Constraints to scalar dark matter candidates from astrophysics

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Outline

- Scalar field dark matter
- Self-gravitating systems made of scalar fields → Boson star (BS)
  1. Generalities
  2. Modeling astrophysical objects with BS:
     - Compact objects → Can BS mimic Sagittarius A*?
     - Can BS model a galactic halo?
- Properties of the scalar field
- Conclusions
Scalar field dark matter

But what is the nature of the dark matter?

- An alternative: WIMPS (CDM)
  1. the appearance of a cuspy density profile of the dark matter
  2. the fail in predicting the number of satellite galaxies around each galactic halo

- Another approach: The Scalar Field Dark Matter model (SFDM)
  The Dark Matter is modeled by a scalar field, associated with an ultra-light spin-zero particle ($m \sim 10^{-23}\text{eV}$)
  - At cosmological scales it behaves as cold dark matter
  - At galactic scales, it does not have its problems: neither a cuspy profile, nor a over-density of satellite galaxies.
Scalar field DM

- MeV dark matter: $m \sim \text{MeV}$, could explain positron excess.
- Axion $m \sim 10^{-3} - 10^{-5}\text{eV}$
- Fuzzy dark matter $m \sim 10^{-23}\text{eV}$

DM properties are known by particle physicist (Lagrangian, EOS...)

What kind of astrophysical object can they form?
Boson stars (BS) are gravitationally bounded systems made of scalar particles.

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu}, \quad \left( \Box - \frac{dV}{d\phi^2} \right) \phi = 0, \]

where \( \Box = \frac{1}{\sqrt{-g}} \partial_\mu \left[ \sqrt{-g} g^{\mu\nu} \partial_\nu \right] \) and the energy-momentum tensor is given by

\[ T_{\mu\nu} = \frac{1}{2} \left( \partial_\mu \Phi \partial_\nu \Phi^* + \partial_\mu \Phi^* \partial_\nu \Phi \right) - \frac{1}{2} g_{\mu\nu} \left( g^{\alpha\beta} \partial_\alpha \Phi \partial_\beta \Phi^* + m^2 |\Phi|^2 + \frac{\lambda}{2} |\Phi|^4 \right). \]

\[ \Lambda = \frac{\lambda M_p^2}{4\pi m^2} \]

Assuming harmonic spherical symmetric fields \( \Phi(r,t) = \sigma(r)e^{-it} \) in a static space-time metric

\[ ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\Omega^2. \]
\[\frac{A'}{A^2 x} + \frac{1}{x^2} \left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} + 1\right) \sigma^2 + \frac{\Lambda}{2} \sigma^4 + \frac{\sigma'^2}{A}\right] = 0,\]
\[\frac{B'}{AB x} - \frac{1}{x^2} \left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} - 1\right) \sigma^2 - \frac{\Lambda}{2} \sigma^4 + \frac{\sigma'^2}{A}\right] = 0,\]
\[\sigma'' + \left(\frac{1}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right) \sigma' + A \left[\left(\frac{1}{B} - 1\right) \sigma - \Lambda \sigma^3\right] = 0\]

**definitions** \(x = rm, \quad R_{10} = \frac{1}{\sqrt{4\pi G}} \sigma, \quad B = E_1^2 B\)

**Boundary Conditions**
- Regular at origin
- Flat geometry at infinity
- Arbitrary \(\sigma(0)\) and \(\Lambda\)

\[M = \frac{1}{2} x_{max} \left[1 - \frac{1}{B(x_{max})}\right] \frac{m_{pl}^2}{m}\]

In the Newtonian limit \(\rho(x) = |\sigma(x)|^2\)
The previous stability studies of BS can be classified in two types:

1. studies that consider infinitesimal perturbations for which the number of particles is conserved. Linear perturbation theory [M. Gleiser, R. Watkins, Nucl. Phys. B319, 733 (1989)]

2. studies that consider finite perturbations and there is no conservation in the number of particles. Finite perturbations are considered, [E. Seidel, W. Suen, Phys. Rev. D42, 384 (1990), J. Balakrishna, E. Seidel, W. Suen, Phys. Rev. D58, 104004 (1998)]
what is the maximum compactness of a BS?
When $\Lambda >> 1$, $\sigma$ decays as $\sim \Lambda^{1/2}$

This suggests a new parametrization

$\sigma_* = \Lambda^{1/2} \sigma$

$x_* = \Lambda^{-1/2} x$

Neglecting terms $O(\Lambda^{-1})$, the KG equation is solved algebraically

$\left( \frac{1}{B} - 1 \right) \sigma_* - \sigma_*^3 = 0$

$\sigma_* = (1/B - 1)^{1/2}$

The equations for the metric are independent of $\Lambda$ and $\sigma_*$. 

$$\frac{B'}{ABx_*} - \frac{1}{x_*^2} \left( 1 - \frac{1}{A} \right) = \frac{1}{2} \left( \frac{1}{B} - 1 \right)^2$$

$$\frac{A'}{A^2x_*} + \frac{1}{x_*^2} \left( 1 - \frac{1}{A} \right) = \frac{1}{2} \left( \frac{1}{B} + 1 \right) \left( \frac{1}{B} - 1 \right)^2$$
BS maximum compactness

\[ 0.0 < C_{BS}(\sigma_c, \Lambda) < 0.158 \]
Compact objects

\[ 3.32 \times 10^{-4} \approx C_{\text{min}} \leq C_{\text{BS}} \leq C_{\text{max}} \approx 0.158. \]

\[ C_{\text{min}} = \frac{M_{\text{Sgr A}^*}}{R_{S2}} \approx \frac{1}{3015}, \]
Can BS mimic Sagittarius A*?
another super massive BH?

\[ M_{\text{NGC 4258}} = 38.1 \pm 0.01 \times 10^6 \, M_\odot, \] while the observations of the rotation curve require a central density of at least \[ 4 \times 10^9 \, M_\odot \, \text{pc}^{-3}, \] which implies a maximum radius \[ R_{\text{max}} \simeq 36000 \, R_S. \]
Can BS model a galactic halo?

A typical DM halo: Mass $\sim 10^{12} M_\odot$, and $R \sim 100$ KpcS.

$$\frac{2M}{R_{99}} \sim 10^{-7} \quad \rightarrow \text{Newtonian BS}$$

$$v(r)^2 = 2BB'$$

$$l \sim \sqrt{\frac{1}{\sigma(0)} \frac{1}{m}}, \quad \frac{v}{c} \sim \sqrt{\frac{1}{\sigma(0)}}$$

$\sigma(0) \sim 10^{-6}, \quad m \sim 10^{-23}$ eV $\rightarrow l \sim 10$ kpc,

$$v \sim 10^{-3} c$$
Can BS model a galactic halo?


Best fit to the DD0 154 rotation curve.

\[ \frac{m^4}{\lambda} \approx 50 \text{eV}^4 \]
Constraining scalar field properties


DM is proposed to be cold, non-dissipative and self-interacting with a scattering cross-section per particle mass given by

$$\frac{\sigma_{2\rightarrow2}}{m_\phi} = 10^{-25} - 10^{-23} \text{ cm}^2 \text{ GeV}^{-1},$$

Applied to scalar field DM

$$\sigma(\phi\phi \rightarrow \phi\phi) = \sigma_{\phi\phi} = \frac{\lambda^2}{16\pi s} = \frac{\lambda^2}{64\pi m_\phi^2},$$

$$9.5 \times 10^5 \text{ eV} \lesssim \frac{m_\phi}{\lambda^{2/3}} \lesssim 9.5 \times 10^7 \text{ eV}.$$
Constraining scalar field properties

\[ 6.5 \times 10^{-9} \lesssim \lambda \lesssim 4.2 \times 10^{-3}, \]
\[ 332 \text{ eV} \lesssim m_\phi \lesssim 2.46 \times 10^4 \text{ eV}, \]
Conclusions

Motivated by possible scalar field DM candidates, we have studied the properties of self-gravitating systems made of spin-zero particles → BS.

BS can mimic SMBH candidates, and the properties of such spin-zero particle are the same for the best SMBH candidates. We have found the required masses and self-interacting coupling constant values needed for that.

The values founded for $m$ and $\lambda$ are compatible with the ones required by collisional DM.

More detailed analysis for the galactic halo are needed in order to check if the same scalar field can explain both: dark compact objects at the center of the galaxies and the galactic DM halo. So far they seem to be different particles.