Title: Science in a Very Large Universe ; The Classical Multiverse of the No-Boundary Quantum State

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Abstract:

Science in a Very Large Universe

Mark Srednicki (UCSB) and Jim Hartle (UCSB)

arXiv:0704.2630 and forthcoming

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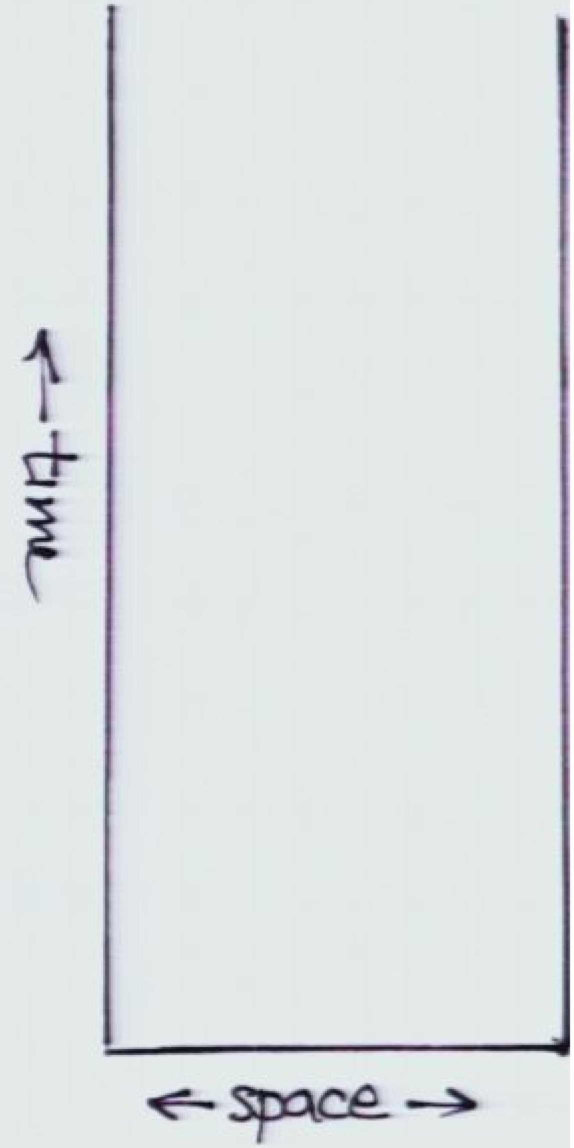
A New Challenge for Science: QM + the Large Multiverse

- We would like to discriminate between theories by whether they predict the data we observe.
- What we know about our data is that the universe exhibits at least one instance of it.
- But in a very large universe the probability that any data occur at least once somewhere approaches one if by no other mechanism than quantum fluctuations for a wide class of theories.
- We can't discriminate between such theories by data alone.

Boltzmann Brains

- A spatially closed universe lasting an infinite time.
- A very small probability per unit four volume that a brain will fluctuate into existence for a short time.
- Since the volume is infinite the probability is one that there are a infinite number of such brains.
- If we are typical in the class of such observers then we are much more likely to have fluctuated into existence a moment ago than to have had 13.7 Gyr of history.



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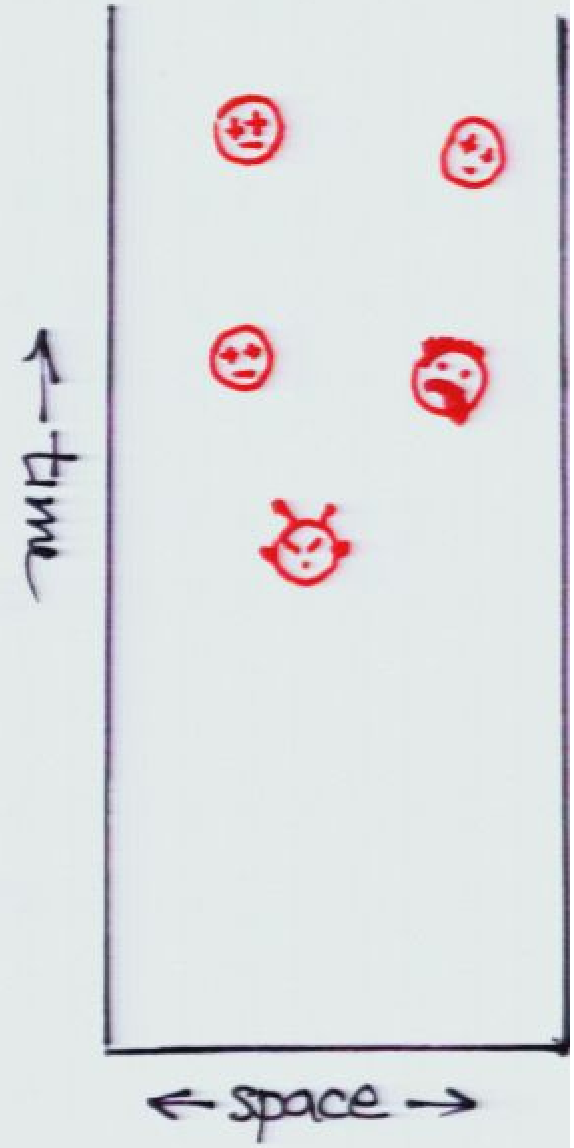

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The New York Times
nytimes.com

January 15, 2008

Big Brain Theory: Have Cosmologists Lost Theirs?

By DENNIS OVERBYE

Correction Appended

It could be the weirdest and most embarrassing prediction in the history of cosmology, if not science.

If true, it would mean that you yourself reading this article are more likely to be some momentary fluctuation in a field of matter and energy out in space than a person with a real past born through billions of years of evolution in an orderly star-spangled cosmos. Your memories and the world you think you see around you are illusions.

The dangers of typicality arguments

- Is there intelligent life on Jupiter?
- No, there can't be because, since Jupiter is larger, there would be many more Jovians than Humans and then we would not be typical observers in the solar system.

Homilies

- We have no data on extraterrestrial observers and therefore no evidence for an assumption that we are typical in any class that contains them.
- There is no evidence that we are unique in the universe and have been randomly selected by any physical process and should not reason as though we were. To do so risks conflict with the likely situation that our data are duplicated in a large universe.
- We are physical systems within the universe and the route to clarity is to make statements that refer to us in terms of our physical description.

Duplication of Data

We are typical by definition in the class of systems that have exactly the same data we do. The class in which every scrap of information we have about the universe is the same, every astronomical observation, every detail of every leaf, and every part of the description of ourselves.

Duplication is the only reliable typicality.

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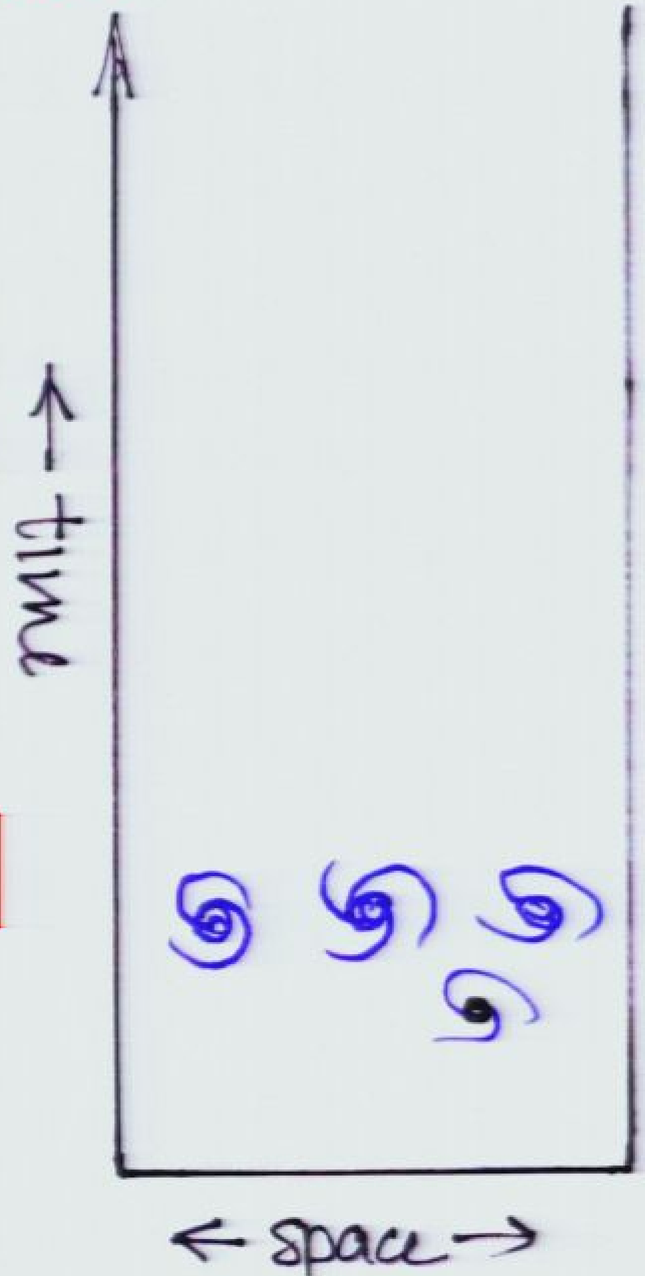

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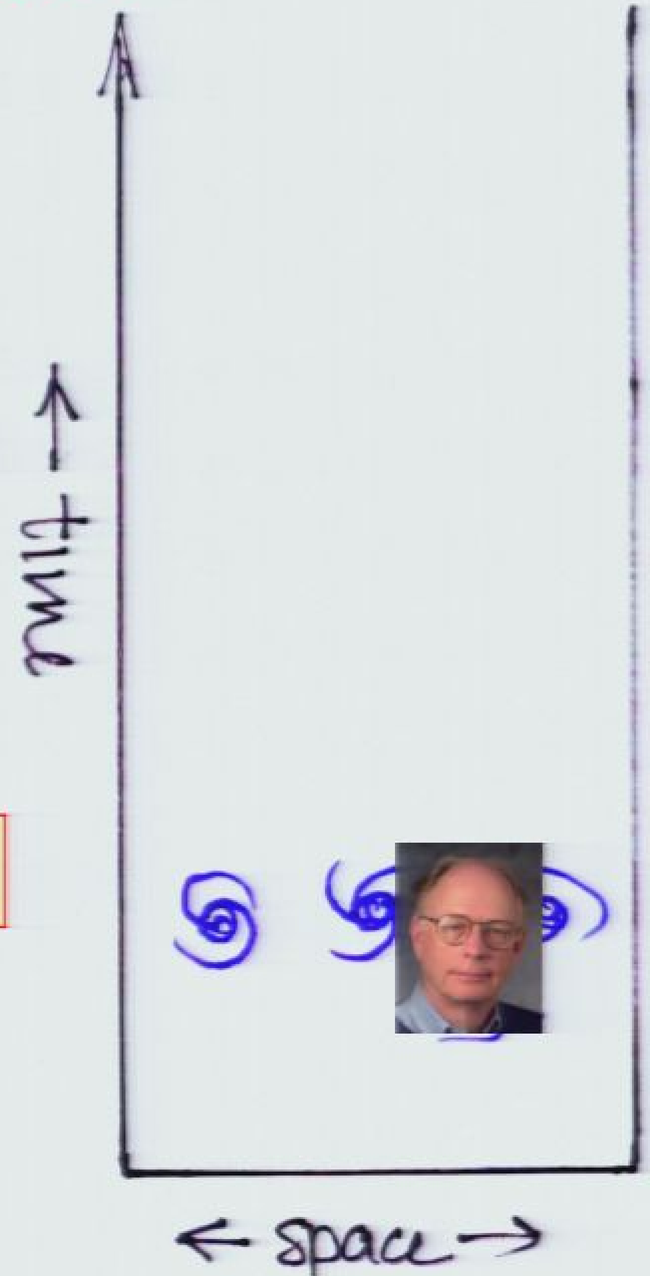

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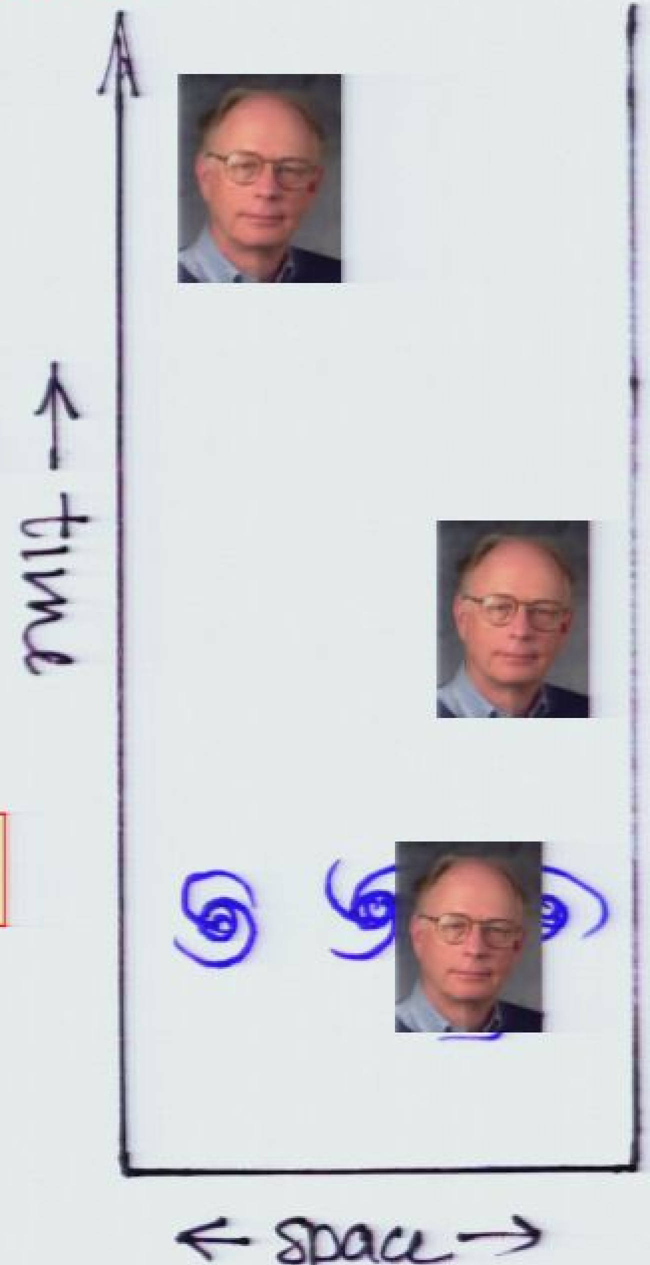

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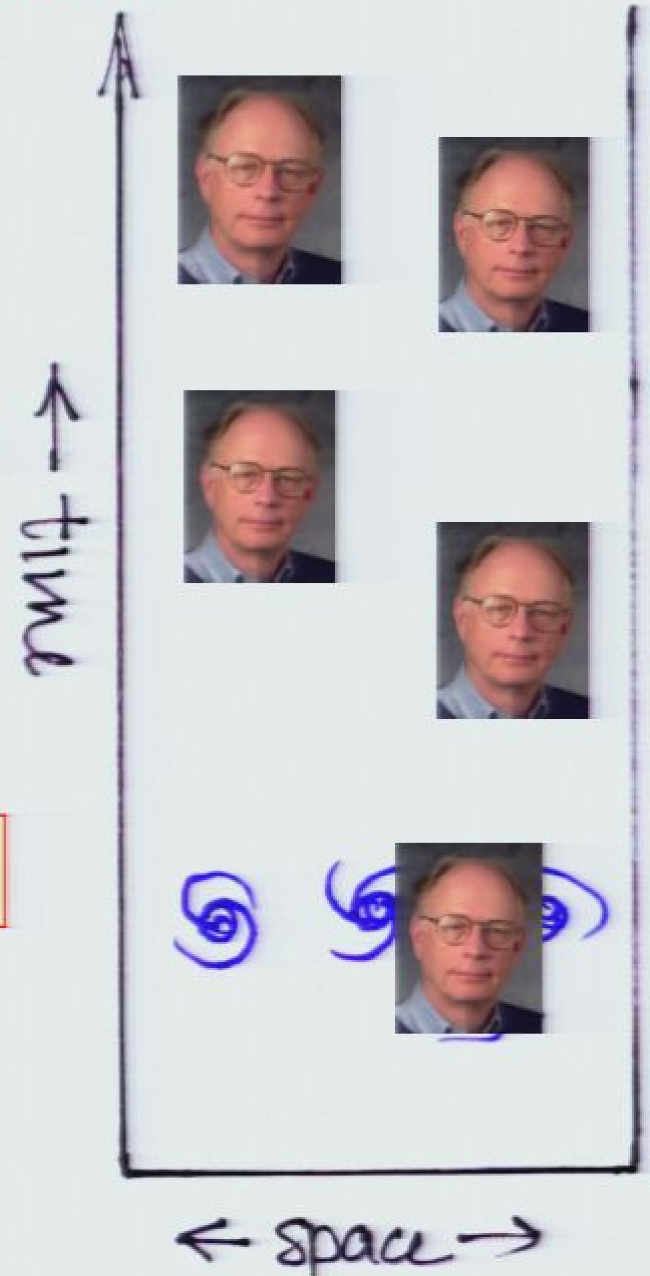

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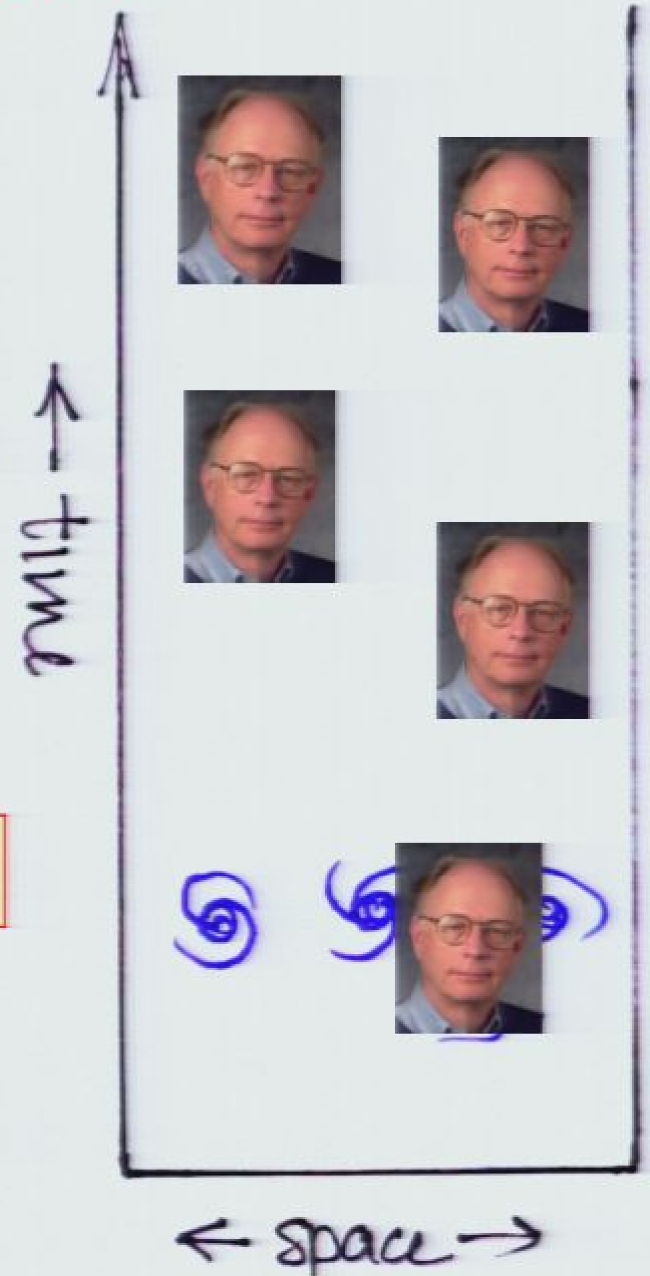
BB's redux: There are an infinite number of BB's that have our data and we are more likely to be one of them.



Bayesian Framework

- Theories $\{T_A\}$: to be discriminated.
- Data D: every piece of information the human scientific IGUS has about the universe including a physical description of itself. (Facts.)
- Likelihoods $p(D|T_A)$: assumed to be calculable. (Logical deduction.)
- Priors $p(T_A)$: (Prejudices)
- Bayes Formula:

$$p(T_A|D) = \frac{p(D|T_A)p(T_A)}{\sum_A p(D|T_A)p(T_A)}$$

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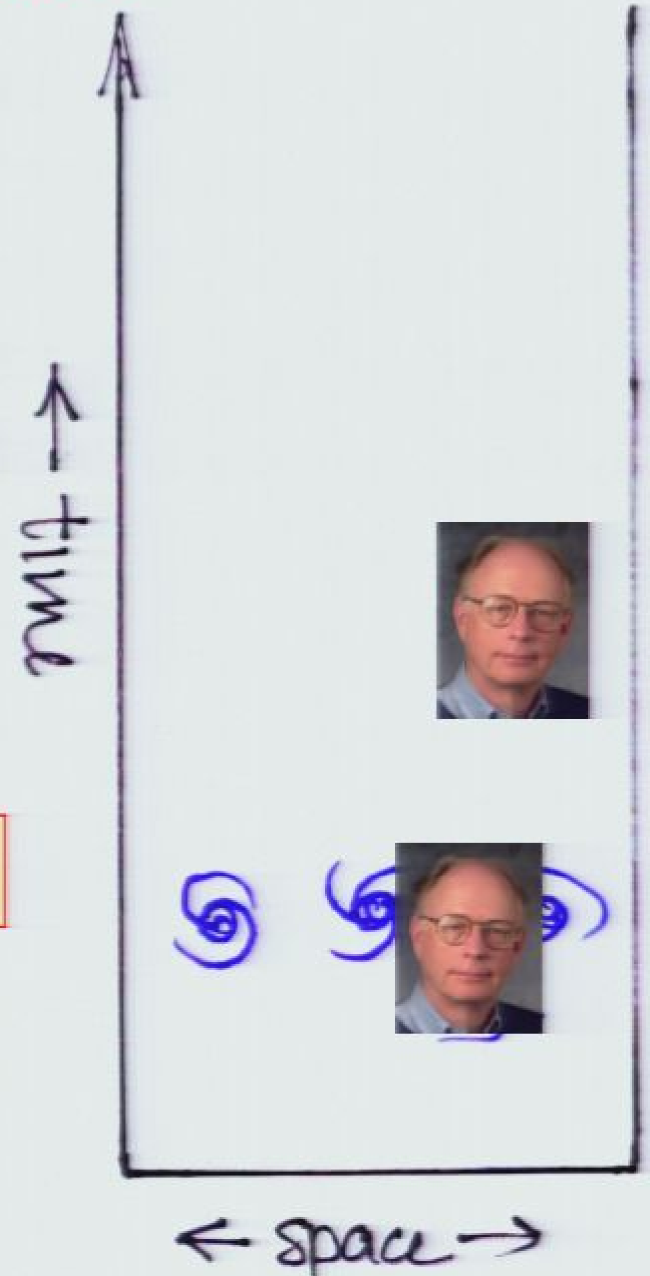

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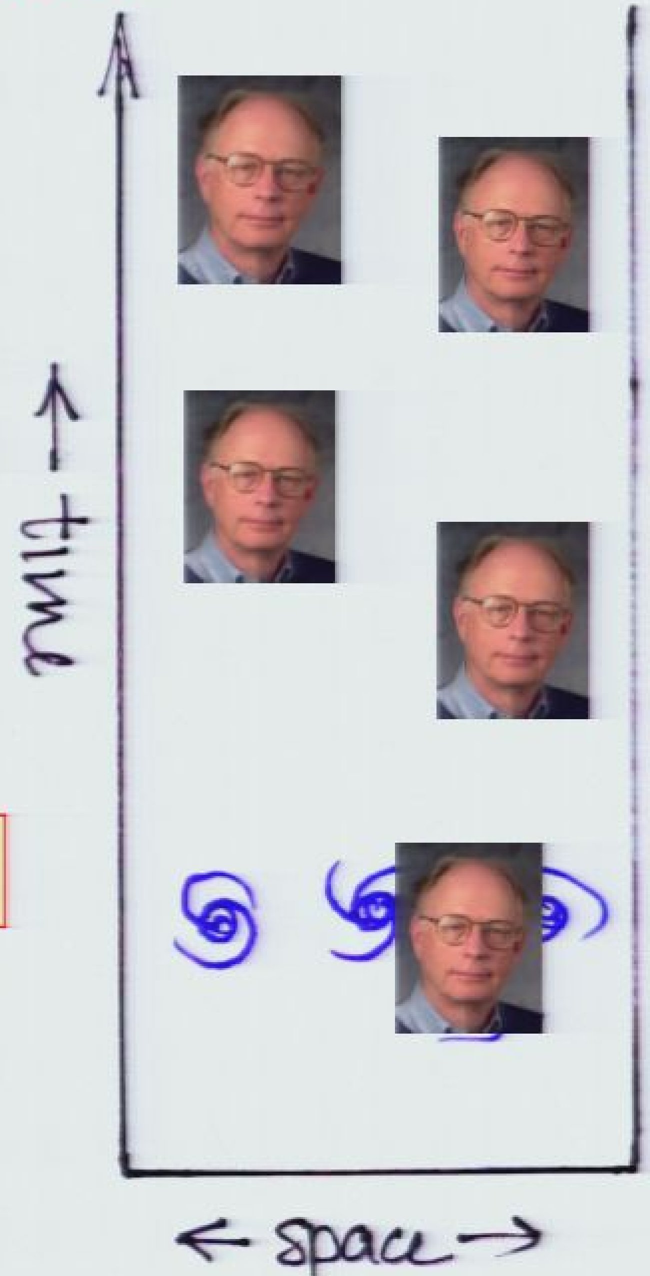

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All we know from our data is that the universe exhibits one instance of it.

The relevant likelihoods for the Bayes procedure are

p(at least one instance of D|T_A)

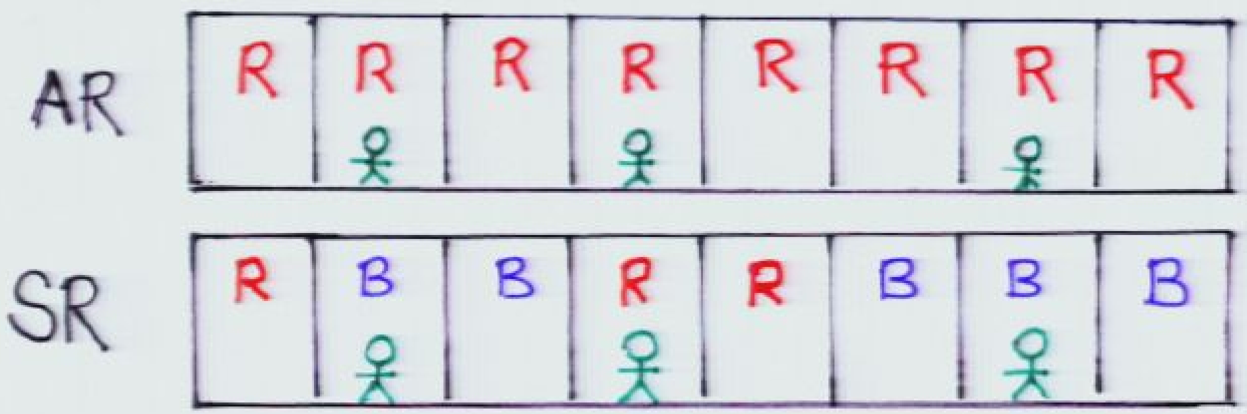
Inferences from Bayes Procedure

- Theories are tested using our data D. What other observers with different data might see, how many of them there are, and what properties they might share with us are irrelevant for this process.
- No additional assumption of typicality is needed if we use the probabilities given by the fundamental theory.
- Two theories that predict equal probabilities that there is at least one instance of our data somewhere are not distinguished by the Bayesian process. A significant probability for further copies does not change the probability that there is at least one instance.

The Red/Blue Model

- A universe consisting of N boxes. The boxes are either red (R) or blue (B). There is a probability p_E that there is an observing system (IGUS) exists in each box. We are one.

- Two theories are proposed:



We exist (E) in one box and see red (R).
Which theory does this data (R,E) favor?

Red/Blue Likelihoods

$$N_R(T) \equiv (\#\text{ red boxes in theory } T) < N$$

$$p(R, E|T) = 1 - (\text{prob of no boxes with } (R, E))$$

$$p(R, E|T) = 1 - (1 - p_E)^{N_R(T)}$$

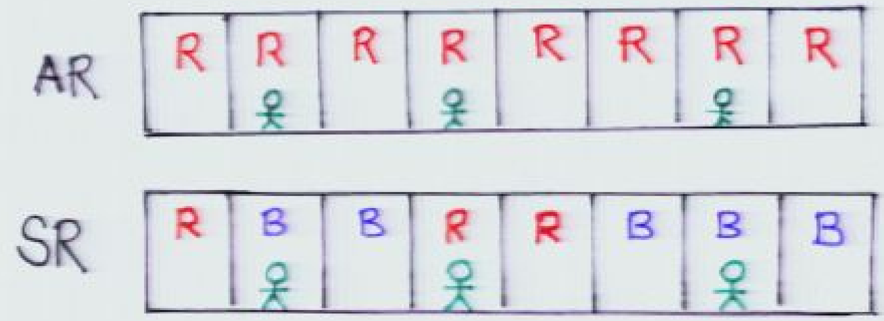
$$p(T_A|D) = \frac{p(D|T_A)p(T_A)}{\sum_A p(D|T_A)p(T_A)}$$

With equal priors the posteriors are

$$p(T|R, E) \propto 1 - (1 - p_E)^{N_R(T)}$$

Limiting Cases of Red/Blue Model

$$p(T|R,E) \propto 1-(1-p_E)^{N_R(T)}$$



- $p_E \approx 1, \quad p(T|R,E) \approx 1$ for both theories --- no discrimination. (we are not rare).

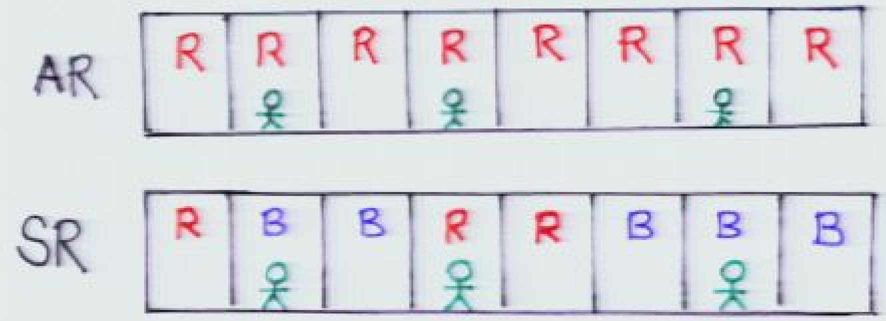
- $p_E \ll 1/N$ (we are rare):

$$p(T|R,E) \propto N_R(T) p_E$$

This is the same as if we were unique in the universe but didn't know what box we were in. AR is favored, discrimination.

Infinite Red/Blue Model

$$p(T|R,E) \propto 1-(1-p_E)^{N_R(T)}$$



In the limit $N_R(T) \to \infty, \quad p(T|R,E) \to 1$, and there is no discrimination between AR and SR on the basis of data.

In an infinitely large universe the probability is one that there is at least one instance of our data no matter how rare it is.

But it gets worse....

No Confidence in Experiment

- Consider a set of theories $T(\Lambda)$ that differ only by the value of a parameter Λ .
- A series of laboratory measurements of the parameter give values $\Lambda_1, \cdots, \Lambda_n$. Which theory does that data favor?
- If the universe is infinite the likelihood that this string occurs at least once approaches one in any theory.

$$p(\Lambda_1, \cdots, \Lambda_n | T(\Lambda)) \approx 1$$

i.e. the experiments say nothing about the value of Λ .

Ways Out

If two theories predict that the probability is one that any data occurs somewhere then we can't distinguish them in the Bayesian framework.

$$p(T|D) = p(T)$$

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- Admit its all in data dependent priors and agree on those.

We favor theories that are ....

simple
beautiful
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economical in assumptions
comprehensive

unifying
explanatory
falsifiable
accessible to intuition
make us typical
relational

But most importantly we favor theories that are predictive, testable, and give a coherent explanation of the data we have.

The utility of a physical theory is its predictive power.

Predictability

- Predictability concerns a stream of data in time, $d_1, \ldots d_n$. A theory is predictive when $p(d'_n|T, d_1, \cdots ; d_{n-1})$ is peaked in d'_n about some particular value which is the prediction.
- We favor theories for which there is a coherent story connecting a past stream of data to predictions of future data.

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Typicality Leading to Predictability

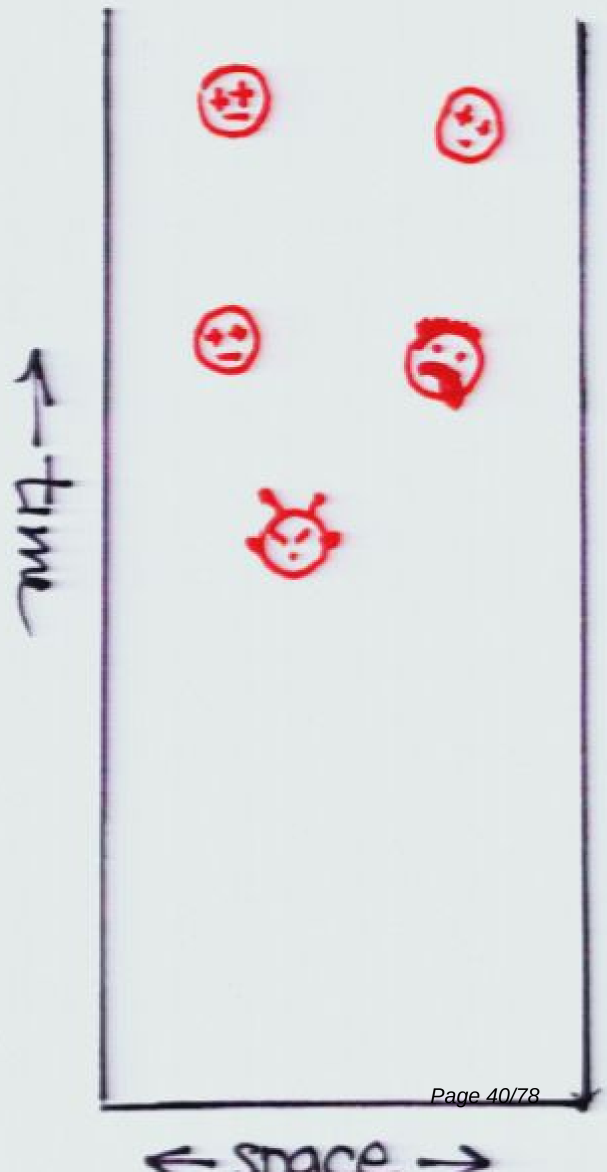
- If we assume that we are typical observers in the solar system we predict that there are no observers on Jupiter.
- But the assumption is risky because it is ad hoc and without basis in a more fundamental theory.

Atypicality Leading to Predictability

- Two theories:
  - UT: the usual theory.
  - UTA: UT + the assumption that we live close to the big bang. ie that we are atypical according to UT.

- UT is not predictive, UTA is, the further assumption is therefore testable.

- Such atypicality assumptions are possible when there is a variable (e.g. location) to make them with.



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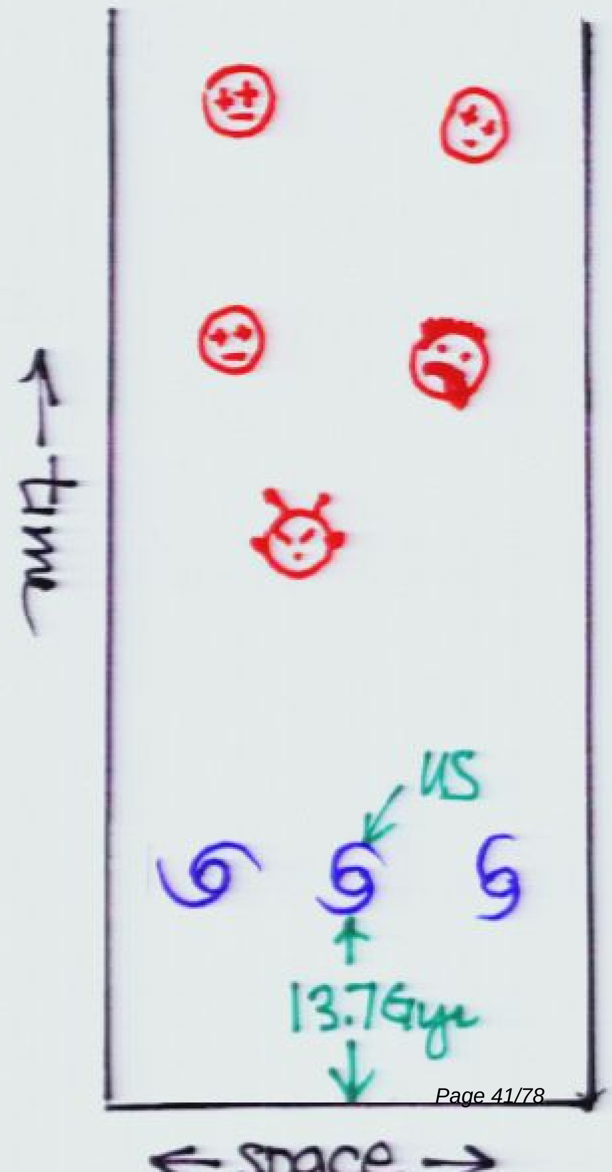

Confidence in Experiment

- Consider a set of theories $T(\Lambda)$ that differ only by the value of a parameter Λ .
- A series of laboratory measurements of the parameter give values $\Lambda_1, \cdots, \Lambda_n$.
- We favor the theory $T(\Lambda_{av})$ where Λ_{av} is the average of $\Lambda_1, \cdots, \Lambda_n$, because it gives a coherent story of the previous measurements (they were accurate) and predicts the results of future ones (they should get Λ_{av} within error.)

The Main Points Again

- When the universe is infinite in either space or time we will not be able to distinguish theories by data alone if the likelihood is one that any data occur somewhere.
- We can distinguish theories otherwise through priors that favor theories that provide a coherent story for the data we have and make testable predictions for data we might acquire.
- Assuming atypicality can lead to predictability just much as assuming typicality.

Expect More Controversy

The Classical Multiverse of the No-Boundary Quantum State

James Hartle, UCSB, Santa Barbara
Stephen Hawking, DAMTP, Cambridge
Thomas Hertog, APC, UP7, Paris

summary: arXiv: 0711.4630 details: arXiv:0803.1663

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The Quasiclassical Realm - A feature of our Universe

The wide range of time, place and scale on which the laws of classical physics hold to an excellent approximation.

- Time --- from the Planck era forward.
- Place --- everywhere in the visible universe.
- Scale --- macroscopic to cosmological.

What is the origin of this quasiclassical realm in a quantum universe characterized fundamentally by indeterminacy and distibuted probabilities?

Classical spacetime is assumed in all formulations of inflationary cosmology.

Classical spacetime is the key to the origin of the rest of the quasiclassical realm.

Only Certain States Lead to Classical Predictions

- Classical orbits are not predictions of every state in the quantum mechanics of a particle.
- Classical spacetime is not a prediction of every state in quantum gravity.

The Classical Multiverse of a Quantum State

- A particular quantum state does not predict one classical history, but rather the probabilities for an ensemble of alternative classical histories (if any at all.)
- This ensemble constitutes the quasiclassical realm which is the classical multiverse of that quantum state.

Classical Spacetime is the Key to the Origin of the Quasiclassical Realm.

The quantum state of the universe is the key to the origin of classical spacetime.

We analyze the classical spacetime predicted by Hawking's no-boundary quantum state for a class of minisuperspace models.

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

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.

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

Classical Pred. in NRQM ---Key Points

Semiclassical form:

$$\Psi(q_0) = A(q_0)e^{iS(q_0)/\hbar}$$

- When $S(q_0)$ varies rapidly and $A(q_0)$ varies slowly, high probabilities are predicted for classical correlations in time of suitably coarse grained histories.
- For each q_0 there is a classical history with momentum p_0 and probability:

$$p_0 = \nabla S(q_0) \qquad p(\text{class.hist.}) = |A(q_0)|^2$$

NRQM -- Two kinds of histories

$$\Psi(q_0) = A(q_0)e^{iS(q_0)/\hbar}$$

- $S(q_0)$ might arise from a semiclassical approximation to a path integral for $\Psi(q_0)$ but it doesn't have to.
- If it does arise in this way, the histories for which probabilities are predicted are generally distinct from the histories in the path integral supplying the semiclassical approximation.

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.

Semiclassical Approx. for the NBWF

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

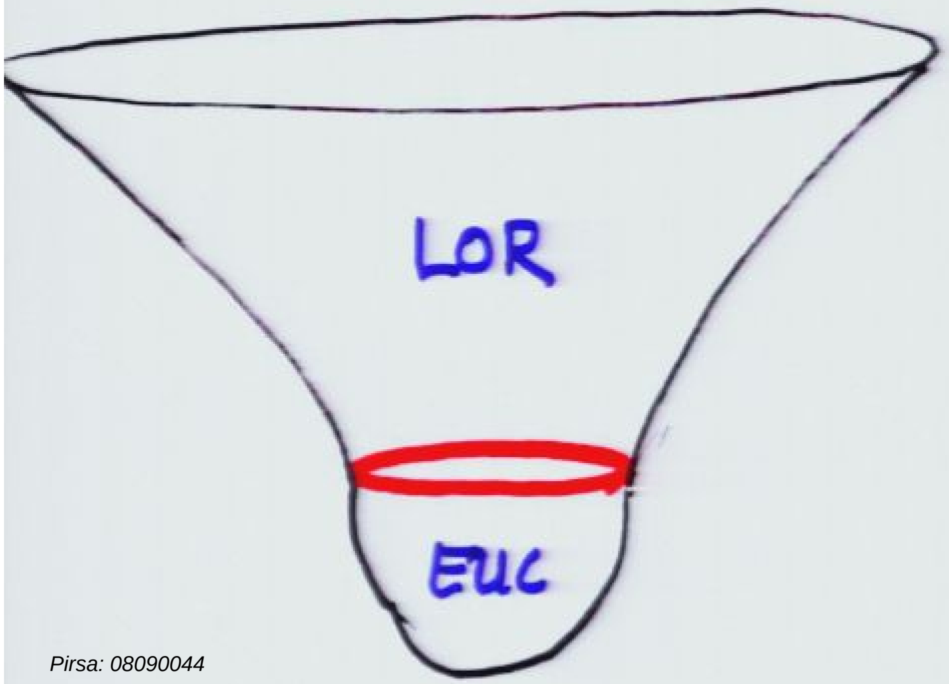
- In certain regions of superspace the steepest descents approximation may be ok.
- To leading order in ħ the NBWF will then have the semiclassical form:

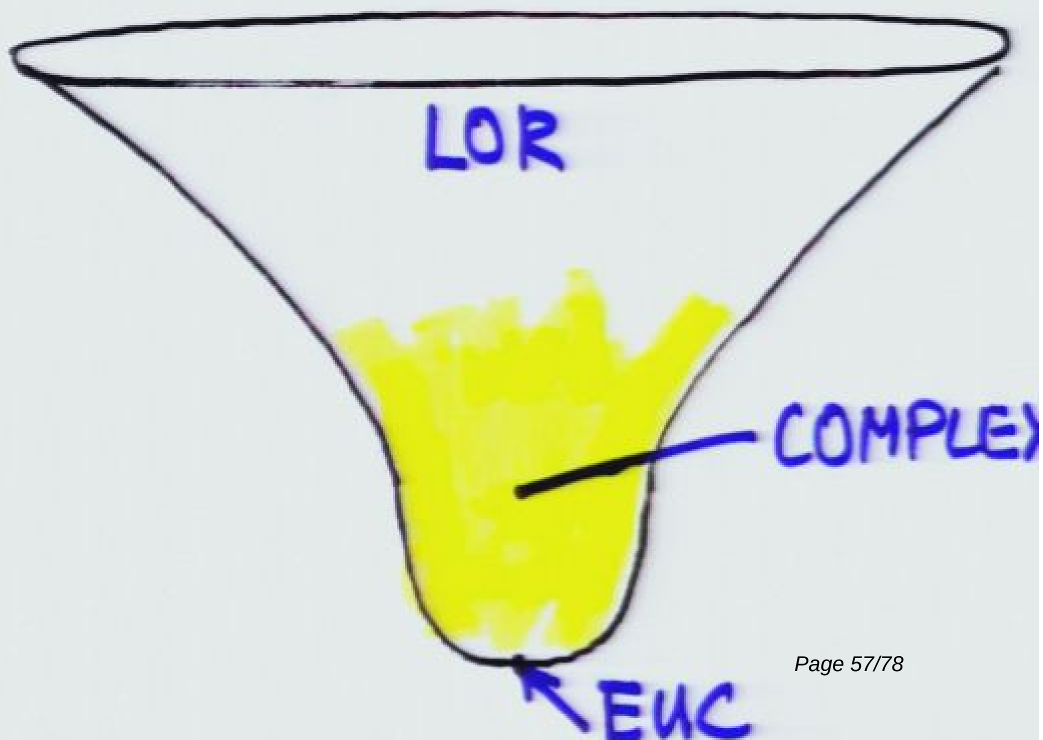
$$\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}.$$

- The next order will contribute a prefactor which we neglect. Our probabilities are therefore only relative.

Instantons and Fuzzy Instantons

In simple cases the extremal geometries may be real and involve Euclidean instantons, but in general they will be a complex --- fuzzy instantons.





Classical Prediction in MSS and The Classicality Constraint

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

- Following the NRQM analogy this semiclassical form will predict classical Lorentian histories that are the integral curves of S, ie the solutions to:

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

- However, we can expect this only when S is rapidly varying and I_R is slowly varying, i.e.

$$|\nabla_A I_R| \ll |\nabla_A S|. \qquad\qquad |(\nabla I_R)^2| \ll |(\nabla S)^2|.$$

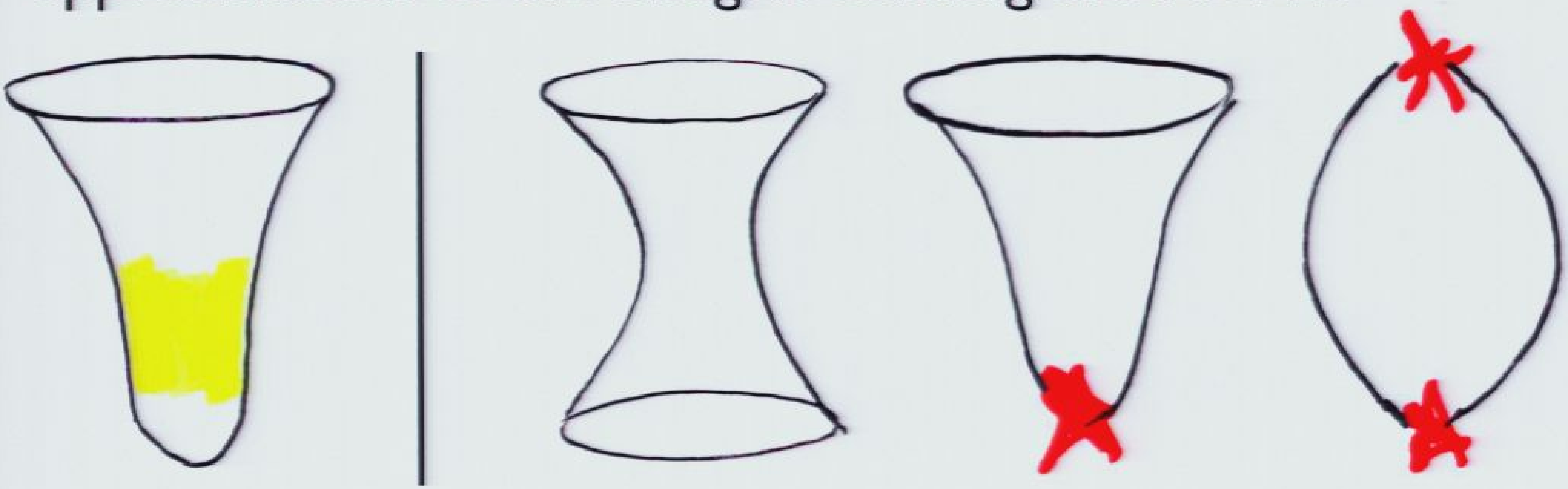
These consitute the classicality condition.

Hawking (1984), Grischuk &Rozhansky (1990), Halliwell(1990)

Class. Prediction --- Key Points

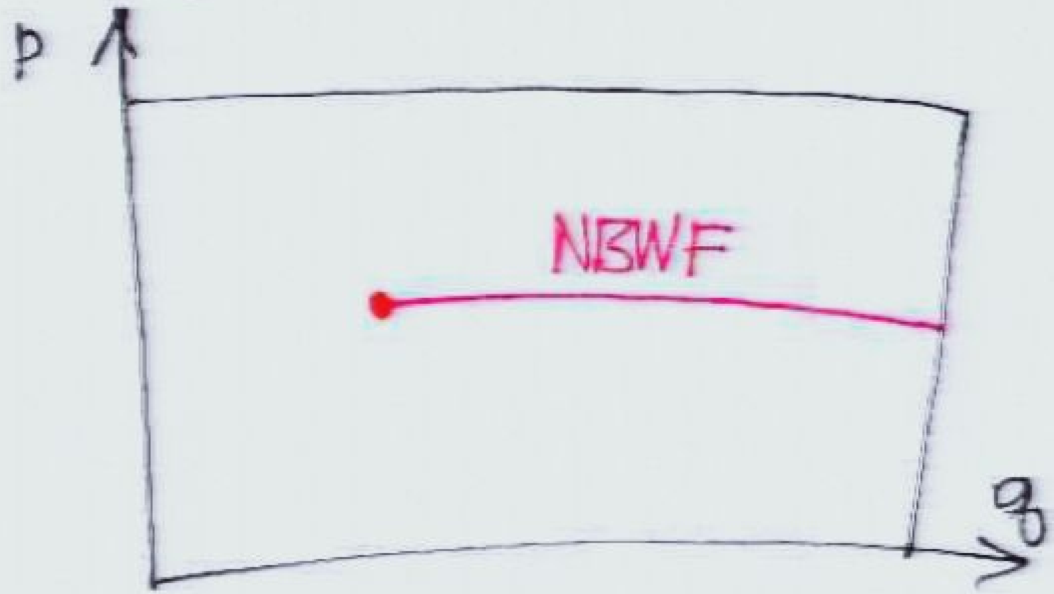
- The NBWF predicts an ensemble of entire, 4d, classical histories.

- These real, Lorentzian, histories are not the same as the complex extrema that supply the semiclassical approximation to the integral defining the NBWF.



No-Boundary Measure on the Classical Multiverse

The NBWF predicts an ensemble (a multiverse) of classical histories labeled by points in classical phase space. The NBWF gives a measure on classical phase space.

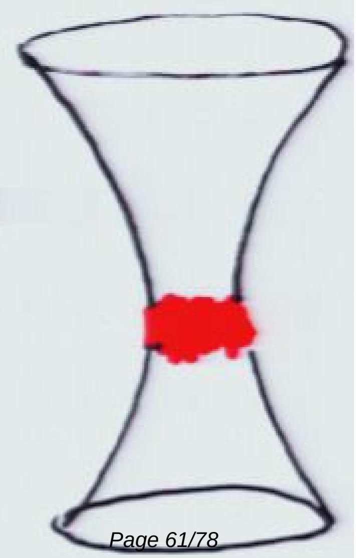


Gibbons Turok '06

The NBWF predicts a one-parameter subset of the two-parameter family of classical histories, and the classicality constraint gives that subset a boundary.

Singularity Resolution

- The NBWF predicts probabilities for entire classical histories not their initial data.
- The NBWF therefore predicts probabilities for late time observables like CMB fluctuations whether or not the origin of the classical history is singular.
- The existence of singularities in the extrapolation of some classical approximation in quantum mechanics is not an obstacle to prediction by merely a limitation on the validity of the approximation.



Equations and BC

$$\hbar = c = G = 1,\ \mu \equiv (3/\Lambda)^{1/2} m,\ \phi \equiv (4\pi/3)^{1/2}\Phi,\ H^2 \equiv \Lambda/3$$

Extremum Equations:

$$\dot{a}^2 - 1 + a^2 + a^2\left(-\dot{\phi}^2 + \mu^2\phi^2\right) = 0$$

$$\ddot{\phi} + 3(\dot{a}/a)\dot{\phi} - \mu^2\phi = 0,$$

$$\ddot{a} + 2a\dot{\phi}^2 + a(1 + \mu^2\phi^2) = 0\ .$$

Regularity at South Pole:

$$a(0) = 0,\ \dot{a}(0) = 1, \dot{\phi}(0) = 0$$

Parameter matching:

$$\phi(0) \equiv \phi_0 e^{i\gamma}$$

$$(\phi_0, \gamma, X, Y) \longleftrightarrow (b, \chi, 0, 0)$$

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You won't follow this.
I just wanted to show how
much work we did.

Extr
Equ

$$\ddot{a} + 2a\dot{\phi}^2 + a(1+\mu^2\phi^2) = 0\ .$$

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Parameter matching:

$$\phi(0) \equiv \phi_0 e^{i\gamma}$$

$$(\phi_0, \gamma, X, Y) \longleftrightarrow (b, \chi, 0, 0)$$

Equations and BC

$$\hbar = c = G = 1,\ \mu \equiv (3/\Lambda)^{1/2} m,\ \phi \equiv (4\pi/3)^{1/2}\Phi,\ H^2 \equiv \Lambda/3$$

You won't follow this.
I just wanted to show how
much work we did.

Extr

Equa

$$\ddot{a} + 2a\dot{\phi}^2 + a(1 + \mu^2\phi^2) = 0\ .$$

Reg

Sout

The only important point is that there is one classical history for each value of the field at the south pole .

Para

matching:

$$(\phi_0, \gamma, X, Y) \longleftrightarrow (b, \chi, 0, 0)$$

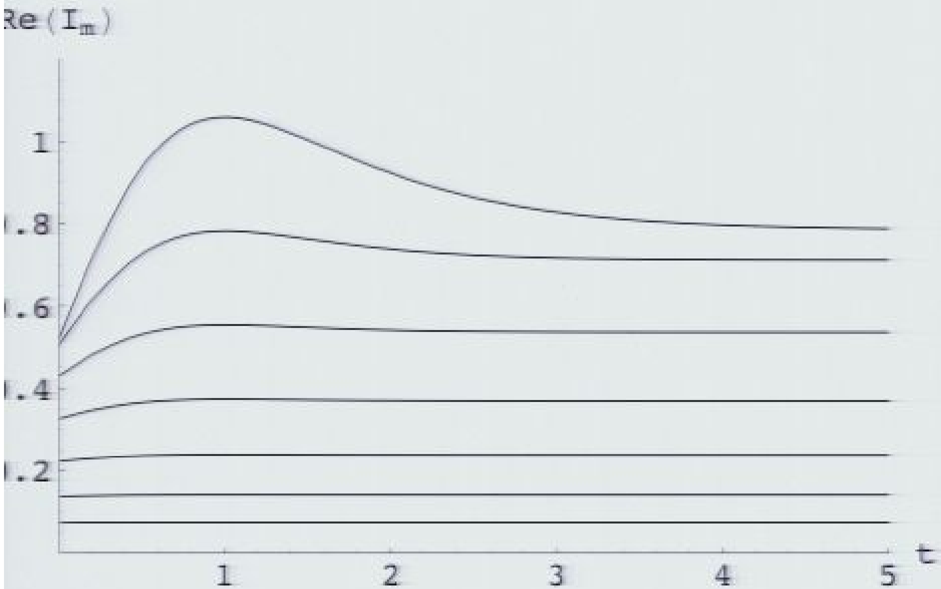
Finding Solutions

- For each ϕ_0 tune remaining parameters to find curves in (b, χ) for which I_R approaches a constant at large b.
- Those are the Lorentzian histories.
- Extrapolate backwards using the Lorentizan equations to find their behavior at earlier times -- bouncing or singular.
- The result is a one-parameter family of classical histories whose probabilities are

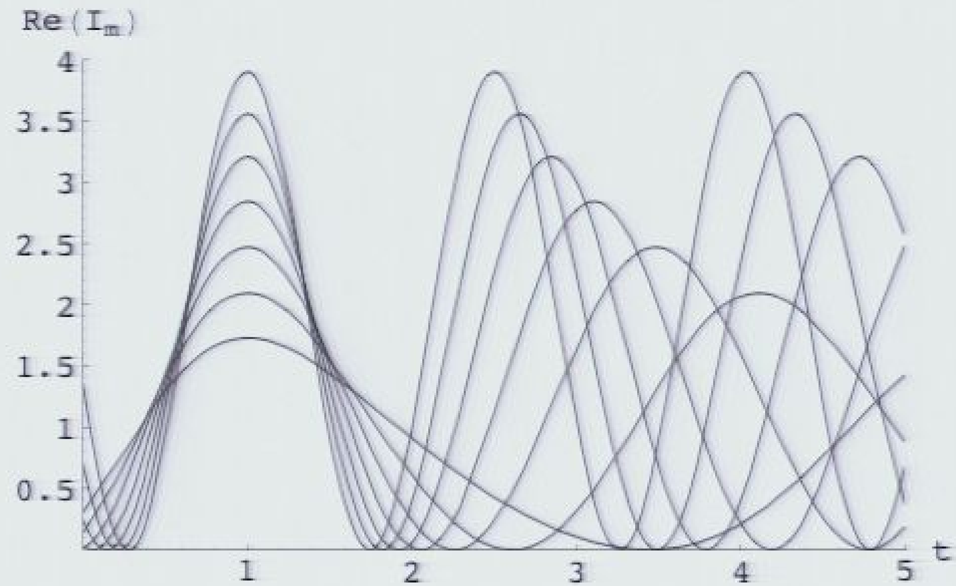
$$p(\phi_0) \propto \exp(-2I_R)$$

Classicality Constraint ---Pert. Th.

Small field perts on deSitter space.



μ<3/2

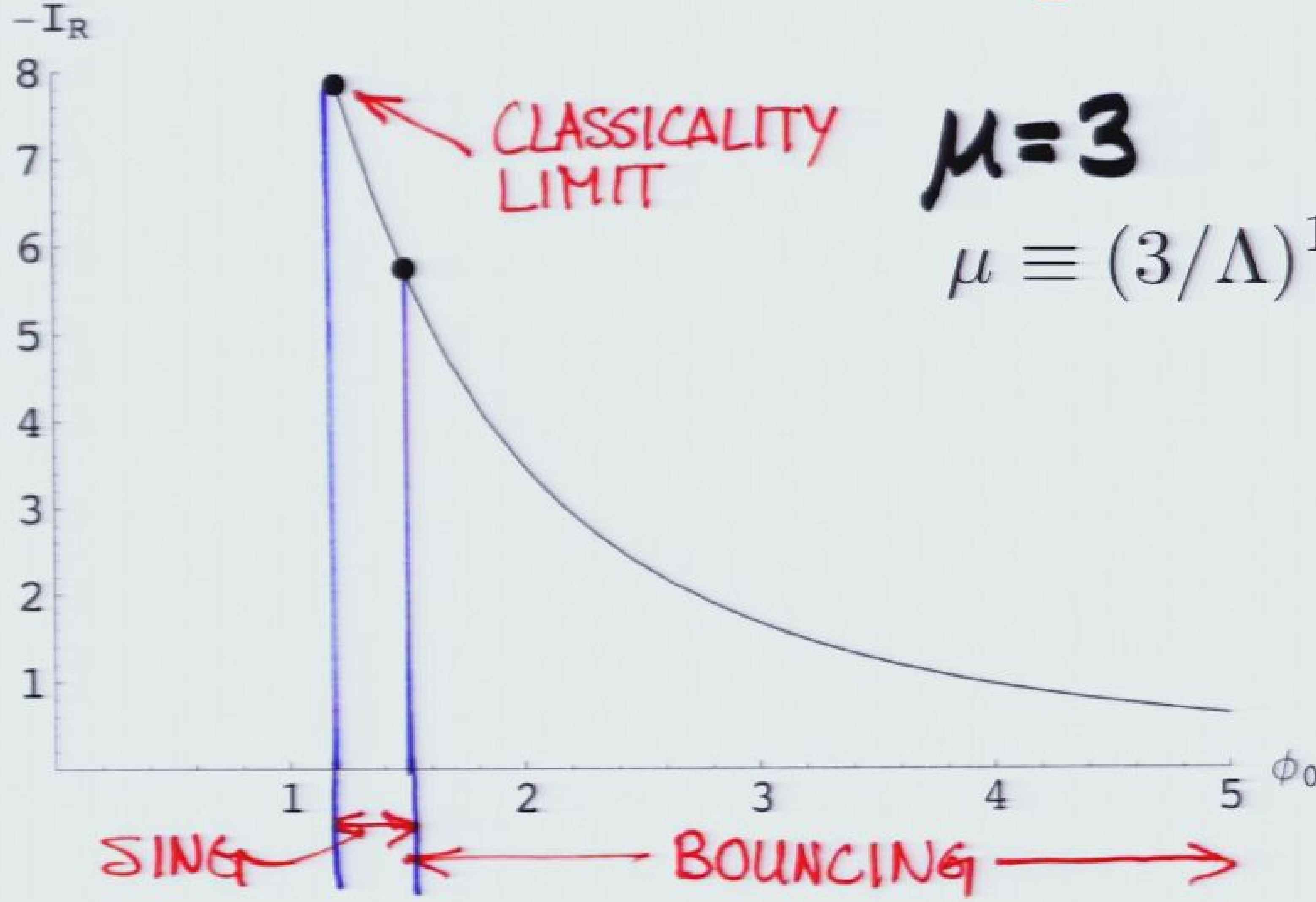


μ>3/2

Classical $\mu \equiv (3/\Lambda)^{1/2} m$ Not-classical

This is a simple consequence of two decaying modes for μ<3/2, and two oscillatory modes for μ>3/2.

Probabilities and Origins

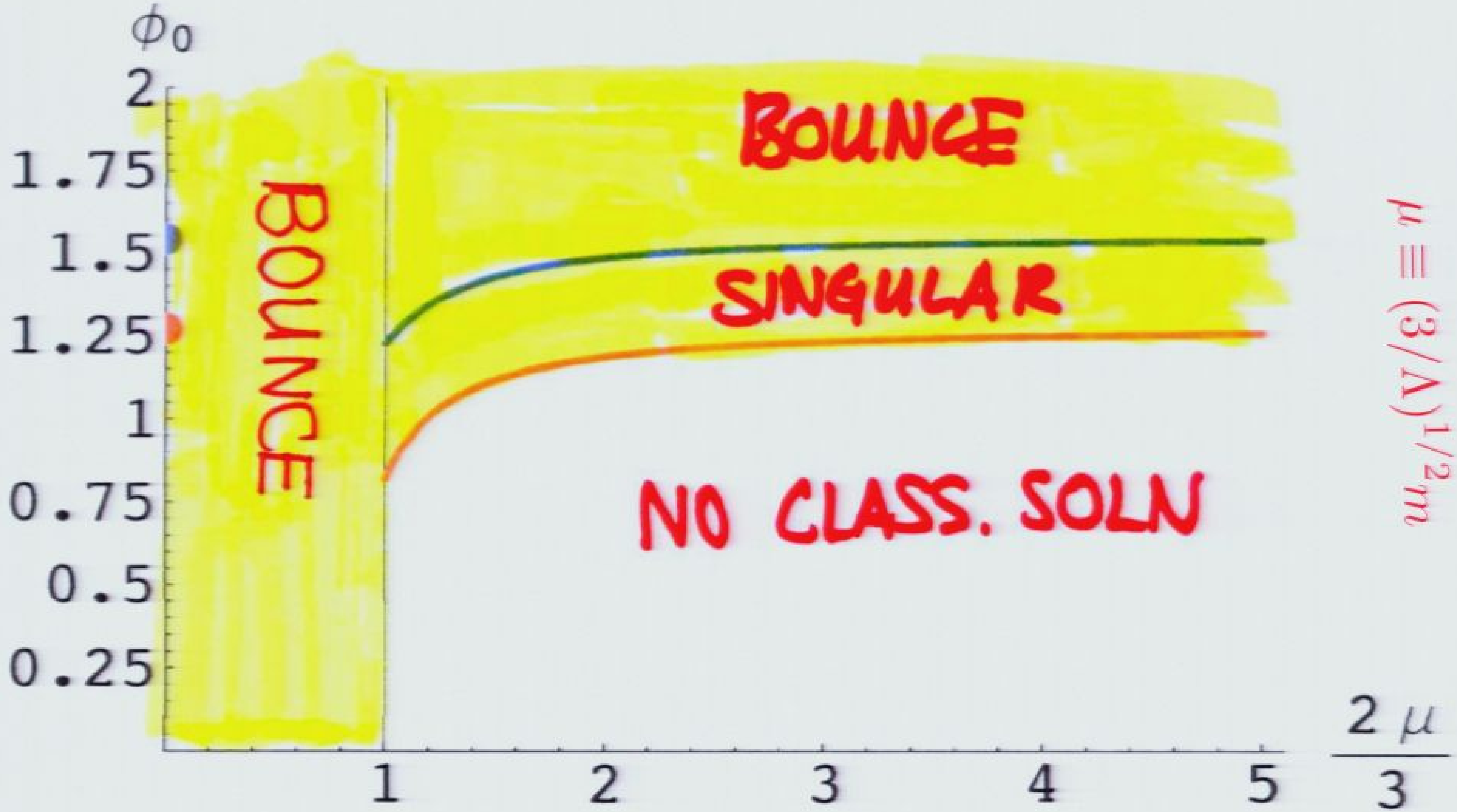


$\mu = 3$

$$\mu \equiv (3/\Lambda)^{1/2} m$$

There is a significant probability that the universe never reached the Planck scale in its entire evolution.

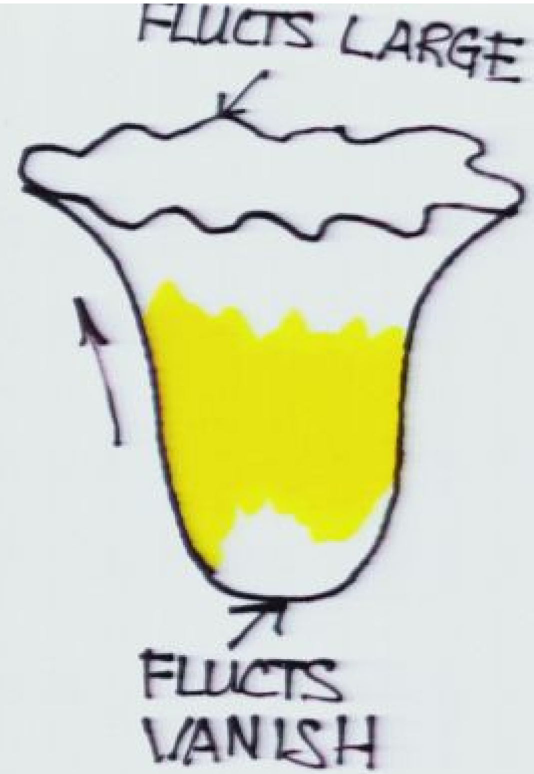
Origins

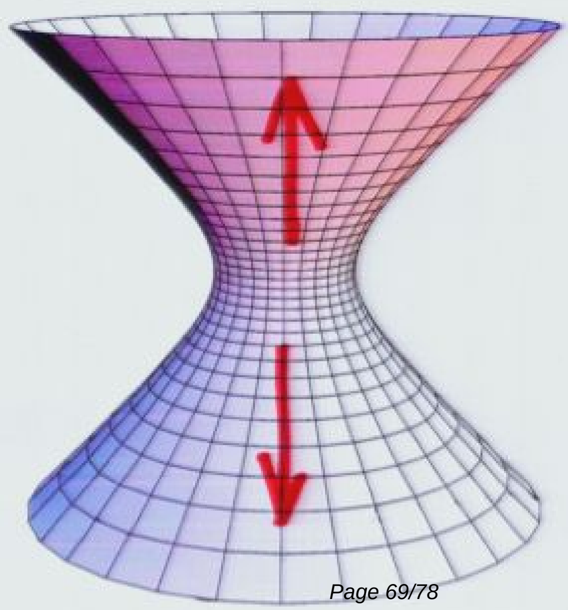


No nearly empty models for μ >3/2, a minimum amount of matter is needed for classicality.

Arrows of Time

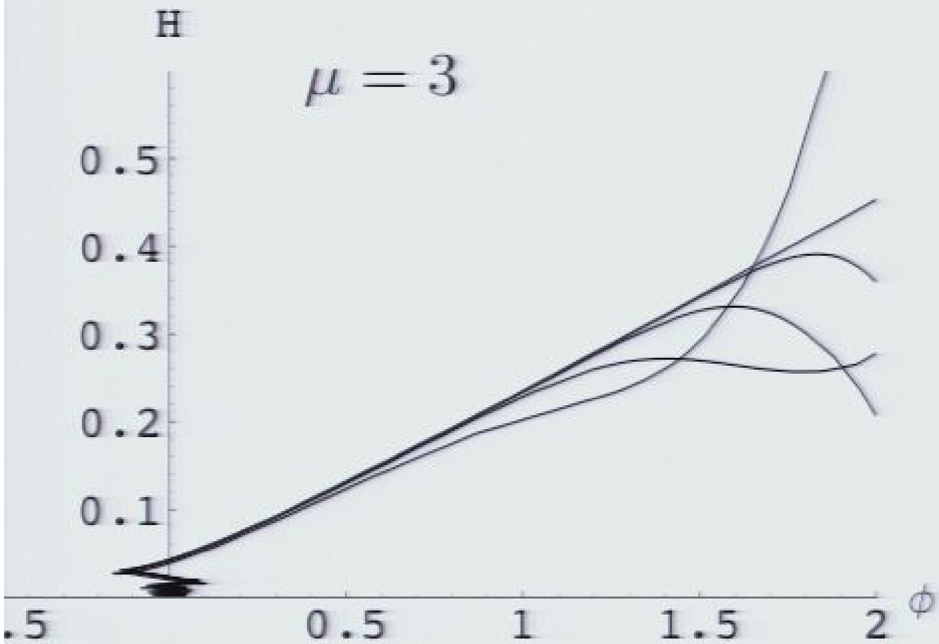
- The growth of fluctuations defines an arrow of time, order into disorder.
- NBWF fluctuations vanish at the South Pole of the fuzzy instanton.
- Fluctuations therefore increase away from the bounce on both sides.
- Time's arrow points in opposite directions on the opposite sides of the bounce.
- Events on one side will therefore have little effect on events on the other.

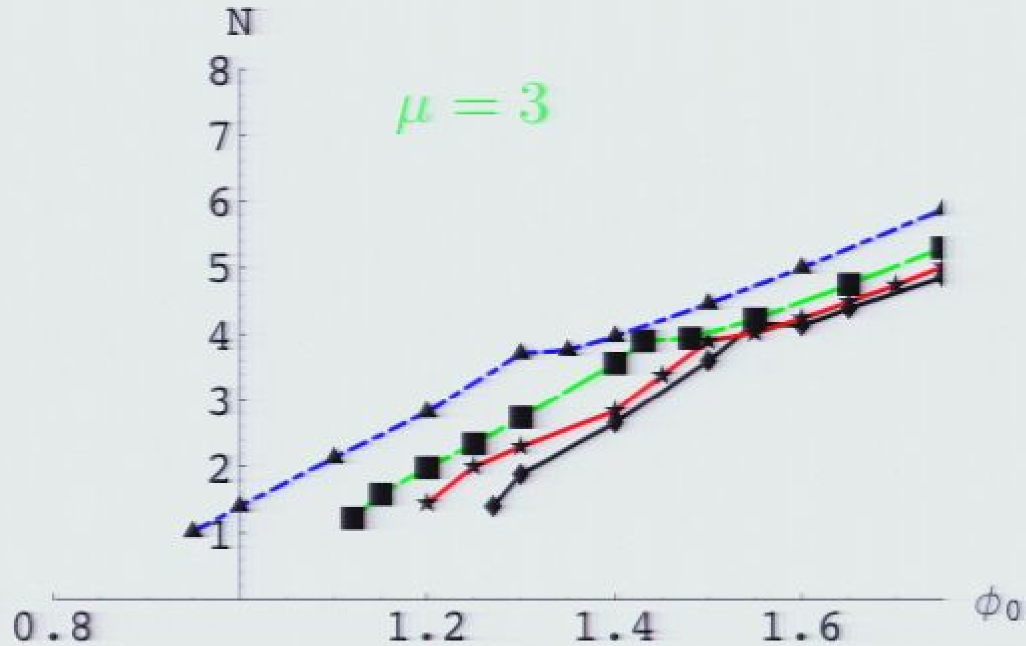




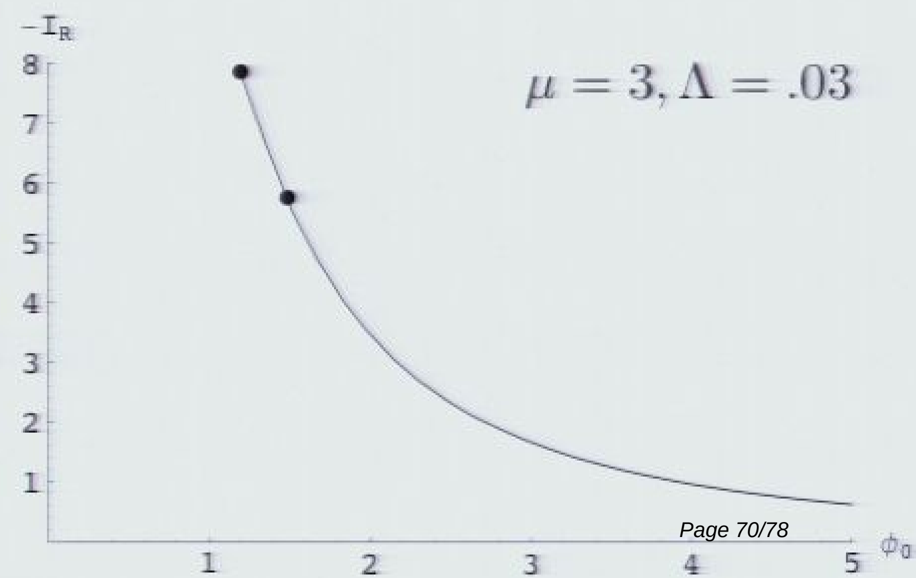
compare Caroll & Chen

Inflation





There is scalar field driven inflation for all histories allowed by the classicality constraint, but a small number of efoldings N for the most probable of them.



Conditional Probabilities

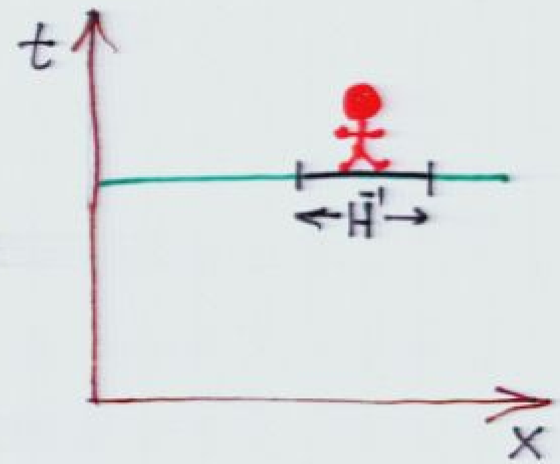
- We should not expect all of our data to be predicted with high probability from the fundamental theory of dynamics and the quantum state.
- Probabilities that test the theory are therefore typically conditional --- assuming some part of our data and predicting others. (Anthropic probs. are a special case.)
- Even probabilities assuming all of our present data are useful as with the top-down probabilities for the past. (Hawking and Hertog).

To test quantum theories of cosmology, we must search all conditional probabilities to find those near 0 or 1.

Probabilities for Our Data

- The NBWF predicts probabilities for entire classical histories.
- Our observations are restricted to a part of a light cone extending over a Hubble volume and located somewhere in spacetime.
- To get the probabilities for our observations we must sum over the probabilities for the classical spacetimes that contain our data at least once, and then sum over the possible locations of our light cone in them.
- This defines the probability of our data in a way that is gauge invariant and dependent only on data on our past light cone.

Sum over location in homo/iso models



- Assume our data locate us on a surface of homogeneity, and approx. data on the past light cone by data in a Hubble vol. on that surface

- Assume we are rare. (If we are everywhere there is no sum).

- The sum multiplies the probability for each history ϕ_0 by

$$V_{\mathrm{surf}}/V_{\mathrm{Hubble}} \approx \exp(3N)$$ N= # efoldings

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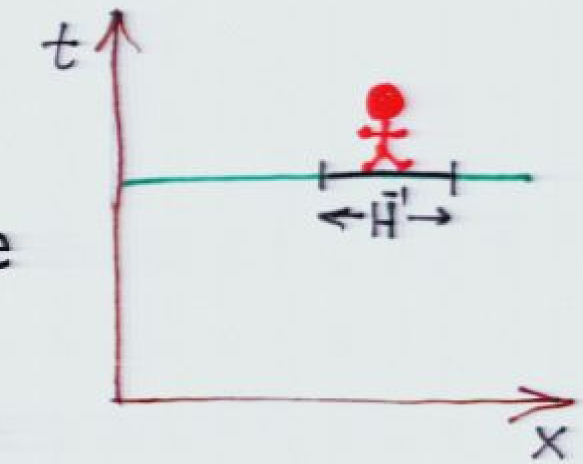
Sum over location in homo/iso models



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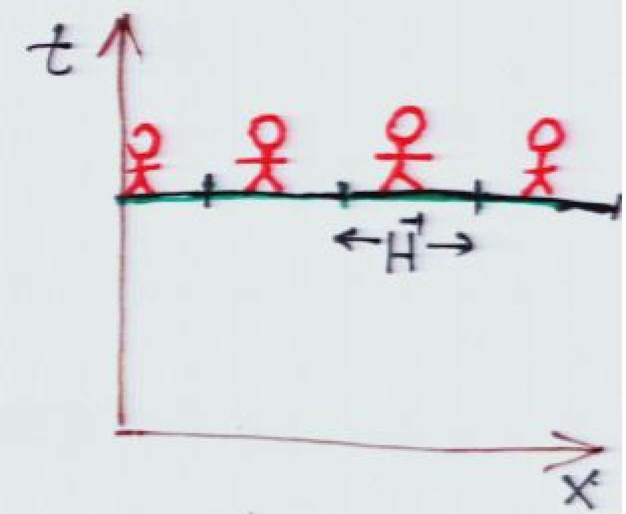

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$$V_{\rm surf}/V_{\rm Hubble} \approx \exp(3N)$$

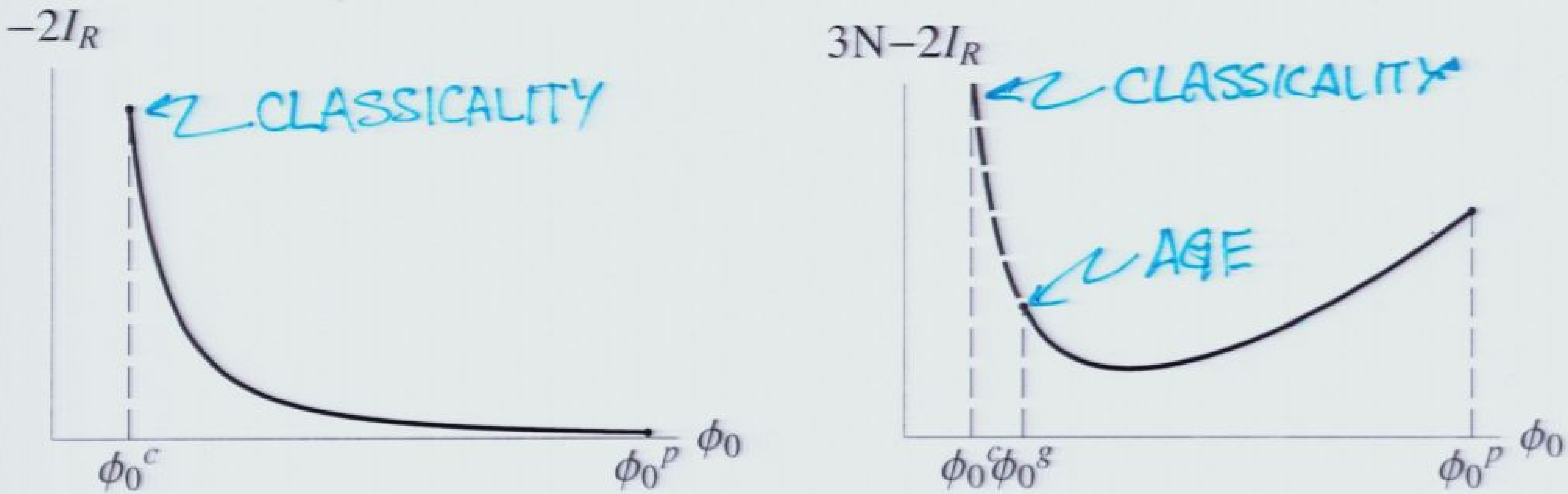
N= # efoldings

Page 97, Hawking 07

Volume Weighting favors Inflation

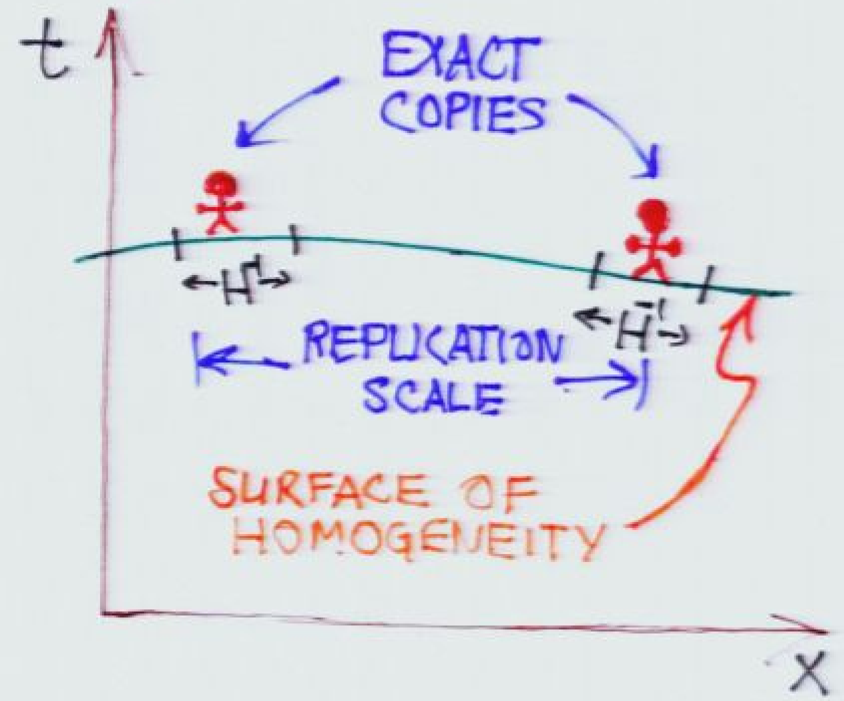
By itself, the NBWF + classicality favor low inflation, but we are are more likely to live in a universe that has undergone more inflation, because there are more places for us to be.

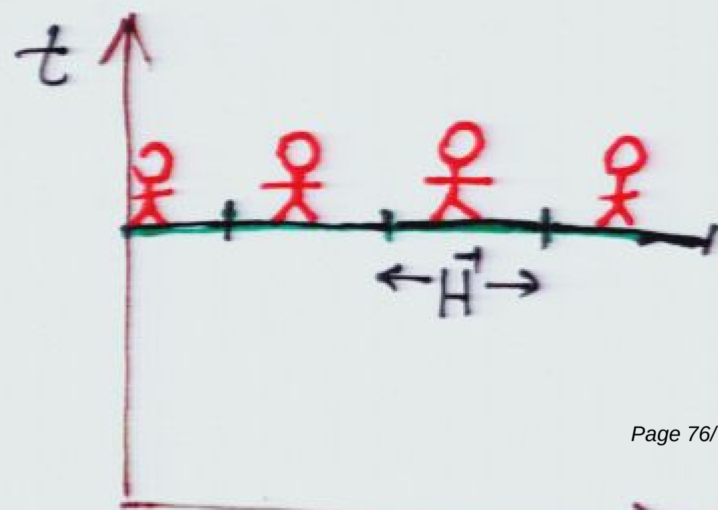
$$p(\phi_0|H_0,\rho) \propto \exp(3N)p(\phi_0) \propto \exp(3N - 2I_R)$$



Replication and Regulation

- We have a large amount of data, everything we know.
- In an infinite universe the probability is 1 that our data is replicated exactly elsewhere.
- In a homogeneous universe the replication scale regulates sums over our location.





Srednicki a.o. 07

Is classical spacetime a vacuum selection principle in string theory?

A quasiclassical realm is a prerequisite for anthropic reasoning, but a much stronger, more objective, more calculable condition.

The Main Points Again

Homogeneous, isotropic, scalar field in a quadratic potential, $\mu > 3/2$

- Only special states in quantum gravity predict classical spacetime.
- The NBWF predicts probabilities for a restricted set of entire classical histories that may bounce or be singular in the past. All of them inflate.
- The classicality constraint requires a minimum amount of scalar field (no big empty U's).
- Probabilities of the past conditioned on limited present data favor inflation.
- The classicality constraint could be an important part of a vacuum selection principle.