Banks Zaks Cosmology

based on arXiv:1912.10532 and arXiv: 2010.02998

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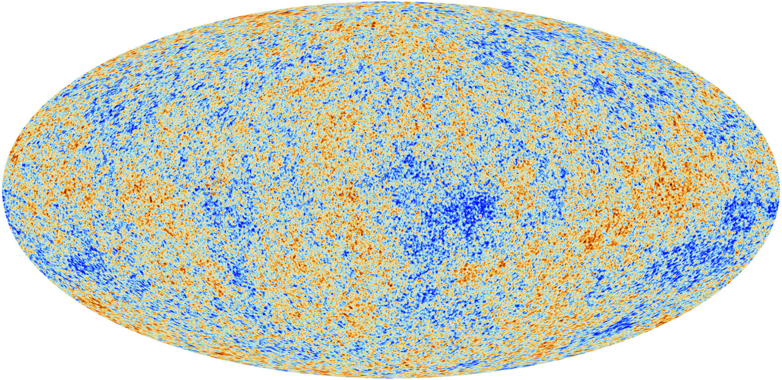
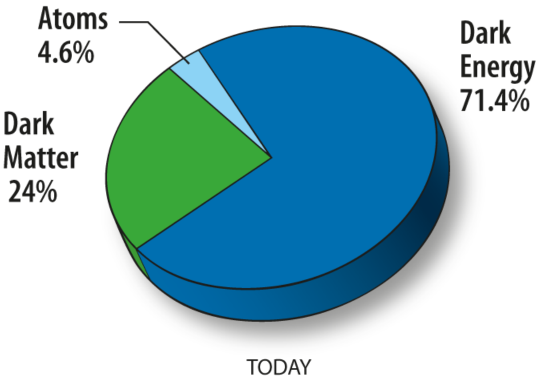
September 9, 2021

Cosmic Microwave Background



$8\,\pi\,G = M_p^{-2}$. where $M_p \simeq 2.5 \times 10^{10}\,GeV$

Cosmic Cake



Problems of Standard Model of Cosmology

- Early Universe:
  - Flatness Problem
  - Horizon Problem
- Late Universe
  - The cosmological Constant Problem (Λ)
  - Problem of Cosmic coincidence

The solution ? New Physics?

This can't help

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \equiv G_{\mu\nu} = T^{SM}_{\mu\nu}$$

Modification in GR part

$$G_{\mu\nu} + G^{new}_{\mu\nu} = T^{SM}_{\mu\nu}$$

Modify the matter sector

$$G_{\mu\nu} = T^{SM}_{\mu\nu} + T^{new}_{\mu\nu}$$

No Scalar fields! Why?

- The only known scalar field is Higgs as opposed to lot of fermions.
- Quantum Gravity opposes the consideration of flat potential.

QG may be inconsistent with scalars

Swampland Conjecture : Field theories should be consistent with string theory in high energy limit. No false vacuum states allowed! Even scalar fields with flat potentials are not allowed which are the important pillars in model building for inflation or dark energy.

Inflation, DE

$\frac{V'}{V} \ll 1$ and $\frac{V''}{V} \ll 1$

Swampland conjecture

$\frac{V'}{V} \sim 1$ or $\frac{V''}{V} \sim 1$

Banks-Zaks ($\mathcal{BZ}$) Theory (Georgi 2007)

$\mathcal{BZ}$ and unpartcles phase

There exists a interesting possibility that physics beyond the Standard Model (SM) may contain a sector that is conformally invariant in the IR region (guaranteed by a zero of the beta function), and classically scale-invariant in the UV; we refer to these as the unparticle (U) and Banks-Zaks (BZ) phases, respectively. The transition region between the two phases is characterized by the scale of dimensional transmutation Λ_u

Thermodynamics of Unparticles (arXiv:0809.0977)

- Trace of the energy momentum tensor (T^μ_μ) of a gauge theory

$$T^\mu_\mu = \frac{\beta}{2g} N \left[F^{\mu\nu}_a F_{a\,\mu\nu} \right] ,$$

- β vanishes in conformal limit.
- Performing Thermal average of $T_{\mu\nu}$ becomes

$$\rho_u - 3p_u \propto \beta(g) \propto T^\delta .$$

- Using laws of thermodynamics

$$\begin{aligned} \rho_u &= \sigma T^4 + B\, T^{4+\delta} , \\ p_u &= \frac{1}{3}\sigma T^4 + \frac{B}{3+\delta} T^{4+\delta} ., \end{aligned}$$

Cosmology with unparticles

Continuity equation : $\dot{\rho}_u = -3H\left(\rho_u + p_u\right)$

$$a \propto \frac{1}{T}\frac{1}{\left(3B(\delta+4)T^{\delta} + 4(\delta+3)\sigma\right)^{1/3}} \propto \; y^{-1}(y^{\delta}-1)^{-1/3}$$

scale factor has a pole at

$$y = 1, \text{where} \;\; y = \frac{T}{T_c} \text{ and } \; T_c = \left[\frac{4(\delta+3)}{3(\delta+4)}\left(-\frac{\sigma}{B}\right)\right]^{\frac{1}{\delta}}$$

Cosmology with unparticles

if

- T_c is real and positive
- $\rho_c = \rho(T_c) > 0$

then there exists an extremum of Temperature. Existence of such an extremum is a source of de Sitter expansion. Also from the cont. eqn. it is clear that

$$\dot{\rho_u}(T_c) = -3H_c(\rho_c + p_c) = 0.$$

Bouncing Solutions

Let's consider with the Universe filled with unparticles only.

In order to get the bounce

- $H(T_b) = 0 \Rightarrow \rho_b = \rho(T_b) = 0$
- $\dot{H}(T_b) > 0 \Rightarrow p_b = p(T_b) < 0$

where $T_b = \left(-\frac{\sigma}{B}\right)^{\frac{1}{\delta}}$ is the Temperature of unparticles at bounce.

In order to get a real and positive value of T_b and negativity of p_b, δ and B are constrained as

$$\boxed{B < 0 \text{ and } \delta \in [-3,0]}$$

Bounce with unparticles only

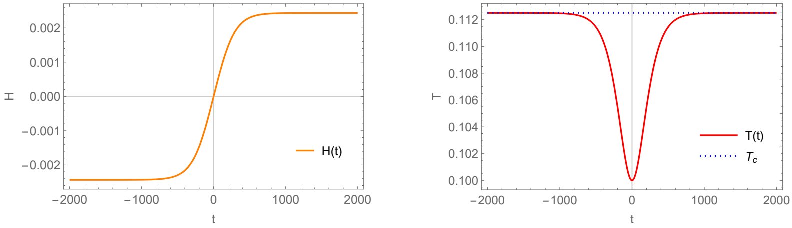


Figure: *Numerical solutions of $H(t)$ (left panel) and T(t) (right panel) for $\sigma = -\delta = 1$ and $B = -0.1$. All quantities are expressed in Planck units. $t = 0$ represents the moment of the bounce. The blue dotted line in the right panel is T_c, the maximal allowed temperature that is asymptotically reached in the infinite past and future.*

Bounce and cyclic solutions: Unparticles + perfect fluid

Let's add a perfect fluid with equation of state w,

$$\rho_f = \rho_{f0}\, a^{-3(1+w)} \text{ and } p_f = w\rho_f$$

Temperature acts as a clock

Since $\rho_f \propto a^{-3(1+w)}$ and $a(T)$, one finds $\rho_f = \rho_f(T)$ and $p_f = p_f(T)$. In this one can express the one dynamical variable T

Rich Phenomenology!

$$T_0 = \left(-\frac{\sigma}{B}(1+\alpha)\right)^{\frac{1}{\delta}} \text{ and } \alpha = \rho_{f0}/\left(\sigma\, T_0^4\right)$$

at $T = T_0$ one has bounce or recollapse of scale factor. T_0 may be a maximum and minimum of T.

Bounce and cyclic solutions

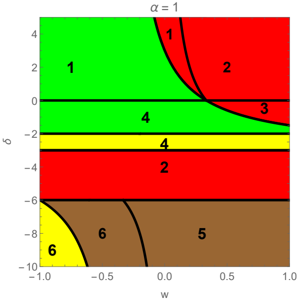


Figure: *Classification of different scenarios at $T = T_0$ for $\alpha = 1$, depending on δ and w. Green / yellow / red / brown correspond to bounce with maximal T, bounce with minimal T, recollapse with minimal T and recollpase with maximal T respectively. Numbers from 1 to 6 represent different cosmological fates*

Bouncing and cyclic solutions

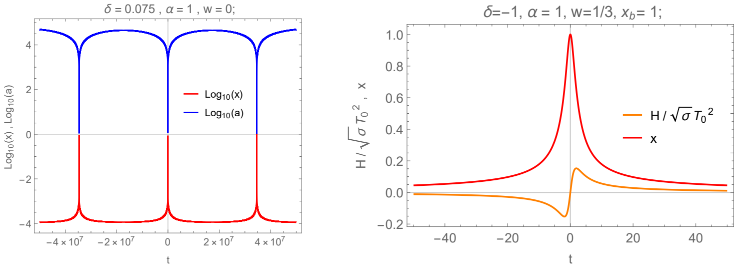


Figure: *Left panel: Evolution of the normalized temperature* $x = T/T_0$ *(red) and the normalized scale factor* $a(t)$ *(blue). This is an example of region* **1** *from parameter space plot. Time is expressed in Planck units. One obtains a cyclic Universe, for which* $T = T_0$ *i.e.* $x = 1$ *is a maximal temperature and this temperature is obtained at the bounce. Right panel : Evolution of normalized temperature and Hubble parameter. This is an example of region* **4** *(green).*

Dark Energy from unparticles

We have already mentioned about the pole of scale factor where $\dot{\rho_u}(T = T_c) = 0$. A well known example where scale admits pole is of Radiation !

$$a(T) \propto \frac{1}{T} \qquad a \longrightarrow \infty \;\; as \;\; T \longrightarrow 0$$

In our case as $T \longrightarrow T_c$ one lies either $T < T_c$(dS bounce) or $T > T_c$, there is no possibility of crossing T_c!

Conditions for Dark Energy

- $T_c > 0$, $\rho_u(T_c) > 0$
- $\frac{da}{dt} \neq 0$ throughout the evolution. Temperature must always decrease while $a(T)$ grows. $T > T_c$
- NEC is obeyed for range of $\delta \in [-3, 0]$

Evolution of unparticles in early and late times

Early times evolution i.e. $T \gg T_c \Rightarrow y \gg 1$

In early times, $\rho_u \propto T^4$ and unparticles act as regular radiation. Effectively one has universe filled with radiation dust.

Late times evolution i.e. $T \simeq T_c \Rightarrow y \simeq 1$

The evolution of Temperature, Energy density and equation of state is given as

$$
\begin{aligned}
y(N) &\simeq 1 + e^{-3N}\,(y_0 - 1)\ , \\
\rho_u(N) &\simeq -\frac{\delta\sigma T_c^4}{3(\delta+4)}\left(1 + e^{-3N} 4(\delta+4)\,(y_0 - 1)\right)\ , \\
w_u &\simeq -1 + e^{-3N}\,4(\delta+4)\,(y_0 - 1)\ ,
\end{aligned}
$$

Background Dynamics

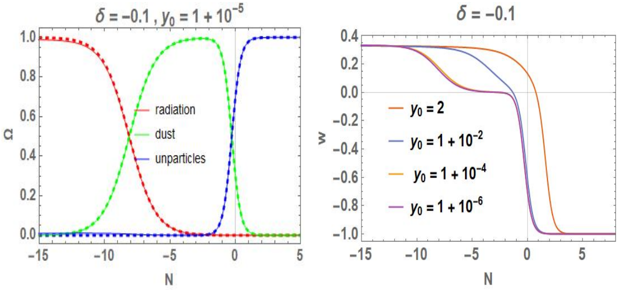


Figure: *Left panel: Comparison of the evolution of density parameters $\Omega(N)$ for each fluid between ΛCDM (dashed) and unparticles (solid) model. The dashed blue curve is the relative density of the CC in the ΛCDM model. Right panel: Evolution of the total equation of state $w(N)$. Both Ω and w weakly depend on δ.*

Consistency with BBN/CMB

$$\left.\frac{\rho_u}{\rho_r}\right|_{BBN} \leq \frac{7}{8}\,(4/11)^{4/3}\,2\Delta N_{eff} \simeq 0.086$$

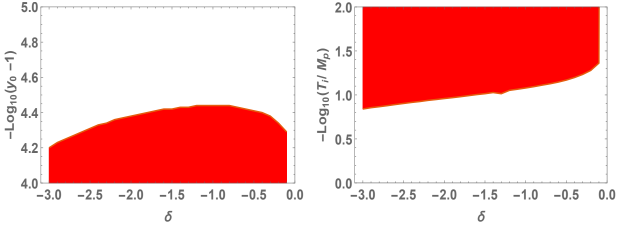


Figure: *Left panel:* $-\log_{10}(y_0 - 1)$ *vs.* δ. *White regions of parameter space are consistent CMB constraints. Right panel: BBN constraints on the* (δ, T_i) *parameter space, where* T_i *is a value of* T_u *for* $\rho_r \simeq \rho \simeq M_p^4$. *Note that any value* $T_u < 0.1 M_p$ *gives a viable* ρ_u/ρ_r *at BBN/CMB.*

Structure Formation with unparticles

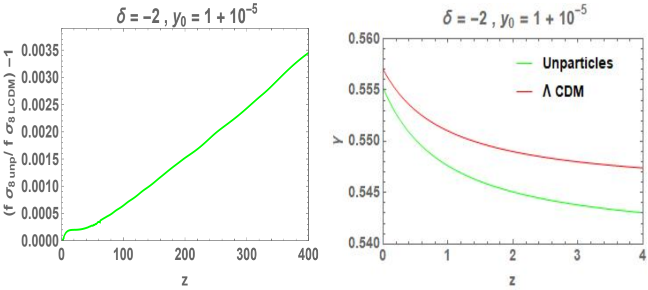
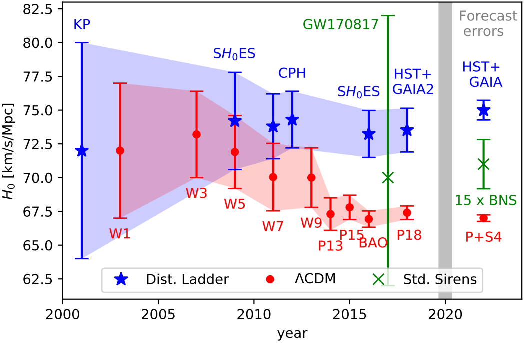


Figure: *Left panel: Relative deviation of $f(z)\sigma_8$ for unparticles compared to ΛCDM for $0 \leq z \leq 1000$. A significant deviation may be seen only at very large redshifts. Right panel: Comparison of the growth index, γ as a function of redshift for our model compared to the ΛCDM prediction.*

Hubble tension



The addition of unparticles ameliorates the Hubble tension to $2-3\sigma$, as it pushes the CMB derived Hubble parameter towards $H_0 = 70km/Mpc/sec$.

Conclusions

- Unparticles provides a possible mechanism to generate the bounce.
- For Universe filled with Unparticles only bounce is a de Sitter which is combination of bounce + Inflation.
- For Unparticles on top of perfect fluid give rise to rich phenomenology. One can get different kind of bouncing cyclic solutions

Conclusions

- For certain range parameter unparticles behave like radiation in high temperature regime and DE like at low temperature.
- Such as model is consistent with Λ CDM at background level while it shows significant difference at level of perturbations.
- Unparticles dark energy avoids swampland conjecture while without modifying gravity.
- the addition of unparticles ameliorates the Hubble tension