Title: Rethinking time at the Big Bang

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Abstract: I will discuss two ways in which revising the notion of time at the Big Bang will lead to testable predictions. I will then contrast these predictions against standard Î›CDM scenario, and cosmological observations. The first model, Holographic Cosmology, is based on a 3d quantum field theory without time, suggesting the possibility of nonperturbative effects on large angles (l<30) in the CMB sky. The second model, Periodic Time Cosmology, relates (past and future) cosmic expansion history to the spectrum of cosmic perturbations by demanding consistency with an exactly periodic notion of time. Comparing this model to observations leads to surprising implications for dark energy and/or neutrino masses in cosmology.

Rethinking Time at the Big Bang

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PI Day
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Introduction

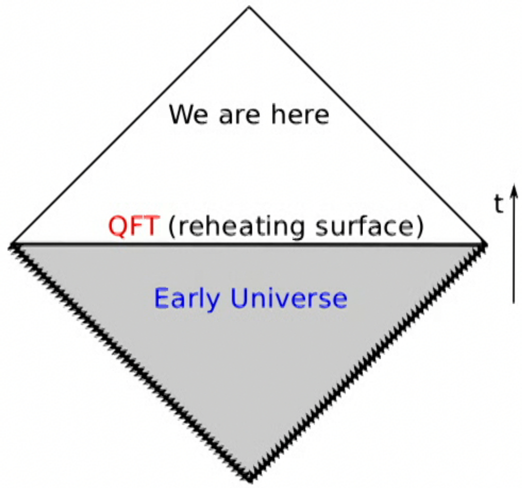
- both models replace inflation with non-standard temporal structure in early universe
  - Holographic Cosmology - non-geometric phase
  - Periodic Time Cosmology - end of universe matched to beginning
- both produce alternate primordial power spectrum with rest of cosmological evolution identical to ΛCDM
- fit to Planck data + BKPlanck dust + BAO in CosmoMC, compared χ^2 against ΛCDM

Some References

- Niayesh Afshordi, Elizabeth Gould, and Kostas Skenderis.
  Constraining holographic cosmology using Planck data.
  arXiv:1703.05385 [astro-ph.CO].
- Niayesh Afshordi, Claudio Corianò, Luigi Delle Rose, Elizabeth Gould, and Kostas Skenderis.
  From Planck data to Planck era: Observational tests of holographic cosmology.
  Phys. Rev. Lett., 118:041301, Jan 2017.
- Richard Easther, Raphael Flauger, Paul McFadden, and Kostas Skenderis.
  Constraining holographic inflation with WMAP.
  JCAP, 1109:030, 2011.
- Paul McFadden and Kostas Skenderis.
  The Holographic Universe.
  J. Phys. Conf. Ser., 222:012007, 2010.

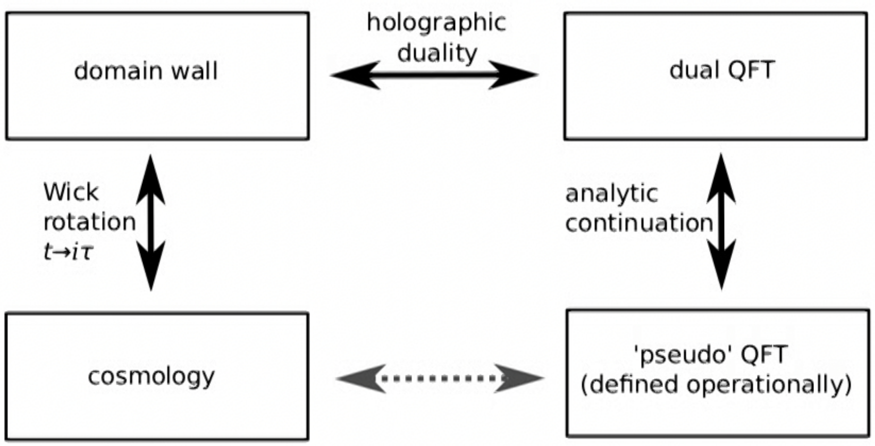
Model Description 1

- construct dual QFT to early universe
- early universe either standard inflation or non-geometric phase which requires dual QFT or quantum gravity to analyze



Model Description 2

- QFT defined by Wick rotation and analytic continuation as no QFT/dS correspondence



Dual QFT Lagrangian (arXiv 1001.2007)

- models are defined by the dual QFT
- use a superrenormalizable (3D Euclidean) QFT

$$S = \frac{1}{g_{YM}} \int d^3x \,\mathrm{tr} \left[\frac{1}{2} F^I_{ij} F^{Iij} + \frac{1}{2} \left(D\phi^J \right)^2 + \frac{1}{2} \left(D\chi^K \right)^2 + \psi^L \not{D} \psi^L \right.$$
$$\left. + \lambda_{M_1 M_2 M_3 M_4} \Phi^{M_1} \Phi^{M_2} \Phi^{M_3} \Phi^{M_4} + \mu^{\alpha\beta}_{M L_1 L_2} \Phi^M \psi^{L_1}_\alpha \psi^{L_2}_\beta \right]$$

- dimensions: g^2_{YM}, ϕ, $A = 1$; $\psi = \frac{3}{2}$
- SU(N), $N \sim 10^4$; parameters are:
  - number of various fields: N, N_ϕ, N_χ, N_ψ
  - coupling constants: $\lambda_{M_1 M_2 M_3 M_4}$, $\mu^{\alpha\beta}_{M L_1 L_2}$, g_{YM}
- QFT not conformal (but has generalized conformal structure)

Modified Spectrum

- difference between models given by primordial power spectra
- both are perturbative
- form for non-geometric case calculated to second order using generalized conformal structure

$$A = A_0 \left(\frac{q}{q_*}\right)^{(n_s-1)+\frac{n_{run}}{2}\ln\left(\frac{q}{q_*}\right)} \rightarrow A = A_0 \frac{1}{1+(gq_*/q)\ln(q/\beta g q_*)}$$

- all parameters are the same except g and $\ln(\beta)$ instead of n_s (and n_{run}) define shape of power spectrum

The holographic cosmology perturbation expansion is expected to break down at low l values for large $|g|$, when $\left|\frac{gq^*}{q}\right|$ becomes large.

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Best Fit Parameters

	HC		ΛCDM	
	best fit	68% range	best fit	68% range
$\Omega_b h^2$	0.02217	0.02215 ± 0.00021	0.02231	0.02229 ± 0.00022
$\Omega_c h^2$	0.1173	0.1172 ± 0.0012	0.1184	0.1186 ± 0.0012
100θ	1.04112	1.04115 ± 0.00042	1.04108	1.04105 ± 0.00041
τ	0.081	0.082 ± 0.013	0.069	0.068 ± 0.013
$10^9 \Delta_0^2$	2.126	2.126 ± 0.058	2.151	2.149 ± 0.054
n_s			0.9682	0.9671 ± 0.0045
α_s			-0.0027	-0.0030 ± 0.0074
g	-0.0070	$-0.0074^{+0.0014}_{-0.0013}$		
$\ln \beta$	0.88	$0.87^{+0.19}_{-0.24}$		
χ^2	11324.5		11319.6	

- $\Delta\chi^2 = 4.8$, difference in likelihood $\sim 2.2\,\sigma$
- $\left|\frac{gq^*}{q}\right| = 2.5$ at $l = 2$, expansion expected to be invalid when $l < 19$

Best Fit Parameters for $l > 30$

	HC		ΛCDM	
	best fit	68% range	best fit	68% range
$\Omega_b h^2$	0.02204	0.02202 ± 0.00022	0.02217	0.02212 ± 0.00024
$\Omega_c h^2$	0.1187	0.1187 ± 0.0014	0.1186	0.1188 ± 0.0013
100θ	1.04097	1.04099 ± 0.00042	1.04101	1.04100 ± 0.00041
τ	0.067	0.066 ± 0.017	0.0695	0.067 ± 0.016
$10^9 \Delta_0^2$	2.044	2.043 ± 0.074	2.151	2.139 ± 0.066
n_s			0.9682	0.9666 ± 0.0047
α_s			0.0083	0.0090 ± 0.0094
g	-0.0130	$-0.0127^{+0.0042}_{-0.0038}$		
$\ln \beta$	1.01	$0.90^{+0.32}_{-0.16}$		
χ^2	824.0		823.5	

- Here, $\Delta\chi^2 = 0.5$, meaning the difference is $< 1\sigma$, negligible.

1. Introduction

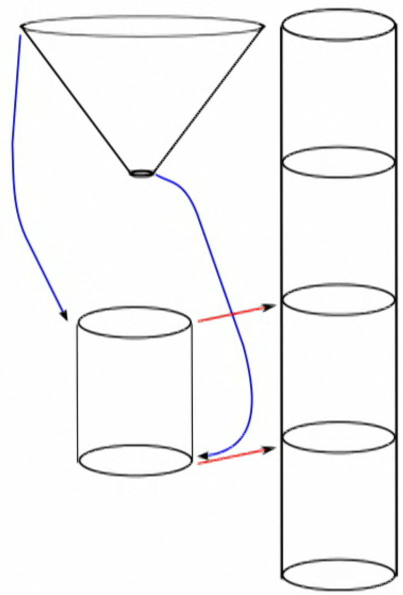
2. Holographic Cosmology
   - Description
   - Comparison of Models

3. Periodic Time Cosmology
   - Description
   - Results

4. Conclusion

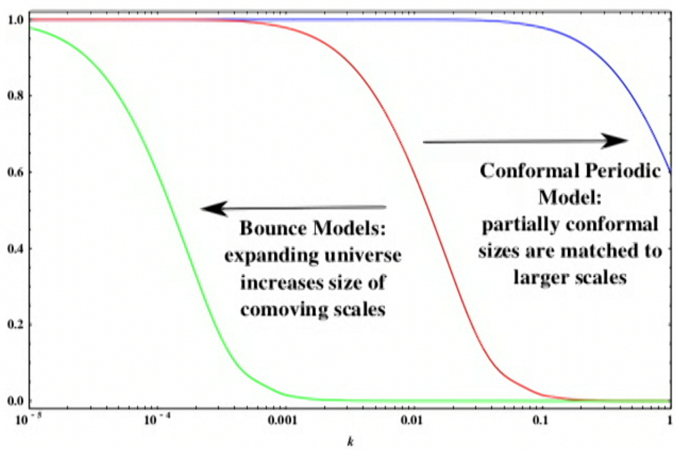
Cyclic Models

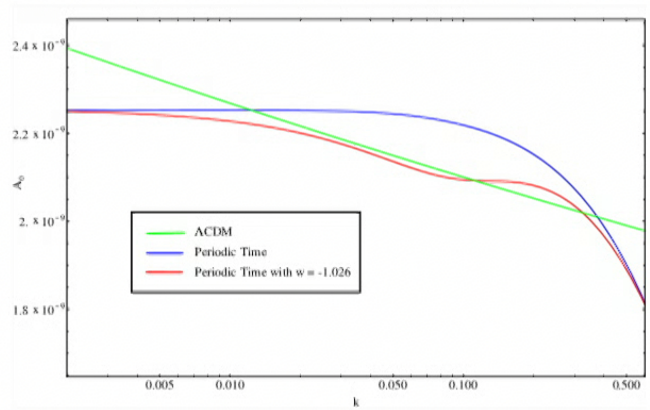
- conception - taking cyclic model and making it exactly periodic
- will use a conformal matching similar to Penrose's Conformal Cyclic Cosmology (CCC)
  - infinite future - all black holes evaporate, no massive matter gets in contact, conformally invariant
  - rescale conformal beginning and end times



Transfer Function

- model matches large scales (with low k) of old spectrum to visible scales in new spectrum





Penrose's CCC, like other cyclic models and inflation, match in the other direction, taking the portion of the transfer function with no power and reforming or constructing the primordial power spectrum at some time.

Description

- parameter α defines relative conformal rescaling of co-moving scales so $k_{old} = \alpha k_{new}$
- $\mathcal{P}(k)$ primordial power spectrum, $T(k) = \frac{\zeta_k(t=\infty)}{\zeta_k(t=0)}$ transfer function
- $\mathcal{P}(k) = A_0 \left|T(\alpha k)\right|^2 \left|T(\alpha^2 k)\right|^2 \ldots$ invariant under evolution + rescaling;
- producing repeating pattern, where each cycle shrinks previous and applies low-pass filter:

- $T(k \to 0) \to 1$, approximate as $\mathcal{P}(k) = A_0 \left|T(\alpha k)\right|^2$
- $\alpha \ll 1$ so for observable k, $T(\alpha k) \sim 1$ and $\mathcal{P}(k)$ is approx. scale invariant with a red tilt

Preliminary Minimum χ^2

- model run in CosmoMC
- lowTEB+highl+lensing+BKP+BAO+highP+tau
- $T(k)$ is evolved to present, although expected to continue to evolve for non-trivial dark energy only

	χ^2 for ΛCDM	χ^2 for PT	$\Delta\chi^2$	σ
6 params	12995.3	13021.1	25.8	5.1
$+\ w \neq -1$	12995.1	12998.5	3.4	1.8
$+\ w,\ w_a$	12994.7	12997.8	3.1	1.8

Preliminary Minimum Parameters

- lowTEB+highl+lensing+BKP+BAO+highP+tau

	ΛCDM	PT
$\Omega_b h^2$	0.02220	0.02225
$\Omega_c h^2$	0.1198	0.1184
100θ	1.04074	1.04094
τ	0.0527	0.0483
$10^9 \Delta_0^2$	2.0900	2.1779
w	-1.0364	-1.0238
n_s	0.9637	
α		0.01125

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α		0.01125

Conclusion

- Holographic Cosmology
  - By constructing a holographic dual on the "reheating surface", a non-geometric alternative to inflation can be constructed.
  - This model was fit to data using CosmoMC and compared to ΛCDM.
  - Holographic cosmology can match observation as well as ΛCDM.
  - The model becomes non-perturbative for low l values or large angles.
- Periodic Time
  - model run in CosmoMC which relates cosmic history to initial conditions at the big bang
  - preliminary results indicate model is viable but disfavored
  - 6 parameter model disfavored by $\sim 5.1\sigma$
  - best results from $w \neq -1$, difference of $\sim 1.8\sigma$