Anisotropic Solid Dark Energy

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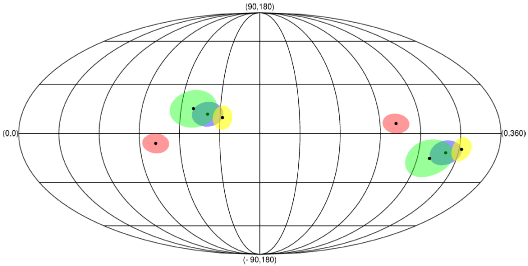
Motivations

- CMB and LSS observations allow the existence of anomalies.
- Anomalies in the peculiar velocities, LQG, anisotropy in the cosmic expansion rate.
- Nature of Dark energy.



arXiv:1401.5044

The solid like model

The standard homogeneous scalar field

$$\langle \phi \rangle \equiv \phi(t)$$

The broken symmetry

$$\phi'(t') \rightarrow \phi(t) + \tau$$

The solid like model

$$\langle \phi^I \rangle \equiv c_I x^I.$$

The broken symmetries

$$\phi'^I \rightarrow \phi^I + a^I,$$
$$\phi'^I \rightarrow \sum_J O^I_J \phi^J.$$

arXiv:0705.1167, arXiv:1210.0569

The model

The action

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{m_{\mathrm{P}}^2}{2}R-\sum_I F^I\left(\Phi^I\right)+\mathcal{L}_r+\mathcal{L}_m\right]\,,\;I=1,2,3\,.$$

The Bianchi-I metric

$$ds^2=-\mathrm{d}t^2+a^2(t)\left(e^{2\beta_1(t)}\mathrm{d}x^2+e^{2\beta_2(t)}\mathrm{d}y^2+e^{2\beta_3(t)}\mathrm{d}z^2\right)\,,$$

The building blocks

$$\Phi^I=g^{\mu\nu}\nabla_\mu\phi^I\nabla_\nu\phi^I=g^{II}\,,$$

The restriction

$$\sum_I\beta_I(t)=0\,,$$

The axi-symmetric Bianchi-I metric

The anisotropy parameters

$$\beta_1(t) \equiv -2\sigma(t),$$
$$\beta_2(t) = \beta_3(t) = \sigma(t),$$

The solid lagrangian

$$\sum_I F^I\left(\Phi^I\right) = F^1\left(\Phi^1\right) + 2F^2\left(\Phi^2\right),$$

The field equations

$$3\,m_{\mathsf{P}}^2 H^2 = F^1 + 2F^2 + \rho_m + \rho_r + 3\,m_P^2\,\dot{\sigma}^2\,,$$
$$-2\,m_{\mathsf{P}}^2 \dot{H} = \frac{2}{3}\Phi^1 F_\Phi^1 + \frac{4}{3}\Phi^2 F_\Phi^2 + \rho_m + \frac{4}{3}\rho_r + 6\,m_{\mathsf{P}}^2\,\dot{\sigma}^2\,,$$
$$m_{\mathsf{P}}^2\ddot{\sigma} + 3m_{\mathsf{P}}^2 H\dot{\sigma} = \frac{2}{3}\left(\Phi^2 F_\Phi^2 - \Phi^1 F_\Phi^1\right)\,.$$

The autonomous system

The variables of the system

$$f_1^2 \equiv \frac{F^1}{3m_{\mathsf{P}}^2 H^2}\,, \quad f_2^2 \equiv \frac{F^2}{3m_{\mathsf{P}}^2 H^2}\,, \quad \Sigma \equiv \frac{\dot{\sigma}}{H}\,, \quad \Omega_m \equiv \frac{\rho_m}{3m_{\mathsf{P}}^2 H^2}\,, \quad \Omega_r \equiv \frac{\rho_r}{3m_{\mathsf{P}}^2 H^2}\,.$$

The constraint in the variables

$$f_1^2 + 2f_2^2 + \Sigma^2 + \Omega_r + \Omega_m = 1\,.$$

The model assumed

$$F^1 \propto \left(\Phi^1\right)^n\,, \quad F^2 \propto \left(\Phi^2\right)^m\,.$$

The EoS of DE

$$w_{\mathsf{DE}} = -1 + \frac{2}{3}\frac{n f_1^2 + 2m f_2^2 + 3\Sigma^2}{(f_1^2 + 2f_2^2 + \Sigma^2)}\,.$$

The autonomous system

The deceleration parameter

$$q \equiv -\ddot{a}a/\dot{a}^2 = \frac{1}{2}\left[1 + (2n-3)f_1^2 + 2(2m-3)f_2^2 + \Omega_r + 3\Sigma^2\right] ,$$

The autonomous system

$$\begin{aligned} f_1' &= f_1\left[q + 1 - n\left(1 - 2\Sigma\right)\right] , \\ f_2' &= f_2\left[q + 1 - m\left(1 + \Sigma\right)\right] , \\ \Sigma' &= \Sigma(q-2) + 2\left(m f_2^2 - n f_1^2\right) , \\ \Omega_r' &= 2\Omega_r(q-1) , \end{aligned}$$

The fixed points

The relevant radiation and matter fixed points

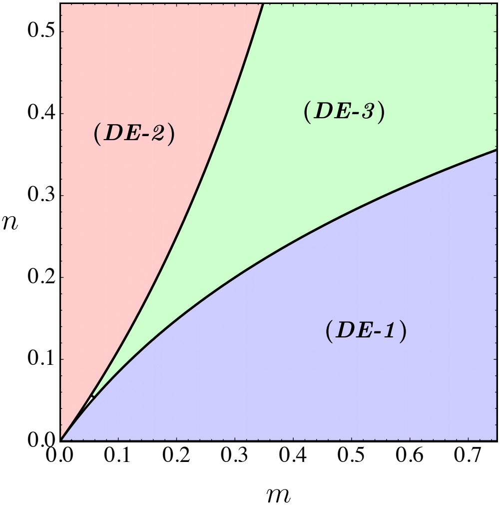
- $(R-1)$ isotropic radiation domination: $\Omega_r = 1, w_{eff} = \frac{1}{3}$.
- $(M-1)$ isotropic matter domination: $\Omega_m = 1, w_{eff} = 0$.

The fixed points

The relevant DE fixed points

- $(DE-1)$ anisotropic DE sourced by f^1:
  $f_1 = \frac{\sqrt{3\,(n+3)(1-n)}}{3-n}, \Sigma = \frac{2n}{n-3}, w_{eff} = -1 + \frac{2n(3+n)(1-n)+8n^2}{(3-n)^2}$.
- $(DE-2)$ anisotropic DE sourced by f^2:
  $f_2 = \frac{\sqrt{3\,(3/2-m)}}{3-m}, \Sigma = \frac{m}{m-3}, w_{eff} = -1 + \frac{2m}{3-m}$.
- $(DE-3)$ anisotropic DE sourced by f^1 and f^2:
  $f_1 = \frac{\sqrt{3(m-n+mn)}}{m+2n}, f_2 = \frac{\sqrt{3(n^2+mn-m+n)}}{\sqrt{2}(m+2n)}, \Sigma = \frac{n-m}{m+2n}$,
  $w_{eff} = -1 + \frac{2mn}{m+2n}$.

Existence and stability conditions

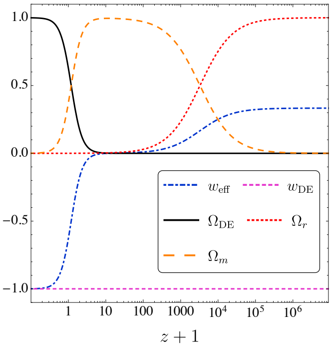


The numerical evolution

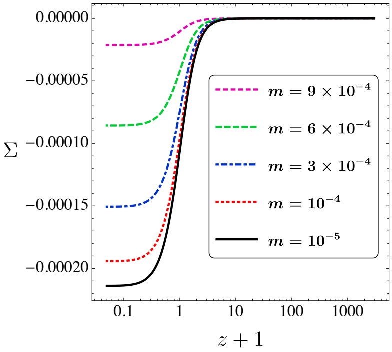
The initial conditions

$$\Omega_{r_i} = 0.99995\,, \quad f_{1_i} = 10^{-14}\,, \quad f_{2_i} = 10^{-14}\,, \quad \Sigma_i = 0\,,$$

The abundance evolution



The shear evolution



Conclusions

- The late-time cosmic acceleration can be successfully supported by the solid DE model.
- Anisotropic DE is an attractor.
- The solid DE model can reproduce the right evolution of the universe: radiation (isotropic) $\rightarrow$ matter (isotropic) $\rightarrow$ DE (anisotropic).
- The EoS of the DE is almost constant throughout the whole evolution.