Quantum vacuum, a cosmic chameleon

Based on C. Moreno-Pulido, J. Solà Peracaula 2005.03164, 2201.05827 & 2207.07111; J. Solà Peracaula 2203.13757

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Introduction

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- Cosmological tensions are a motivation for new physics. Looking from different directions.
- Cosmological principle permits VED to be a function $\rho_{\rm vac}(\chi(t))$, where $\chi(t)$ is a dynamical variable.
- VED faces vast theoretical problems, "the CC problem" regarding the $\sim m^4$ terms.

$$\rho_{\rm vac}^{\rm obs}/\rho_{ZPE} \sim \rho_{\rm vac}^{\rm obs}/m_e^4 \sim 10^{-34}. \tag{1}$$

and "the coincidence problem",

$$\rho_{\rm vac}^0 \sim \rho_{\rm m}^0. \tag{2}$$

Running Vacuum Models

Running Vacuum Models

- Family of parametrizations of VED with long trajectory in literature. The Canonical RVM is

$$\rho_{\rm vac}(H) = \frac{3}{8\pi G_N}\left(C_0 + \nu H^2\right), \tag{3}$$

where $|\nu| \ll 1$.

- Similar models have been explored. [1]
- In particular, the RRVM was recently tested

$$\rho_{\rm vac}(R) = \frac{3}{8\pi G_N}\left(c_0 + \frac{\nu}{12}R\right), \tag{4}$$

with $R = 12H^2 + 6\dot{H}$ is the Ricci scalar.

[1] J. Solà Peracaula *et al* 1602.02103, 1703.08218, 1705.06723, 2102.12758.

Running Vacuum Models

- For type I models with threshold, $\rho_{\rm m} \approx \rho_{\rm m}^0 a^{-3+3\frac{\nu}{4}}$,

$$\rho_{\rm vac}(a) = \begin{cases} \rho_{\rm vac}^0 + \frac{\nu}{4}\rho_m^0(a^{-3} - 1) & , \quad a > a_{th}, \\ \rho_{\rm vac}(a_{th}) & , \quad a < a_{th}. \end{cases} \tag{5}$$

  Recent activation of the dynamics of DE.

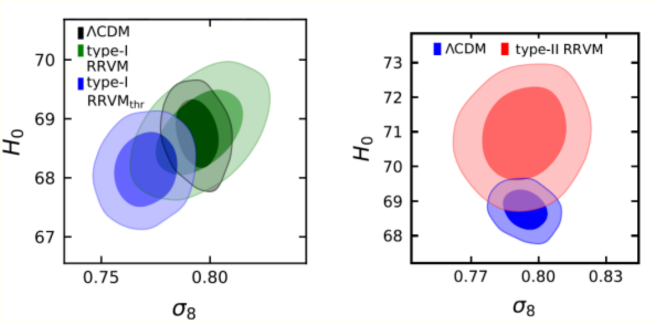
- For type II, $G(a) \sim 1 + \epsilon \ln a$, with $\epsilon \sim \mathcal{O}(\nu)$, and

$$\rho_{\rm vac}(a) \approx \frac{3c_0}{8\pi G_N}(1 + 4\nu) + \nu\rho_m^0 a^{-3}, \tag{6}$$

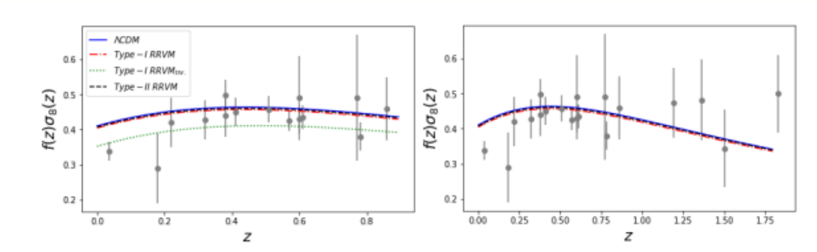
  The initial value of G considered a free parameter.

Running Vacuum Models

Since $\dot{\rho}_{\rm vac} \neq 0$ the perturbation equations are affected producing a departure from ΛCDM. Confronted against *SnIa* + *BAO* + $H(z)$ + $f\sigma_8(z)$ + *Planck* data.



Running Vacuum Models



- The Type I model with threshold has a bigger impact on solving the σ_8 tension.
- The Type II model seems to be able to alleviate the H_0 tension without altering the σ_8 one.
- There were no strong theoretical grounds from QFT or quantum gravity supporting them.

Renormalization of Vacuuum Energy

Renormalization of Vacuum Energy

- We start with EH action+ρ_Λ. For simplicity, in the matter sector only a scalar field ϕ,

$$S = -\int dx^4 \sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\nu\phi\partial_\mu\phi + \frac{1}{2}(m^2 + \xi R)\phi^2\right) \quad (7)$$

  where ξ is a non-minimal coupling.
- With a flat FLRW background, $g_{\mu\nu} = a^2 diag(-1, 1, 1, 1)$.
- Splitting the field in a background part and in a fluctuating part

$$\phi(\tau, \mathbf{x}) = \phi(\tau) + \delta\phi(\tau, \mathbf{x}). \quad (8)$$

Renormalization of Vacuum Energy

- The Fourier decomposition in modes is

$$\delta\phi(\tau, \mathbf{x}) = \frac{1}{(2\pi)^{(3/2)}\, a} \int dk^3 \left[A_k e^{i\mathbf{kx}} h_k(t) + A_k^\dagger e^{-i\mathbf{kx}} h_k^*(t)\right], \tag{9}$$

  with usual commutation relations.
- KG eq: $h_k'' + \Omega_k^2 h_k = 0, \Omega_k \equiv k^2 + a^2 m^2 + a^2 (\xi - 1/6) R$
- Traditional solution: WKB ansatz and recursive iterations,

$$h_k(\tau) \sim W_k^{-1/2}(\tau) e^{-i \int_1^\eta W_k(\tau_1) d\tau_1}, \tag{10}$$

  such that $W_k^2 = \Omega_K^2 - \frac{1}{2}\frac{W_k''}{W_k} + \frac{3}{4}\left(\frac{W_k'}{W_k}\right)^2$

Renormalization of Vacuum Energy

- Background evolving slowly. Solution is organized in what we call adiabatic orders $\equiv$ number of time derivatives.
- We can use conjecture the renormalized Zero-Point Energy:

$$\langle T_{00}^{\delta\phi}\rangle_{\rm ren}(M) \equiv \langle T_{00}^{\delta\phi}\rangle(m) - \langle T_{00}^{\delta\phi}\rangle^{(0-4)}(M)$$
$$= \frac{a^2}{128\pi^2}\left(-M^4 + 4m^2M^2 - 3m^4 + 2m^4 \log\frac{m^2}{M^2}\right)$$
$$- \frac{3a^2H^2\left(\xi - \frac{1}{6}\right)}{16\pi^2}\left(m^2 - M^2 - m^2\log\frac{m^2}{M^2}\right) + \mathcal{O}\left(H^4, \frac{H^6}{m^2}, \dots\right) \tag{11}$$

M is an arbitrary off-shell mass scale.

Renormalization of Vacuum Energy

- We define

$$\langle T_{\mu\nu}^{\rm vac}\rangle(M) \equiv -\rho_\Lambda(M) g_{\mu\nu} + \langle T_{\mu\nu}^{\delta\phi}\rangle_{\rm ren}(M) \tag{12}$$

In plain words "$VED = ZPE + \Lambda$",

$$\rho_{\rm vac}(M) = \frac{\langle T_{00}^{\delta\phi}\rangle_{\rm ren}(M)}{a^2} + \rho_\Lambda(M). \tag{13}$$

- Set $M = H$ and do the subtraction at two different scales,

$$\rho_{\rm vac}(H) = \rho_{\rm vac}(H_0) + \frac{3\nu_{\rm eff}}{8\pi}\left(H^2 - H_0^2\right) m_{Pl}^2 + \mathcal{O}(H^4), \tag{14}$$

where $\nu_{\rm eff} \equiv \frac{\left(\xi - \frac{1}{6}\right)}{2\pi}\frac{m^2}{m_{Pl}^2}\ln\frac{m^2}{H_0^2}$ is expected to be small.

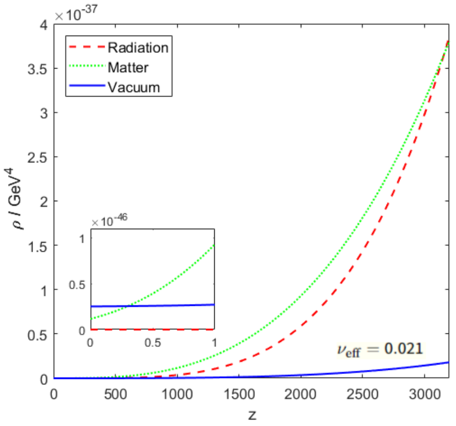
Chameleonic VED

Chameleonic VED

- Mild dynamics: Two values, at H_1, H_2, of the vacuum energy in the late times are smoothly related through $\sim \nu_{eff} m_{Pl}^2 (H_1^2 - H_2^2)$.
- Running free from $\sim m^4$ terms.
- Gravitational constant is also shown to be running (logarithmically),

$$G(H) \approx \frac{G(H_0)}{1 - \nu_{\rm eff} \frac{\ln H^2/H_0^2}{\ln m^2/H_0^2}}. \tag{15}$$

Chameleonic VED



Evolution of the energy densities for $\nu_{\text{eff}} = 0.02, \Omega_m^0 = 0.32, \Omega_r^0 = 0.0001.$

Chameleonic VED

- Analogously one may compute the associated vacuum pressure. One can infer the equation of state:

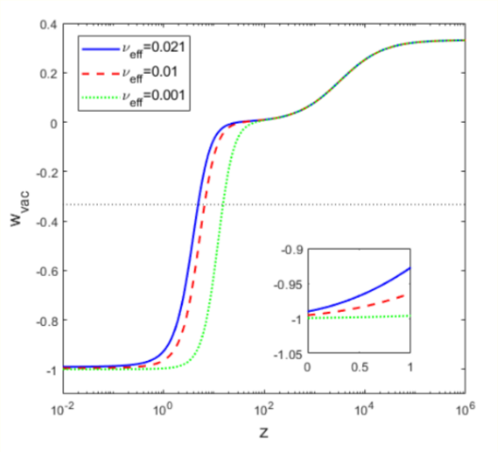
$$1 + w_{\rm vac}(z) \approx \frac{\nu_{\rm eff}\left(\Omega_m^0(1+z)^3 + \frac{4}{3}\Omega_r^0(1+z)^4\right)}{\Omega_{\rm vac}^0 + \nu_{\rm eff}\left[-1 + \Omega_m^0(1+z)^3 + \Omega_r^0(1+z)^4 + \Omega_{\rm vac}^0\right]}. \quad (16)$$

- Vacuum Energy has a chameleonic EoS, mimicking the dominant component.
- It behaves as Dark Energy ($w_{\rm vac} < -0.33$) for low redshifts,

$$w_{\rm vac}(z) = -1 + \nu_{\rm eff}\frac{\Omega_m^0}{\Omega_{\rm vac}}(1+z)^3, \quad (17)$$

Eventually $w_{\rm vac} = -1$ if $z \to -1$.

Chameleonic VED



The VED has a quintessence behaviour for $\nu_{\text{eff}} > 0$.

Conclusions and Future works

Conclusions and Future works

- We presented a computation of VED from QFT in curved spacetime.
- VED is mildly dynamical in the late universe. G is expected to vary logarithmically.
- The EoS for vacuum is not -1 along the whole story, mimics the dominant component and behaves as quintessence DE in the late universe.
- The higher powers in the adiabatic expansion may have an interesting role in the primeval era.
- All in all, the extra features of the VED may alleviate the σ_8 and H_0 tension, but should be contrasted with data.

THANKS!!

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