One Bubble to Rule Them All

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with thanks for collaboration and discussion to Stephen Hawking and Mark Srednicki.

PITP Meeting
Probing the Mystery:
Theory and Experiment in Quantum Gravity
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Quantum Gravity: Experiment and Tests?

It seems unlikely that we will have laboratory experiments that test strong field quantum gravity in the immediate future.

$$E_{\rm pl} \equiv \sqrt{\hbar c^5/G} \sim 10^{19}\,{\rm Gev}$$

But at the beginning of the the universe we have an experiment already done where Planck energies are reached, and there is 14 Gyr of data scattered over 14 Gpc of space today.

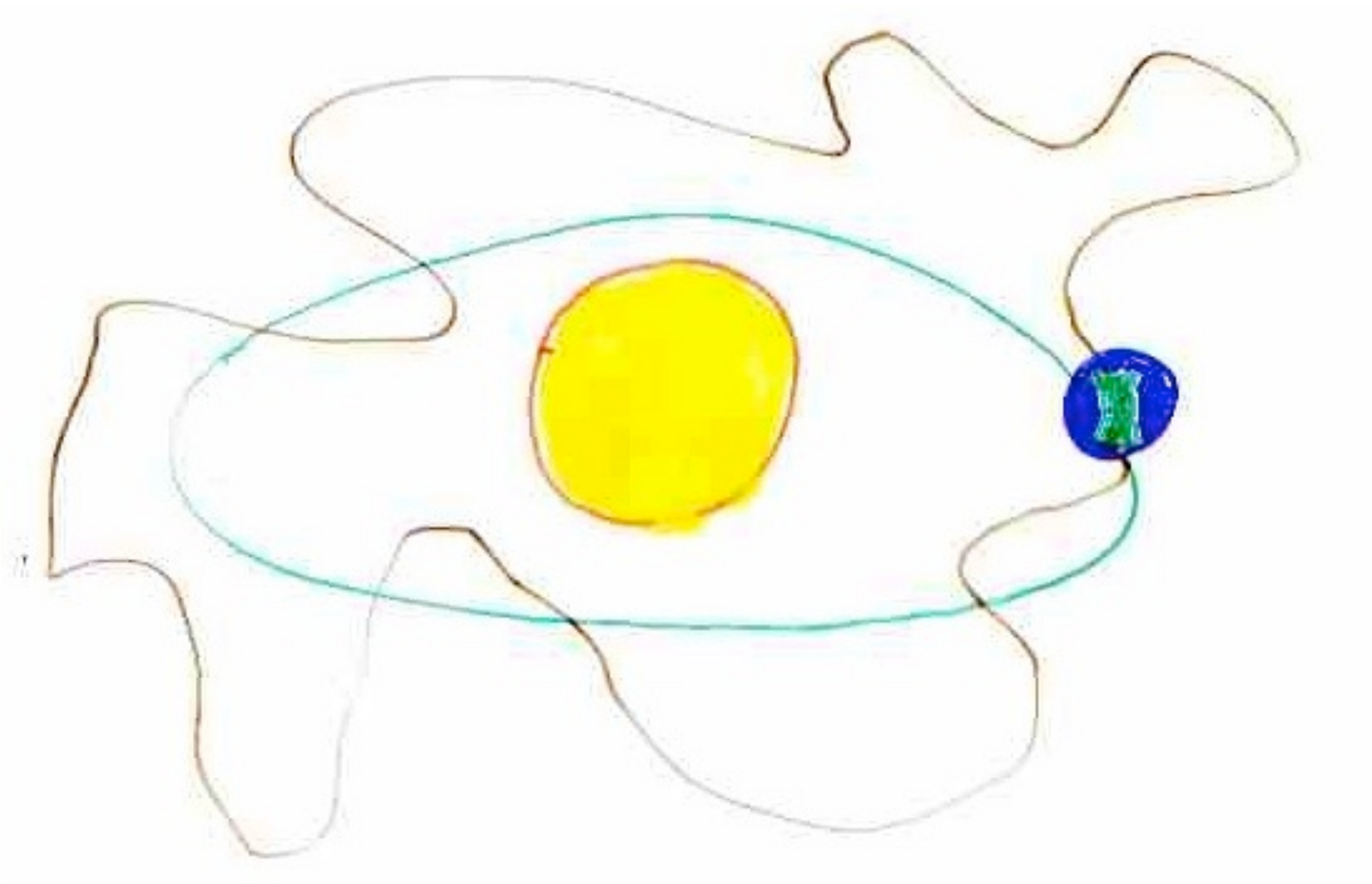
Quantum Cosmology

Cosmological Observations of the Universe's Classical History

Most of our observations of the universe on cosmological scales are of properties of its quasiclassical history:

- The homogeneity and isotropy on scales above 100Mpc. The vast age.
- The rate of expansion, the amounts of dark matter, dark energy, baryons, radiation.
- The evolution of fluctuations to make the CMB, galaxies, stars, planets, biota, us, etc.

Classical behavior is a matter of quantum probabilities of coarse-grained alternative histories of the closed system being correlated in time by deterministic laws.



A Quantum Universe

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

Ψ

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

Contemporary Final Theories Have Two Parts

$$H \qquad \Psi$$

Some regularities of the universe come mostly from H and others from ψ .

An unfinished task of unification?

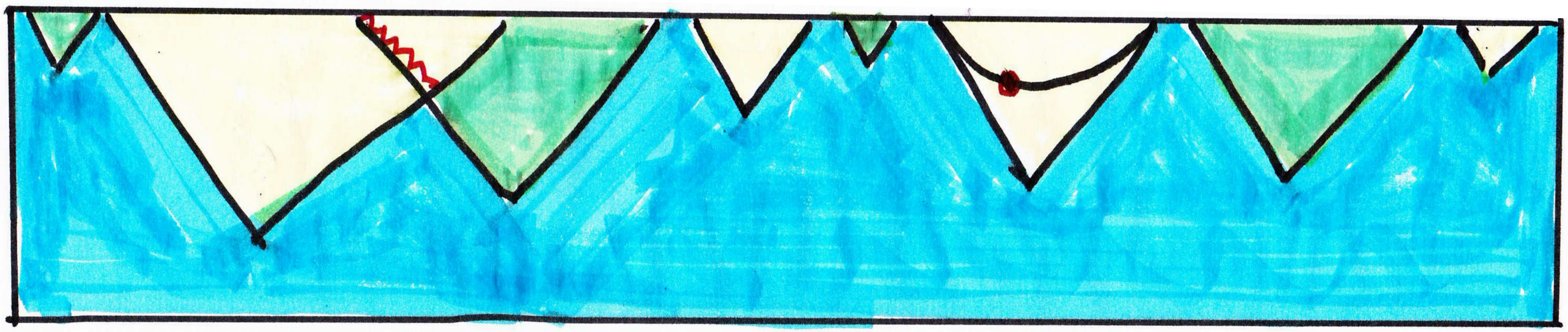
H

- 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

Eternal Inflation



- Our observations are restricted to one Hubble volume.
- That is but one of an infinite number of Hubble volumes on a reheating surface in one bubble.
- That is but one of an infinite number of bubbles in a universe that is very large.

How do we predict the results of our observations that test and utilize the theory?

Eternal Inflation is a Quantum Phenomena

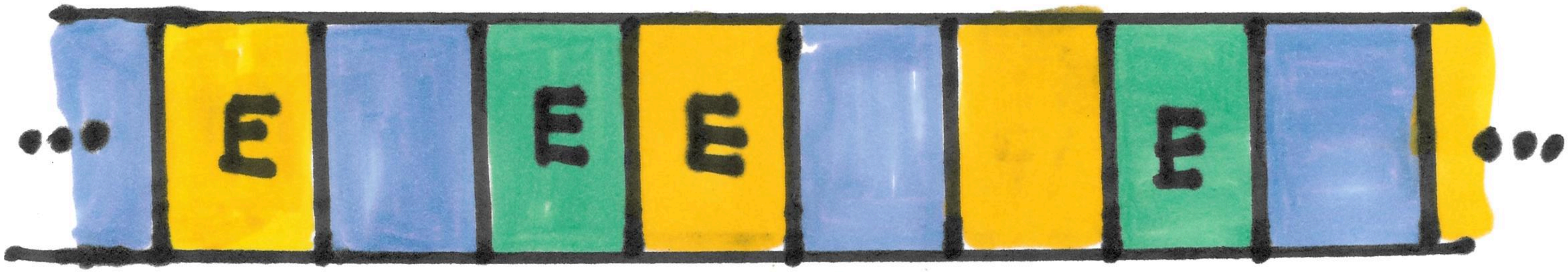
- Classical physics is deterministic, eternal inflation is not.
- Probabilities in a stochastic treatment of eternal inflation are quantum probabilities for large fluctuations.

Eternal inflation is therefore naturally treated in a fully quantum mechanical context (H, Ψ).

Five Pillars

- Quantum state Ψ: Specifying probabilities of alternative coarse-grained histories of the universe.
- Quantum spacetime: An ensemble of alternative classical histories of spacetime with probabilities from Ψ .
- Quantum Observers: Observers as physical systems within the universe with a quantum probability to exist in any Hubble volume and a probability to be replicated in many.
- Our Observations: Focus on probabilities for our observations in our Hubble volume which are conditioned on a description of the observational situation.
- Adapted Coarse Grainings: Use coarse grainings that follow observations and ignore unobservable features of the universe such as very large scale structure.

Box Model Universe



Each box is Y,G,B with probabilities p_Y, p_G, p_B

Observers exist (E) with a probability p_E in Y, G and 0 in B.
We are equally likely to be any of the instances of E.

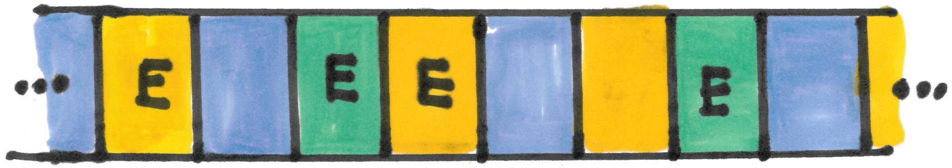
All boxes are statistically the same.

Probabilities of fine grained histories:

$$(p_Y)^{n_Y}(p_G)^{n_G}(1-p_Y-p_G)^{N-n_Y-n_G}(p_E)^{n_E}(1-p_E)^{N-n_E}.$$

Not well defined at infinite N

Box Model Universe

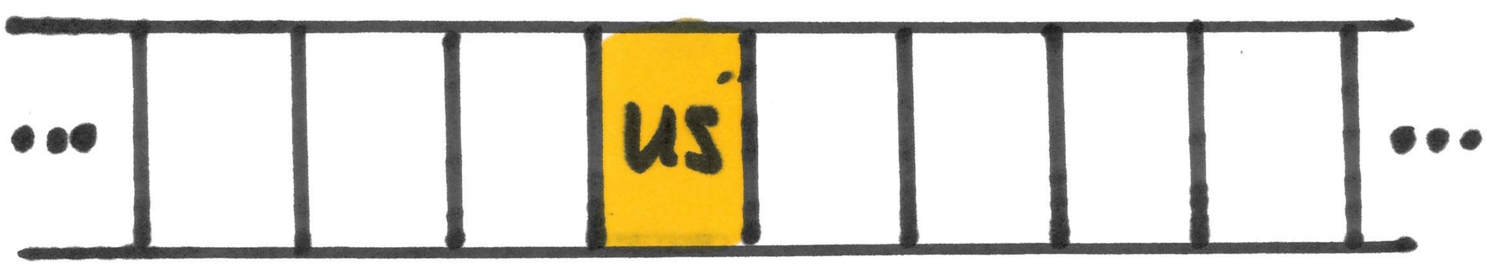


$$(p_Y)^{n_Y}(p_G)^{n_G}(1-p_Y-p_G)^{N-n_Y-n_G}(p_E)^{n_E}(1-p_E)^{N-n_E}.$$

What is the probability that we observe Y (WOY)?

We could try to sum the fine grained probabilities.

But its easier to coarse grain over every box but ours assuming at least one copy of us exists.



$$p(WOY) = p_Y.$$

No problem with the limit of an infinite number of boxes.

Coarse Graining in Physics

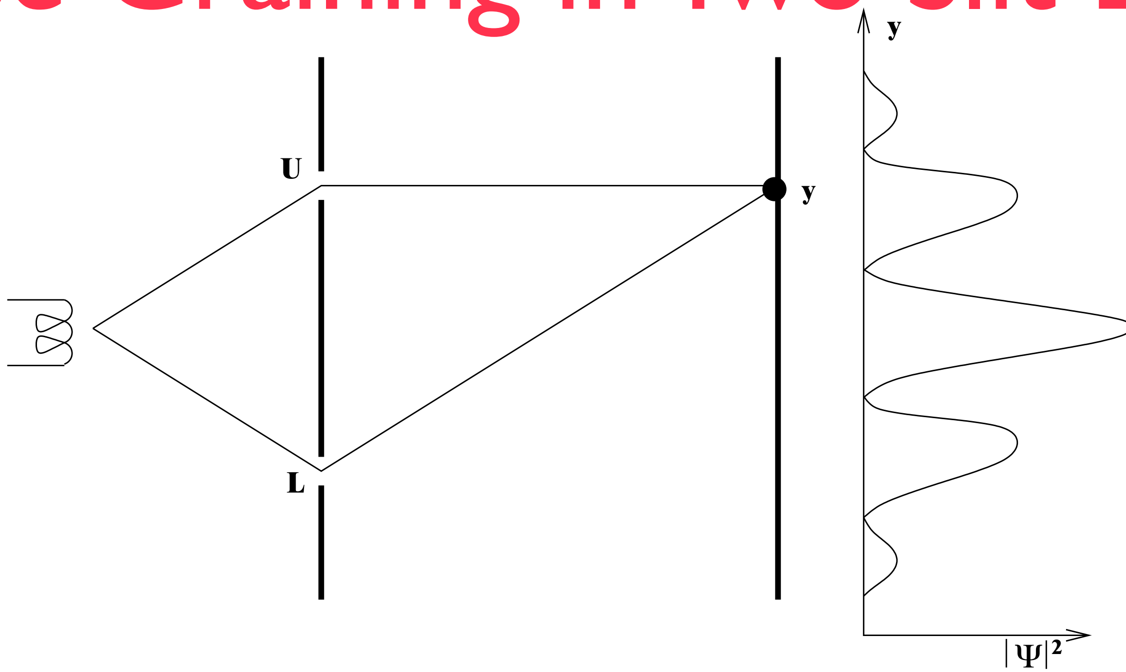
Coarse Graining in Statistical Mechanics

- Fine grained: Atoms in a box have a complex arrangement that changes in time.
- We only observe coarse-grained quantities like total energy, momentum, and number in fairly big volumes.
- Near equilibrium statistical mechanics provides probabilities for the values of these coarse-grained quantities directly without calculating fine-grained histories of the atoms.

In classical physics coarse-graining could be considered a choice forced on us by our puny ability to collect, store, recall, and manipulate data.

But in quantum physics coarse-graining is necessary to have probabilities at all

Coarse Graining in Two Slit Experiment



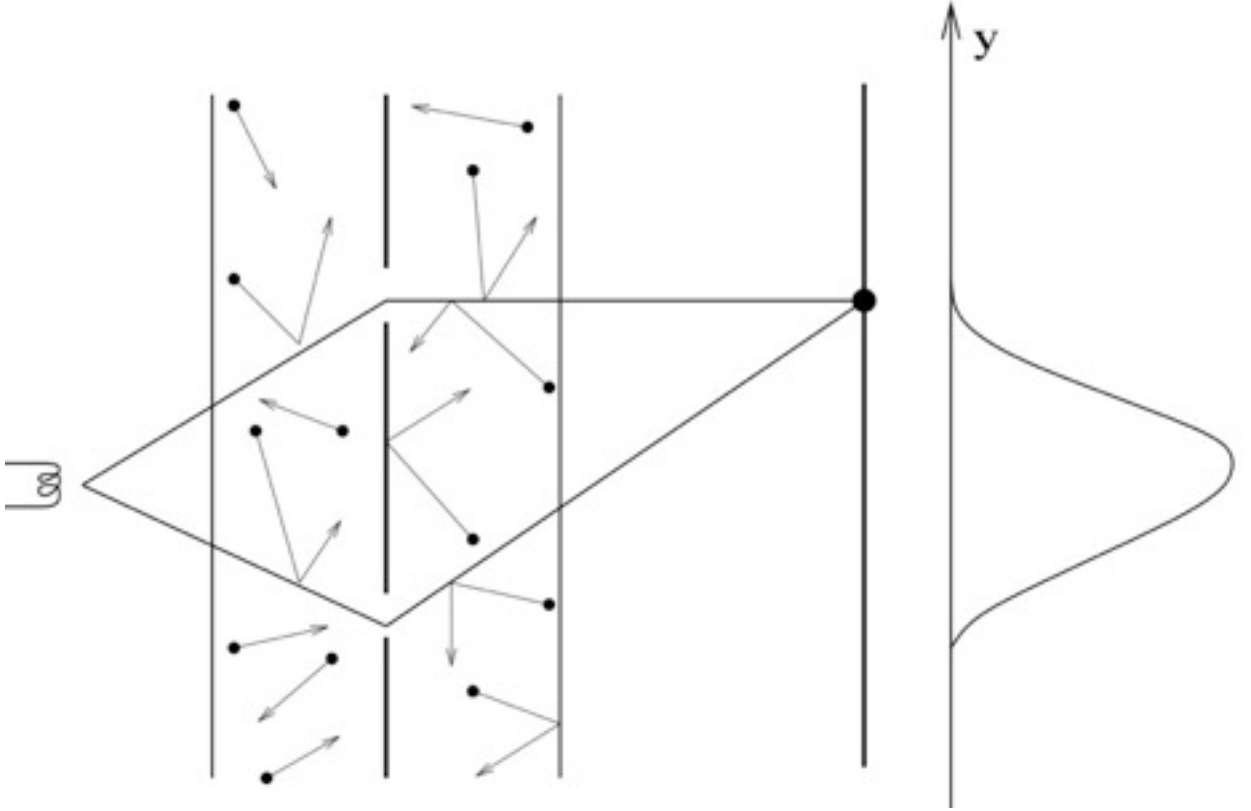
Consider the alternative histories where the electron went through U or L.

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

$$p(y) \neq p_U(y) + p_L(y)$$

It is inconsistent to assign probabilities to this set of histories -- need further coarse graining.

Decoherence of Coarse Grained Histories by interactions that carry away phases.



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |U\rangle)|\phi\rangle \cdots |\phi\rangle$$

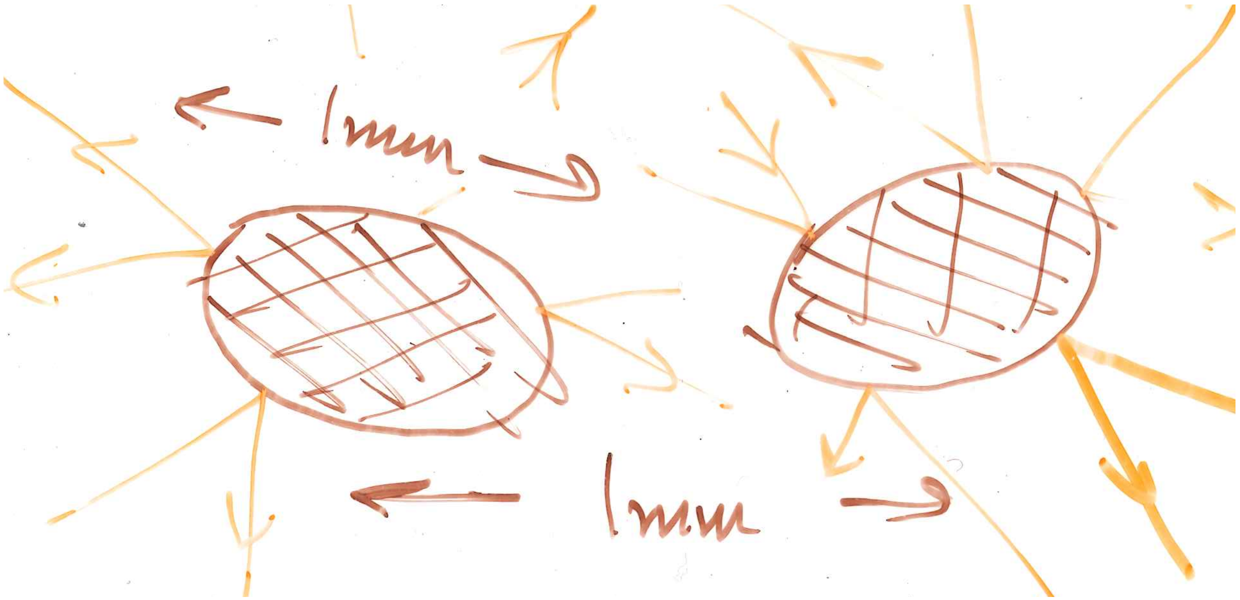
$$|\Psi(y,U)\rangle = \frac{1}{\sqrt{2}}|y,U\rangle S_U|\phi\rangle \cdots S_U|\phi\rangle \quad |\Psi(y,L)\rangle = \frac{1}{\sqrt{2}}|y,L\rangle S_L|\phi\rangle \cdots S_L|\phi\rangle$$

$$\langle \Psi_U(y)|\Psi_L(y)\rangle \propto [\langle\phi|S_U^\dagger S_L|\phi\rangle]^N = (<1)^N \to 0$$

$$p(y) = p_U(y) + p_L(y)$$

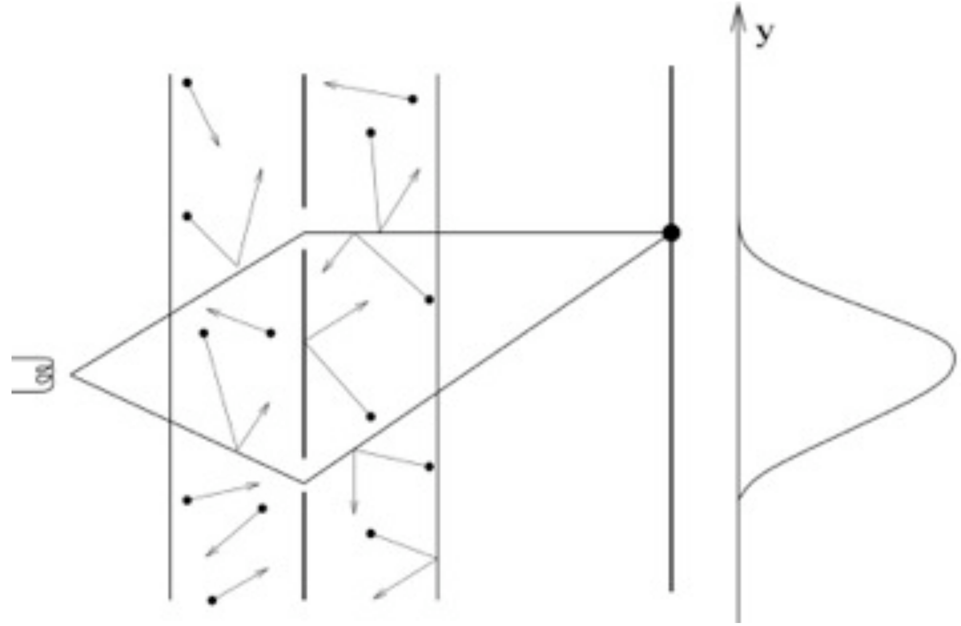
Decoherence is Widespread in the Universe

Joos and Zeh '85



- One dust grain in a superposition of two positions, deep in intergalactic space.
- Relative phases dissipate in of order 10^{-9} s from the 10^{11} CMB photons that scatter every second.

Coarse Graining by Summing Amplitudes in QM



$$p(y) = p_U(y) + p_L(y)$$

$$= ||\Psi_U(y)||^2 + ||\Psi_L(y)||^2$$ Sum probs

$$= ||\Psi_U(y) + \Psi_L(y)||^2$$ Sum amps

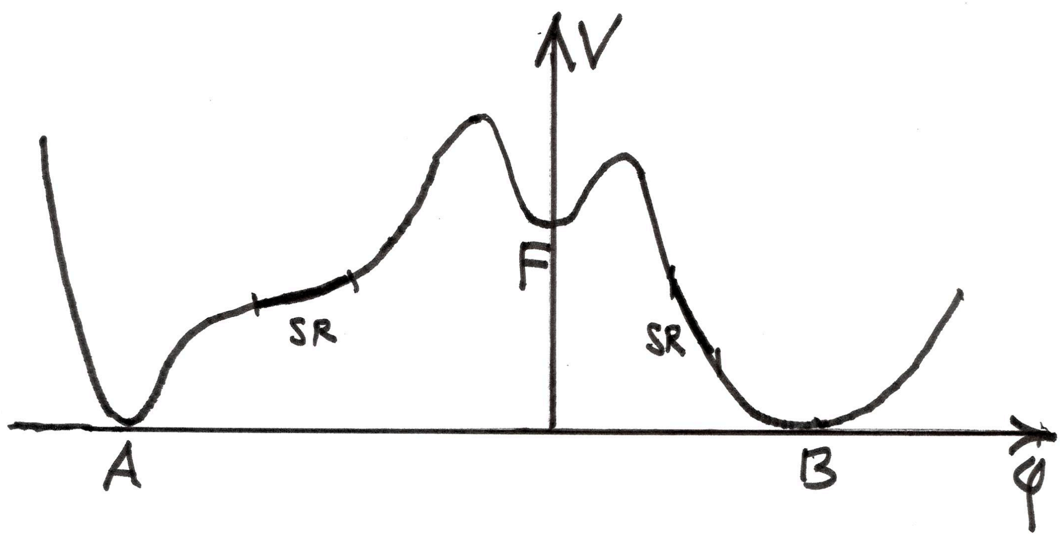
Since: $\langle \Psi_U(y) | \Psi_L(y) \rangle = 0$

Essence of sum-over-histories quantum mechanics.

Local Prediction in False Vacuum Eternal Inflation

A Model of False Vacuum EI

- (H) Einstein gravity coupled to a single scalar field.
- (Ψ) A quantum state.



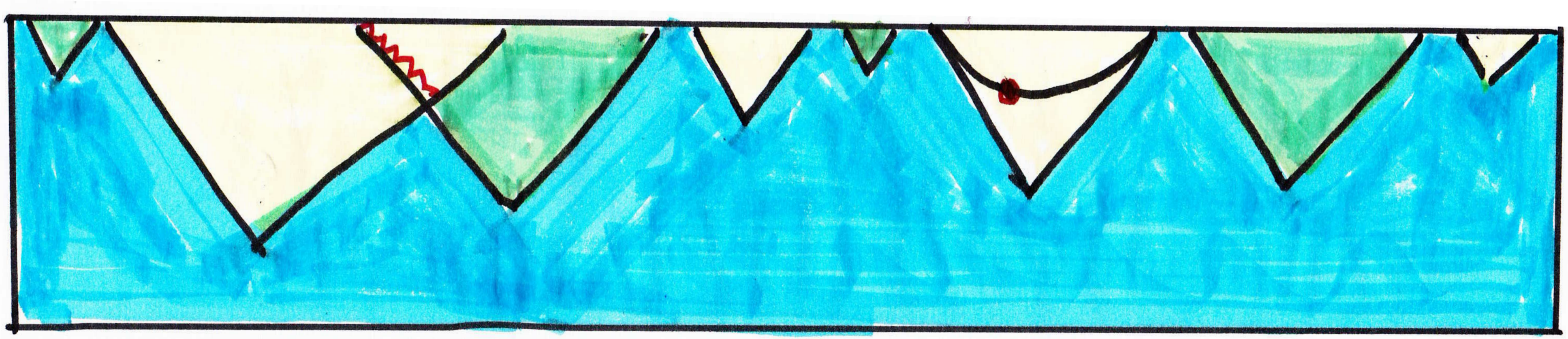
- One false vacuum F and two true vacua A and B.
- Nucleation of true vacuum bubbles A or B are the dominant exit channels from F.
- Different slow roll regimes leading to different predictions for the CMB in A or B.

Assumptions for Illustrative Calculation

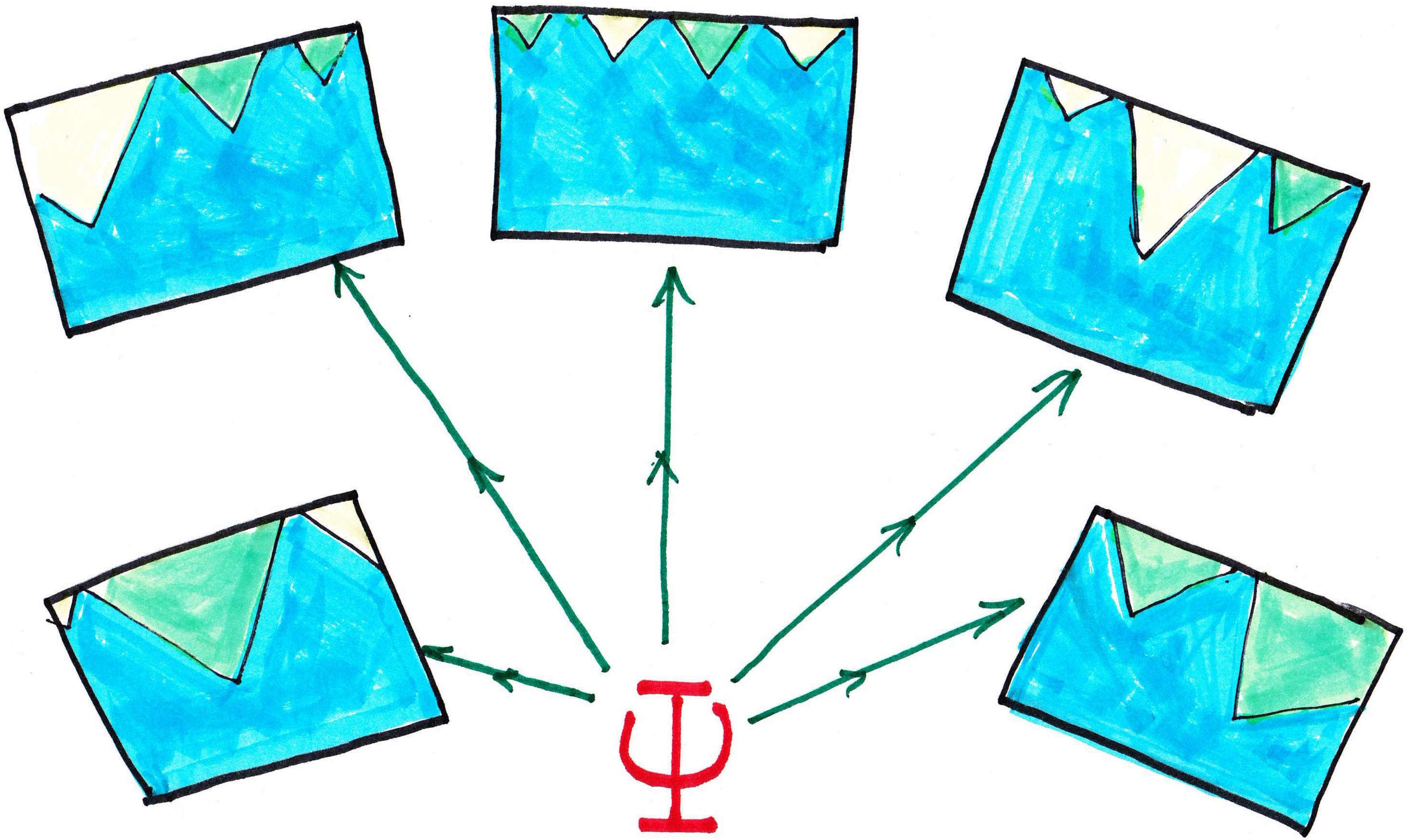
- An initial quantum state that predicts a history of false vacuum inflation. We focus on this for a while.
- Zero probability (p_E) for us to exist in the false vacuum F.
- Low rate of nucleation so that bubble collisions and the back reaction of other bubbles can be neglected.
- Then we are either in a bubble of type A or a bubble of type B.

Classicality and Quasiclassical Histories

- Histories of geometry and field behave classically when the quantum probability is high that they have correlations in time summarized by classical equation of motion.
- Quasiclassical histories behave classically for stretches interrupted by quantum events like bubble nucleation.



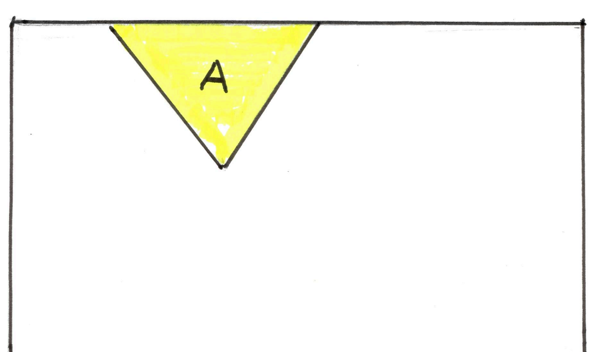
No One Spacetime but An Ensemble of Possible Ones

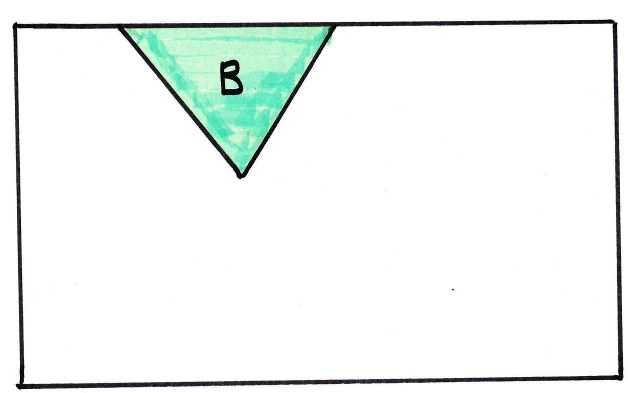


We assume that all sets of histories we consider decohere.

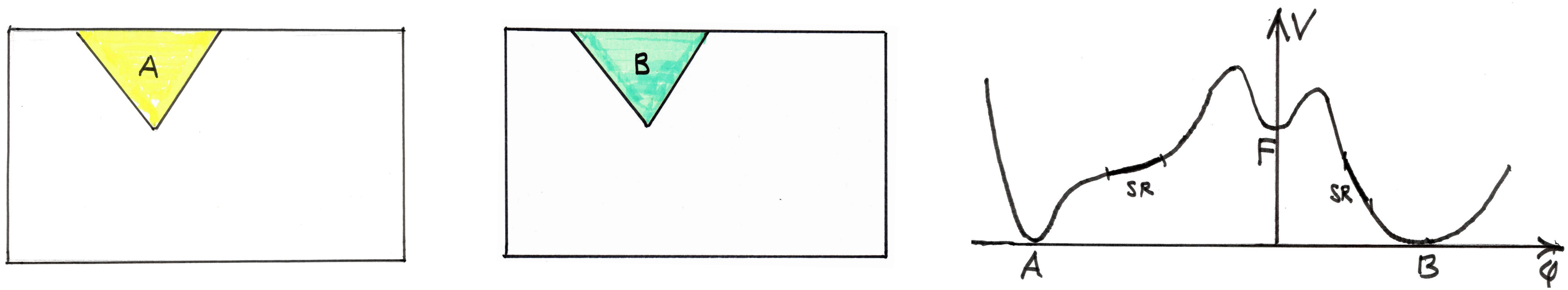
Coarse Graining for Local Obs.

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



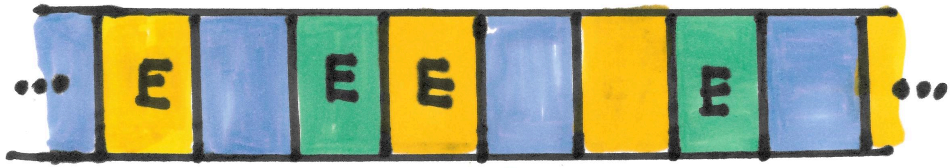
The probabilities to nucleate bubbles of different kind in a false vacuum were calculated by Coleman and DeLuccia.

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

The probabilities for which CMB we observe are:

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

Box Model Universe



$$(p_Y)^{n_Y}(p_G)^{n_G}(1-p_Y-p_G)^{N-n_Y-n_G}(p_E)^{n_E}(1-p_E)^{N-n_E}.$$

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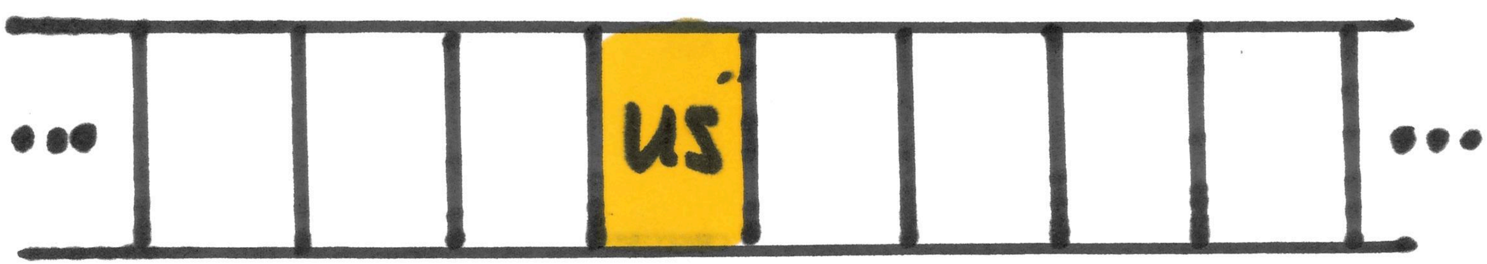
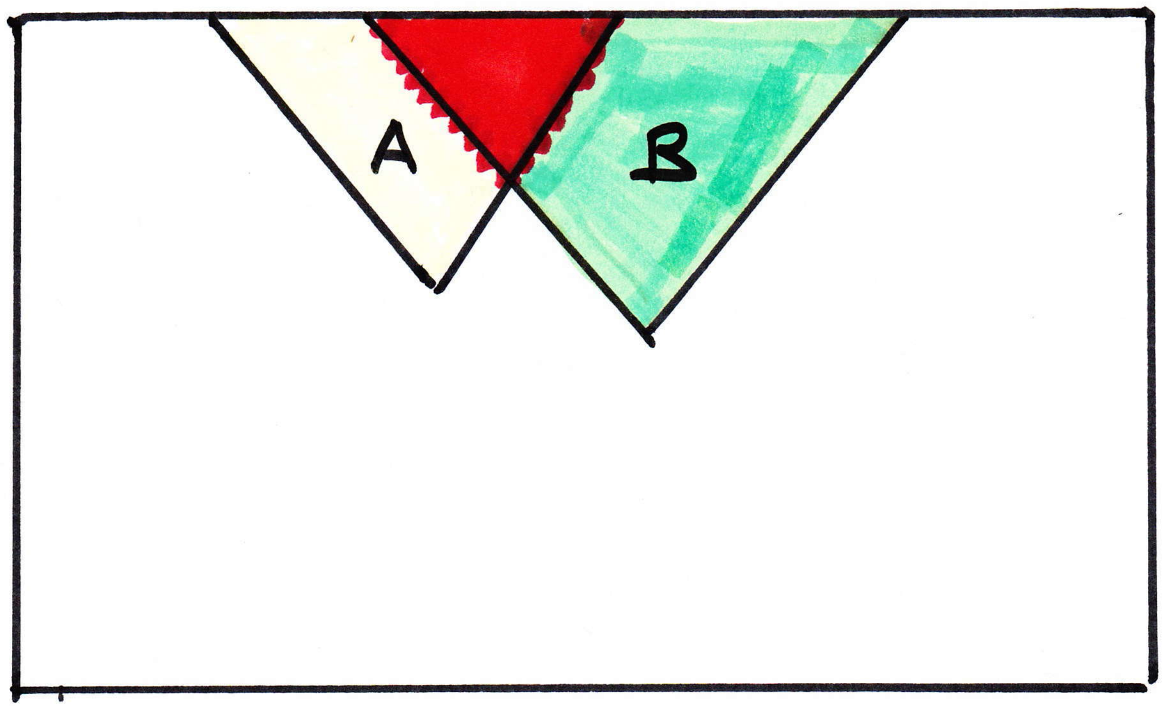


$$p(WOY) = p_Y.$$

Bubble Collisions

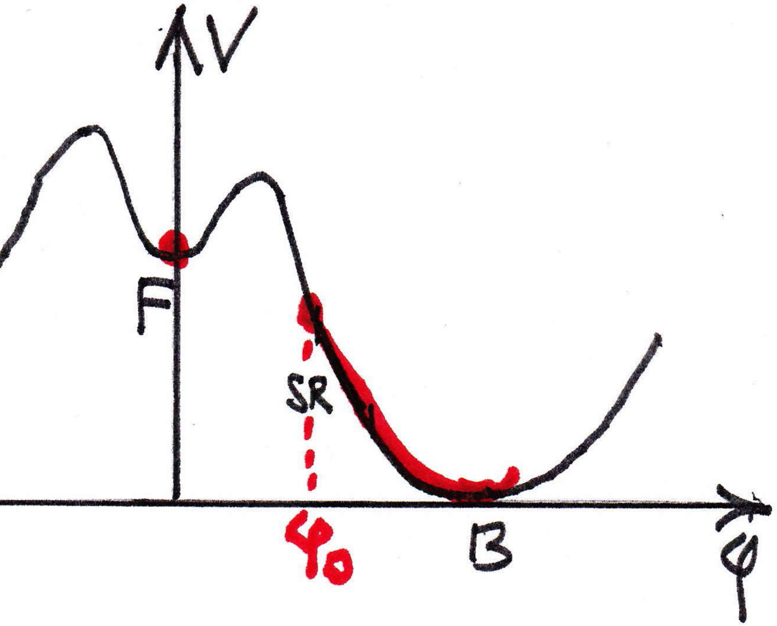


Effectively a new kind of bubble.

CDL probabilities are predicted from the NBWF through the Gratton-Hertog-Turok (GHT) instanton.

Similarly we expect the probability for a white spot in the CMB to be predicted from the NBWF.

No Boundary Wave Function
Ensemble of Classical Histories



The probabilities for our observations are the NBWF probabilities for those histories multiplied the probability that there is at least one copy of us which is

$$1-(1-p_E)^N \approx p_E N$$

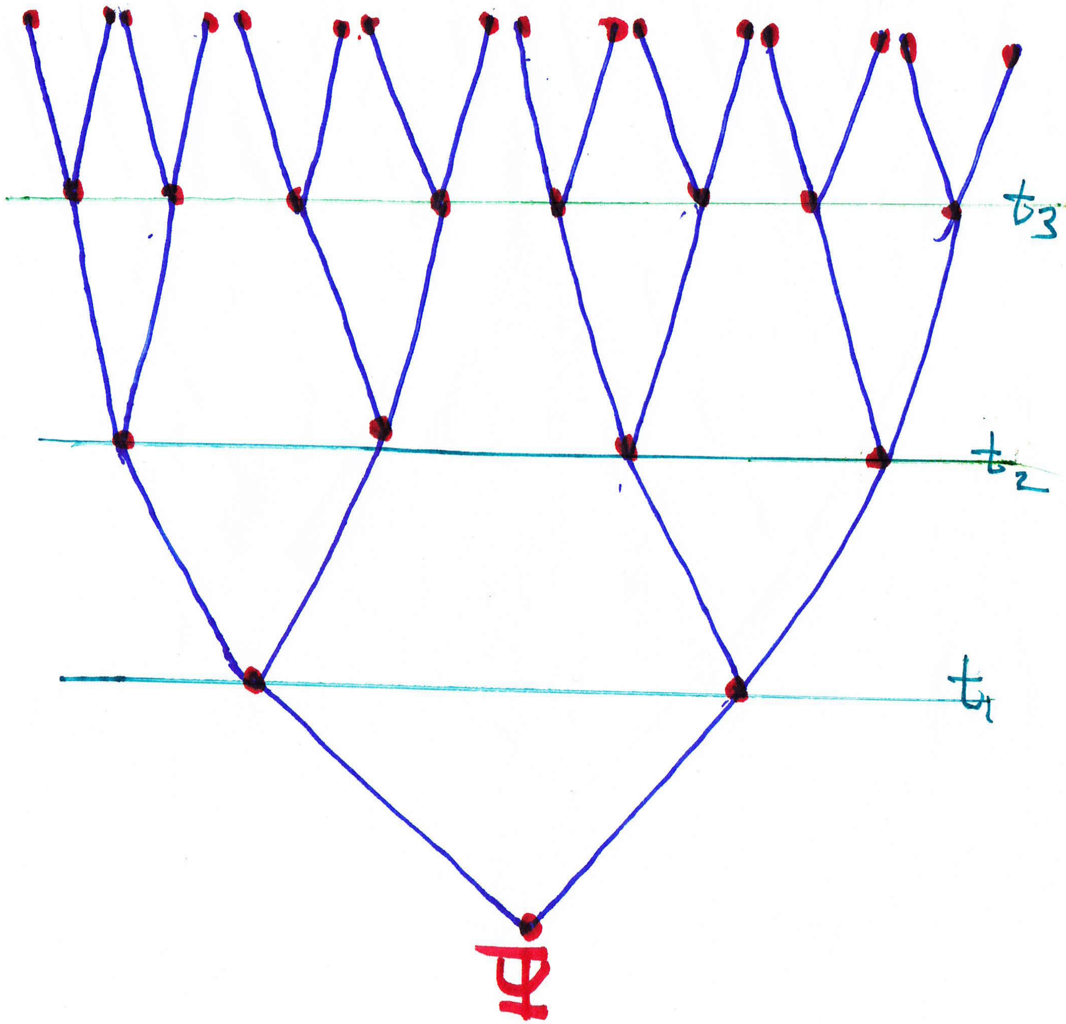
Histories with finite N are suppressed by p_E.

The NBWF ensemble of classical histories is dominated by the ones with the lowest exit from eternal inflation.

The bubble that
rules them all
is our bubble!

	Quantum Cosmology Eternal Inflation	Traditional Eternal Inflation
Target Probabilities	Probabilities for observations in our Hubble volume	Probabilities for observations in our Hubble volume
Spacetime	Ensemble of classical spacetime histories with quantum probabilities	One classical spacetime in which quantum events take place (eg. nucleation)
Observers like us	Quantum systems within the U with a probability p_E to exist in any H-vol.	Classical -- assumed to exist in all hospitable environments
Importance of Large Scale Structure	Details unimportant for local observations.	Central to the definition of probabilities (measure).
Origin of Probabilities for local observation	The quantum state of the universe.	Ratios of numbers of environments for observers of different kinds defined by a sequence of cutoffs (measure)

No Fine-Grained Infinite Future?



- Extending histories into the infinite future is an operation of fine-graining which risks losing decoherence.
- Many more branch state vectors have to be orthogonal

$$\langle \Psi_\alpha | \Psi_\beta \rangle \propto \delta_{\alpha\beta}$$

- Hilbert space rapidly fills up.

In the far future a fine grained mosaic of bubbles may not decohere.

Main Points Again

- False vacuum EI implies quasiclassical histories describing a mosaic of bubbles of true vacuum separated by inflating regions. We are in one bubble.
- Our local observations are described by a much coarser set of quasiclassical histories that ignores any structure outside our Hubble volume.
- Under modest assumptions, probabilities for our observations can be calculated directly from the universe's quantum state. No further `measure' is needed.
- The relative probabilities that we find ourselves in different kinds of bubbles is specified by the action of their CDL instantons.
- This is significantly different from traditional EI.

Is there a measure problem in inflationary cosmology?

YES

Its the problem of
what is the
quantum state of the
universe.