Stirren and shaken

Dynamical behavior of boson stars and dark matter cores

Lorenzo Annulli, PhD@CENTRA, Instituto Superior Técnico

June 25, 2020

6th IDPASC/LIP PhD Students Workshop

Main idea

In General Relativity, ultralight bosons can clump to form self-gravitating structures

These solutions, called Newtonian boson stars (NBS), seem to be a good description of dark matter (DM) cores in haloes (fuzzy DM models)

Typical bosons masses are $\sim 10^{-22}$ eV

- Stability
- Interaction with surrounding bodies

  In which way the presence of a black hole changes the local DM density?

  When a star crosses a NBS, will change its properties? To which extent?

- Impact on scalar and gravitational wave (GW) emission

  Nontrivial environmental effect on GW phase?

Newtonian boson stars

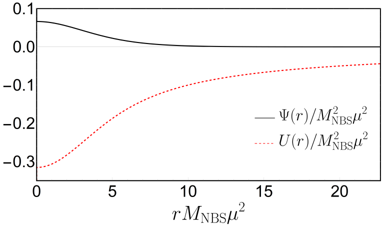
$U(1)$-invariant, self-interacting, complex scalar field Φ minimally coupled to gravity

$$\mathcal{S} \equiv \int d^4x\sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi^* - \frac{\mu^2}{2}|\Phi|^2\right)$$

Assuming Φ non-relativistic, spherically symmetric and stationary, $\Phi = \Psi(r)e^{-i(\mu-\gamma)t}$, in the Newtonian limit

Schrödinger-Poisson: $\nabla^2\Psi = 2\mu\left(\mu U + \gamma\right)\Psi\,, \quad \nabla^2 U = 4\pi\mu^2\Psi^2$

Fundamental NBSs satisfy the scaling-invariant mass-radius relation $M_{\rm NBS} \simeq 9.1/(R_{\rm NBS}\mu^2)$



What we do: perturbations

Dynamical response to external perturbers, which disturb the spherically symmetric, stationary background,

$$\Phi = \left[\Psi_0(r) + \delta\Psi(t,r,\theta,\varphi)\right] e^{-i\Omega t}$$

Linearized system of equations

$$i\partial_t \delta\Psi = -\frac{1}{2\mu}\nabla^2\delta\Psi + (\mu U_0 + \gamma)\,\delta\Psi + \mu\Psi_0\delta U$$
$$\nabla^2\delta U = 4\pi\left[\mu^2\Psi_0\left(\delta\Psi + \delta\Psi^*\right) + P\right]$$

The fluctuation $\delta\Psi$ can be used to calculate physical quantities such as energy, linear and angular momenta radiated, from the flux of certain currents,

$$\left(\dot{E}^{\rm rad}, \dot{P}_i^{\rm rad}, \dot{L}_z^{\rm rad}\right) = \lim_{r\to\infty} r^2 \int d\theta d\varphi \sin\theta\, \left(\delta T^S_{r\mu}\xi^\mu_t, \delta T^S_{r\mu}e^\mu_i, \delta T^S_{r\mu}\xi^\mu_\varphi\right)$$

Things we computed

Free perturbations

- Small perturbations aka Quasi Normal Modes

Sourced perturbations

Static

- A super massive black hole sitting in the center of a DM halo
- A black hole eating its host DM halo

Dynamics

- Massive objects plunging into boson stars
- A perturber oscillating at the center
- Low-energy and high-energy binaries within boson stars

Things we computed

Free perturbations

- Small perturbations aka Quasi Normal Modes

Sourced perturbations

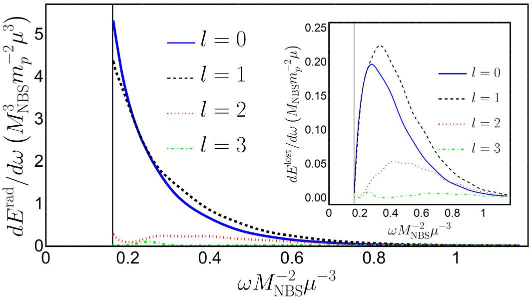
Static

- A super massive black hole sitting in the center of a DM halo
- A black hole eating its host DM halo

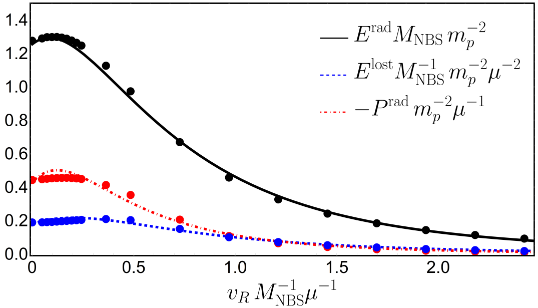
Dynamics

- Massive objects plunging into boson stars
- A perturber oscillating at the center
- Low-energy and high-energy binaries within boson stars

Plunge



$dE^{\rm rad}/d\omega\,(M_{\rm NBS}^3 m_p^{-2}\mu^3)$
$\omega M_{\rm NBS}^{-2}\mu^{-3}$
$l=0$
$l=1$
$l=2$
$l=3$
$dE^{\rm lost}/d\omega\,(M_{\rm NBS} m_p^{-2}\mu)$



$E^{\rm rad} M_{\rm NBS}\, m_p^{-2}$
$E^{\rm lost} M_{\rm NBS}^{-1}\, m_p^{-2}\mu^{-2}$
$-P^{\rm rad}\, m_p^{-2}\mu^{-1}$
$v_R\, M_{\rm NBS}^{-1}\mu^{-1}$

Binary

Outlook

First self-consistent calculation of dynamical friction in these backgrounds

Binaries “stir” the NBS core, backreaction affects GW at leading $-6PN$

Gravitational collapse to a BH is accompanied by only a small change in the DM core

The NBS gets accreted, for realistic parameters only after several Hubble times

Benchmark for numerical relativity simulations involving BS in extreme mass-ratio regime.

Extensions: eccentric motion, self-gravitating vectors or other nonlinearly interacting scalars.