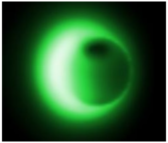

VII Black Holes Workshop

Light-rings as observational evidence for event horizons

Caio F. B. Macedo,
V. Cardoso, L. C. B. Crispino, H. Okawa and P. Pani

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Contents

Introduction & Motivation

- Many massive stars are unstable against gravitational collapse.
- Exotic stars: boson stars and gravastars.
- Gravitational wave physics.
- Very compact spinning objects can be unstable: Ergoregion instability.
- Ultracompact objects: No horizons and *Light-rings* (Comins and Schutz, Proc. R. Soc. Lond. A **364**, 211).
- Can ultracompact objects be unstable? (Keir, 1404.7036)
- Here we study the linear modes of ultracompact objects.

Ultracompact objects

Spherical ultracompact objects are described by

$$ds^2 = -f(r)dt^2 + B(r)dr^2 + r^2 d\Omega_2^2. \tag{1}$$

The radial equation for null geodesics in the above spacetime is given by

$$Bf\dot{r}^2 = E^2 - V_{\rm geo} \equiv E^2 - L^2 \frac{f}{r^2}. \tag{2}$$

The maxima and minima points of $V_{\rm geo}$ corresponds to unstable and stable geodesics.

Eikonal limit of the modes

- Schwarzschild spacetime: Unstable LR. (Cardoso *et al.*, 0812.1806)
  $\Re(\omega) \rightarrow$ Angular frequency of the circular null geodesic.
  $\Im(\omega) \rightarrow$ Instability timescale of the circular null geodesic (Lyapunov exponents).

- Ultracompact objects: Stable LR.
  $\Re(\omega) \rightarrow$ Angular frequency of the *stable* circular null geodesic.
  $\Im(\omega) \rightarrow$ Becomes abitrarily small.

Ultracompact models: Constant density stars and gravastars

- Constant density stars: Idealized (toy) model

$$f(r) = \frac{1}{4R^3}\left(\sqrt{R^3 - 2Mr^2} - 3R\sqrt{R - 2M}\right)^2, \tag{3}$$

$$B(r) = \left(1 - \frac{2Mr^2}{R^3}\right)^{-1}. \tag{4}$$

- Gravastars: Devised to mimick black holes (Mazur and Mottola, gr-qc/0109035)

$$f(r) = B(r)^{-1} = 1 - \frac{2M}{R}\frac{r^2}{R^2}. \tag{5}$$

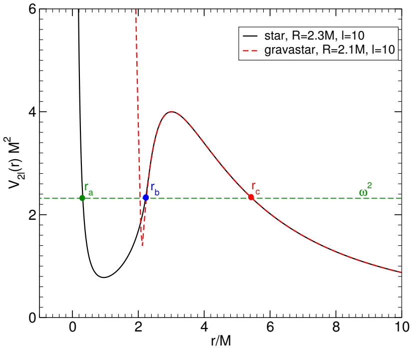
Perturbations

Various classes of perturbations are described by a master equation

$$\left[\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r_*^2} + V_{sl}(r)\right]\Psi(r,t) = 0\,, \tag{6}$$

where $\frac{\partial^2}{\partial r_*^2} = \frac{f}{B}\frac{\partial^2}{\partial r^2} + \frac{f}{2B}(\frac{f'}{f} - \frac{B'}{B})\frac{\partial}{\partial r}$ and

$$\begin{aligned} V_{sl}(r) &= f\left[\frac{l(l+1)}{r^2} + \frac{1-s^2}{2rB}\left(\frac{f'}{f} - \frac{B'}{B}\right)\right. \\ &\left. +8\pi(p_{\rm rad} - \rho)\delta_{s2}\right]\,. \end{aligned} \tag{7}$$

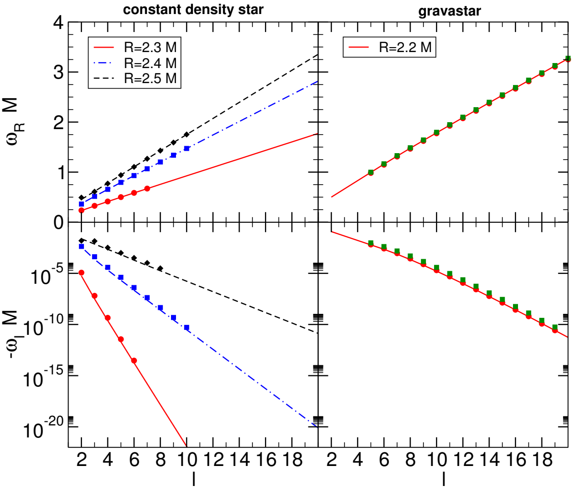


$$\int_{r_a}^{r_b} \frac{dr}{\sqrt{f/B}} \sqrt{\omega_R^2 - V_{sl}(r)} = \pi\,(n + 1/2)\,, \tag{8}$$

$$\omega_I = -\frac{1}{8\omega_R \gamma} e^{-\Gamma}\,, \tag{9}$$

$$\omega \sim \Omega_{\mathrm{LR2}}\, l - i\, b\, e^{-cl} \qquad l \gg 1\,. \tag{10}$$

Numerical results: Spectrum of linear perturbations

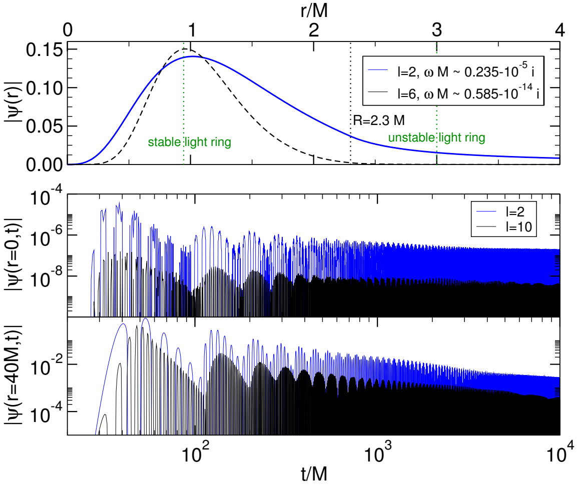


Numerical results: Time evolution of wavepackets

We evolve an initial Gaussian wavepack in the star spacetime:

$$\dot{\Psi}(0,r) = \exp\left[-\frac{(r + 2\log(r-R) - r_0)^2}{\sigma^2}\right]. \tag{11}$$

Numerical results: Time evolution of wavepackets



Ergoregion instability (Comins and Schutz, Proc. R. Soc. Lond. A **364**, 211)

If we set rotation on, we have

$$ds^2 = -F(r)dt^2 + B(r)dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta (d\phi - \varpi(r)dt)^2 \,, \quad (12)$$

and the scalar field equation is

$$\psi'' + m^2 \frac{B}{F}(\bar{\omega} + V_+)(\bar{\omega} + V_-)\psi = 0 \,, \quad (13)$$

where

$$V_\pm = -\varpi \pm \frac{\sqrt{F}}{r} \,. \quad (14)$$

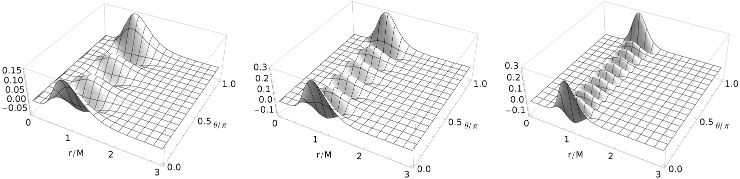
Possible nonlinear outcomes

There are some possible outcomes from the nonlinear regime:

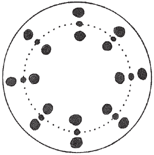
- **Other dissipative mechanisms become relevant**: No collapse.
- **Nonlinear effects become relevant**: Collapse or fragmentation.

Possible nonlinear outcomes

Formation of small BHs (Bizon and Rostworowski, 1104.3702v5), (Okawa *et al.*, 1409.0533v2)



"Boiling fluid" (Lehner and Pretorius, 1006.5960)



- We show evidences that any object with a light ring are BHs.
- This is based on the fact that these objects possesses long-living modes at linear level.
- Two outcomes are possible: Decreasing of compactness or BH formation.
- For BH formation: Nonlinear instabilities and weakly turbulence.
- Turning on rotation: Ergoregion instability (linear level).

Acknowledgments

grit
http://centra.tecnico.ulisboa.pt/network/grit/

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