XXXVI Annual Meeting of the Division of Particles and Fields

Scalar field dark matter with two components: combined approach from particle physics and cosmology

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September 30, 2022

Experimental evidence

What is dark matter?

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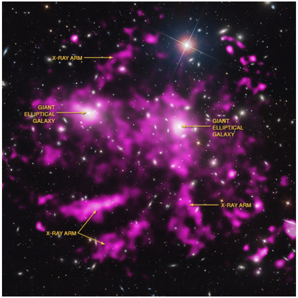

Figure: Coma Cluster. Credits: X-ray: NASA/CXC/M-PE/J.Sanders et al, Optical: SDSS

Figure: Bullet Cluster. Credits : X-ray : NASA / CXC/ CfA / M.Markevitch et al. ; Lensing Map : NASA / STScI; ESO WFI; Magellan / U.Arizona/ D.Clowe et al. Optical : NASA/STScI; Magellan / U.Arizona / D.Clowe et al.;

Motivation

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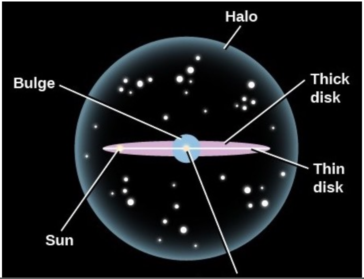
Lack of experimental evidence in the search for dark matter

Objective

Introduce complex scalar fields motivated in particle physics to the cosmological model of dark matter.



The model

Dark matter cosmological model

- Ultralight scalar field
- $V(|\phi|) = \mu^2 |\phi|^2 + \sigma^2 |\phi|^4$
- $m_\phi > 10^{-21}$eV

- Non-interacting
- Reproduce the structure of the Universe
- Galactic halos
- Rotational velocity profiles

Scalars fields in the particle physics

Scalar fields in the particle physics

- Higgs-like
- Axion-like

Axión-like

- Goldstone boson
- U(1) SSB, f_a
- $m_a \not\leftarrow$ radiative corrections of QCD
- $m_a \approx 6\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$
- Non-perturbative physics scale Λ_a
- $V_a(\Phi_a) = \Lambda_a^4\left[1 - \cos\left(\frac{\Phi_a}{f_a}\right)\right]$

Higgs-like

- SM scalar extension
- stable and inert doublet
- $\Phi_h = \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}\Phi_1 + i\Phi_2\\ \Phi_3 + i\Phi_4\end{pmatrix}$
- DMC $\rightarrow \Phi^0$
- $V_h(\Phi_h) = m_h^2(\Phi_h^\dagger\Phi_h) + \frac{\lambda_h}{2}(\Phi_h^\dagger\Phi_h)^2$
- $m_h \sim$ GeV

Transition from quantum field theory to classical theory.

Quantum field theory → Classical theory

Real quantum fields → Complex classical fields

↓

Avoid wave oscillation induced to space-time structure

Two complex scalar fields model

We coupled to gravity the general model with two complex scalar fields,

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{c^4}{16\pi G}R + \mathcal{L}_{\Phi_1,\Phi_2}\right). \tag{1}$$

Where,

$$2\mathcal{L}_{\Phi_1,\Phi_2} = -\nabla^\mu\Phi_1^*\nabla_\mu\Phi_1 - \nabla^\mu\Phi_2^*\nabla_\mu\Phi_2 - V(\Phi_1,\Phi_2). \tag{2}$$

The variation with respect to the fields Φ_1 and Φ_2 gives the following equations of motion:

$$\begin{aligned} \Box\Phi_1 - \frac{dV}{d|\Phi_1|^2}\Phi_1 &= 0 \\ \Box\Phi_2 - \frac{dV}{d|\Phi_2|^2}\Phi_2 &= 0 \end{aligned} \tag{3}$$

A two complex scalar fields model

In the homogeneous case, (FL + $k=0$),

$$H^2 = \frac{8\pi G}{3c^2}[\rho_r(t) + \rho_b(t) + \rho_\Lambda(t) + \rho_{\Phi_1,\Phi_2}], \quad (4)$$

ρ_x corresponds to the energy density associated to the energy momentum tensor of $x = r, b, \Lambda$ components and,

$$\rho_{\Phi_1,\Phi_2} = \frac{1}{2c^2}|\partial_t\Phi_1|^2 + \frac{1}{2c^2}|\partial_t\Phi_2|^2 + \frac{1}{2}V(\Phi_1,\Phi_2). \quad (5)$$

$$p_{\Phi_1,\Phi_2} = \frac{1}{2c^2}|\partial_t\Phi_1|^2 + \frac{1}{2c^2}|\partial_t\Phi_2|^2 - \frac{1}{2}V(\Phi_1,\Phi_2). \quad (6)$$

We need to solve the system of differential equations (3) y (4)

We consider,

$$V(\Phi_1,\Phi_2) = V_1(\Phi_1) + V_2(\Phi_2), \quad (7)$$

then

$$\rho_{\Phi_1,\Phi_2} = \rho_1 + \rho_2 \qquad \rho_1 = \frac{1}{2c^2}|\partial_t\Phi_1|^2 + \frac{1}{2c^2}V_1(\Phi_1)$$
$$p_{\Phi_1,\Phi_2} = p_1 + p_2 \qquad \rho_2 = \frac{1}{2c^2}|\partial_t\Phi_2|^2 + \frac{1}{2c^2}V_2(\Phi_2) \quad (8)$$

Potentials

Representative cases:

- Higgs-like

$$V_h(\Phi_h) = m_h^2(\Phi_h^\dagger \Phi_h) + \frac{\lambda_h}{2}(\Phi_h^\dagger \Phi_h)^2, \qquad \Phi_h = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix}.$$

$m_h = 100\text{GeV}, \quad \lambda_h = 1.$

- Axion-like

$$V_a(\Phi_a) = \frac{1}{2}\left(m_a^2 \Phi_a^2 - \frac{1}{12}\frac{m_a^2}{f_a^2}\Phi_a^4 \right).$$

$m_a \approx 6 \times \mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$, $f_{a,GUT} = 10^{16}$GeV and $f_{a,Plank} = 10^{19}$GeV.

- Ultralight scalar field (Classical),

$$V(|\phi|) = \mu^2 |\phi|^2 + \sigma^2 |\phi|^4.$$

$m = 5.7 \times 10^{-10}\mathrm{eV}$ y $\lambda = -5.40 \times 10^{-70}$.

We assume that the potentials are valid during all the evolution of the Universe.

Time evolution of energy density

Initial conditions:

- $a = 1$,
- Ω_i, constrained by observations.
- $\Omega_{DM_0} = \rho_1 + \rho_2$, at $a = 1$.

$$\rho_1(a=1) = k\Omega_{DM_0}\rho_{\text{crit}},$$

$$\rho_2(a=1) = (1-k)\,\Omega_{DM_0}\rho_{\text{crit}}.$$

Possible double scalar field models

- Model I = Classical + Higgs
- Model II = Axion + Higgs
- Model III = Classical + Axión

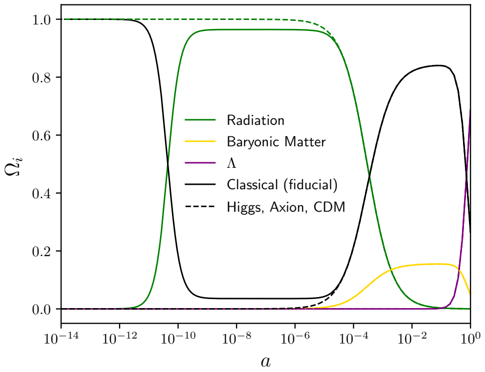


Figure: Time evolution of energy density. The solid lines correspond to the classical positive self-interaction fiducial cosmology. The dashed lines are the reference CDM Universe, which happens to coincide in this plot to the Higgs and axion (GUT, Planck) cases.

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Time evolution of equations of state

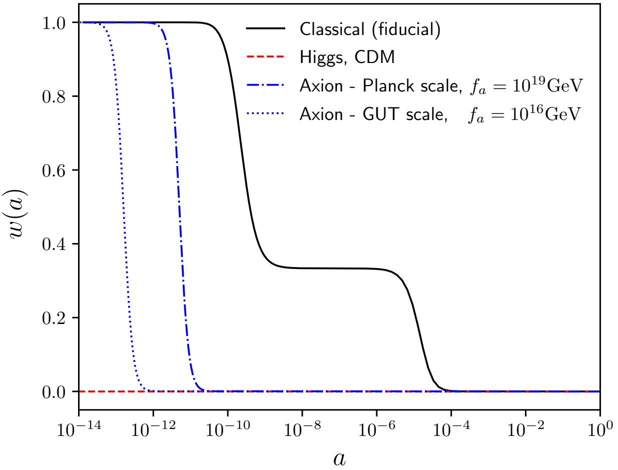
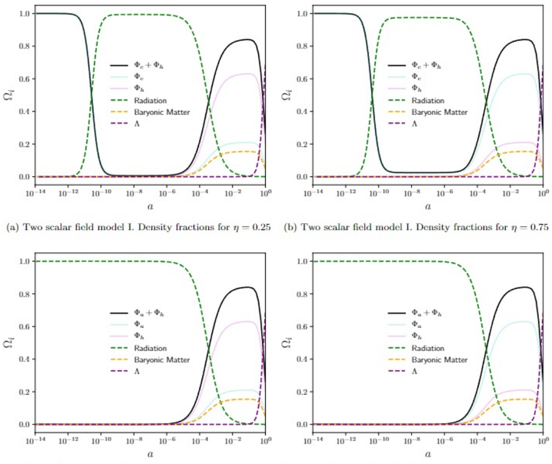


Figure: Time evolution of equations of state. The positive self-interaction classical field undergoes three phases, the negative self-interaction case undergoes two and the Higgs field remains indistinguishable from ΛCDM.

Cosmological evolution of the two complex scalar fields model



(a) Two scalar field model I. Density fractions for $\eta = 0.25$ (b) Two scalar field model I. Density fractions for $\eta = 0.75$

(c) Two scalar field model II. Density fractions for $\eta = 0.25$ (d) Two scalar field model II. Density fractions for $\eta = 0.75$

Figure: Evolution of the density parameters of the Universe. All solid lines correspond to the scalar field dark matter model with two components and the dashed lines represent the rest of the density contributions. Top panel: Two scalar field model I (Classical + Higgs). Bottom panel: Two scalar field model II (axion+Higgs).

Effective number of neutrino species ($N_{\rm eff}$)

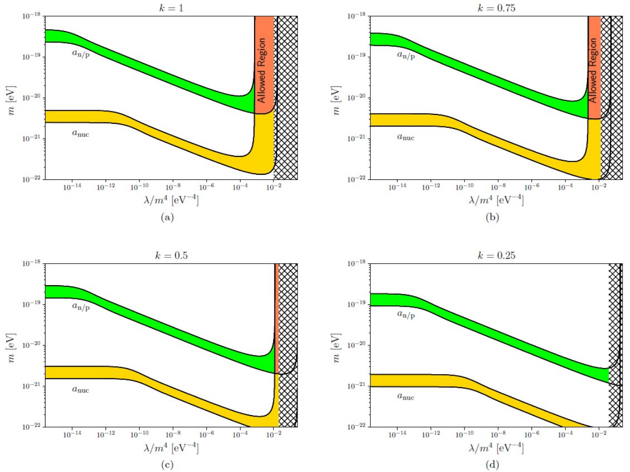


Figure: Constraints from $z_{\rm eq}$ and $N_{\rm eff}$ within 1σ for the two scalar field Model I. The crosshatched region represents the values of the scalar field parameters not allowed by the $z_{\rm eq}$ constrain. The green and yellow bands are the allowed regions from the $N_{\rm eff}$ constrain, at $a_{\rm n/p}$ and $a_{\rm nuc}$ respectively. The red band is the region consistent with both the $z_{\rm eq}$ and $N_{\rm eff}$, throughout BBN, constraints.

Conclusion

Constraints from Effective number of neutrino species

One field

Classical	√
Higgs-like = ΛCDM	X
Axion-like	X

Two fields

Axion + Higgs	X
Higgs + Classical	√

Models with two scalar fields are viable. In particular the Classical + Higgs model produces a cosmological model that remains consistent with constraints satisfied by the single classical scalar field, we can consider up to 58% of Ω_{DM} to be a Higgs-like field if the remaining 42% is the classical one.


THANK YOU :)