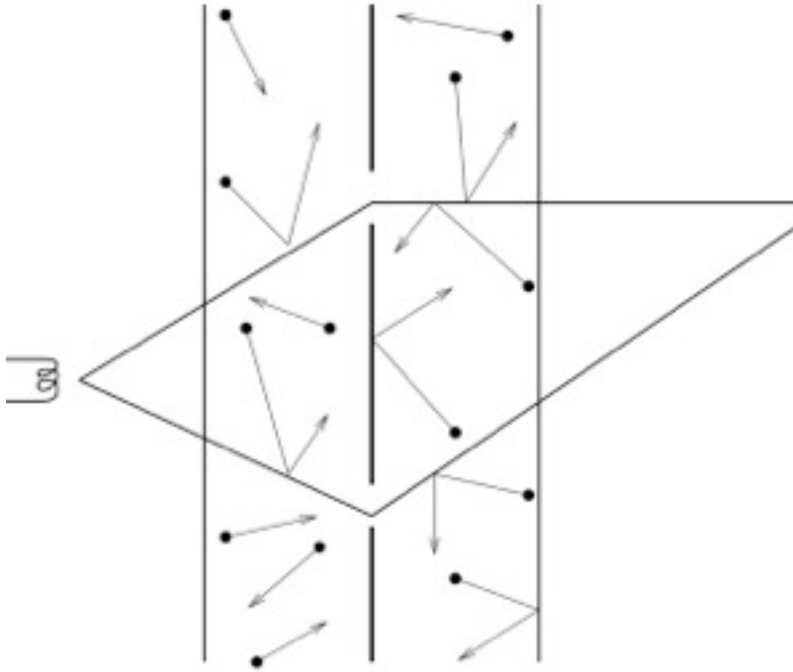
Interference an Obstacle to Assigning Probabilities to Histories



$$|\psi_U(y) + \psi_L(y)|^2 \neq |\psi_U(y)|^2 + |\psi_L(y)|^2$$

It is inconsistent to assign probabilities to this set of histories.

Which Sets of Histories Can be Assigned Probabilities?

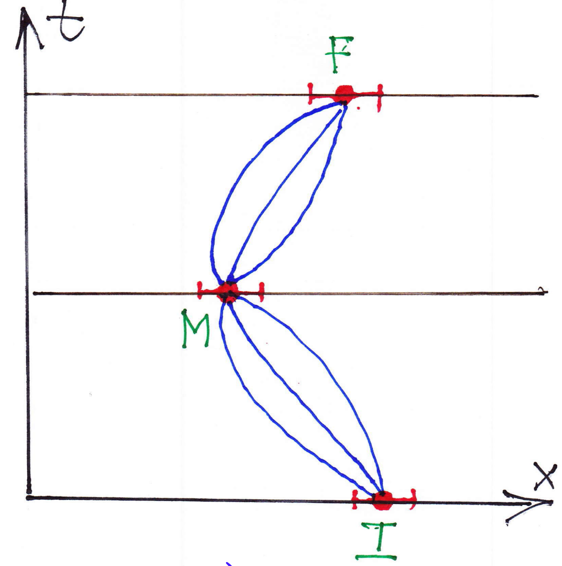


Textbook QM: Assign probabilities only to sets of histories that have been measured.

DH: Assign probabilities to sets of histories that decohere, ie. for which there is negligible interference between members of the set as a consequence of H and Ψ like an environment.

Decoherence implies Consistent Probabilities.

Decoherence Enables Coarse Graining



$$(\text{Prob.for history IMF}) \equiv p(IMF)$$

$$p(IMF) = |A(F, M, I)|^2$$

Coarser Grained: $p(IF) = \Sigma_M \, p(IMF)$

If decoherence: $p(IF) = |A(F, I)|^2$

For decoherent sets there are two equivalent ways of coarse graining: Sum the probabilities or sum the amplitudes ---effectively leaving the ignored alternative out.

QM: Coarse Graining = Ignoring

Coarse Graining Enables Top-Down

Hawking and Hertog, arXiv: hepth/0062091

We don’t have to calculate the fine-grained evolution of the universe from the beginning to understand it now.

Rather we do a coarser grained calculation putting in some data now and asking how it got this way.

Biological evolution is another example.

Quantum Nucleation of Bubbles of True Vacuum in a Classical False Vacuum

Minisuperspace Models

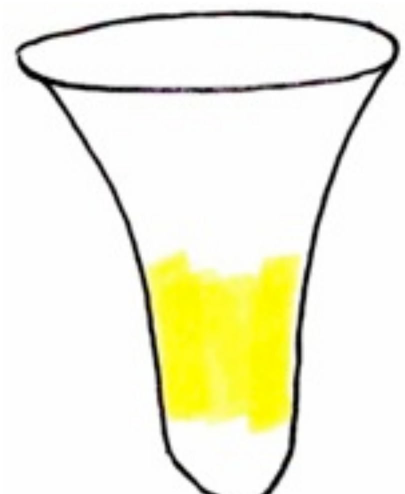
Homogeneous, isotropic, and closed configurations of geometry and a scalar field.

$$ds^2 = -dt^2 + a^2(t)d\Omega_3^2 \qquad \phi = \phi(t)$$

Dynamics: General Relativity, plus potential $V(\phi)$

$$\boxed{\Psi = \Psi(b, \chi).}$$

(b,χ)



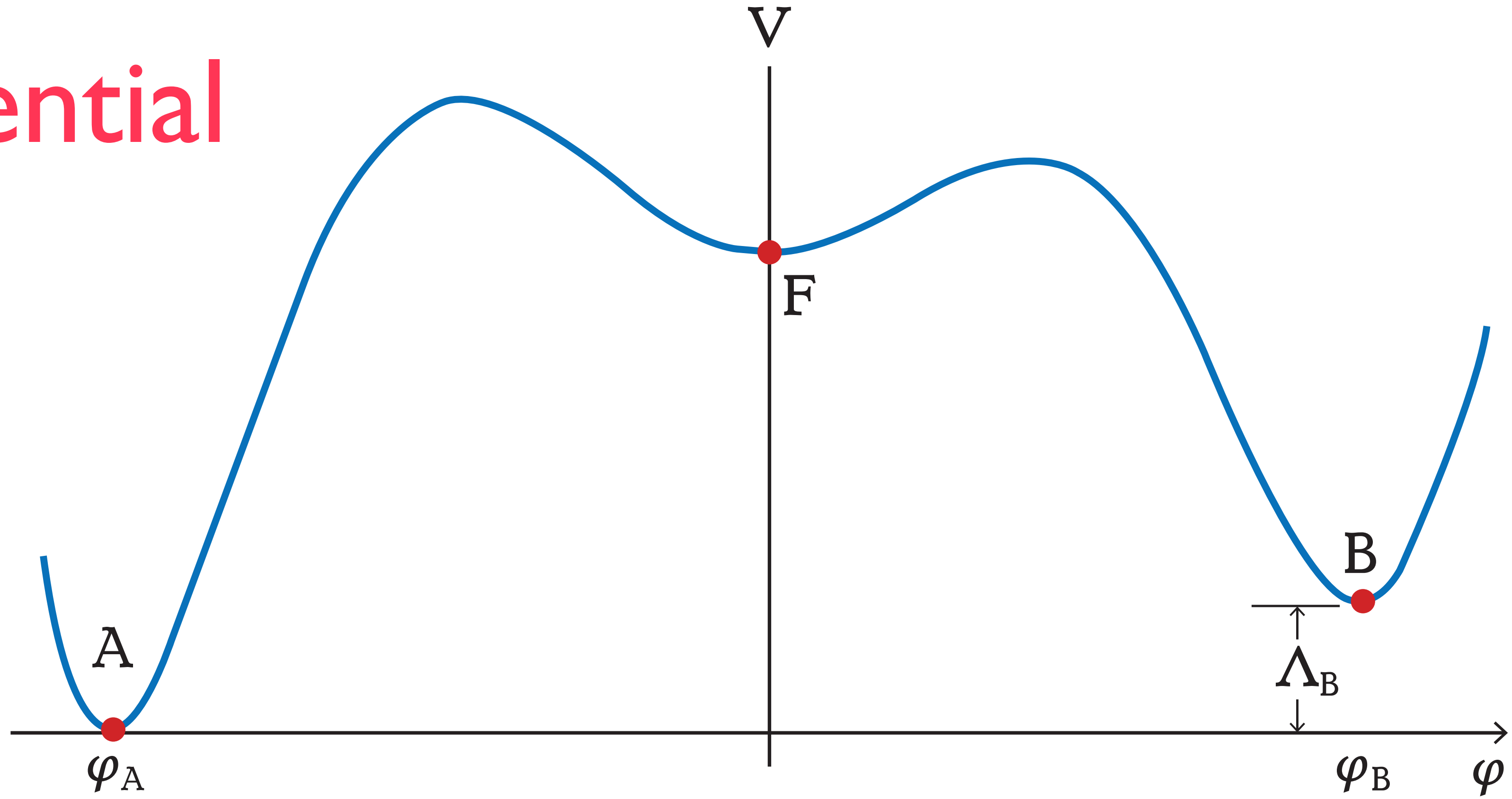
φ0

No boundary wave function in the semiclassical approximation:

$$\Psi_{NB}(b, \chi) \approx \exp[-I_{\rm ext}(b, \chi)/\hbar]$$

The saddle point action is generally complex

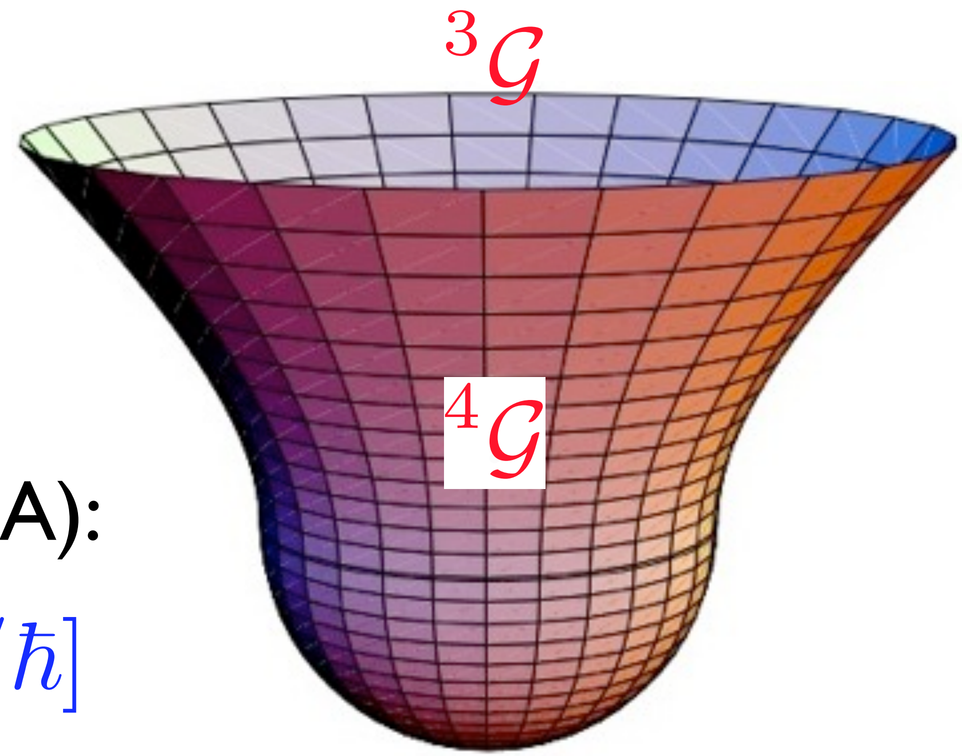
Potential



- One false vacuum F and two true vacua A and B.
- Nucleation of true vacuum bubbles A or B by quantum tunneling dominate exit channels from F.
- Different histories labeled by starting values of φ.
- Different slow roll regimes leading to different predictions for the observed CMB in A or B and different predictions for the cosmological constant.

The No-Boundary Quantum State of the Universe

Stephen Hawking



Saddle Point Geometry

Semiclassical Approximation (SA):

$$\Psi(^{3}\mathcal{G}) \approx \exp[-I_{\mathrm{ext}}(^{3}\mathcal{G})/\hbar]$$

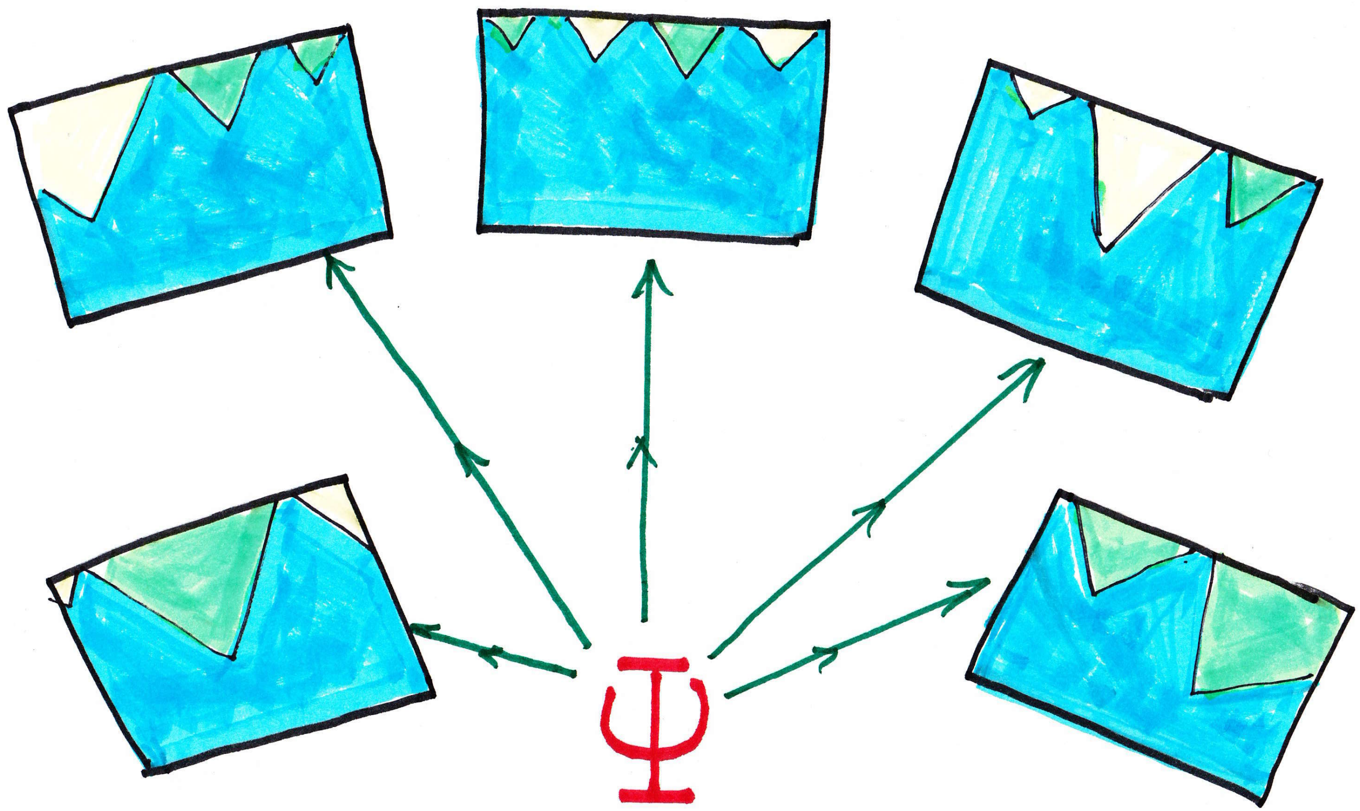
In SA a wave function is defined by the collection of saddle points that approximate it.

Specifying Saddle Points

- If the wave function has an integral representation the contour specifies the saddle points.
- The NBWF is usually specified by a `Euclidean’ integral but can be specified by a `Lorentzian’ one 1705.05340.
- But as in ordinary quantum mechanics every state does not have to have an integral representation. The NBWF saddle points can also be specified by a dual field theory 1111.6090.

For the power of this see the next talk!

Not One Classical Spacetime but a Multiverse of Possible Ones



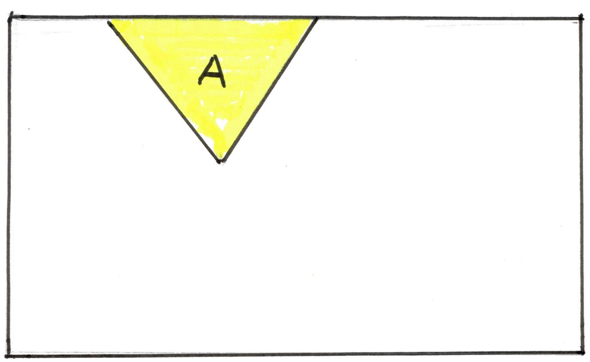
The state and its classical ensemble have deSitter symmetries which the individual histories do not.

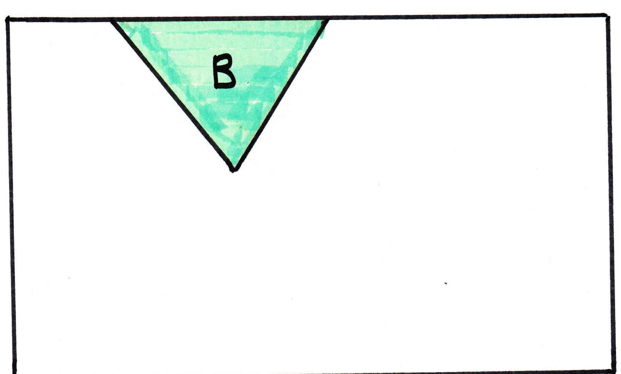
Coarse Graining for Local Obs.

- Coarse grain of everything outside our bubble. Not by summing fine-grained probabilities over everything outside, but by summing amplitudes -- ignoring the other bubbles. .

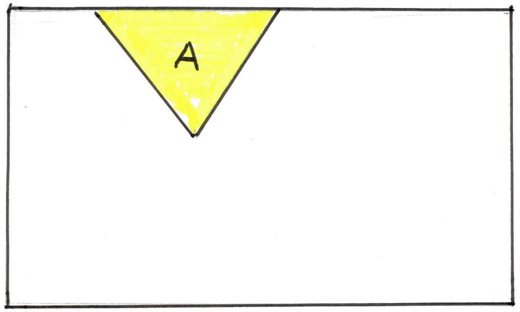
- Then there are only two histories. One in which our bubble nucleated somewhere, sometime, in true vacuum A and the other in true vacuum B.

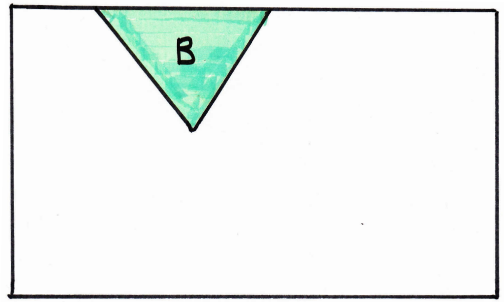
- From the symmetries of deSitter these are the same as the probabilities that A or B nucleated in a particular place in spacetime.

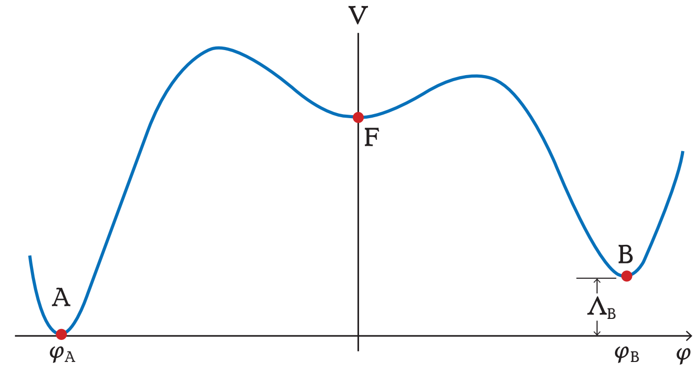




Probs. for Our CMB Observations







The probabilities to nucleate bubbles of different kind in a false vacuum were calculated by Coleman and DeLuccia.

There is least one copy of us in any bubble as long as probability of our observing situation is not zero since the reheating surfaces are infinite.

The probabilities for which CMB we observe are:

$$\frac{p(WOA)}{p(WOB)} = \frac{p_{\mathrm{CDL}}(A)}{p_{\mathrm{CDL}}(B)}$$

For this example
no measure was necessary to
predict probabilities for observations
beyond that supplied by the NBWF,
even though in a finer grained
picture there might be a very large
number of bubbles.

Multiverses

Multiverses

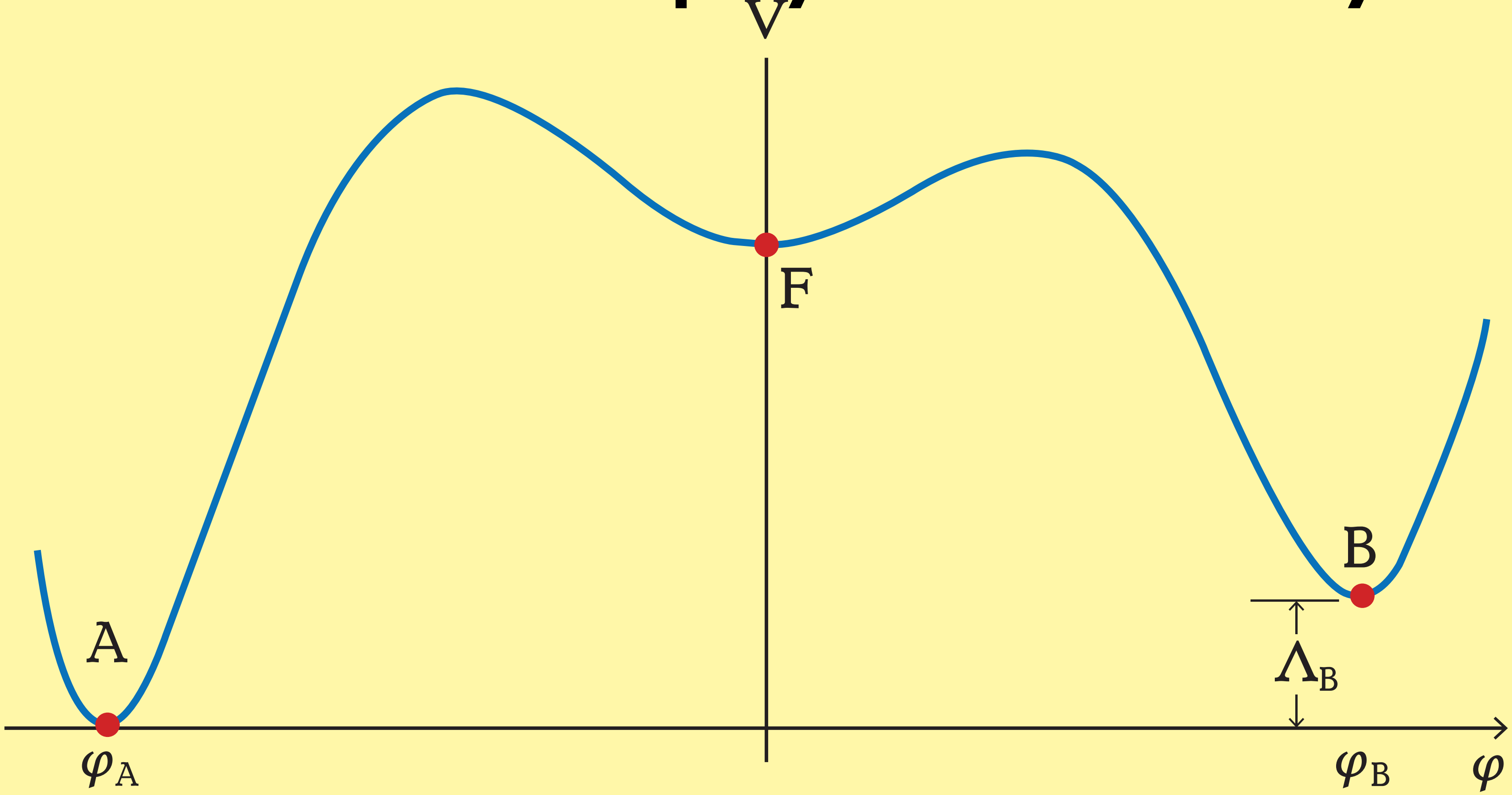
A situation where the theory presents a multiplicity of possibilities only one of which is realized, observed, or experienced.

The quantum multiverse of classical histories of the universe.

The multiverses of true vacuum bubbles in false vacuum eternal inflation with different predictions for the cosmological constant.

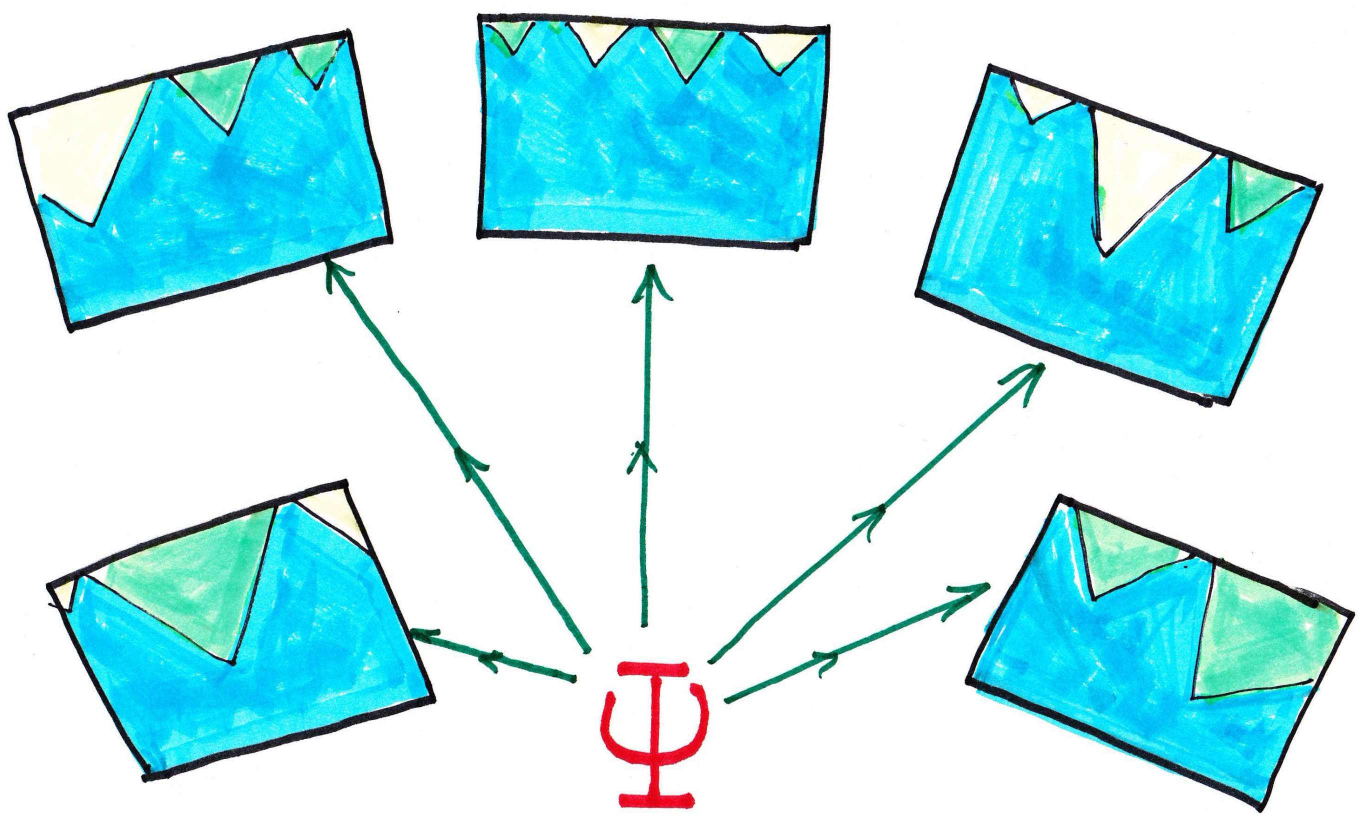
Quantum mechanics generically predicts multiverses.

Multiverses Enable Anthropic Selection because they provide a mechanism for the constants of physics to vary.



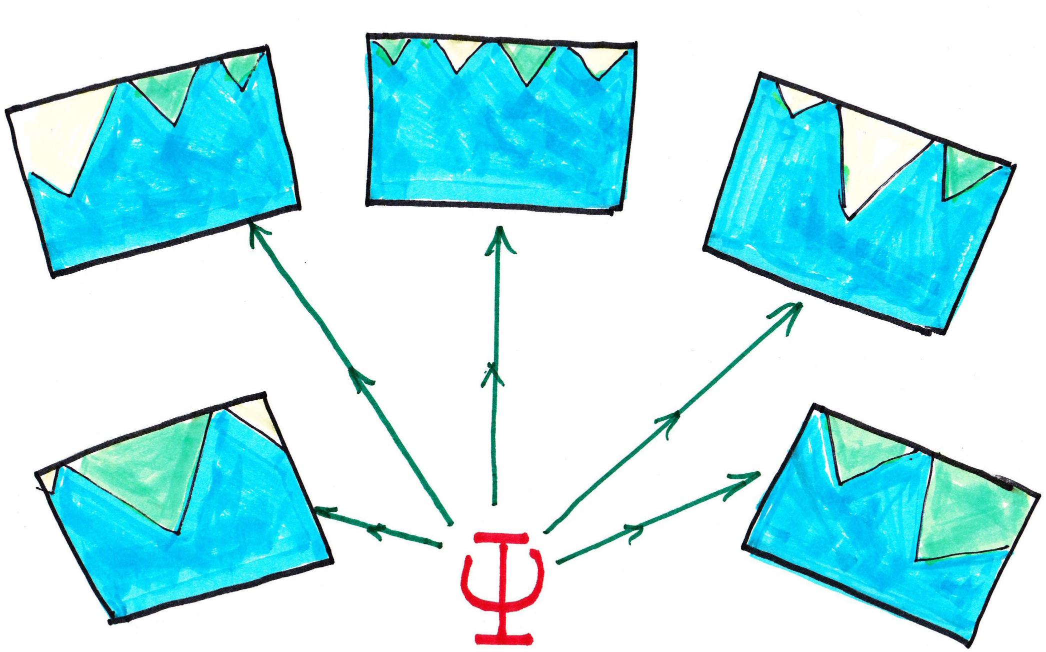
Bubble Multiverses of the NBWF

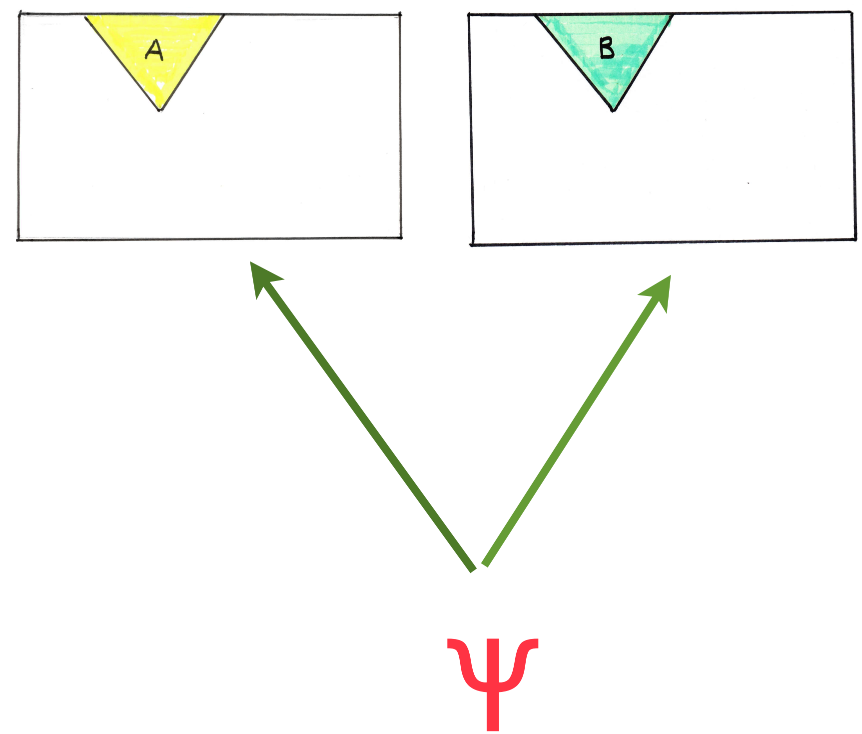
There is not just one history with bubbles but an ensemble of possible histories one of which is realized.



Bubble Multiverses of the NBWF

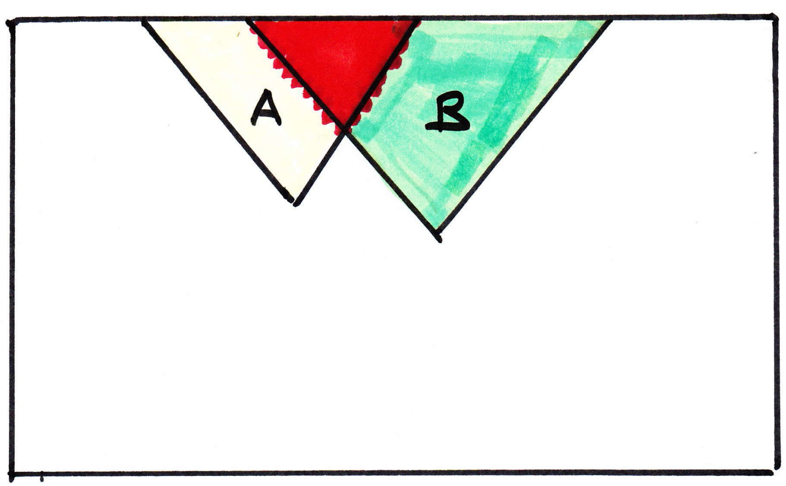
There is not just one bubble universe ensemble but rather different ones at different levels of coarse graining emerging from the same physics (H,Ψ).





What Can We See?

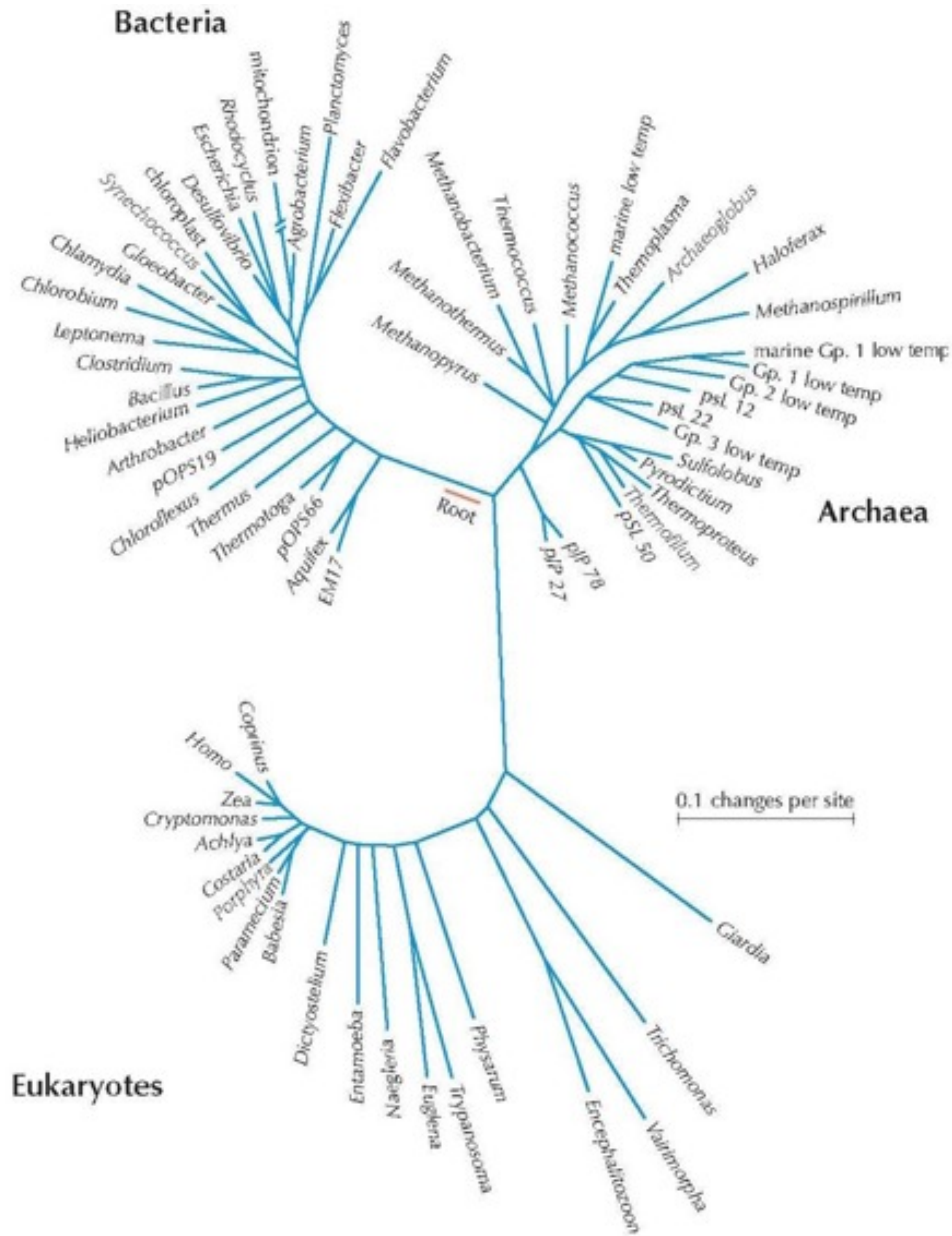
- We don't `see' the other histories in the ensemble. Schroedinger's cat does not observe the dead cat.
- We don't see the other bubbles that are spacelike separated from us.
- We might see another bubble that collides with ours.



The Multiverse of Biological Evolution

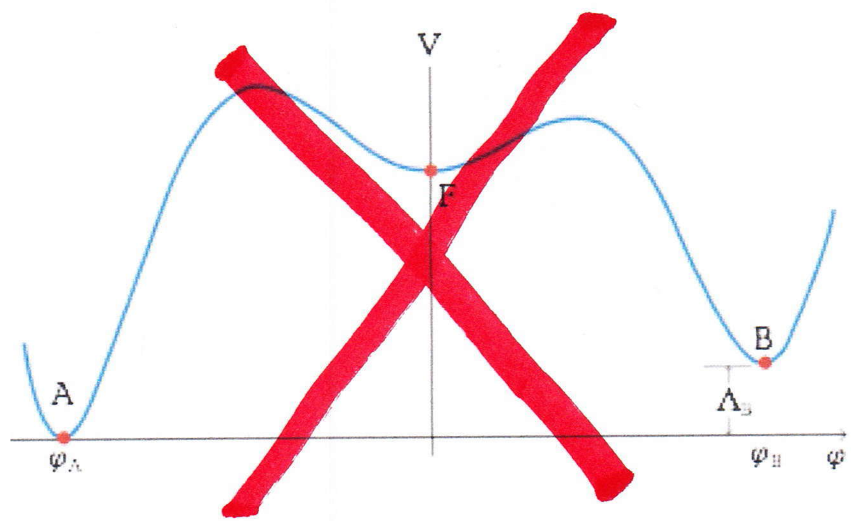
We can't observe that directly ---
It's in the past.

We can't observe the multiverse of bubbles that are spacelike separated from us.



Are Multiverses Falsifiable?

Yes! - if the ingredients that go into its construction are falsified: A theory of the quantum state, a theory of dynamics that allows different vacua, a landscape where the constants vary, etc



Just like the theory of evolution is falsified if the mechanisms of genetic variation (mutation, genetic drift recombination) and fitness landscapes and are falsified.

H

- classical dynamics
- laboratory experiment eg CERN.

Ψ

- classical spacetime
- early homo/iso +inflation
- fluctuations in ground state
- arrows of time
- CMB, large scale structure
- isolated systems
- topology of spacetime
- num. of large and small dims.
- num. of time dimensions
- coupling consts. eff. theories

classical lorentzian spacetime	yes
early homo/iso + inflation	yes
fluctuations start in ground state	yes
arrows of time	yes
isolated systems	yes
CMB, Large scale structure	yes
anthropic selection	yes
quasiclassical realm	yes
quant. field theory in backgrounds	yes
local prediction in eternal inflation	yes
complexity from simplicity	yes

Scorecard for the No-Boundary Wave Function

``Nothing We Do Now Compares to What We Hope to Do”

topology of spacetime	hints
num. of large & small dim.	hints
num. of time dimensions	hints
unification of H and Ψ	hints
locality	
populating landscapes	hints
generalizations of QM for QC	hints


Happy Birthday Stephen!
There is Still Much to Do
A. Zytkov

Ψ

0704.2630
0711.4630
0803.1663
0905.3877
0906.0042
1001.0262
1004.3816
1309.0493
1502.06770
1503.07205
1604.03580
1612.01952
1705.05340