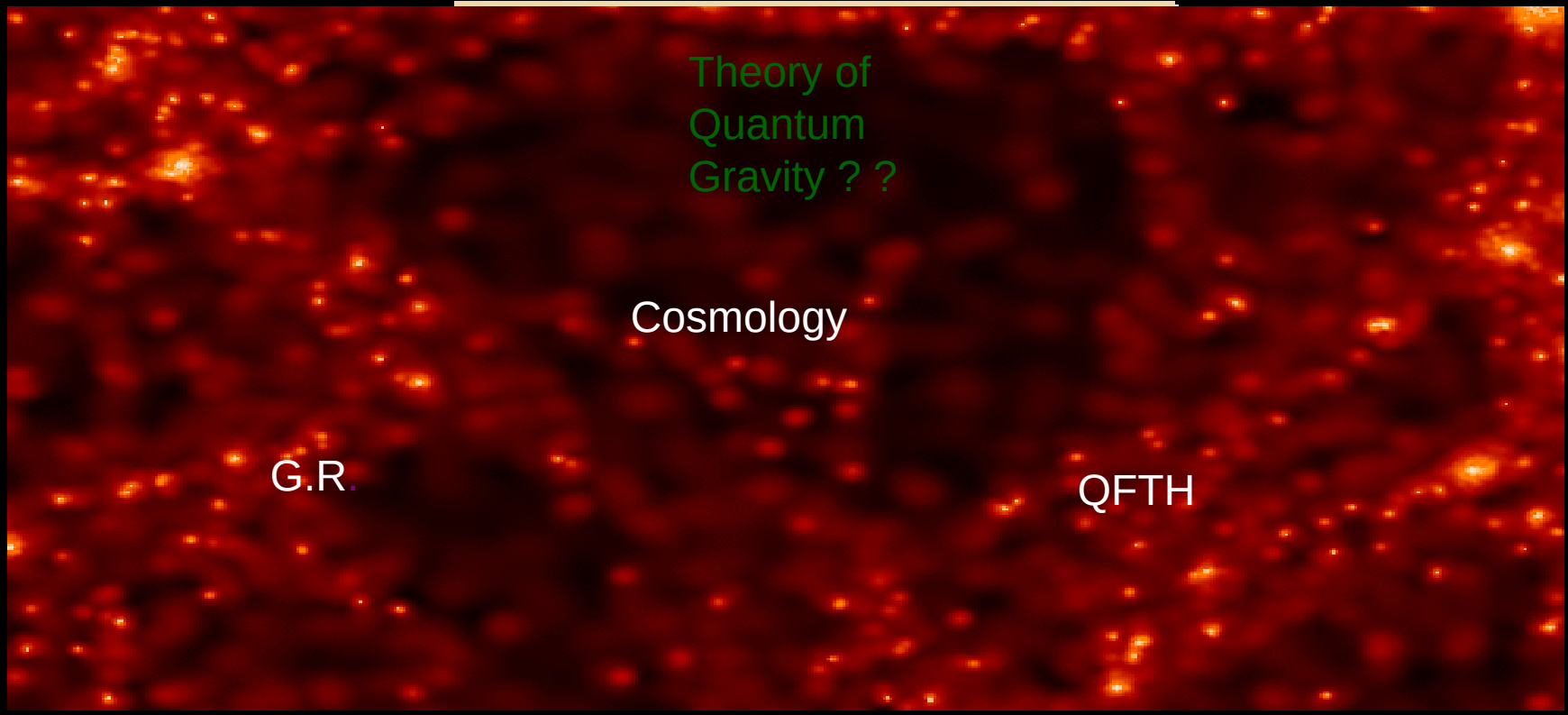
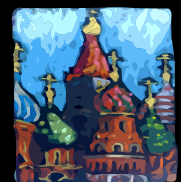
COSMOLOGICAL IMPLICATIONS OF THE LANDSCAPE



"The (Really) Dark Side of the Universe", Madrid June 2006

Laura Mersini-Houghton UNC - Chapel Hill



New Physics for The 'Big Questions'…?

- The Trouble with the Initial Conditions

  - Why did we start in such a low entropy state?

  - Statistical Arguments: $P = Exp[\ S\ ] = Exp\{\ 1/\Lambda\ \}$,
    Highly Disfavor High energy inflation !!!!!!

- Thermodynamic Arrow of Time and Probability for Inflationary Big Bang?

  - The Gravity, the Quantum and Thermodynamics,
    (*Unitarity, Causality and 2nd Law of Thermodynamics*) ?!

  - Need a fundamental Theory to address the incompatibility among them!

- What is Dark Energy, Λ ? What is Dark Matter ?

- Are Hierarchies of Scales in Nature Related?
  - Higgs scale vs. Λ vs. M_{PL}

- Observational Signatures of Quantum Gravity ?! Not to mention WMAP anomalies and more cosmic coincidences…

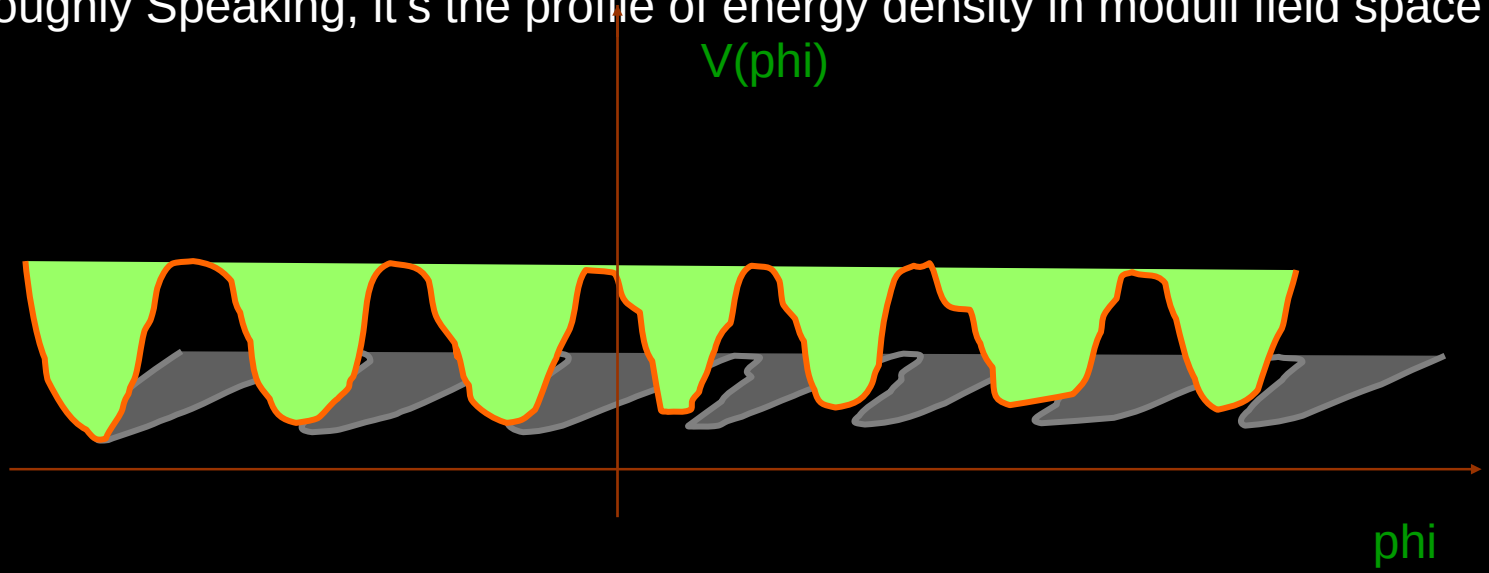
String Theory is the Leading Candidate of Quantum Gravity

- Emerging Picture: A landscape of many solutions. Each of which can potentially host a universe.

- The Vacua Solutions in String Theory obtained after compactifying 6-Dim.,Contain a (3+1)-Dim world like our universe!

- About 10 ^ 500 of them in the landscape, (e.g. BP 2000)

- Roughly Speaking, it's the profile of energy density in moduli field space



Why Worry About It? Bad News?

- Implications for cosmology:

  - Which vacua in this vastness is 'home' to our Universe?

  - Can it address the fundamental questions for the Early and Late time cosmology?

- Implications for String Theory:

  - Does the theory lose its predictive powers and become non-falsifiable?

No!

A Landscape Picture Must be Expected of Any Theory of Quantum Gravity!

- ***How Else can we ask the fundamental and basic questions***:

- Why do we Have the Initial Conditions, Constants of Nature etc.?
  - ***Without Implying***
- As compared to what Other choices?

Fundamental Questions about our Universe Do imply the Existence of a Phase Space for the Initial Conditions, a.k.a, a Landscape

What Selection Criterion?

2 Current Proposals:

- Anthropic Selection???
- Quantum Dynamics Selection, (similar to Higgs).

Dynamic Selection Proposal

Allow WaveFunction of the Universe to propagate on the landscape. Solve Wheeler-DeWitt equation, (WDW).

Calculate the Probability Distribution for the band of solutions obtained from WDW.

Maximum of Probability Distribution gives the Most Probable Universe.

Wheeler DeWitt (WDW) Equation

Minisuperspace = Field Space spanned by variables [ϕ, a]: ϕ parameterizes landscape vacua, with potential V (φ) ; a(t) the scale factor for the metric of spatially flat and homogenous 3-geometries

$$ds^2 = [-\mathcal{N}\, dt^2 + a^2(t) d\mathbf{x}^2]$$

N *is a lapse function that can be set to* ***N*** *= 1. The combined action, (gravity + landscape moduli):*

$$S = S_g + S_\phi = \int d^4x\sqrt{-g}\left[\frac{R}{\kappa^2} - \frac{\dot{\phi}^2}{2} - V(\phi)\right]$$

Wheeler DeWitt Equation is the:

Hamiltonian constraint on WaveFunctional $\Psi(a,\phi)$

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

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

- 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

$$L_g=\frac{1}{2}N\left[-\frac{a\dot{a}^2}{N^2}-a^3\Lambda\right]$$

$$L_\phi=\frac{a^3\mathcal{N}}{2}\left(-\frac{\dot{\phi}^2}{\mathcal{N}}-V(\phi)\right)$$

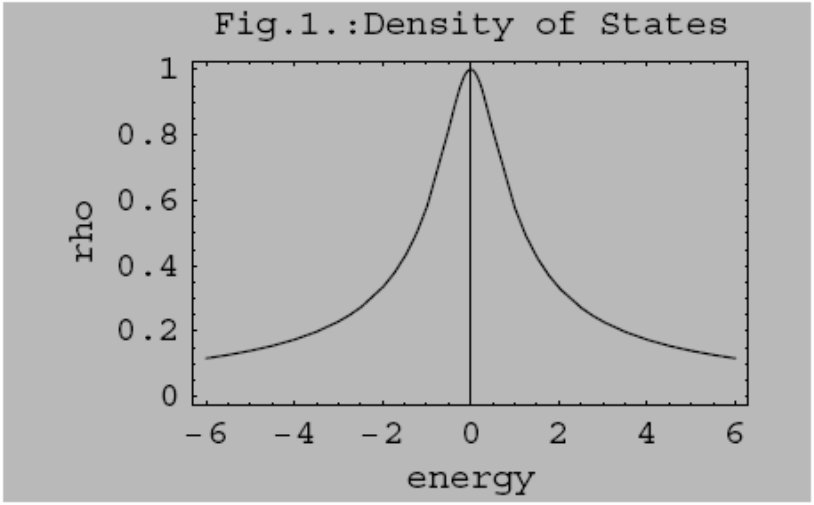
Applied to non-SUSY Sector. Example

Random Matrix Theory (RMT)

- *Solution for the wavefunction of the universe for the non-SUSY sector are 'Anderson'-localized:*
- *Probability distribution, obtained from Density of States "ρ(E)," is peaked around the universe with zero vacuum energy:*

$$\Psi_j(x,\alpha) \simeq \frac{1}{\hat{\epsilon_j}^{1/4}\sqrt{l_j}} e^{\pm i\sqrt{\hat{\epsilon_j}}\alpha - \frac{(x-x_j)}{2l_j}}$$

$$\sqrt{\hat{\epsilon_j}}\alpha = H_j t$$

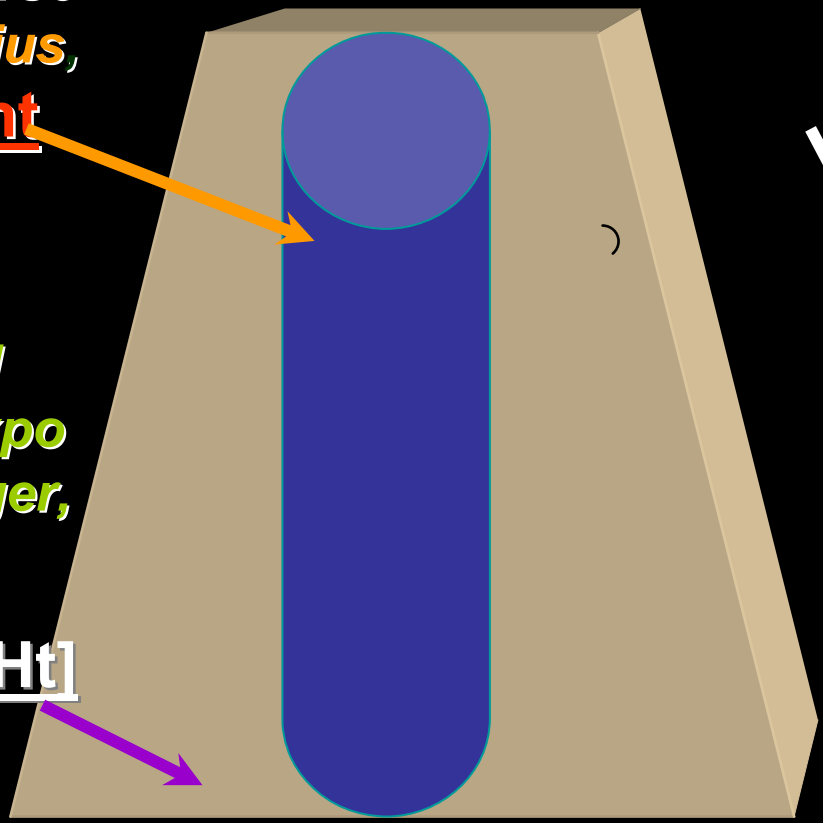


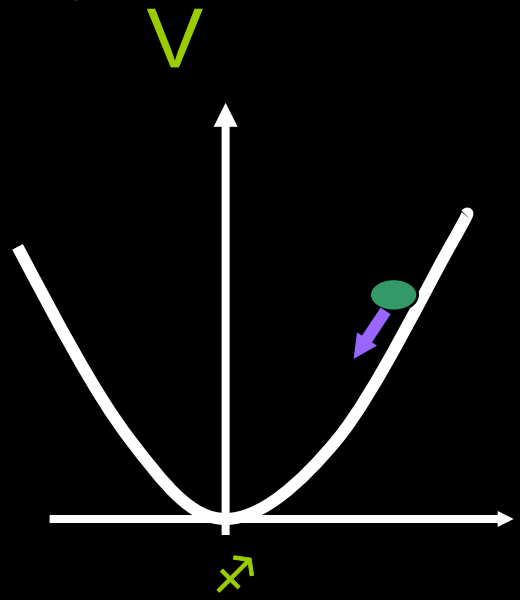
What About Start of Inflation? How Did we decohere from the Others?

Alas…P=|Ψ|^2 not Enough ! Need an Observer who Measures and Decohere our Solutions/Universe from Others.

VisibleUniverse =Hubble radius,

H=Constant





The physical Universe=Exponentially larger, size

a(t) = Exp[Ht]

Entropy of which Patch?

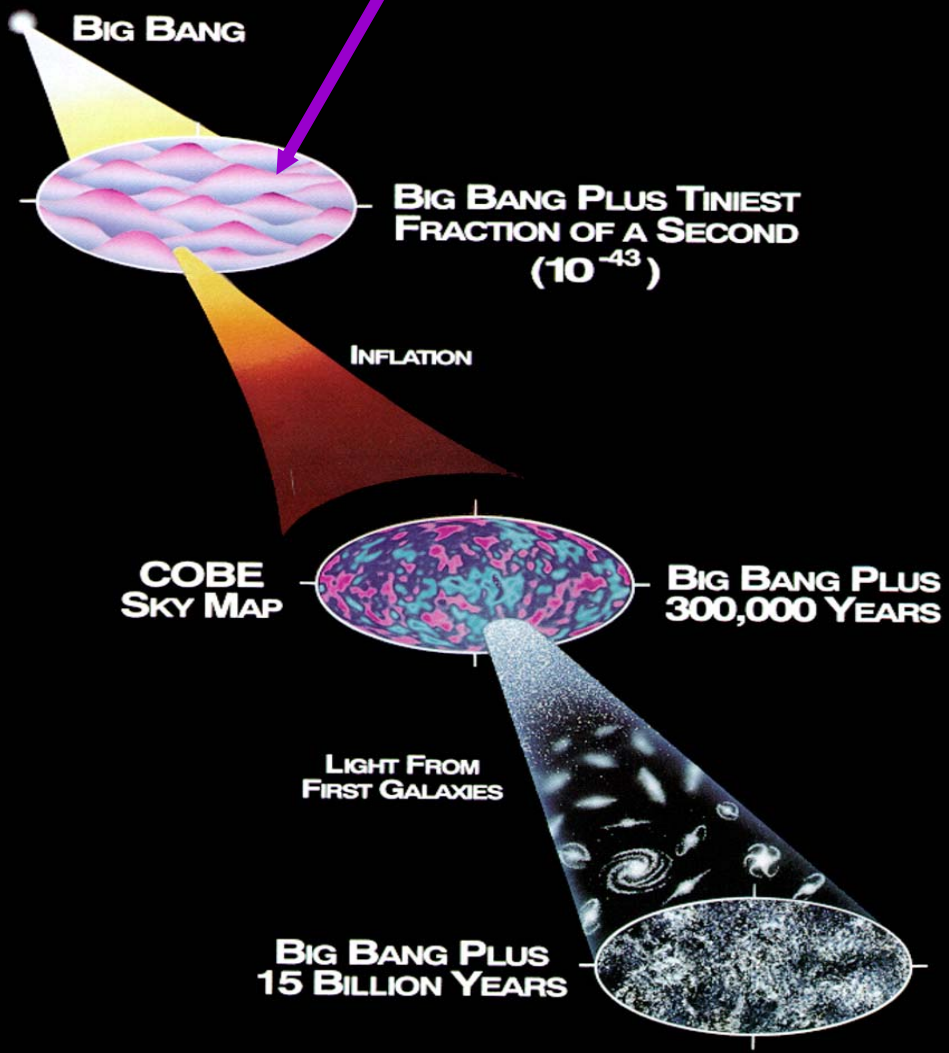
Does Eternal Inflation Help?

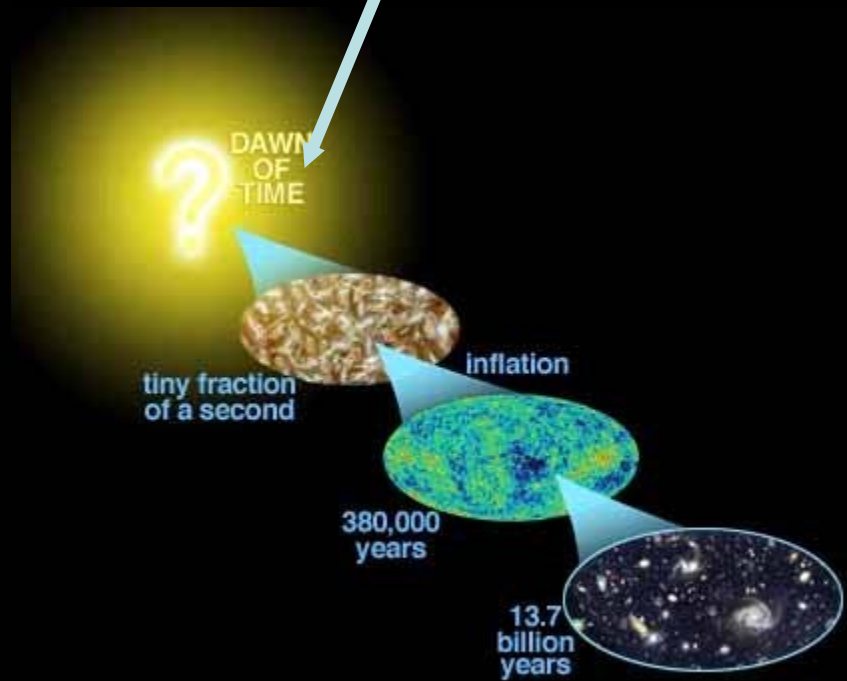
The Universe is Infinite. Our Hubble patch is a tiny

A MetaUniverse for Initial Big BangS

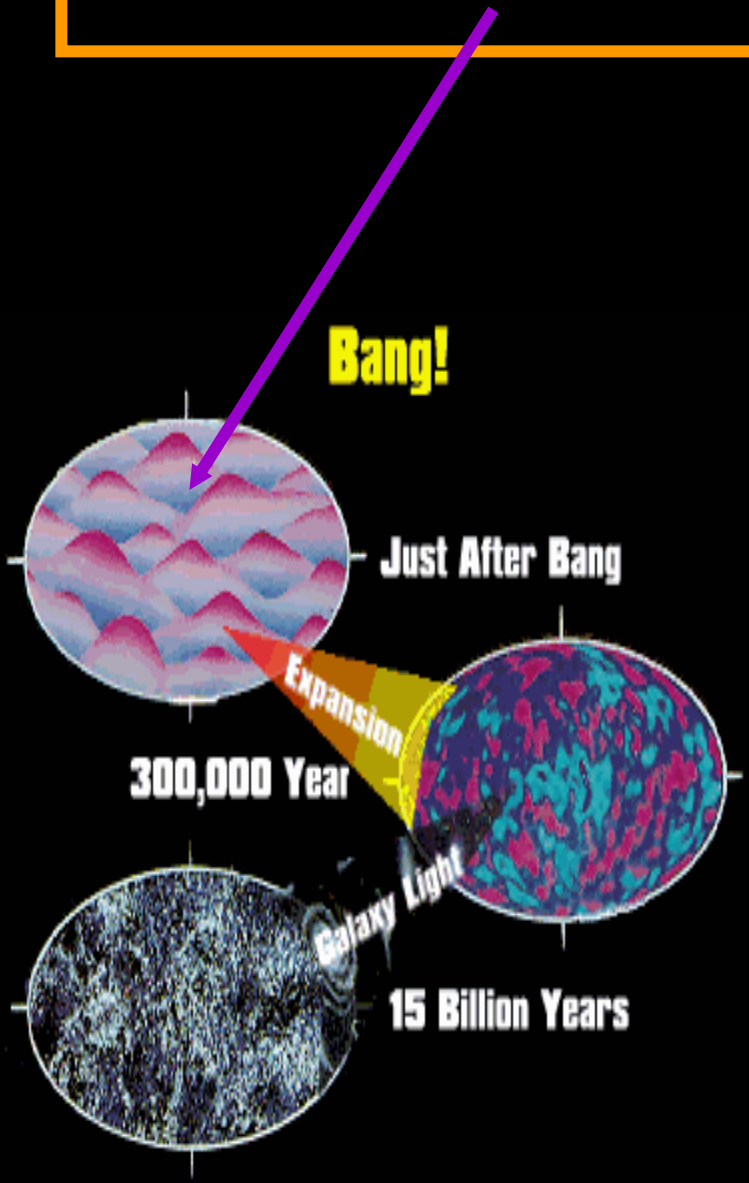
Phase space of I.C. …

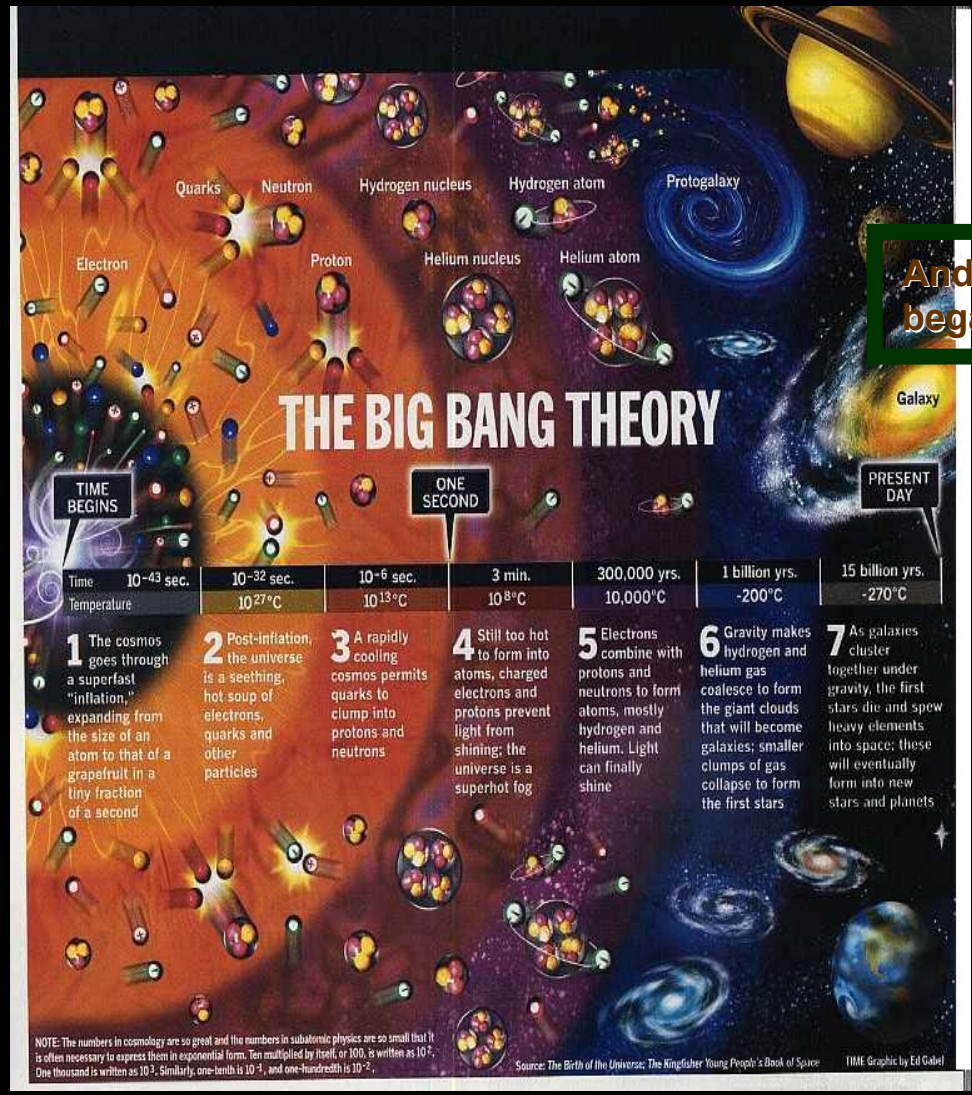
Quantum Gravity? String Landscape?





Recall the 'Wild' Idea: If String Theory is valid beyond GR cutoff, shouldn't the String Landscape be the Metauniverse of Initial Conditions





And so it began

the Landscape Multiverse and Decoherence…

Consequences of this proposal:

- **The Landscape is the physical Phase Space of the Initial Conditions for the MetaUniverse/Multiverse**

because

Every vacuum on the field space of landscape is a potential starting state for 'giving birth' to a Universe

A Landscape Picture is to be Expected of any Theory of Quantum Gravity

Asking the question:
"Why does our Universe have the Init. Cond. , L, SM, Etc. "
IMPLIES:
" As Compared to What Other Choices?"

An 'Internal Observer' can Not Ask These Questions - (S) he has only 1 Sample ?!

Inflation, Thermodynamic Arrow of Time and Initial Entropy

1. Identify the Observer/"Watcher"

- **Long wavelength massive moduli fluctuations a good candidate. (Weak Gravitational coupling to system)**

2. Address decoherence of our patch/wavepacket from the others

- ***Cross-Correlation in density matrix show how fast gravity [a(t)], moduli [phi], decohere.***

3. Backreaction of massive fluctuations results in a 'Master Equation'.

An informed guestimate for quantum entaglement and assumptions of Ergodicity where Gravitational Degrees of Freedom are concerned:

(Originates from friction of: Unitarity, Causality, Thermodynamics of Gravity)

1. Backreaction-Master Equation

1- Backreaction of long wavelength perturbations Decoheres our universe from other patches on phase space.

2- Minisuperspace {α, f, f_n} becomes infinite dimension.

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

$$\Psi(\alpha, \phi, f_n) \approx \Psi_0(\alpha\phi)\Pi_n \psi_n(\alpha f_n)$$

WDW becomes Master Equation

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

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

Gravity vs.Matter: Dynamic Selection of Initial Conditions

- *During inflation U<0.*

$$U(\alpha\phi) = \left[\frac{n^2-1}{2}e^{-2\alpha} - \frac{m^2}{2}\right]e^{6\alpha}$$

$$-\mu_n^2 = U(\alpha, f_n)f_n^2 \leq 0$$

- *This gives rise to Gravitational Instability*

$$\psi_n \simeq e^{-\mu_n \alpha} e^{i\mu_n \phi}$$

$$\ddot{f}_n + 3H\dot{f}_n + \frac{U_{\pm}}{a_I^3} f_n = 0$$

Patches with { H<m, ϕ <1} Collapse

Only patches with { H>m, ϕ>1} Survive

$$U(\alpha,\phi) = \left[(\frac{n^2-1}{2})e^{-2\alpha} + \frac{m^2}{2} + \frac{9m^2\phi^2}{y^2} - \frac{6m^2\phi}{y}\right]e^{6\alpha}$$

Y= $\left(\frac{\partial S}{\partial \alpha}\right)/\left(\frac{\partial S}{\partial \phi}\right) \approx \frac{\dot{\alpha}}{\dot{\phi}}$. During inflation $y \simeq 3\phi_I$.

Density Matrix Provides Information on Quantum Entaglement

Tracing over the fluctuations, {f_n}: Gravity, a[t], decoheres first. Quantum entanglement in Phi.

$$\rho = \int \Psi(\alpha, \phi, f_n)\Psi(\alpha', \phi', f_n')\Pi_n df_n df_n'$$
$$\simeq \rho_0 e^{-\gamma a^2(\phi-\phi')^2)} e^{-\frac{(a\pi)^6 H^4 \mu^4 (\phi-\phi')^2}{\phi_I^2}}.$$

The density matrix doesn't comute with Hamiltonian: Ergodicity? Poincarre Recurrence?

$$[\hat{H}, \rho] \neq 0$$

Out-of Equilibrium Phenomenon! Thermostatistics arguments do not apply-thus the paradoxes.

Inflation,Entropy and Arrow of Time

Gravity is a 'Negative Heat Capacity' System

- *Gravity+Matter Not in Thermal Equilibrum.*
- *Statistical Arguments may be Invalid, thus lead to paradoxes.*
- *Out-of-Eqlb. Methods needed to address: "Why did we start in such a low entropy?"*
- *Eternal inflation may not be sufficient.*

Entropy and Arrow of Time:

Opposite Tendency of Matter vs. Gravitational Degrees of Freedom to Eqlb. Pick a Low Initial Entropy.

$$s \simeq (r_I - r_{f_n})^2 \quad r_I \simeq H_I^{-1} \quad r_{f_n} \simeq (H_I^{-3/2} < \phi_I \sqrt{U} >).$$

Remarks

- **Quantum Dynamic Selection for Initial Conditions of Inflation**
- **Quantum Cosmology on the Landscape provides a calculational formalism for exploring cosmological implications of string theory.**
- **Gravitational degrees of freedom must not be treated with statistical mechanics, which by definition assumes equilibrum.**
- **Gravity+Matter is out-of equilibrum due to opposing tendencies: Entropy roughly corrected by B.H.vs. DeSitter horizons. This may be the first step to reconcile the friction between inflationary I.C., entropy and Arrow of Time.**
- **Ergodicity explicitly broken. Implications for holography, causal patch physics, L, and observational imprints from quantum entaglement.**

Can these ideas be tested?

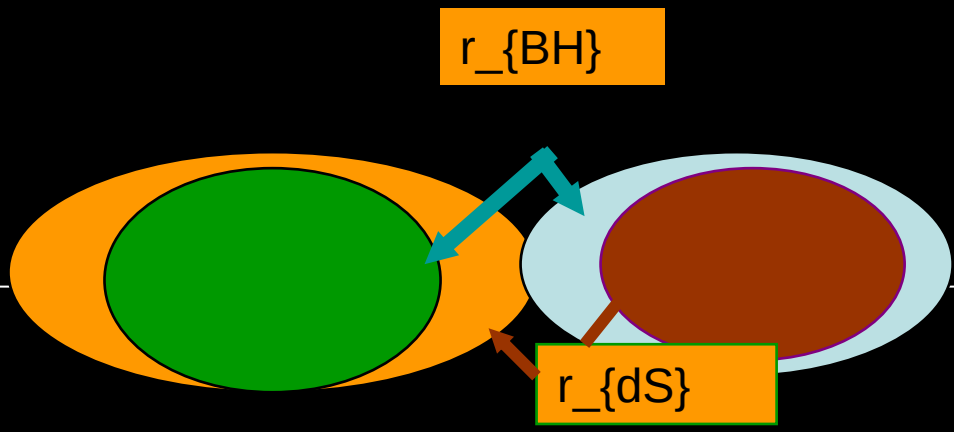
- A very radical approach, but :

  Does it make predictions that can be tested??

An Initial Entangled State Can't Evolve To a Pure State due to Unitarity:

-Traces of quantum *entaglement*?

- *M_{SUSY} relation to width of correlation*



Final Thoughts

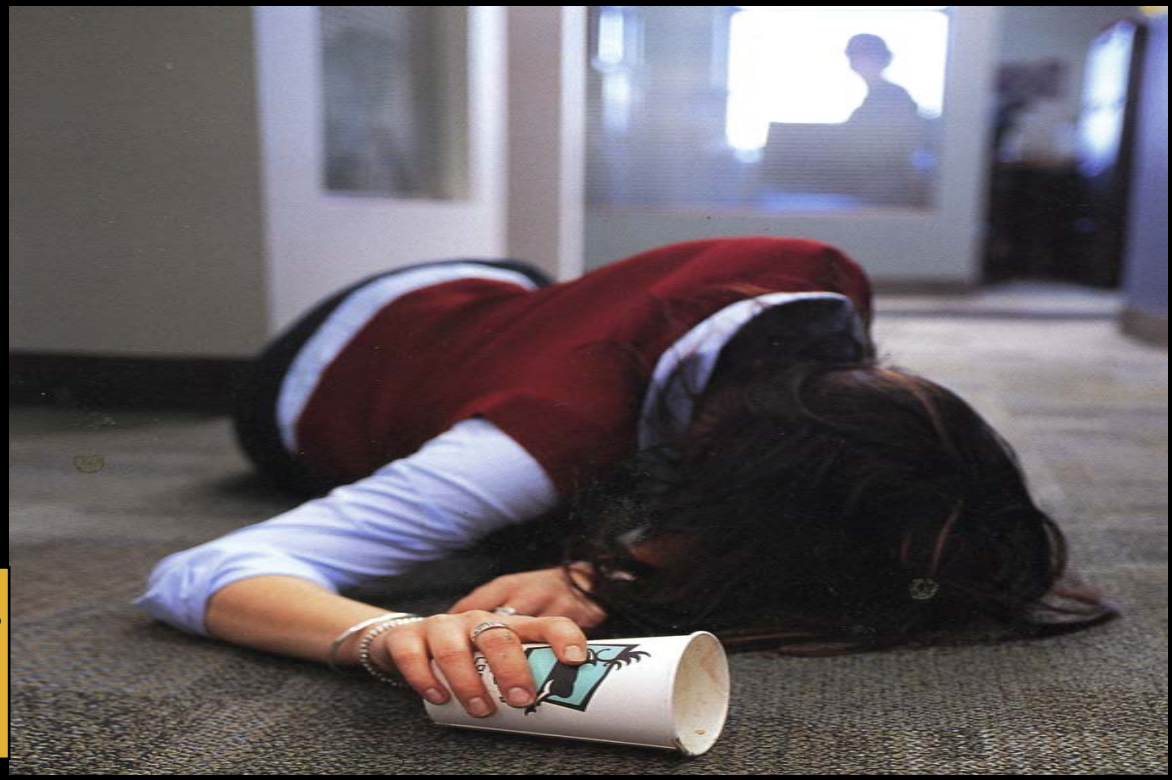
- A landscape phase space is to be expected of any quantum gravity theory
- (Gravity +Matter) Degrees of Freedom- out of equilibrium system. Initial conditions Have to be Selected Dynamically!
- Implications for Holography and UV/IR Entanglement...
- Traces of Quantum Entanglement or Other Imprints from Quantum Gravity Era Likely to be Testable
- Weak Lensing Surveys of Large Scale Structure May Provide a Wealth Of New Information for Cosmology after WMAP

Where Did This All Come From?

What determines the arrow of time?

Why did we start in such an orderly state?

What does the future hold? Does the past determine the future?



Childlike curiosity to the beauty of nature's mysteries…