Title: Eternal Inflation in the Light of Quantum Cosmology

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Abstract: If the universe is a quantum mechanical system it has a quantum state.
This state supplies a probabilistic measure for alternative histories of the universe. During eternal inflation these histories typically develop large inhomogeneities that lead to a mosaic structure on superhorizon scales consisting of homogeneous patches separated by inflating regions.
As observers we do not see this structure directly. Rather our observations are confined to a small, nearly homogeneous region within our past light cone. This talk will describe how the probabilities for these observations can be calculated from the probabilities supplied by the quantum state without introducing a further ad hoc measure.

Eternal Inflation in the Light of Quantum Cosmology

Stephen Hawking, DAMTP, Cambridge
Thomas Hertog, APC, UP7, Paris
and Universiteit Leuven (fall).

Mark Srednicki, UCSB, Santa Barbara

Perimeter Institute, July 13, 2011

A Quantum Universe

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

Ψ

That is the problem of Quantum Cosmology.

A Quantum Mechanics of Cosmological Histories

Ψ

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Ψ

The state predicts probabilities for alternative spacetimes and what goes on in them.

Can the
quantum state of the universe
predict the probabilities for
our local observations
in histories with
eternal inflation
without a further `measure'?

Five Pillars

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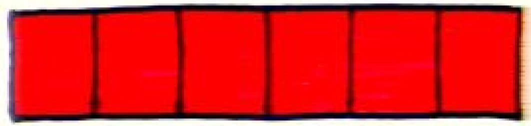
- Our Observations: Focus on probabilities for our observations in our Hubble volume which are conditioned on a description of the observational situation.

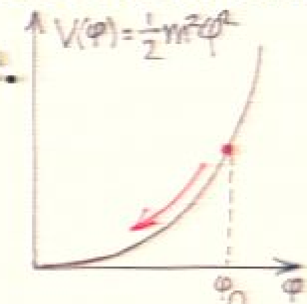
- Adapted Coarse Grainings: Use coarse grainings that follow observations and ignore unobservable features of the universe such as very large scale structure.

Parts of the Talk:

- Box Models: Where we will learn how a quantum theory of the observer can lead to top-down weighting for probabilities for observation.



- One minimum: Where we will learn how to calculate probabilities for histories exhibiting eternal inflation from a wave function of the universe.



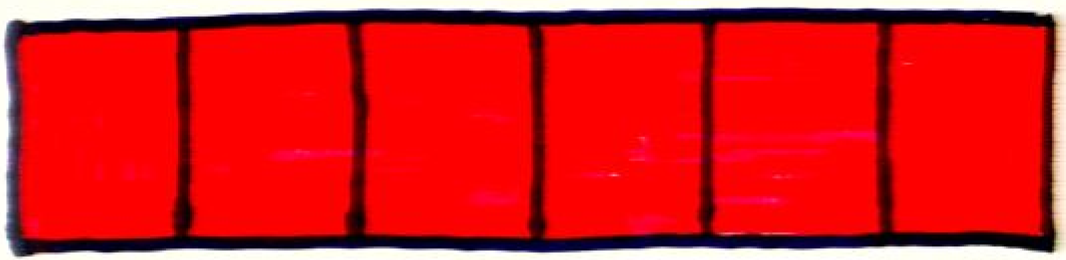
- Landscapes: Where we will learn how to calculate the probabilities that we are in different minima in a toy landscape.

Box Models

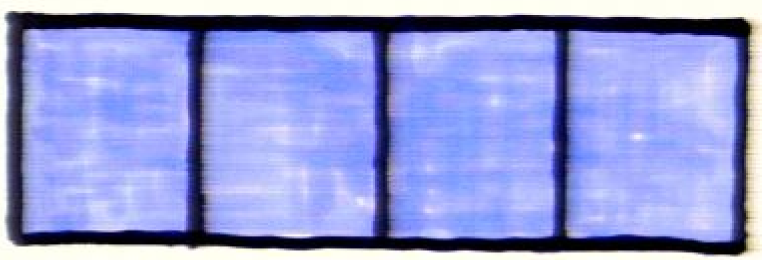
A Model Universe of Hubble Volumes

A universe with two possible configurations of Hubble volumes (1 and 2), with colors red and blue (CMB).

N_1 boxes, all red, occurring with probability p(1).



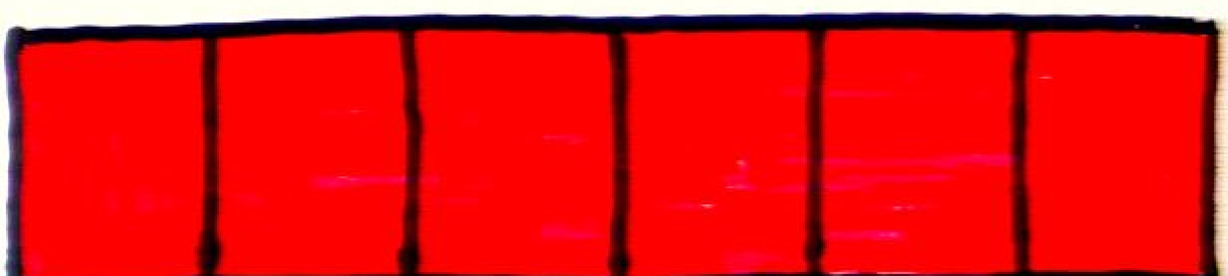
N_2 boxes, all blue, occurring with probability p(2)



p(1) and p(2) are called bottom-up (BU) probabilities.

Model Universe - Observers

- As observers we are physical systems within the universe with only a probability to have evolved in any Hubble volume.
- We are not certain to exist in any Hubble volume, and in a very large universe may be replicated elsewhere.
- This is modeled by assuming a probability p_E for an observer like us to exist (E) in any Hubble volume the same for all of them. (More realistic than most.)



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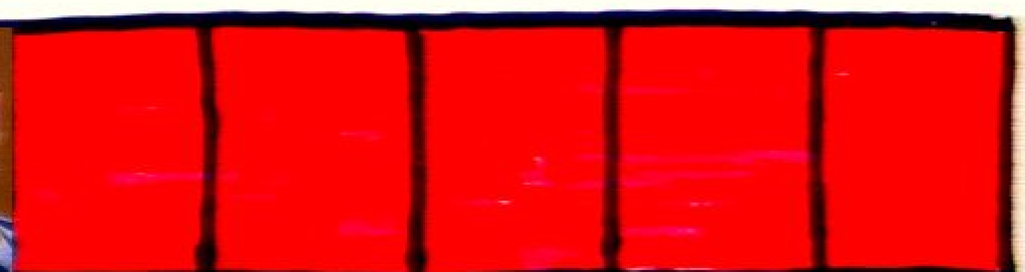

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Model Universe - Observers

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- We … ume, and … else …

p_E includes the probability of the accidents of 3 Gyr of biological evolution and is very, very small.

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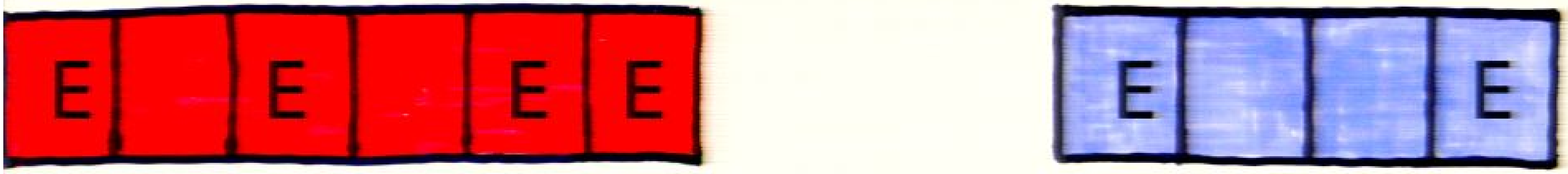
What is the probability that we see red ?



- Assume we are equally likely to be any of the incidences of E (typicality assumption).
- The probability that we see red (WSR) is the probability that we are in the history with all red boxes.
- This is NOT the probability that the history 1 with all red boxes occurs, p(1), because that could happen with no observers.
- Rather the probability that we see red is proportional to the probability that 1 occurs with at least one instance of E, p(1, at least one E).

The probability that we see red (WSR)

The probability that there is at least one instance of E in the history k is

$$p(\text{at least one } E) = 1 - p(\text{no } E) = 1 - (1 - p_E)^{N_k}$$

$$p(WSR) \propto p(1)[1 - (1 - p_E)^{N_1}]$$

$$p(WSB) \propto p(2)[1 - (1 - p_E)^{N_2}]$$

$$p(WSR) = \frac{p(1)[1 - (1 - p_E)^{N_1}]}{\sum_k p(k)[1 - (1 - p_E)^{N_k}]}$$

Such conditional probabilities are called top-down (TD) probabilities and the factor $[1 - (1 - p_E)^{N_k}]$ is the top-down weighting.

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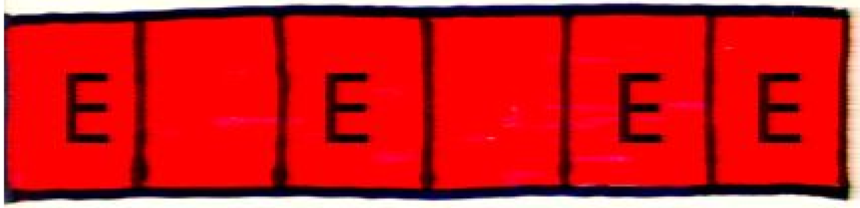

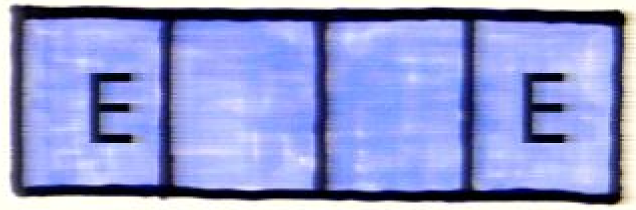

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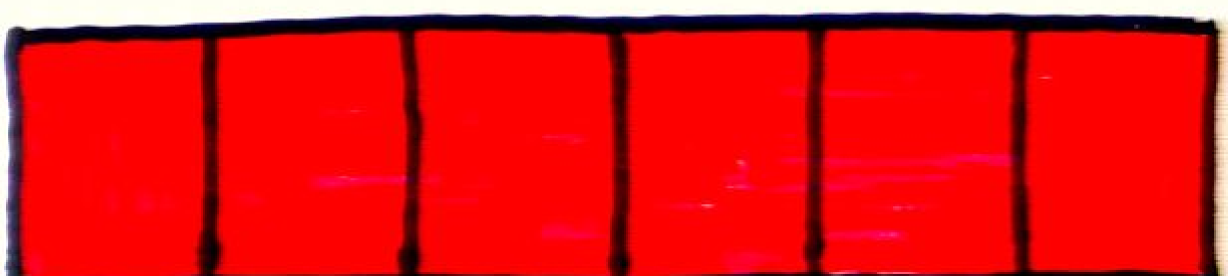

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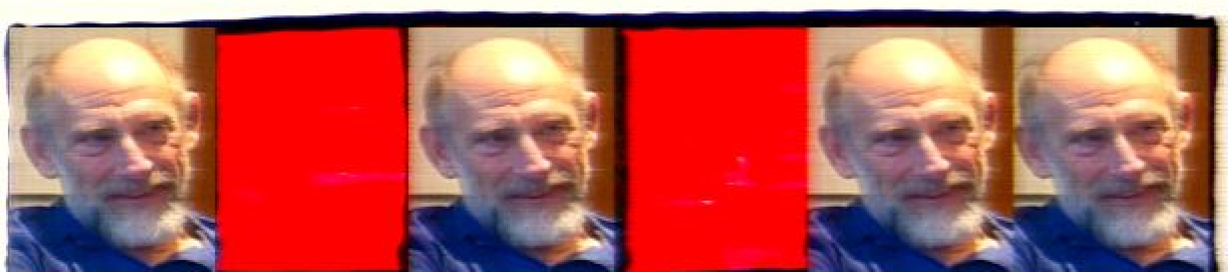

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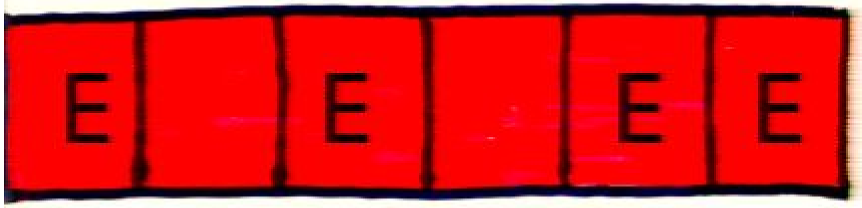

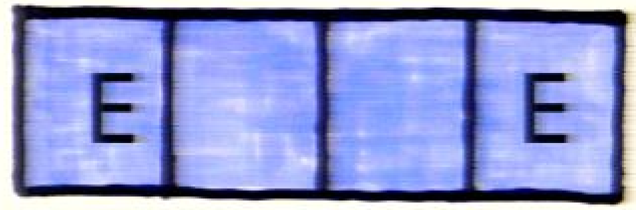

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Such conditional probabilities are called top-down (TD) probabilities and the factor $[1 - (1 - p_E)^{N_k}]$ is the top-down weighting.

Top-down weighting
is not a choice, but
an inevitable consequence
of treating observers
as quantum mechanical systems.

Important Limiting Cases

$N \ll 1/p_E$ We are rare,

$N \gg 1/p_E$ We are common.

$$p(WSR) = \frac{p(1)[1-(1-p_E)^{N_1}]}{\sum_k p(k)[1-(1-p_E)^{N_k}]}$$

$p_E N_1 \ll 1 \quad p_E N_2 \ll 1 \quad p(WSR) \approx \frac{N_1 p(1)}{N_1 p(1) + N_2 p(2)}$

This is volume weighting --- favors large N.

$p_E N_1 \gg 1 \quad p_E N_2 \ll 1 \quad p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$

Suppresses small N.

$p_E N_1 \gg 1 \quad p_E N_2 \gg 1 \quad p(WSR) \approx p(1)$

No top-down weighting.

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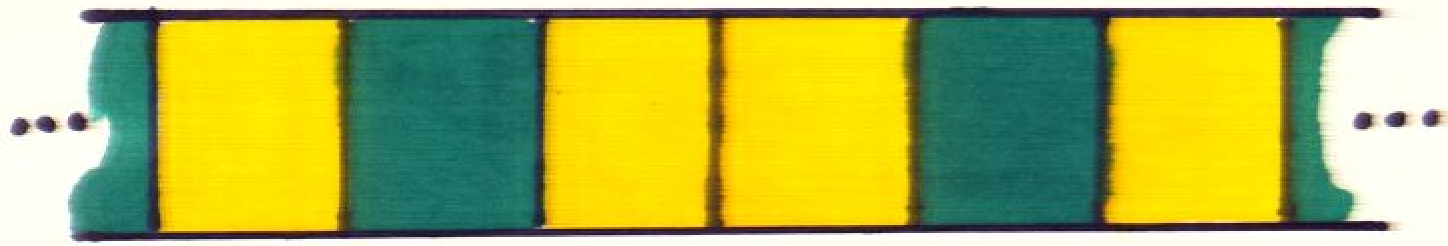
In all three cases, p_E drops out!

An Improved (Y,G) Model

- Two kinds of Hubble volumes k=1,2. Each has a probability $p(Y|k)$ to be yellow (Y) and $p(G|k) = 1 - p(Y|k)$ green (G). There are an infinite number of boxes in each kind (common limit). A fine-grained history is a configuration of Y's and G's for each k.

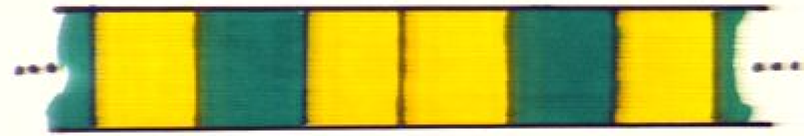


- The probability of any particular fine-grained history is

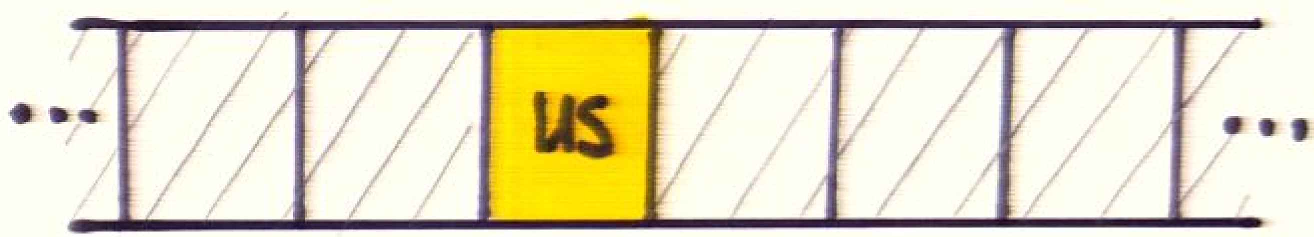
$$p(k)p(Y|k)^{n_Y}p(G|k)^{n_G} = 0$$

- Physical alternatives are coarse-grainings of these histories. Their probabilities are sums of those for the infinite number of fine-grained histories in each coarse-grained one.

Coarse-graining



- What is the probability that we see Y?
- Calculating for finite N's (cutoffs) and taking limits (as before) leads to ambiguities from the ratio N_1/N_2.
- Rather calculate directly using a coarse-graining that follows the color in our box and ignores the others, summing over the probabilities of whether they others are Y or G.



- The result is

$$p(WSY) = \sum p(Y|k)p(k)$$

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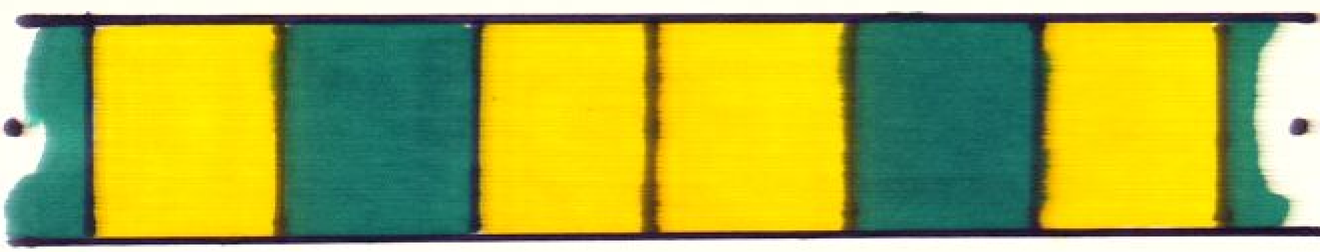

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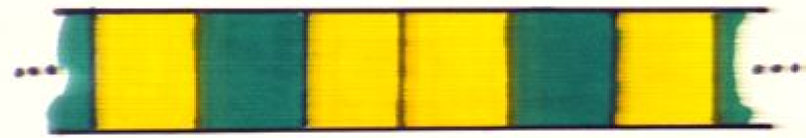

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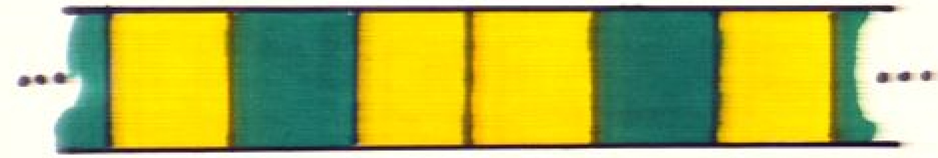
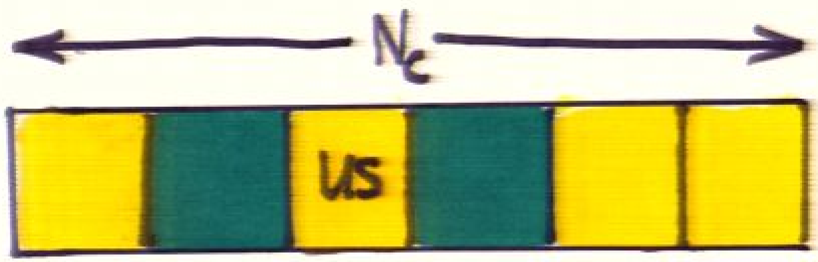
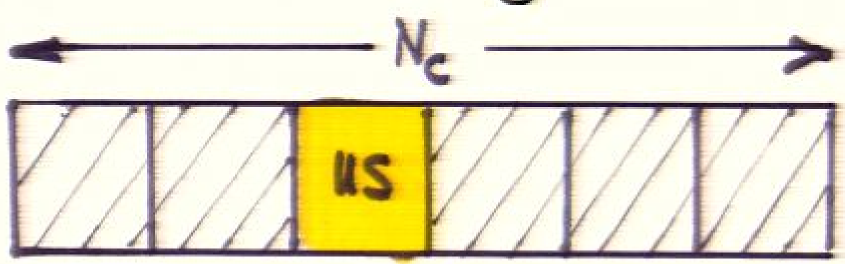


- What is the probability that we see Y?
- Assume a finite number of boxes N_c and take the limit as it becomes infinite.
- Its ambiguous to take the limit first and then coarse-grain.



- Rather coarse grain first and then take the limit



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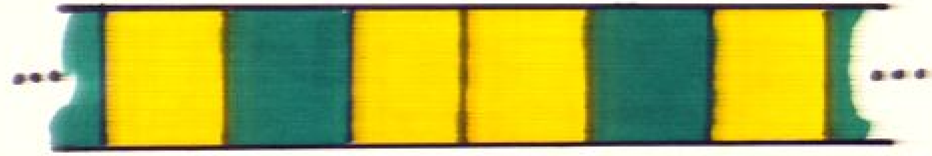

- What is the probability that we see Y?

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- It arse-
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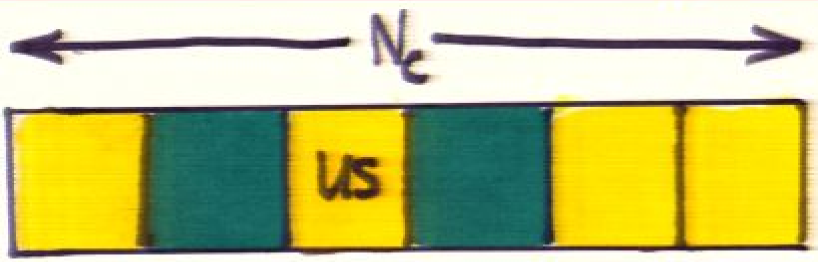
> Coarse-graining is the key to finiteness and definition, but requires an ensemble of histories to sum over, not just one.



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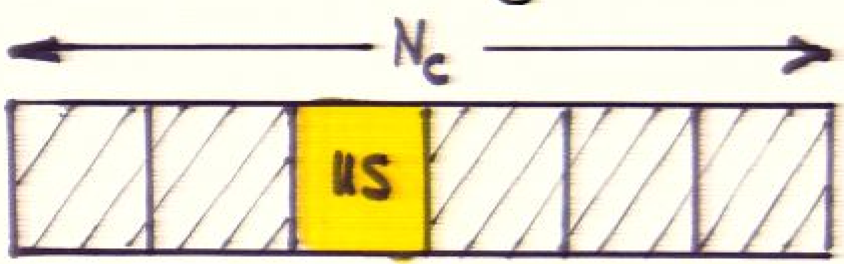

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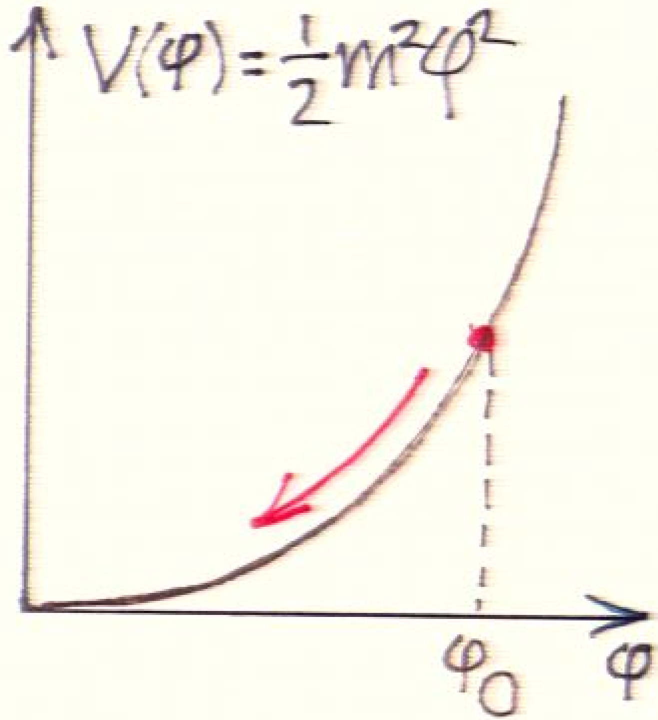
More General Models

- The (Y,G) model assumes that all Hubble volumes in the same history have the same probabilities for Y and G.
- But each Hubble volume in history could have some further property j on which the probabilities for Y and G depend (e.g. being in one kind of bubble or another) then

$$p(WSY) = \sum_{kj} p(Y|jk)p(j|k)p(k)$$

One Minimum

Qualitative EI



- A scalar field φ moving in a potential $V(\varphi) = (1/2)m^2\varphi^2$

- A quantum state Ψ (NBWF)

- From Ψ derive the (BU) probabilities for the ensemble of homo/iso classical background histories labeled by the value φ_0 at the start of roll down (the p(k)).

- Add linear fluctuations in the scalar field and geometry.

Selection for EI

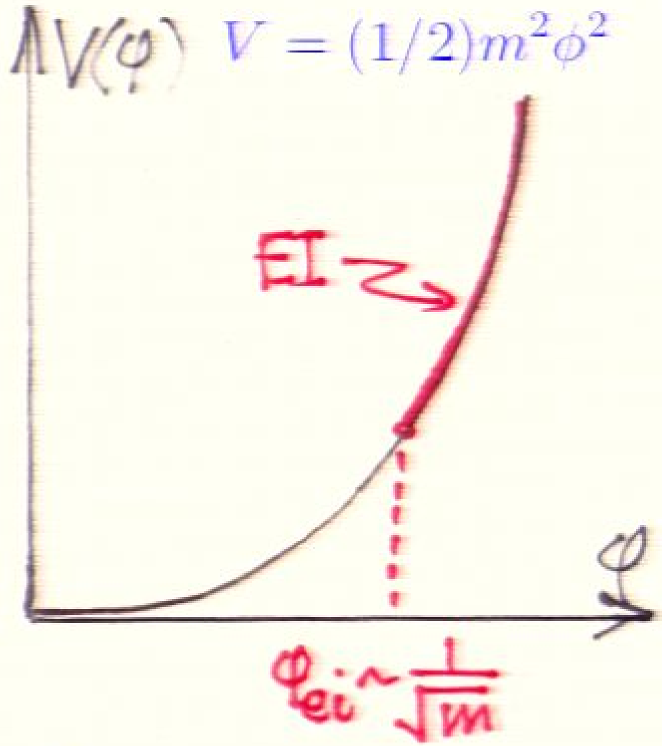
- Regime of eternal inflation $V^3 > (V')^2$

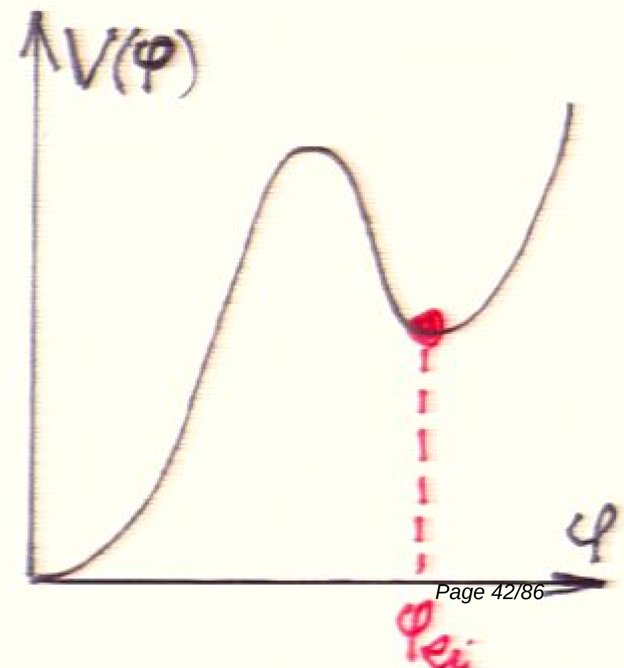
- Fluctuations that leave the horizon during EI grow large and make the universe inhomogeneous on superhorizon scales.

- Constant density surfaces become large. TD weighting suppresses histories that do not have EI.

$$p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$$

- For EI histories TD=BU.





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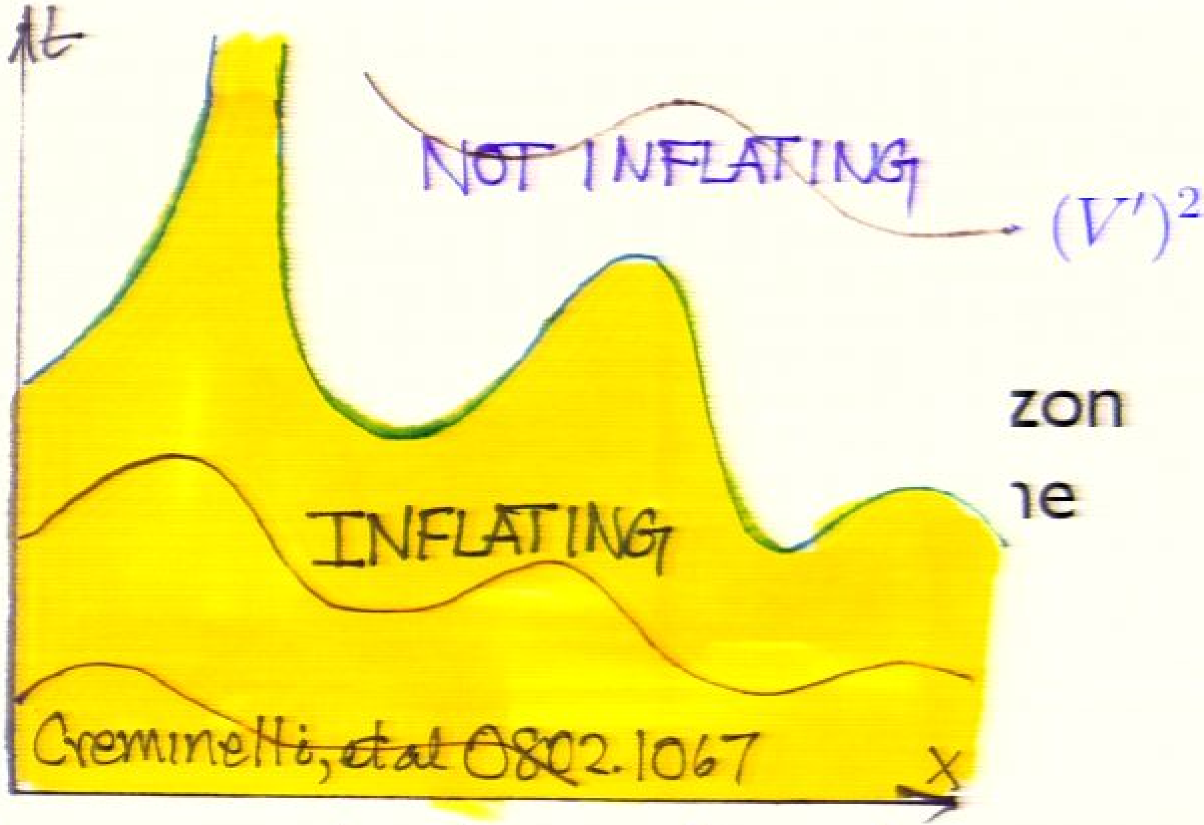

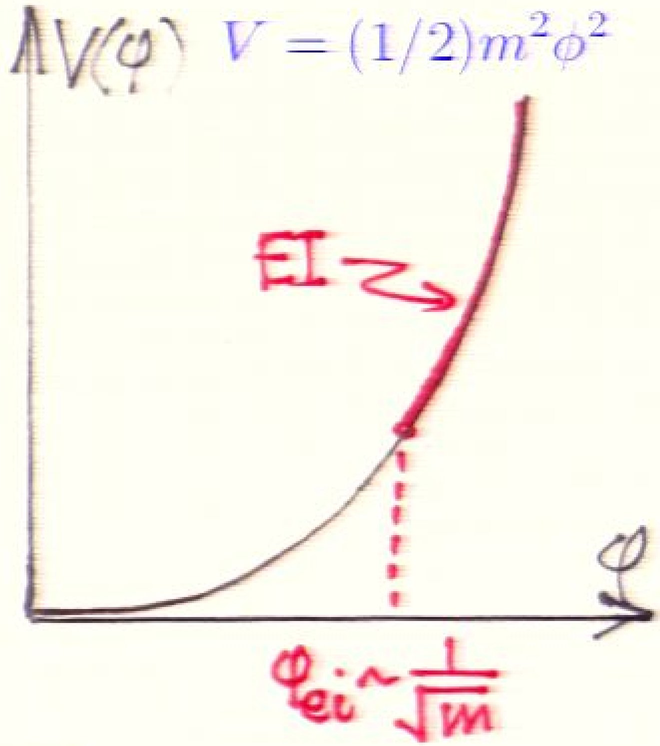

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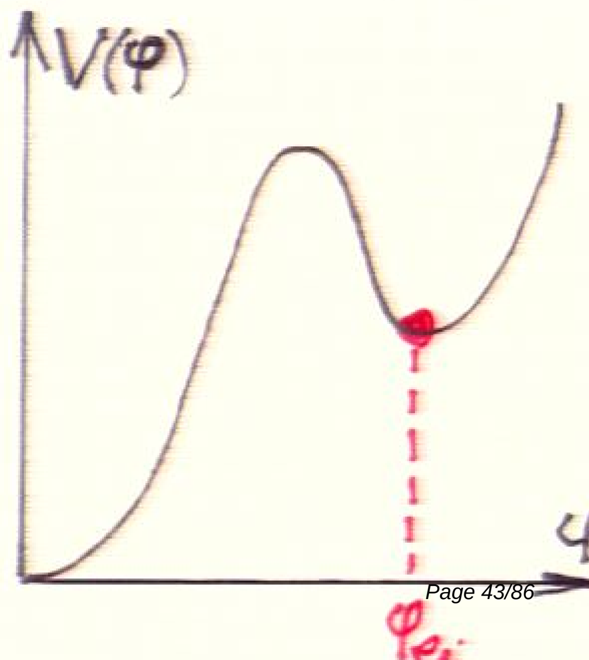

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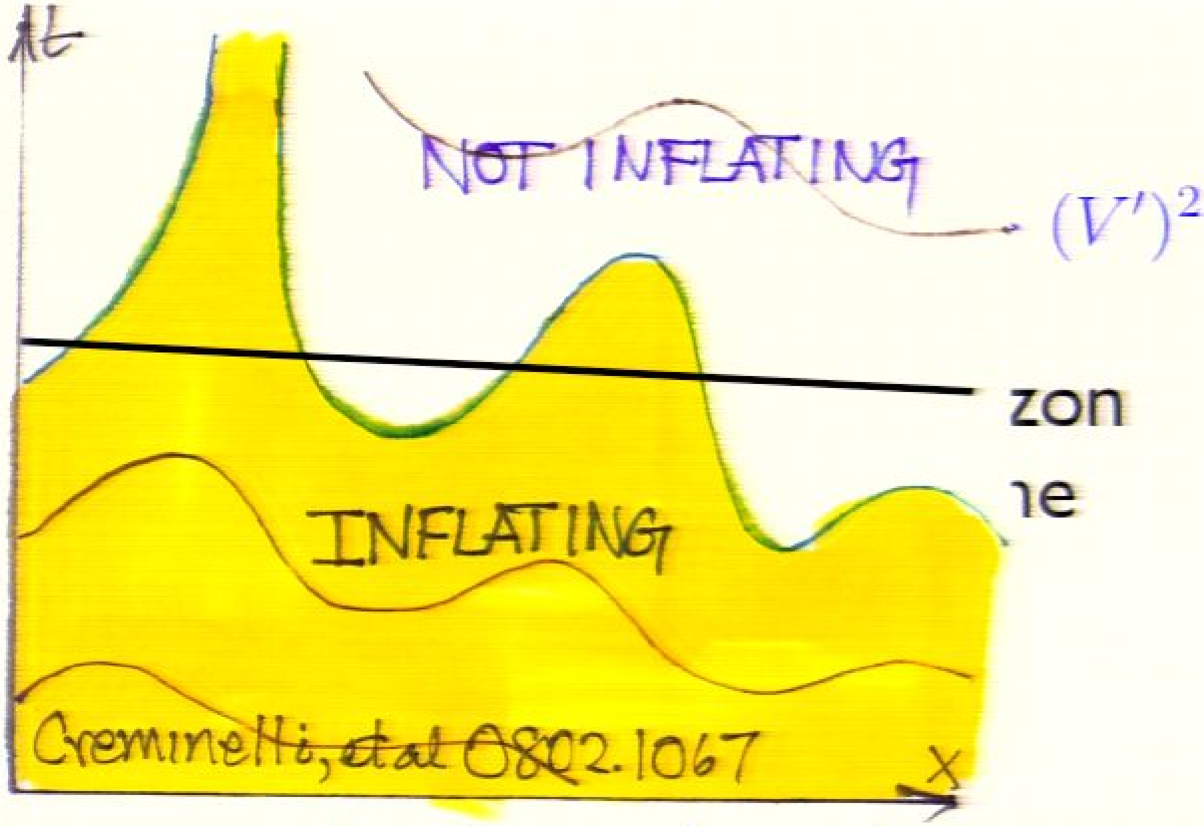

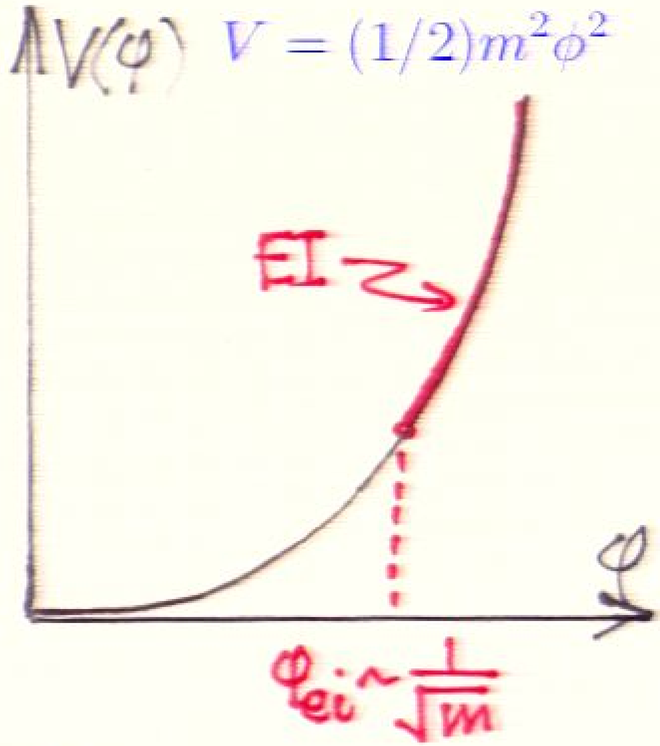

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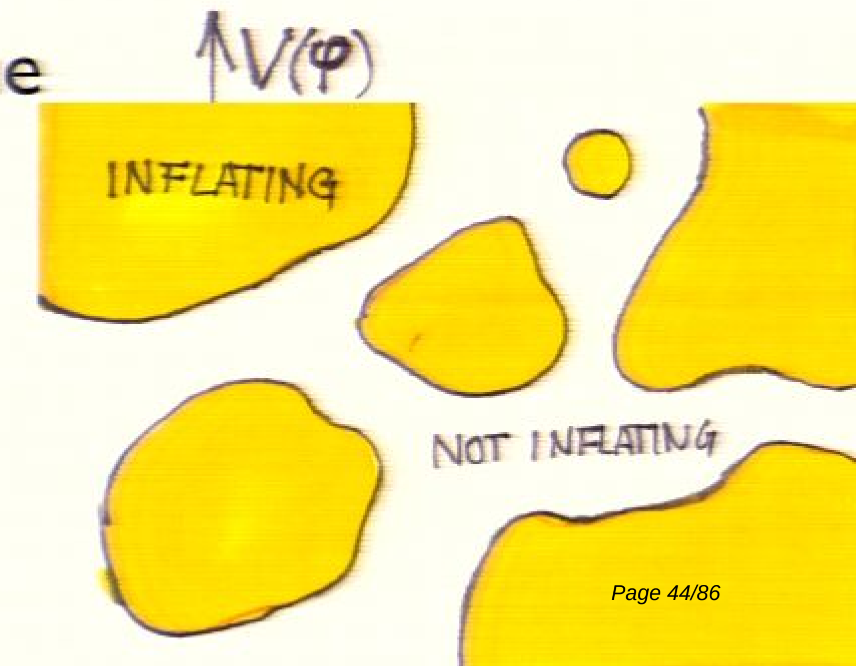
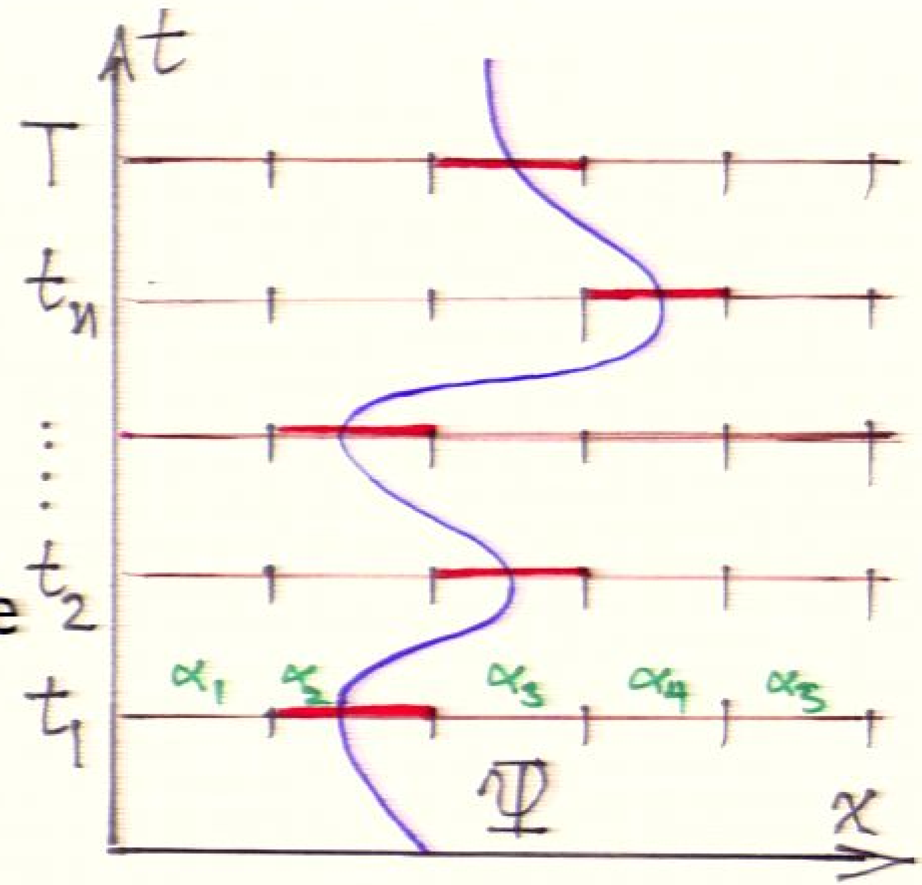


Causality

- Causality implies that observations today do not depend on what will go on in the future.
- How far we are from the start of inflation, what patterns we might observe in the CMB, etc, depend on what happened in our past light cone.
- We may calculate the probabilities for future histories, but should coarse grain (sum) over future alternatives to get probabilities for observations today.

Coarse Graining the Future in NRQM



- Consider a state $|\Psi\rangle$ and projections $\{P_\alpha(t)\}$ onto a set of ranges of x, $\{\Delta_\alpha\}$
- The probability that the particle is in region α_1 at a time t_1

$$p(\alpha_1) = ||P_{\alpha_1}(t_1)|\Psi\rangle||^2$$

- We could calculate this probability by first calculating the probabilities of future histories and then summing

$$p(\alpha_n, \cdots, \alpha_1) = ||P_{\alpha_n}(t_n) \cdots P_{\alpha_1}(t_1)|\Psi\rangle||^2$$

$$p(\alpha_1) = \sum_{\alpha_n, \cdots, \alpha_2} p(\alpha_n, \cdots, \alpha_1) = ||P_{\alpha_1}(t_1)|\Psi\rangle||^2$$

Coarse Graining the Future in NRQM

- Consider a state $|\Psi\rangle$ and projections $\{P_\alpha(t)\}$ onto a set of ranges of x, $\{\Delta_\alpha\}$
- The probability that the particle is in region α_1 at a time t_1

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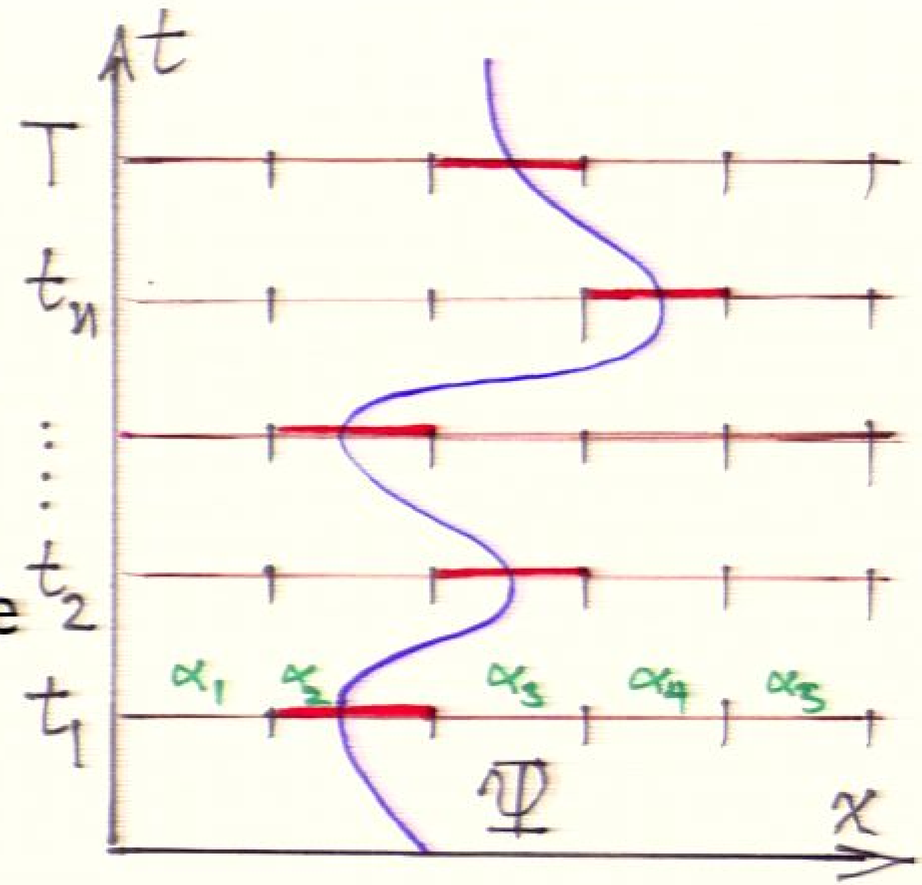

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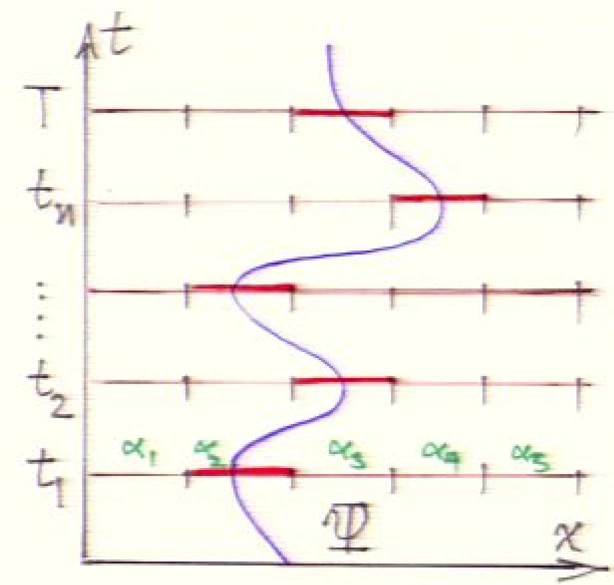
Its easier and more secure to calculate directly the coarse grained probabilities that ignore the future.

Coarse Graining is Inevitable



- Histories that extend to infinite time have probability zero.

$$|| \cdots P_{\alpha_n}(t_n) \cdots P_{\alpha_1}(t_1)|\Psi\rangle||^2 = 0$$

- Bundling histories together -- coarse graining -- is necessary just to get non-zero probabilities.

- For that more than one history is needed.

- Why not just start with the coarse graining relevant for observation?

The no-boundary wave function (NBWF) is a model of the quantum state determining probabilities for classical histories (p(k)) and for the observations in a Hubble volume ($p(Y|k)$).

$$\Psi = \int_{\mathcal{C}} \delta g \delta \phi \exp(-I[g, \phi])$$

Minisuperspace Models

Geometry: Homogeneous, isotropic, closed.

$$ds^2 = (3/\Lambda)\left[N^2(\lambda)d\lambda^2 + a^2(\lambda)d\Omega_3^2\right]$$

Matter: cosmological constant Λ plus homogeneous scalar field moving in a quadratic potential.

$$V(\Phi) = \frac{1}{2}m^2\Phi^2$$

Theory: Low-energy effective gravity.

$$I_C[g] = -\frac{m_p^2}{16\pi}\int_M d^4x(g)^{1/2}(R - 2\Lambda) + (\text{surface terms})$$

No-Boundary Wave Function (NBWF)

$$ds^2 = (3/\Lambda)\left[N^2(\lambda)d\lambda^2 + a^2(\lambda)d\Omega_3^2\right]$$

$$\Psi(b,\chi) \equiv \int_C \delta N \delta a \delta\phi \exp(-I[N(\lambda), a(\lambda), \phi(\lambda)]/\hbar).$$

The integral is over all $(a(\lambda), \phi(\lambda))$ which are regular on a disk and match the (b, χ) on its boundary. The complex contour is chosen so that the integral converges and the result is real.

Not all classical spacetimes predicted

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$$\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}$$

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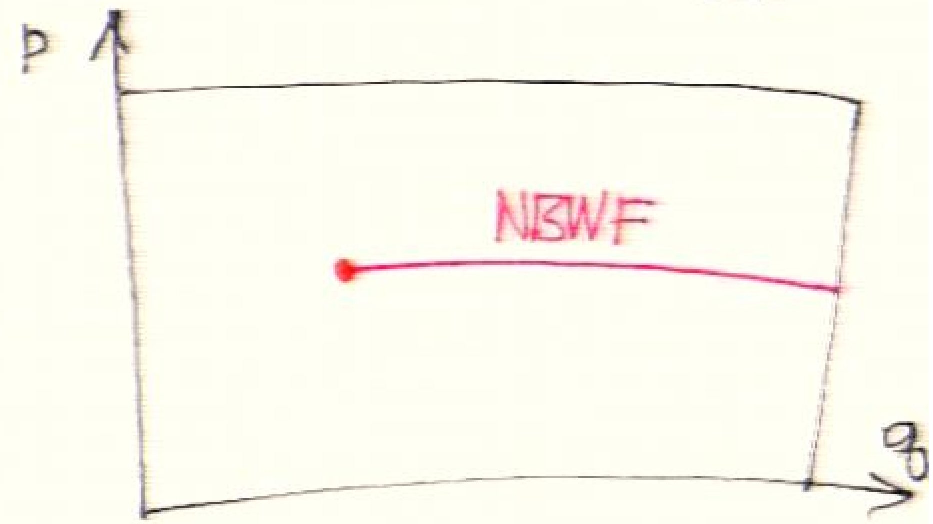
$$p_A = \nabla_A S \qquad \text{prob(class hist)} \propto \exp(-2I_R/\hbar)$$

Provided! $|\nabla_A I_R| \ll |\nabla_A S|$



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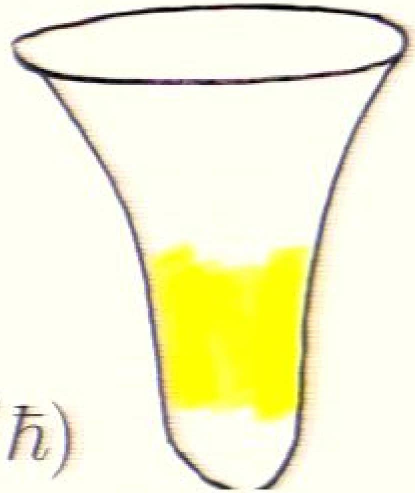

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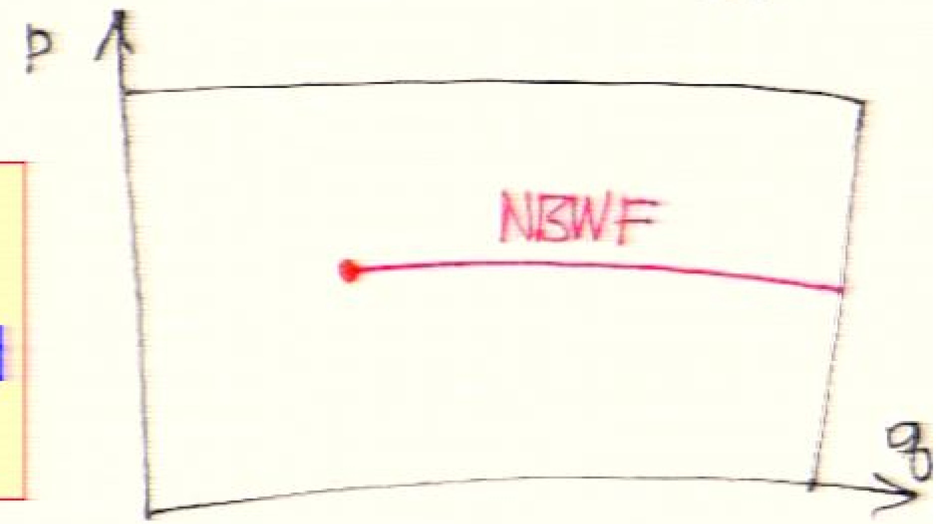

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- All histories exhibit scalar field driven inflation.

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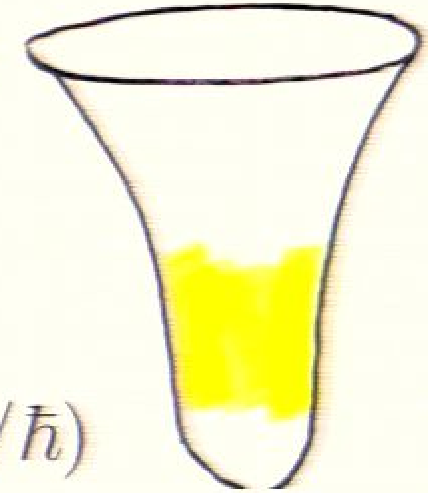

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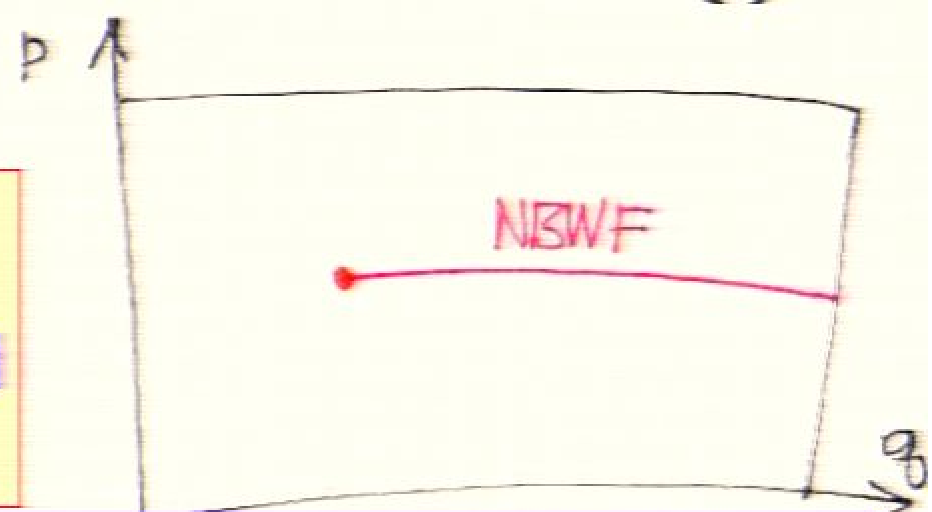

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- All histories exhibit scalar field driven inflation.

Any WKB state that predicts classical spacetime restricts classical phase space to a surface of half the number of dimensions

NBWF Fluctuation Probabilities

$$p(z_{(n)}|\phi_0) \approx \sqrt{\frac{\epsilon_* n^3}{2\pi H_*^2}} \exp\left[-\frac{\epsilon_*}{2H_*^2} n^3 z_{(n)}^2\right]$$

where ϵ_* and H_* are the slow roll and expansion parameters when the mode leaves the horizon $n = a_* H_*$

- This is essentially the Bunch-Davies vacuum (not a surprise.)
- Fluctuations are large when

$$\frac{H_*^2}{\epsilon_*} \geq 1 \qquad \text{or} \qquad \frac{V^3}{V'^2} \geq 1$$

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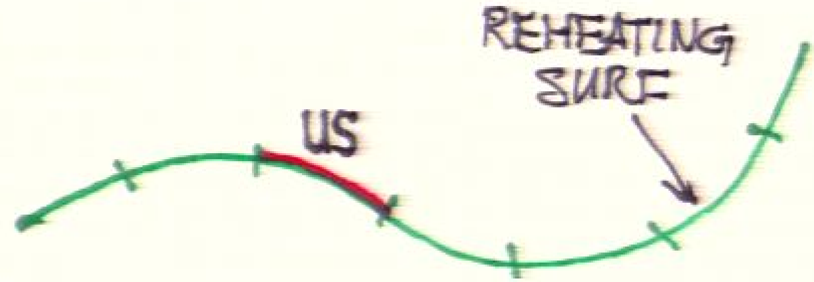
Probabilities for CMB



$$p(W\,S\,Y) = \sum_k p(Y|k)p(k)$$

$$p(W\,S\;C_\ell^{\rm obs}) = \sum_{\phi_0,F} p(C_\ell^{\rm obs}|\phi_0,F)p(\phi_0,F)$$

Denote superhorizon fluctuations by F. Consider the local observable $C_\ell^{\rm obs}$ in our Hubble volume and the ansatz:

$$p(C_\ell^{\rm obs}|\phi_0,F) \approx p(C_\ell^{\rm obs}|\phi_0,F=0)$$

I.e. assume that for the purpose of calculating local observables we can ignore the back reaction on the reheating surface produced by large superhorizon modes that left their horizons during EI.

Every Hubble volume is then the same and coarse graining outside ours is easy as in the (Y,G) model.

Support for the Ansatz

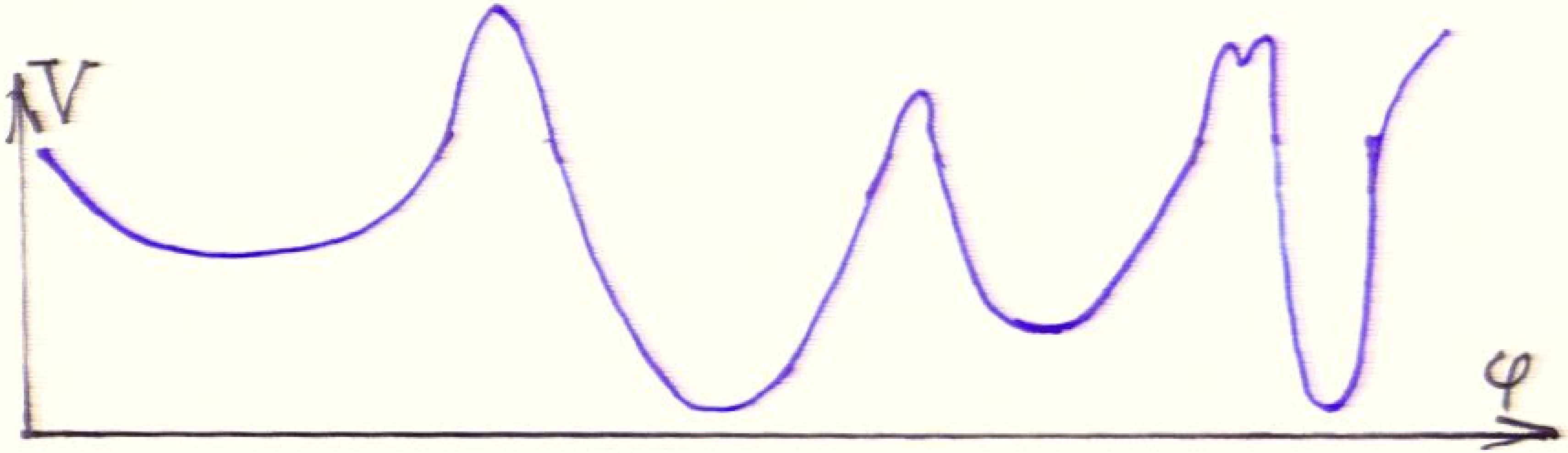
$$p(C_\ell^{obs}|\phi_0, F) \approx p(C_\ell^{obs}|\phi_0, F=0)$$

- Cosmic no-hair theorems: These say just the ansatz provided there are a sufficient number of efolds after N the exit from EI. Since $N \sim 1/m \sim 10^6$ this condition seems ok.
- Explicit calculation in solutions with big inhomogeneities on large scales and linear fluctuations on small scales like the GHT bubble instanton.
- This ansatz is not a new principle of quantum mechanics or a further measure but a testable approximation.

Hertog and Turok Giddings and Sloth

Landscapes

A Model Landscape



- Different minima K with

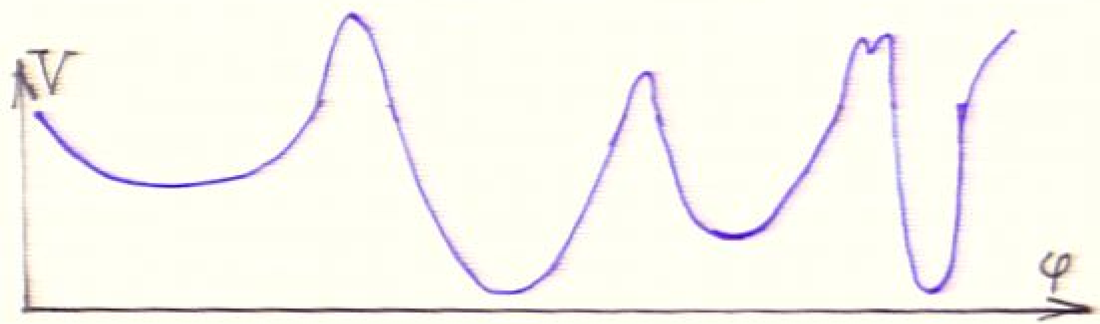
$$V_K(\phi) \approx \Lambda_K + \mu_K \phi^{n_K}$$

and big potential barriers between them (no tunneling in leading order semiclassical.)

- Objective: The probability $p(n, \Lambda, \mu | D)$ for the parameters of our minimum given our data D.

- Assume the NBWF for illustration.

Mechanisms for the Selection of Landscape Regions (`Potentials')



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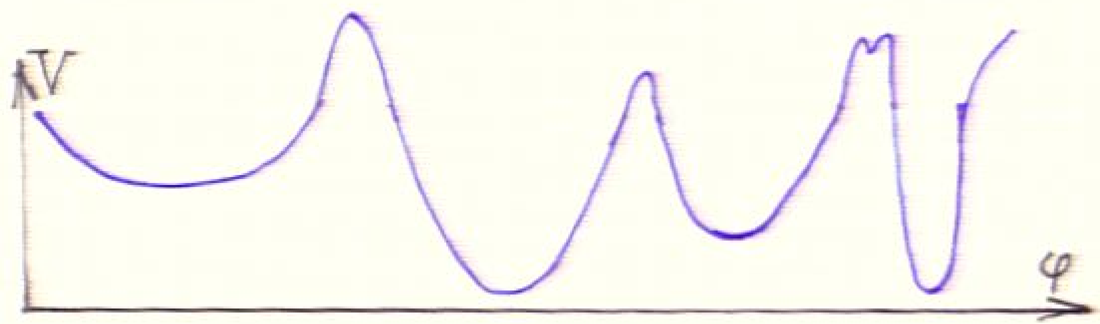

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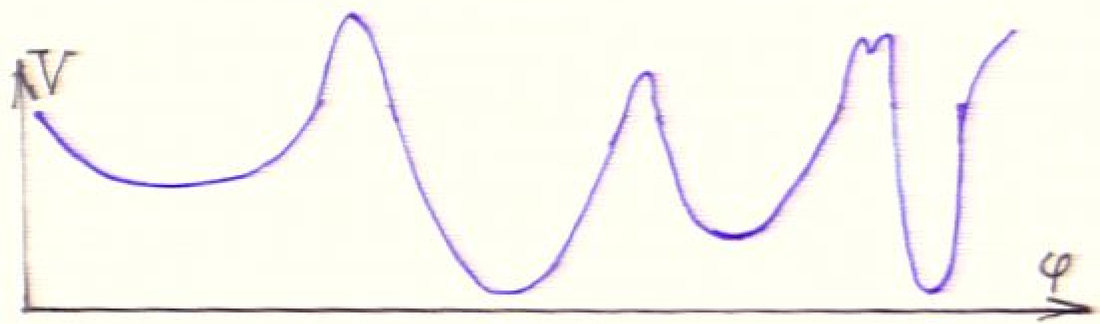

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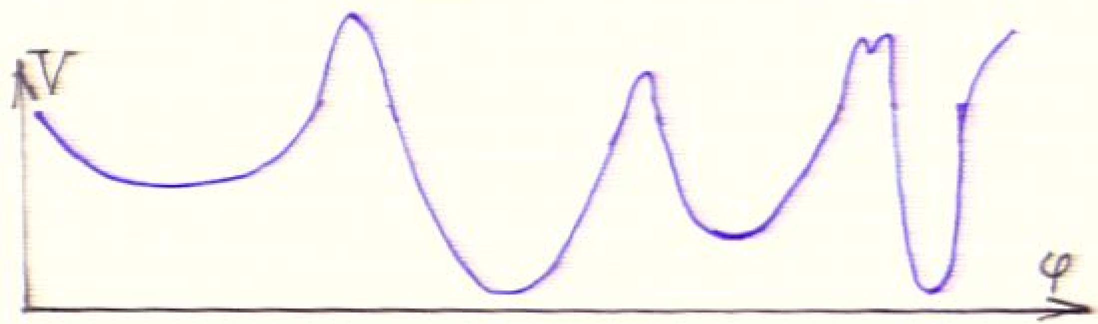

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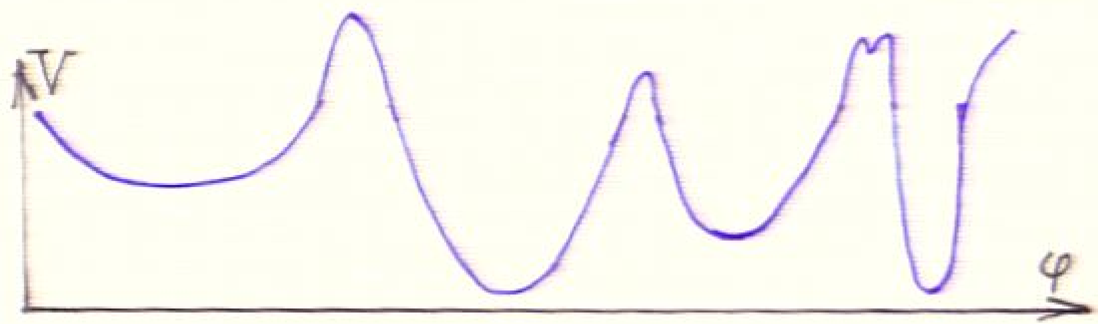
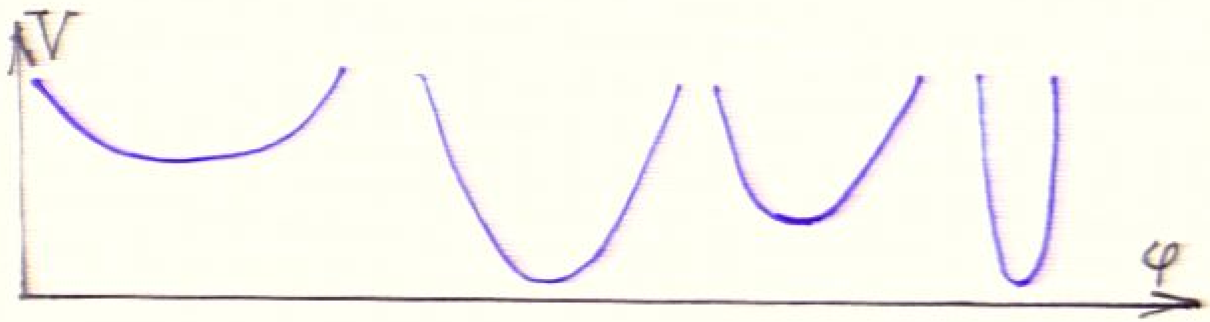


- Selection for potentials that allow a classical realm (an ensemble of classical histories.)
- Selection for potentials that allow eternal inflation.
- Selection for histories around a given minimum that have the lowest exit from eternal inflation.
- Selection `anthropically' for parameters consistent with our local data.

Selection for a Classical Realm



- $\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}\,.$

- Require a potential that leads to
$$|\nabla_A I_R| \ll |\nabla_A S|$$

- Numerical evidence suggests that this happens when the potential allows for slow roll inflation (not too steep).

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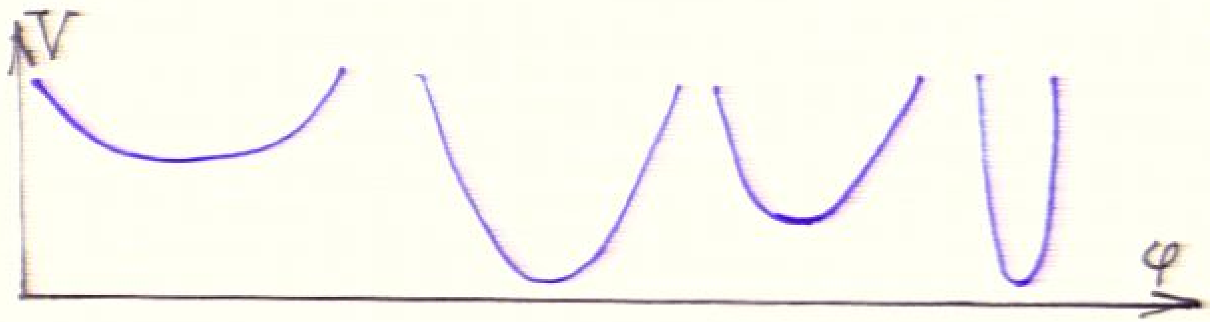

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Selection for Eternal Inflation

Top-down weighting suppresses histories with small reheating surfaces compared to histories with the large (or infinite) reheating surfaces generated by eternal inflation.

$$p(WSR) \approx \frac{p(1)}{p(1) + N_2 p_E p(2)} \approx 1$$

Selection for the History with the Lowest Exit from Eternal Inflation

$$p(\phi_{0K}) \propto \exp\left(\frac{\pi}{\Lambda_K + V_K(\phi_{0K})}\right)$$

Among the selected set of eternally inflating histories with $\phi_0 > \phi_{ei}$ the one with $\phi_0 \approx \phi_{ei}$ will dominate.

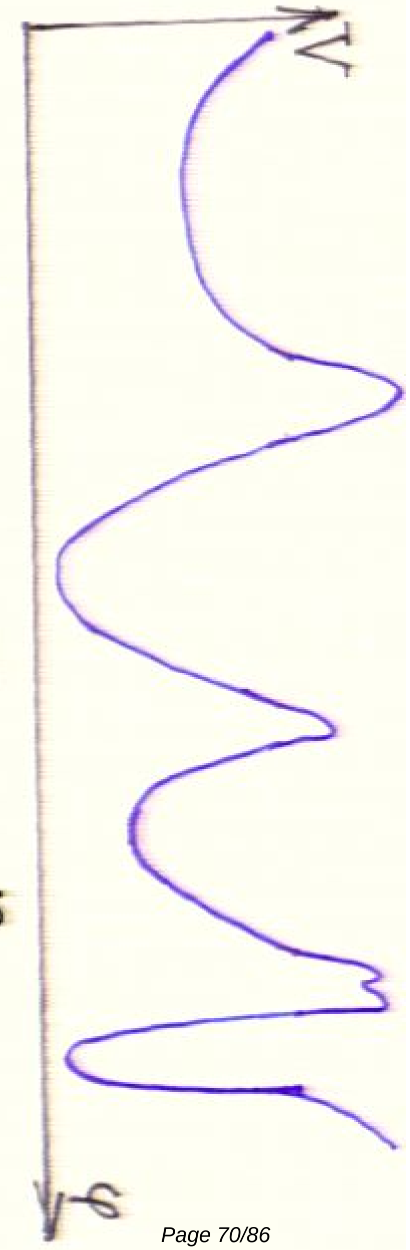
Quadratic Minima Dominate

$$V_K(\phi) \approx \Lambda_K + \mu_K \phi^{n_K}$$

- Assume Λ's approx. zero and the μ's approx. comparable (to be justified self-consistently).
- In the region selected for classicality and EI. and for the dominant history at the exit of EI

$$p(n_K|\mu_K) \propto \exp\left[\pi/V(\phi_{ei})\right] \approx \exp(\mu_K^{-2/2+n_K})$$

- Assuming the μ's are comparable this implies that the lowest value of n_K =2 dominates.
- Standard CMB calculations mean that we predict a spectral index of .97 and a scalar tensor ratio of about 10%



`Anthropic' Selection

$$(\text{TD weight}) = 1-(1-p_E)^N$$

$$p_E = p(D|n, \Lambda, \mu)$$

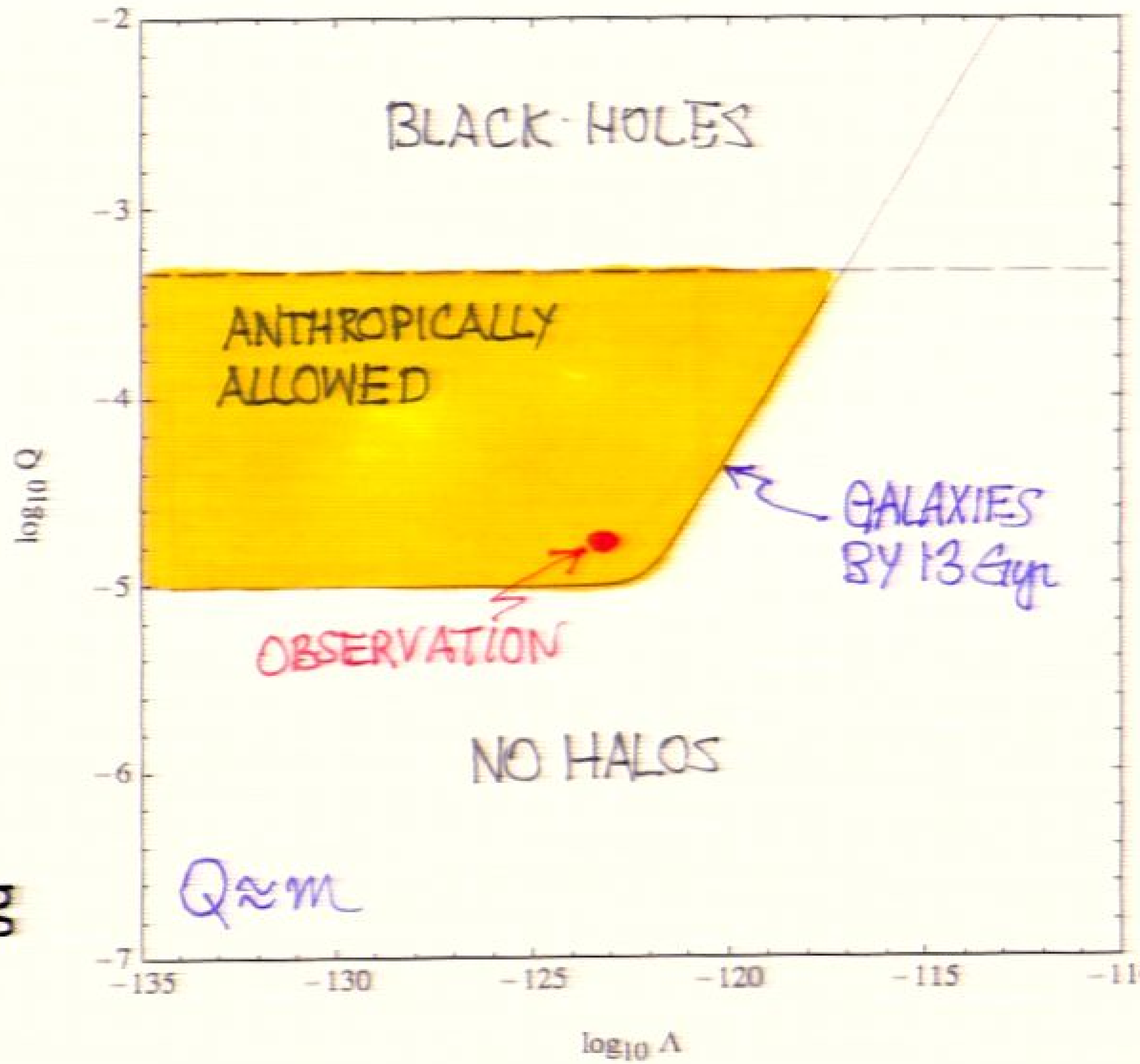
- For parameters where the data can't exist $p_E = 0$ then TD weight $= 0$ no matter what N is.
- This is traditional `anthropic' selection emerging at a fundamental level by including observers as quantum physical systems within the universe.
- NBWF probabilities can help with anthropic selection by supplying priors that are not uniform.

Anthropic Reasoning
is not a choice, but
an inevitable consequence
of treating observers
as quantum mechanical systems.

Anthropic Selection

$(D|\Lambda, m)$ is the basis for raditional anthropic election. Non-zero p is nthropically allowed.

Weinberg got good esults by putting in the bserved m and assuming uniform prior for Λ.



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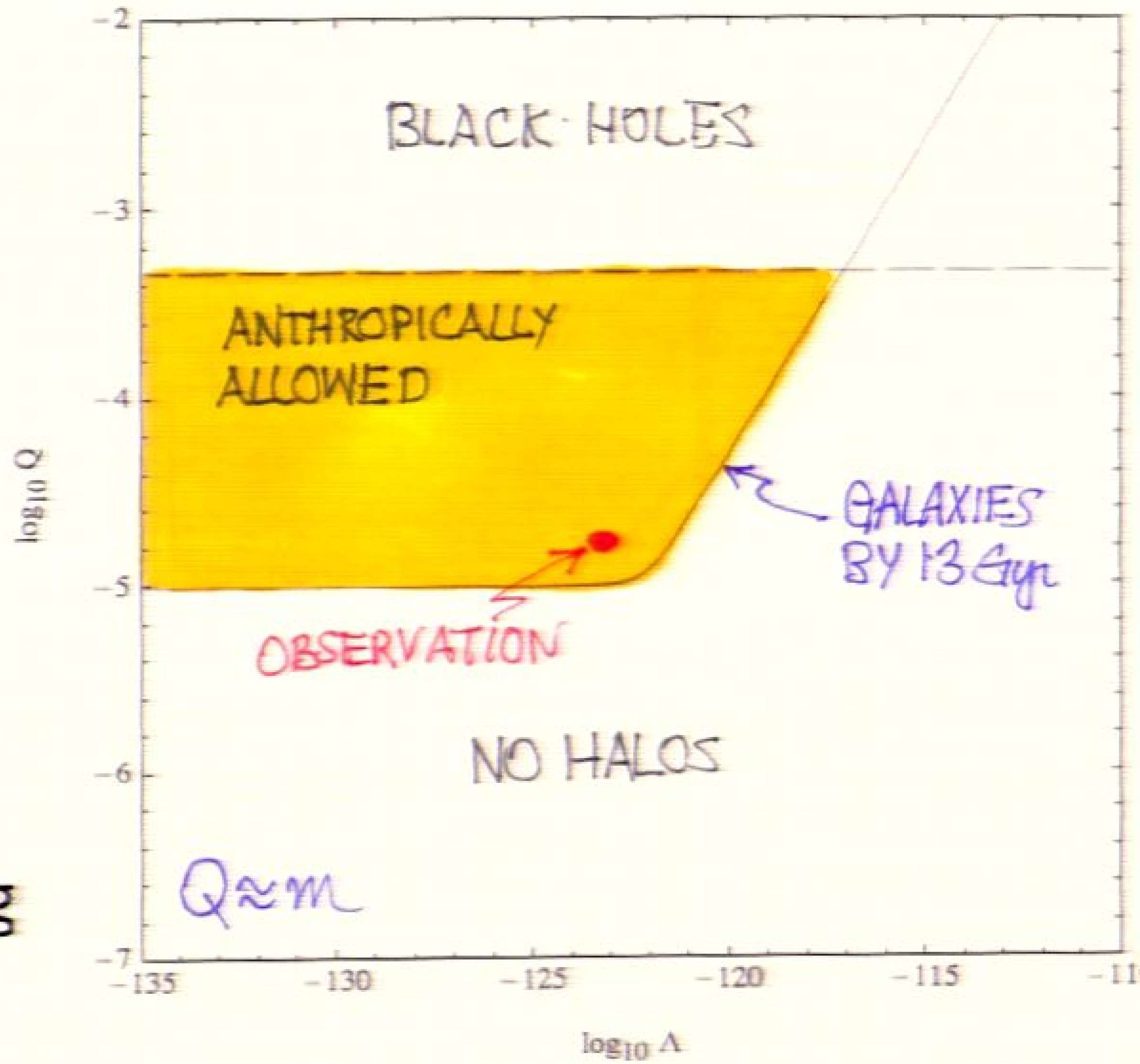

But Livio & Rees, Tegmark & Rees etc showed the result got worse by letting Q scan with uniform priors on both.

But the NBWF supplies the prior!

NBWF Aided Anthropics

$$p(\Lambda, m|D) \propto p(D|\Lambda, m)p(\Lambda, m)$$

$$p(\Lambda, m) \approx \exp(\pi/V(\phi_{ei}))$$
$$\approx \exp[\pi/(\Lambda + m/2)]$$
$$\approx \exp(2\pi/Q)$$

NBWF favors the lowest value of Q in the anthrop. allowed range.

This restores Weinberg's anthropic argument for Λ.

$$Q \sim 10^{-5}, \quad \Lambda \sim 10^{-123}.$$

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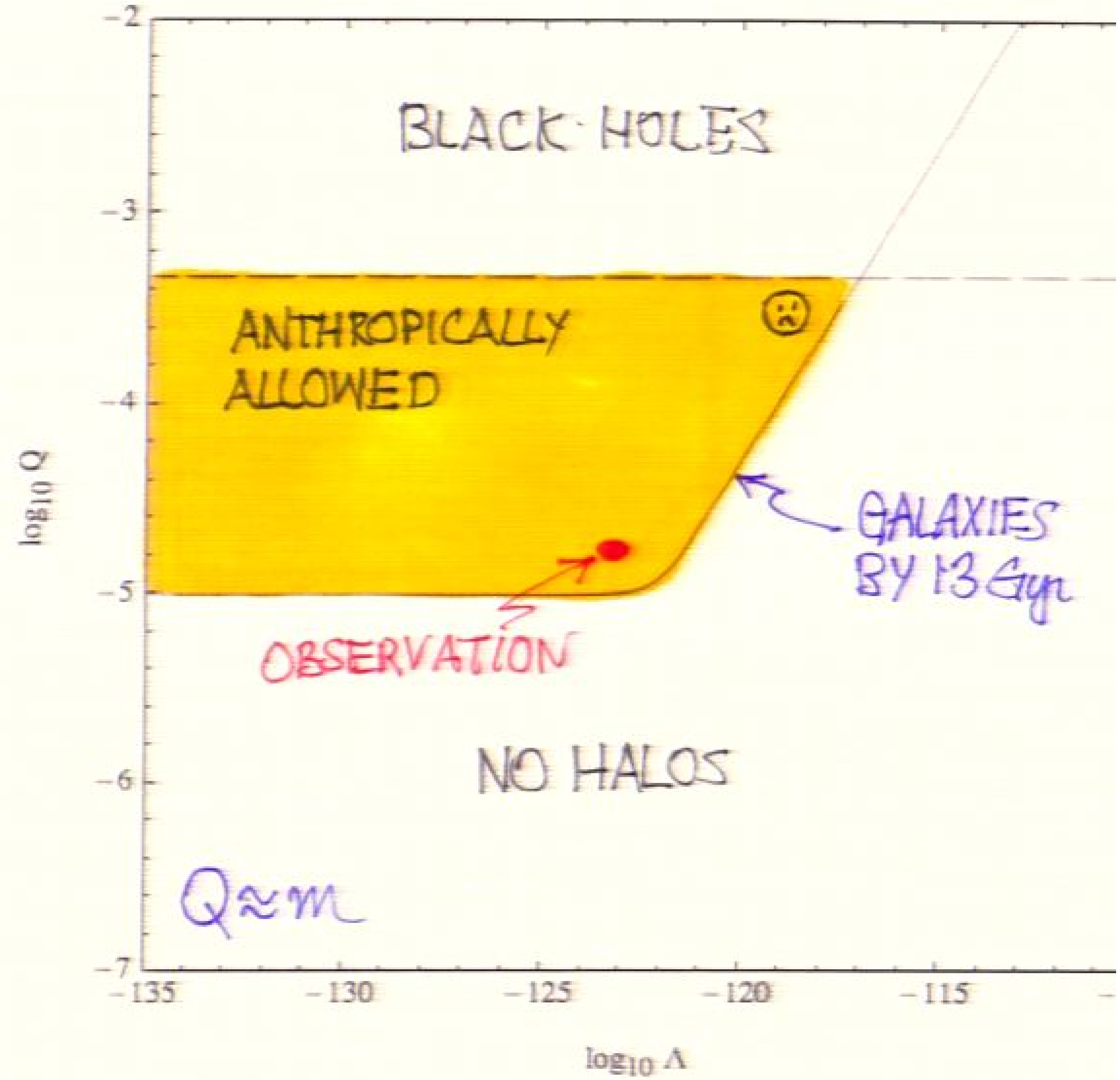

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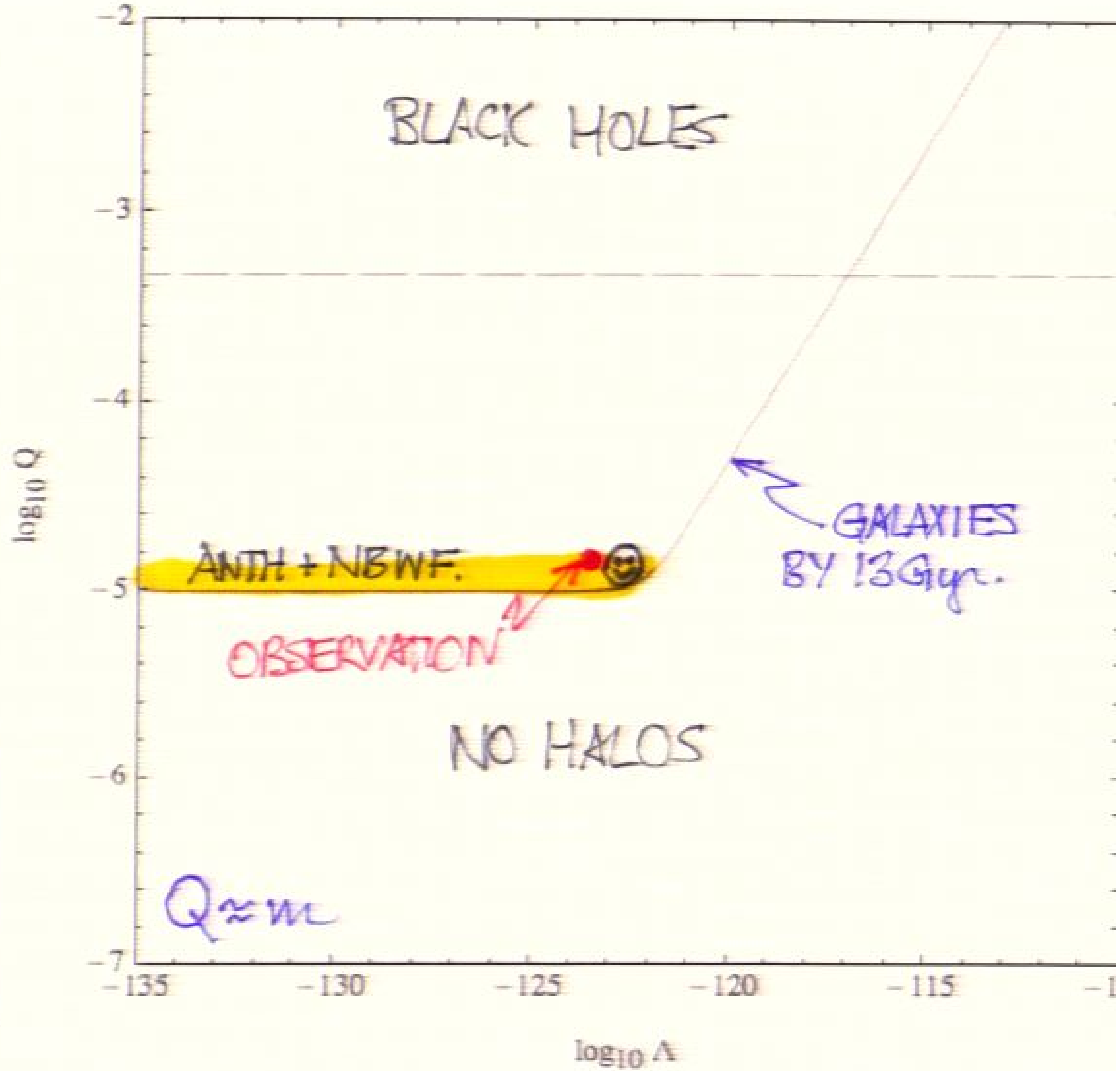

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The Main Points Again

- If the universe is a quantum system it has a quantum state. This supplies probabilities (BU) for alternative classical histories of the universe.
- Observers of the universe are physical systems within it with only a probability to exist in any Hubble volume.
- Probabilities for observation (TD) are necessarily conditioned on a description of the observational situation including what's doing the observing.
- By coarse graining over everything outside the past light cone of our H-vol, probabilities for observation can be calculated even with the large inhomogeneities generated by EI without a further measure.

Neil's Challenges

- Getting inflation --- a special state.
- Fine-tuned potentials -- Potentials in the landscape with inflation are selected by classicality, and potentials with EI by TD weighting.
- Small Λ --- anthropically selected.
- Measure problem ---- quantum mechanics + coarse graining gives observational predictions without counting.
- Reliance on anthropic arguments. --- They seem inevitable to discuss the conditional probabilities for our observations.

Agree

- Something besides classical phase space is needed to say that the universe inflates. (NT)
- The solution to the measure problem will come from quantum mechanics and involve quantum gravity. (AG)
- There was eternal inflation in our past in particular models. (BF)
- We haven't yet solved the problem of counting the number of observers doing this or that (AG), but we don't need that for making local predictions.

Disagree

- One classical spacetime in which various quantum events happen.
- A measure independent of the quantum state of the universe.
- One meaning to the question of whether the universe inflates (TD vs BU).
- Anthropic arguments are a choice.

Don't know yet

- Predicting the large scale mosaic structure, the multiverse, etc. It appears not very well defined.
- pA/pB = <NA>/<NB>, might conceivably be true for some measure but should be a consequence of quantum probabilities. (JH'68, ALT'10). Agreement with the quantum mechanical calculation would be a test of the measure.

Is there a measure problem in inflationary cosmology?

Is there a measure problem in inflationary cosmology?

YES!

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

Ψ

0711.4630
0803.1663
0905.3877
1001.0262
1009.2525
1104.1733

0704.2630
0906.0042
1004.3816

	Quantum Cosmology EI	Traditional EI
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)
)bservers like us	Quantum systems within the U with a probability to exist.	Classical -- assumed to exist in all hospitable environments
Origin of Probabilities	The quantum state of the universe.	Ratios of numbers of observers def. by measure
Importance of the future	Irrelevant to the future of our Hubble volume	Central to the definition of the measure.
Importance of the past	central to local observations	distant past irrelevant except to start off EI
Importance of the state	central	measure chosen so predictions are ind. of state