Unified Dark Sector

Jan Ø. Lindroos

Department of physics and technology, University of Bergen
&
Bergens Forskningsstiftelse

In collaboration with
Institute of Theoretical Astrophysics, University of Oslo

June 27, 2011

Unified Dark Sector: Outline

- Brief intro: Dark matter and Dark Energy
- Overview of the concordance model ΛCDM
- Motivation for Unified Dark Matter models
- UDM fluids
- An example: Chaplygin Gas
- Scalar Field Approach
- A viable example: K-essence of Born-Infeld type

Dark Matter and Dark Energy: Basics

- Data from observations of CMB anisotropies, large scale structure, galaxy and cluster dynamics and supernovae redshifts seem to indicate that 96% of the matter in the universe is non-baryonic.[1]
- The standard interpretation is that roughly 22% is made up of Dark Matter (DM) and 74% in the form of Dark Energy (DE)
- The dark matter component is believed to act as a pressureless component, and are the main gravitational source for structure formation.
- The dark energy is belived to be a homogeneous component with negative pressure and is responsible for the late time acceleration of the universe.

[1] Ofer Lahav and Andrew R Liddle. The Cosmological Parameters 2010. 2010

Dark Matter and Dark Energy: Candidates

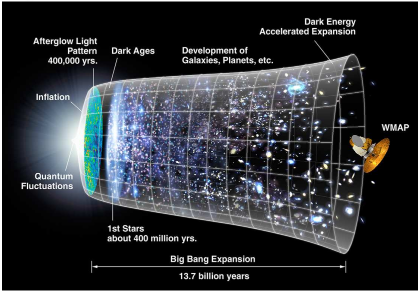
- Dark Matter Candidates:
  - Simplest choice: Weakly Interacting Massive Particles (WIMPS)
  - Alternative: Non-WIMP particle scenarios, modified gravity theories
- Dark Energy Candidates
  - Simplest choice: Cosmological Constant Λ
  - Alternative: Dynamical scalar field ϕ

$$\rho_\phi = \dot{\phi}^2 + V(\phi) \quad , \quad p_\phi = \dot{\phi}^2 - V(\phi) \overset{\dot{\phi}^2 \ll V(\phi)}{\longrightarrow} p_\phi = -\rho_\phi$$

- Unified Dark Matter: Single component accounting for early structure formation (DM) and late time acceleration (DE)

Concordance Model: flat ΛCDM

- Simplest solution: A model with a cosmological constant Λ and a pressureless component gives ΛCDM



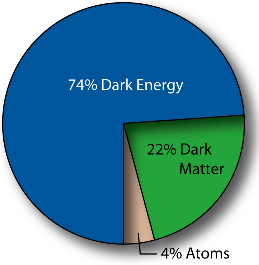


Figure: ΛCDM evolution with inflation and energy content today

- Data consistent with a flat ΛCDM model with $\Omega_{DM0} = 0.22$ and $\Omega_{\Lambda 0} = 0.74$

Why UDM scalar field models?

- Scalar fields proposed to describe both DM, DE and inflation, natural to try to relate them
- No explanation for why $\Omega_{DM} \sim \Omega_{DE}$ today
- No theoretical justification for the smallness of ρ_{DE}
- ΛCDM not perfect: Some discrepancies with respect to data (Large Scale Velocity Flows, High-z SnIa, ...) [2]

[2] L. Perivolaropoulos. Six Puzzles for LCDM Cosmology. 2008

Unified Dark Matter

- UDM tries to account for both DM and DE using a single component.

$$\rho = \rho_{DM} + \rho_{\Lambda}$$

- A plethora of models giving a background evolution consistent with data
- Examples:
  - (Generalized) Chaplygin Gas
  - (Generalized) Scherrer Solutions
  - Perfect fluid with affine equation of state

An Example: Chaplygin Gas

- Introduce a new perfect fluid with an exotic equation of state [3,4]

$$p = -A\rho^{-1} \;\rightarrow\; \rho = \sqrt{A + \frac{B}{a^6}}$$

- small a, $(a^6 \ll \frac{B}{A}) : \rho \;\rightarrow\; \sqrt{B}a^{-3}$ (behaves as DM)
- large a, $(a^6 \gg \frac{B}{A}) : \rho \;\rightarrow\; \sqrt{A} \;\;,\;\; p \;\rightarrow\; -\sqrt{A}$ (behaves as DE)
- This determines the background evolution, perturbations described by underlying scalar field.

$$\text{Canonical: } \mathcal{L}(\phi) = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) \quad , \quad V(\phi) = \frac{1}{2}\sqrt{A}\left(\cosh 3\phi + \frac{1}{\cosh 3\phi}\right)$$

$$\text{Non-canonical: } \mathcal{L}(\phi) = -\sqrt{A(1-BX)} \;,\; X = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

- Generalized Chaplygin Gas (GCG) $p = -A\rho^{-\alpha}$

[3] Alexander Yu. Kamenshchik, Ugo Moschella, and Vincent Pasquier. An alternative to quintessence. *Phys. Lett.*, B511:265–268, 2001

[4] Havard Sandvik, Max Tegmark, Matias Zaldarriaga, and Ioav Waga. The end of unified dark matter? *Phys. Rev.*, D69:123524, 2004

Unified Dark Matter Scalar Fields

- Large class of UDMs can be described by the general lagrangian [5]

$$\mathcal{L}_\phi = F(X) - V(\phi) \quad , \quad X = -\frac{1}{2}\partial_\mu \phi \partial^\mu \phi$$

- Pressure and density (perfect fluid)

$$p_\phi = \mathcal{L}_\phi \quad , \quad \rho_\phi = 2X\frac{\partial p_\phi}{\partial X} - p_\phi \quad , \quad \omega_\phi = \frac{p_\phi}{2X(\partial p_\phi/\partial X) - p_\phi}$$

- Cosmological Evolution

Background: $\left(\frac{\partial p_\phi}{\partial X} + 2X\frac{\partial^2 p_\phi}{\partial X^2}\right)\ddot{\phi} + \frac{\partial p_\phi}{\partial X}(3H\dot{\phi}) + \frac{\partial^2 p_\phi}{\partial \phi \partial X}\dot{\phi}^2 - \frac{\partial p_\phi}{\partial \phi} = 0$

Perturbations: $u'' - c_s^2 \nabla^2 u - \frac{\theta''}{\theta}u = 0$

[5] Daniele Bertacca, Nicola Bartolo, and Sabino Matarrese. Unified Dark Matter Scalar Field Models. 2010

Unified Dark Matter Scalar Fields

- An important general feature is the appearance of an effective speed of sound c_s

$$c_s^2 = \frac{\partial p/\partial X}{\partial \rho/\partial X} = \frac{\partial p/\partial X}{(\partial p/\partial X) + 2X(\partial^2 p/\partial X^2)}$$

- c_s gives rise to a sound horizon λ_J below which the field does not cluster
- c_s changes the evolution of the gravitational potential Φ.
- Changes in Φ affects CMB photons passing through, altering the CMB spectrum (ISW effect).
- Viable models should have $\lambda^2 \gg \lambda_J^2$ for all scales of cosmological interest.
- This constraint can be used to constrain existing models, and as a guideline for constructing viable models.

GCG constraint: $\alpha < 10^{-4}$, Viable Model: K-essence of Born-Infeld type

Viable Model: Born-Infeld K-essence

- Assumes Lagrangian of the form $\mathcal{L} = F(X) + V(\phi)$ with [6]

$$F(X) = -\sqrt{1 - \frac{2X}{M^4}} \quad , \quad V(\phi) = \alpha \frac{\sinh(\beta\phi) + \mu}{1 + \sigma \sinh^2(\beta\phi)}$$

$$c_s^2 = 1 - \frac{2X}{M^4}$$

- Gives right background evolution
- Gives small enough sound speed c_s & ISW comparable to observations.
- Kinetic terms of this type appear in the low energy limit of string theory and brane cosmology
- Could be distinguished from ΛCDM by EUCLID and Pan-STARRS

[6] Daniele Bertacca, Nicola Bartolo, Antonaldo Diaferio, and Sabino Matarrese. How the Scalar Field of Unified Dark Matter Models Can Cluster. *JCAP*, 0810:023, 2008