The Initial Condition of the Universe

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1654: “The World Was Created at 6pm on 22 October 4004 BC”, Ussher.

The Problem of the Initial Condition of the Universe: High Energy Inflation is an Extraordinary Unlikely Event!

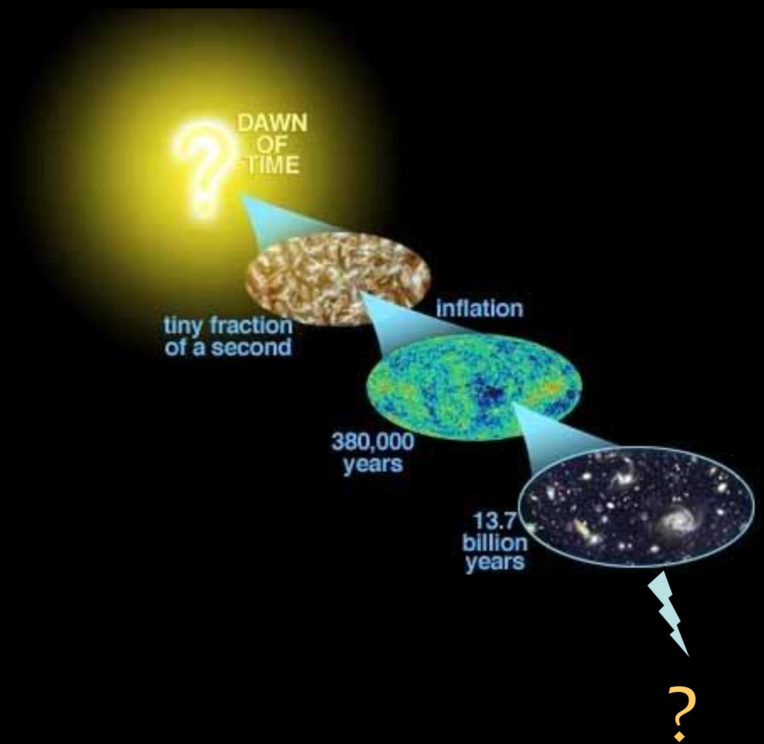
- **What selected these Initial Conditions?**

Chances: $1/10^{10^{123}}$!

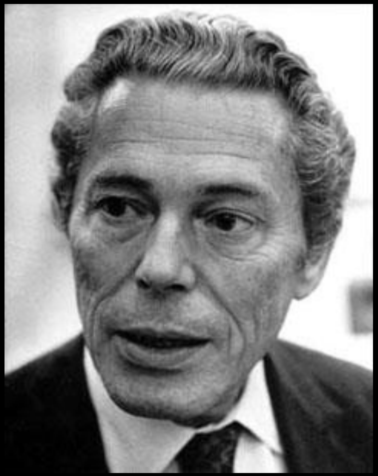
Equivalent to Demanding 2 Conditions:

i) Exquisite Homogeneity of Initial Patch,

ii) Slow Roll of Inflaton at High Energy



A Non-Anthropic Approach the Problem



- “Among all the occurrences possible in the universe the a priori probability of any particular one of them verges upon zero. Yet the universe exists; particular events must take place in it, the probability of which (before the event) was infinitesimal.... Destiny is written concurrently with the event, not prior to it... The universe was not pregnant with life nor the biosphere with man. Our number came up in the Monte Carlo game. Is it surprising that, like the person who has just made a million at the casino, we should feel strange and a little unreal?”
  — Jacques Monod, *Chance and Necessity*

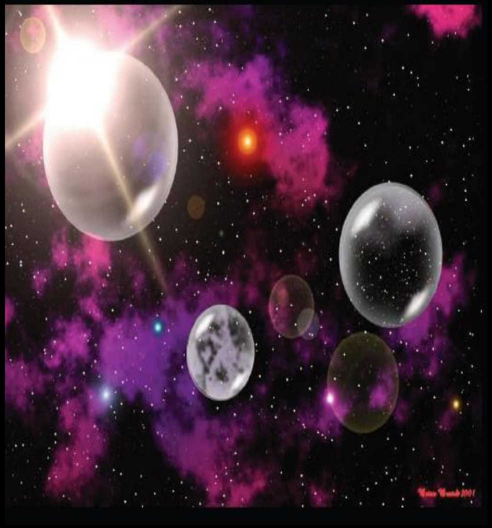
- “...the scientific attitude implies what I call the postulate of objectivity—that is to say, the fundamental postulate that there is no plan, that there is no intention in the universe...”

To Address the Problem of the Origins We Need to Extend Our Theory of Spacetime to a Multiverse Framework

How Else Can we Ask: Why did we start with this Universe?

- **The Many Worlds**
- **Quantum Landscape**
- **Eternal Inflation**

Implications: Our Universe is not at the center of Cosmos; rather it is a humble member in a vastness.



Eternal Inflation to the Rescue ?

Philosophy:

Once Inflation Starts, it never Stops.
No Need to Worry about Far Past I.C.

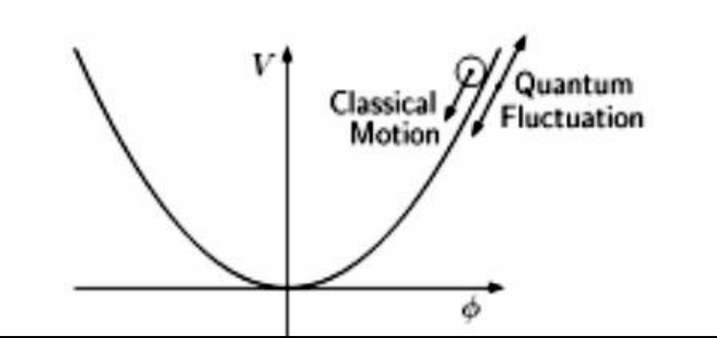
Reason:

Large Field Fluctuations Have a Nonzero Probability to Occur .
Sure, it's Miniscule but Multiply it With the Newly Produced Volume ?!

Get a Large Probability – More than 100%.
In Fact, It's Infinite !!!!!!

New Problem : The Measure(s) is Infinite !

Eternal Inflation: Basics



$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0\,.$$

$$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\left[\frac{\dot{\phi}^2}{2} + V(\phi)\right]\,.$$

Linde : ‘Eternally Existing Selfreproducing Inflationary Universe’, PLB175 ‘86.

- Long wavelength Perturbations Frozen. Coarse-Grain Subhorizon Modes.

$$< f(x_1t_1)f(x_2t_2) >= \frac{H^3}{4\pi^2}\delta(t_1-t_2)\frac{sin(z)}{z}\,.$$

, i $z = aH|x_1 - x_2|$. n.

$$D = \frac{H^3}{8\pi^2}.$$

- $3H\dot{\phi}(x,t) + V'(\phi) = f(x,t).$ Equation for

$$\frac{\partial P_\phi}{\partial t} = \frac{1}{3H}\frac{\partial}{\partial \phi}\left[V'(\phi)P_\phi\right] + \frac{H^3}{8\pi^2}\frac{\partial^2 P_\phi}{\partial^2 \phi} = \frac{\partial}{\partial \phi}\left[\frac{1}{3H}P_\phi\frac{\partial V}{\partial \phi} + \frac{\partial}{\partial \phi}(DP_\phi)\right]\,.$$

Metric Perturbations Track Field Fluctuations: Related by Einstein Equations

Mukhanov et al., IJMPA '87. Use Newtonian gauge for metric:

$$ds^2 \simeq dt^2 - a(x,t)^2 dx^2$$

Perturb it:

$$ds^2 \simeq \left(1 + 2\Phi(x,\tau)\right) d\tau^2 - \left(1 - 2\Psi(x,\tau)\right) dx^2$$

-By Einstein Eqns: $\delta\rho/\rho = -2\,\Psi$ and $\Psi = \Phi$. Thus metric PDF:

$$\Delta_\Phi^2 \simeq <\Phi^2> \simeq \frac{2^{1/2} V'^2}{3(3\pi V M_p^3)^{1/2}} \tau$$

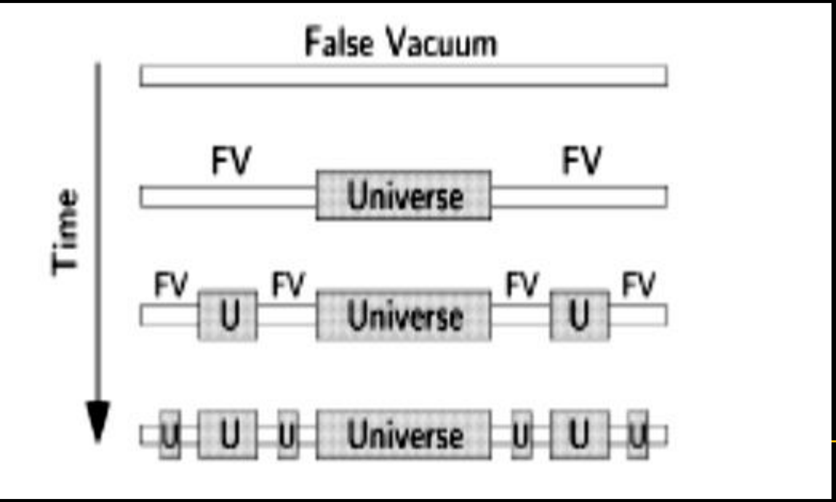
- Spacetime becomes a Fractal, d<3 : (Vilenkin et al. PLB199, '87),

where $d = 3 - \frac{D\pi^2}{4\phi_0^2}$, ϕ_0 is boundary of excursions.

Globally a Fractal Spacetime:

- Inflation produces Inhomogeneities. They all add up. On Superhorizon Scales: $\delta\rho/\rho \geq 0(1)$.
- Many Inflationary Pockets Leads to Highly Inhomogeneous Global Volume.
- Claim is EI is Generic: False Vacuum Decay or Chaotic Type

See e.g. Guth 2007, Vilenkin.



Problems Related to the Infinite Measure

1. **Counting Number of Fluctuation, Not Probability**
2. **Homogeneity Condition Broken** (Trodden et al. PRD61' 98)

- *Probability Occupied by Homog. Volume, Dim=d-3.*

$$P \simeq \int_{-\phi_0}^{\phi_0} P_\phi d\phi \approx \frac{4}{\pi} e^{-\frac{D\pi^2 t}{4\phi_0^2}}$$

- *Thus most Volume is Inhomogeneous (Trivially! it is a Fractal)*

$$V_3^{inh} \simeq e^{dHt} \qquad d = 3 - \frac{D\pi^2}{4\phi_0^2}$$

- *Condition to Get Inflating Domains Broken:*

$$[\, d - 3 \,] = \{\, m^2/3H^2,\ \lambda^{1/2}/12\pi,\ 4\pi/3\,\Gamma \,\}$$

A Proposal for Eternal Inflation Measure

LMH and Malcolm Perry 2013

- Include Homogeneity Requirement in Measure

$$P_i = P_{st} \times P_\phi$$

Since Field Excursion Random, h-Volumes Independent. Fractal Spacetime. Thus Probability of Field Randomly Finding Smooth Homog. Domains on this 4-Volume is:

- $P_{st} = \dfrac{V^h}{V tot} = \left(\dfrac{x}{R}\right)^{(3-d)}$ ***e.g.*** $P = P_\phi \times P_{st} \simeq B e^{-A(\phi^2 - \phi^2)} (Hx)^{\frac{m^2}{3H^2}} e^{-(\frac{m^2}{3H^2})Ht}$

For False Vacuum: $P_\phi \cong \Gamma$ ***and*** $[3\text{-}d] = 4\pi/3\ \Gamma$

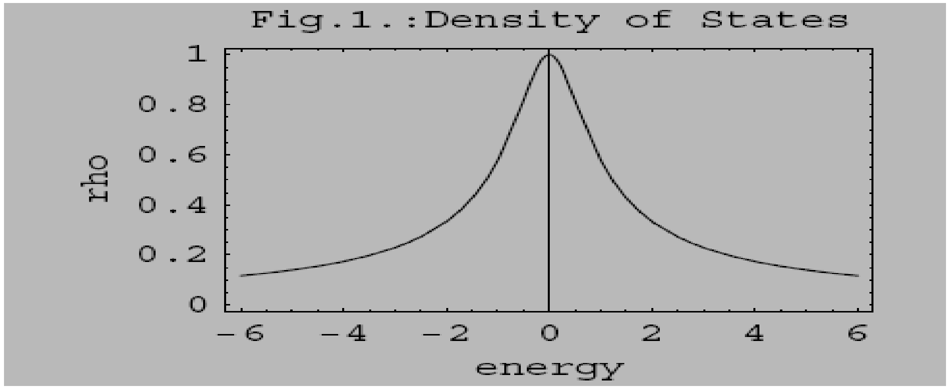
The Quantum Landscape Multiverse
2004+ Proposal: " QM on the Landscape "

1. Allow WaveFn. Of the Universe to Propagate on the Landscape Potential, "WDW Eqn. ", [LMH, CQG22; LMH+AK EPJC49], *2004-2005*

2. Include Decoherence. Triggered by Long λ Massive Fluctuations. Need Observer that 'Watch/Measure ' the System, [LMH+RH, PRD74, etc.], *2005*

3. Derive Predictions to Test the Theory. Calculate Nonlocal Quantum Entanglement from Decoherence = Shift to WaveFn. Trajectory, [LMH+RH+TT, 'Avatars of the Landscape I' PRD 77 and 'Avatars of the Landscape II' PRD 77], *2005-2006*

WdW Equation:



$$\hat{\mathcal{H}}\Psi(a,\phi) = 0$$

$$\mathcal{H} = \frac{1}{2e^{3\alpha}}\left[-p_\alpha^2 + p_\phi^2 + e^{6\alpha}V(\phi)\right]$$

With :

$$p_a = \frac{\partial L_g}{\partial \dot{a}} = -\frac{a\dot{a}}{N}. \qquad p_\phi = \frac{\partial L_\phi}{\partial \dot{\phi}} = -a^3\dot{\phi}.$$

Where :

$$L_g = \frac{1}{2}N\left[-\frac{a\dot{a}^2}{N^2} - a^3\Lambda\right] \; ; \; L_\phi = \frac{a^3N}{2}\left(-\frac{\dot{\phi}^2}{N} - V(\phi)\right)$$

INCLUDE DECOHERENCE:
Backreaction-Master Equation

Backreaction of Long Wavelength Perturbations Decoheres our Universe from other patches on Phase Space. They are the Environment.

$$h_{ij} = a^2(\Omega_{ij} + \epsilon_{ij}), \quad \phi = \phi_0 + \Sigma_n f(a)_n Q^n.$$

WDW becomes Master Equation

$$\left[\hat{H}_0 + \Sigma_n H_n\right] \Psi(\alpha, \phi, f_n) = 0.$$

$$\hat{H}_0 \Psi(\alpha, \phi, f_n) = < -\Sigma_n \frac{\partial^2}{\partial f_n^2} + e^{6\alpha} U(\alpha, \phi,) f_n^2 > \Psi.$$

<u>SOLUTIONS</u> :

(Anderson Localization)

Solutions Exist Only in a Band of High Energy Initial Conditions , (Up to String M, then Poincare Rec.).

$\Psi \sim \mathrm{Exp}[-(S_0 + S_f)]$, Solutions only for :

$S \sim S_\Lambda - S_f > 0$ <u>"Condition for Survival"</u>

Only Those Can Overcome the Backreaction of Fluctuations and Produce a 'Survivor' Universe. Low Energy I.C. are 'Terminal'.

Deriving Predictions:

- **Calculate and trace forward the shift in Wavefunction path induced by quantum entanglement with all else, from the time of Decoherence .**

- **Quantum Entanglement Contributes an Additional Superhorizon Nonlocal Modification Term coupled to the Inflaton, in the Gravitational Potential. (This term in the Friedman Equation is derived from the energy shift of the Classical Path in Phase Space.No room for guessing or tweaking).**

Astrophysical Tests:

Entanglement Imprints on Friedman Equation

$$H^2 = \frac{1}{3M_P^2}\left[V(\phi) + \frac{1}{2}\left(\frac{V(\phi)}{3M_P^2}\right)^2 F(b,V)\right] \equiv \frac{V_{\rm eff}}{3M_P^2} \qquad (4.2)$$

where

$$F(b,V) = \frac{3}{2}\left(2 + \frac{m^2 M_P^2}{V}\right)\log\left(\frac{b^2 M_P^2}{V}\right) - \frac{1}{2}\left(1 + \frac{m^2}{b^2}\right)\exp\left(-3\frac{b^2 M_P^2}{V}\right). \qquad (4.3)$$

Constrain SUSY Scale from Flatness and CMB Conditions

$$(\nabla T/T)_{\rm quad} \approx r_H^2 \nabla^2 \delta\phi = (ck_1/H_0)^2 \delta\phi \approx 0.5 (r_H/L_1)^2 (\delta\rho/\rho)_1.$$

$$\Delta V / (\Delta\phi)^4 \leq O(10^{-7})$$

$$10^{-10} M_P < b < 10^{-8} M_P$$

Predictions from Modified Newtonian Potential (2005-2006) :

Void Predicted at z<1 with size ~200Mpc. Observed in 2006-2012+, (WMAP,Rudnick et al, WMAP), Planck 2013, 2015

$$\Phi = \Phi^0 + \delta\Phi \simeq \Phi^0 \left[1 + \frac{f(b,V)}{\rho}\left(\frac{r}{L_1(k,b)}\right)^2\right].$$

CMB: Running n_s. Suppressed sigma_8. Observed WMAP/SDSS 2008 +

LSS: Power Enhanced at Cluster Scales. Planck 2013

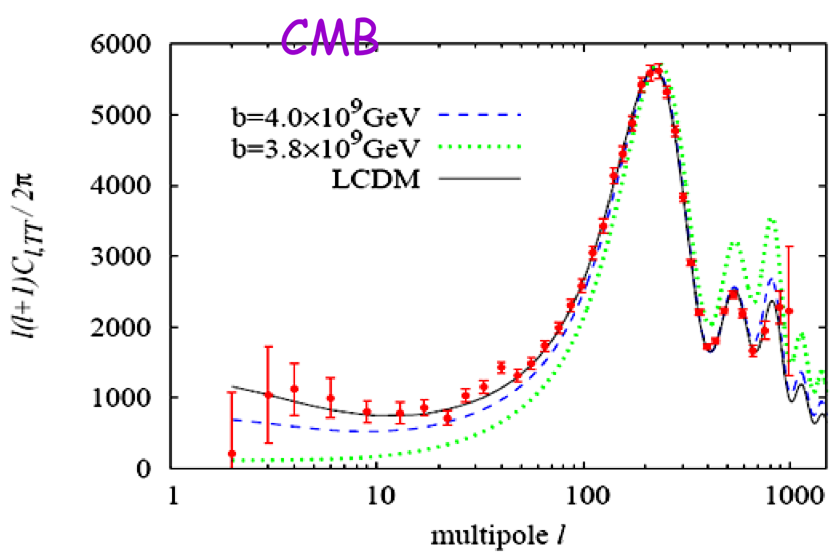


FIG. 1: CMB TT power spectra for the cases with $b = 4.0 \times 10^9$ GeV (dash-line) and 3.8×10^9 GeV (dot-line). For reference, the spectrum for the ΛCDM case (solid-line) and the data from WMAP3 are also plotted.

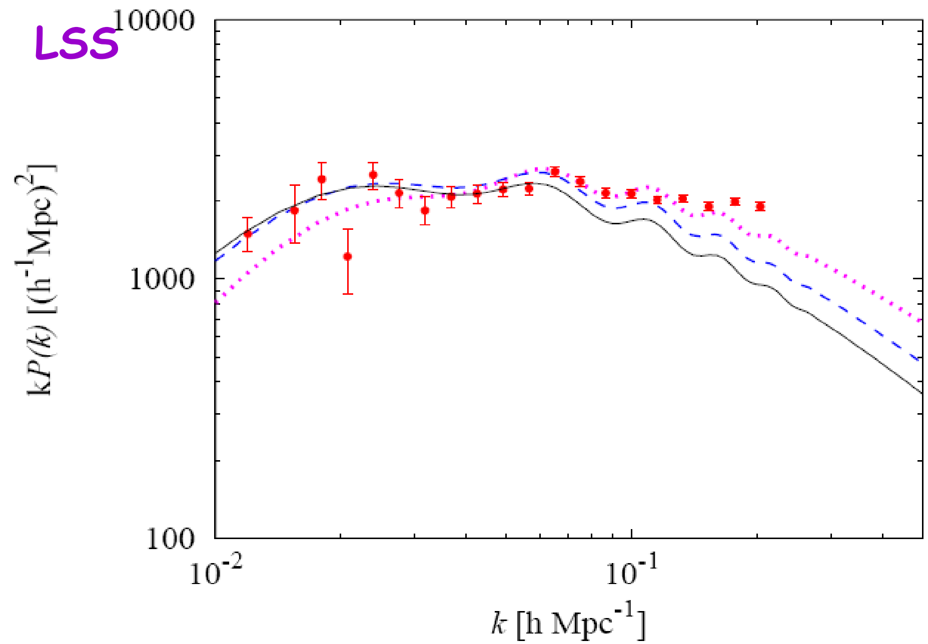


FIG. 2: Matter power spectra for the same values of b as Fig.1,

R. Holman, L. Mersini-Houghton and T. Takahashi, PRD77: *hep-th/0611223 hep-th/0612142*

PREDICTIONS (2005-2006)	TESTS (2006-2015)
1. Cold Spot/Giant Void	WMAP, Rudnick et al. (8 months later), Planck '13, '15
2. $Sigma_8$ = 0.8; Running n_s from Red to Blue (less power at low l's to more power)	WMAP and SDSS '07; Planck '13
3. Suppressed TT-Spectra l<10	WMAP, Planck '13
4. Dipole, Quadrupole, Octupole: Additional Source leads to Alignment; Suppression; Preferred Direction; Power Asymmetry	WMAP, Planck '13
5. SUSY Breaking Scale Much Higher. LHC Wont Find SUSY at TeV	LHC '12, '15?
6. CMB Fine Scale at High l's, More power : Features revealed by Cross Correlations	Planck '13 .

Can the Three Theories of the Multiverse Converge to a Unified Framework for the Initial Conditions?

1. Merging of Eternal Inflation and the Landscape into a Single Picture is Unlikely

2. The Many Worlds Is Already Nested into the Quantum Landscape Framework.

Selection Criterion for the Initial Conditions of our Universe Emerges Dynamically.

Predictions are Derived from Quantum Entanglement.

If a disordered lattice of potential wells gives bubbles than all material in nature, including us, should be made of bubbles.