Cosmological interaction of vacuum energy and dark matter

Clara Hormigos Feliu

Universitat de Barcelona

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Outline

- Introduction
- Approach
- Results
- Conclusions

Current densities

- Barionic matter: $\Omega_b \simeq 0.05$
- Dark matter (DM): $\Omega_c \simeq 0.24$
- Dark energy (DE): $\Omega_D \simeq 0.72$

WMAP Collaboration, 2013

Equation of state of DE ($p_D = \omega_D \rho_D$): $\omega_D = -1.006 \pm 0.045$

Planck Collaboration, 2015

Dark energy

Possible descriptions:

- Cosmological constant, Λ ($\omega_\Lambda = -1$)
  ΛCDM description

- Modified gravity

- Scalar fields:
  - Quintessence ($\omega_\phi > -1$)
  - Phantom fields ($\omega_\phi < -1$)

- **Dynamic vacuum**
  Evolving Λ, $\omega_D(z)$

Dark energy as a dynamic vacuum

- Friedmann's equations take the known form:

$$3H^2 = 8\pi G(a)\Big(\rho_m + \rho_r + \rho_\Lambda(a)\Big) \quad (1)$$

$$3H^2 + 2\dot{H} = -8\pi G(a)\Big(\frac{\rho_r}{3} - \rho_\Lambda(a)\Big), \quad (2)$$

  with $\rho_\Lambda(a) = \frac{\Lambda(a)}{8\pi G(a)}$.
- Need to postulate the evolution of $\rho_\Lambda(a)$
- Possible coupling of ρ_Λ to ρ_m and G

Approach

- Find evolution of densities, H and G
- Identify possible anomalous conservation laws

and also...

- Find an effective equation of state (EoS) for dark energy

Studied models

$$\rho_\Lambda(H;\nu,\alpha) = \frac{3}{8\pi G}\left(c_0 + \nu H^2 + \frac{2}{3}\alpha\dot{H}\right) \tag{3}$$

Solà *et al*, 2015 & 2016

- Type G: evolving G, ΛCDM evolution of ρ_m, ρ_r
- Type A: $G = const.$, modified evolution of ρ_m, ρ_r

$$\dot{\rho}_\Lambda = -q_V H \rho_\Lambda \tag{4}$$

Salvatelli *et al*, 2014

- Type S, S' (different fits)

Effective equation of state

- Comparison with scalar field EoS (not interacting with dark matter)
- Impose equality of the models' Hubble functions,

$$E^2(z) = \Omega_m^0 f_m(z, r_i)(1+z)^{\alpha_m} + \Omega_\Lambda^0 f_\Lambda(z, r_i)\,, \tag{5}$$

with theoretical scalar field Hubble function:

$$E_D^2(z) = \tilde{\Omega}_m^0 (1+z)^{\alpha_m} + \tilde{\Omega}_D^0 \zeta(z)\,. \tag{6}$$

- Obtain $\omega_D(z)$

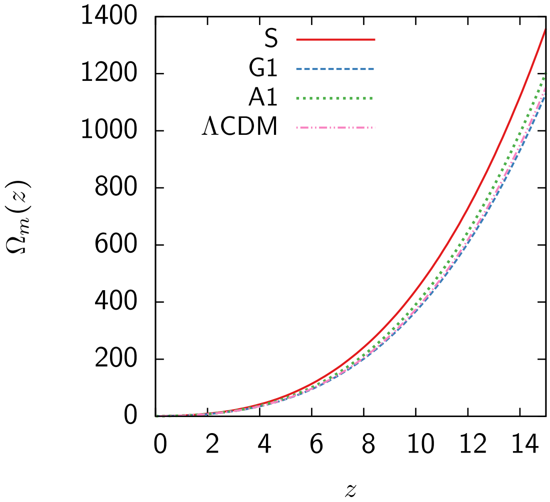
Basilakos & Solà, 2013

Conservation laws

- Type G: $\dot{G}(\rho_m + \rho_r + \rho_\Lambda) + G\dot{\rho}_\Lambda = 0$
  - ρ_m and ρ_r follow conventional conservation laws
  - Coupling to G is essential for a dynamic vacuum

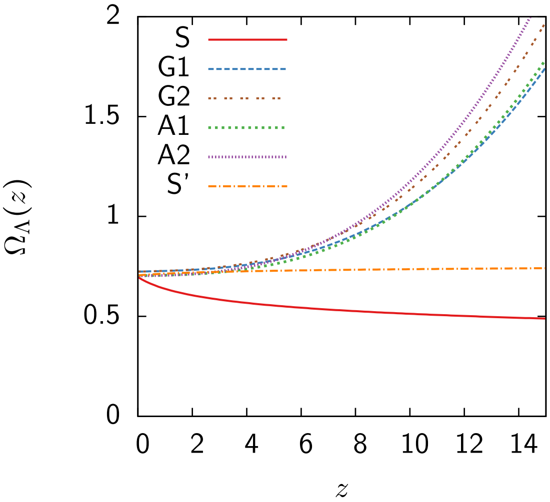
- Type A and S: $\dot{\rho}_m + \dot{\rho}_r + 3H(\rho_m + \rho_r) = -\dot{\rho}_\Lambda$
  - Anomalous matter conservation laws
  - Dynamic vacuum couples to matter

Normalized matter density



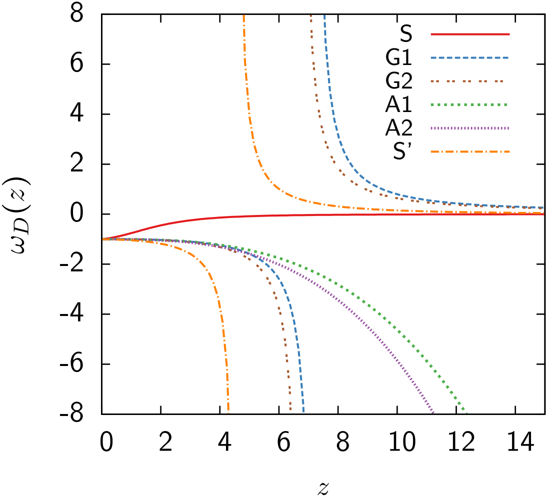
- Evolution close to ΛCDM

Normalised vacuum density



- Evolution differs from ΛCDM ($\Omega_\Lambda \simeq 0.7$)

Effective equation of state



Effective behavior:

- Phantom field-like: G, A (S')
- Quintessence-like: S

Conclusions

- Dynamical vacuum models provide an alternative explanation of dark energy with
  - No need for external fields
  - Significant improvement when fit to data
- Need to postulate an evolution of ρ_Λ
- Introducing a dynamical vacuum leads to anomalous conservation laws
- Effective EoS can differ from ΛCDM and explain possible $\omega_D \neq -1$

Thank you for your attention

Normalised vacuum density

ΛCDM:
$\Omega_\Lambda(z) = \Omega_\Lambda^0 \simeq 0.7$

Type G:
$\Omega_\Lambda(z) = (1+z)^3\Big((1+z)^{-3\xi}(1-\frac{\Omega_m^0}{\xi}) + \Omega_m^0(\xi^{-1}-1)\Big)$

Type A:
$\Omega_\Lambda(z) = \Omega_\Lambda^0 + \Omega_m^0(\xi^{-1}-1)((1+z)^{3\xi}-1)$

Type S:
$\Omega_\Lambda(z) = \Omega_\Lambda^0(1+z)^{q_V}$

Akaike and Bayesian criteria with respect to ΛCDM

Model	ΔAIC	ΔBIC
RVM (G,A)	27.66	25.44
Q_Λ (S)	17.13	14.91

Solà, De Cruz Pérez, Gómez-Valent, Nunes (2016)

ΔAIC, ΔBIC $= 6 - 10 \rightarrow$ "strong evidence" against ΛCDM
ΔAIC, ΔBIC $> 10 \rightarrow$ "very strong evidence" against ΛCDM

Evolution of ρ_Λ

- "Running constant", QFT

$$\frac{d\rho_\Lambda}{d\ln\mu^2} = \frac{1}{4\pi}\sum_i \left[a_i M_i^2 \mu^2 + b_i \mu^4 + \frac{c_i \mu^6}{M_i^2} + ...\right] \tag{7}$$

$$\mu \sim H$$

Solà, 2016. arXiv:1601.01668v2

FLRW metric:

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1 - Kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right) \tag{8}$$

Field equations:

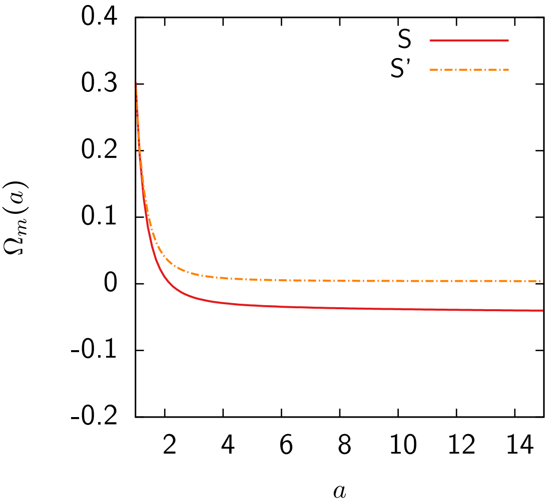
$$R_{\mu\nu} - \frac{1}{2}R = 8\pi G\tilde{T}_{\mu\nu}\,, \qquad \tilde{T}_{\mu\nu} \equiv T_{\mu\nu} + g_{\mu\nu}\rho_\Lambda \tag{9}$$

Bianchi identities:

$$\nabla^\mu\left(G\tilde{T}_{\mu\nu}\right) = 0 \tag{10}$$

Local conservation law:

$$\frac{d}{dt}\left(G\rho\right) + 3GH(\rho + p) = 0 \quad (11)$$



Evolution of the normalized non-relativistic matter density with the scale factor for model S.