Dynamical cosmic vacuum in the Universe

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The accelerating universe

• 1998: Accurate measurement of the luminosity distance-redshift curve of distant SNIa carried out by the Supernova Cosmology Project and the High-z Supernova Search Team.

Our Universe is speeding up! The so-called concordance $\Lambda$CDM model fits well the data. A positive rigid $\Lambda$ could explain the 70% of the energy content of the universe.
Some details on the cosmological constant (CC)

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \]

\[ p_{\Lambda} = -\rho_{\Lambda} \quad \text{The CC behaves like vacuum} \]

\[ T_{\mu\nu} = \sum_{N} p_{N} g_{\mu\nu} - (\rho_{N} + p_{N}) U_{\mu}^{N} U_{\nu}^{N} \]

Easy interpretation from the thermodynamical point of view. Universe <-> box expanding adiabatically

\[ \Delta U = \rho_{\Lambda} \Delta V \]

Due to its negative pressure, the CC has repulsive gravitational power!

\[ \frac{\dot{a}}{a} = \frac{4\pi G}{3} (2\rho_{\Lambda} - 2\rho_{r} - \rho_{m}) \]
Existing problems
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Several contributions to the this energy density:
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$$\rho^{(0)}_\Lambda \sim 10^{-47} \text{GeV}^4$$

Several contributions to the this energy density:

I. Zero-point energy

$$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$
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II. Electroweak vacuum

\[ \rho_{\text{ind}}^{(0)} \sim -10^8 \text{GeV}^4 \]
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III. Pure geometrical term in the lhs of Einstein’s equations
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\]

\[
\frac{\rho_m(z)}{\rho_\Lambda(z)} = \frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}} (1 + z)^3
\]
Existing problems

• Why is the current value of the matter energy density of the same order of the vacuum energy density?

$$\frac{\Omega_m^{(0)}}{\Omega_{\Lambda}^{(0)}} \sim \mathcal{O}(1)$$

$$\frac{\rho_m(z)}{\rho_{\Lambda}(z)} = \frac{\Omega_m^{(0)}}{\Omega_{\Lambda}^{(0)}}(1 + z)^3$$

Density equality at $z \approx 0.33$, when the Universe was $\approx 10$ Gyrs old, almost $4$ Gyrs ago.
Different approaches to alleviate the existing problems

• Scalar field theories: k-essence (quintessence, phantom field, etc.)

\[ S = \int d^4x \sqrt{-g} \left[ \frac{R}{16\pi G} + P(\phi, X) \right] + S_m \]

\[ X = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \]

• Scalar-tensor gravity, i.e. Brans-Dicke theory.

\[ S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} f(\varphi, R) - \frac{1}{2} \xi(\varphi)(\nabla \varphi)^2 \right] + S_m(g_{\mu\nu}, \Psi_v) \]

• Chaplygin gas

\[ p = -\frac{A}{\rho^\alpha} \quad A > 0 \quad 0 < \alpha < 1 \]

• Modified gravity theories, i.e. f(R) gravity.

• \( \Lambda XCDM \) cosmon models.

• Dynamical vacuum in QFT in curved space-time.
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MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION


- Their Diagnostic:

\[ \Omega_{m} h^2 (H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1 + z_i)^3 - (1 + z_j)^3} \]
MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION


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\[ Om h^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1 + z_i)^3 - (1 + z_j)^3} \]

• In the ΛCDM:

\[ H^2(z) = H_0^2 \left( 1 + \Omega_m^0 [(1 + z)^3 - 1] \right) \]

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• In the \( \Lambda \)CDM:

\[ H^2(z) = H_0^2 \left( 1 + \Omega_m^{(0)} ((1 + z)^3 - 1) \right) \quad \Rightarrow \quad \Omega m h^2 = \Omega_m^{(0)} \left( \frac{H_0}{100} \right)^2 \]

Planck 2015

Using the available Hubble function data set

\[ \Omega m h^2 = \Omega_m^{(0)} h^2 = 0.1415 \pm 0.0019 \quad \text{and} \quad \Omega m h^2 = 0.1250 \pm 0.0039 \]
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• In the ΛCDM:

\[ H^2 (z) = H_0^2 \left( 1 + \Omega_m (0) [(1 + z)^3 - 1] \right) \quad \rightarrow \quad \Omega_{m} ^2 = \Omega_m (0) \left( \frac{H_0}{100} \right)^2 \]

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\( \neq \)

Probably, Λ must be dynamical

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Dynamical cosmic vacuum in the Universe
Possible consequences of the variation of $\Lambda$

Bianchi identity

$$\nabla^\mu G_{\mu\nu} = 0$$

Einstein’s equations

$$\nabla^\mu (G T_{\mu\nu}) = 0$$

Covariant conservation laws

For $\nu=0$

$$\frac{d}{dt} [G(\rho_m + \rho_\Lambda)] + 3 G H (\rho_m + p_m) = 0$$
Possible consequences of the variation of $\Lambda$

**I: G is constant and matter exchanges energy with the vacuum.**


\[
\dot{\rho}_\Lambda + \dot{\rho}_m + 3H \rho_m = 0
\]
Possible consequences of the variation of $\Lambda$

II: \textit{G is time-dependent and matter is covariantly conserved.}


\[ \dot{\rho}_\Lambda + \frac{\dot{G}}{G} (\rho_m + \rho_\Lambda) = 0 \]
\[ \dot{\rho}_m + 3H \rho_m = 0 \]
Possible consequences of the variation of $\Lambda$

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- III: I+II
Possible consequences of the variation of $\Lambda$

I: $G$ is constant and matter exchanges energy with the vacuum.


II: $G$ is time-dependent and matter is covariantly conserved.


III: I+II
$\beta$ function for $\Lambda$

Renormalization Group Equation:

$$\frac{d\Lambda(\mu)}{d \ln \mu} = \frac{1}{(4\pi)^2} \left[ \sum_i C_i \mu^2 + \sum_i D_i \frac{\mu^4}{M_i^2} + \ldots \right]$$
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After identifying \( \mu \) with the Hubble function and integrating we find:

\[ \Lambda(t) = c_0 + \sum_{k=1} \alpha_k H^{2k}(t) + \sum_{k=1} \beta_k \dot{H}(t) \]

Some References:

**β function for Λ**

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**LOW-ENERGY LIMIT**

\[
\Lambda(H) = C_0 + C_H H^2 + C_H \dot{H}
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---

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The higher derivative terms are important during inflation. See the references:

RVM model. Background solutions

We consider $\Lambda(H) = 3(c_0 + \nu H^2)$ interacting with dark matter.
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\[
\begin{align*}
\dot{\rho}_{dm} + 3H\rho_{dm} &= Q, \\
3H^2 &= 8\pi G(H) \left( \rho_m + \rho_r + \rho_{\Lambda}(H) \right)
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with

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Q = -\dot{\rho}_\Lambda = \nu H (3\rho_{dm} + 3\rho_b + 4\rho_r)
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Q = -\dot{\rho}_{\Lambda} = \nu H (3\rho_{dm} + 3\rho_b + 4\rho_r)
\]

\[
\xi = 1 - \nu
\]

\[
E^2(a) = 1 + \frac{\Omega_m^{(0)}}{\xi} (a^{-3\xi} - 1) + \Omega_r^{(0)} (a^{-4} - 1) + \frac{\nu \Omega_r^{(0)}}{4 - 3\xi} \left[ 3(1 - a^{-4}) + \frac{4}{\xi} (a^{-3\xi} - 1) \right]
\]
RVM model. Background solutions

Energy densities

Radiation
\[ \rho_r = \rho_r^{(0)} a^{-4} \]

Baryons
\[ \rho_b = \rho_b^{(0)} a^{-3} \]

Dark matter
\[ \rho_{dm} = \rho_{dm}^{(0)} a^{-3\xi} + \rho_b^{(0)} (a^{-3\xi} - a^{-3}) + \frac{4\nu \rho_r^{(0)}}{3\xi - 4} (a^{-4} - a^{-3\xi}) \]

Vacuum
\[ \rho_\Lambda = \rho_\Lambda^{(0)} + \frac{\nu}{\xi} (\rho_{dm}^{(0)} + \rho_b^{(0)}) + \frac{\nu \rho_r^{(0)}}{4 - 3\xi} \left[ \frac{1}{4} (a^{-4} - 1) + \frac{\nu}{\xi} (a^{-3\xi} - 1) \right] \]
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\[ \rho_\Lambda = \rho_\Lambda^{(0)} + \frac{\nu}{\xi} (\rho_{dm}^{(0)} + \rho_b^{(0)}) + \frac{\nu \rho_r^{(0)}}{4 - 3\xi} \left[ \frac{1}{4} (a^{-4} - 1) + \frac{\nu}{\xi} (a^{-3\xi} - 1) \right] \]

Of course, all the background functions reduce to the ΛCDM ones in the limit \( \nu = 0 \).
RVM model. Linear structure formation

The differential equation that governs the behavior of the matter perturbations at the linear level is:

\[
D''(a) + \left[ \frac{3}{a} + \frac{H'(a)}{H(a)} + \frac{\Psi(a)}{aH(a)} \right] D'(a) - \left[ \frac{4\pi G \rho_m(a)}{H^2(a)} - \frac{2\Psi(a)}{H(a)} - a \frac{\Psi'(a)}{H(a)} \right] \frac{D(a)}{a^2} = 0
\]

with

\[
\Psi \equiv -\frac{\dot{\rho}_\Lambda}{\rho_m}
\]

Initial conditions (\(z=100\)):

\[
\begin{align*}
s &= 3\xi - 2 \\
\delta_m(a_i) &= a_i^s \\
\delta_m'(a_i) &= sa_i^{s-1}
\end{align*}
\]
Fitting analysis

Cosmological observables used in the fitting analysis:

1. JLA set of Ia supernovae of Betoule et al. (2014).

\[ \mu = m - M = 5 \log d_L + 25 \]
\[ d_L(z, p) = c(1 + z) \int_0^z \frac{dz'}{H(z')} \]

2. BAO data

3. CMB R shift parameter and acoustic length with the covariance matrix of the compressed likelihood analysis for Planck 2015 TT+TE+EE+lowP data.
Fitting analysis

4. 30 Hubble points obtained with the differential age method.

5. LSS formation data

<table>
<thead>
<tr>
<th>Survey</th>
<th>$z$</th>
<th>$f(z)\sigma_0(z)$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>6dFGS</td>
<td>0.067</td>
<td>0.423 ± 0.055</td>
<td>[30]</td>
</tr>
<tr>
<td>SDSS-DR7</td>
<td>0.10</td>
<td>0.37 ± 0.13</td>
<td>[31]</td>
</tr>
<tr>
<td>GAMA</td>
<td>0.18</td>
<td>0.29 ± 0.10</td>
<td>[32]</td>
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<tr>
<td></td>
<td>0.38</td>
<td>0.44 ± 0.06</td>
<td>[33]</td>
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<tr>
<td>DR12 BOSS (2015)</td>
<td>0.32</td>
<td>0.392 ± 0.061</td>
<td>[19]</td>
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<tr>
<td></td>
<td>0.57</td>
<td>0.445 ± 0.038</td>
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<td>DR12 BOSS* (2016)</td>
<td>0.32</td>
<td>0.427 ± 0.052</td>
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<td>WiggleZ</td>
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<td>[34]</td>
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<tr>
<td></td>
<td>0.41</td>
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<tr>
<td>VIPERS</td>
<td>0.7</td>
<td>0.380 ± 0.065</td>
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<td>VVDS</td>
<td>0.77</td>
<td>0.49 ± 0.18</td>
<td>[37],[38]</td>
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<tr>
<td>SDSS-I/II/III</td>
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<td>0.408 ± 0.055</td>
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<tr>
<td></td>
<td>0.6</td>
<td>0.433 ± 0.066</td>
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</table>
Main results. Best-fit values

<table>
<thead>
<tr>
<th>Model</th>
<th>$h$</th>
<th>$\omega_b = \Omega_b h^2$</th>
<th>$n_s$</th>
<th>$\Omega_m$</th>
<th>$\nu_i$</th>
<th>$\varepsilon^2_{\text{min/df}}$</th>
<th>$\Delta\text{AIC}$</th>
<th>$\Delta\text{BIC}$</th>
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<tr>
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<td>$0.309 \pm 0.005$</td>
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<td>99.84/86</td>
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<td>-</td>
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<td>RVM</td>
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<td>25.44</td>
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<td>$0.00206 \pm 0.00053$</td>
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<td>$Q_A$</td>
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<td>$0.297 \pm 0.004$</td>
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Phenomenological models:

\[ Q_{dm} : \quad Q_{dm} = 3\nu_{dm} H \rho_{dm} \]

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Main results. Best-fit values

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<tr>
<th>Model</th>
<th>$h$</th>
<th>$\omega_b = \Omega_b h^2$</th>
<th>$n_s$</th>
<th>$\Omega_m$</th>
<th>$\nu_i$</th>
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<td>$\Lambda$CDM</td>
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Phenomenological models:

- Model $Q_{dm}$: $Q_{dm} = 3\nu_{dm} H \rho_{dm}$
- Model $Q_A$: $Q_A = 3\nu_A H \rho_A$

Recall that...

RVM: $Q = \nu H (3\rho_{dm} + 3\rho_b + 4\rho_r)$
The Akaike and Bayesian information criteria

• Model selection criteria
• They penalize the use of extra parameters in the model
• Given two competing models describing the same data, the model that does better is the one with smaller AIC and BIC values.
• For $N$ observational points and $n$ fit parameters they read:

$$AIC = \chi^2_{\text{min}} + 2nN/(N-n-1)$$

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BIC criterion is more stringent than the AIC
The Akaike information criterion

\[(\Delta \text{AIC})_{ij} = (\text{AIC})_i - (\text{AIC})_j.\]

\[\Delta_{ij} \equiv |\Delta (\text{AIC})_{ij}|\]

Rule of thumb:

• \(\Delta_{ij} < 2\) no evidence
• \(6 \geq \Delta_{ij} \geq 2\) strong evidence
• \(6 \leq \Delta_{ij}\) very strong evidence
The Bayesian information criterion

\[ \Delta(BIC)_{ij} = (BIC)_i - (BIC)_j \quad \Delta_{ij} \equiv |\Delta(BIC)_{ij}| \]

Rule of thumb:

- \( \Delta_{ij} < 2.5 \) no evidence
- \( 5 \geq \Delta_{ij} \geq 2.5 \) weak evidence
- \( 10 \geq \Delta_{ij} \geq 5 \) strong evidence
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Main results. Best-fit values

Evidence in favour of the dynamical vacuum models!

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The dynamical vacuum models are able to fit the linear structure formation data better.
Main results. Contour lines

ΛCDM is disfavored at ≈4σ c.l.
Summary

1. We have analyzed some dynamical vacuum models. We have focused our attention on the RVM, in which the vacuum energy density depends functionally on the Hubble rate. It is motivated from RG arguments in QFT in curved space-time.

2. These kind of models are able to fit considerably better the current observational data than the concordance $\Lambda$CDM one at a confidence level of 4$\sigma$.

3. If dark energy is vacuum-like, then the data strongly prefer a mildly evolving $\Lambda$. 
Thank you very much for your attention