Superfluid dark stars

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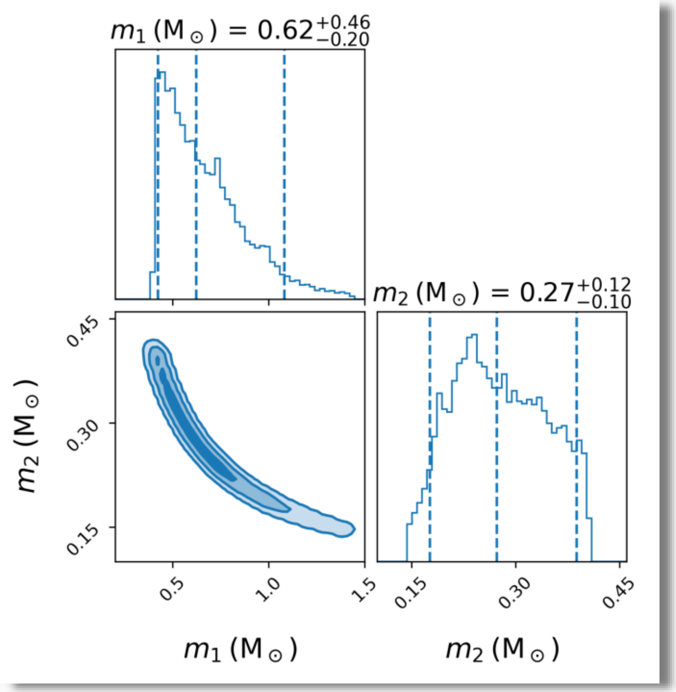
Introduction

Puzzle: SSM200308

We explore the phenomenology of the merger of sub-solar compact objects in the presence of a superfluid scalar matter field.



Prunier+ (2023), arXiv:2311.16085

Introduction - Boson Stars

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Boson Stars: Gravitational Equilibria of Self-Interacting Scalar Fields

Monica Colpi,[a] Stuart L. Shapiro, and Ira Wasserman
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853
(Received 13 August 1986)

Spherically symmetric gravitational equilibria of self-interacting scalar fields ϕ with interaction potential $V(\phi) = \frac{1}{4}\lambda|\phi|^4$ are determined. Surprisingly, the resulting configuration may differ markedly from the noninteracting case even when $\lambda \ll 1$. Contrary to generally accepted astrophysical folklore, it is found that the maximum masses of such boson stars may be comparable to the Chandrasekhar mass for fermions of mass $m_{\text{fermion}} \sim \lambda^{-1/4} m_{\text{boson}}$.

Solitonic solution: $\phi(r)e^{-i\omega t}$

Order parameter: $\phi(r)$

Chemical potential: ω

Equation of State

$$\mathcal{L} = D_\nu \Phi^* D^\nu \Phi - m_{\rm B}^2 |\Phi|^2 - \lambda |\Phi|^4 \qquad D_\nu = \partial_\nu - i\mu\delta_{\nu 0}$$

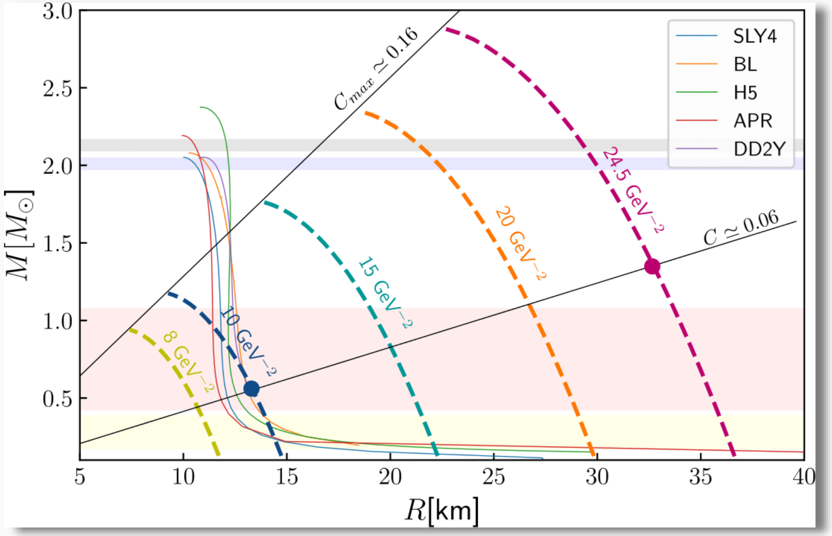
Chemical Potential (μ)

$$P(\mu) = \frac{(\mu^2 - m_{\rm B}^2)^2}{4\lambda}$$

$$\epsilon = 2\frac{m_{\rm B}^2}{\sqrt{\lambda}}\sqrt{P} + 3P \Longrightarrow \hat{\epsilon} = 3\hat{P} + 2\sqrt{\hat{P}}$$

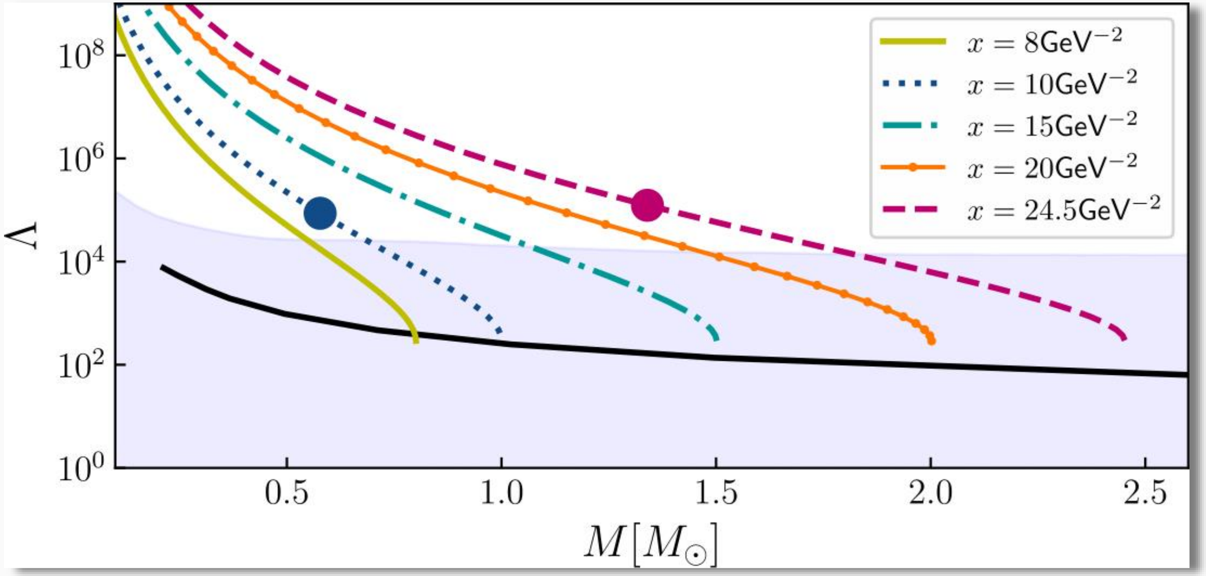
$$x = \frac{\sqrt{\lambda}}{m_{\rm B}^2}$$

$$c_s^2 = \frac{1}{3 + \frac{m_B^2}{\sqrt{\lambda}}\frac{1}{\sqrt{P}}} < \frac{1}{3}$$



Tidal deformability

$$\Lambda = \frac{2}{3\mathcal{C}^5} k_2$$



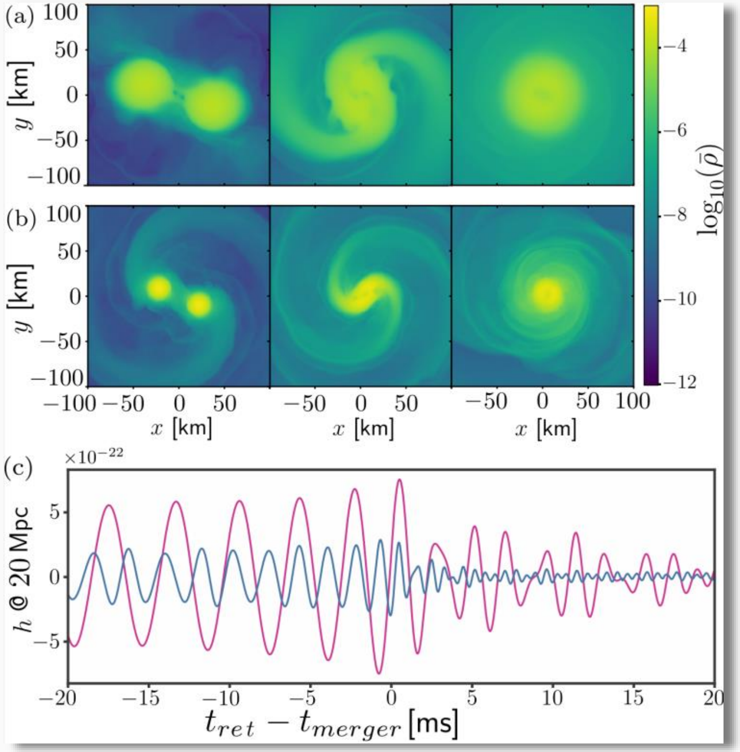
Merging

einstein toolkit → Dynamical evolution of GRHD equations using the BSSN formulation of Einstein Field Equations for a perfect fluid with fixed EoS.

LORENE

Langage Objet pour la RElativité NumériquE → Computation of initial conditions using the conformal thin-sandwich approach.

Merging



(a) $M_b = 1.4\, M_\odot$

$R \simeq 32.5\,\mathrm{km}$

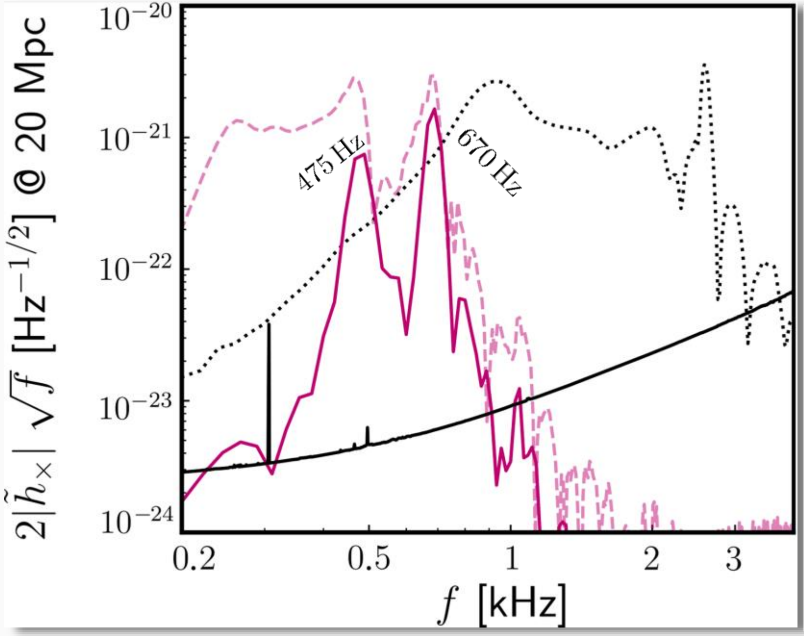
Initial distance 90 km

(b) $M_b = 0.6\, M_\odot$

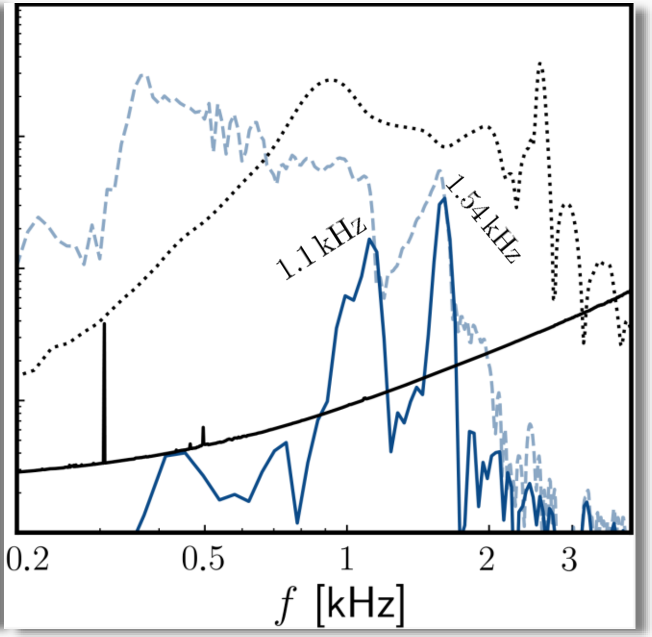
$R \simeq 13.1\,\mathrm{km}$

Initial Distance 50 km

Amplitude spectral density



$M_b = 1.4\, M_\odot$



$M_b = 0.6\, M_\odot$

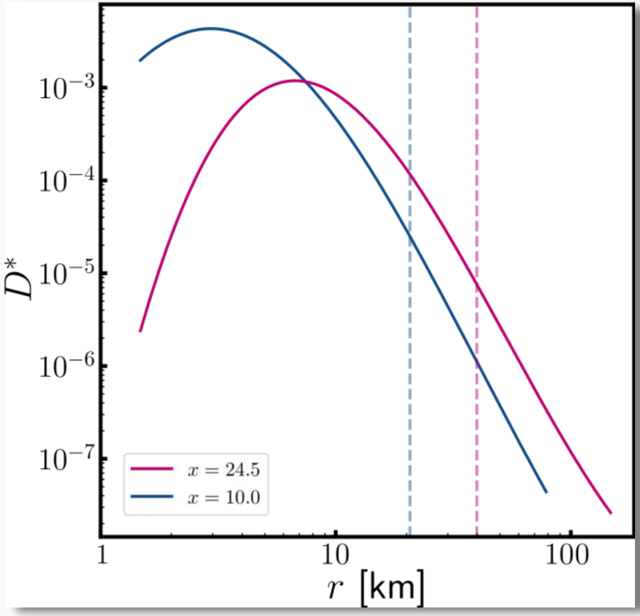
Ejecta

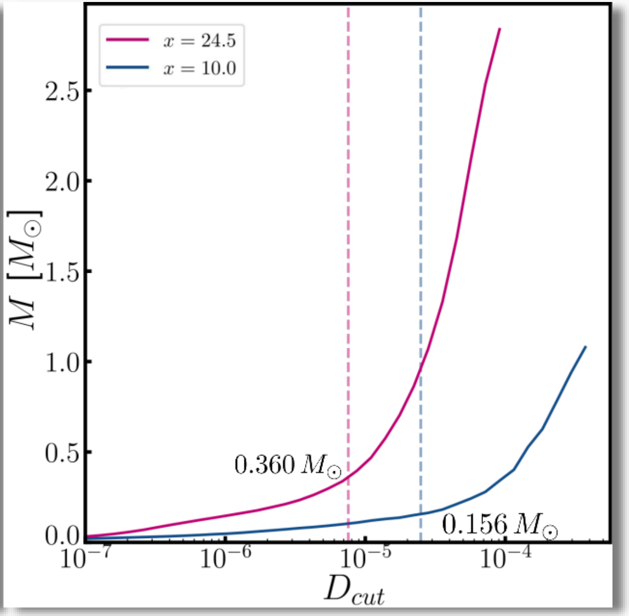
$$D = \sqrt{\gamma}\bar{\rho}W$$

$$D^*(r) = \frac{1}{2\pi}\int_{-\pi}^{\pi} D \, \mathrm{d}\phi$$

$$\Downarrow$$

$$\frac{\mathrm{d}\log(\mathrm{D}^*)}{\mathrm{d}\log(\mathrm{r})} = -4.53$$





Temperature

Simulations performed at $T = 0$.

Virial theorem: $T \sim \langle E_K \rangle \sim \langle U \rangle \sim \alpha m_{\rm B} \mathcal{C}$

Critical temperature: $T_c \sim \dfrac{\hat{\epsilon}_0^{2/3}}{x^{4/3} m_{\rm B}^{5/3}} + \lambda^{2/3} \hat{\epsilon}_0^{1/3} + \cdots$

$T < T_c$ gives the upper bounds

$$m_{\rm B} \lesssim \alpha^{-3/8} \mathcal{C}^{-3/8} \epsilon_0^{1/4} x^{-1/2}$$
$$\lambda < \hat{\epsilon}_0\, \mathcal{C}^{-3/2}\, \alpha^{-3/2}$$

Summary

1. Superfluid bosonic matter allows to reach any point in the M-R diagram, tuning the interaction potential and strenght.
2. Systems of equal compactess but different $x = \frac{\sqrt{\lambda}}{m_{\mathrm{B}}^2}$ are obtained via appropriate rescaling.
3. Full GRHD simulations show that the gravitational signal emitted is similar to that of standard compact binary systems in both amplitude and frequency domain.
4. However, frequencies are much lower with respect to standard matter for equal masses.

Thank you!

arXiv:2403.03833