Unified Dark Sector

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Unified Dark Sector: Outline

- Brief intro: Dark matter and Dark Energy
- Overview of the concordance model $\Lambda CDM$
- Motivation for Unified Dark Matter models
- UDM fluids
- An example: Chaplygin Gas
- Scalar Field Approach
- A viable example: K-essence of Born-Infeld type
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 believed 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 $\Lambda$
  - Alternative: Dynamical scalar field $\phi$

  \[ \rho_\phi = \dot{\phi}^2 + V(\phi) , \quad p_\phi = \dot{\phi}^2 - V(\phi) \quad \Rightarrow p_\phi = -\rho_\phi \]

- **Unified Dark Matter:** Single component accounting for early structure formation (DM) and late time acceleration (DE)
Concordance Model: flat $\Lambda CDM$

- Simplest solution: A model with a cosmological constant $\Lambda$ and a pressureless component gives $\Lambda CDM$

Figure: $\Lambda CDM$ evolution with inflation and energy content today

- Data consistent with a flat $\Lambda CDM$ 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 $\rho_{DE}$
- $\Lambda CDM$ not perfect: Some discrepancies with respect to data (Large Scale Velocity Flows, High-z SNIa, ...) \(^2\)
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 \(^3,^4\)

\[
p = -A \rho^{-1} \quad \rightarrow \quad \rho = \sqrt{A + \frac{B}{a^6}}
\]

- 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.

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

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

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

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Unified Dark Matter Scalar Fields

- Large class of UDMs can be described by the general lagrangian \( \mathcal{L}_\phi = F(X) - V(\phi) \), \( X = -\frac{1}{2} \partial_\mu \phi \partial^\mu \phi \)

- Pressure and density (perfect fluid)

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

- Cosmological Evolution

Background:

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

Perturbations:

\[
u'' - c_s^2 \nabla^2 u - \frac{\theta''}{\theta} u = 0
\]

Unified Dark Matter Scalar Fields

- An important general feature is the appearance of an effective speed of sound $c_s$
  
  $$c_s^2 = \frac{\partial p/\partial X}{\partial \rho/\partial X} = \frac{\partial p/\partial X}{(\partial p/\partial X) + 2X(\partial^2 \rho/\partial X^2)}$$

- $c_s$ gives rise to a sound horizon $\lambda_J$ below which the field does not cluster.

- $c_s$ changes the evolution of the gravitational potential $\Phi$.

- Changes in $\Phi$ 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 $^6$

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

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

- 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 $\Lambda CDM$ by EUCLID and Pan-STARRS

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