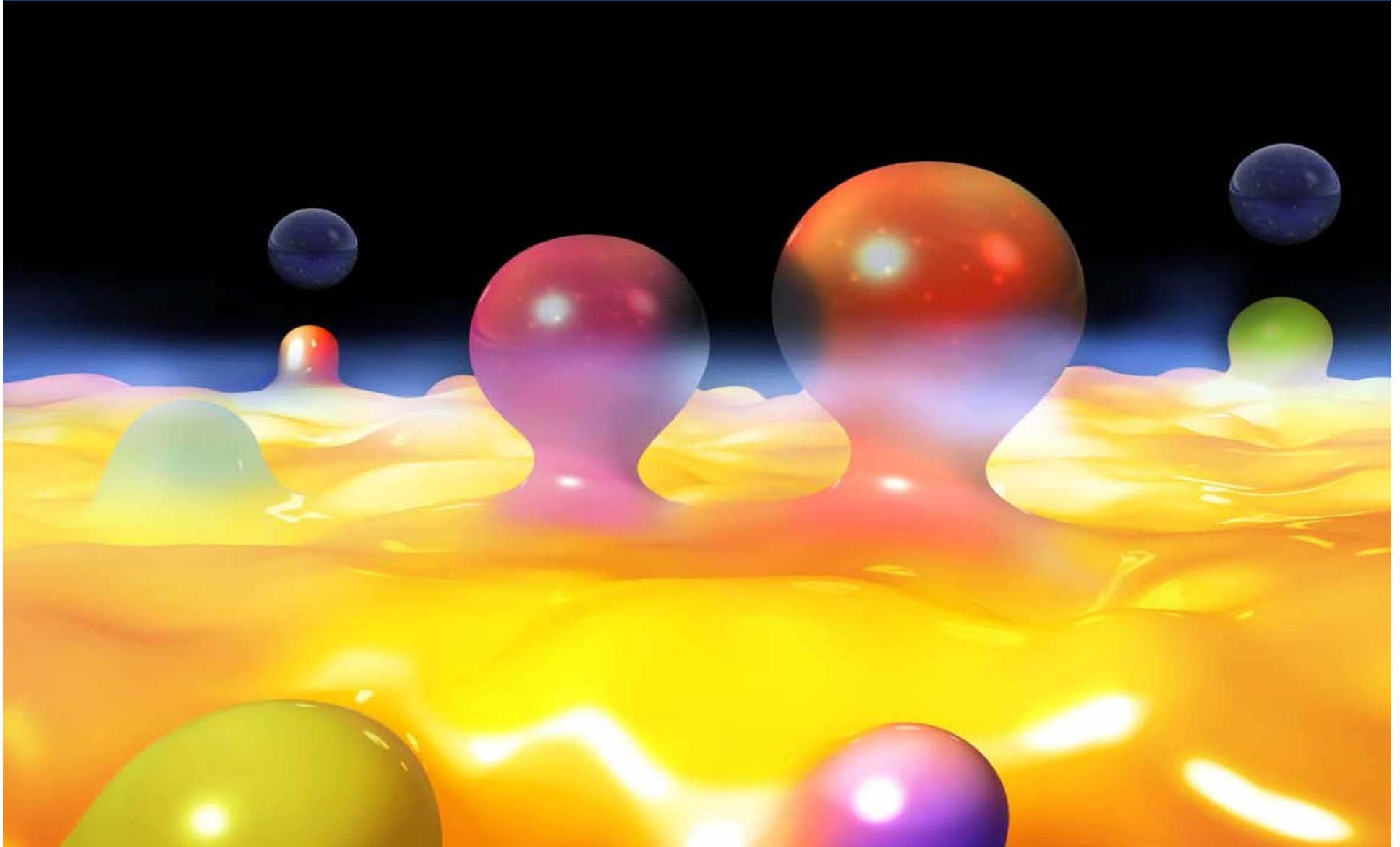


# Origins of the Universe from the Landscape Multiverse Post Planck



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CAP, Ann Arbor, 2013

# The Question:

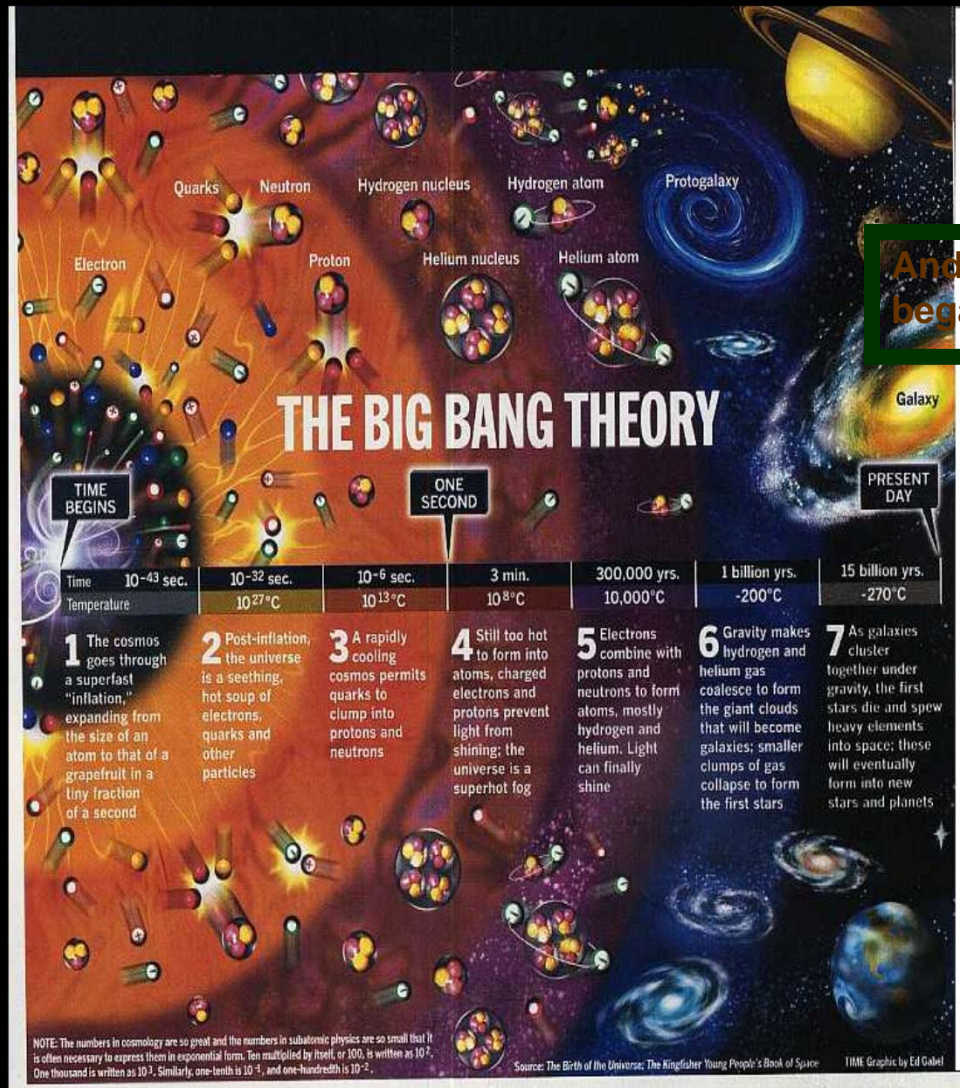
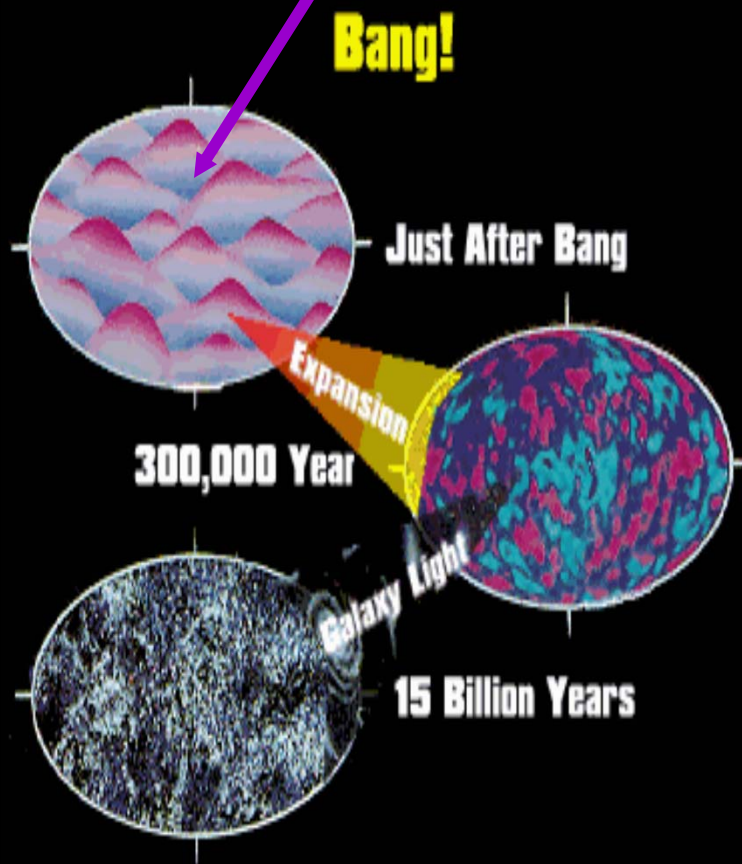
- **WHY DID OUR UNIVERSE START IN SUCH AN INCREDIBLY LOW ENTROPY SPECIAL STATE?**
- **PHILOSOPHY ADVOCATED (SINCE 2004): NEED A MULTIVERSE TO MEANINGFULLY ADDRESS THIS QUESTION ! SHIFT THE PARADIGM AWAY FROM SYMMETRY BREAKING.**

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Discovery of the Landscape of String Theory is Good News !

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# 'A Wild' Idea 2004: The String Theory Landscape Provides the Quantum Multiverse for the Ensemble of Initial Conditions



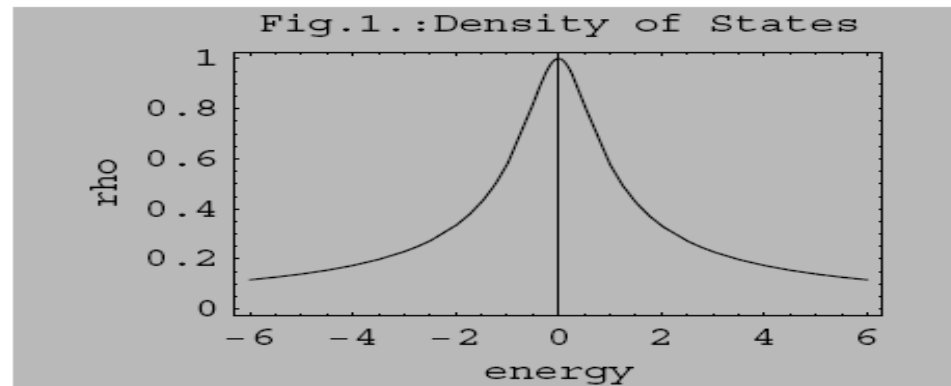
And so it began

# 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  $\lambda$  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:



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

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

With :

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

Where :

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

;

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

# 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

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

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

# SOLUTIONS : ( **Anderson Localization** )

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

$$\Psi \sim \text{Exp}[-(S_0 + S_f)], \text{ Solutions only for :}$$
$$S \sim S_\Lambda - S_f > 0 \quad \underline{\text{"Condition for Survival"}}$$

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

## **REMARKS:**

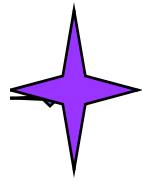
- High Energy Inflation Not a Special State. The most probable when gravity is switched on. (Gravity is a 'negative heat capacity system')
- Selection of the Low Entropy Initial State, determined by Out-of-Eqlb. quantum dynamics of grav. +matter D.o.F's.
- Universe can not be born from a high entropy state, thus Arrow of Time locally.
- Classicality Not Assumed, (decoherence).
- Many Worlds of QM is clearly embedded in this Theory of Origins from the Landscape. But No Splitting once Universe(s) Decohere.



## Deriving Predictions:

- Calculate and trace forward the shift in Wavefunction path induced by quantum entanglement with all else, from the time of Decoherence .
- The Entanglement Effect contributes a (Superhorizon) Nonlocal Modification term in the Friedman Equation Coupled to Inflaton Potential. (This term is derived from the energy shift of the Classical Path in Phase Space, i.e. there is no room for guessing or tweaking).

## Astrophysical Tests:



### Entanglement Imprints on Friedman Equation

$$H^2 = \frac{1}{3M_{\text{P}}^2} \left[ V(\phi) + \frac{1}{2} \left( \frac{V(\phi)}{3M_{\text{P}}^2} \right)^2 F(b, V) \right] \equiv \frac{V_{\text{eff}}}{3M_{\text{P}}^2} \quad (4.2)$$

where

$$\begin{aligned} F(b, V) = & \frac{3}{2} \left( 2 + \frac{m^2 M_{\text{P}}^2}{V} \right) \log \left( \frac{b^2 M_{\text{P}}^2}{V} \right) \\ & - \frac{1}{2} \left( 1 + \frac{m^2}{b^2} \right) \exp \left( -3 \frac{b^2 M_{\text{P}}^2}{V} \right). \end{aligned} \quad (4.3)$$



### Constrain SUSY Scale from Flatness and CMB Conditions

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

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

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

## Predictions from Modified Newtonian Potential (2005-2006) :

Void Predicted at  $z < 1$  with size  $\sim 200 \text{ Mpc}$ . Observed in 2006-2012+,  
(Rudnick et al, WMAP), Waiting for Planck ?

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

CMB: Running  $n_s$ . Suppressed  $\sigma_8$ . Observed WMAP/SDSS 2008 +  
LSS: Power Enhanced at Cluster Scales. Planck 2012-2013 ?

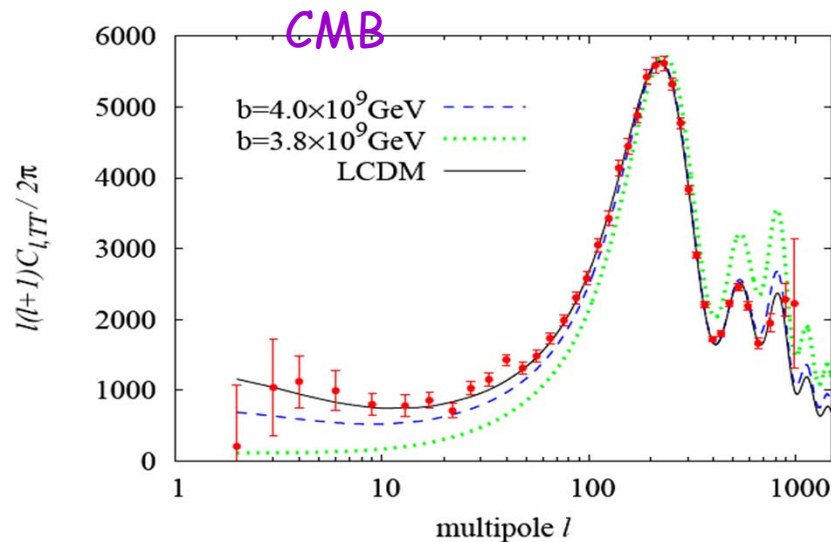


FIG. 1: CMB TT power spectra for the cases with  $b = 4.0 \times 10^9 \text{ GeV}$  (dash-line) and  $3.8 \times 10^9 \text{ GeV}$  (dot-line). For reference, the spectrum for the  $\Lambda\text{CDM}$  case (solid-line) and the data from WMAP3 are also plotted.

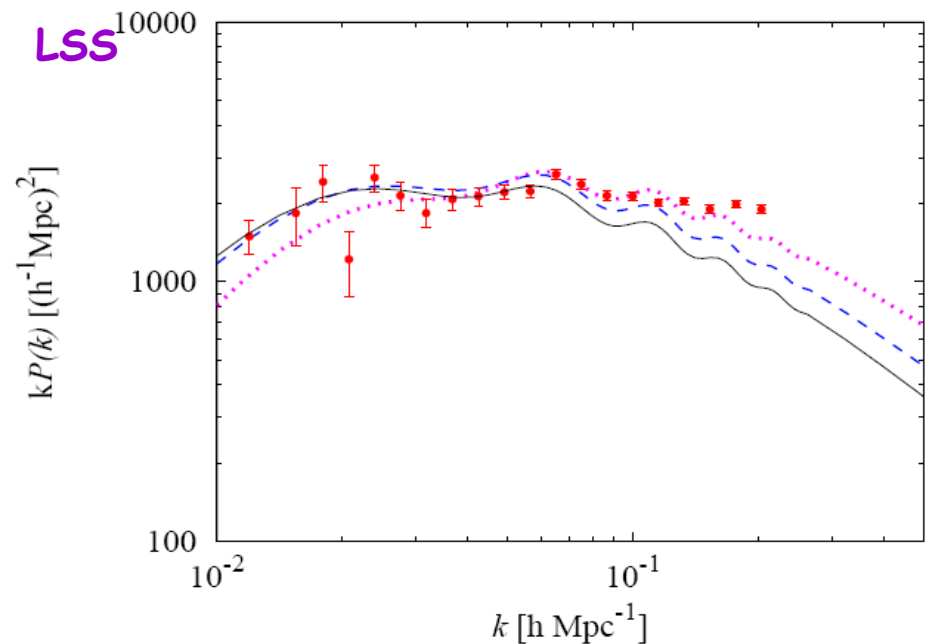


FIG. 2: Matter power spectra for the same values of  $b$  as Fig.1,

## Signatures Planck Can Also Check to Uniquely Discriminate this Theory:

### Cross-Correlating Cosmic Shear with CMB

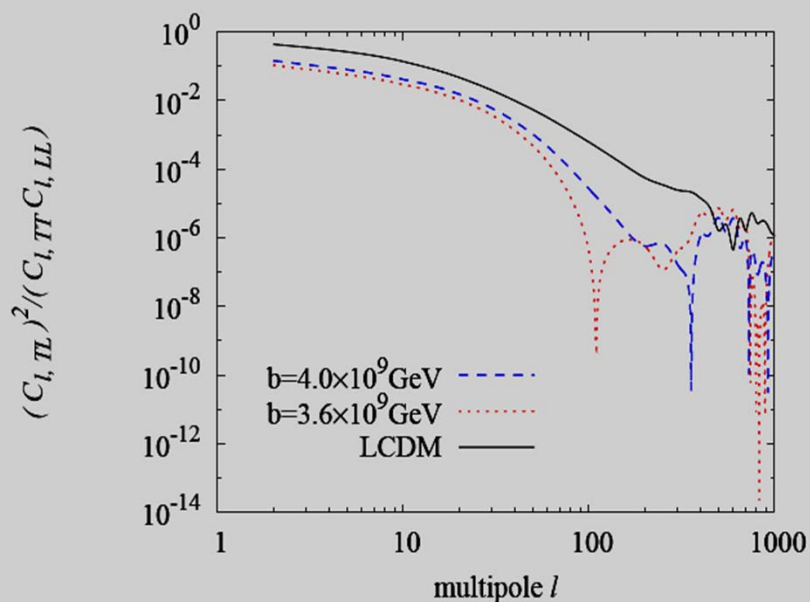


FIG. 4: The same as Fig.3 except we plotted the larger range of multipoles here.

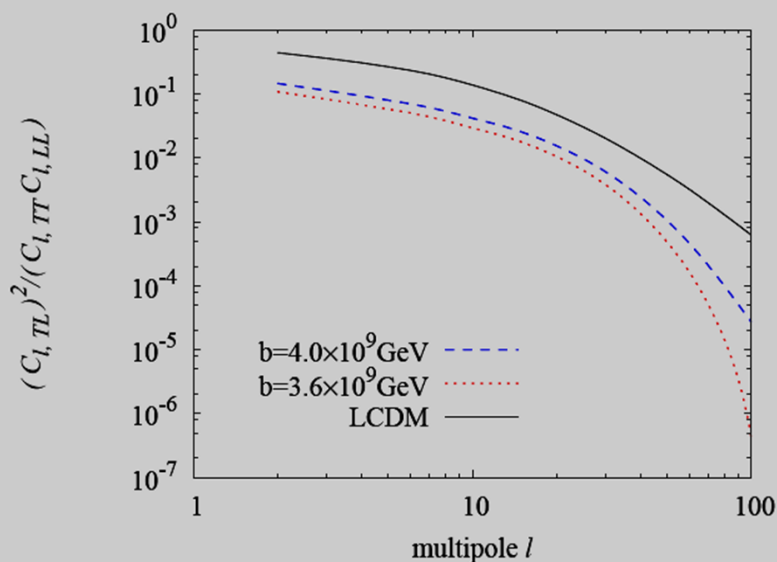


FIG. 3: Cross correlation between lensing and temperature are plotted. We assumed  $b = 4.0 \times 10^9$  (dash-line) GeV and  $3.6 \times 10^9$  GeV (dot-line) in this figure. For comparison, the case with  $\Lambda$ CDM (solid-line) is also plotted.

## PREDICTIONS ('05-'06)

- 1. Cold Spot/Giant Void
- 2.  $\sigma_8 = 0.8$ ; Running  $n_s$  from Red to Blue (less power at low  $l$ 's to more power)
- 3. Suppressed TT-Spectra  $l < 10$
- 4. Dipole, Quadrupole, Octupole: Additional Source leads to Alignment; Suppression; Preferred Direction; Power Asymmetry
- 5. Bulk Flow of Structure, 'Dark Flow'.
- 6. SUSY Breaking Scale Much Higher. LHC Wont Find SUSY at TeV
- 7. CMB Fine Scale at High  $l$ 's, More power : Features revealed by Cross Correlations

## TESTS ('06-'13)

- WMAP, Rudnick et al. (8 months later), Planck '13
- WMAP and SDSS '07; Planck '13
- WMAP, Planck '13
- WMAP, Planck '13
- NASA, (Kashlinsky et al., Watson et al.,) '08-'12. Planck (Pierpaoli et al., Atro-Barandela...). Have to Wait?!
- LHC '12
- Planck '13 .

# Significance of the Theory :

- Explains the Origins of the Universe: Why Did the Universe Start in Such an 'Incredibly Special State'
- Theory is Generic: Any Initial Conditions Phase Space/Landscape Structure that Contains Any Amount of Disorder in Distribution of Energies will Generically Localize Wavefunctions, a.k.a Produce Family of Universes Born at High Energies and Decohered !
- Theory Provides a Formalism on How to Calculate in Any Phase Space of Initial Conditions. No Phenomenology, No Anthropics, and No Guessing Needed. All Information Can Be Obtained By solving Physics Equations. Only Assumption: Quantum Mechanics is Valid.
- Any Initial Conditions Phase Space that is Perfectly Ordered (e.g. SUSY sector), Does Not Localize Wavefunctions = It Can Not Produce Universes!
- A Series of Predictions. *No Postdictions*. Highly Constrained in 'tweaking' parameters 'to fit' tests. Thus Observations Can Directly Rule Out or Confirm the Theory.
- Lessons Learned: Two Ingredients in Any Theory of the Origins of the Universe are CRUCIAL: i) Decoherence Must Be Included; ii) Phase Space Multiverse Must be Solved for as an N-Body Problem in Order to Capture All Relevant Physics.
- **Price= Extend Physics to Multiverse Framework ! But Observational Tests Provide Strong Evidence Already for the Rich Structure Beyond our Universe and for the Multiverse!**



# In a Nutshell:

