Constraints to scalar dark matter candidates from astrophysics

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Outline

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

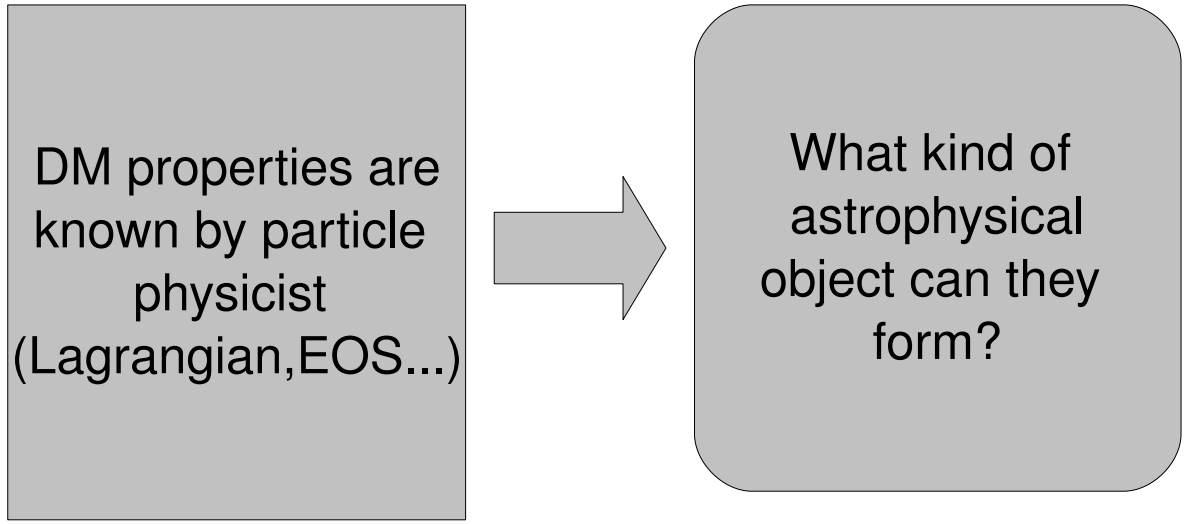
Scalar field dark matter

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 ($m \sim 10^{-23}$eV)
  - At cosmological scales it behaves as cold dark matter
    T. Matos, L.A. Urena-Lopez, Class. Quant. Grav. **17** L75 (2000),
    V. Sahni and L.M. Wang, Phys. Rev D **62**, 103517 (2000).
  - At galactic scales, it does not have its problems: neither a cuspy profile, nor a over-density of satellite galaxies.
    A. Bernal, T. Matos, D. Nuñez, Rev. Mex. A.A. 44, 149 (2008)
    T. Matos, L.A. Urena-Lopez, Phys. Rev. D **63**, 063506 (2001)

Scalar field DM

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



Self-gravitating system made of scalar field $\rightarrow$ BS

Boson stars (BS) are gravitationally bounded systems made of scalar particles.

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

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

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

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

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

$$ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\Omega^2\,.$$

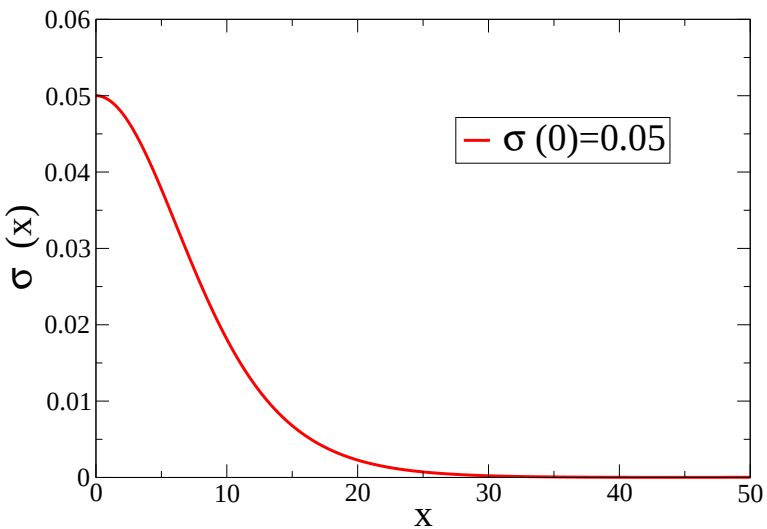
BS

$$\frac{A'}{A^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} + 1\right)\sigma^2 + \frac{\Lambda}{2}\sigma^4 + \frac{\sigma'^2}{A}\right] = 0\,,$$

$$\frac{B'}{ABx} - \frac{1}{x^2}\left(1 - \frac{1}{A}\right) - \left[\left(\frac{1}{B} - 1\right)\sigma^2 - \frac{\Lambda}{2}\sigma^4 + \frac{\sigma'^2}{A}\right] = 0\,,$$

$$\sigma'' + \left(\frac{1}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right)\sigma' + A\left[\left(\frac{1}{B} - 1\right)\sigma - \Lambda\sigma^3\right] = 0$$

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



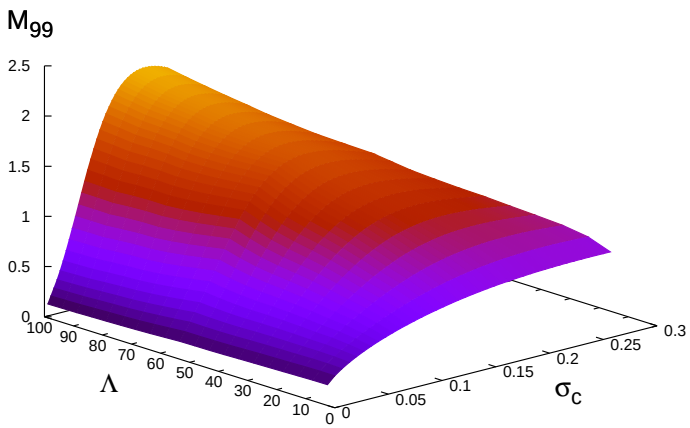
Boundary Conditions

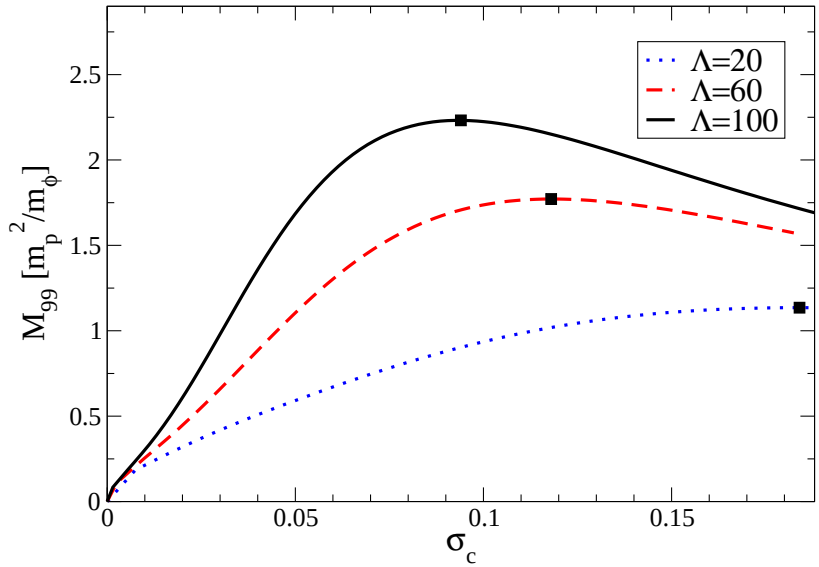
- Regular at origin
- Flat geometry at infinity
- Arbitrary $\sigma(0)$ and Λ

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

In the Newtonian limit $\rho(x) = |\sigma(x)|^2$

BS



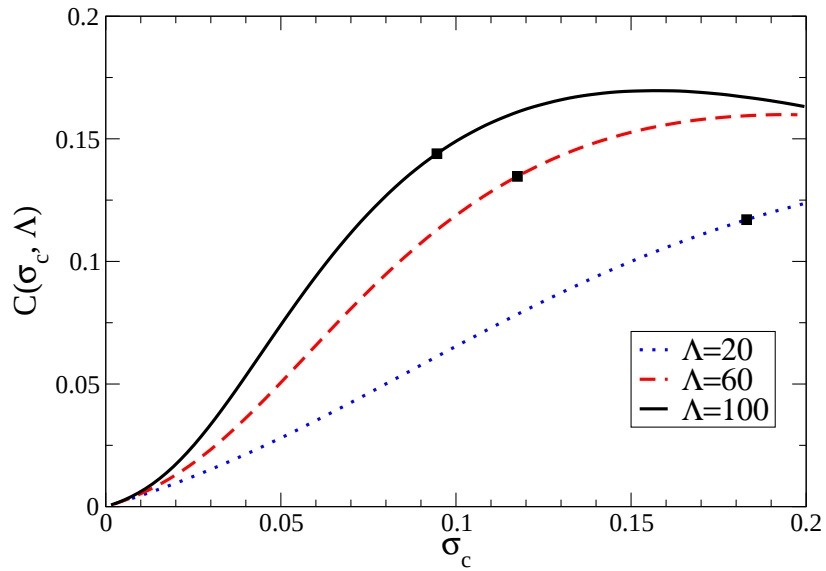


The previous stability studies of BS can be classified in two types:

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)]

BS

$$C(\sigma_c, \Lambda) \equiv \frac{M_{99}(\sigma_c, \Lambda)}{R_{99}} ,$$



what is the maximum compactness of a BS?

BS maximum compactness

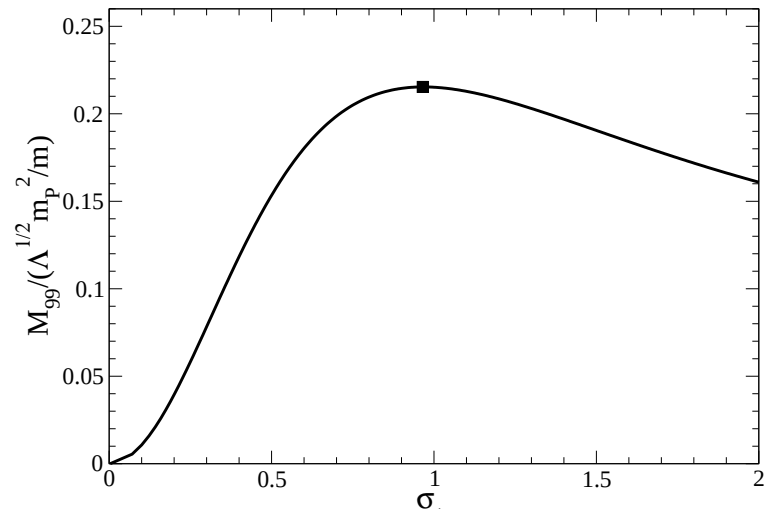
When $\Lambda >> 1$, σ decays as $\sim \Lambda^{1/2}$
This suggest a new parametrization
$\sigma_* = \Lambda^{1/2}\sigma$
$x_* = \Lambda^{-1/2}x$
Neglecting terms $O(\Lambda^{-1})$, the KG equation is solved algebraically $\left(\frac{1}{B} - 1\right)\sigma_* - \sigma_*^3 = 0$

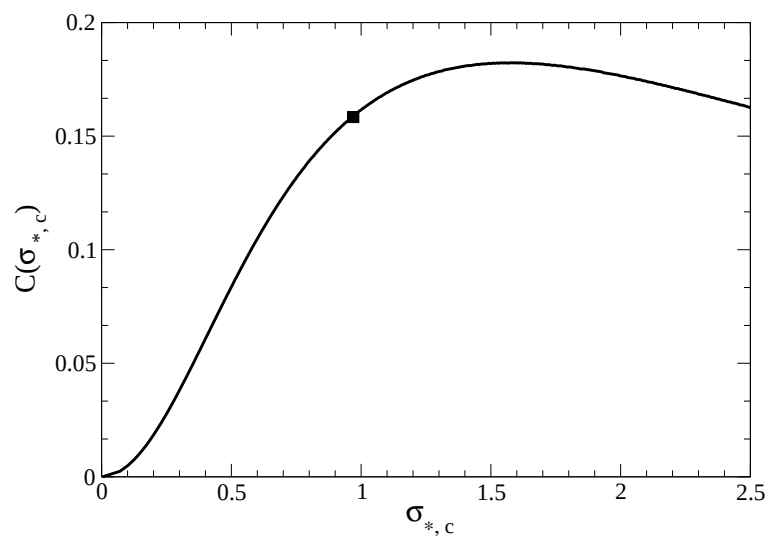
$$\sigma_* = (1/B - 1)^{1/2}$$

The equations for the metric are independent of Λ and σ_*.

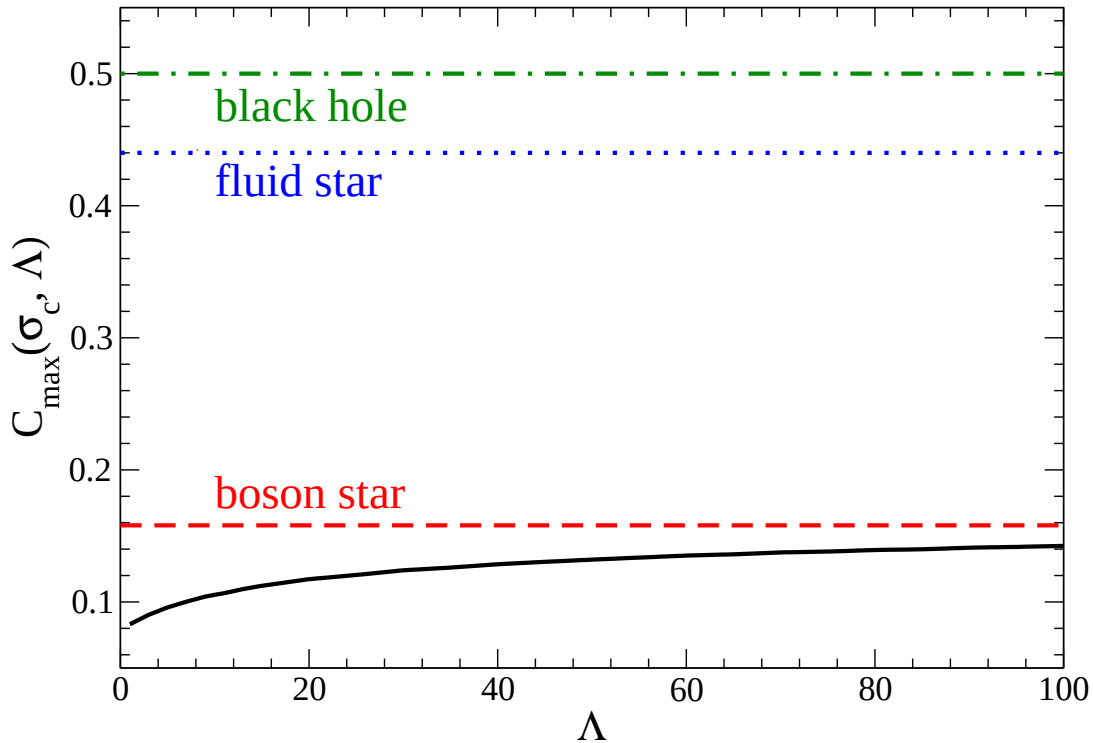
$$\frac{B'}{ABx_*} - \frac{1}{x_*^2}\left(1 - \frac{1}{A}\right) = \frac{1}{2}\left(\frac{1}{B} - 1\right)^2$$

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



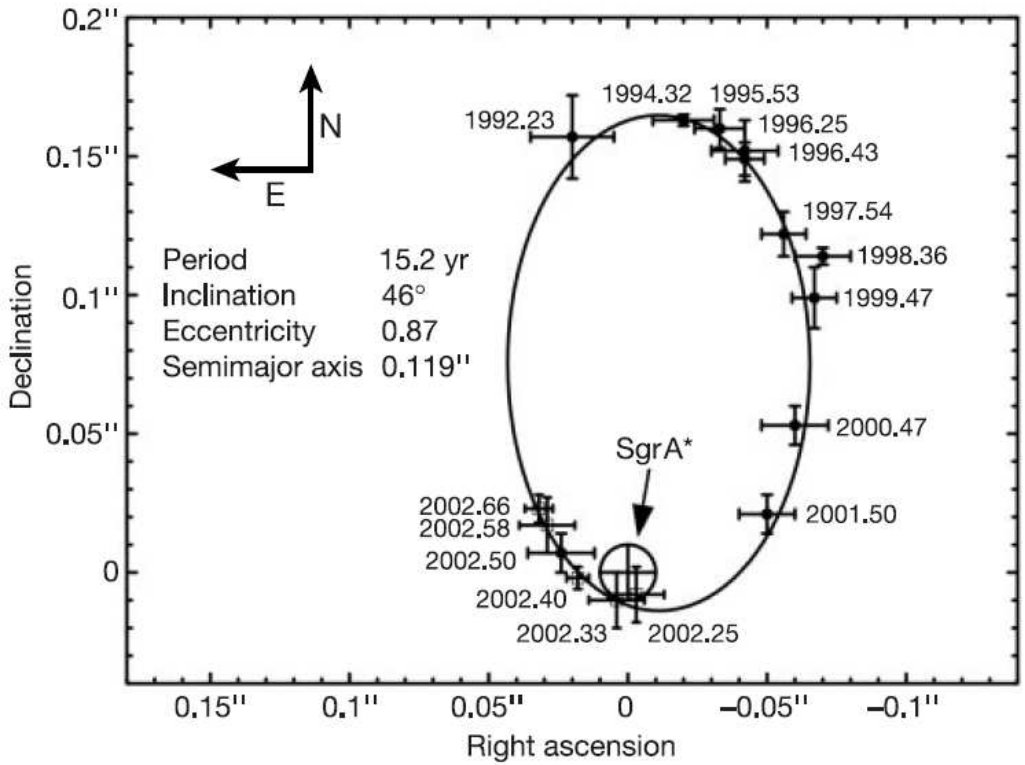


BS maximum compactness



$$0.0 < C_{BS}(\sigma_c, \Lambda) < 0.158$$

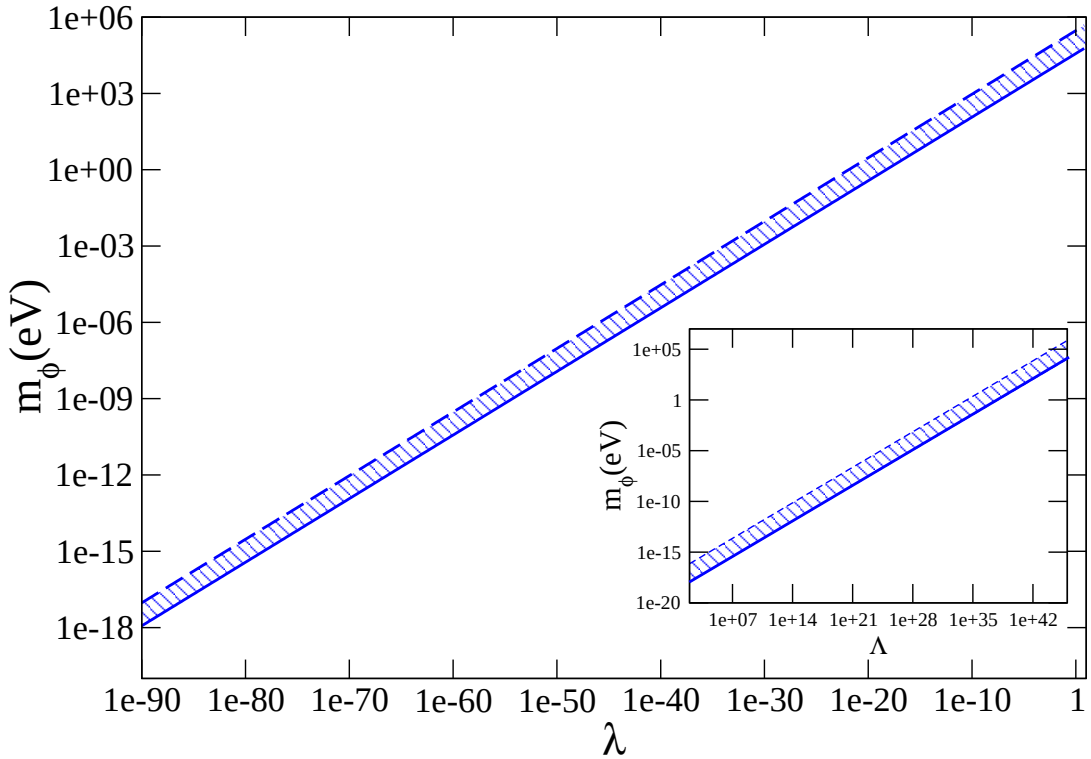
Compact objects



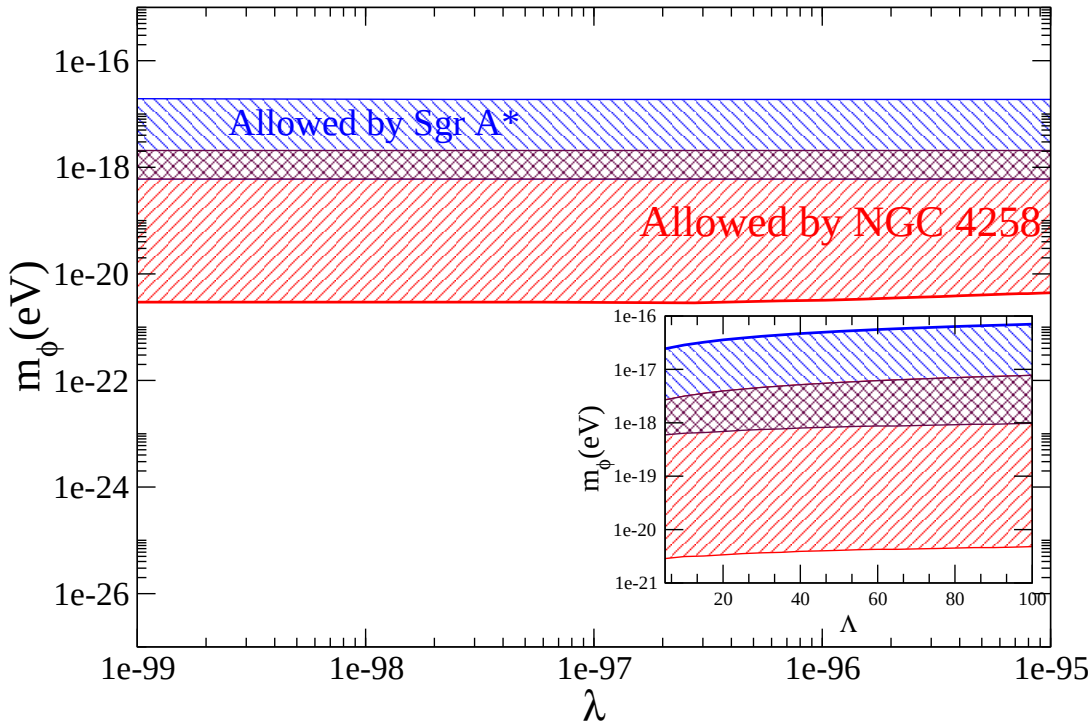
$$3{,}32 \times 10^{-4} \simeq C_{\min} \leq C_{\mathsf{BS}} \leq C_{\max} \simeq 0{,}158\,.$$

$$C_{\mathsf{min}} = \frac{M_{\mathsf{Sgr\ A^*}}}{R_{S2}} \simeq \frac{1}{3015}\,,$$

Can BS mimic Sagittarius A*?



another super massive BH?



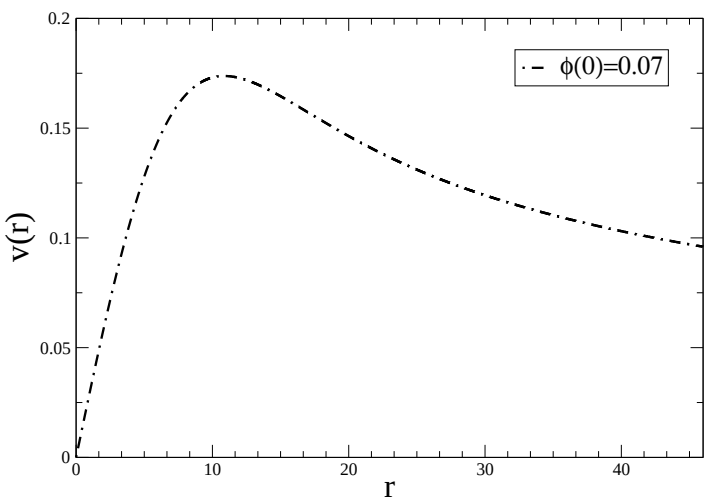
$M_{\text{NGC 4258}} = 38{,}1 \pm 0{,}01 \times 10^6\, M_\odot$, while the observations of the rotation curve require a central density of at least $4 \times 10^9\, M_\odot$ pc^{-3}, which implies a maximum radius $R_{\max} \simeq 36000\, R_{\rm S}$

Can BS model a galactic halo?

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

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

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



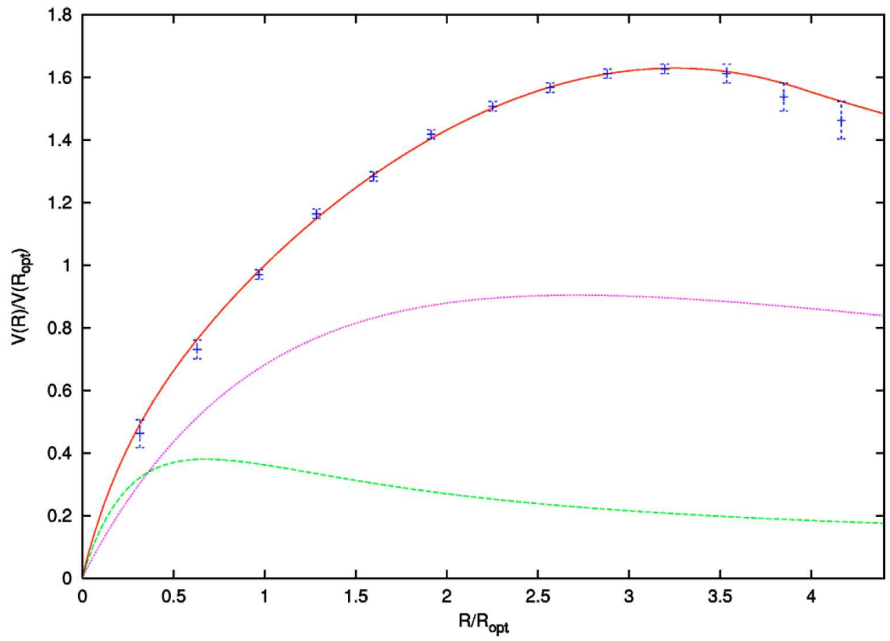
$$l \sim \sqrt{\frac{1}{\sigma(0)}}\frac{1}{m}\,, \quad \frac{v}{c} \sim \sqrt{\frac{1}{\sigma(0)}}$$

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

$$v \sim 10^{-3} c$$

Can BS model a galactic halo?

A. Arbey, J. Lesgourgues, and P. Salati, *Galactic halos of fluid dark matter*, *Phys. Rev. D* **68** (2003) 023511



Best fit to the DD0 154 rotation curve.

$$\frac{m^4}{\lambda} \simeq 50\text{eV}^4$$

Constraining scalar field properties

D. N. Spergel and P. J. Steinhardt, *Observational Evidence for Self-Interacting Cold Dark Matter*, *Phys. Rev. Lett.* **84** (2000) 3760–3763.

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

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

- Applied to scalar field DM

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

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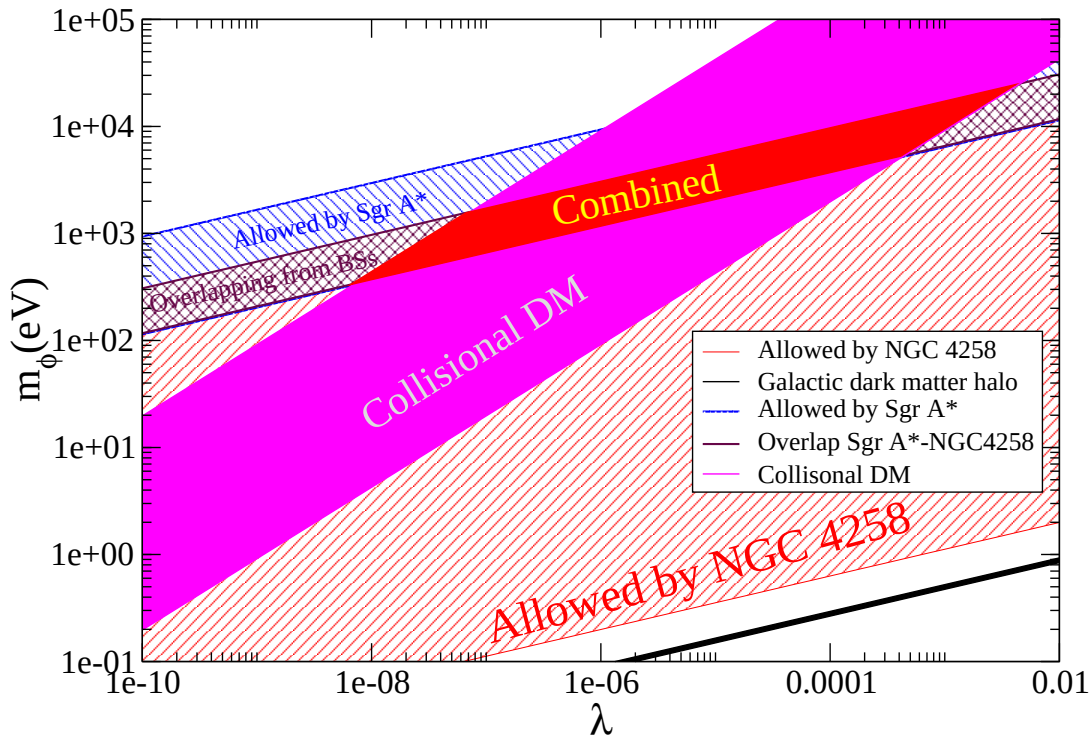
$$9{,}5 \times 10^5\ \text{eV} \lesssim \frac{m_\phi}{\lambda^{2/3}} \lesssim 9{,}5 \times 10^7\ \text{eV}\,.$$

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 $\rightarrow$ 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 λ 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.