The Unifying Dark Fluid Model

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Dark Matter Problem

Different scales involved

- Galactic scale
  - Galaxy Rotation Curves
  - Galaxy Collisions
- Cluster Scale
  - X-Ray Observations
  - Weak Lensing
  - Bullet Cluster
- Cosmological Scale
  - Supernovæ of type Ia
  - Cosmic Microwave Background
  - ...

Dark Matter Candidates

- **Baryonic Dark Matter**
- **WIMPs**
- **Other particles/fields**: axions, Kaluza-Klein particles, ...
  Exotic and non-baryonic particles
- **Modified Gravitation Laws**
  MOND, TeVeS, Scalar-tensor theories, Extra-dimensions, Brane worlds, ...

Dark Energy Problem

72% of the Universe energy has a negative pressure!

- **Cosmological Constant**
  A new physics constant...
- **Vacuum Energy**
  Applying Quantum Field Theory to Dark Energy?
  Not very Successful yet...
- **Quintessence**
  Dark energy as a real scalar field?
- **...**

Quintessence

Quintessence = real homogeneous scalar field

- Lagrangian density: $\mathcal{L} = g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)$
- Density and pressure: $\begin{cases} \rho_\varphi = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) \\ P_\varphi = \frac{1}{2}\dot{\varphi}^2 - V(\varphi) \end{cases}$
- Friedmann equations: $\begin{cases} \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum\rho - \frac{k}{a^2} \\ \frac{\ddot{a}}{a} = -\frac{3\pi G}{3}\left(\sum\rho + 3\sum P\right) \end{cases}$
- Klein-Gordon equation: $\ddot{\varphi} + 3H\dot{\varphi} + \frac{\partial V}{\partial\varphi} = 0$
- Usual potentials: $\begin{array}{l} V(\varphi) = \alpha\varphi^{-\beta} \\ V(\varphi) = \alpha\exp(-\beta\varphi) \\ V(\varphi) = \alpha\left[\cosh(\beta\varphi) - 1\right]^n \end{array}$

Dark Fluids?

What if Dark Matter and Dark Energy are in interaction?

Dark Fluids?

What if they are different aspects of a same dark component?

Dark Fluids?

To answer these questions, we need to model the interactions

Dark Fluids?

$\Rightarrow$ **Dark fluid:**
One unique fluid to replace dark energy and dark matter

Dark Fluids?

Must satisfy the observational constraints

Today:

- Matter behaviour at local scales
- Repulsing behaviour at cosmological scales

In the Early Universe:

- Matter behaviour at all scales.

Dark Fluids?

Advantages

- One unique Dark Fluid instead of two...
- Model dark energy / dark matter interactions
- **Can be made up of scalar field!**

Massive and Complex Scalar Field

- $\mathcal{L} = g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi - V(\phi)$
- $V(\phi) = m^2|\phi|^2$

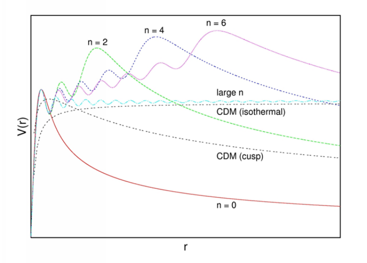
A. Arbey, J. Lesgourgues & P. Salati, Phys. Rev. D 64, 123528 - Phys. Rev. D 65, 083514 - Phys. Rev. D 68, 023511

Galaxy Rotation Curves (1)

- **Internal rotation**: $\phi(\vec{x},t) = \frac{\sigma(r)}{\sqrt{2}} e^{i\omega t}$
- **Static and isotropic metric**:
  $d\tau^2 = e^{2u} dt^2 - e^{2v} \left\{ dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2 \right\}$
- **Klein-Gordon equation**:
  $e^{-2v} \left\{ \sigma'' + \left(u' + v' + \frac{2}{r} \right) \right\} + \omega^2 e^{-2u} \sigma - m^2 \sigma = 0$
- **Einstein equations**:
  $2v'' + v'^2 + \frac{4v'}{r} = -8\pi G e^{2v} \left\{ e^{-2u} \frac{\omega^2 \sigma^2}{2} + e^{-2v} \frac{\sigma''}{2} + \frac{m^2 \sigma^2}{2} \right\}$
  $u'' + v'' + u'^2 + \frac{1}{r}(u' + v') =$
  $8\pi G \left\{ e^{2v} \left[e^{-2u} \frac{\omega^2 \sigma^2}{2} - e^{-2v} \frac{\sigma''}{2} - \frac{m^2 \sigma^2}{2} \right] + \rho_{baryon} \right\}$

Galaxy Rotation Curves (2)

Resolution $\rightarrow$ discrete number of solutions, *i.e.* fundamental and excited states

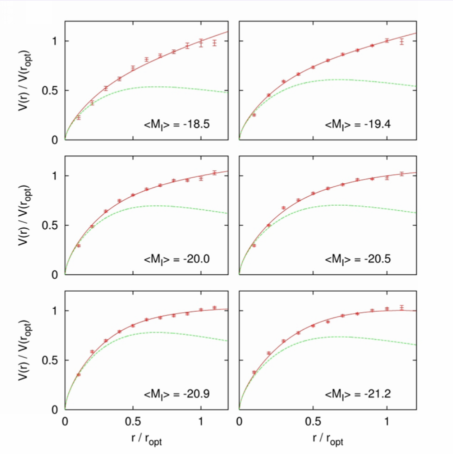


To ensure stability, we consider only the fundamental and less-energetic state, n=0

Newtonian limit: $\omega^2 \approx m^2 \rightarrow P \approx (\omega^2 - m^2)\sigma^2 \approx 0$

Rotation curves obtained with: $v^2(r) = r\frac{\partial}{\partial r}\Phi_{grav}(r) = rc^2 u'(r)$

Galaxy Rotation Curves (3)



Universal Rotation Curves (Persic, Salucci & Stel)

The favoured mass is around 10^{-23} **eV**!

Confirmed by the study of the rotation curve of DDO 154

Cosmological Behaviour

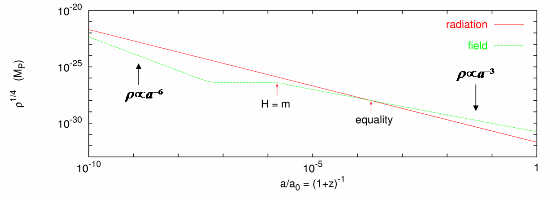
Friedmann-Lemaître Universe with radiation and scalar field

Internal rotation: $\phi(t) = \frac{\sigma(t)}{\sqrt{2}} e^{i\theta(t)}$

Friedmann equation: $3H^2 = 8\pi G(\rho_\gamma + \rho_\phi)$

with $\rho_\phi = \frac{1}{2}\left\{\left(\frac{d\sigma}{dt}\right)^2 + \left(\frac{d\theta}{dt}\right)^2 \sigma^2 + m^2\sigma^2\right\}$

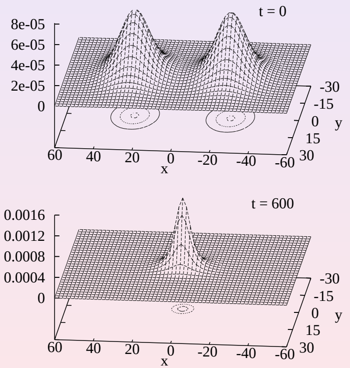
Klein-Gordon equation: $\begin{cases} \frac{d^2\sigma}{dt^2} + \frac{3}{a}\frac{da}{dt}\frac{d\sigma}{dt} + m^2\sigma - \left(\frac{d\theta}{dt}\right)^2 \sigma = 0 \\ \frac{d^2\theta}{dt^2}\sigma + \frac{3}{a}\frac{da}{dt}\frac{d\theta}{dt}\sigma + 2\frac{d\theta}{dt}\frac{d\sigma}{dt} = 0 \end{cases}$



The field has an adequate matter behaviour since recombination!

Collisions

C. Palenzuela, I. Olabarrieta, L. Lehner, S. Liebling, Phys. Rev. D75 (2007) 064005



Very complex systems, difficult to simulate!

Towards Unification

$$\left.\begin{array}{r}\rho^{cosmo}(t_0) \approx 9 \times 10^{-29}\ \mathrm{g.cm}^{-3} \\ \rho^{Milky\ Way}(\vec{r}_\odot, t_0) \approx 5 \times 10^{-24}\ \mathrm{g.cm}^{-3}\end{array}\right\} \Rightarrow \rho^{galaxy} \gg \rho^{cosmo}$$

Need for an inhomogeneous scenario!

$$\omega_\phi \equiv \frac{P_\phi}{\rho_\phi} \qquad \omega_\phi(a) \approx \omega_\phi^0 + (1-a)\omega_\phi^a$$

Observational constraints: Dark Fluid parameters

- $\Omega_\phi^0 = 1.005 \pm 0.006$
- $\omega_\phi^0 = -0.80 \pm 0.12$
- $\omega_\phi^a = 0.9 \pm 0.5$

A. Arbey, astro-ph/0506732 - A. Arbey, Open Astron. J. 1, 27

Unifying Scalar Field (1)

Complex Scalar Field

- $\mathcal{L} = g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi - V(\phi)$

Tentative potentials:

- $V(\phi) = m^2|\phi|^2 + \alpha|\phi|^{-\beta}$
- $V(\phi) = m^2|\phi|^2 + \alpha\exp(-\beta|\phi|)$
- $V(\phi) = m^2|\phi|^2 + \alpha\left[\cosh(\beta|\phi|) - 1\right]^n$

$m^2|\phi|^2$: responsible for the local scale behaviour

The other term determines the cosmological behaviour

A. Arbey, Phys. Rev. D 74, 043516

Unifying Scalar Field (2)

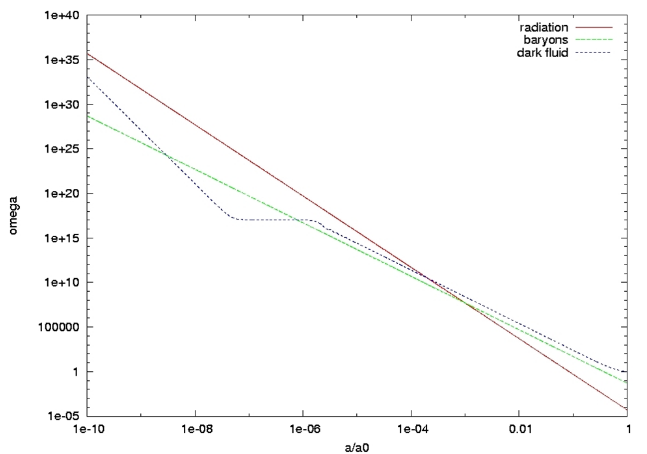
Promising potential:

$$V(\phi) = m^2|\phi|^2 + Ae^{-B|\phi|^2}$$

- m fixed by galaxy scales: $m \sim 10^{-23}$ eV
- B fixed by cluster scales: $B \approx 10^{-22}$ eV^{-2}
- A fixed by cosmological scales: $A \approx \rho_0^{dark\ energy}$

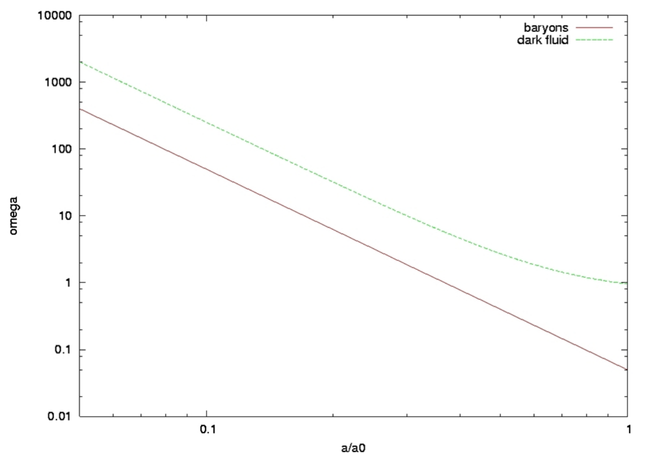
A. Arbey, Phys. Rev. D 74, 043516

Cosmological Behaviour



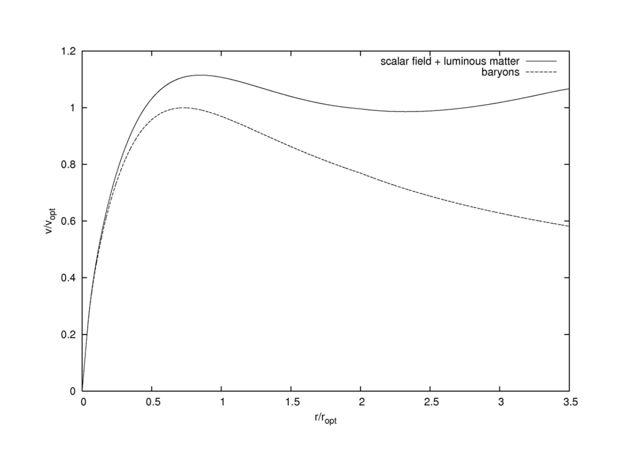
Correct cosmological behaviour

Cosmological Behaviour



Correct cosmological behaviour

Local Behaviour



Correct behaviour at galactic scales

Quantum Corrections

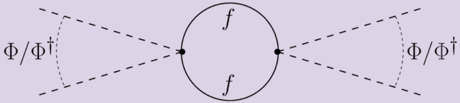
Coupling to fermions?

$$\mathcal{L}_{fermion} = \bar{\Psi}^\dagger(x)[i\gamma^\mu \nabla_\mu - \gamma^5 m_f(\Phi)]\Psi(x)$$

Effective potential (effective field theory approach):

$$V_{1-loop}(\Phi_{cl}) = V(\Phi_{cl}) - \frac{\Lambda_f^2}{8\pi^2}[m_f(\Phi_{cl})]^2$$

with Λ_f: momentum cutoff



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Quantum-resistivity condition: $m_f(\Phi_{cl}) = m_f^0 + \delta m_f(\Phi_{cl})$

For $\Lambda_f \approx 10^{-3}$ M_{Planck} and $m_f^0 \approx 100$ GeV: $\delta m_f(\Phi_{cl}) \ll 10^{-79}$ GeV

OR: $\delta m_f(\Phi_{cl}) \propto |\Phi_{cl}|^2$ or $\delta m_f(\Phi_{cl}) \propto \exp(-B|\Phi_{cl}|^2)$

Severely restricted!

Conclusions and Perspectives

Many Constraints on these models

- Constraints on the matter behaviour
- Constraints on the dark energy behaviour
- Inhomogeneous modeling: local vs. large scales
- Quantum behaviour/coupling to fermions?

Perspectives

- Scalar field dark fluid: Structure formation scenario
- Scalar field dark fluid: finding an adequate potential
- Relations with quantum field theory, quantum gravity, brane theories?
- Triple unification: dark energy + dark matter + inflaton?