New applications of unparticles: Inflation, dark energy, bouncing cosmologies, and Hubble tension

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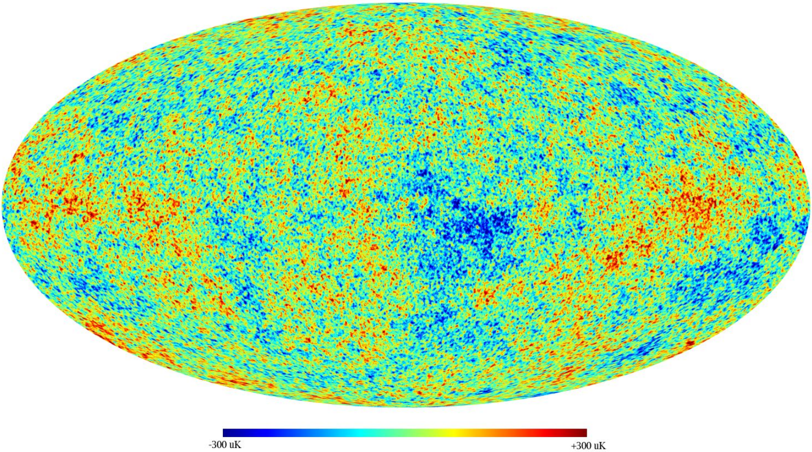
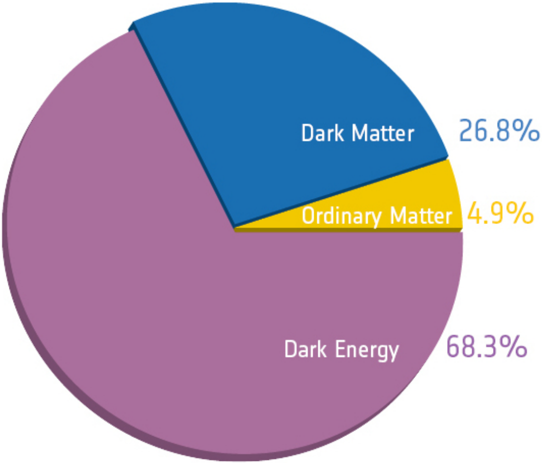
arXiv:1912.10532 + 2010.02998
with Ido Ben-Dayan and Utkarsh Kumar

Cosmic Microwave Background



$8\pi G = 1 = M_p^{-2}$, where $M_p \simeq 2.5 \times 10^{18} GeV$

Cosmic cake



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Since GR works perfectly well let's try new matter fields

$$G_{\mu\nu} = T^{SM}_{\mu\nu} + \text{new stuff} \quad \text{(no scalars this time)} \tag{3}$$

Why no scalars?

First of all, we know only one fundamental scalar we're sure of vs tons of fermions and vectors. But that's not the reason it is worth to consider the alternatives!

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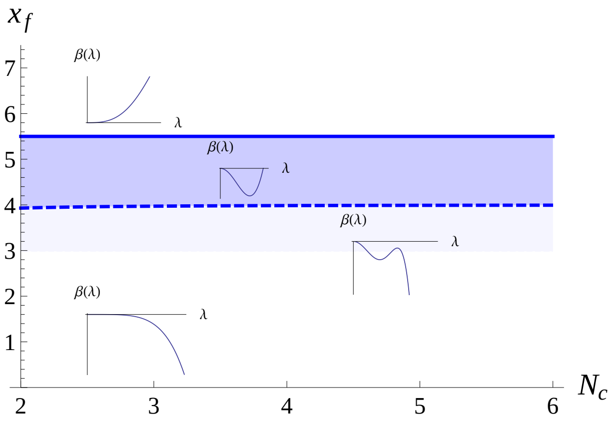
String theory may in inconsistent with scalars

Swampland conjecture: We want our field theory to be consistent with the string theory in high energies. No false vacuum states allowed! Even flat scalar potentials are not allowed! And they are the ABC of model building in inflation and dark energy.

Inflation, DE	**Swampland conjecture**
$\frac{V_\phi}{V} \ll 1$	$\frac{V_\phi}{V} \sim 1$

Unparticles

Maybe best explained in [Tuominen, arxiv:1206.5772]



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Long story short:

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- This theory may have a non-trivial IR fixed point. We calculate the thermal average around it and we call the thermal expectation value of our Banks-Zaks particles " the unparticle stuff"
- We get $\rho_u - 3p_u = AT^{4+\delta} \to A, \delta$ depends on β function, coupling, etc.

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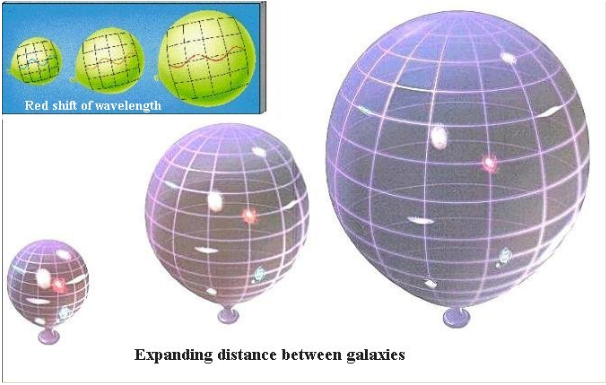
a) Unparticles in the low energy limit (low temperatures, late Universe)
   - Behave collectively like some strange unparticle stuff (more about it in a second)
   - They are decoupled from the Standard Model
   - Effectively they're dark particles!

FRW spacetime and the scale factor



Each scale grows like $a(t)$, where $a(t)$ is the scale factor. You can set $a(t_0) = a_0 = 1$. The volume of the Universe grows like $a(t)^3$.

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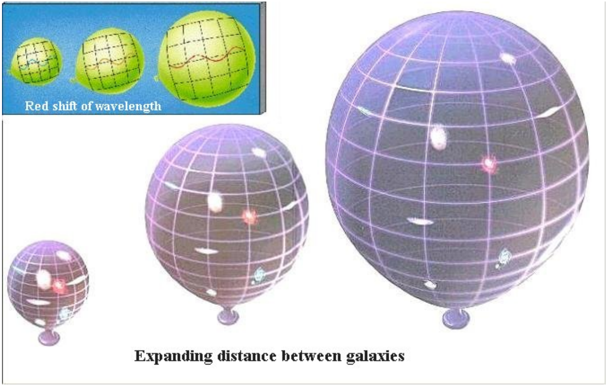

$$3H^2 = 3\left(\frac{\dot{a}}{a}\right)^2 = 8\pi G\rho \qquad (4)$$

$$-2\dot{H} = 8\pi G(\rho + p) \qquad (5)$$

Thermodynamics of unparticles (Grządkowski and Wudka 2008)

Using the first law of thermodynamics one finds

$$\rho_u = \sigma T^4 + A\left(1 + \frac{3}{\delta}\right) T^{4+\delta} \equiv \sigma T^4 + B\, T^{4+\delta}\,, \qquad (6)$$

$$p_u = \frac{1}{3}\sigma T^4 + \frac{A}{\delta} T^{4+\delta} \equiv \frac{1}{3}\sigma T^4 + \frac{B}{3+\delta} T^{4+\delta}\,. \qquad (7)$$

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$$\rho_r \propto T_r^4\,, \qquad T_r \propto \frac{1}{a} \quad \to \text{that's regular radiation} \tag{8}$$

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Continuity equation: $\dot{\rho}_u + 3H(\rho_u + p_u) = 0$

$$a \propto \frac{1}{T}\left(\frac{\delta^2\sigma}{(\delta+3)\,(3A(\delta+4)\,T^\delta + 4\delta\sigma)}\right)^{1/3} \propto\ y^{-1}(y^\delta - 1)^{-1/3} \tag{9}$$

Pole of a scale factor

The scale factor has a pole at

$$y = 1\,, \quad \text{where} \quad y = \frac{T}{T_c} \quad \text{and} \quad T_c = \left[\frac{4(\delta+3)}{3(\delta+4)}\left(-\frac{\sigma}{B}\right)\right]^{\frac{1}{\delta}} \quad (10)$$

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Such a lower/upper bound may be a natural source of de Sitter expansion, because from the continuity equation one finds

$$\dot{\rho}_u(T_c) = -3H(\rho_c + p_c) = 0 \qquad (11)$$

Bouncing solutions

Let's start with the Universe filled ONLY with unparticles

As we already know in order to get a bounce one needs some real T_b, for which

- $H(T_b) = 0$, which means that $\rho_b = \rho(T_b) = 0$
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Indeed, there's a unique solution!

$$T_b = \left(-\frac{\sigma}{B}\right)^{\frac{1}{\delta}} \tag{12}$$

In order to get a real value of T_b one needs $B < 0$. Plus, in order to get a negative p_b one needs

$$\delta \in [-3, 0] \tag{13}$$

Bouncing solutions with unparticles only

Whenever you have a bounce, you have a dS solution!

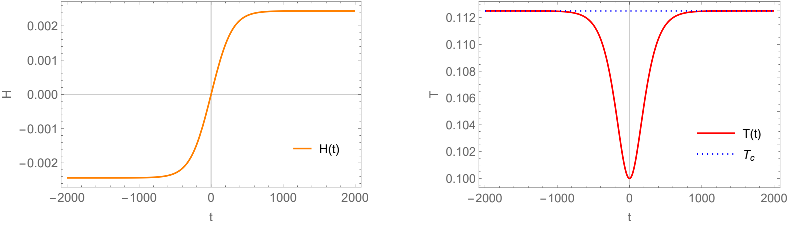

Figure: Numerical solutions of $H(t)$ (left panel) and T(t) (right panel) for $\sigma = -\delta = 1$ and $B = -0.1$. $t = 0$ represents the moment of the bounce. The blue dotted line in the right panel is T_c, the maximal allowed temperature that is asymptotically reached in the infinite past and future.

Null Energy Condition is always violated, there's no graceful exit and superhorizon perturbations keep growing! Temperature is growing with the volume!

Let's add the matter fields!

Let's assume that there is another matter component, which is some perfect fluid

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Since $\rho_f \propto a^{-3(1+w)}$ and $a = a(T)$ one finds $\rho_f = \rho_f(T)$ and $p_f = p_f(T)$ We can express the whole evolution using one dynamical variable! How awesome is that?

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Rich phenomenology!

$$T_0 = \left(-\frac{\sigma}{B}(1+\alpha)\right)^{\frac{1}{\delta}}, \quad \alpha \equiv \rho_{f0}/(\sigma T_0^4) \tag{15}$$

At $T = T_0$ one can obtain a bounce or a re-collapse of a scale factor. T_0 may be a maximum or minimum of T. 4 options altogether!

Phase diagram

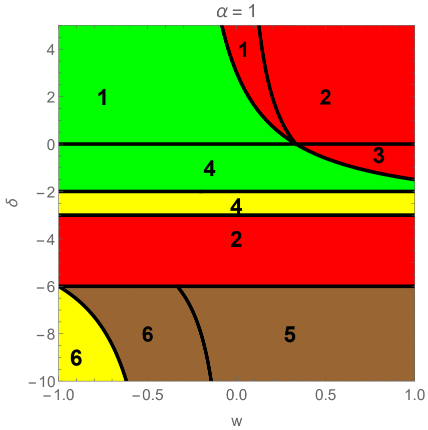
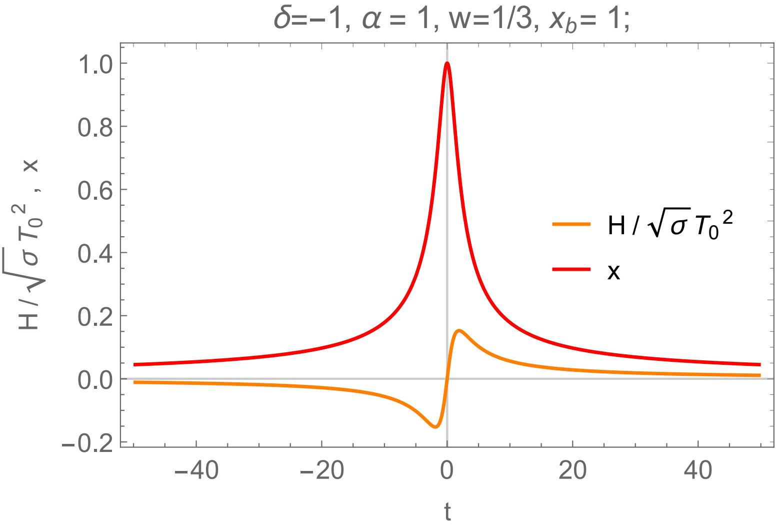
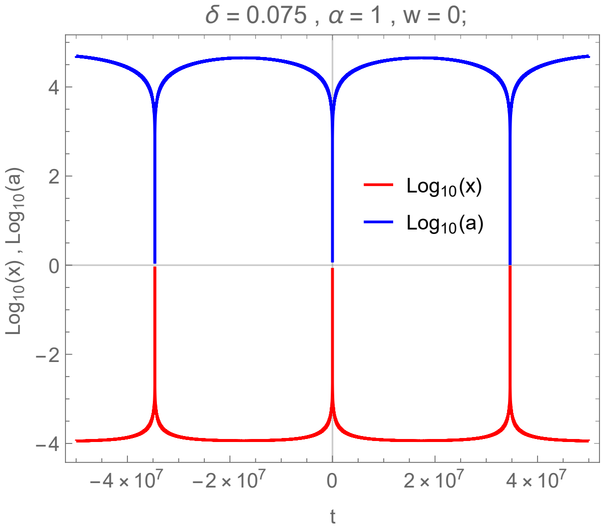


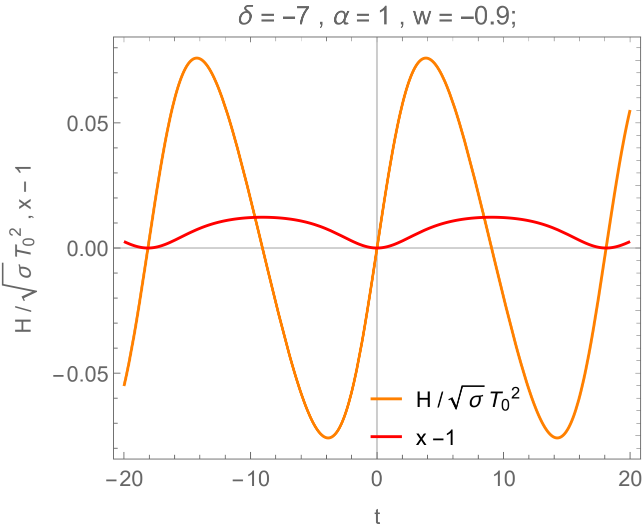
Figure: *Classification of different scenarios at $T = T_0$ for $\alpha = 1$, depending on δ and w. Green / yellow / red / brown correspond to bounce with maximal T, bounce with minimal T, re-collapse with minimal T and re-collapse with maximal T respectively. Numbers from 1 to 6 represent different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

Realistic bouncing Universe - green, number 4



Realistic cyclic Universe - red and green, number 1




δ = −7 , α = 1 , w = −0.9;
0.05
0.00
−0.05
H / √σ T₀², x − 1
H / √σ T₀²
x −1
−20
−10
0
10
20
t

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- For the Universe filled with unparticles only the only bounce is a de Sitter bounce - looks like a bounce + inflation, but it doesn't work
- For unparticles + matter you can have a "normal" bounce, de Sitter bounce, realistic and unrealistic cyclic Universe
- Quite a few cases, for which the Universe collapses and reaches singularity

Dark energy from unparticles

We already mentioned that $\dot{\rho}_u(T = T_c) = 0$, where $T = T_c$ is a pole of a scale factor. We do know another example of $a(T)$ with a pole! Radiation!

$$a(T_r) \propto \frac{1}{T_r} \qquad a \to \infty \text{ for } T_r \to 0 \tag{16}$$

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Conditions for dark energy

- $T_c > 0$, $\rho_c > 0$
- $\frac{da}{dT} \neq 0$ throughout the whole evolution. Temperature must ALWAYS decrease, while $a(t)$ grows. $T > T_c$
- NEC never violated $\Rightarrow$ $\delta \in (-3, 0)$

Early and late evolution of unparticles

Early evolution, i.e. $T \gg T_c$, $y = T/T_c \gg 1$

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

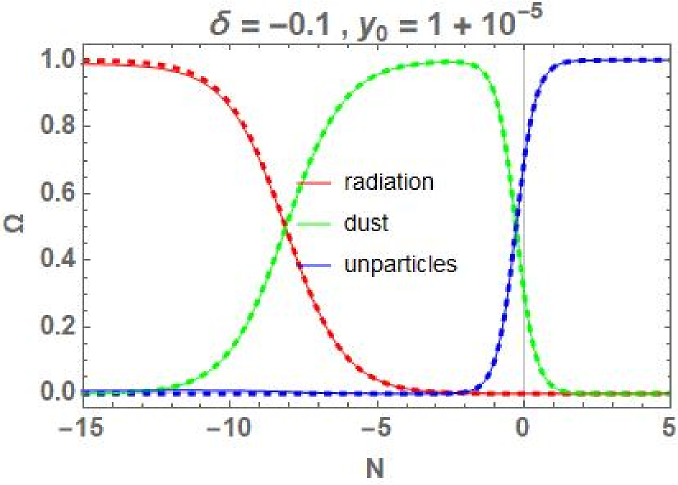
One can solve the system analytically as a function of e-folds, which gives

$$T(N) \simeq T_c \left(1 + e^{-3N} \frac{y_0^3 \left(y_0^\delta - 1\right)}{\delta}\right), \quad (17)$$

$$\rho_u(N) \simeq \rho_c \left(1 + e^{-3N} \frac{4(\delta+4) y_0^3 \left(y_0^\delta - 1\right)}{\delta}\right), \quad (18)$$

$$w_u \simeq -1 + e^{-3N} \frac{4(\delta+4)\, y_0^3 \left(y_0^\delta - 1\right)}{\delta}, \quad (19)$$

Consistency with ΛCDM



$$\left.\frac{\rho_u}{\rho_r}\right|_{BBN} \leq \frac{7}{8}(4/11)^{4/3}\, 2\Delta N_{eff} \simeq 0.086\,, \qquad (20)$$

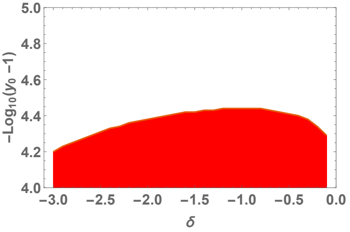
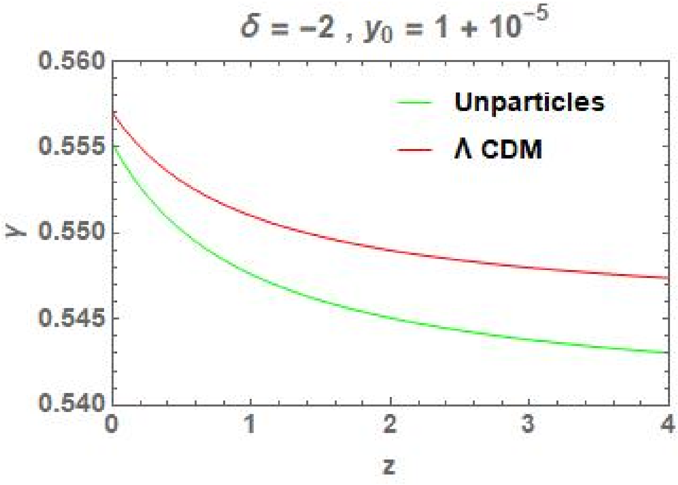
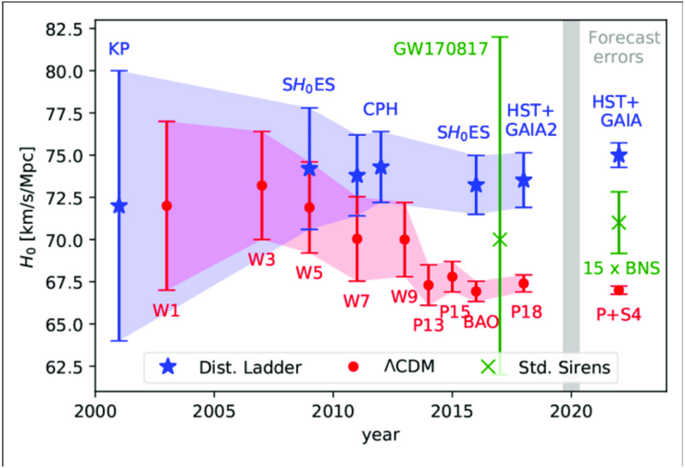


Figure: *Left panel:* $-\log_{10}(y_0 - 1)$ *vs.* δ. *White regions of parameter space are consistent CMB constraints. Right panel: BBN constraints on the* (δ, T_i) *parameter space, where* T_i *is a value of* T_u *for* $\rho_r \simeq \rho \simeq M_p^4$. *Note that any value* $T_u < 0.1M_p$ *gives a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


δ = −2 , y0 = 1 + 10−5
Unparticles
Λ CDM
γ
z
0.560
0.555
0.550
0.545
0.540
0
1
2
3
4

Hubble tension



Increasing N_{eff} helps!

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- In such a case they have a minimal allowed temperature!
- Such a model is very consistent with ΛCDM, which is both good and bad
- Unparticles may help to decrease the Hubble tension!