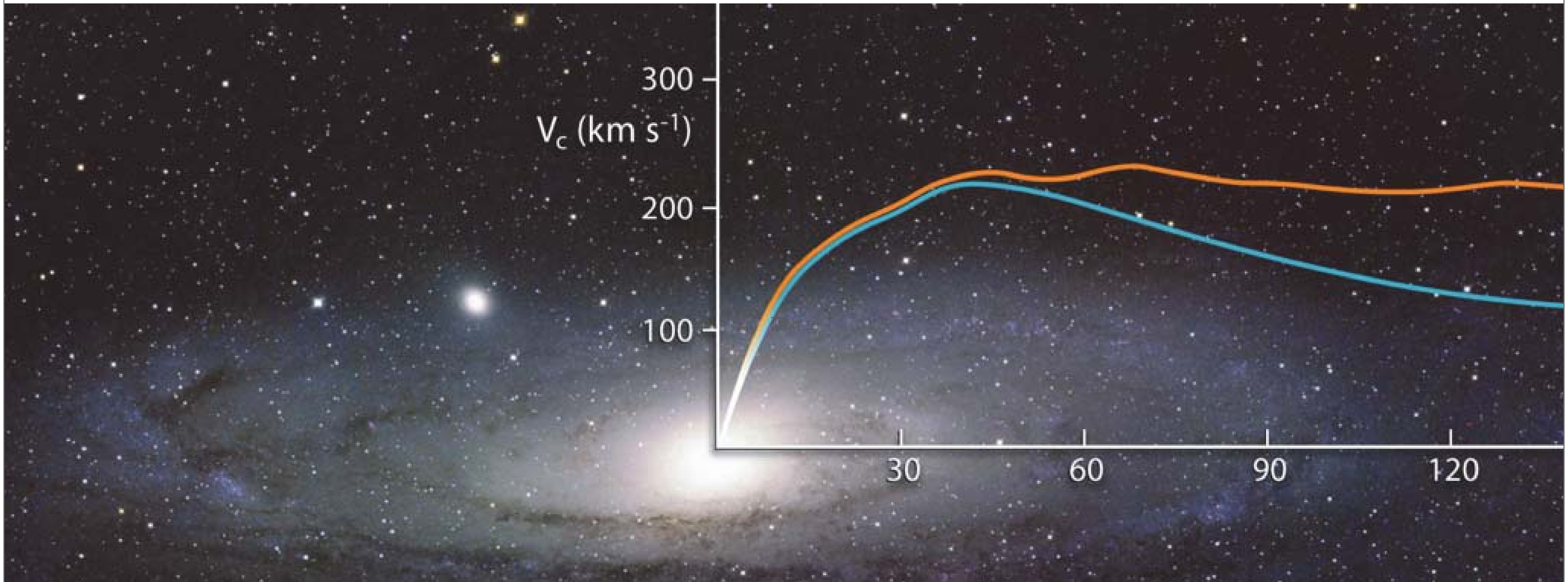
Boson stars as galactic dark matter halos



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Outline

Multi-state Boson stars (MSBS)

- Motivation
- The Einstein-Klein-Gordon system
- Initial data for MSBS
- Stable and unstable configurations
- The fate of multi-state configurations
- Rotation curves
- Conclusions

Work in progress: mixed Boson-Fermion stars (MFBS)

- Questions to be addressed
- The EKG + fluid equations
- Initial data for MFBS
- Future work

Motivation

The process of galaxy formation ? The nature of dark matter ?

Dark matter (DM) in galaxies: disagreement between the light and mass distribution.

Rotational curves problem: the radial profile of gravitating matter does not match that of the sum of all luminous components.

Cold Dark Matter Models

Weakly interacting massive particles (WIMP)

- cuspy density profile of DM in the galaxy
- the number of satellite galaxies around each galactic halo

Motivation

Scalar field dark matter models

The DM particle is an ultralight massive spinless boson ($m \sim 10^{-23}$ eV)

Further Analysis of a Cosmological Model with Quintessence and Scalar Dark Matter (Tonatiuh Matos and L. Arturo Urena-Lopez 2000)

Bosons form condensates described by a coherent scalar field (Boson stars) :

- the gravity attraction balances the dispersive character of the scalar field
- all particles in ground state - stable, but not flat Rotation Curves
- all particles in excited state - unstable, flat Rotation Curves

Multi-state boson stars = bosons in different coexisting states

The Einstein-Klein-Gordon system

Einstein equations:
$$
\begin{aligned}
R_{ab} &- \frac{R}{2} g_{ab} = 8\pi T_{ab}, \\
T_{ab} &= \sum_{n=1}^{P} T_{ab}^{(n)}, \\
T_{ab}^{(n)} &= \frac{1}{2}\left[\partial_a \bar{\phi}^{(n)} \partial_b \phi^{(n)} + \partial_a \phi^{(n)} \ \partial_b \bar{\phi}^{(n)}\right] \\
&- \frac{1}{2} g_{ab}\left[g^{cd}\partial_c \bar{\phi}^{(n)} \partial_d \phi^{(n)} + V\left(|\phi^{(n)}|^2\right)\right].
\end{aligned}
$$

Klein-Gordon equations:
$$
\begin{aligned}
\Box \phi^{(n)} &= \frac{dV}{d|\phi^{(n)}|^2}\phi^{(n)} \\
V(|\phi^{(n)}|^2) &= m^2 \ |\phi^{(n)}|^2 .
\end{aligned}
$$

Regularization of the Z3 system

Spherically symmetric spacetime:

$$ds^2 = -\alpha^2 dt^2 + g_{rr} dr^2 + r^2 g_{\theta\theta} d\Omega^2$$

Redefine the variables:

$$\begin{aligned} \tilde{g}_{\theta\theta} &= r^2 g_{\theta\theta}, \\ \tilde{D}_{r\theta}{}^{\theta} &= D_{r\theta}{}^{\theta} + \frac{1}{r} \end{aligned}$$

Eliminate the $1/r^2$ terms coming from the coordinate singularity:

$$\tilde{Z}_r = Z_r + \frac{1}{4r}\left(1 - \frac{g_{rr}}{g_{\theta\theta}}\right).$$

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Initial data for multi-state Boson stars

Polar-areal coordinates:

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

Harmonic ansatz:

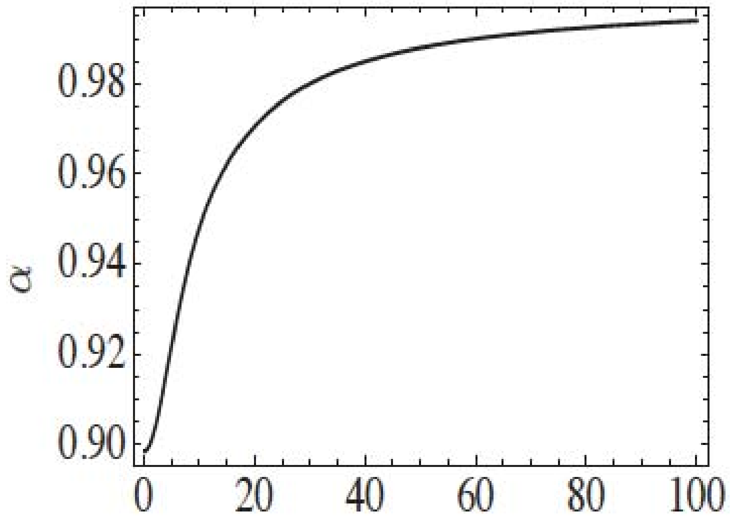
$$\phi^{(n)}(t,r) \quad = \quad \phi_n(r)\, e^{-i\omega_n t}.$$

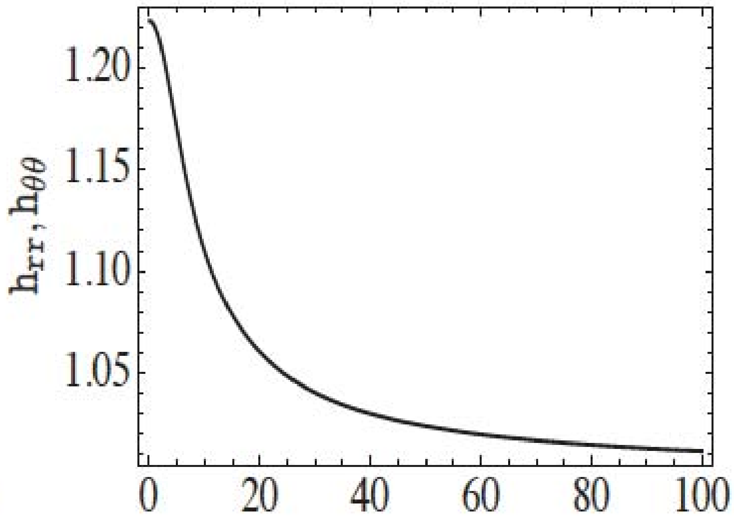
K = 0 and the momentum constraint is satisfied;

- Provide equilibrium equations for $\{\phi_n\,,\Phi_n\,,a\,,\alpha\}$;
- Impose regularity conditions at the origin and asymptotic flatness;
- Solve a 3-parameter shooting problem $\{\phi_n(0)\,,\omega_n\,,\alpha(0)\}$;

Initial data for MSBS: Fraction 0.4

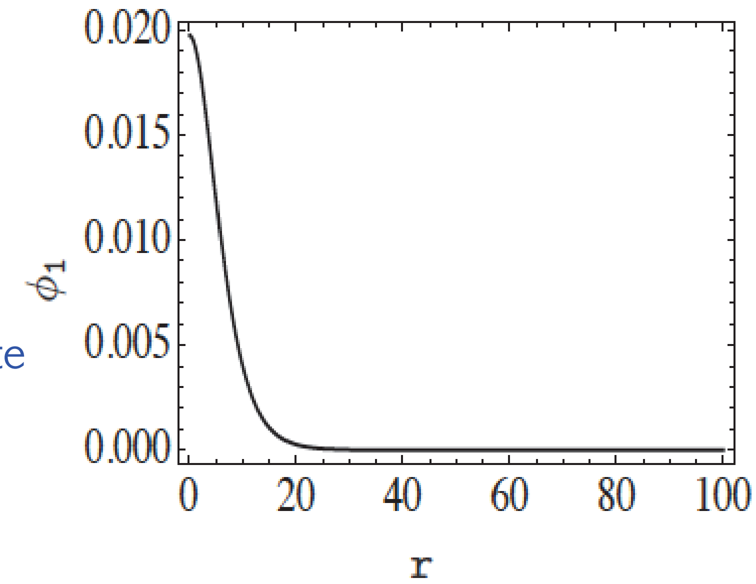
The lapse function

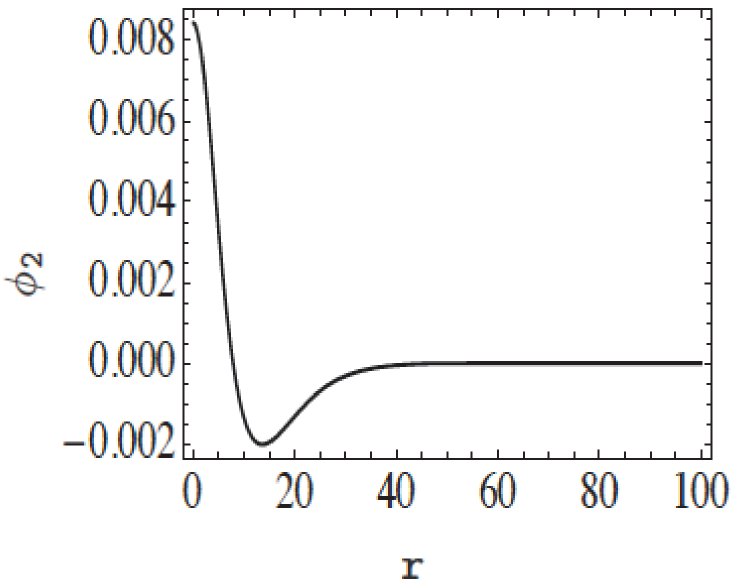




The coefficients of the spatial metric

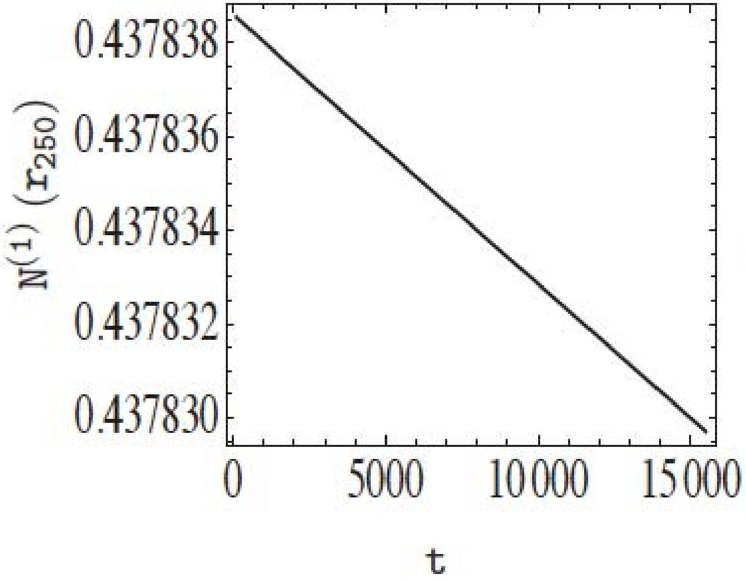
Scalar field in the ground state

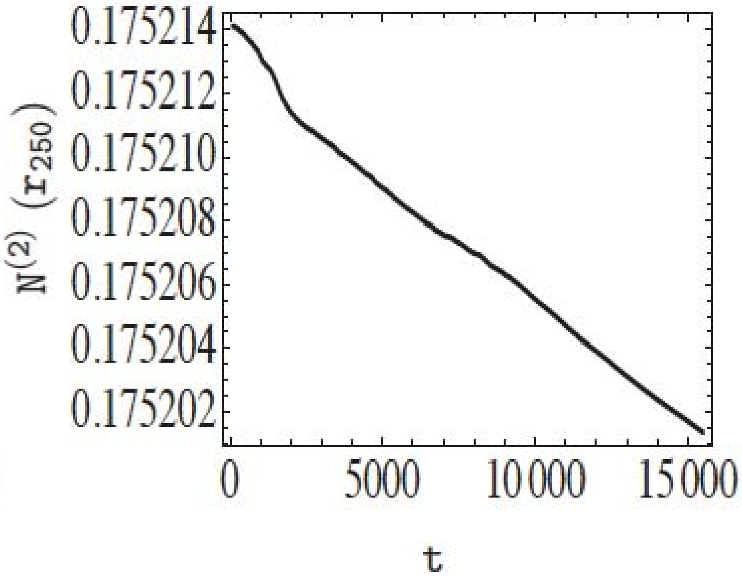




Scalar field in the first excited state

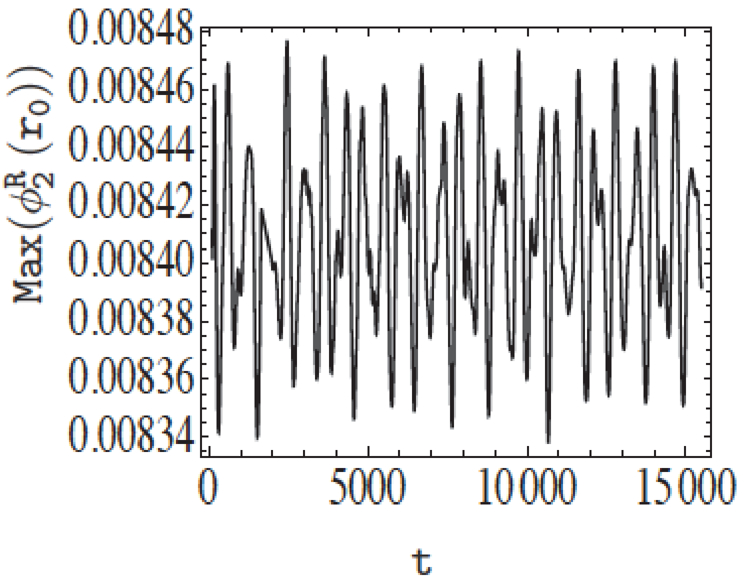
Stable MSBS: Fraction 0.4

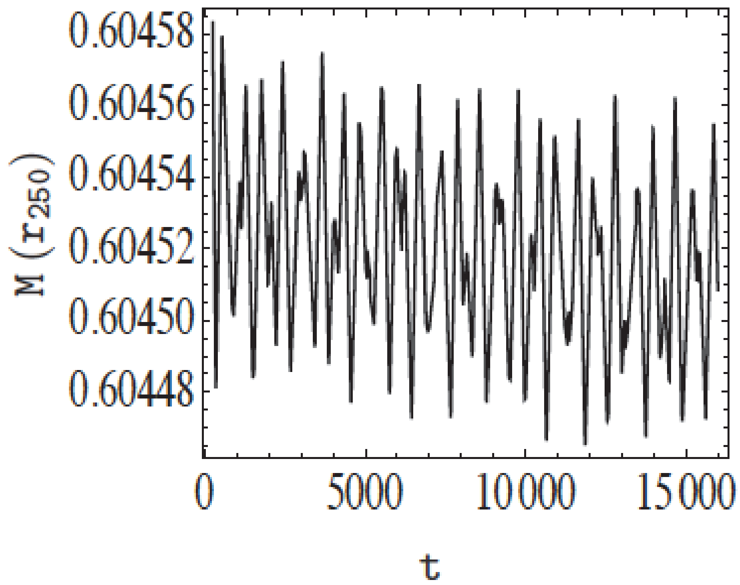




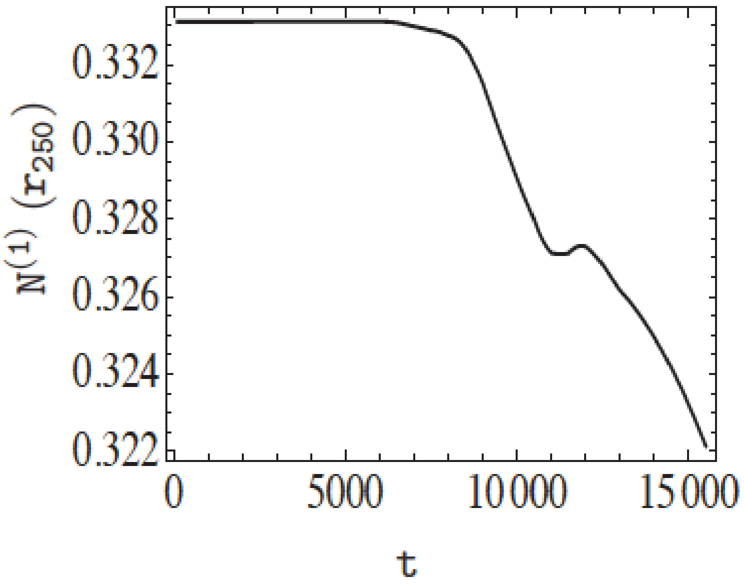
- 0.004% in the total number of particles N1, N2.

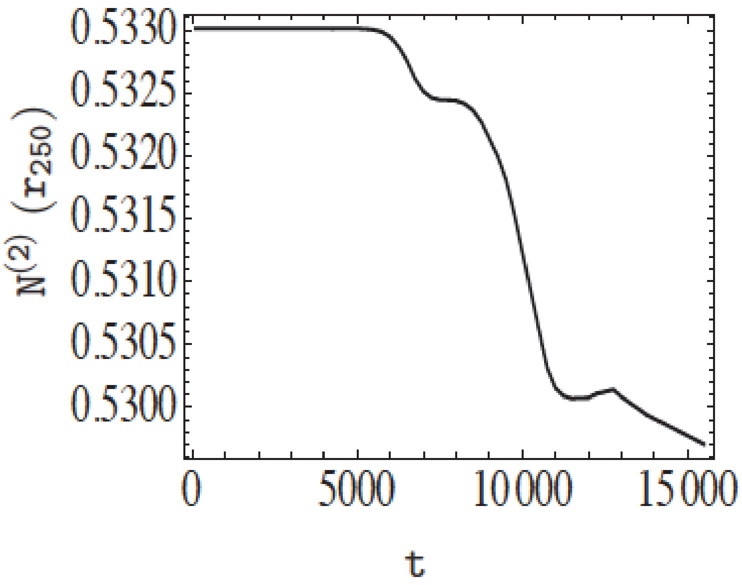
Low amplitude oscillations in the maximum value of the scalar field and the mass M.





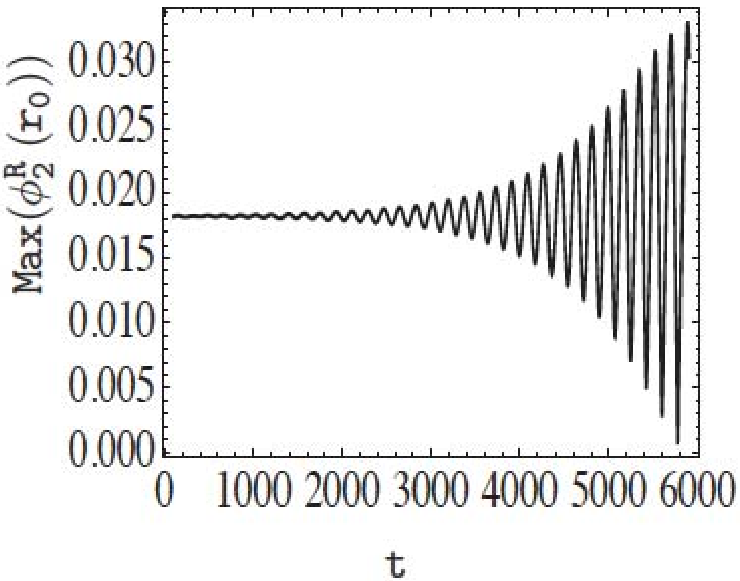
Unstable MSBS: Fraction 1.6

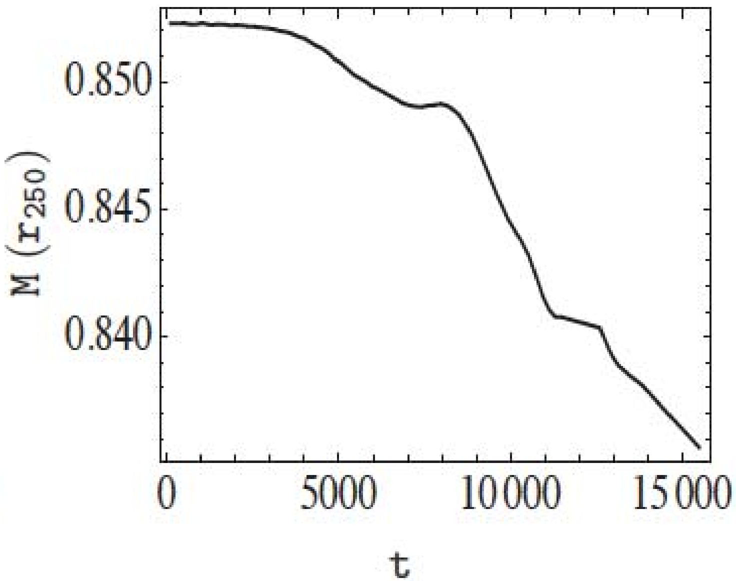




- 2%

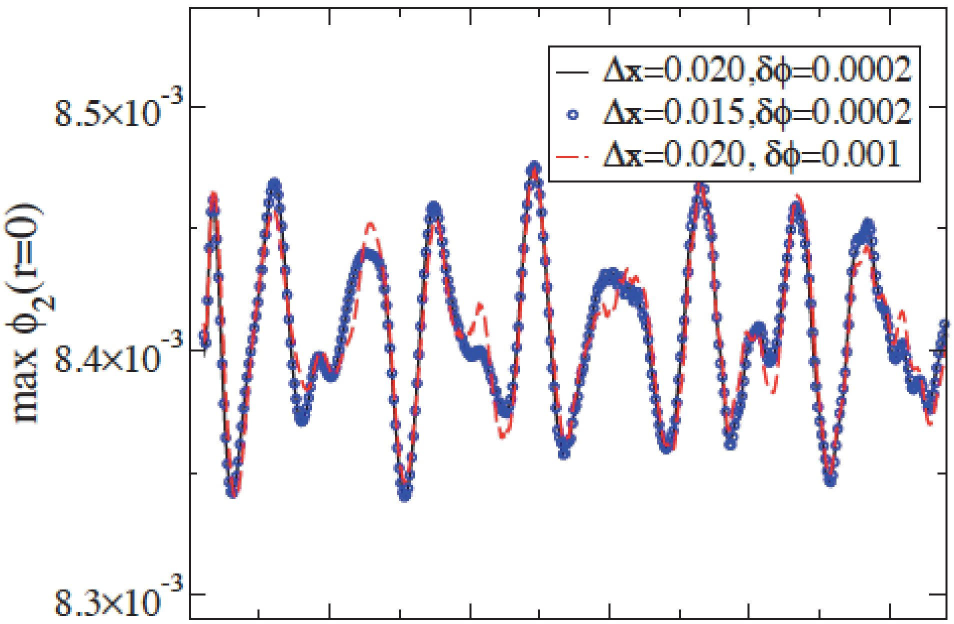
in the total number of particles N1, N2 and the mass M





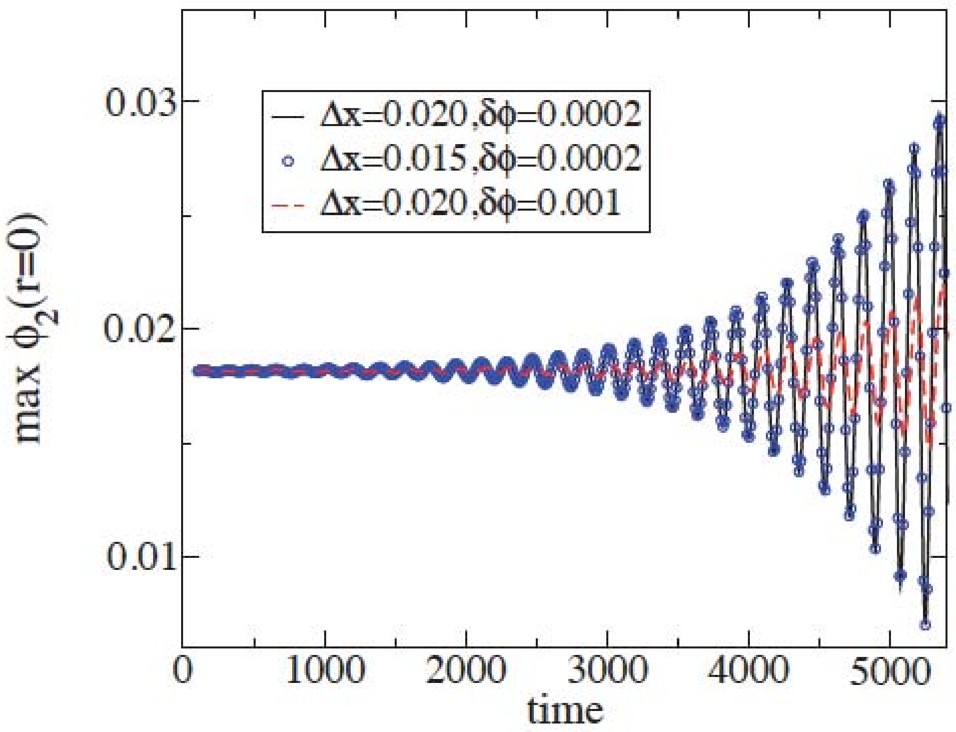
High amplitude oscillations: $A = \exp(\sigma t)\ cos(\omega t + \varphi)$

Stability under radial perturbations



Maximum central value of the scalar field for fraction 0.4.

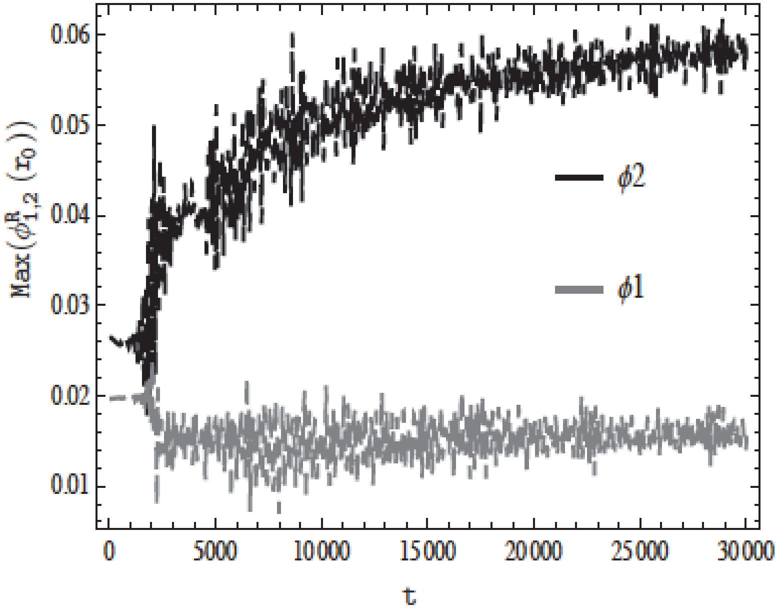
Stable against various radial perturbations with various amplitudes, at different resolutions.



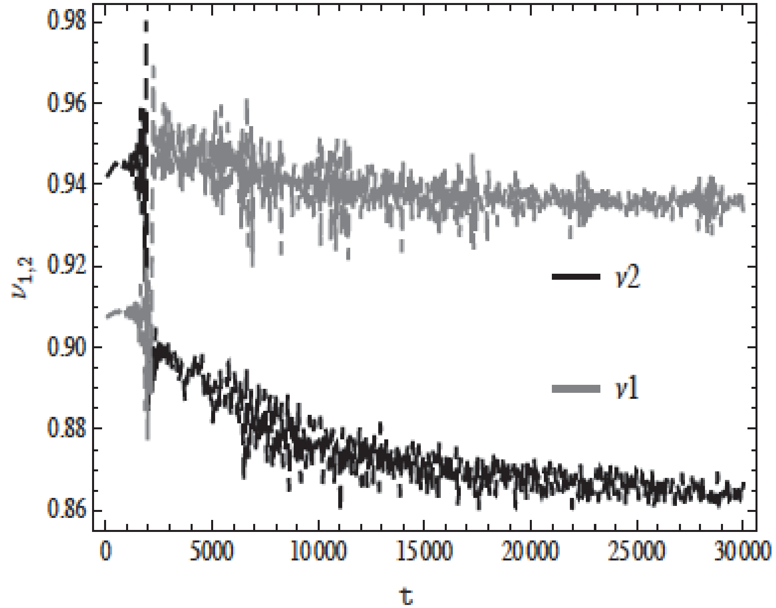
Maximum central value of the scalar field for fraction 1.6.

Unstable configuration. The instability can be triggered sooner by radial perturbations.

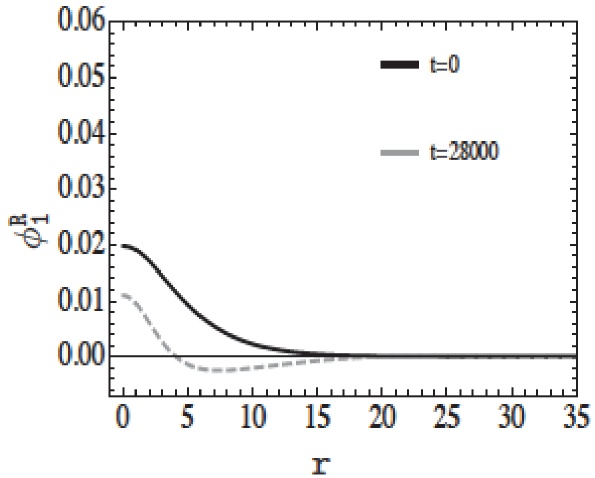
Final state of MSBS: Fraction 3.0



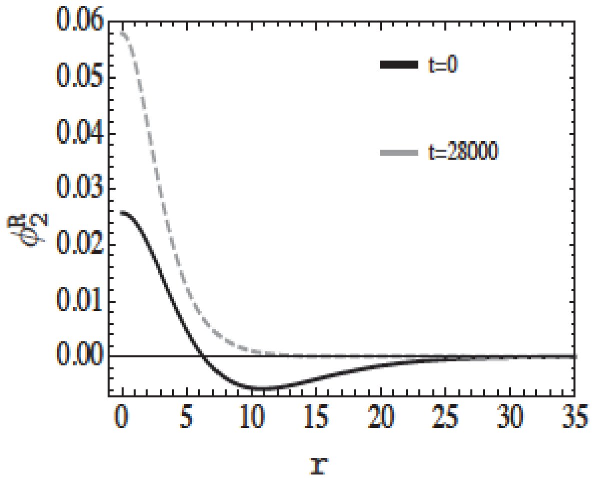
Maxima of the central value of the scalar fields.



The frequencies of the scalar field oscillations.



Initially ground state, later excited



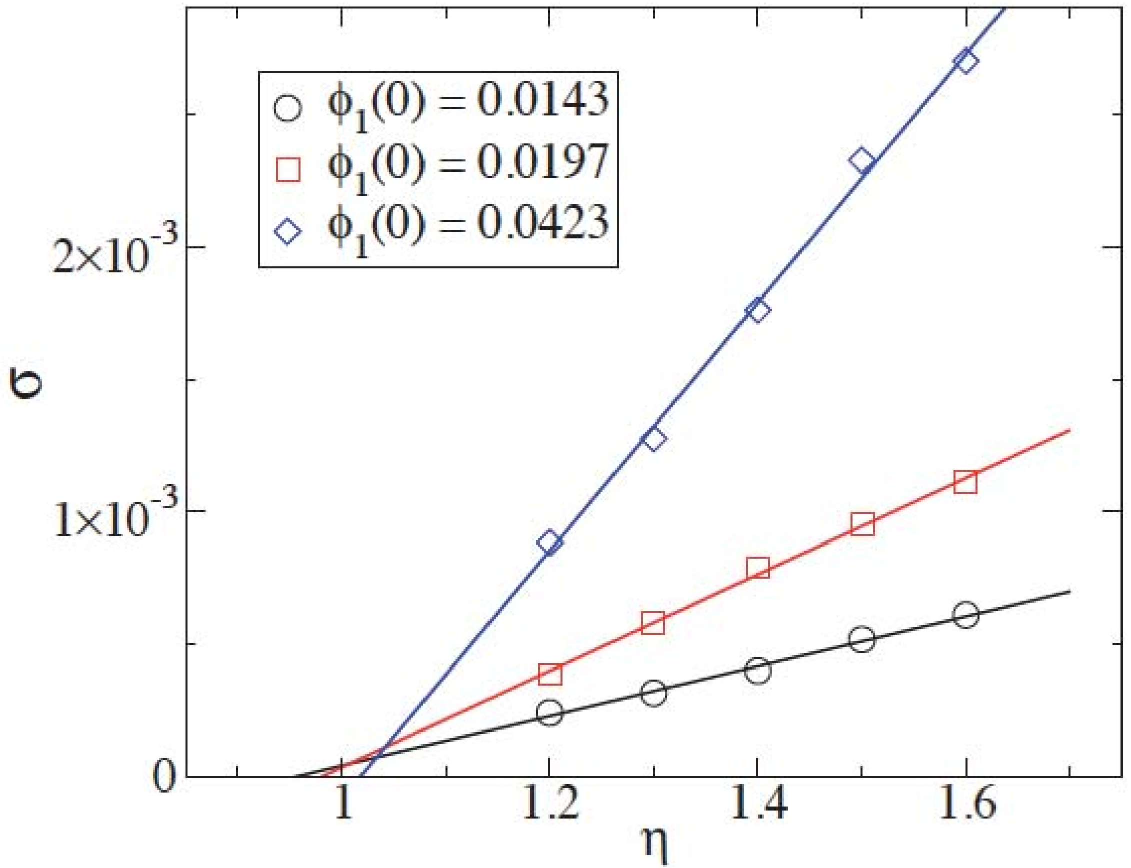
Initially excited, later ground state

Flip-Flop of the ground - excited states.

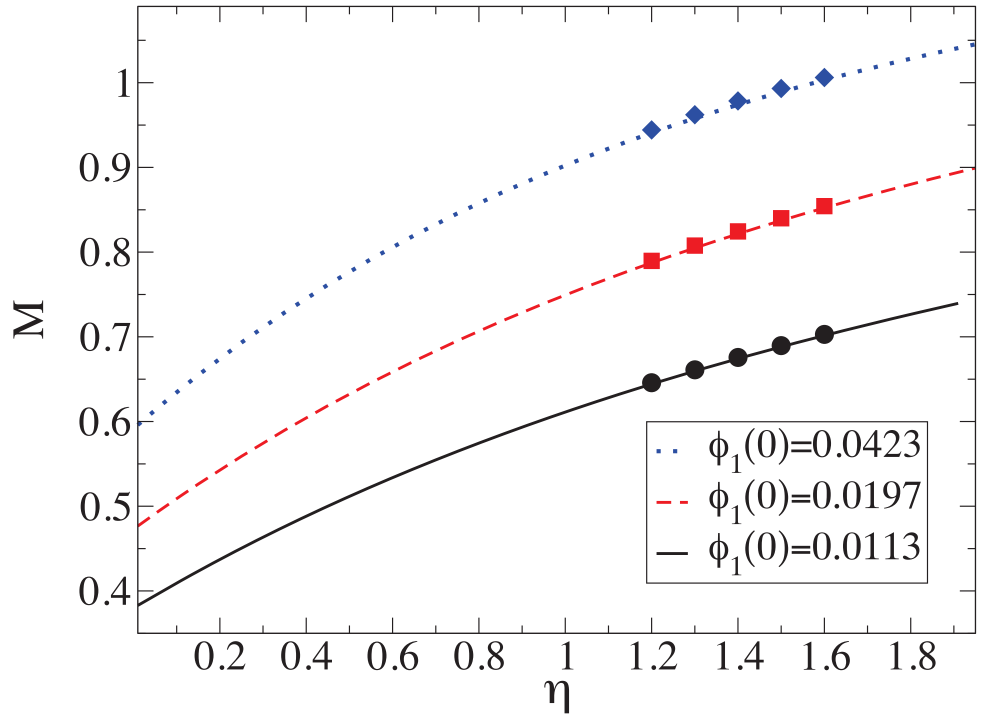
Stability range for MSBS

The MSBS configurations with N2/N1 〈 1 are STABLE.

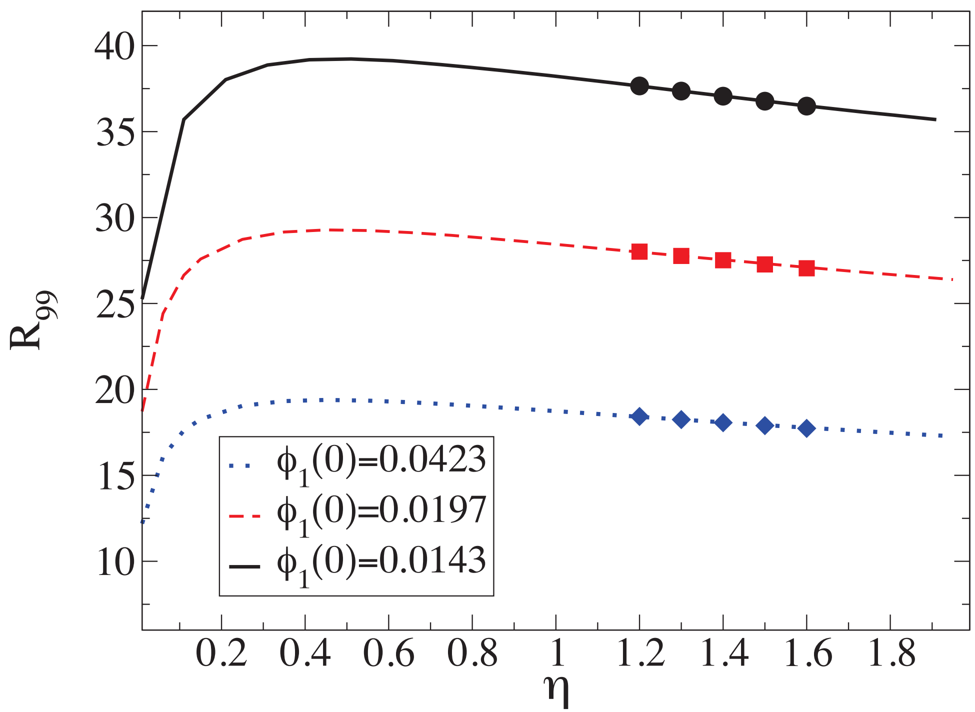
The MSBS with N2/N1 〉 1 are initially unstable, but evolve into STABLE configurations by reversing the states (flip-flop).



Stability range for MSBS



Configurations used for determining the stability range.

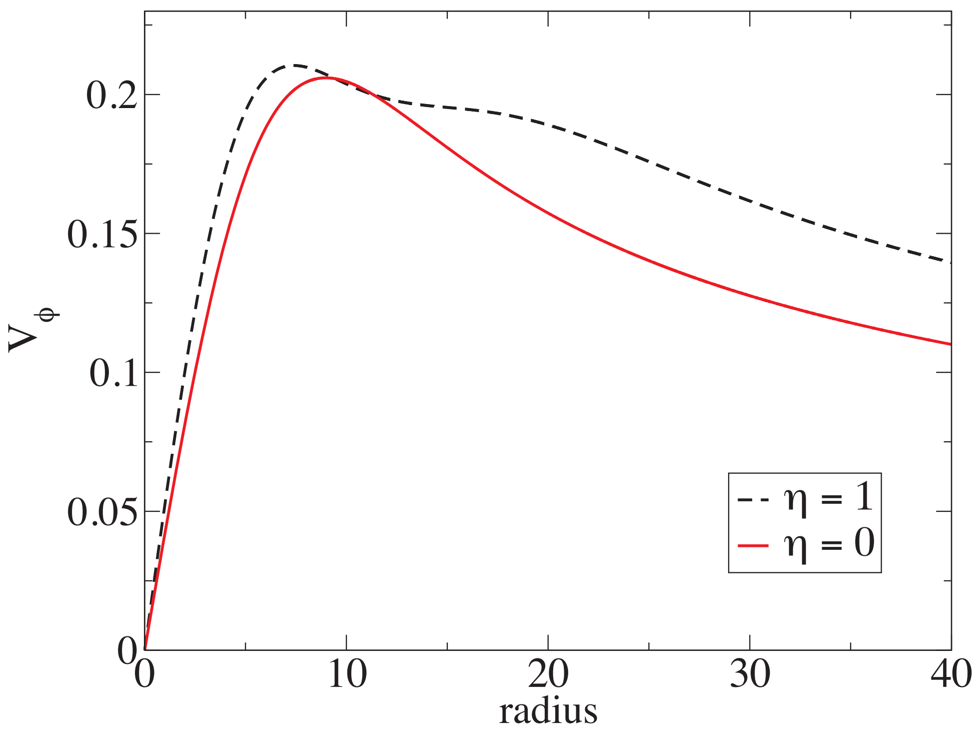


The mass and radius for different central values of the ground state field.

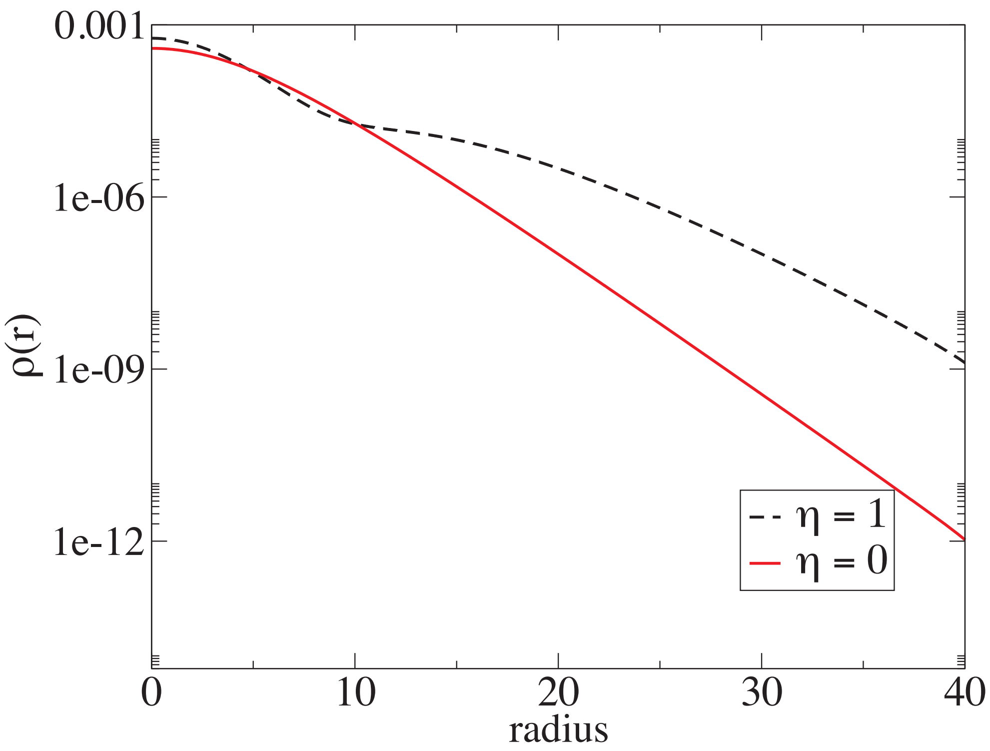
Rotation curves

Multi-State-Boson-Stars with ground state + 1st exicited state

lead to flatter profiles of the rotation curves at large radii.



Rotation curves for a BS and a MSBS with the same value of the scalar field.

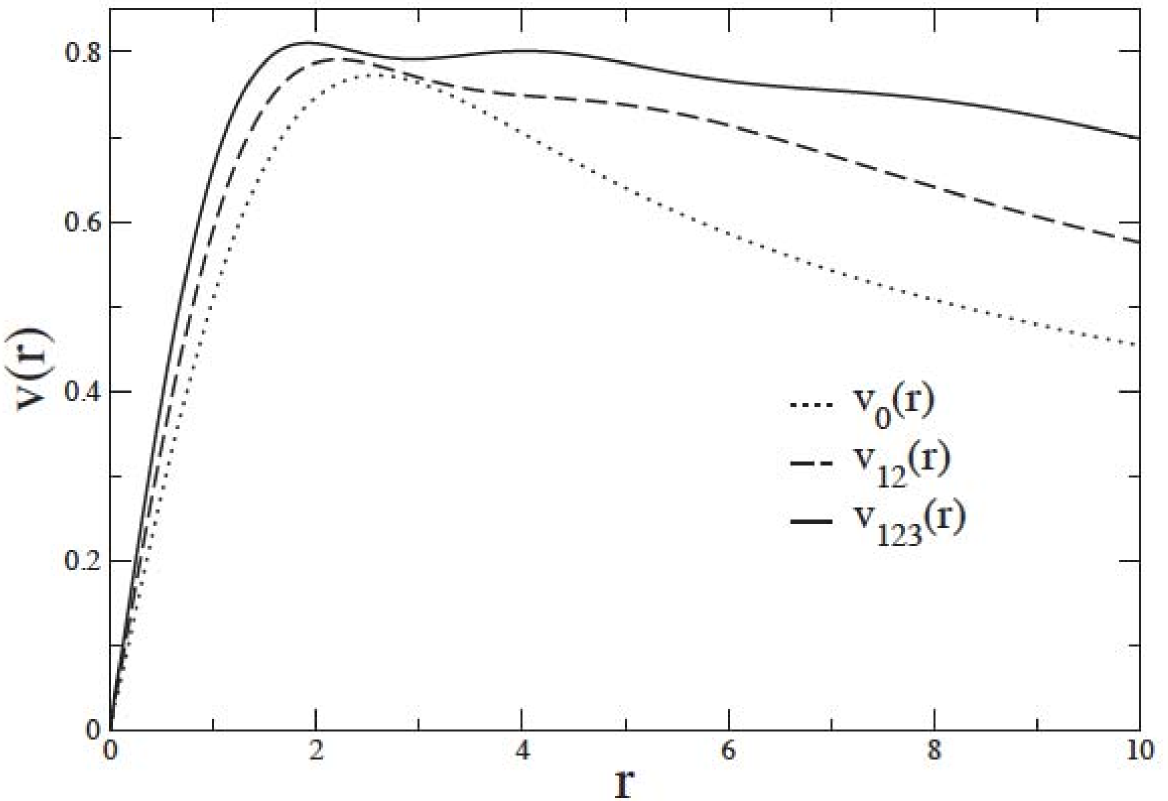


Density profiles for a BS and a MSBS with the same value of the scalar field.

Rotation curves

Multi-State-Boson-Stars with ground state + exicited states

lead to flatter profiles of the rotation curves at large radii.



Rotation curves for a MSBS with a ground state, first excited state and second excited state with the same value of the scalar field.

Conclusions

MSBS

- long-term stability
- extra degrees of freedom for different masses and sizes of galaxies
- allow a better fit in the Keplerian tail at large radius for the density profiles and the rotation curves.

Multi-state Boson Stars, Phys. Rev. D 81 (2010).

Galactic dark matter halo made of spin-zero bosons, AIP Conf. Proc. 1241, 335.

3D simulations with various perturbations and stability study.

Theory, observations and numerical simulations should play a balanced role in the search and understanding dark matter.

Work in progress: Boson-Fermion Stars

Consider mixed boson star configurations (ground + excited states) plus a fermion star, as test-models of dark and visible matter.

Questions to be addressed:

Can a fermion star stabilize excited boson star configurations? (dark matter halos with dust particles)

Can a boson star prevent the collapse of a massive fermion star? (the mass of neutron stars)

Which are the oscillation modes of these mixed stars? (detect dark matter condensed around neutron stars)

Mixed Boson-Fermion stars

Consider scalar fields coupled with an ideal fluid in a spherically symmetric and stationary configuration.

$$T_{ab} = T_{ab}^{(n)} + (\rho(1+\epsilon)+p)u_a u_b + p g_{ab}$$

Einstein equations:

$$\begin{aligned} R_{ab} &- \frac{R}{2} g_{ab} = 8\pi T_{ab}, \\ T_{ab} &= \sum_{n=1}^{P} T_{ab}^{(n)}, \\ T_{ab}^{(n)} &= \frac{1}{2}\left[\partial_a \bar{\phi}^{(n)} \partial_b \phi^{(n)} + \partial_a \phi^{(n)} \; \partial_b \bar{\phi}^{(n)}\right] \\ &- \frac{1}{2} g_{ab}\left[g^{cd}\partial_c \bar{\phi}^{(n)} \partial_d \phi^{(n)} + V\left(|\phi^{(n)}|^2\right)\right]. \end{aligned}$$

Mixed Boson-Fermion stars

Klein-Gordon equations:

$$\Box\phi^{(n)} = \frac{dV}{d|\phi^{(n)}|^2}\phi^{(n)}$$

$$V(|\phi^{(n)}|^2) = m^2\ |\phi^{(n)}|^2\,.$$

Fluid evolution equations: $\nabla_b T^{ab} = 0$

$$D = \rho W,$$

$$\tau = hW^2 - p - D,$$

$$S_r = hW^2 v_r.$$

Ideal Equation of State: $p = (\Gamma - 1)\rho\epsilon$

Initial data for mixed stars

Polar-areal coordinates:

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

Harmonic ansatz:

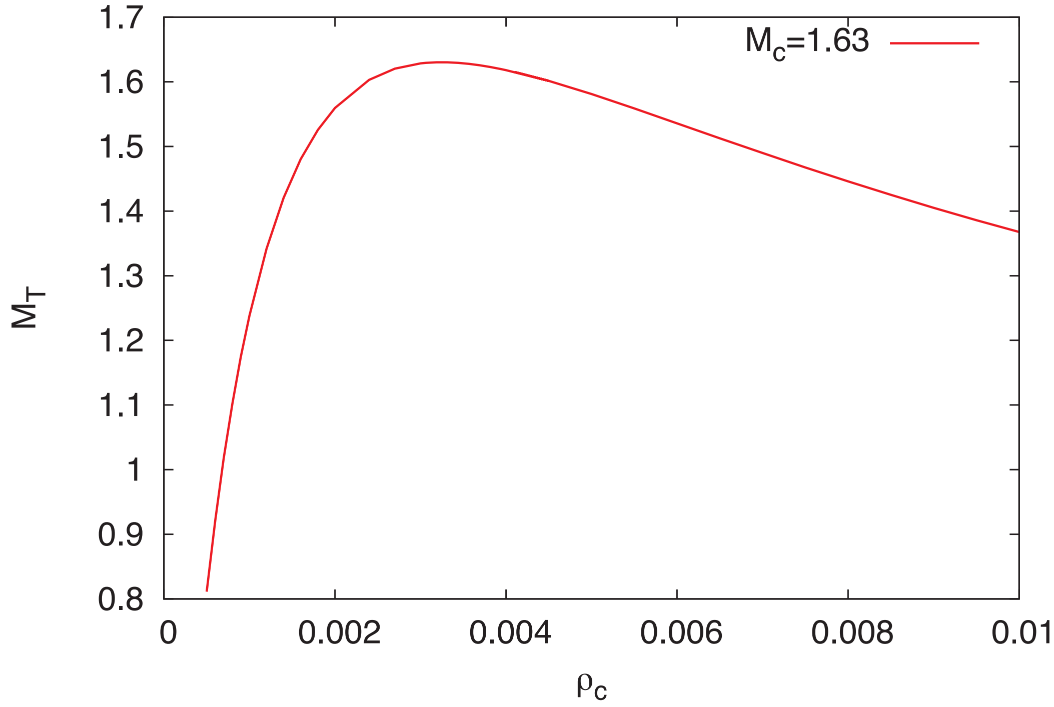
$$\phi^{(n)}(t,r) = \phi_n(r)\, e^{-i\omega_n t}.$$

K = 0 and impose the conservation of the momentum density for the fluid;

- Provide equilibrium equations for $\{\phi_n\,,\Phi_n\,,a\,,\alpha\,,p\}$;
- Impose regularity conditions at the origin and asymptotic flatness;
- Solve a shooting problem $\{\phi_n(0)\,,\omega_n\,,\alpha(0)\,,p\}$;

Initial data Polytropic EoS: $p(r) = K\rho^\Gamma$

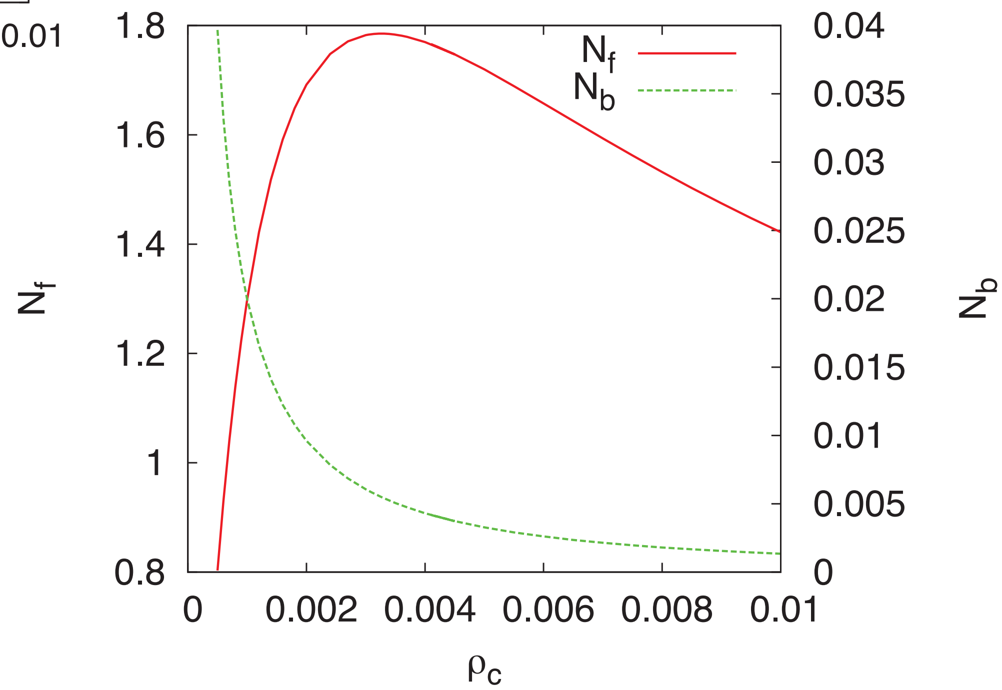
Initial data for mixed stars



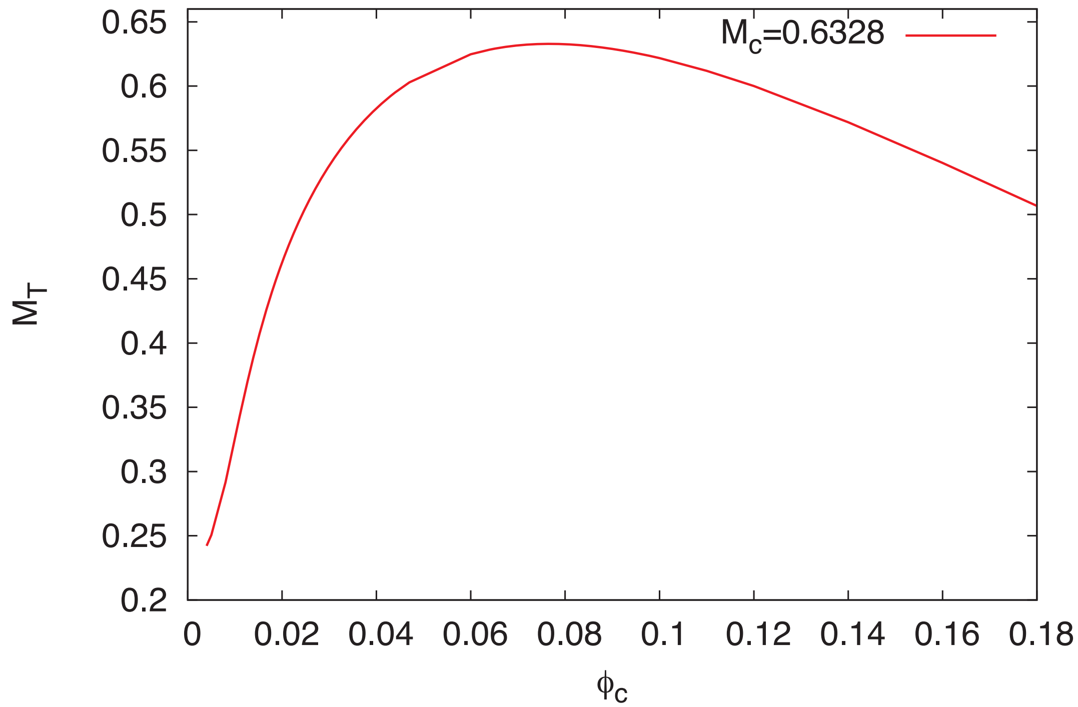
The total mass of a boson-fermion star as a function of the fluid density for a fixed value of the scalar field in the center:

$$\phi_c = 0.02$$

The total number of a fermions and bosons as a function of the fluid density in the center, for a fixed value of the scalar field.



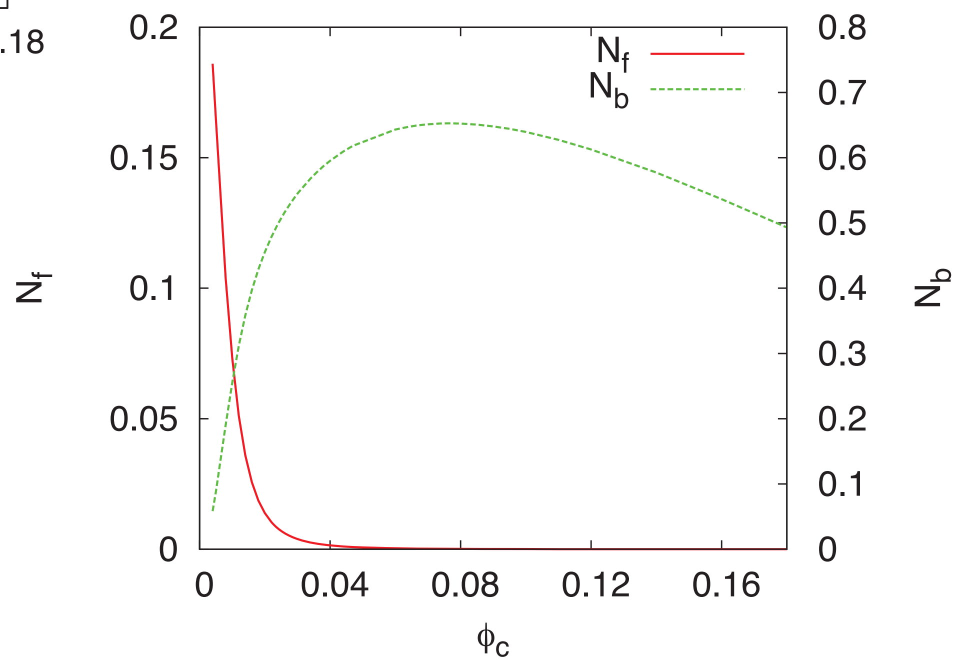
Initial data for mixed stars



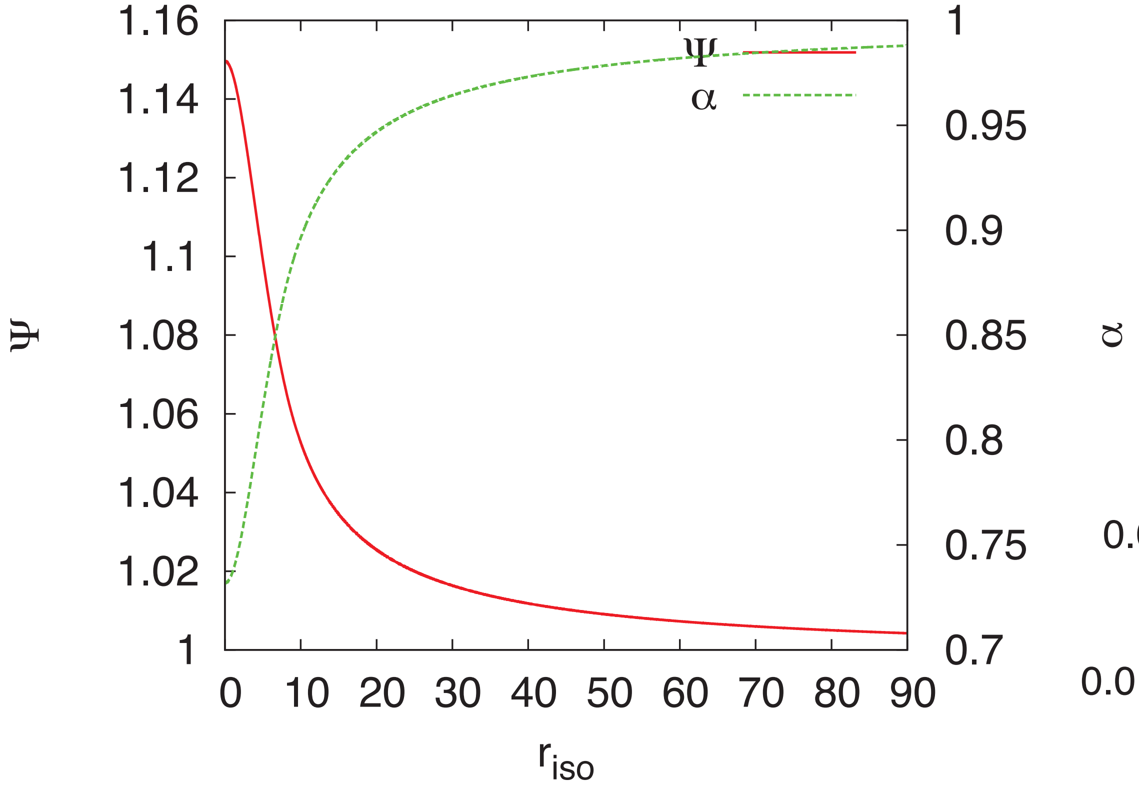
The total mass of a boson-fermion star as a function of the scalar field, for a fixed value of the fluid density in the center:

$$\rho_c = 0.01$$

The total number of a fermions and bosons as a function of the scalar field in the center, for a fixed value of the fluid density.



Initial data for mixed stars

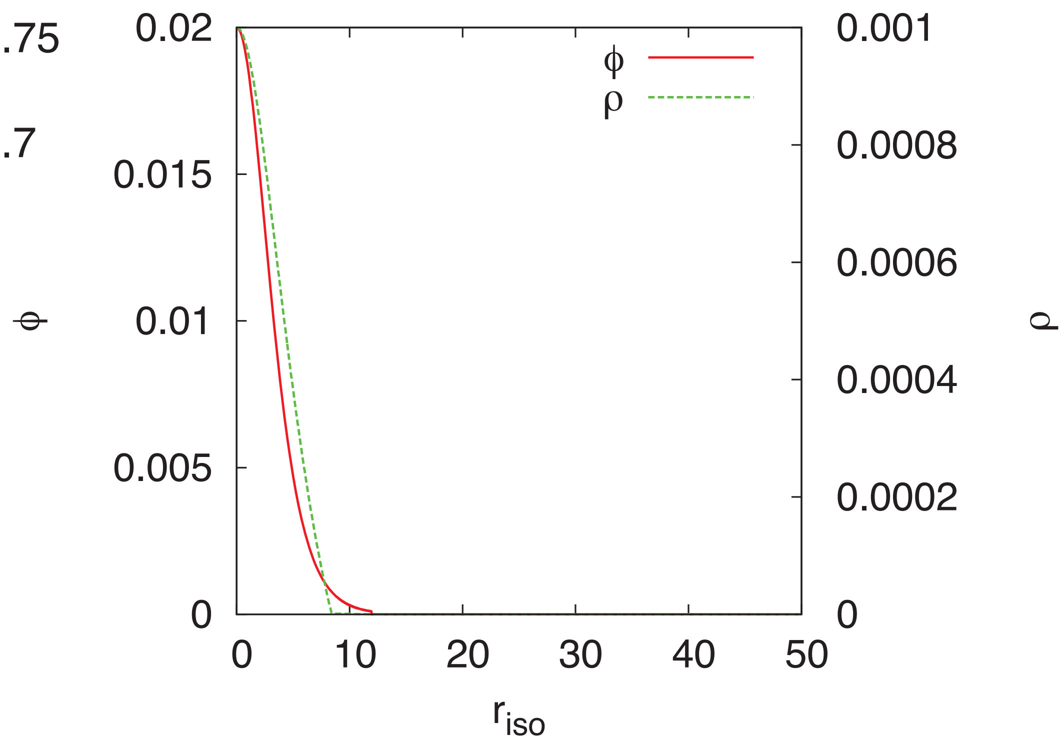


The conformal factor and the lapse function for a boson-fermion star.

$$\Gamma = 2, K = 100$$

The scalar field and fluid density for a boson-fermion star.

$$\phi_c = 0.02, \rho_c = 0.01$$



Future Work

Study the stability of the mixed boson-fermion configurations in long term numerical evolutions with different initial data.

Extract the oscillation modes.

Compare against 3D numerical results.

Dark matter detection?

Observations report an excess of galactic cosmic ray electrons at high energies which could arise from (annihilation of) dark matter particles. (J. Chang et al. An excess of cosmic ray electrons at energies of 300.800 GeV. Nature, 456:362–365, 2008.)

A possible detection of dark matter particles hitting the Earth has been announced by the DAMA collaboration.
(R. Bernabei et al. Direct detection of dark-matter particles. Nuovo Cim., 123B: 928–931, 2008.)