Title: Eternal Inflation Multiple Universes and other Dark Matters

Date: Feb 28, 2005 11:00 AM

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Abstract:

Eternal Inflation, Multiple Universes, and other **Dark Matters**.

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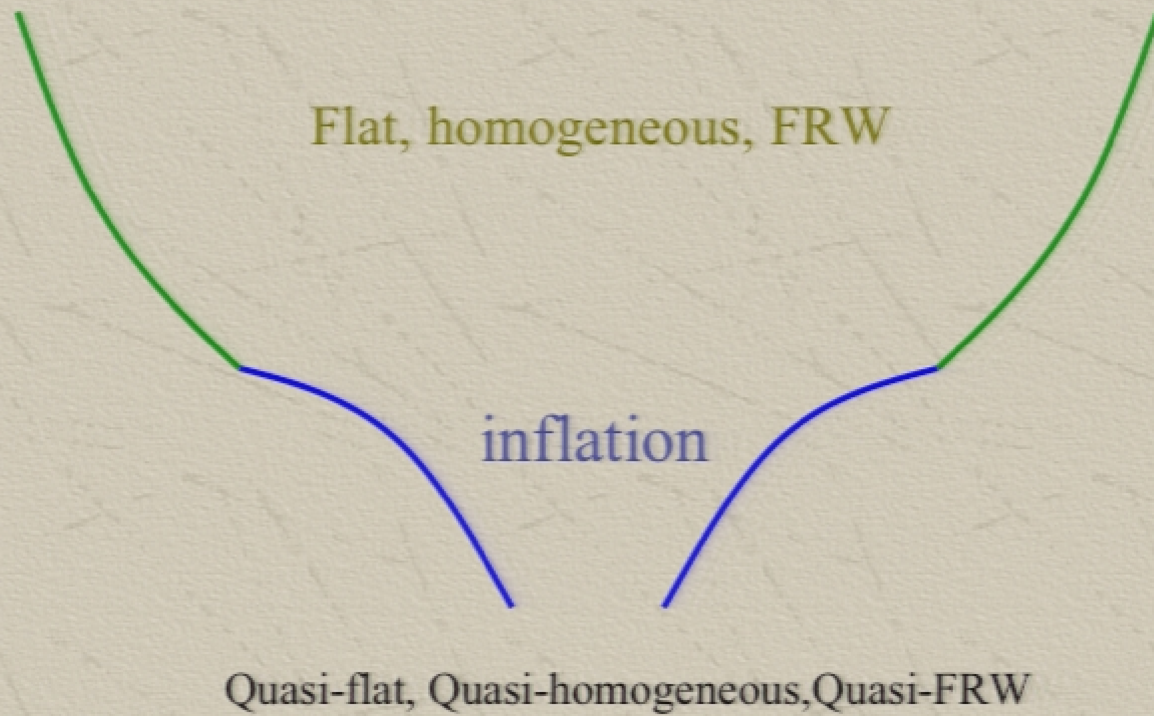
Inflation

Unsatisfactory features of big bang:

- Trans-horizon homogeneity
  -> "special" initial conditions.
- Near flatness -> "special" initial conditions.
- *ad-hoc* initial density fluctuations.
- Unwanted defects from GUT era.

Inflation now widely accepted as a cure.

Enter Inflation



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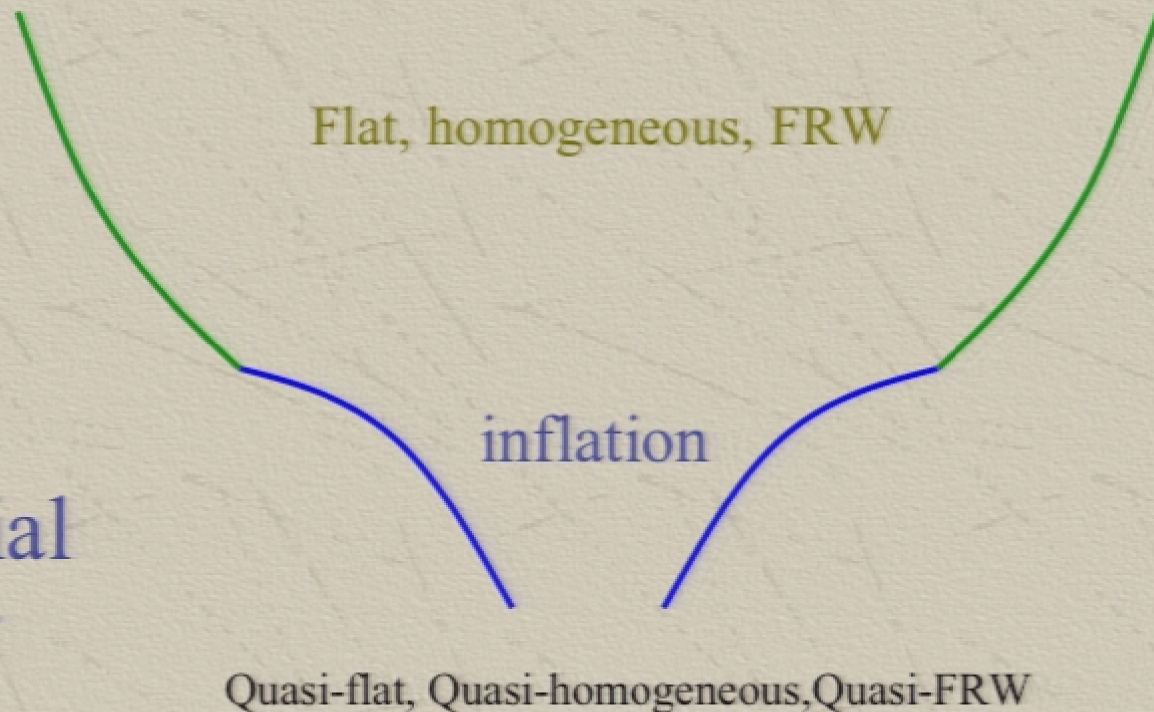

Problems:

- Still need initial conditions for inflation.

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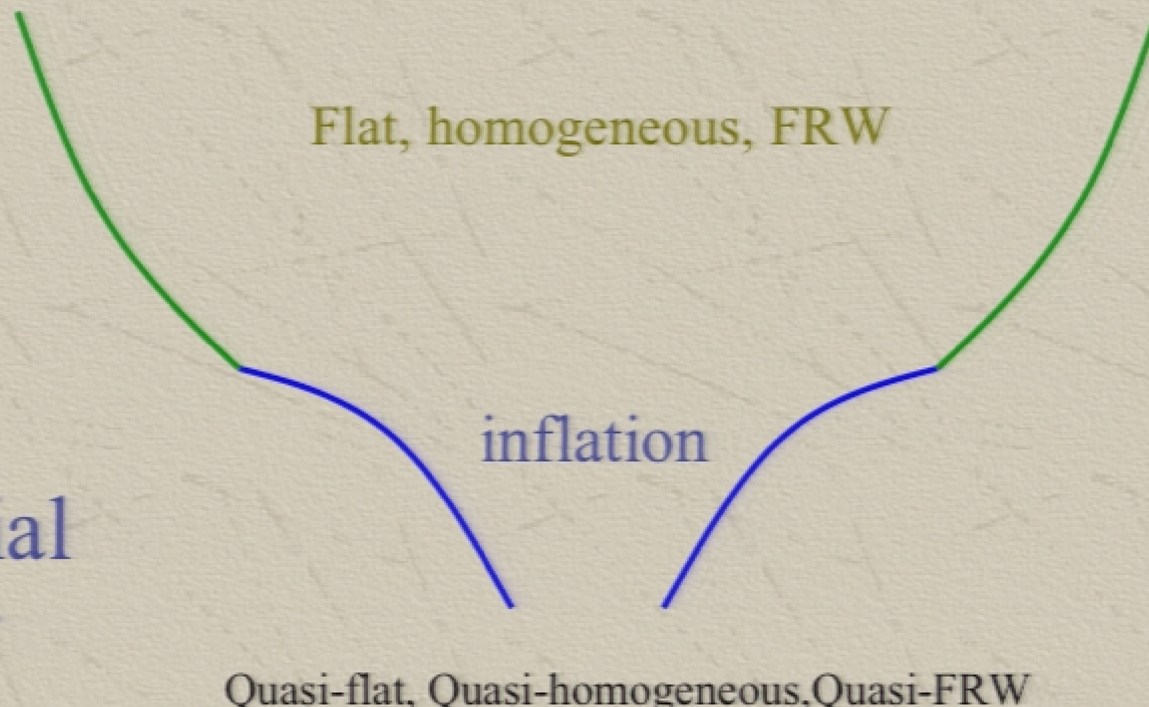


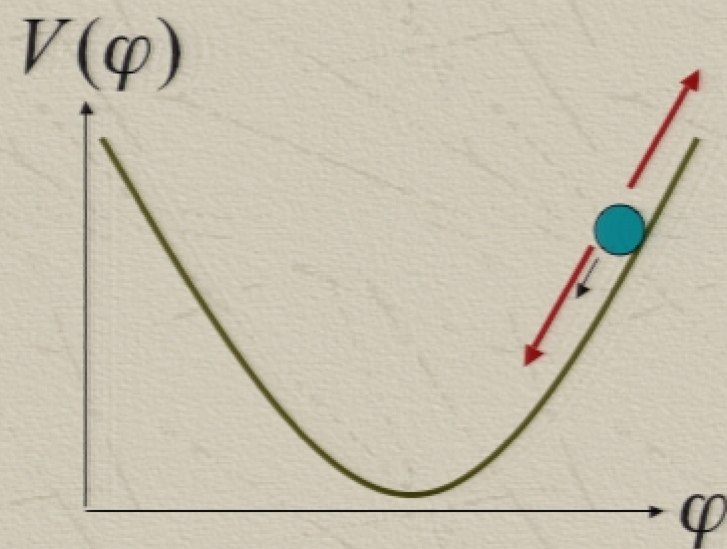
Problems:

- Still need initial conditions for inflation.
- Inflation never ends!

Semi-eternal Inflation

Once started, inflation generically does not end.

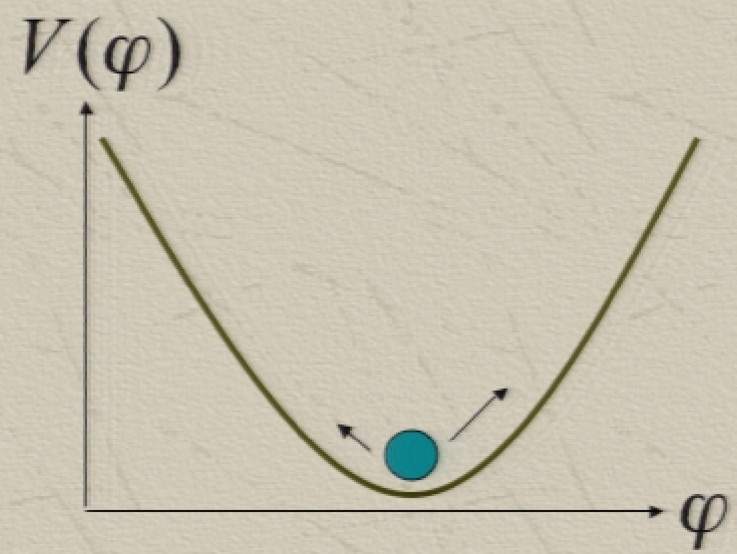
- When quantum fluctuations are accounted for, volume loss to lower potential smaller than volume gained from expansion.



Semi-eternal Inflation

Once started, inflation generically does not end.

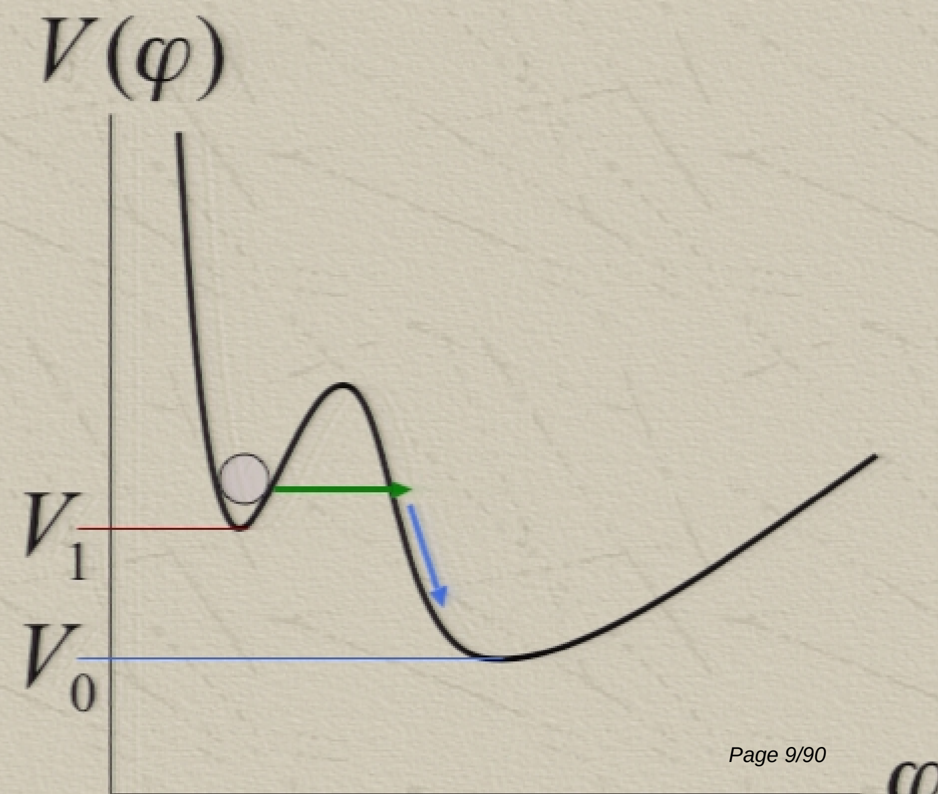
- Only occasionally does the universe reheat in some region.



Semi-eternal Inflation

This picture can be criticized,
but:

- Simple example: double-well potential.
- Tunneling events –> bubbles of V_0
- Slow-roll inflation, reheating in bubbles.
- Inflating bulk endures!



Semi-eternal Inflation

Inflating bulk endures:

Nucleation rate/4-volume

- Inflating fraction:

$$f_{\rm inf} = \exp\left[-\lambda \frac{4\pi(t-t_0)}{3H^{-3}}\right]$$

Available 4-volume

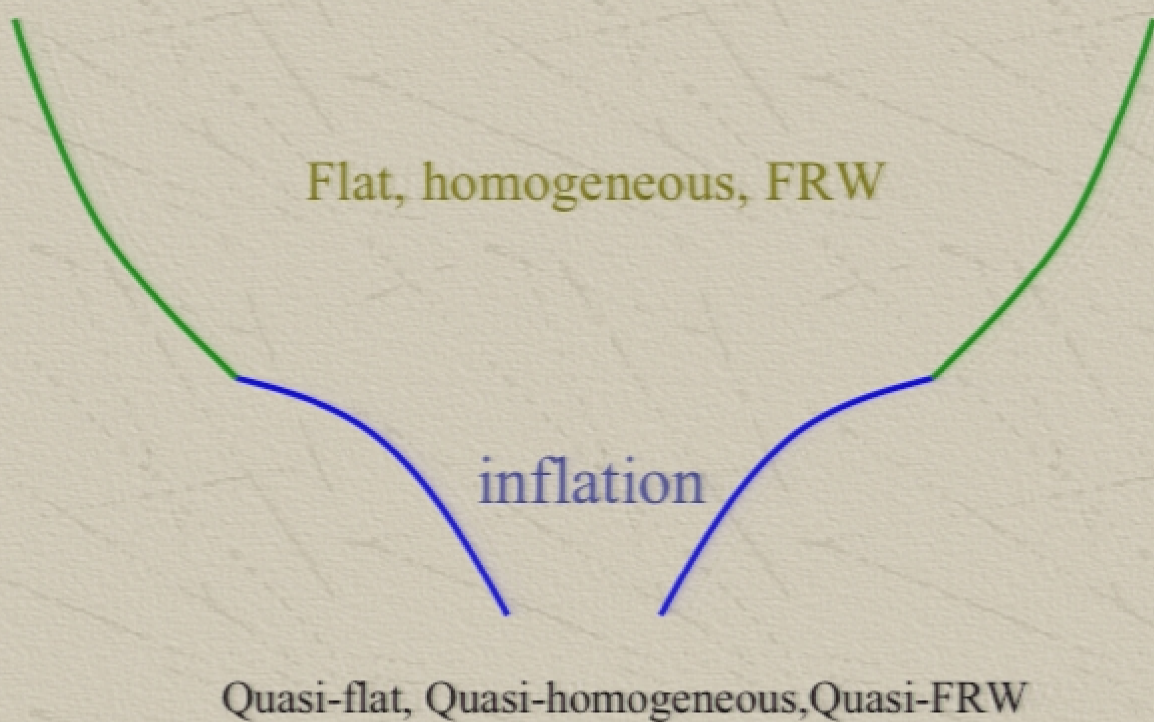
- Inflating volume:

$$v_{\rm inf} \propto \exp(3Ht) f_{\rm inf} \propto \exp(3 - 4\pi\lambda/3H^4)Ht$$

***Grows* for small λ!**

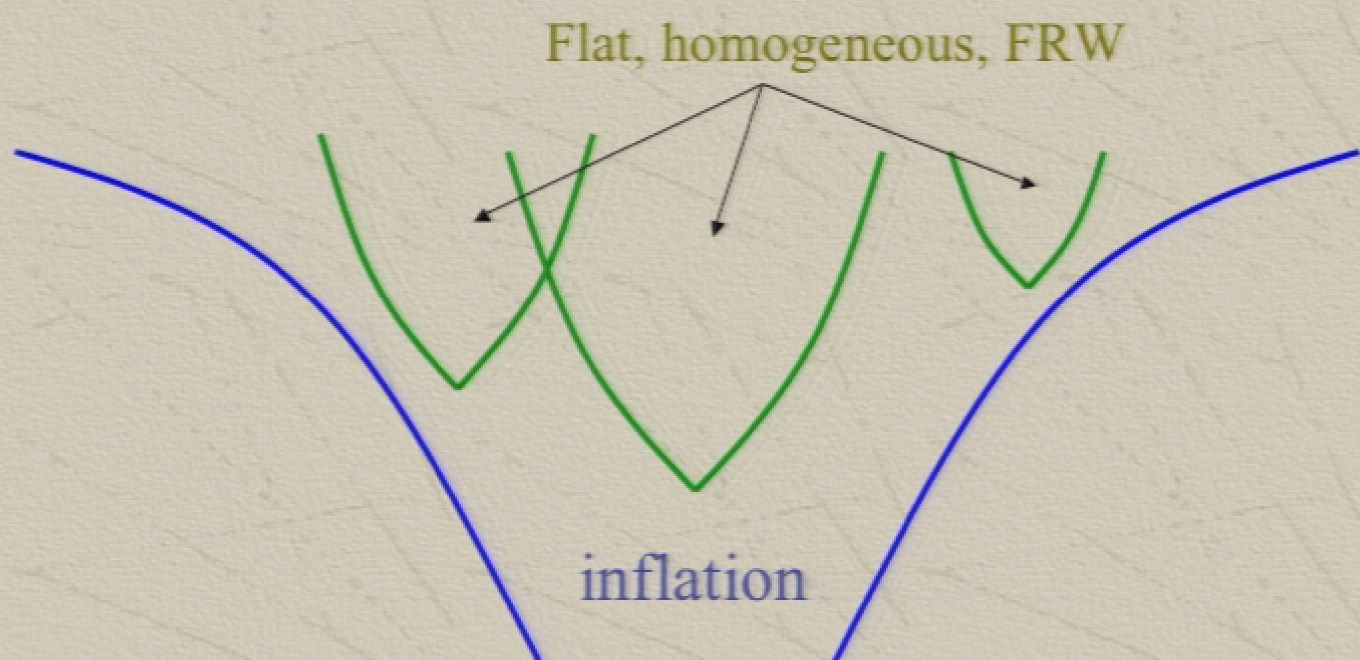
Note: V_0 does not appear; relative expansion rate irrelevant

Semi-eternal Inflation



Semi-eternal Inflation

-> "quasi-steady-state" distribution of thermalized + inflating regions.



Quasi-flat, Quasi-homogeneous,Quasi-FRW

Multiverses

- **Inflation:** gives rise to many FRW-like regions. These “universes” could have different properties.

  and also:

- **String theory:** ‘Low’-energy physics given by particular minimum in “landscape”?
- **Quantum Cosmology:** Different decoherent branches of cosmic wavefunction -> different cosmic properties.

Multiverses

"Fundamental theory of cosmology"

=

(string theory)+(inflation)+(quantum cosmology) ?

All three prospective components have same property:

no *unique* prediction likely!

How do we test such an FTC?
Predictions in a multiverse

Assume: ensemble of actually existing "sub-universes". Parameters α_i characterizing sub-universes vary.

Assume: A probability distribution $P(\alpha_i)$ of a randomly chosen baryon (or comoving volume element) residing in a sub-universe characterized by parameters α_i .

Develop: Some way to connect $P(\alpha_i)$ to what we observe.

Predictions in a multiverse

Issue 1:

Is there a unique prescription to connect $P(\alpha_i)$ to what we observe?

Issue 2:

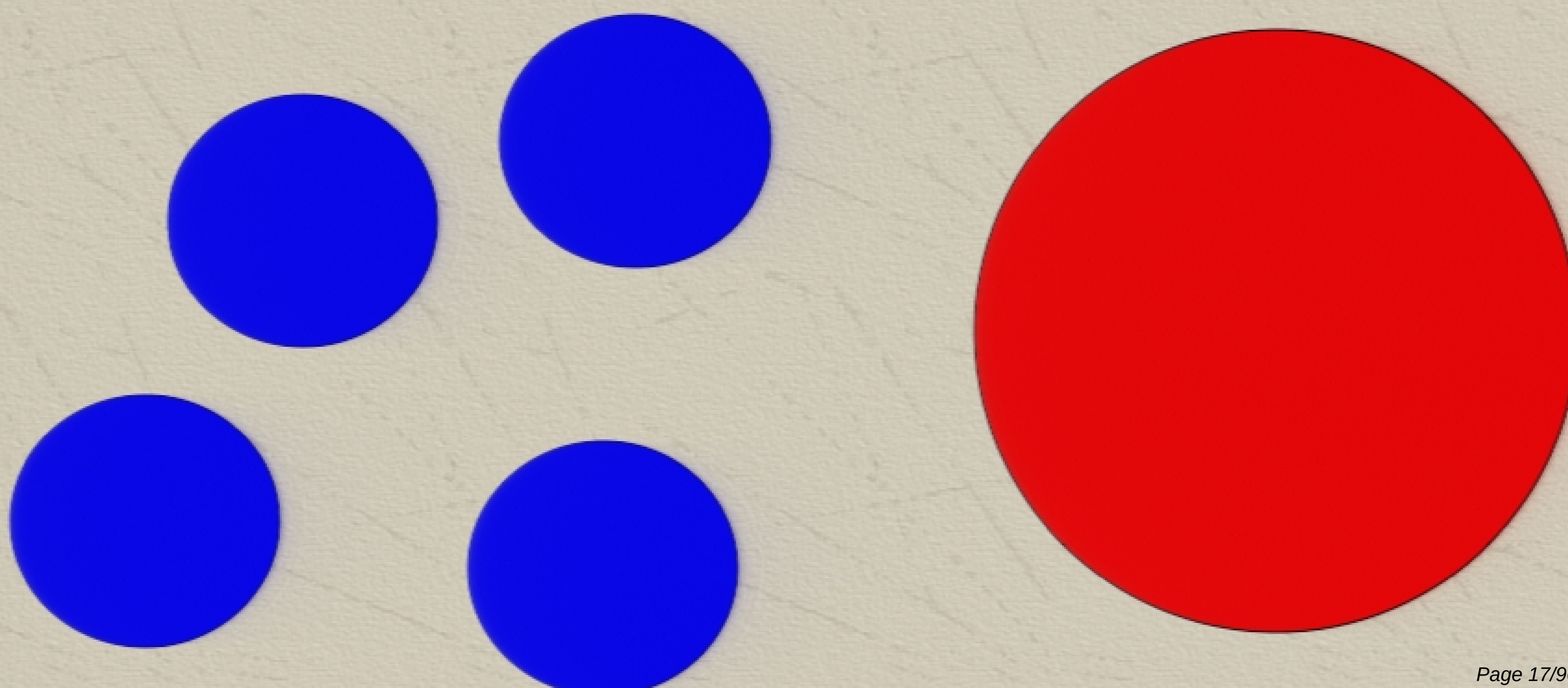
What role is played by the "Anthropic principle"?

Issue 3:

In eternal inflation, does $P(\alpha_i)$ even make sense?

Issue 1

There is *no* unique way to connect $P(\alpha_i)$ to what we observe.



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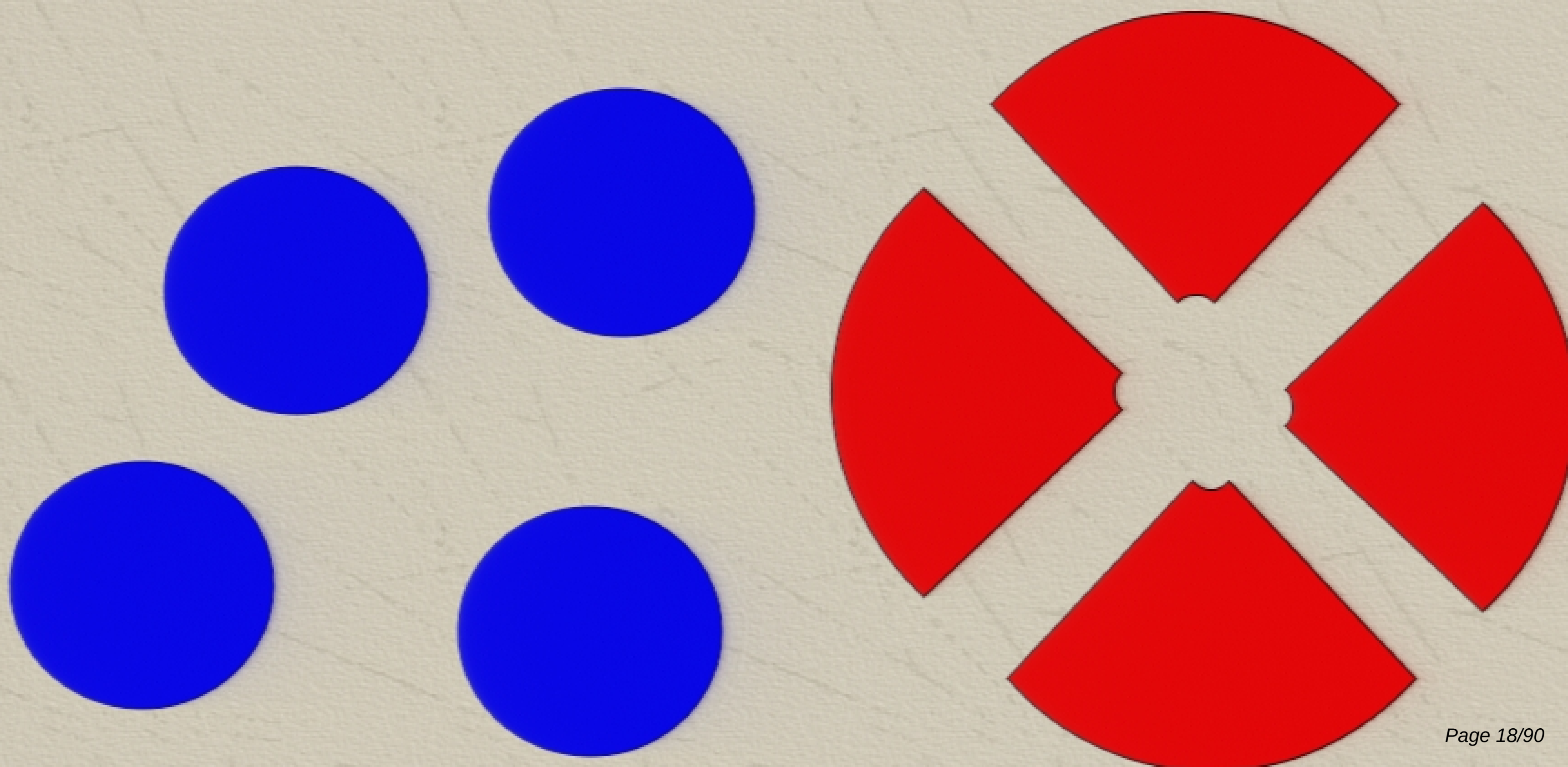

Issue 1

There is *no* unique way to connect $P(\alpha_i)$ to what we observe.

Three basic approaches (See Aguirre & Tegmark 04):

- **"Bottom-up":** compare our universe to "most typical" in ensemble (weight by universe? By volume? By baryon?)
- **"Top-down":** compare our universe to most typical universe *matching previous observations*. (Why accept today what was a wrong prediction yesterday?)
- **"Anthropic":** compare to most typical *observed* universe (what the <bleep> is an observer?)

Worse yet: *different predictions* regarding future observation.

Example: assume there are *many* (N >> 1) *independent* dark components, governed by

$$P(\eta_i),\ \eta_i = \Omega_{DM,i} / \Omega_b$$

Dark matter candidates

- Lightest stable supersymmetric particle
- Axions
- Kaluza-Klein particles
- Q-balls
- Heavy neutrinos
- Primordial black holes
- Mirror matter
- Cryptons
- LIMPs
- Monopoles
- Quark nuggets
- CHAMPS
- D-Matter
- Brane-world DM

Etcetera…

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Bottom up:

Unlikely for any two to have comparable density.

Worse yet: *different predictions* regarding future observation.

Example: assume there are *many* (N >> 1) *independent* dark components, governed by

$$P(\eta_i),\ \eta_i = \Omega_{DM,i} / \Omega_b$$

Bottom up:

Fine-tuning for any two to have comparable density.

Anthropic or top down:

Natural for many to have comparable density!

The top-down approach.

- Condition on all known data, predict unknown:
  limit to subset of universes with $\alpha_i = \alpha_{i,\text{obs}}$ for already-observed parameters.
- Within this subset, find $P(\alpha_k)$ for others.
- Prediction for η_i? Observationally, $\eta \equiv \sum_i \eta_i = 6.$
  - If $P(\eta_i)$ peaks at $\eta_i << 6$ fine.
  - For rest, maximize product $\prod_i P(\eta_i)$ subject to $\eta = 6$.
  - Suppose $P(\eta_i) \propto \eta_i^{\beta_i}$, then $\eta_i = \beta_i / \sum_j \beta_j$

- **Prediction: many components of similar density!**

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- To reconcile the observed values of a set of parameters with the (very different) values that might be expected on some fundamental grounds.
- To explain why the observed parameter values appear 'fine-tuned' for life.

Method of (weak) anthropic arguments: the 'anthropic program'

- Calculate $\Sigma(\alpha_i)$, the probability a particular set of values for the parameters α_i will be observed, accounting for the fact that only certain values allow observers.

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- Calculate $\Sigma(\alpha_i)$, the probability a particular set of values for the parameters α_i will be observed, accounting for the fact that only certain values allow observers.
- ***If*** this probability is concentrated near values similar to those *we* observe, then we can claim to have ‘explained’ the observed values.

Essential Ingredients of Cosmological Anthropic Arguments

1. Multiverse
2. Probability distribution $P(\alpha_i)$

Essential Ingredients of Cosmological Anthropic Arguments

3. A definition of what constitutes an 'observer' capable of measuring the values of the parameters α_i in a sub-universe.

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Essential Ingredients of Cosmological Anthropic Arguments

4. A computation of the number $\chi(\alpha_i)$ of observers per baryon (or per comoving volume element) that would arise in a universe with parameters α_i.

Assume observers are similar to us. How do you count them?

Galaxies? Not clearly necessary.

Stars maybe?

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5. The *assumption* that we inhabit a universe with parameters values at or near the values that would be observed by a typical randomly chosen observer (the 'principle of mediocrity').

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News Release

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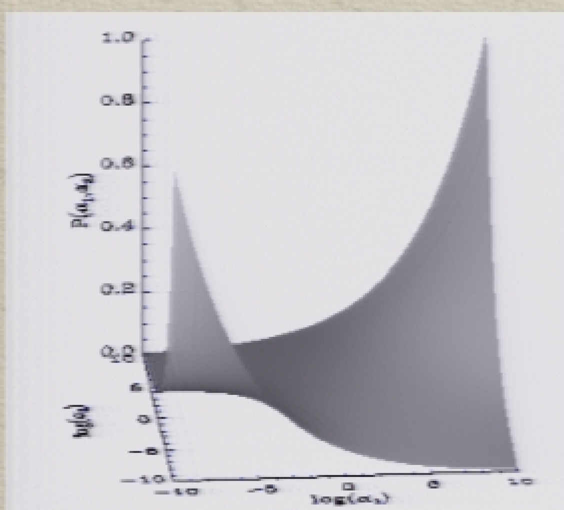
The end result: predictions of α_i (hopefully)

Combine a-priori probabilities $P(\alpha_i)$ with 'anthropic factor' $\chi(\alpha_i)$ to obtain probability distribution $\Sigma(\alpha_i)$ of observed parameters:



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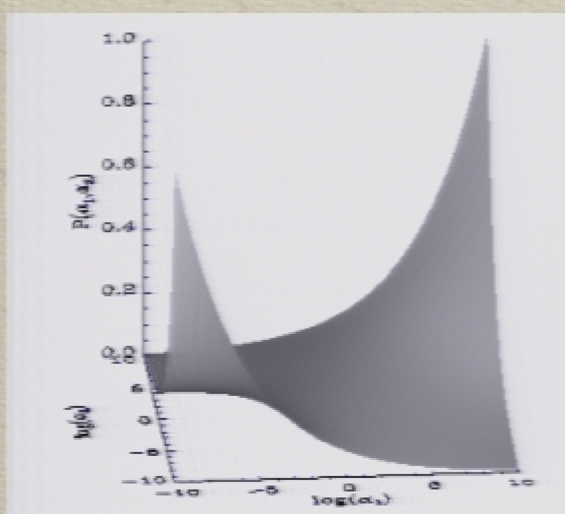

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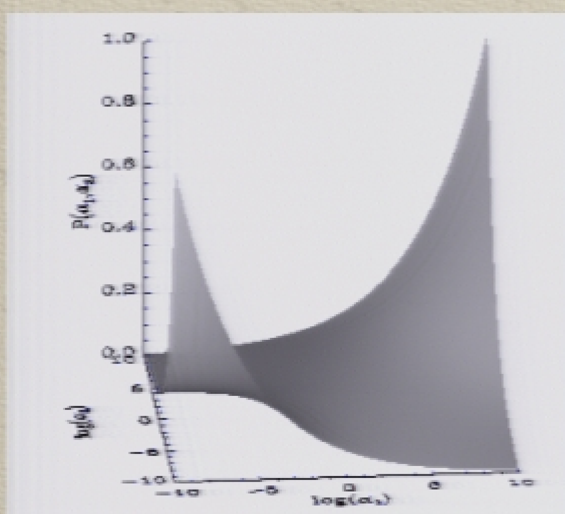
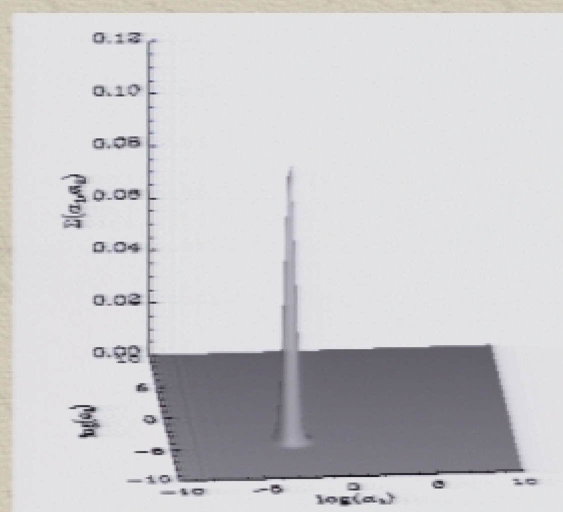


$P(\alpha_i)$

$\times$



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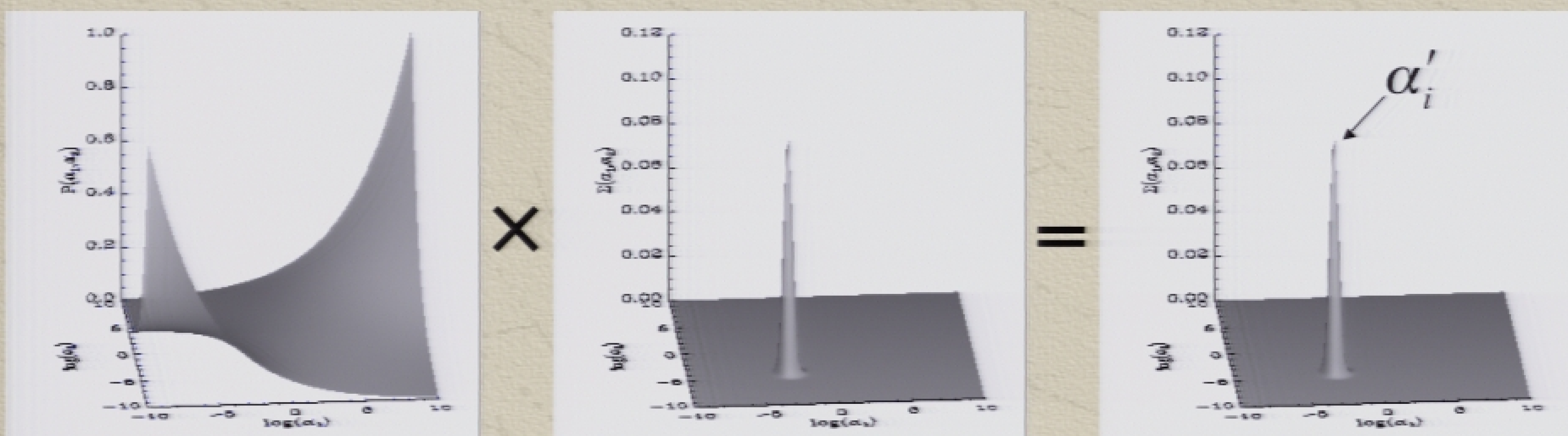


$P(\alpha_i)$ $\chi(\alpha_i)$ $\Sigma(\alpha_i)$

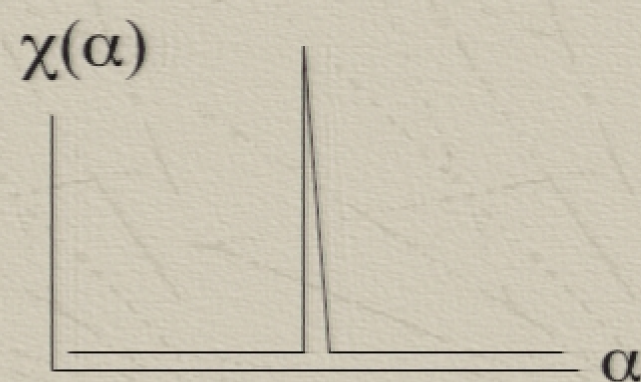
What forms can "anthropic factor" take?

1. δ-function:

   Great! *P(α)* doesn't matter!

   "Classic" idea of anthropic principle: we live in the (unique) type of universe allowing life.

   (or: Disaster! We can learn nothing about *P(α)*!)



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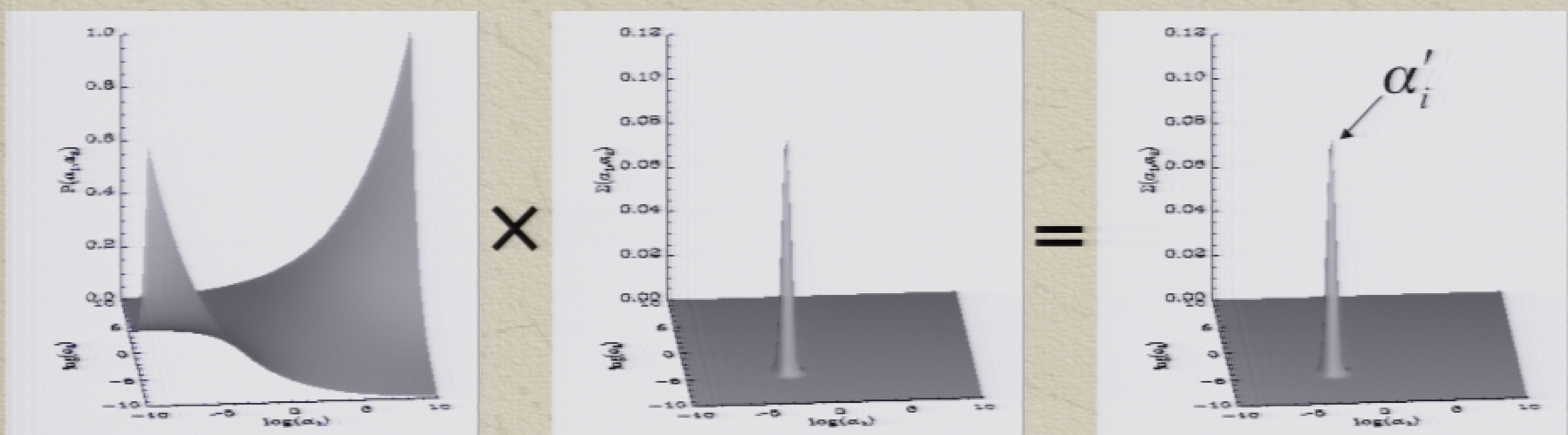

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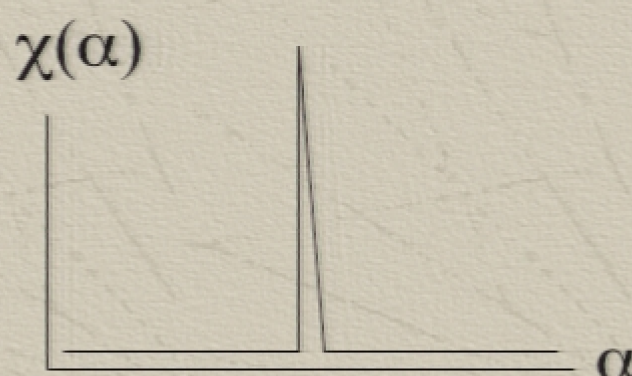
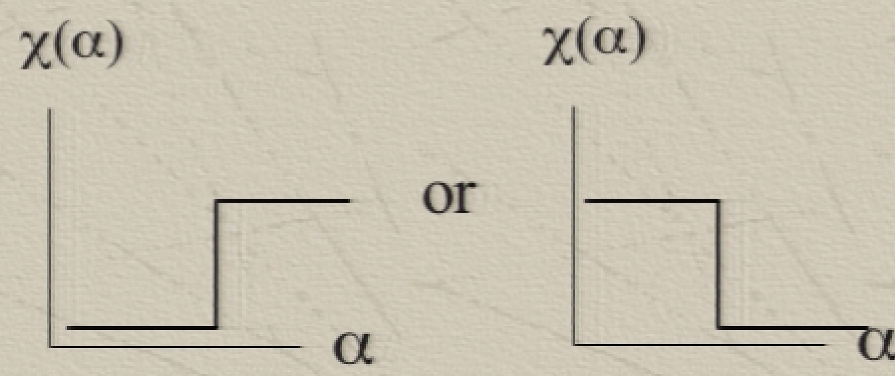




2. Θ-function: just force minimal or maximal value.

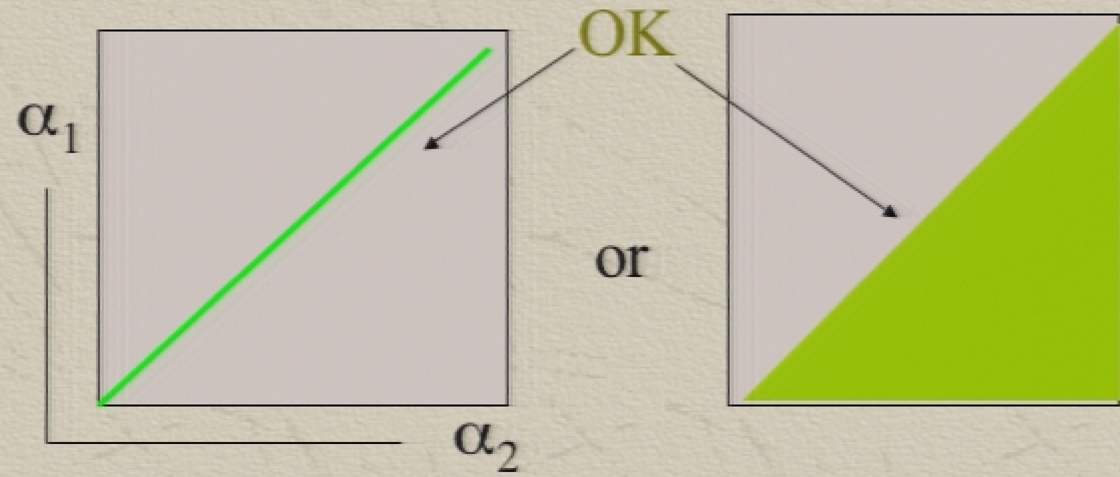
Consider *maximal probability* subject to this.

Example: cosmological constant arguments (Weinberg et al.; Vilenkin, Garriga et al.)

Predict: Λ small but nonzero.

(similar argument for small, nonzero ν mass; see Tegmark & Vilenkin).

Problem: arguments change if multiple parameters vary.



3. Degeneracies in anthropic factor $\chi(\alpha)$.

These are inevitable. e.g:

Multiple dark matters: (recall Issue 1.)

Only *total* η_{DM} is anthropically important.

As for top-down, maximize probability $\prod_i P(\eta_i)$
subject to constraint on η.

–> **Multiple components of similar density.** (*if* AP forces $\eta \sim \eta_{obs}$.)

Degeneracies in anthropic factor $\chi(\alpha)$.

-> Multiple components of similar density

Moreover, same argument can be applied to dark energy, or density perturbations.

This is awful:

AP, devised to explain coincidences, predicts there should be more. The "preposterous universe" should get ***even worse!***

This is great:

The AP, as a methodology, makes a general prediction.

Degeneracies in anthropic factor $\chi(\alpha)$.

Degeneracies also undermine anthropic arguments: e.g.

High Λ truncates structure formation at some density.

But, high perturbation amplitude Q speeds up structure formation.

or:

High Q makes halos denser –> stellar collisions.

But, lower baryon density can compensate.

Is this a serious problem?

Parameters specifying a big-bang cosmology

- Q: the amplitude of primordial perturbations
- η_γ: the photon-to-baryon ratio
- η_{DM} : the dark matter-to-baryon mass ratio
- η_L : the lepton-to-baryon ratio
- R : the curvature scale
- Λ: the cosmological constant

Can any or all of these be very different without preventing the formation of observers like us ? (AA01)

Hot Cosmologies: Variations on ours

For HBB-like cosmologies, Tegmark & Rees (1997) have worked out constraints. Let η_{DM} be fixed, then:

- For sufficient cooling: $\frac{Q}{10^{-6}} \geq \left(\frac{\eta_\gamma}{10^9}\right)^{4/3}$
- To avoid stellar encounters: $\frac{Q}{10^{-4}} \leq \left(\frac{\eta_\gamma}{10^9}\right)^{8/7}$
- To avoid too-early Λ-domination: $\frac{\Lambda}{\Lambda_{OBS}} \leq 10\left(\frac{\eta_\gamma}{10^9}\right)^{-4}\left(\frac{Q}{10^{-5}}\right)^{3}$

Note the degeneracy between Q and η_γ **.**

But let's go far-out: A Cold Cosmology

The 'hot big bang' assumes $\eta_\gamma \approx 10^9$ since (at least) the nucleosynthesis epoch.

Consider, though, a cosmology in which $\eta_\gamma \approx 1$ **.**

A Cold Cosmology

- Nucleosynthesis: High density allows primordial heavy elements (tune using η_γ, η_L).
- Structure formation: low early Jeans mass:

$$M_J = (\eta_L + \eta_\gamma)^2$$

A Cold Cosmology: two scenarios

Supermassive first stars:

- Radiation at Eddington limit creates CBR, ionizes gas.
- Galaxies form later, as in HBB, with remnants of VMOs as dark matter.
- Seems as likely to form observers as our universe.

$$Q_8 > 1 \quad \eta_{DM} \approx 0$$

Solar mass first stars:

- First stars in dense clusters.
- Subsequent hierarchical structure formation
- Stellar encounters would doom protoplanetary disks, but stars are evaporated first.

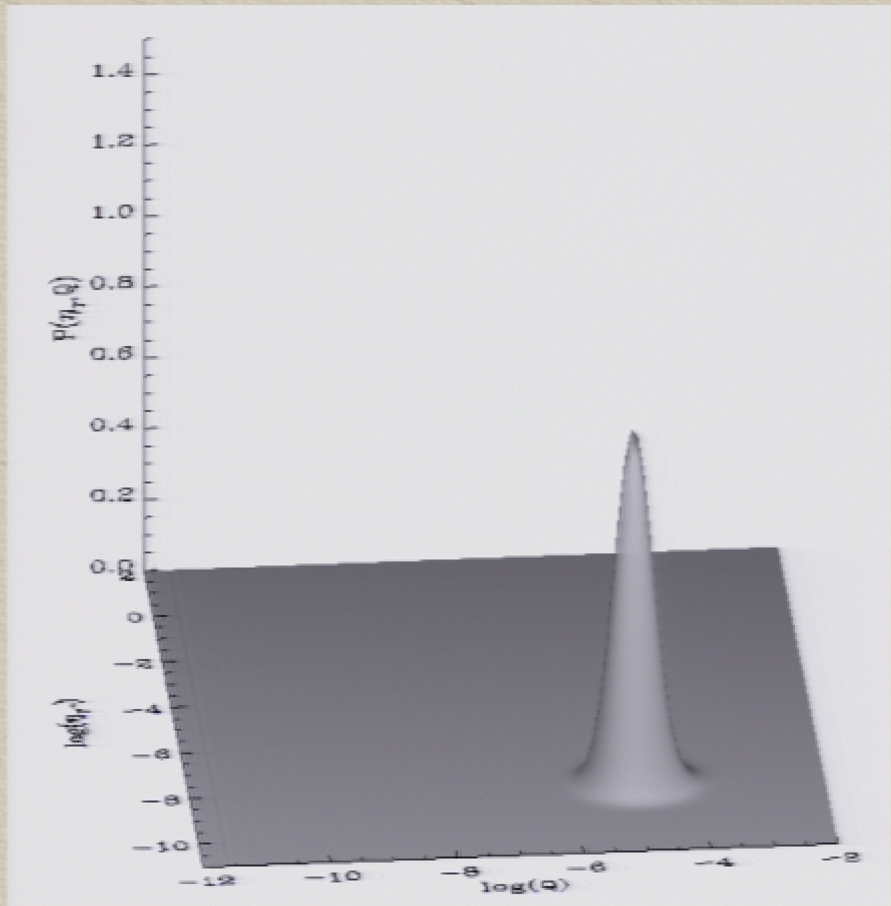
$$10^{-3} \leq Q_8 \leq 1,$$

$$\eta_{DM} \approx 0 - few$$

Huge Λ, 1/R possible!

Implications for χ

- Consider Q, η_γ .
- Recall hope (?) of sharply peaked χ.



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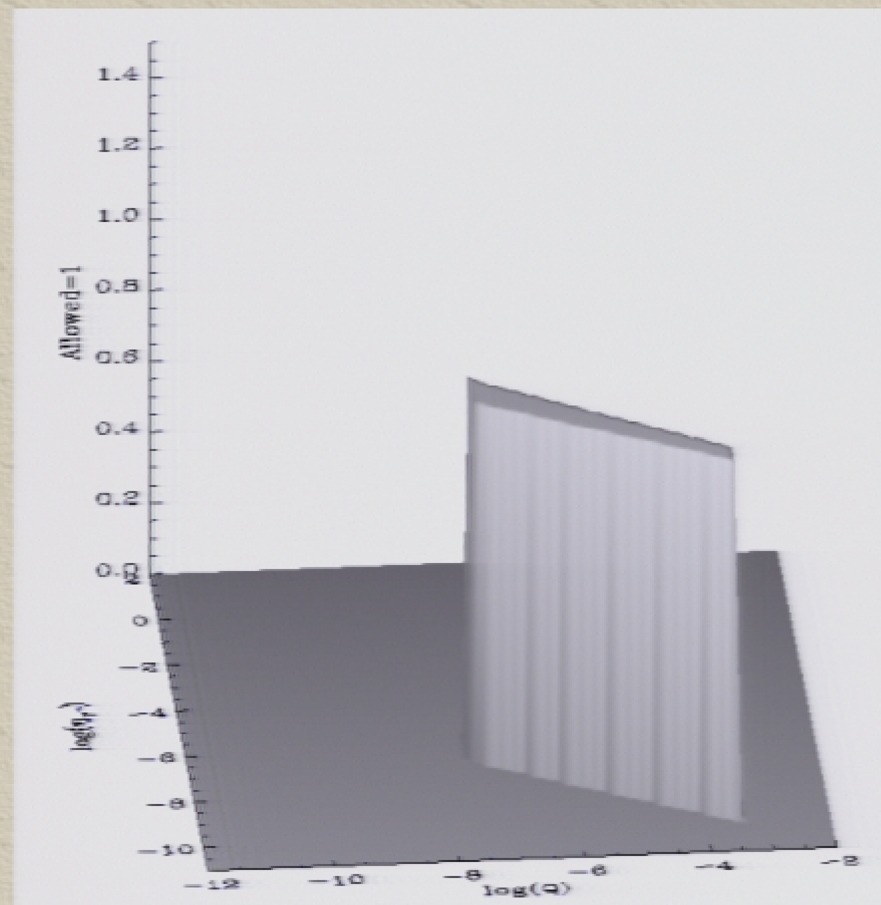

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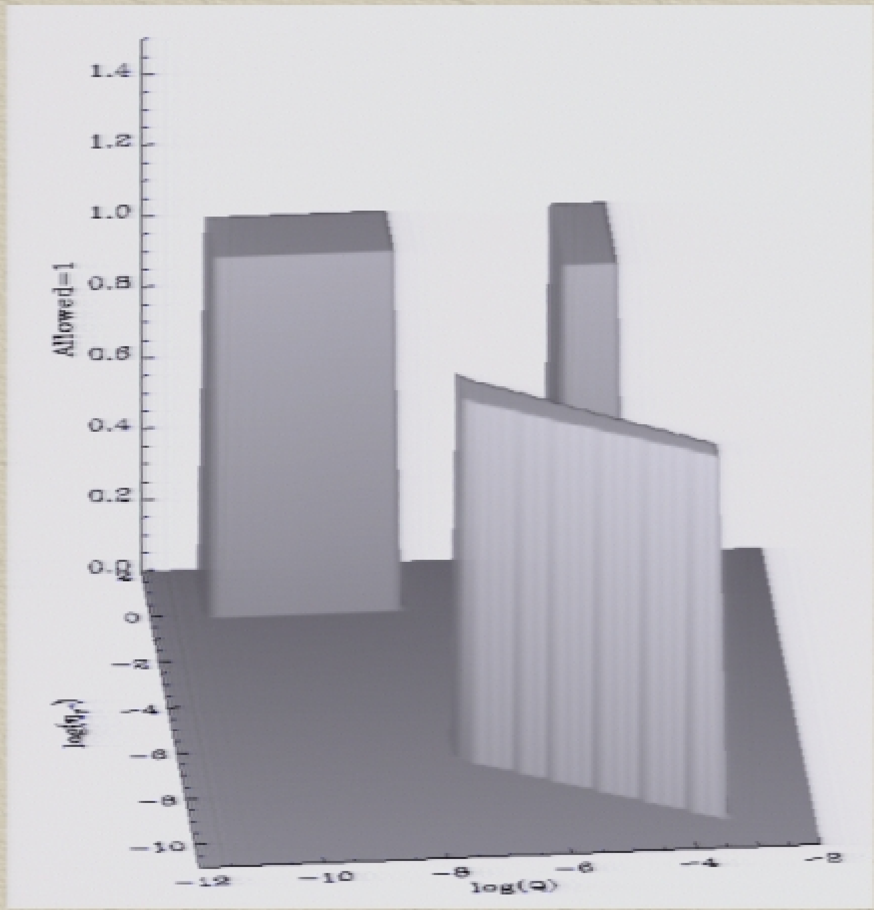

Implications for χ

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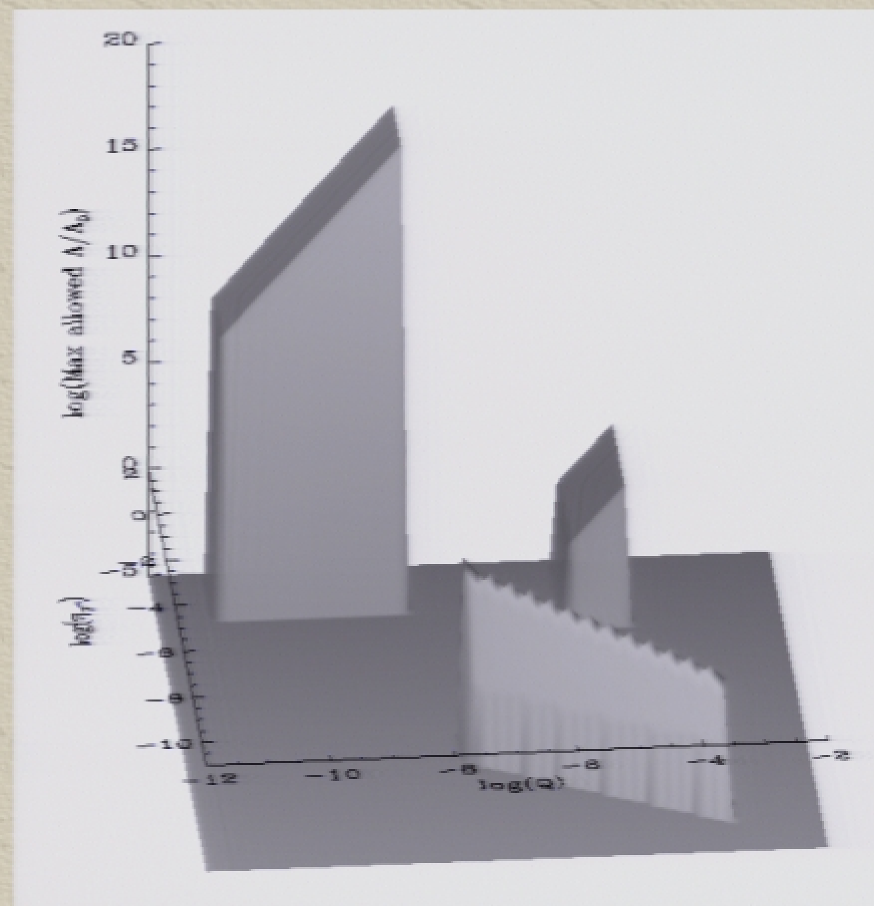
- But near HBB, degeneracy allows different values.
- CBB allows *very* different values.
- This in turn allows extremely different values of, e.g., Λ or R.



Bottom line: *big* degeneracies exist in χ for cosmological parameters

Issue 3

- Even if we know the physical theory, can we compute *P*?

Consider semi-eternal inflation, ask innocent questions, e.g.:

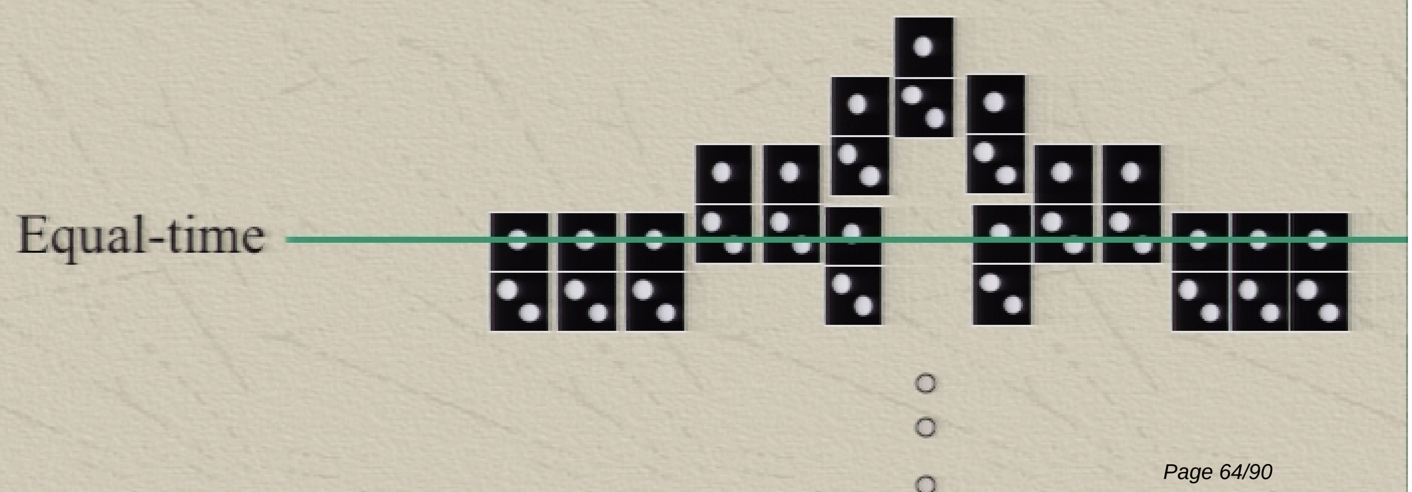
What is the cosmic time since the big-bang (Guth)?

Any observer: *finite*, but typical time: *infinite*.

What is the average age (since reheating) of an observer?

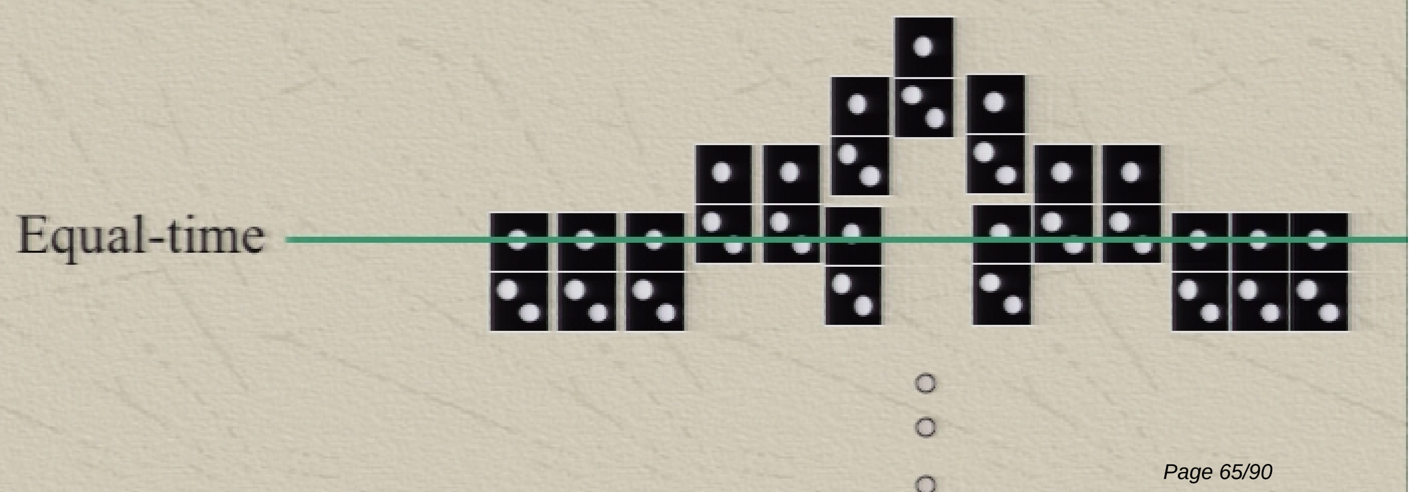
Tiny! Equal-time slice is youth-dominated.

Idea:



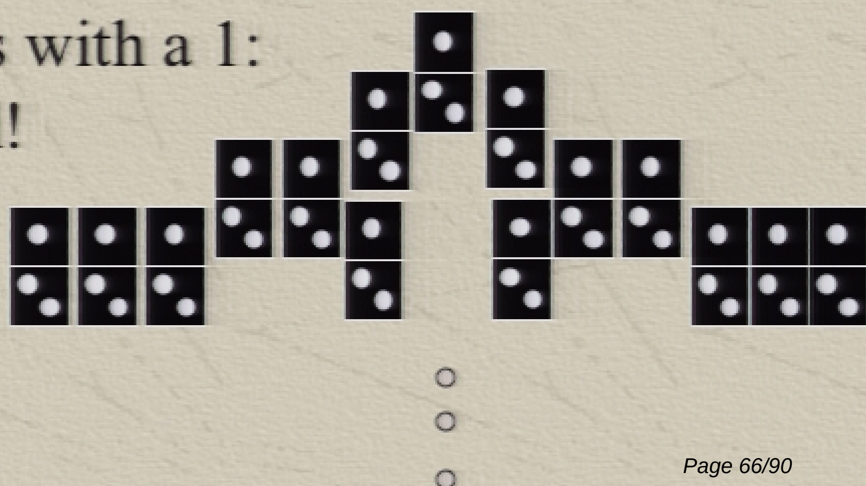
Idea:

- (Guth): Imagine that universe is dominos. At each instance, you line up 2 1's for each 2. Twice as many 1s as 2s at each time. 1s are twice as probable!



Well-meaning people disagree:

- (Guth): Imagine that universe is dominos. At each instance, you line up 2 1's for each 2. Twice as many 1s as 2s at each time. 1s are twice as probable!
- (Aguirre): But you know by construction that each 2 comes with a 1: the probabilities must be equal!
- (Guth): no.
- (Aguirre): yes.



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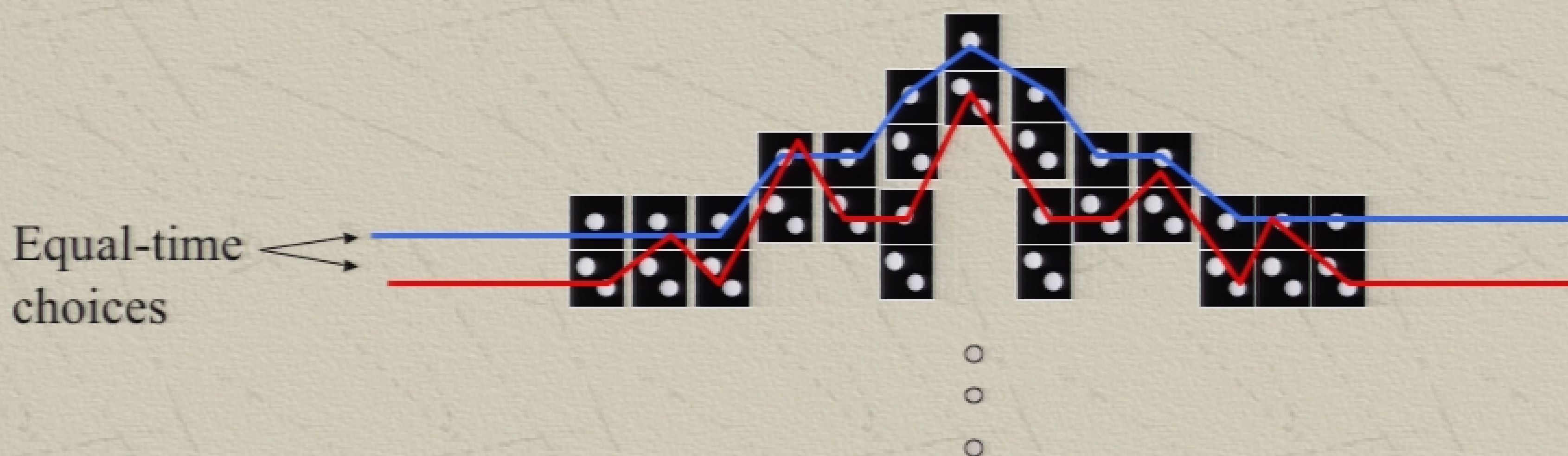

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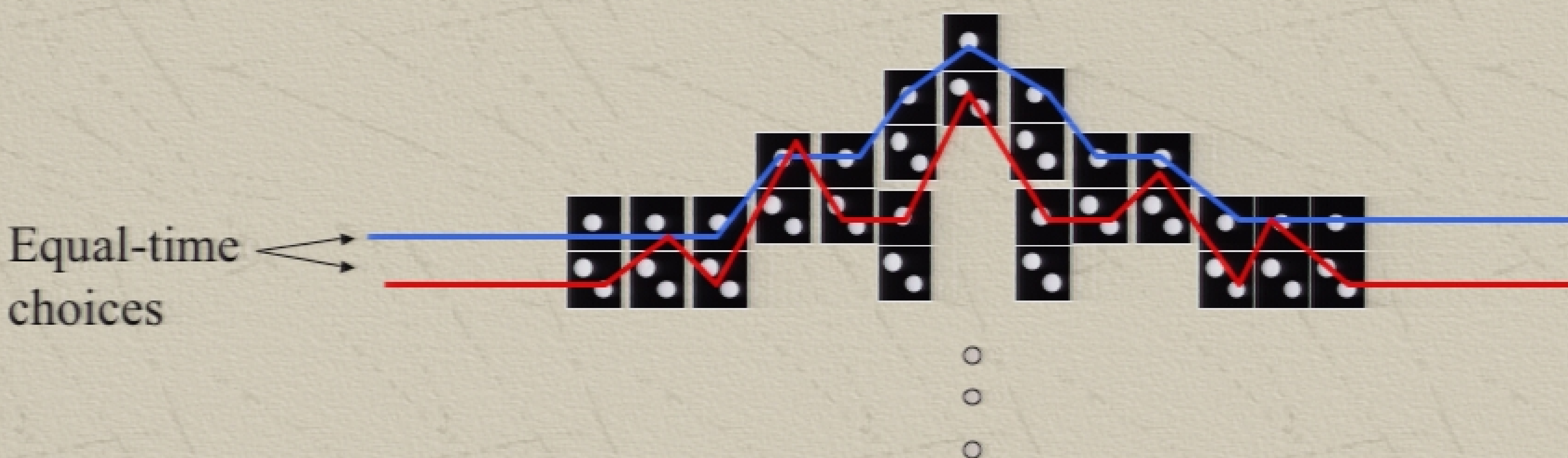


Semi-eternal Inflation

In fact it is much worse than this suggests:

1. Each bubble universe is infinite.
2. Nearly-infinite number of bubble universes at each time.
3. Infinitely many times.

Semi-eternal Inflation

Some work has been done toward removing this ambiguity (Linde & Mezluhmian; Vilenkin et al.)

My contention: these are partly connected with *cosmological boundary conditions.*

Tough to talk about in semi-eternal inflation due to:

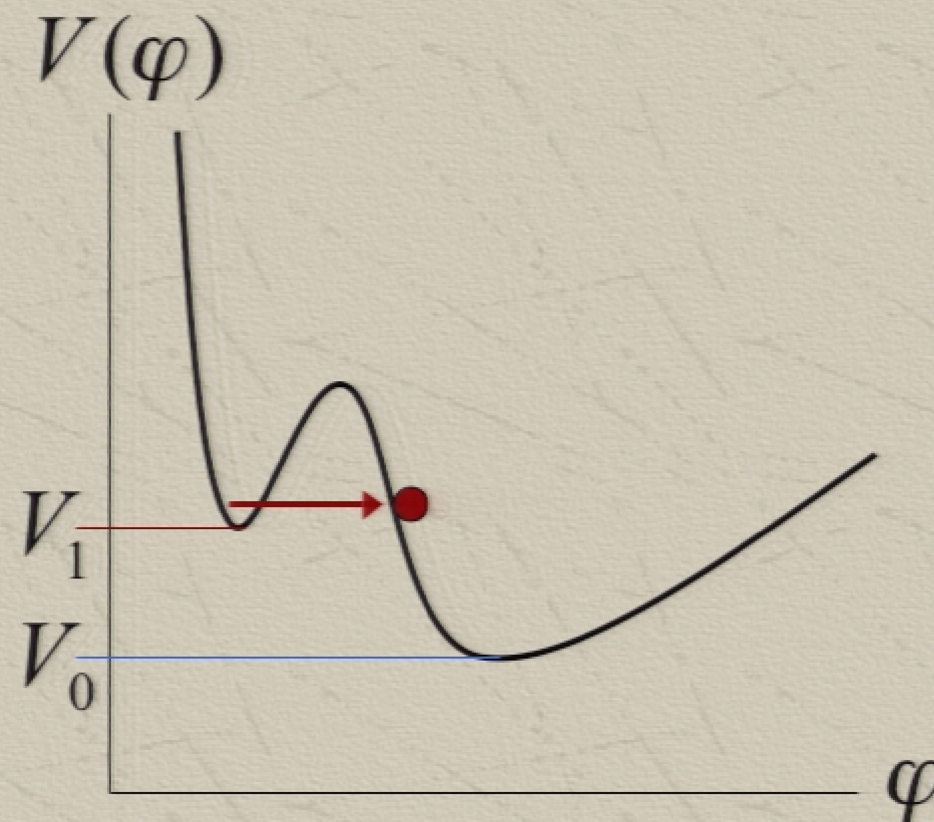
- Initial cosmological singularity
- Infinite inflation between any observer and big-bang.

Semi-eternal Inflation

Some funny features of semi-eternal inflation may go away, and the boundary conditions be specified if inflation, as well as having no end, **had no beginning** (AA & S. Gratton 2003)

Steady-State eternal inflation

- Let's analyze the double-well case.



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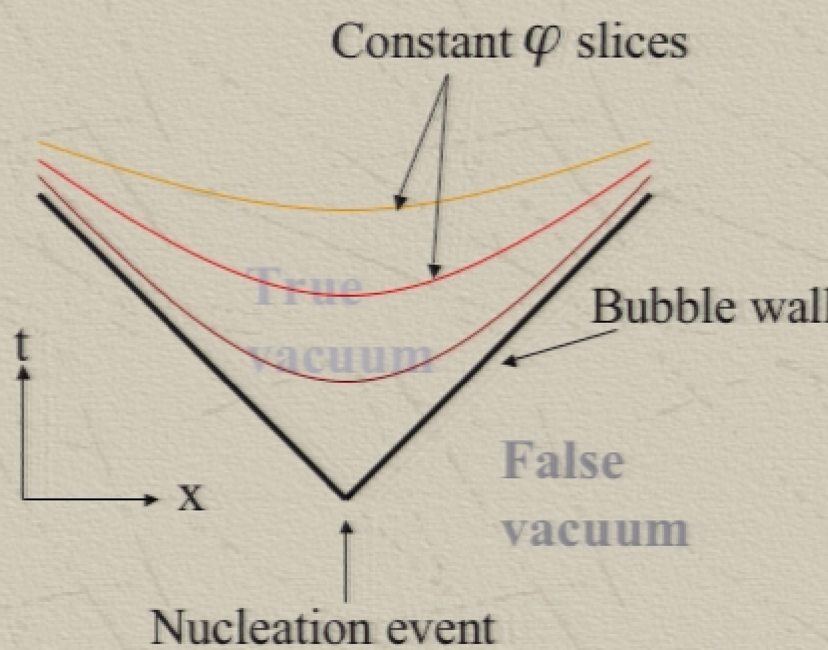

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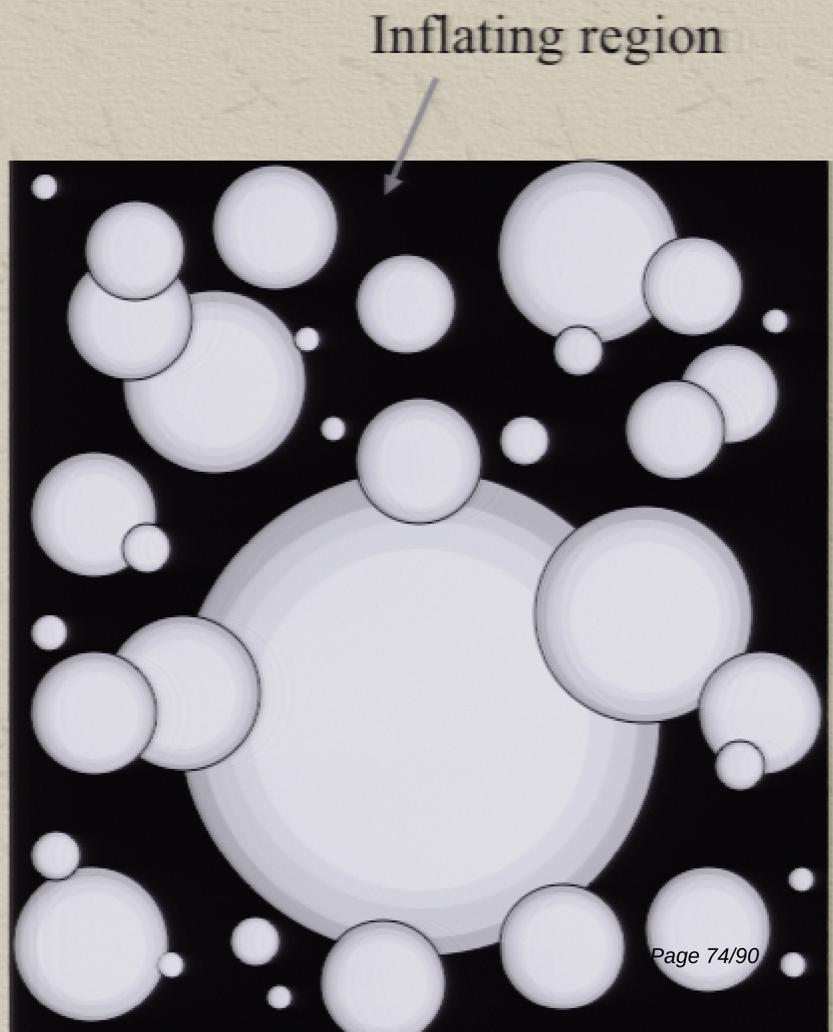

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Strategy: make state *approached* by semi-eternal inflation *exact*.

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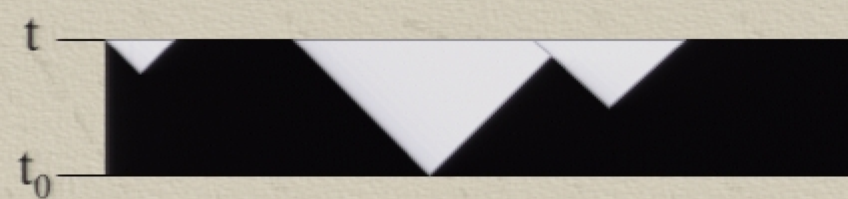

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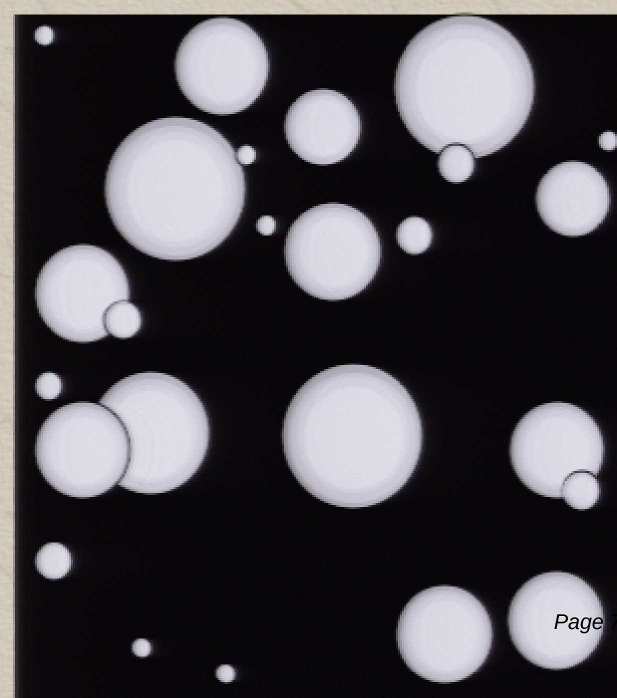
- Consider bubbles formed between t_0 and t.



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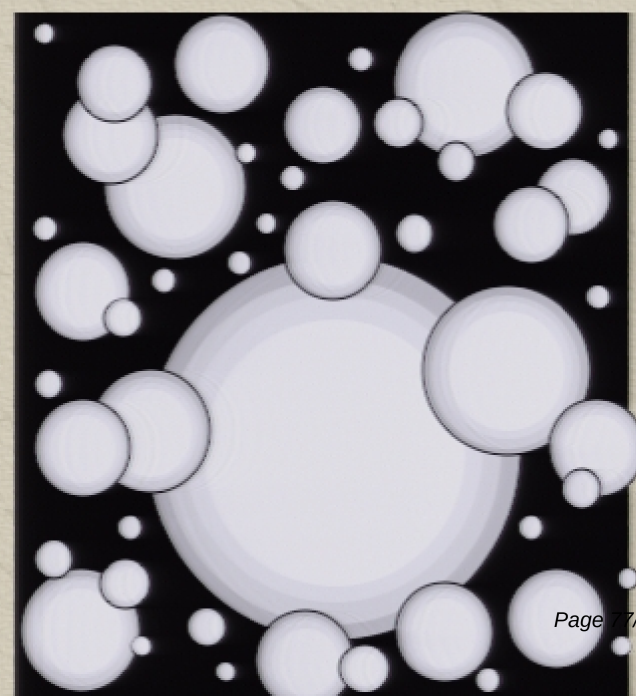

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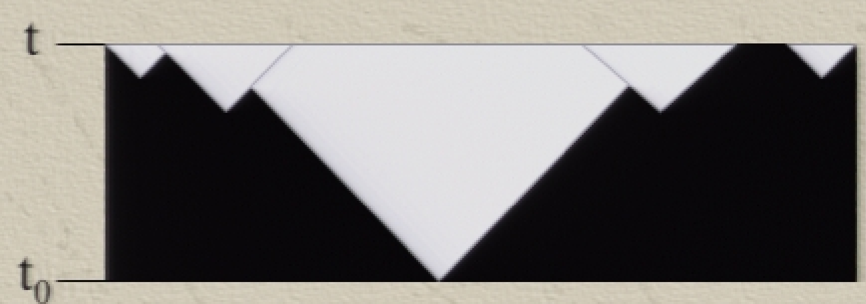

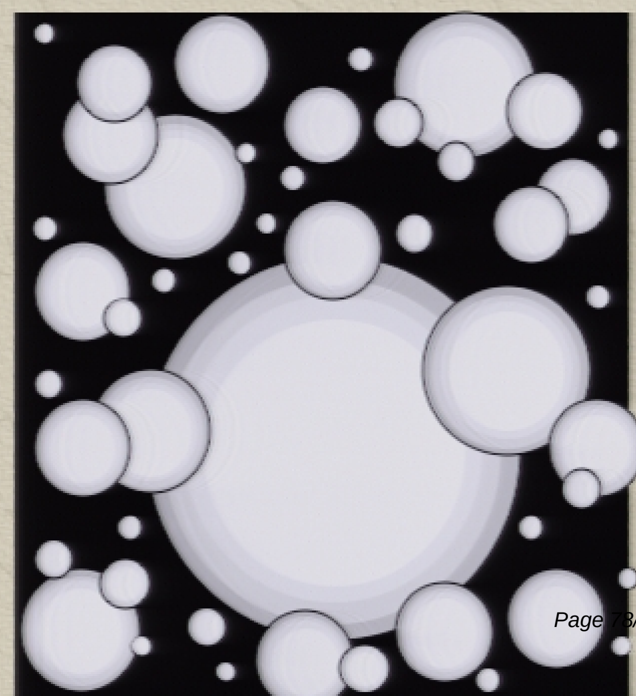

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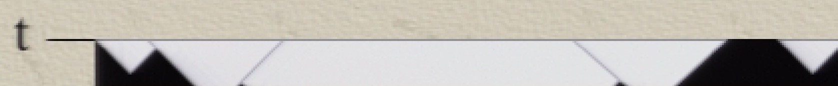

model has:

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  - Inflaton field in false vacuum on an infinite null surface $\mathscr{I}^-$.
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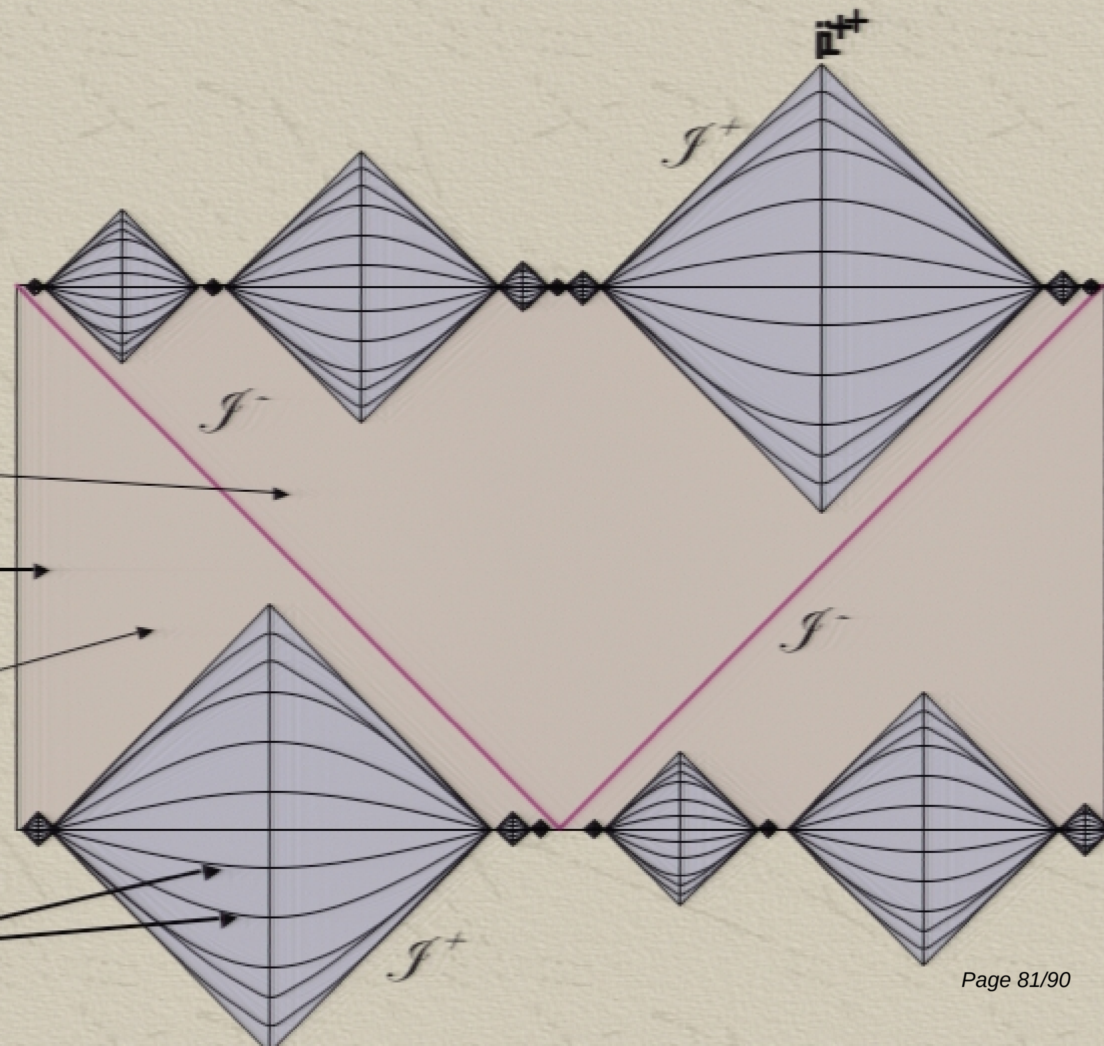
Penrose diagram for truly eternal inflation.

Singularity free,
eternally inflating



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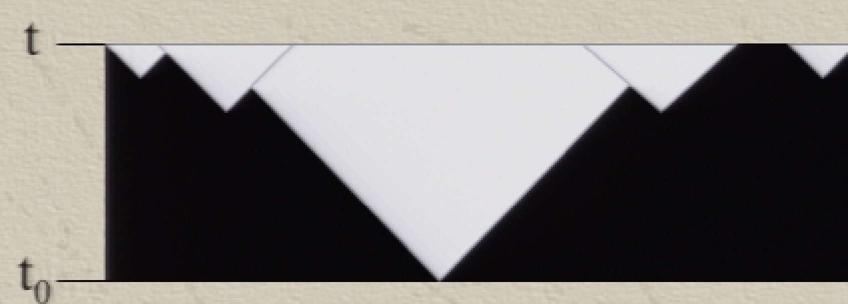

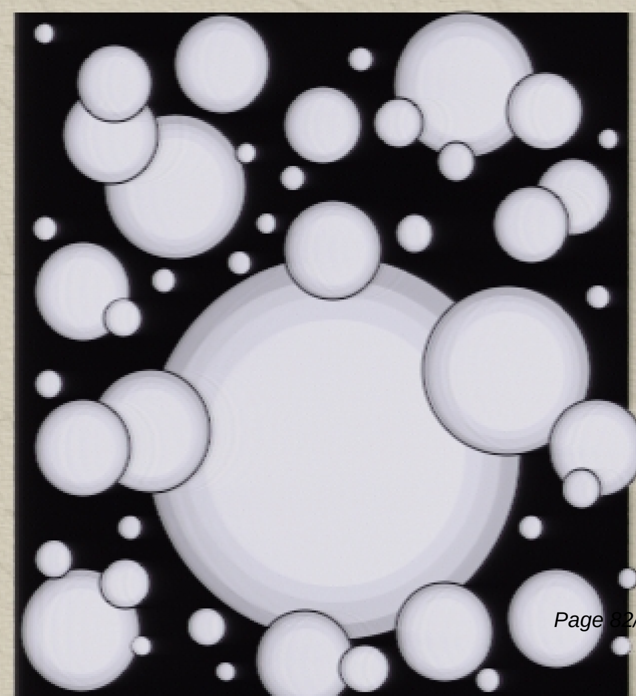

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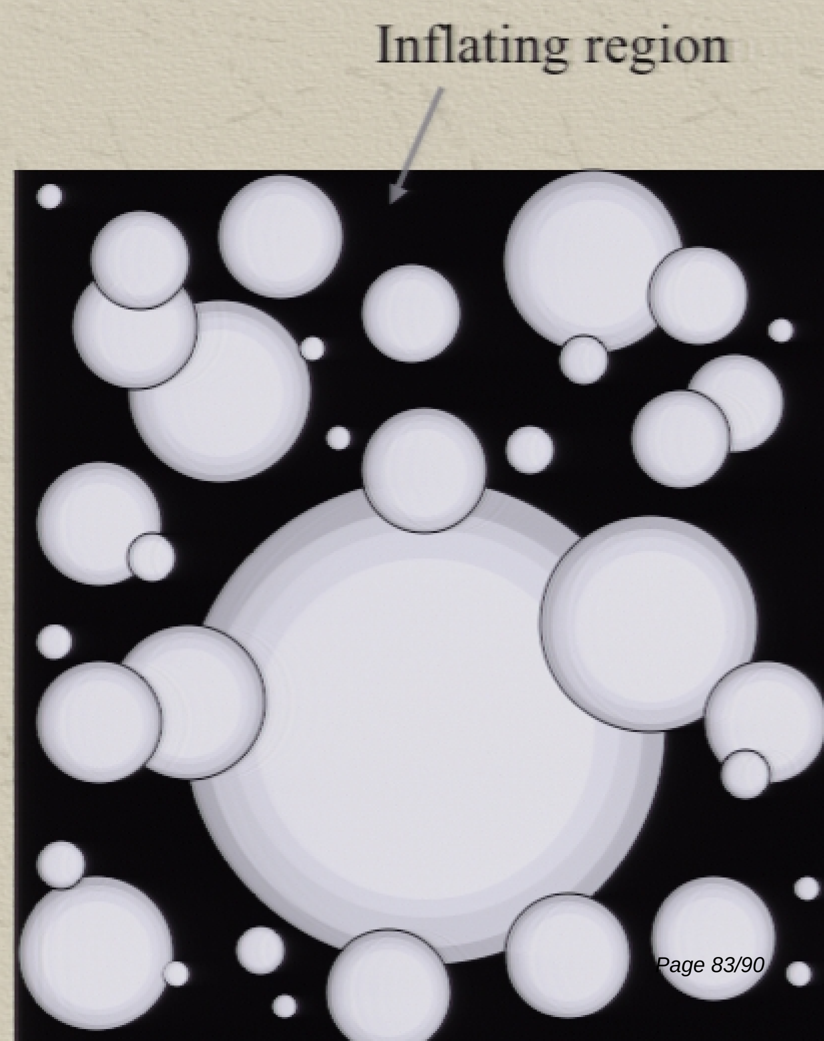

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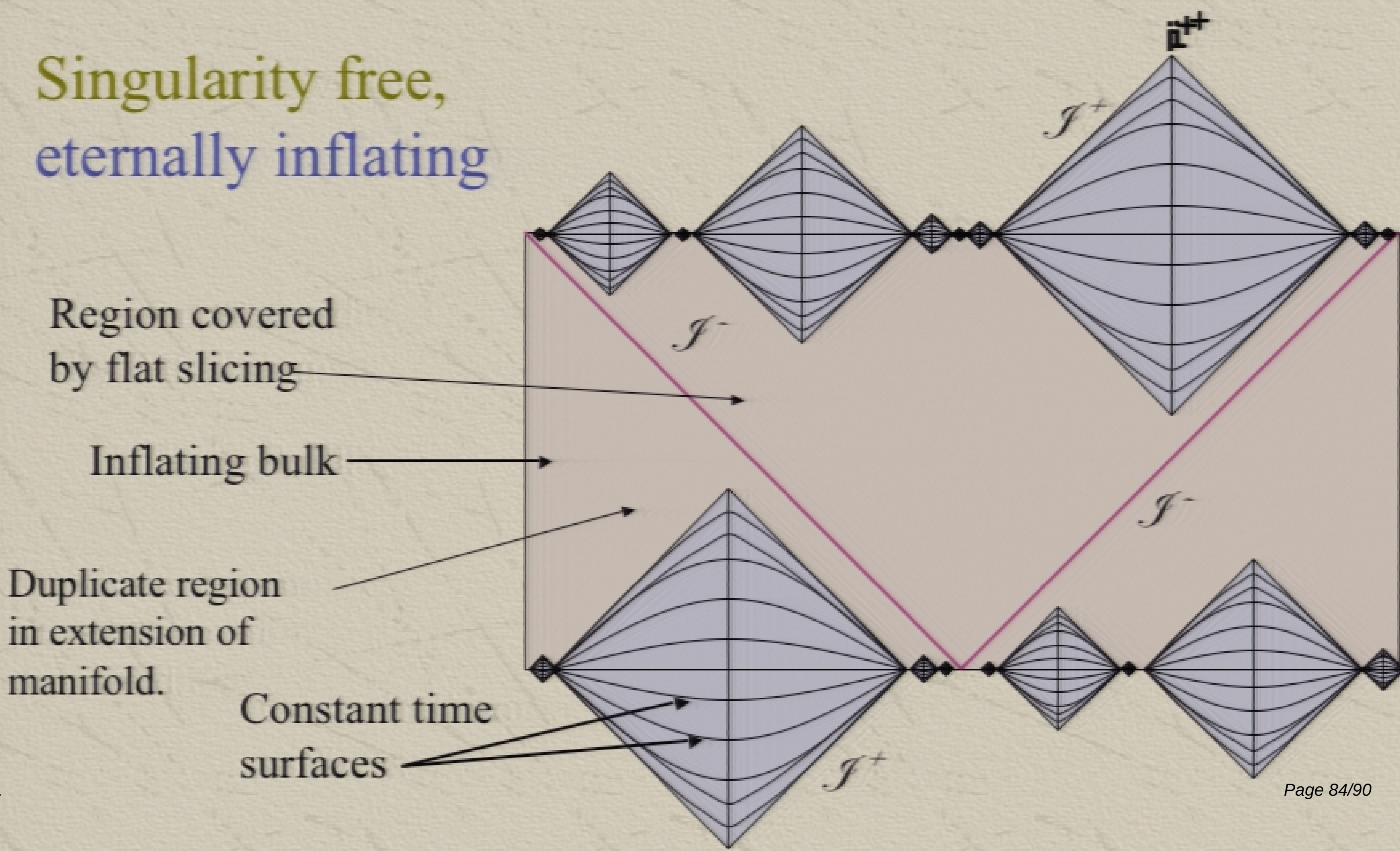

Steady-State eternal inflation

Nice properties (vs. inflation or semi-eternal inflation):

- *No cosmological singularity.*
- No horizon problem: all points on boundary surface are at small ($< H^{-1}$) distance from each other.
- Simple B.C.s based on physical principle.
- Funny aspects of semi-eternal inflation resolved:
  - Time since big-bang *infinite*, for any and all observers.
  - There is a particular time-slicing such that all times exactly equal on cosmological level.

Conclusions

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- It is not clear how to compute probabilities in infinite ensembles: **Measure problem.**
- Past-eternal inflation appears possible. It may aid in resolving some probability issues, and clarifying role of cosmological boundary conditions.