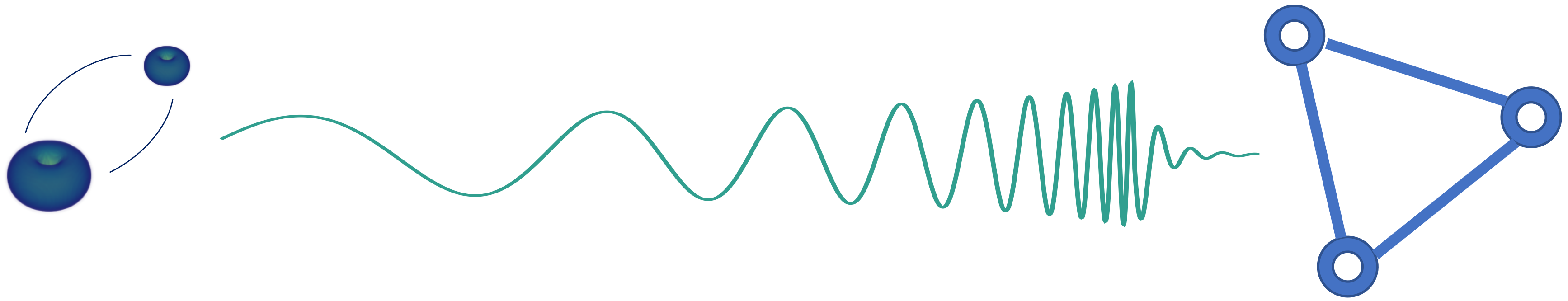
BOSON STARS AS TARGETS OF GRAVITATIONAL-WAVE SEARCHES AND PROBES OF NEW FUNDAMENTAL FIELDS



PhD Seminars, Sapienza 21-03-2023

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SAPIENZA UNIVERSITÀ DI ROMA

erc European Research Council

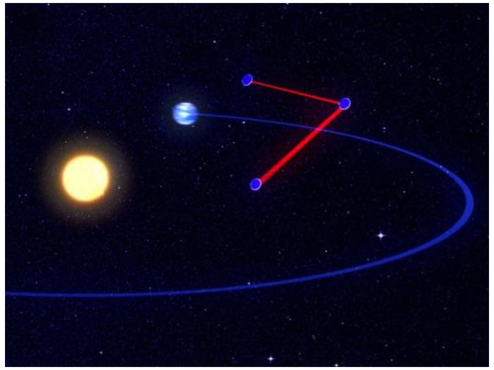
DarkGRA

Gravitational-wave astronomy era

- Gravitational waves from binary systems are routinely observed by LIGO/Virgo.
- In the near future:

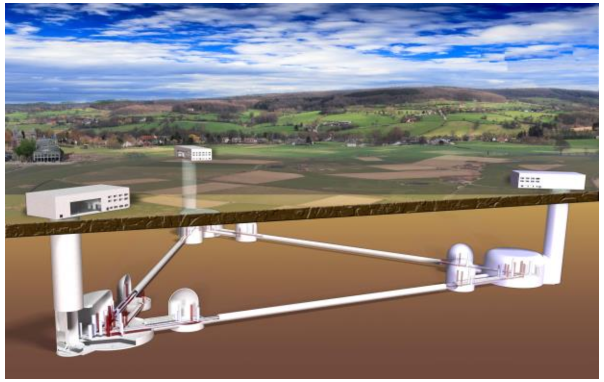
LISA (Laser Interferometer Space Antenna) – Launch expected in 2034

- Cluster of 3 spacecrafts in heliocentric orbit
- Equilater triangle with $5 \cdot 10^6 km$ arm lenght
- Sensitivity band ~ 0.1 mHz $- 1$ Hz



ET (Einstein Telescope) – Contruction will start in 2026

- Ground-based, triangle-shaped interferometer
- $10\ km$ arm length (LIGO-Virgo $\sim 3\ km$)
- Sensitivity band ~ 1 Hz $- 10^4$Hz



Detection of thousands of mergers of binary systems with a mass range from few to 10^7 *solar masses*

Opportunity to test the nature of compact objects with unprecedented accuracy

Exotic Compact Objects in the Universe?

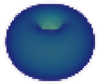
- The actual paradigm is that an astrophysical compact object, which is hevier than few solar masses, is a Black Hole (BH).

Exotic Compact Object: *An object which is neither a BH or a Neutron Star*

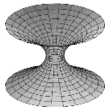
- The observation of an ECO would imply some new physics:

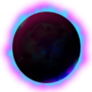
Exotic matter sources — *Extentions of General Relativity*

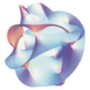
Exotic Compact Objects


Boson stars


Proca stars


Wormholes


Hairy Black Holes


Fuzzballs

. . .

Astrophysical processes are insensitive to the geometry near the horizon: ***we need Gravitational Waves!***

Properties of Boson Stars

- Boson stars (BSs) are stationary configurations of a massive, complex scalar field, bound by gravity and could represent astrophysical objects which:

  - Can be almost as compact as Black Holes and can mimick their phenomenology

  - Are regular (no singularity at the center, no event horizon)

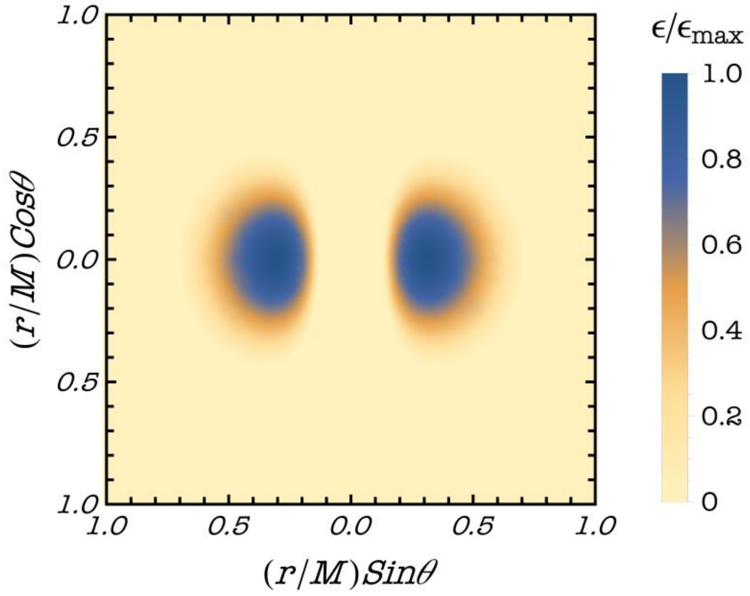
  - Could stand for some fraction of the dark matter content of the Universe

- Can be described in classical field theory:

$$G_{ab} = 8\pi T_{ab}\,, \qquad \frac{1}{\sqrt{-g}}\partial_a\left(\sqrt{-g}\,g^{ab}\,\partial_b\phi\right) = \frac{dV(|\phi|^2)}{d|\phi|^2}\,\phi$$

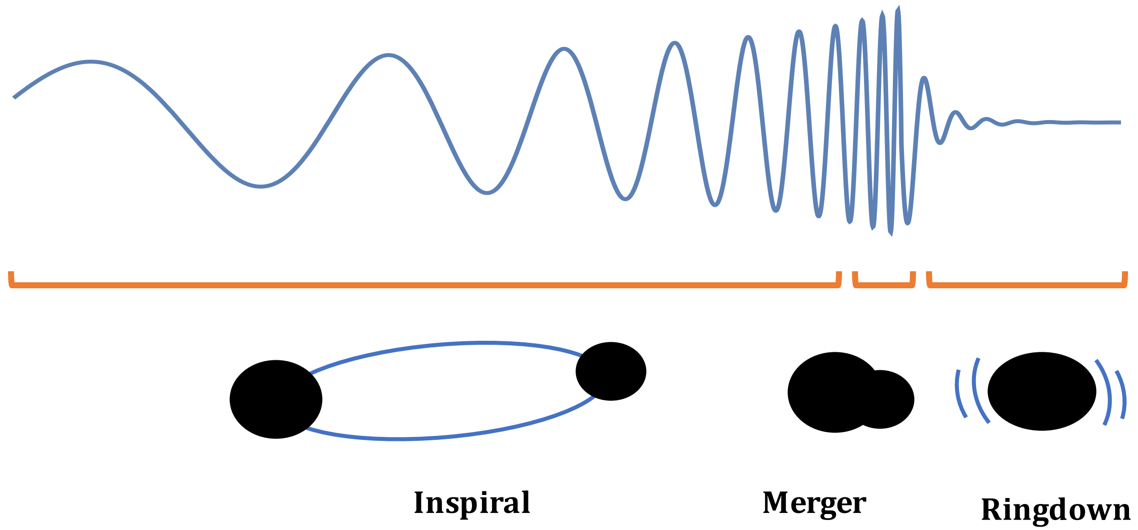
Einstein equations — Klein-Gordon equation

Energy-density plot of a boson star



Stages of a binary coalescence

- The gravitational waveform from a binary coalescence can be thought as divided in three stages



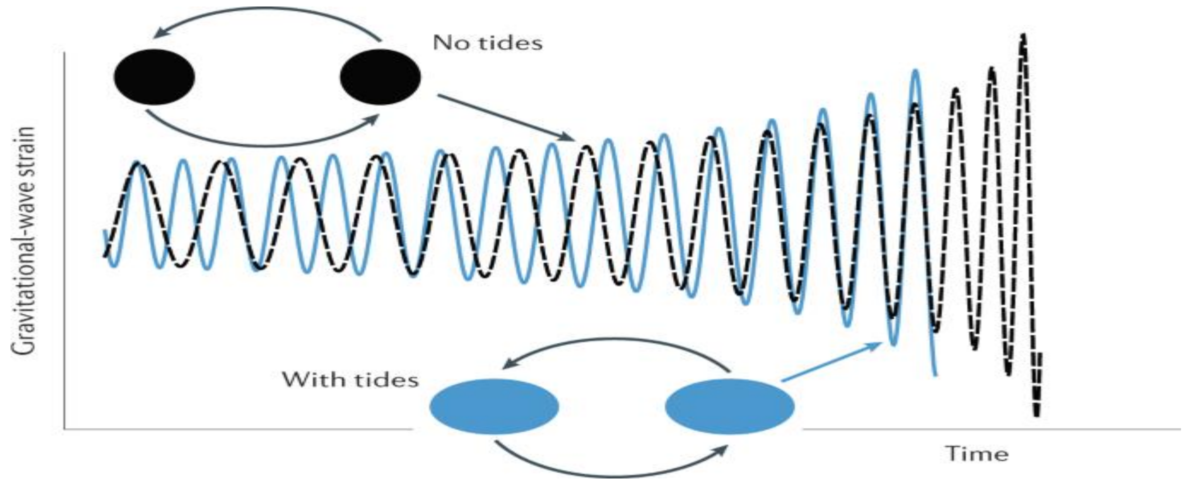
Post-Newtonian expansion in weak gravity and small velocities

Numerical Relativity 3+1 non-linear simulations

Description of the final remnant as an oscillating object with characteristic frequecies

A coherent inspiral waveform model

- Post-Newtonian (PN) expanded waveform in $x = \frac{1}{c^2}(\pi M f)^{\frac{2}{3}} \sim (v/c)^2$ including finite size effects:



$$h \sim \mathcal{A}(f) e^{i\psi(f)} \rightarrow \psi(f) = \psi_{pp}(f) + \psi_{tidal}(f) + \psi_{quad}(f) \propto x^{-\frac{5}{2}}\left(\sum_{n=0}^{7} \alpha_n(f) x^{\frac{n}{2}}\right)$$

Point particle relative terms $\propto x^0 \ldots x^{\frac{7}{2}}$ (0PN, 3.5PN)

C.K. Mishra et.al, Phys. Rev. D, 93, 8 (2016), 084054

Tidal corrections $\propto x^5$, x^6 (5PN, 6PN)

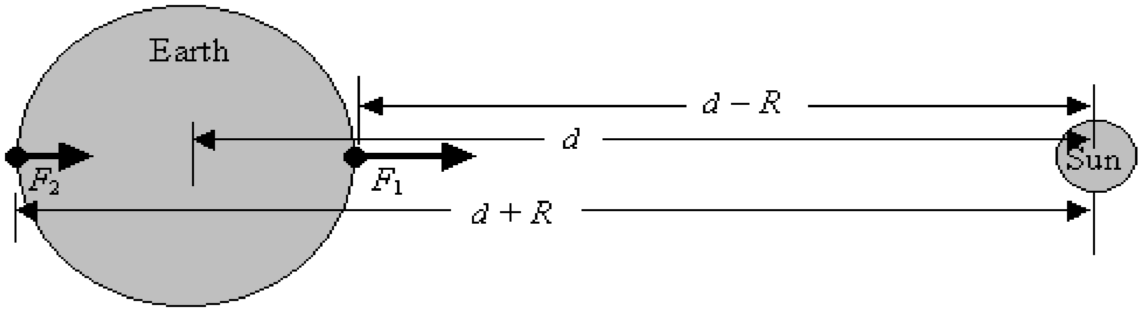
Lackey and L. Wade, Phys. Rev. D, 91, (2015) 4 043002

Quadrupole relative corrections $\propto x^2$, x^3 (2PN, 3PN)

Krishnendu et.al, Phys. Rev. Lett.,119,9 (2017) 091101

Tidal deformability

- The presence of the companion induces a quadrupole moment in the star as response to the external tidal field:



$$F_2 = \frac{GMm}{(d+R)^2} \qquad F_1 = \frac{GMm}{(d-R)^2} \qquad \Delta F = F_2 - F_1 = \frac{GMm}{d^2}\left[\left(1+\frac{R}{d}\right)^{-2} - \left(1-\frac{R}{d}\right)^{-2}\right]$$

- The same happens in General Relativity and can be studied as a perturbation problem of the spherically symmetric background spacetime:

$$g_{00} = -1 + \frac{2M}{r} + \frac{3Q_{ij}}{r^3}\left(n_i n_j - \frac{\delta_{ij}}{3}\right) + O\left(\frac{1}{r^4}\right) - \varepsilon_{ij} x_i x_j + O(r^3)$$

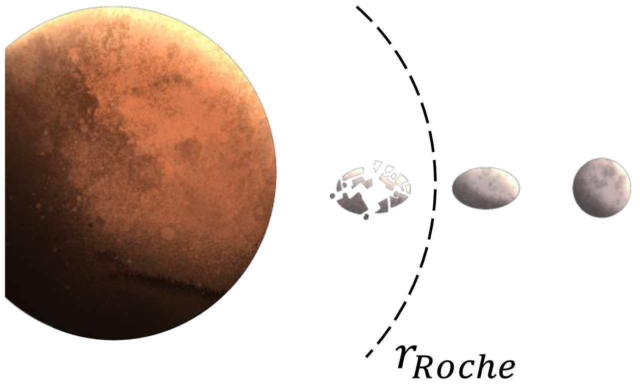
$$Q_{ij} = -\lambda_T \varepsilon_{ij}$$

λ_T is the tidal deformability

Tidal deformability of boson stars

- Dimensionless tidal $\Lambda = \lambda_T / M^5$ for BSs (*N. Sennett et al.*, Phys. Rev. D, 96, 2 (2017) 024002)

$$\frac{M}{M_B} = \frac{\sqrt{2}}{8\sqrt{\pi}}\left[-0.828 + \frac{20.99}{\log\Lambda} - \frac{99.1}{(\log\Lambda)^2} + \frac{149.7}{(\log\Lambda)^3}\right] \longrightarrow \boxed{\Lambda = \Lambda\left(\frac{M}{M_B}\right)}$$



We fixed the maximum frequency of the waveform to that corresponding to the Roche radius:

$$f_{Roche} = \frac{c^3}{\pi G M M_\odot}\sqrt{\frac{1}{q^2} + q + 3\left(1 + \frac{1}{q}\right)}\left(\frac{\mathcal{C}_2}{\gamma}\right)^{\frac{3}{2}} Hz$$

$\mathcal{C}_2$ = Compactness of the secondary

γ = Numerical factor $\gamma \sim 2$

Multipole moments in General Relativity

- The Newtonian potential satisfy the Laplace equation $\nabla^2 V = 0$,:

$$V(R,\theta,\varphi) = \sum_{k=0}^{\infty}\sum_{l=-k}^{k}\frac{M_{k,l}Y_k^l(\theta,\varphi)}{R^{k+1}} \xrightarrow[R \to 1/r]{} \tilde{V}(r,\theta,\varphi) = \sum_{k=0}^{\infty}\sum_{l=-k}^{k} M_{k,l}Y_k^l(\theta,\varphi)r^k$$

Consider now the Taylor expansion of $\tilde{V}$:

$$\tilde{V}(x^a) = \sum_{k=0}^{\infty}\frac{x^{a_1}\dots x^{a_k}}{k!}\partial_{a_1}\dots\partial_{a_k}\tilde{V}\Big|_{r=0}$$

- $Y_k^l(\theta,\varphi)r^k$ polinomial of degree k in $(x^1,x^2,x^3) = (r\sin\theta\cos\varphi, r\sin\theta\sin\varphi, r\cos\theta) \Rightarrow$

$$M_{k,l} \leftrightarrow \partial_{a_1}\dots\partial_{a_k}\tilde{V}\Big|_{r=0}$$

There is a correspondence between multipole moments and these quantities at infinity

- This definition have been generalized to stationary and asimptotically flat spacetimes in General Relativity (Geroch 1970, Hansen 1974).

Multipole moments of Boson Stars

- Stationary **axysimmetric** spacetime $\Rightarrow$

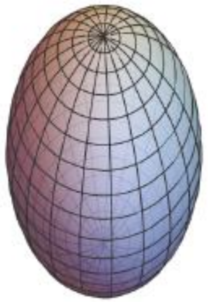
  scalar mass moments M_0, M_2... and current moments S_1, S_3...

$$M = M_0$$
$$J = S_1$$
$$Q = M_2$$
quadrupole moment

...

$M_2 = 0$

$M_2 < 0$



$M_2 > 0$

For a Kerr black hole

$$M_l + iS_l = M^{l+1}(i\chi)^l$$

$$\chi = \frac{J}{M^2},$$

Not true for a generic compact object!

Multipole moments of Boson Stars

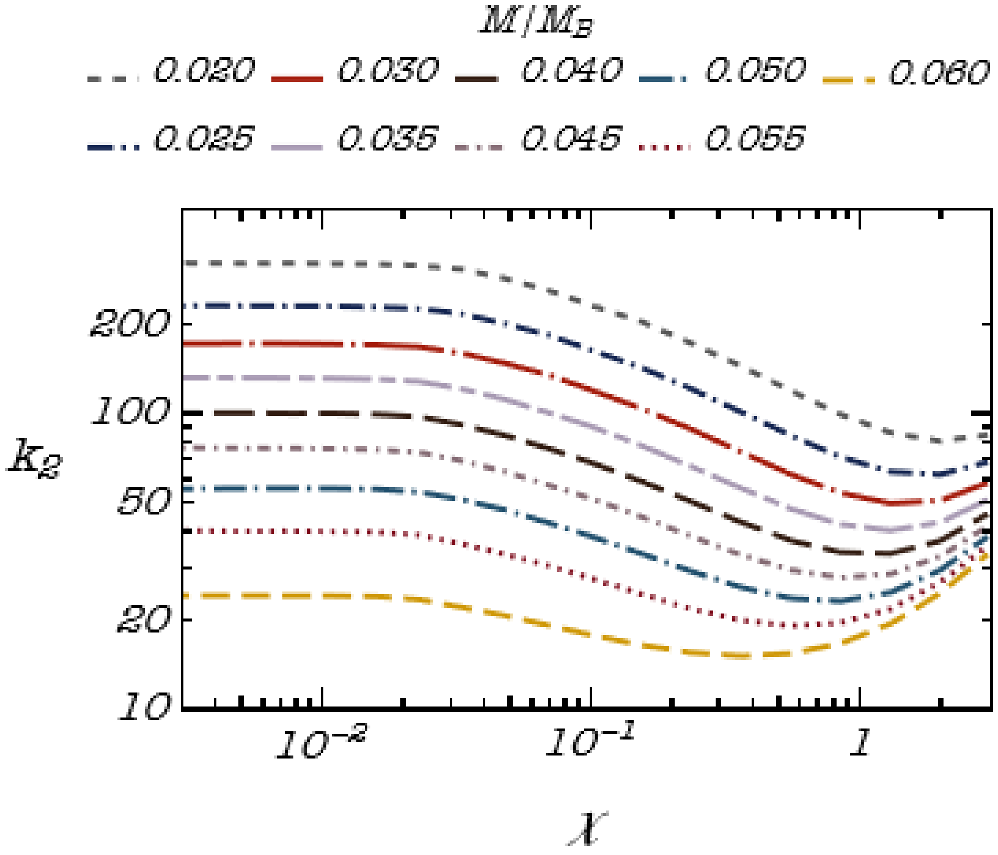
Kerr black hole

$$M_2 = -\chi^2 M^3$$

Boson Star

$$M_2 = -\kappa_2(\chi, M/M_B)\chi^2 M^3$$

$$\frac{\sqrt{\lambda\hbar}}{m_S^2} M_P^3$$



$$M_{max} \approx 0.06 M_B \approx 10^5 M_\odot \sqrt{\lambda\hbar}\left(\frac{\text{MeV}}{m_S}\right)^2$$

The multipolar structure of fast rotating boson stars: *M. Vaglio, C. Pacilio, A. Maselli, P. Pani,* arXiv:2203.07442 (2022)

Parameter estimation - Setting

- Bayesian parameter estimation on injected signals

prior — likelyhood

posterior — $$p(\vec{\theta}|d) = \frac{\pi(\vec{\theta})\mathcal{L}(d|\vec{\theta},\mathcal{H})}{\int d^m\theta\pi(\vec{\theta})\mathcal{L}(d|\vec{\theta},\mathcal{H})}$$ — evidence

- Spins alligned with $\vec{L}$:

$$\vec{\theta} = (\mathcal{M}, \eta, \chi_1, \chi_1, M_B)$$

Chirp mass — Symmetric mass ratio — Component spins — $\boldsymbol{M_B} = (\lambda^{\frac{1}{2}}/m^2)\ M_p^3$

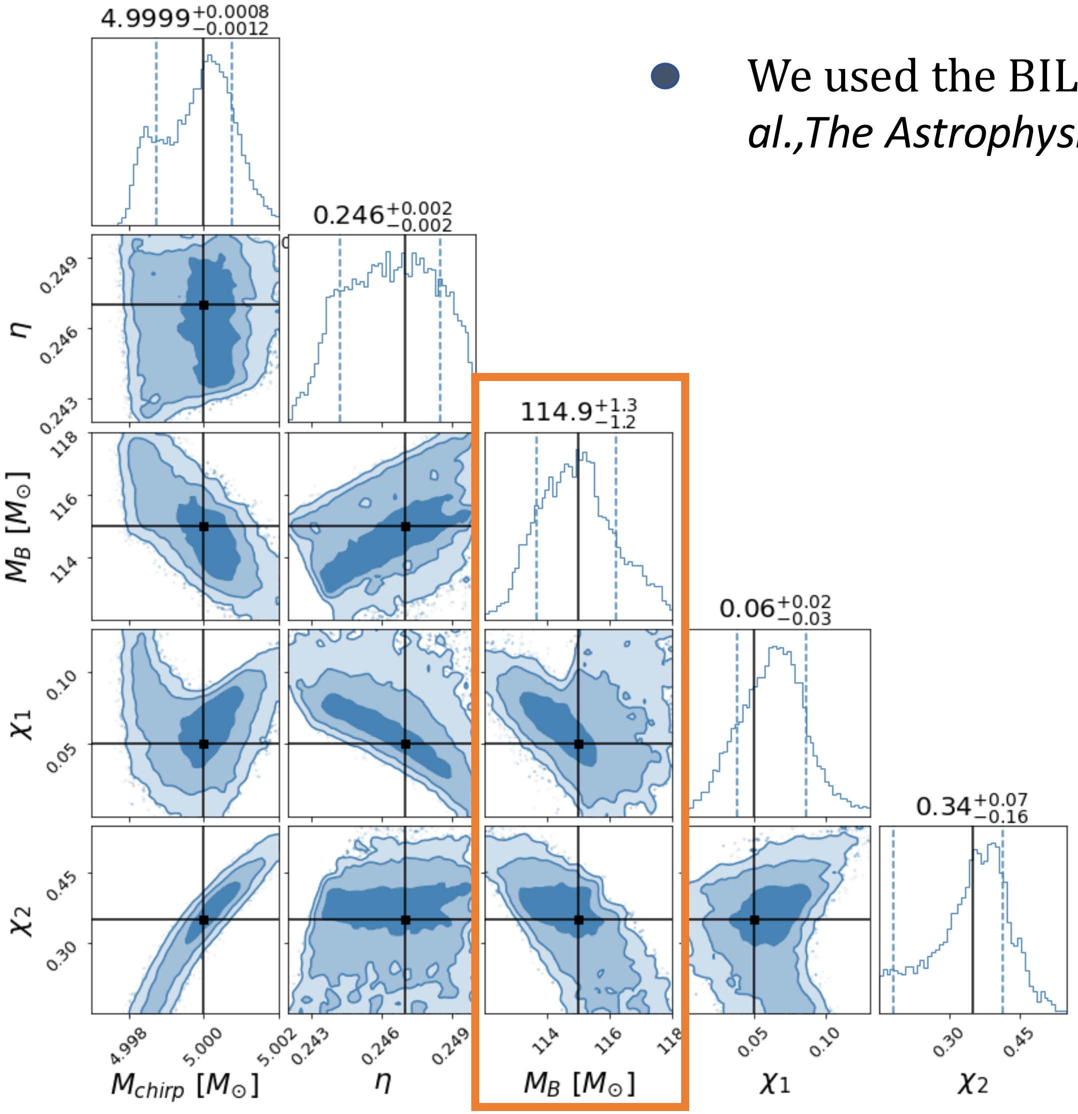
Fixed parameters:

$\boldsymbol{ra}, \boldsymbol{dec}$ sky localization angles
$\boldsymbol{\iota}$ system inclination angle
$\boldsymbol{\psi}$ wave polarization angle

Marginalized parameters:

$\boldsymbol{dL}$ Luminosity distance
$\boldsymbol{t_c}, \boldsymbol{\phi_c}$ time and phase at coalescence

Parameter estimation - Results

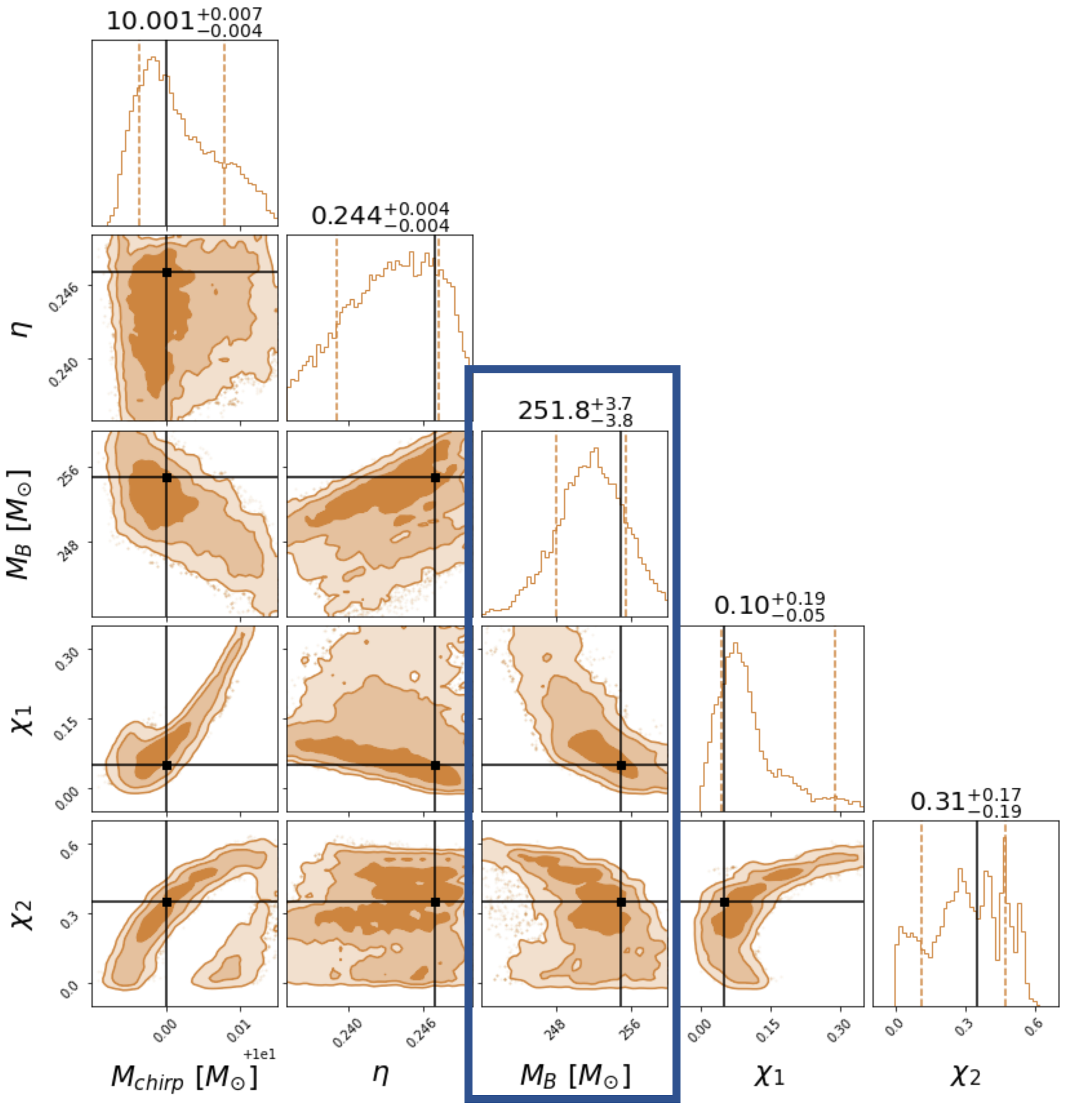


- We used the BILBY Bayesian Inference Library (Ashton, Gregory *et al.,The Astrophysical Journal Supplement Series, voln.241,2019*).

Injection and recovery of a signal with the Einstein Telescope ($SNR = 130$):

- $\mathcal{M} = 5M_\odot$
- $q = 0.8$
- $M_B = 115M_\odot$
- $\chi_1 = 0.05$
- $\chi_2 = 0.35$
- $f_{Roche} = 127Hz$

Parameter estimation - Results



Injection and recovery of a signal with the Einstein Telescope (SNR = 130):

- $\mathcal{M} = 10M_\odot$
- $q = 0.8$
- $M_B = 255M_\odot$
- $\chi_1 = 0.05$
- $\chi_2 = 0.35$
- $\boldsymbol{f_{Roche} = 50Hz}$ ←

Conclusions and perspectives

We have seen how to develop a coherent waveform template for the inspiral of rotating self-interacting BSs taking finite size effects into account :

- We have characterized the tidal deformability and the quadrupole moment $M_2 \sim \chi^2$ of boson stars as smoking gun signatures from departures from the signal of a black hole binary

- With ET at SNR ~ 100 it is possible to constraint the fundamental couplings of the scalar theory with ~1% accuracy:

(m_1, m_2)	$\delta \mathcal{M}_{rel}$	$\delta \eta_{rel}$	$\delta M_{B_{rel}}$	$\delta \chi_{1_{rel}}$	$\delta \chi_{2_{rel}}$
$(6.4, 5.2) M_\odot$	0.015%	0.8%	1.0%	48%	37%
$(12.8, 10.3) M_\odot$	0.05%	1.7%	1.5%	92%	43%

In agreement with F.M. analysis: *C. Pacilio, M. Vaglio, A. Maselli, P. Pani. Phys.Rev. D* 102 (2020) 8, 083002

Next steps and future works:

- Generalization to other BS's models: change $V(|\phi|^2)$, Vector bosonic stars, universal relations…

- Model selection between different potentials and boson star families