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Prolate Proca stars

The non-spherical ground state of Proca stars

PLB: 852 138595, Arxiv: 2311.14800

C. Herdeiro, E. Radu, N. Sanchis-Gual,
N. Santos, Etevaldo Costa

Take home message

Staticity plus stability implies non-sphericity.

Inspiration/Motivation

Why do we care about Proca?

Proca stars, constructed for a massive, free, complex field minimally coupled to Einstein's gravity, are good black hole mimickers.

- Under certain conditions, they can mimic the shadow of an astrophysical Kerr black hole.
- Some real gravitational-wave signals from black hole mergers are well described as Proca stars with a consistent boson mass across multiple events.

Multipolar *scalar* stars

Horizonless self-gravitating solitons describing localized energy lumps, made up of massive, complex scalar fields

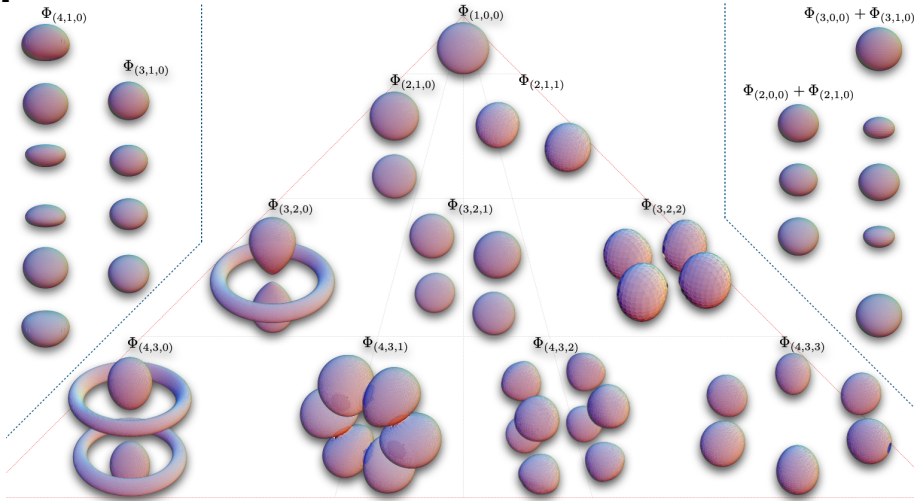
Model

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \partial_\alpha \Phi \partial^\alpha \bar{\Phi} - \mu^2 \Phi \bar{\Phi}\right] .$$

In the absence of gravity, solutions are described by

$$\Phi = e^{-i\omega t}\sum_{\ell,m} c_{\ell m} R_\ell(r) Y_{\ell m}(\theta,\phi), \qquad R_\ell(r) = \frac{1}{\sqrt{r}} K_{\ell+\frac{1}{2}}\left(r\sqrt{\mu^2-\omega^2}\right) .$$

Multipolar *scalar* stars



C.A.R. Herdeiro, 2021

Proca stars

Self-gravitating configurations forming a compact horizonless object. The star forms a stationary, soliton-like solution

Model

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{4}\mathcal{F}_{\alpha\beta}\bar{\mathcal{F}}^{\alpha\beta} - \frac{\mu^2}{2}\mathcal{A}_\alpha\bar{\mathcal{A}}^\alpha)\right] .$$

Proca stars

Model

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{4}\mathcal{F}_{\alpha\beta}\bar{\mathcal{F}}^{\alpha\beta} - \frac{\mu^2}{2}\mathcal{A}_\alpha\bar{\mathcal{A}}^\alpha)\right] \ .$$

Previously constructed for

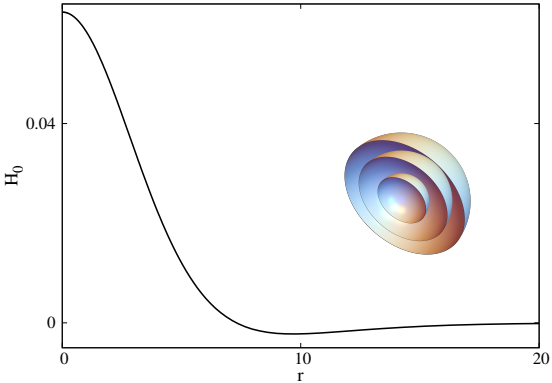
Spherical Symmetry

$$\mathcal{A} = e^{-i\omega t}\left(iH_1(r)dr + H_0(r)dt\right) \ .$$

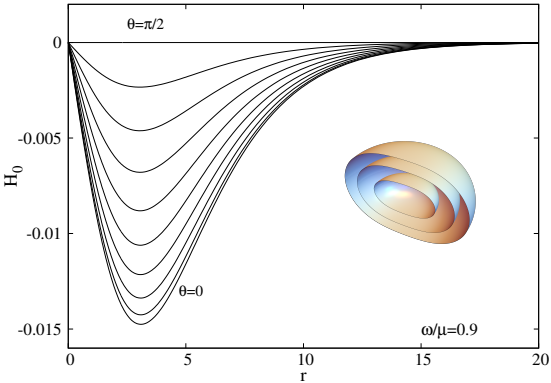
(Rotating) Axial Symmetry

$$\mathcal{A} = e^{i(m\varphi-\omega t)}\left(\frac{H_1(r,\theta)}{r}dr + H_2(r,\theta)d\theta + iH_3(r,\theta)\sin\theta d\varphi + iH_0(r,\theta)dt\right) \ .$$

Spherical Solutions



Rotating Solutions



Multipolar *Proca* stars

- The Proca equation admits separability in Minkowski spacetime.
- Solutions are not everywhere regular.
- This model has a richer spectrum. For instance, it admits electric and magnetic static solutions.
- Will gravity regularize such solutions?

Multipolar *Proca* stars

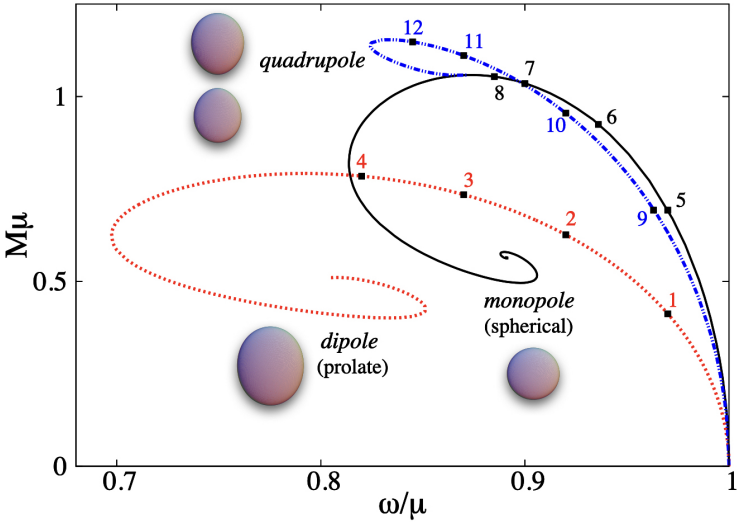
We assume the matter field ansatz

$$\mathcal{A} = e^{-i\omega t}\left(\frac{H_1(r,\theta)}{r}dr + H_2(r,\theta)d\theta + iH_0(r,\theta)dt\right) ,$$

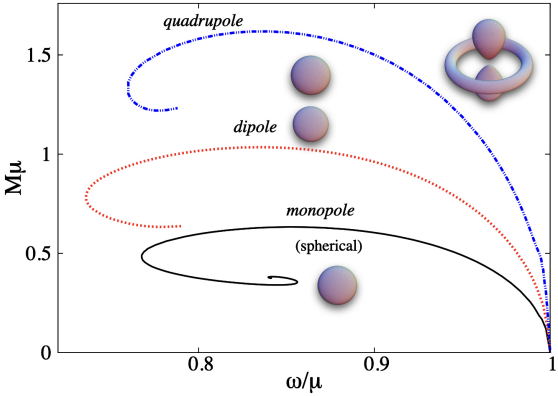
and the line element

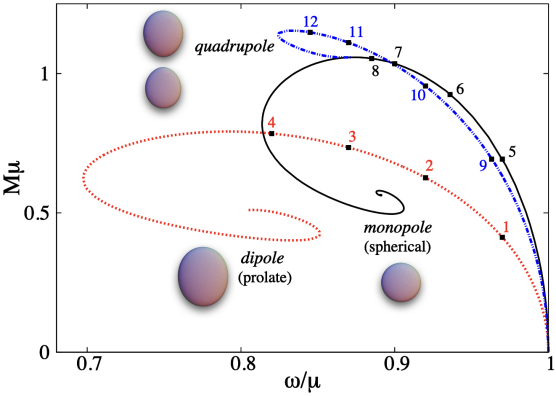
$$\mathrm{d}s^2 = -e^{2F_0}\,\mathrm{d}t^2 + e^{2F_1}\left(\,\mathrm{d}r^2 + r^2\,\mathrm{d}\theta^2\right) + e^{2F_2}r^2\sin^2\theta\mathrm{d}\varphi^2 .$$

Multipolar *Proca* stars



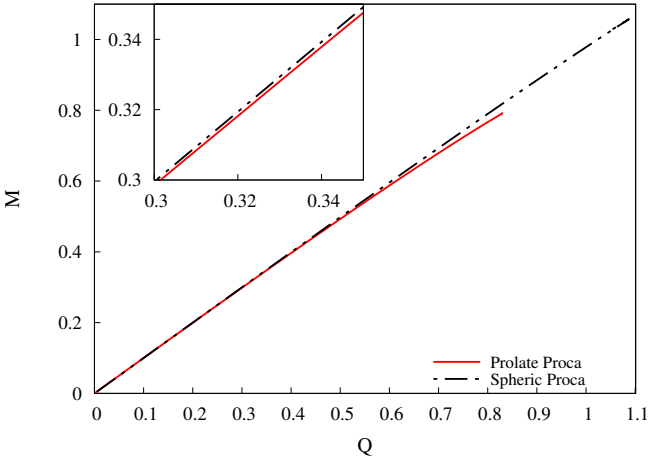
Multipolar *Proca* stars





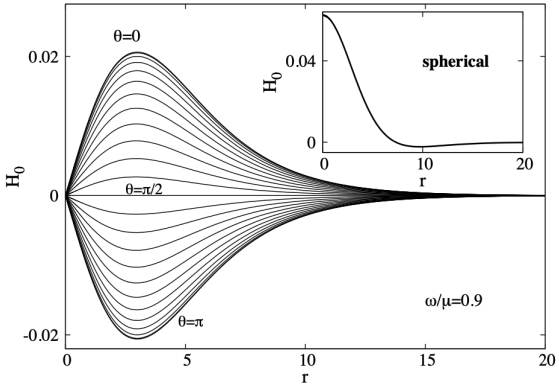
Stability

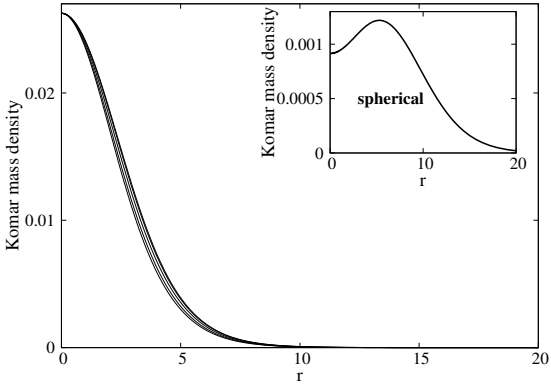
1. Prolate stars have lower energy in the Proca family.



Stability

1. Prolate stars have lower energy in the Proca family.
2. Prolate stars are nodeless and the maximum of the Komar mass density is at the origin.





Stability

1. Prolate stars have lower energy in the Proca family.
2. Prolate stars are nodeless and the maximum of the Komar mass density is at the origin.
3. Spherical Proca stars are stable against spherical perturbations.

Stability

1. Prolate stars have lower energy in the Proca family.
2. Prolate stars are nodeless and the maximum of the Komar mass density is at the origin.
3. Spherical Proca stars are stable against spherical perturbations.
4. Performing 3D numerical relativity evolutions,

Dipolar/**P**rolate	Monopolar/**S**pherical	**Q**uadrupolar
1-(0.970,0.412) *Stable*	**5**-(0.970,0.693) $S \to P$	**9**-(0.965,0.693) $Q \to P$
2-(0.920,0.626) *Stable*	**6**-(0.936,0.924) $S \to P$; $[\mathbb{Z}_2]$ $S \to P$ (xy)	**10**-(0.920,0.955) $Q \to P$
3-(0.870,0.735) *Stable*	**7**-(0.900,1.04) $S \to P$; $[\mathbb{Z}_2]$ $S \to P$ (xy)	**11**-(0.870,1.11) $Q \to BH$
4-(0.820, 0.785) *Stable*	**8**-(0.885,1.05) $S \to P$	**12**-(0.845,1.15) $Q \to BH$

Conclusions

1. We report new solutions of the Einstein-complex-Proca system.

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1. We report new solutions of the Einstein-complex-Proca system.
2. Our findings indicate that vector bosonic stars favor non-spherical (prolate) ground states over unstable spherical configurations.

FCT
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