Doubly Coupled Quintessence

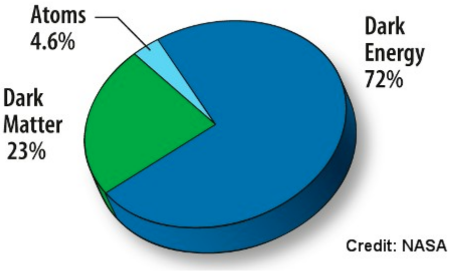
Mikjel Thorsrud

24th Sep, 2012

arxiv:1205.6261

"Cosmology of a scalar field coupled to matter and an isotropy-violating Maxwell field",
M. Thorsrud, D.F. Mota, S. Hervik, (2012, arxiv:1205.6261).

Cosmology



Coupled Quintessence

Doubly Coupled Quintessence:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \mathcal{L}_M(h^2(\phi)g_{\mu\nu}, \Psi_i) - \frac{1}{4}f^2(\phi)F_{\mu\nu}F^{\mu\nu}\right],$$

where:

$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu.$$

Field equations

Local energy and momentum conservation:

$$\nabla_\mu \left(T^{\mu(\phi)}_\nu + T^{\mu(A)}_\nu + T^{\mu(M)}_\nu \right) = 0$$

Matter field equations:

$$\nabla_\mu T^{\mu(\phi)}_\nu = -Q_A 2\mathcal{L}_A \nabla_\nu \phi - Q_M T_M \nabla_\nu \phi,$$
$$\nabla_\mu T^{\mu(A)}_\nu = +Q_A 2\mathcal{L}_A \nabla_\nu \phi,$$
$$\nabla_\mu T^{\mu(M)}_\nu = +Q_M T_M \nabla_\nu \phi.$$

Field equations

Local energy and momentum conservation:

$$\nabla_\mu \left(T^{\mu(\phi)}_{\nu} + T^{\mu(A)}_{\nu} + T^{\mu(M)}_{\nu} \right) = 0$$

Matter field equations:

$$\begin{aligned}
\nabla_\mu T^{\mu(\phi)}_{\nu} &= -Q_A 2\mathcal{L}_A \nabla_\nu \phi - Q_M T_M \nabla_\nu \phi, \\
\nabla_\mu T^{\mu(A)}_{\nu} &= +Q_A 2\mathcal{L}_A \nabla_\nu \phi, \\
\nabla_\mu T^{\mu(M)}_{\nu} &= +Q_M T_M \nabla_\nu \phi.
\end{aligned}$$

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Motivation

- The scalar-matter coupling is studied extensively in the literature, see e.g. Amendola 1999 (arxiv:9908023) and Copeland et.al. 2006 (arxiv:0603057).
- The scalar-Maxwell coupling is studied so far only in the context of early universe inflation, see e.g. Soda 2012 (arxiv:1201.6434).
- In effective four-dimensional actions, typically both couplings are present simultaneously.
- Historically first example: Kaluza & Klein almost a century ago.
- Very common in modern higher dimensional theories such as string theories.
- Want to understand the cosmological consequences of this scenario.

Doubly Coupled Quintessence

Doubly Coupled Quintessence:

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \mathcal{L}_M(h^2(\phi)g_{\mu\nu}, \Psi_i) - \frac{1}{4}f^2(\phi)F_{\mu\nu}F^{\mu\nu},$$

We consider:

$$V(\phi) = V_0 e^{\lambda\phi(t)}, \quad h(\phi) = e^{Q_M\phi(t)}, \quad f(\phi) = e^{Q_A\phi(t)}.$$

Parameter space:(λ, Q_M, Q_A)

Example: "Quintessence as a runaway dilaton", Gaspirini et.al. 2002 (arxiv:0108016).

and

$$A_\mu = (0, A_x(t), 0, 0)\,,$$
$$ds^2 = -dt^2 + a_\parallel^2(t)dx^2 + a_\perp^2(t)(dy^2 + dz^2),$$

Doubly Coupled Quintessence

Doubly Coupled Quintessence:

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \mathcal{L}_M(h^2(\phi)g_{\mu\nu}, \Psi_i) - \frac{1}{4}f^2(\phi)F_{\mu\nu}F^{\mu\nu},$$

We consider:

$$V(\phi) = V_0 e^{\lambda\phi(t)}, \quad h(\phi) = e^{Q_M\phi(t)}, \quad f(\phi) = e^{Q_A\phi(t)}.$$

Parameter space:(λ, Q_M, Q_A)

Example: "Quintessence as a runaway dilaton",

Gaspirini et.al. 2002 (arxiv:0108016).

and

$$A_\mu = (0, A_x(t), 0, 0)\,,$$
$$ds^2 = -dt^2 + a_\parallel^2(t)dx^2 + a_\perp^2(t)(dy^2 + dz^2),$$

Doubly Coupled Quintessence:

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \mathcal{L}_M(h^2(\phi)g_{\mu\nu}, \Psi_i) - \frac{1}{4}f^2(\phi)F_{\mu\nu}F^{\mu\nu},$$

We consider:

$$V(\phi) = V_0 e^{\lambda\phi(t)}, \quad h(\phi) = e^{Q_M\phi(t)}, \quad f(\phi) = e^{Q_A\phi(t)}.$$

Parameter space:(λ, Q_M, Q_A)

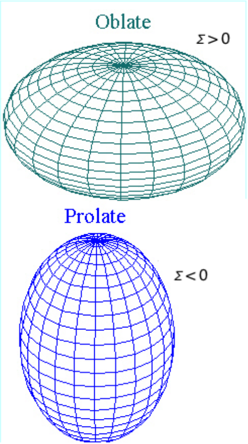
Example: "Quintessence as a runaway dilaton",

Gaspirini et.al. 2002 (arxiv:0108016).

and

$$A_\mu = (0, A_x(t), 0, 0)\,,$$
$$ds^2 = -dt^2 + a_{\|}^2(t)dx^2 + a_{\perp}^2(t)(dy^2 + dz^2),$$

Spacetime



Observational motivation

- CMB provides evidence that the universe is remarkably isotropic.
- Still interesting to consider deviations from the idealized model.
- Supernovae data allows anisotropy in the expansion rate at the one-percent level today (Campanelli et al., 2009).
- Several reported anomalies hints toward violation of isotropy.

Observational motivation

- CMB provides evidence that the universe is remarkably isotropic.
- Still interesting to consider deviations from the idealized model.
- Supernovae data allows anisotropy in the expansion rate at the one-percent level today (Campanelli et al., 2009).
- Several reported anomalies hints toward violation of isotropy.

Observational motivation

- CMB provides evidence that the universe is remarkably isotropic.
- Still interesting to consider deviations from the idealized model.
- Supernovae data allows anisotropy in the expansion rate at the one-percent level today (Campanelli et al., 2009).
- Several reported anomalies hints toward violation of isotropy.

Observational motivation

- CMB provides evidence that the universe is remarkably isotropic.
- Still interesting to consider deviations from the idealized model.
- Supernovae data allows anisotropy in the expansion rate at the one-percent level today (Campanelli et al., 2009).
- Several reported anomalies hints toward violation of isotropy.

Low CMB quadrupole

- ΛCDM expectation value:

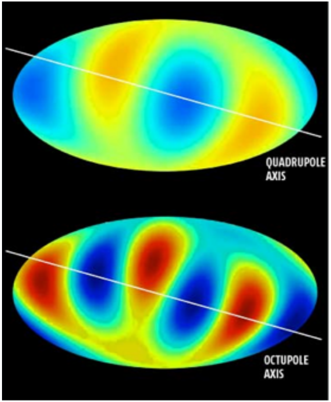
$$<\mathcal{Q}^2> \simeq 1200\mu K^2.$$

- WMAP:

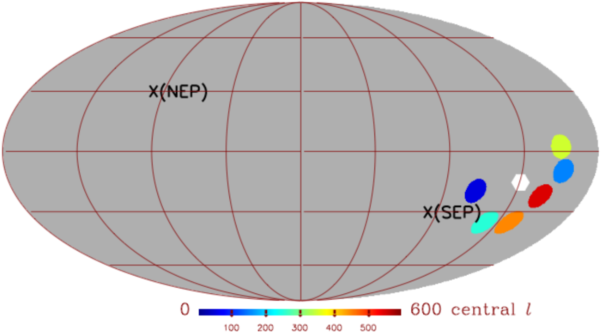
$$\mathcal{Q}^2 \simeq 200\mu K^2.$$

Axis of Evil

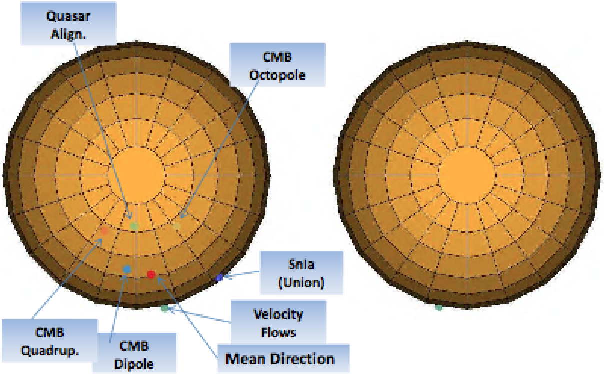
"Axis of Evil": Oliveira-Costa et.al. 2004 (arxiv:0307282), Schwarz et.al. 2004 (arxiv:0403353)



From F.K.Hansen et.al. 2009 (arXiv:0812.3795):



From L. Perivolaropoulos, 2011 (arXiv:1104.0539):



Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Summary

Remember just the following points:

- We are considering a very social scalar field interacting with both matter and a vector.
- Strength of matter coupling controlled by: Q_M.
- Strength of vector coupling controlled by: Q_A.
- Shape of potential of the scalar field controlled by: λ.
- Parameter space: (λ, Q_M, Q_A).

Phase space analysis

- Goal: to identify interesting regions of parameter space.
- Method: dynamical system analysis.
- Instead of focusing on particular solutions, we are first more interested in properties of the set of all solutions.
- After a qualitative understanding is achieved, we are certainly interested in quantitative aspects as well!
- In particular we are interested in solutions close to ΛCDM.

Phase space analysis

- Goal: to identify interesting regions of parameter space.
- Method: dynamical system analysis.
- Instead of focusing on particular solutions, we are first more interested in properties of the set of all solutions.
- After a qualitative understanding is achieved, we are certainly interested in quantitative aspects as well!
- In particular we are interested in solutions close to ΛCDM.

Phase space analysis

- Goal: to identify interesting regions of parameter space.
- Method: dynamical system analysis.
- Instead of focusing on particular solutions, we are first more interested in properties of the set of all solutions.
- After a qualitative understanding is achieved, we are certainly interested in quantitative aspects as well!
- In particular we are interested in solutions close to ΛCDM.

Phase space analysis

- Goal: to identify interesting regions of parameter space.
- Method: dynamical system analysis.
- Instead of focusing on particular solutions, we are first more interested in properties of the set of all solutions.
- After a qualitative understanding is achieved, we are certainly interested in quantitative aspects as well!
- In particular we are interested in solutions close to ΛCDM.

Phase space analysis

- Goal: to identify interesting regions of parameter space.
- Method: dynamical system analysis.
- Instead of focusing on particular solutions, we are first more interested in properties of the set of all solutions.
- After a qualitative understanding is achieved, we are certainly interested in quantitative aspects as well!
- In particular we are interested in solutions close to ΛCDM.

Dynamical system analysis

Introduce dimensionless variables:

- Energy parameters: $\Omega_i \equiv \frac{\rho_i}{3H^2}$,
- We consider: Ω_A, $\Omega_{\rm kin}$, $\Omega_{\rm V}$, Ω_m, Ω_r
- Shear degree of freedom: $\Sigma \equiv \frac{H_\perp - H}{H}$
- $\Sigma^2 + \Omega_A + \Omega_{\rm kin} + \Omega_V + \Omega_m + \Omega_r = 1$

Dynamical system analysis

Introduce dimensionless variables:

- Energy parameters: $\Omega_i \equiv \frac{\rho_i}{3H^2}$,
- We consider: Ω_A, $\Omega_{\rm kin}$, $\Omega_{\rm V}$, Ω_m, Ω_r
- Shear degree of freedom: $\Sigma \equiv \frac{H_\perp - H}{H}$
- $\Sigma^2 + \Omega_A + \Omega_{\rm kin} + \Omega_V + \Omega_m + \Omega_r = 1$

Introduce dimensionless variables:

- Energy parameters: $\Omega_i \equiv \frac{\rho_i}{3H^2}$,
- We consider: Ω_A, $\Omega_{\rm kin}$, $\Omega_{\rm V}$, Ω_m, Ω_r
- Shear degree of freedom: $\Sigma \equiv \frac{H_\perp - H}{H}$
- $\Sigma^2 + \Omega_A + \Omega_{\rm kin} + \Omega_V + \Omega_m + \Omega_r = 1$

Dynamical system analysis

Introduce dimensionless variables:

- Energy parameters: $\Omega_i \equiv \frac{\rho_i}{3H^2}$,
- We consider: Ω_A, Ω_{kin}, Ω_{V}, Ω_m, Ω_r
- Shear degree of freedom: $\Sigma \equiv \frac{H_\perp - H}{H}$
- $\Sigma^2 + \Omega_A + \Omega_{\text{kin}} + \Omega_V + \Omega_m + \Omega_r = 1$

Autonomous system

$$
\begin{aligned}
\frac{dX}{d\alpha} &= (X+\lambda)\left(3(\Sigma^2-1)+\frac{1}{2}X^2\right)+2X\Omega_A+3(2Q_A+\lambda)\Omega_A \\
&\quad +3\lambda(\Omega_m+\Omega_r)+\frac{3}{2}\Omega_m X+2\Omega_r X-3Q_M\Omega_m, \\
\frac{d\Sigma}{d\alpha} &= 2\Omega_A(\Sigma+1)+\Sigma\left[3(\Sigma^2-1)+\frac{1}{2}X^2+\frac{3}{2}\Omega_m+2\Omega_r\right], \\
\frac{d\Omega_A}{d\alpha} &= 2\Omega_A\left[3(\Sigma^2-1)+\frac{1}{2}X^2-Q_A X+1-2\Sigma+2\Omega_A+\frac{3}{2}\Omega_m+2\Omega_r\right], \\
\frac{d\Omega_m}{d\alpha} &= \Omega_m\left[-3+6\Sigma^2+X^2+Q_M X+4\Omega_A+3\Omega_m+4\Omega_r)\right], \\
\frac{d\Omega_r}{d\alpha} &= \Omega_r\left[-4+6\Sigma^2+X^2+4\Omega_A+3\Omega_m+4\Omega_r)\right].
\end{aligned}
$$

Fixed points satisfy:
$\frac{dX}{d\alpha} = \frac{d\Sigma}{d\alpha} = \frac{d\Omega_A}{d\alpha} = \frac{d\Omega_m}{d\alpha} = \frac{d\Omega_r}{d\alpha} = 0,$

-Fixed points characterize phase space and can be classified in repellers, saddles and attractors.
-Corresponds to self-similar solutions with $\dot{H} \propto H^2$.

Isotropic fix points

	(i1±)	RDE(i2)	(i3)	(i4)	ϕMDE(i5)	(i6)	ϕDE(i7)
X	$\pm\sqrt{6}$	0	$-\frac{1}{Q_M}$	$-\frac{4}{\lambda}$	$-2Q_M$	$\frac{3}{Q_M-\lambda}$	$-\lambda$
Σ	0	0	0	0	0	0	0
Ω_A	0	0	0	0	0	0	0
Ω_m	0	0	$\frac{1}{3Q_M^2}$	0	$1-\frac{2Q_M^2}{3}$	$\frac{-3-\lambda Q_M+\lambda^2}{(Q_M-\lambda)^2}$	0
Ω_r	0	1	$1-\frac{1}{2Q_M^2}$	$1-\frac{4}{\lambda^2}$	0	0	0
Ω_ϕ	1	0	$\frac{1}{6Q_M^2}$	$\frac{4}{\lambda^2}$	$\frac{2Q_M^2}{3}$	$\frac{Q_M(Q_M-\lambda)+3}{(Q_M-\lambda)^2}$	1
ω_ϕ	1	–	1	$\frac{1}{3}$	1	$\frac{-Q_M(Q_M-\lambda)}{Q_M(Q_M-\lambda)+3}$	$-1+\frac{\lambda^2}{3}$
ω_{eff}	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2Q_M^2}{3}$	$\frac{-Q_M}{Q_M-\lambda}$	$-1+\frac{\lambda^2}{3}$

Table 1. The isotropic fix-points.

Anisotropic fix points

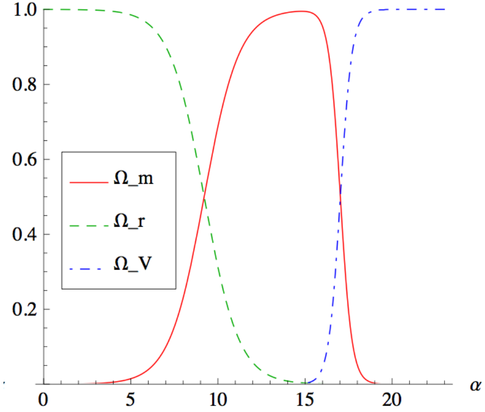
	(a1±)	(a2)	(a3)	AϕMDE(a4)
X	free	$-\frac{4}{\lambda}$	$-\frac{1}{Q_M}$	$-\frac{3(Q_A+3Q_M)}{4+(2Q_A+Q_M)(3Q_A+Q_M)}$
Σ	$\pm\sqrt{1-\frac{X^2}{6}}$	$\frac{2Q_A}{\lambda}$	$\frac{Q_A}{2Q_M}$	$\frac{-1+2Q_M(2Q_A+Q_M)}{4+(2Q_A+Q_M)(3Q_A+Q_M)}$
Ω_A	0	$\frac{Q_A}{\lambda}$	$\frac{Q_A}{4Q_M}$	$\frac{3}{2}\frac{[2+(3Q_A-Q_M)(Q_A+Q_M)][-1+2Q_M(2Q_A+Q_M)]}{[4+(2Q_A+Q_M)(3Q_A+Q_M)]^2}$
Ω_m	0	0	$\frac{2+3Q_A^2}{6Q_M^2}$	$3\frac{[2+(3Q_A-Q_M)(Q_A+Q_M)][3+2Q_A(2Q_A+Q_M)]}{[4+(2Q_A+Q_M)(3Q_A+Q_M)]^2}$
Ω_r	0	$\frac{\lambda^2-\lambda Q_A-6Q_A^2-4}{\lambda^2}$	$\frac{4Q_M^2-Q_M Q_A-3Q_A^2-2}{4Q_M^2}$	0
Ω_ϕ	$1-\Sigma^2$	$2\frac{2+Q_A^2}{\lambda^2}$	$\frac{1}{6Q_M^2}$	$\frac{3}{2}\frac{(Q_A+3Q_M)^2}{[4+(2Q_A+Q_M)(3Q_A+Q_M)]^2}$
ω_ϕ	1	$-1+\frac{8}{3(2+Q_A^2)}$	1	1
$\omega_{\rm eff}$	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{Q_M(Q_A+3Q_M)}{4+(2Q_A+Q_M)(3Q_A+Q_M)}$

	$(a5)$	AϕDE(a6)
X	$\frac{3}{Q_M-\lambda}$	$-\frac{12(2Q_A+\lambda)}{8+(2Q_A+\lambda)(6Q_A+\lambda)}$
Σ	$\frac{\lambda-6Q_A-4Q_M}{4(Q_M-\lambda)}$	$\frac{2(\lambda^2+2\lambda Q_A-4)}{8+(2Q_A+\lambda)(6Q_A+\lambda)}$
Ω_A	$-3\frac{(2Q_M-\lambda)(6Q_A+4Q_M-\lambda)}{16(Q_M-\lambda)^2}$	$3\frac{[\lambda^2+2\lambda Q_A-4][8+(6Q_A-\lambda)(2Q_A+\lambda)]}{(8+(2Q_A+\lambda)(6Q_A+\lambda))^2}$
Ω_m	$-3\frac{8+(6Q_A+4Q_M-3\lambda)(2Q_A+\lambda)}{8(Q_M-\lambda)^2}$	0
Ω_r	0	0
Ω_ϕ	$\frac{3}{8}\frac{8+6Q_A^2+6Q_A Q_M+4Q_M^2-\lambda(Q_A+3Q_M)}{(Q_M-\lambda)^2}$	$6\frac{16+56Q_A^2+24Q_A^4+32Q_A\lambda+20Q_A^3\lambda+2\lambda^2+2Q_A^2\lambda^2-Q_A\lambda^3}{(8+(2Q_A+\lambda)(6Q_A+\lambda))^2}$
ω_ϕ	$-1+\frac{8}{8+6Q_A^2+6Q_A Q_M+4Q_M^2-\lambda(Q_A+3Q_M)}$	$-1+\frac{8(2Q_A+\lambda)^2}{16+56Q_A^2+24Q_A^4+32Q_A\lambda+20Q_A^3\lambda+2\lambda^2+2Q_A^2\lambda^2-Q_A\lambda^3}$
$\omega_{\rm eff}$	$-\frac{Q_M}{Q_M-\lambda}$	$-\frac{8+12Q_A^2-3\lambda^2}{8+(2Q_A+\lambda)(6Q_A+\lambda)}$

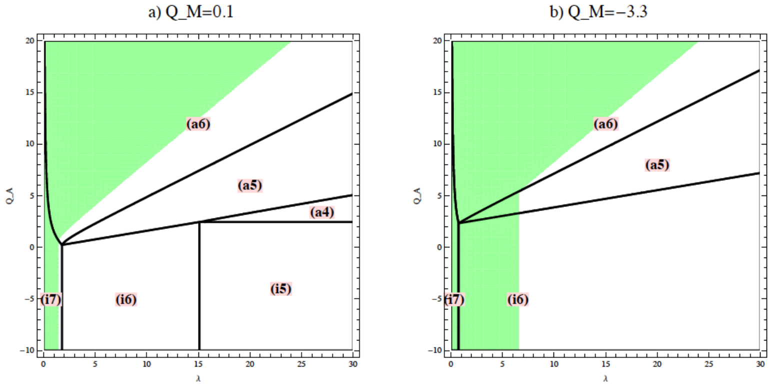
Table 2. The anisotropic fix-points.

Approach

- Fix-points corresponds to exact power-law solutions.
- Phase space is characterized by these solutions.
- Goal: -to understand the cosmology of the model, not mathematical completeness.
- First step: analyze the fix-point solutions individually.
- Second step: analyze trajectories that connects these solutions.
- Third step: identify interesting parameter regions.
- Forth step: analyze special cases of trajectories which are close to ΛCDM.


1.0
0.8
0.6
0.4
0.2
0
5
10
15
20
α
Ω_m
Ω_r
Ω_V

Parameterspace



Strong Vector Coupling Regime

Strong Vector Coupling Regime:

$$|Q_A| \gg 1, \quad |Q_A| \gg |Q_M|, \quad |Q_A| \gg \lambda.$$

Strong Vector Coupling Regime

Definition: $p = \omega_{\text{eff}}\rho$.
Cosmologically Viable Trajectory:

$$(\omega_{\rm eff} \simeq 1/3) \quad \to \quad (\omega_{\rm eff} \simeq 0) \quad \to \quad (\omega_{\rm eff} < -1/3).$$

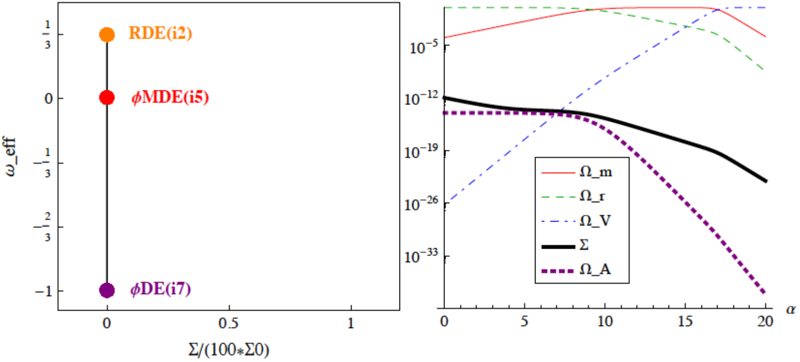
In our model this sequence can be achieved in various ways:

$$\Big(\text{RDE(i2)}\Big) \quad \to \quad \begin{pmatrix} \text{A}\phi\text{MDE(a4)} \\ \text{or} \\ \phi\text{MDE(i5)} \end{pmatrix} \quad \to \quad \begin{pmatrix} \text{A}\phi\text{DE(a6)} \\ \text{or} \\ \phi\text{DE(i7)} \end{pmatrix}.$$

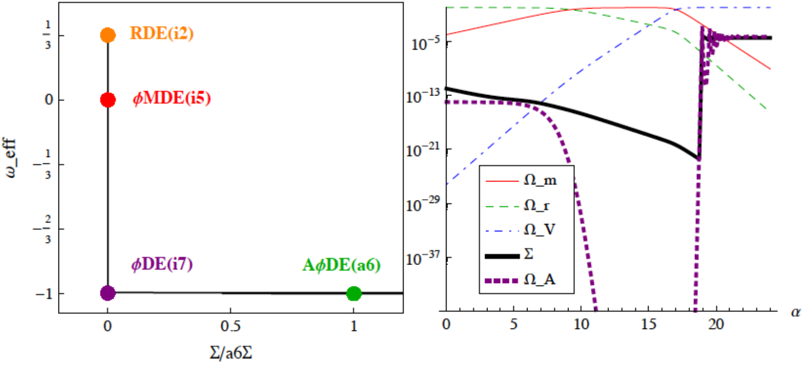
- Let us look at examples of each of the four trajectories.
- In each case we use exactly the same initial conditions for the dynamical variables $(\Sigma, \Omega_A, \Omega_{\text{kin}}, \Omega_m, \Omega_r)$.
- The only difference is the parameters of the model (λ, Q_M, Q_A)

Simulation

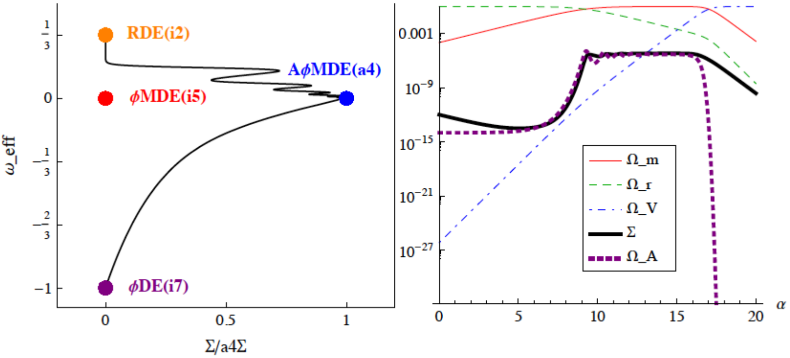
Example 1: isotropic both in the matter and dark energy dominated epochs.



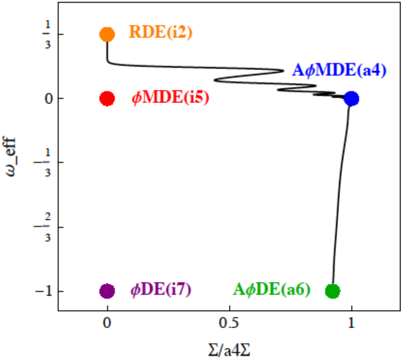
Example 2: isotropic in the matter dominated era and anisotropic in the dark energy dominated era.

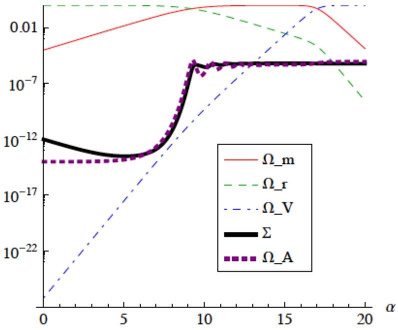


Example 3: anisotropic in the matter dominated era and isotropic in the dark energy dominated era.



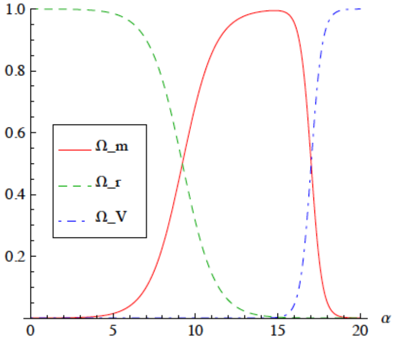
Example 4: anisotropic in both the matter and dark energy dominated epochs.





Simulation

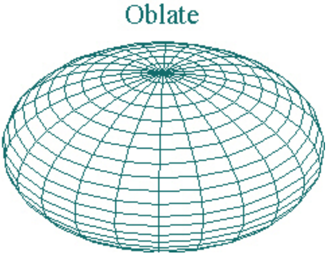
Example 4: anisotropic in both the matter and dark energy dominated epochs.



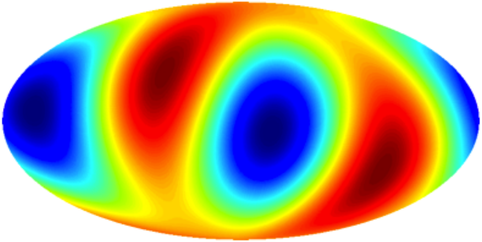
Observational Constraints

- We want to constrain the parameters of the model observationally.
- Since the universe expands anisotropically, the redshift of photons depends on direction of propagation. Gives signature in CMB.

An initial comoving sphere will evolve into a oblate spheroid:



CMB quadrupole.



Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$\begin{aligned} |Q_M/Q_A| &\lesssim 10^{-5} \\ |\lambda/Q_A| &\lesssim 10^{-4} \end{aligned}$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$\begin{aligned} |Q_M/Q_A| &\lesssim 10^{-5} \\ |\lambda/Q_A| &\lesssim 10^{-4} \end{aligned}$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$|Q_M/Q_A| \lesssim 10^{-5}$$
$$|\lambda/Q_A| \quad \lesssim 10^{-4}$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$\begin{aligned} |Q_M/Q_A| &\lesssim 10^{-5} \\ |\lambda/Q_A| &\lesssim 10^{-4} \end{aligned}$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$
\begin{aligned}
|Q_M/Q_A| &\lesssim 10^{-5} \\
|\lambda/Q_A| &\lesssim 10^{-4}
\end{aligned}
$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$
\begin{aligned}
|Q_M/Q_A| &\lesssim 10^{-5} \\
|\lambda/Q_A| &\lesssim 10^{-4}
\end{aligned}
$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

Observational Constraints

- This gives rise to a shear quadrupole, $\mathcal{Q}_a$.
- We denote the inflationary quadrupole $\mathcal{Q}_i$.
- $\mathcal{Q}_a$ is homogenous, while $\mathcal{Q}_i$ is subject to cosmic variance!
- The total (observed) quadrupole depends on $\mathcal{Q}_a$, $\mathcal{Q}_i$ and their mutual orientation!
- Constraint: $(\mathcal{Q}_a)^2 \lesssim <\mathcal{Q}_i^2> \simeq 1200\mu K^2$.
- Translated into the parameters of our model:

$$
\begin{aligned}
|Q_M/Q_A| &\lesssim 10^{-5} \\
|\lambda/Q_A| &\lesssim 10^{-4}
\end{aligned}
$$

- The low observed quadrupole is not improbable if $\mathcal{Q}_a \sim \mathcal{Q}_i$ (Campanelli et.al. 2011, arxiv:1103.2658).

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:

$$a \propto t^{\frac{2}{3}\left(1-\frac{1}{6}\frac{Q_M}{Q_A}\right)}$$

  -scale factor during the matter dominated era in ΛCDM:

$$a \propto t^{\frac{2}{3}}$$

- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:
  $$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$
  -scale factor during the matter dominated era in ΛCDM:
  $$a \propto t^{\frac{2}{3}}$$
- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:

$$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$

  -scale factor during the matter dominated era in ΛCDM:

$$a \propto t^{\frac{2}{3}}$$

- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:
  $$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$
  -scale factor during the matter dominated era in ΛCDM:
  $$a \propto t^{\frac{2}{3}}$$
- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:

$$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$

  -scale factor during the matter dominated era in ΛCDM:

$$a \propto t^{\frac{2}{3}}$$

- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:

  -mean scale factor during AϕMDE:

  $$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$

  -scale factor during the matter dominated era in ΛCDM:

  $$a \propto t^{\frac{2}{3}}$$

- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

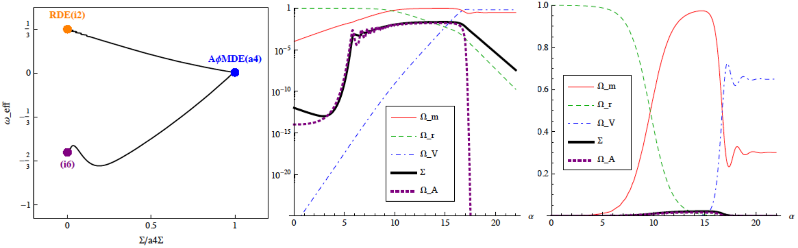
ΛCDM limit

- The smallness of $|Q_M/Q_A|$ and $|\lambda/Q_A|$ have several consequences.
- Firstly, it means that the universe expands almost isotropically.
- Secondly it implies that the background expansion history is very close to ΛCDM.
- Example:
  -mean scale factor during AϕMDE:
  $$a \propto t^{\frac{2}{3}(1-\frac{1}{6}\frac{Q_M}{Q_A})}$$
  -scale factor during the matter dominated era in ΛCDM:
  $$a \propto t^{\frac{2}{3}}$$
- Well defined ΛCDM limit: $|Q_M/Q_A| \to 0$ and $|\lambda/Q_A| \to 0$.
- Thus the CMB quadrupole is the only possible signature on the background level.
- Need to consider perturbations for a better understanding of the phenomenology!

A more exotic possibility

- The trajectories we have focused to now are qualitatively new, but quantitatively very close to ΛCDM.
- But there is also a more exotic possibility.
- In ΛCDM the future attractor is the deSitter solution.
- Could the present universe be a global attractor?

Present universe as a global attractor



Summary

- We have investigated the cosmological consequences of a scalar field interacting both with matter and an isotropy violating Maxwell field.
- Found genuinely new behavior due to the double coupling.
- Identified a parameter region giving interesting and viable cosmology.
- Needs to understand the perturbations.