Multi-state boson stars as a model for the galactic dark matter halo

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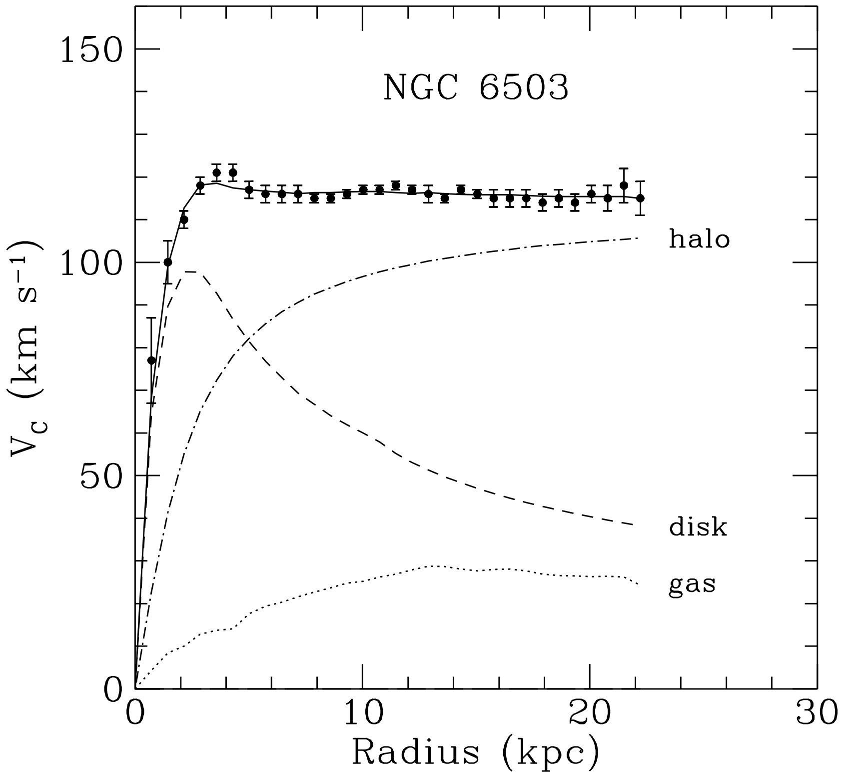
Plan of the talk

- Why boson stars?
- (One-state) Boson Stars
- Multi-State Boson stars (MSBS)
  - Equilibrium configurations
  - Stability of MSBS
- MSBS as a galactic halo

Dark matter as a motivation

The most convincing and direct evidence for dark matter on galactic scales comes from the observations of the *rotation curves* of galaxies, namely the graph of circular velocities of stars and gas as a function of their distance from the galactic center.



Dark matter as a motivation

- At galactic scales
  - *Weak modulation of strong lensing* around individual massive elliptical galaxies. This provides evidence for substructure on scales of $\sim 10^6 \mathrm{M}_\odot$
  - *Weak gravitational lensing* of distant galaxies by foreground structure
  - The *velocity dispersions of dwarf spheroidal galaxies* which imply mass–to–light ratios larger than those observed in our "local" neighborhood.
  - The *velocity dispersions of spiral galaxy satellites* which suggest the existence of dark halos around spiral galaxies, similar to our own, extending at galactocentric radii $\gtrsim 200$ kpc, i.e. well behind the optical disc. This applies in particular to the Milky Way, where both dwarf galaxy satellites and globular clusters probe the outer rotation curve.

Dark matter as a motivation

- At cosmological scales
  Starting from a cosmological model with a fixed number of parameters, the best-fit parameters are determined from the peak of the N-dimensional likelihood surface. From the analysis of the WMAP data alone:
  $\Omega_b h^2 = 0{,}024 \pm 0{,}001 \quad , \Omega_M h^2 = 0{,}14 \pm 0{,}02.$
  Including astronomical measurements of the power spectrum from large scale structure (2dFGRS) and the Lyman α forest:
  $\Omega_b h^2 = 0{,}0224 \pm 0{,}0009 \quad \Omega_M h^2 = 0{,}135^{+0{,}008}_{-0{,}009}.$

The big problem...

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 (DM) in the center of the galaxy , which is in contradiction with the flat profile obtained by the analysis of the high resolution data of low surface brightness galaxies and,
2. the fail in predicting the number of satellite galaxies around each galactic halo, exceeding far beyond what is observed around the Milky Way.

SFDM as a viable model for DM

- Another approach: The Scalar Field Dark Matter model (SFDM) The Dark Matter is modeled by a scalar field with a ultra-light associated 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)

SFDM estructures & Boson Stars

1. As the universe expands, the scalar fields cool together with the rest of the particles until they decouple from the rest of the matter. After that, only the expansion of the universe will keep cooling the scalar field. If the scalar field fluctuations is under the critical temperature, the object will collapse as a BEC.
2. The gravitational collapse of bosons clouds is the mechanism that could lead to a Boson Star. In this case the scalar field is collapsed in the same state, leading a coherent scalar field configuration. The system is well described by a classical field.

Boson Stars

R. Ruffini, S. Bonazzola Phys. Rev. 187, 1767 (1969).

- The semi-classical limit

$$G_{\alpha\beta} = 8\pi G \langle Q|\hat{T}_{\alpha\beta}|Q\rangle$$

$$\hat{T}_{\alpha\beta} = \partial_\alpha \hat{\Phi} \partial_\beta \hat{\Phi} - \frac{1}{2} g_{\alpha\beta} \left(\partial^\sigma \hat{\Phi} \partial_\sigma \hat{\Phi} + \mu^2 \hat{\Phi}^2 \right) ,$$

$$\hat{\Phi} = \sum_{nlm} \left[\hat{b}_{nlm} \Phi_{nlm}(t, \mathbf{x}) + \hat{b}^\dagger_{nlm} \Phi^*_{nlm}(t, \mathbf{x}) \right] ,$$

$$|Q\rangle = |N_{100}, N_{200}, N_{210}, \ldots\rangle ,$$

Due to orthogonality of the quantum states:

$$\langle Q|\hat{T}_{\alpha\beta}|Q\rangle = \sum_{n=1}^{\infty} \sum_{l=1}^{n-1} \sum_{m=-l}^{l} \langle N_{nlm}|\hat{T}_{\alpha\beta}|N_{nlm}\rangle ,$$

and the Einstein eq. reads

$$G_{\alpha\beta} = 16\pi G \sum_{n,l,m} N_{nlm} \, T_{\alpha\beta(nlm)}$$

Boson Stars

- The Klein-Gordon equation:

$$\left(\Box - \mu^2\right) \hat{\Phi}(t, \mathbf{x}) = 0$$

but remember

$$\hat{\Phi} = \sum_{nlm} \left[\hat{b}_{nlm} \Phi_{nlm}(t, \mathbf{x}) + \hat{b}^{\dagger}_{nlm} \Phi^{*}_{nlm}(t, \mathbf{x})\right] ,$$

and then, each field coefficient satisfies:

$$\left(\Box - \mu^2\right) \hat{\Phi}_{nlm}(t, \mathbf{x}) = 0$$

- A Boson star is a solution of Einstein + Klein-Gordon eqs.

One-State Boson Stars

Let's take only one-state of the scalar field and we will assume:

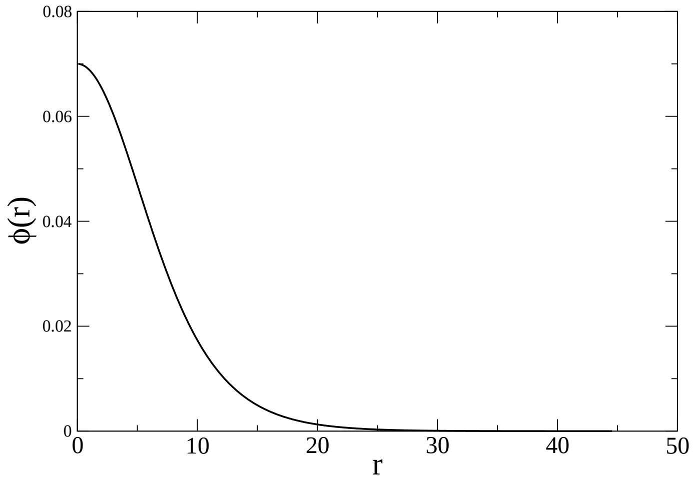
- Spherically, static metric

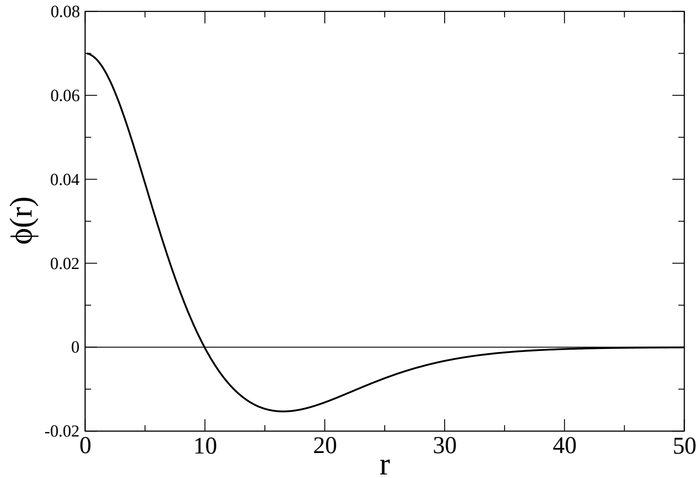
$$ds^2 = -\alpha^2(t,r)dt^2 + a^2(t,r)dr^2 + r^2 d\Omega$$

- Harmonic dependence on the fields, and $l = m = 0$;

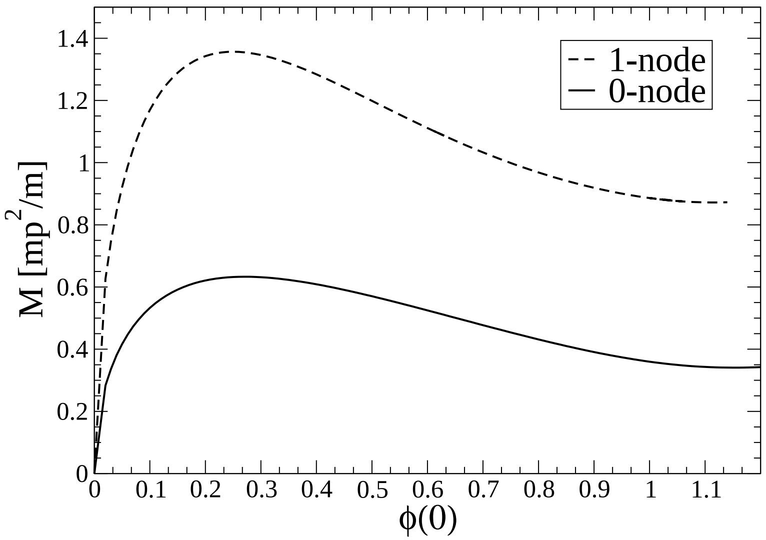
$$\sqrt{8\pi G}\,\Phi_{nlm}(t,\mathbf{x}) \to e^{-i\gamma t}\phi(r)\,,$$

Well known solutions for one state:





Stability of one state BS



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

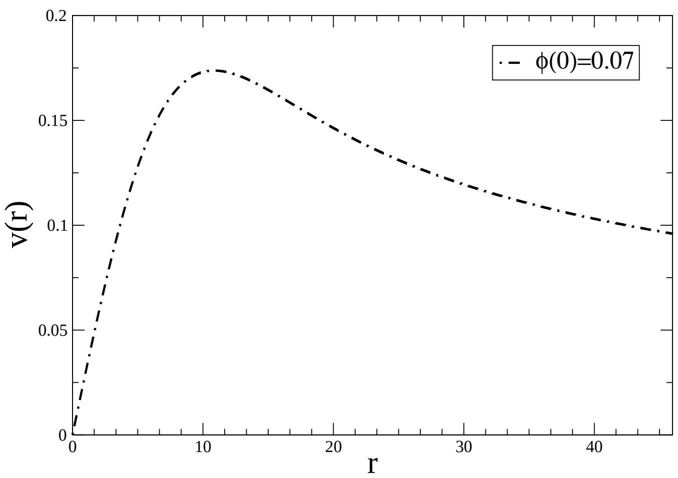
1. studies that consider infinitesimal perturbations for which the number of particles is conserved. Linear perturbation theory [M. Gleiser, R. Watkins, Nucl. Phys. **B319**, 733 (1989)]

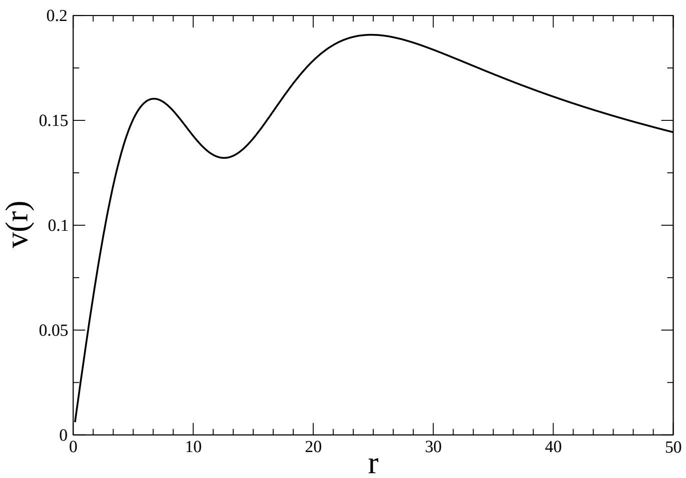
2. studies that consider finite perturbations and there is no conservation in the number of particles. Finite perturbations are considered, [E. Seidel, W. Suen, Phys. Rev. **D42**, 384 (1990), J. Balakrishna, E. Seidel, W. Suen, Phys. Rev. **D58**, 104004 (1998)]

Can one-state BS be a galactic halo?

For static spherically symmetric metric, the tangential velocity squared of a point particle on circular orbit is

$$v(r)^2 = 2\alpha\alpha'$$





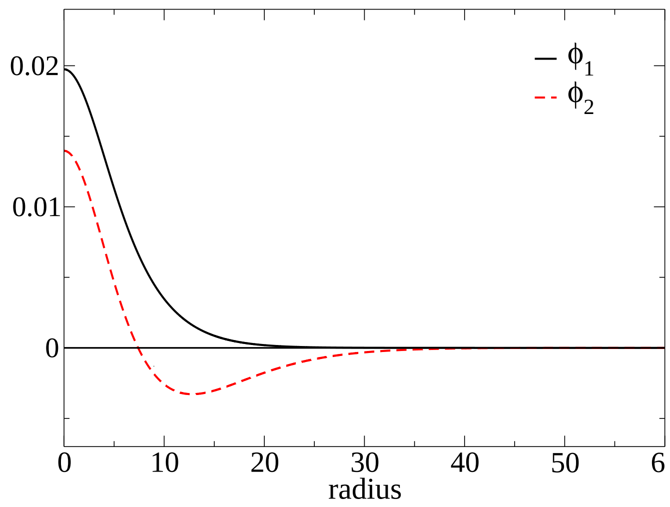
Multi-State Boson Stars

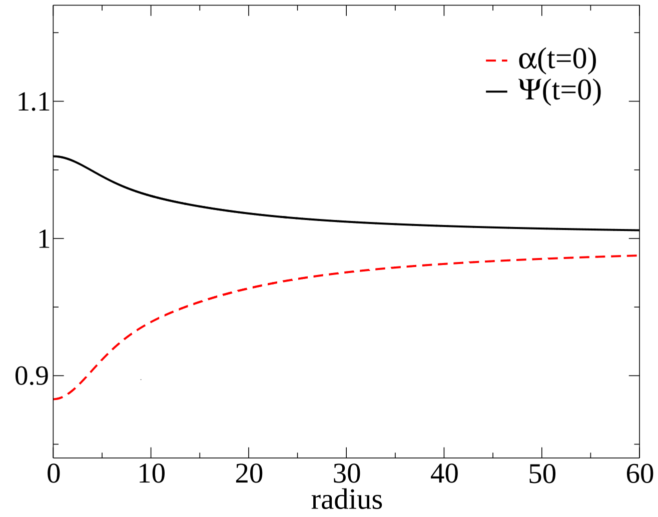
Now, let's take **two-states: the ground and the first excited state**, and let's construct the Boson star produced for this multi-state field.

$$\begin{aligned}
\partial_r a &= \frac{a}{2}\left\{-\frac{a^2-1}{r} + 4\pi r \sum_{n=1}^{N}\left[\left(\frac{\omega_n^2}{\alpha^2}+m^2\right)a^2\phi_n^2 + \Phi_n^2\right]\right\}, \\
\partial_r \alpha &= \frac{\alpha}{2}\left\{\frac{a^2-1}{r} + 4\pi r \sum_{n=1}^{N}\left[\left(\frac{\omega_n^2}{\alpha^2}-m^2\right)a^2\phi_n^2 + \Phi_n^2\right]\right\}, \\
\partial_r \phi_n &= \Phi_n, \\
\partial_r \Phi_n &= -\left\{1 + a^2 - 4\pi r^2 a^2 m^2\left(\sum_{s=1}^{N}\phi_s^2\right)\right\}\frac{\Phi_n}{r} - \left(\frac{\omega_n^2}{\alpha^2}-m^2\right)\phi_n\, a^2.
\end{aligned}$$

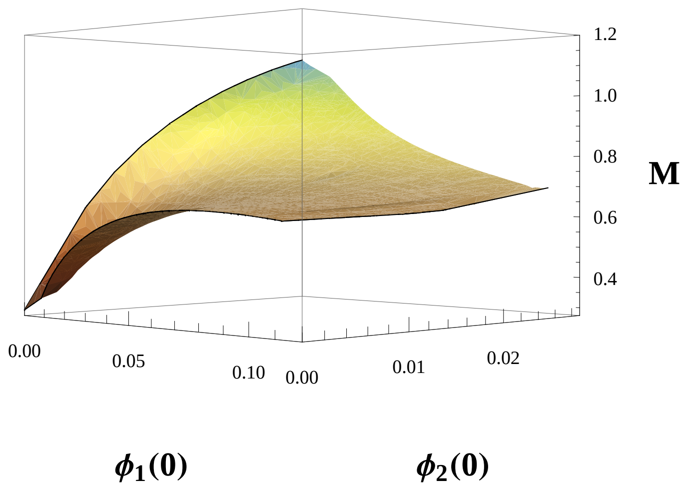
for $n = 0, 1$. It was assumed harmonic dependence on time $\Psi_n(x,t) = e^{-iw_n t}\phi_n(r)$ and static, spherically symmetric metric.

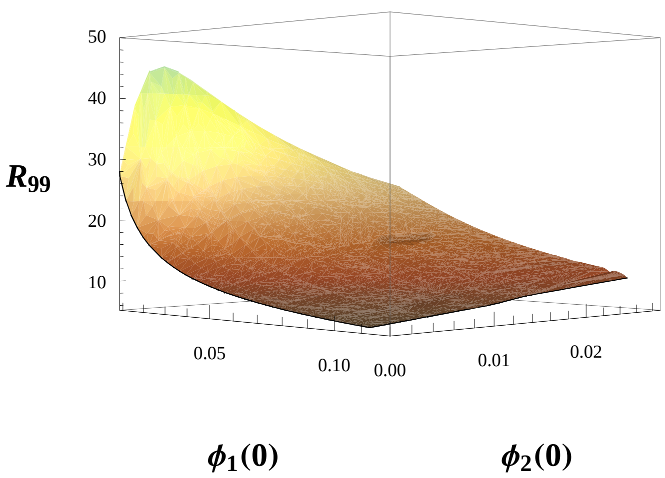
Multi-State Boson Stars





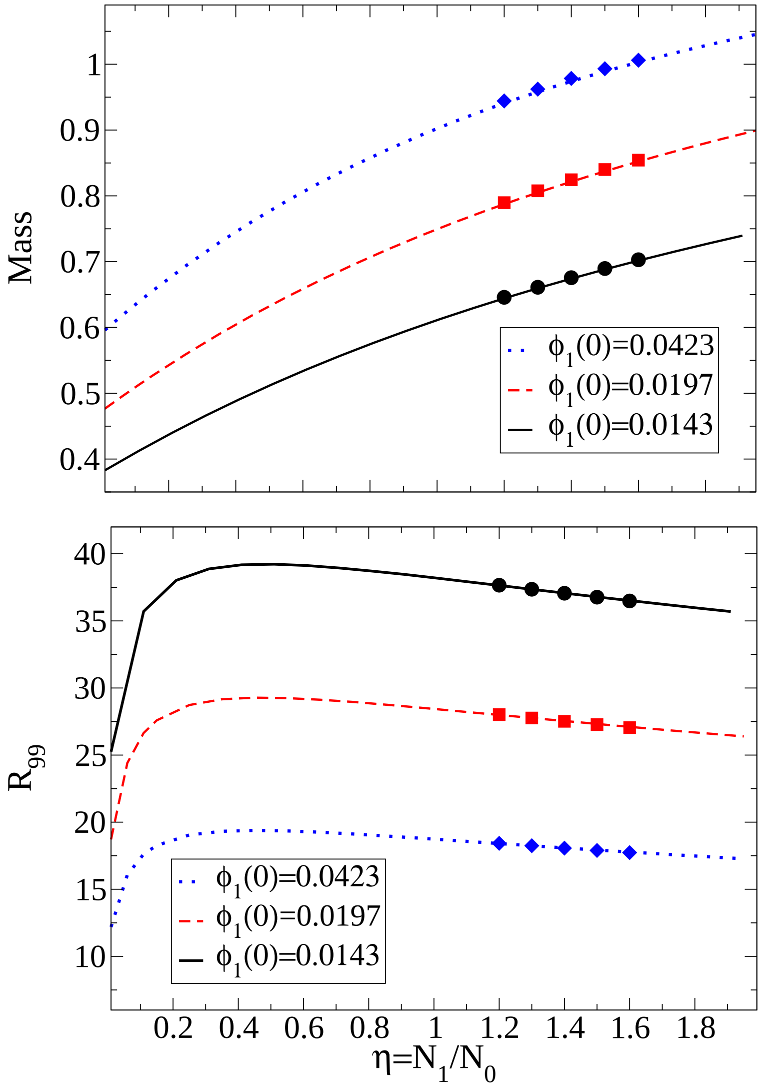
Equilibrium configurations

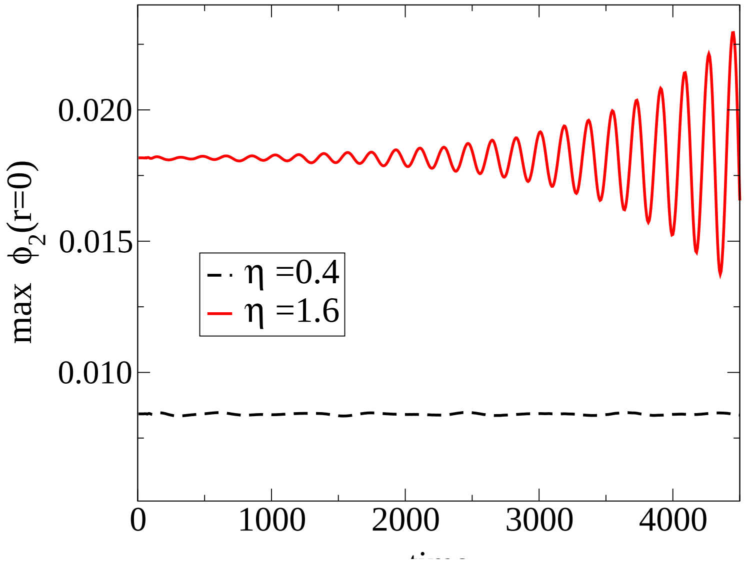


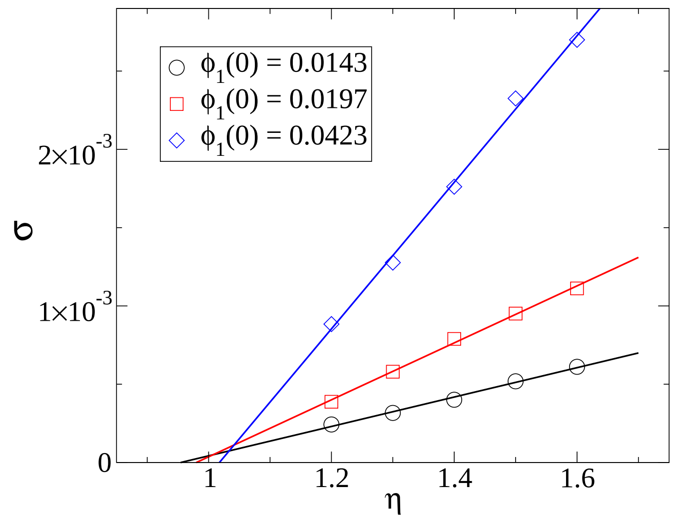


$\omega_1, \omega_2, N_1, N_2$

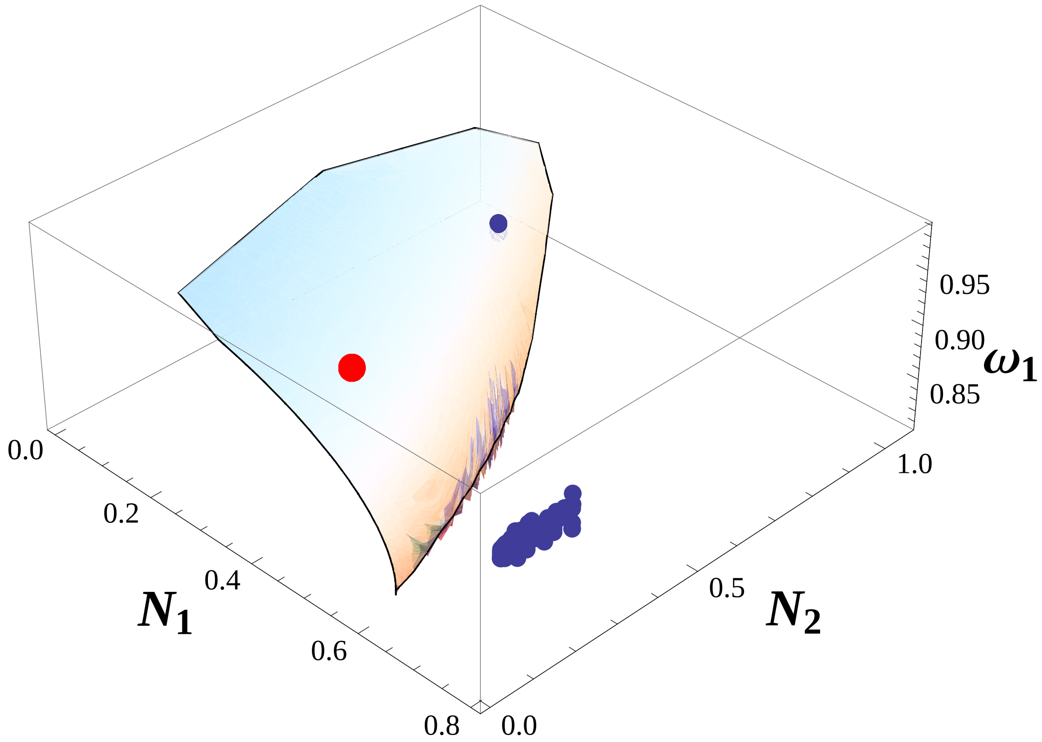
Are MSBS stable?







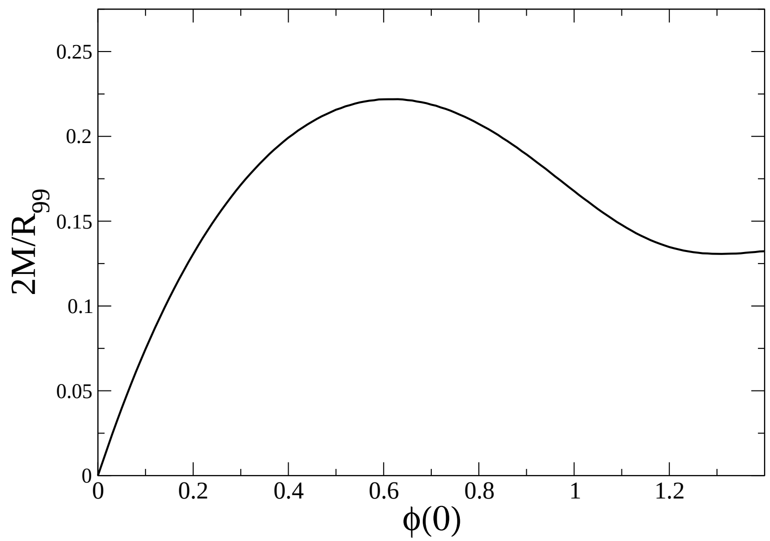
Are MSBS stable?



	ω_1	ω_2	$N^{(1)}$	$N^{(2)}$
Equilibrium	0.87	0.94	0.604	0.126
Evolved Δ x = 0.020	$0{,}864 \pm 0{,}004$	$0{,}936 \pm 0{,}006$	0.71	0.16
Evolved Δ x = 0.015	$0{,}862 \pm 0{,}003$	$0{,}934 \pm 0{,}010$	0.706	0.126
Evolved Δ x = 0.010	$0{,}872 \pm 0{,}010$	$0{,}940 \pm 0{,}005$	0.696	0.124

Is necessary a Relativistic MSBS?

- Compactness of a single MSBS



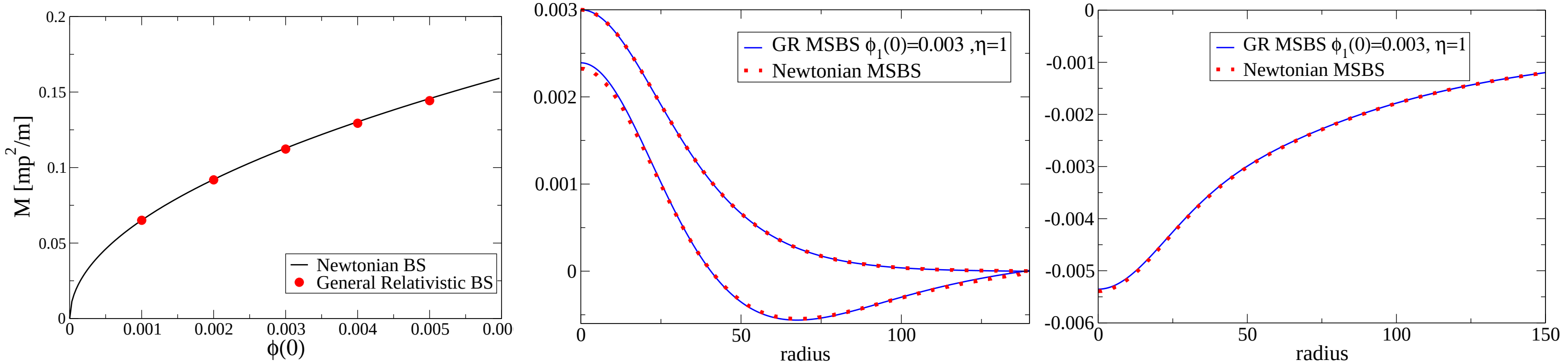
A typical DM halo: Mass $\sim 10^{12} M\odot$, and $R \sim 100$ KpcS.

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

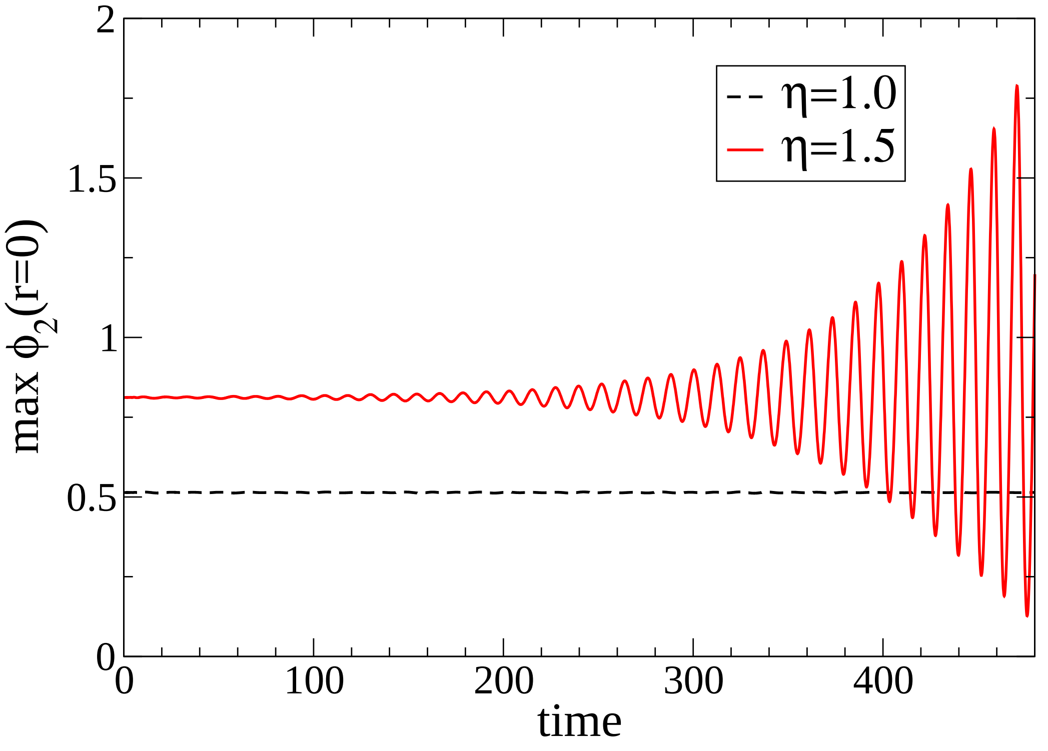
Newtonian MSBS

$$\frac{1}{r^2}\frac{\partial^2(r^2 U)}{\partial r^2} = \sum_{n=1}^{\mathcal{I}} |\Psi_n|^2 \,,$$

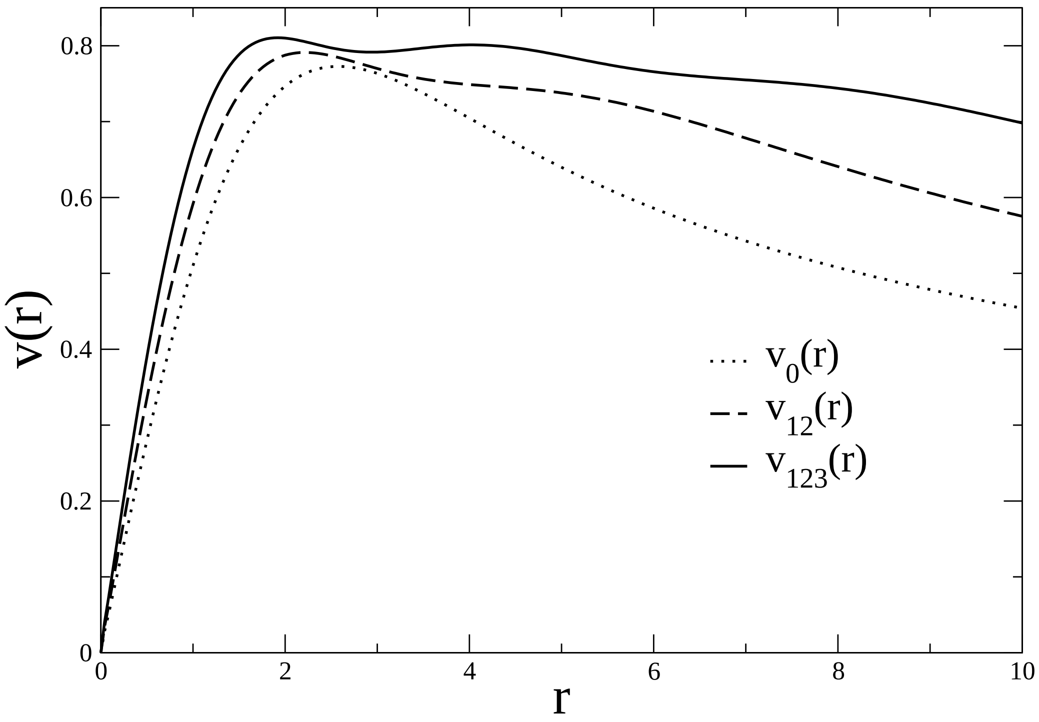
$$i\frac{\partial \Psi_n}{\partial t} = -\frac{1}{2r^2}\frac{\partial^2(r^2\Psi_n)}{\partial r^2} + U\Psi_n \,, \quad n = 1,..,\mathcal{I}$$



Stabilitv of Newtonian MSBS



Towards a realistic DM halo



By allowing more general MSBS, there are extra free parameters coming from the different fractions between the ground and excited states. These parameters change not only the total mass, but also the compactness of the final object. The extra degrees of freedom may allow a better fit of the models to different galaxies.

Conclusions

- It has been done a generalization of Boson stars. It consists in the inclusion of several states of the scalar field.
- Evidence of their stability under finite perturbations is presented.
- It has been obtained the Newtonian limit of MSBS
- MSBS can be used as a model of the galactic dark matter halo