Searching for evidences of Exotic Compact Objects from the spin distribution of compact binary coalescences

Adriano Frattale Mascioli

Contact: adriano.frattalemascioli@uniroma1.it

Sapienza University of Rome & INFN-Roma1

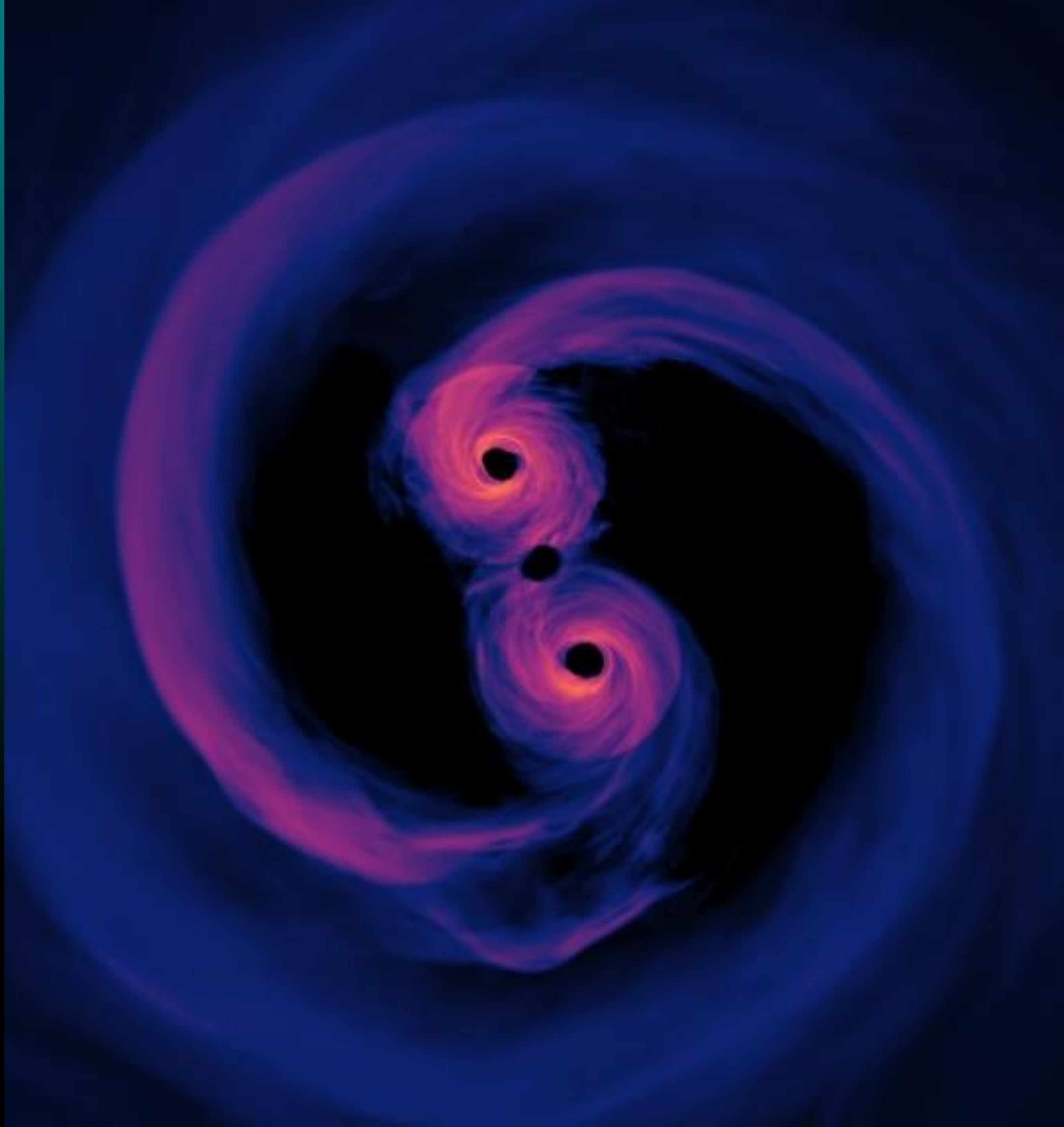
In **collaboration** with:

Simone Mastrogiovanni (INFN-Roma1 & Sapienza)

Elisa Maggio (AEI, Potsdam)

GraSP, 25/10/2023

Pisa



Outline of the work

RATIONALE

- ✓ **Gravitational waves** (GWs) from **compact binary coalescence** (CBC) represent a novel tool to investigate the **nature of compact objects**.
- ✓ **Exotic Compact Objects (ECOs)** could in principle be distinguished by **Black Holes (BHs)** through minor phenomenological effects, like the **ergoregion instability**.

STRUCTURE OF THE WORK

1. **Hierarchical Bayesian inference** using GWs from the **population** of binary black holes (BBHs) of the **third observing run** (O3).
2. **Spins as figures of merit**: assume different spin distribution for populations of BHs and ECOs.
3. **Assume firstly** a population of only ECOs, and **then** a **mixed** one.

*K. Ng et al. Phys. Rev. D **103**, 063010 (2021)*
*K. Ng et al. Phys. Rev. D **126**, 151102 (2021)*

Why Exotic Compact Objects?

Black holes are fascinating objects but present theoretical controversies (curvature singularity, information loss paradox).

Exotic Compact Objects: A possible solution → Horizonless objects

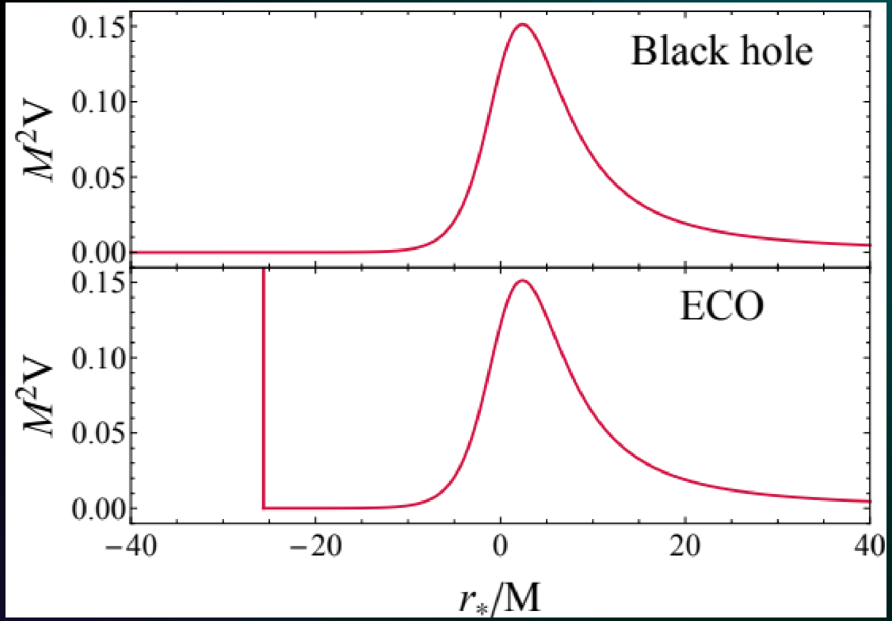
1. Correction to GR
2. Beyond SM fields coupled to gravity

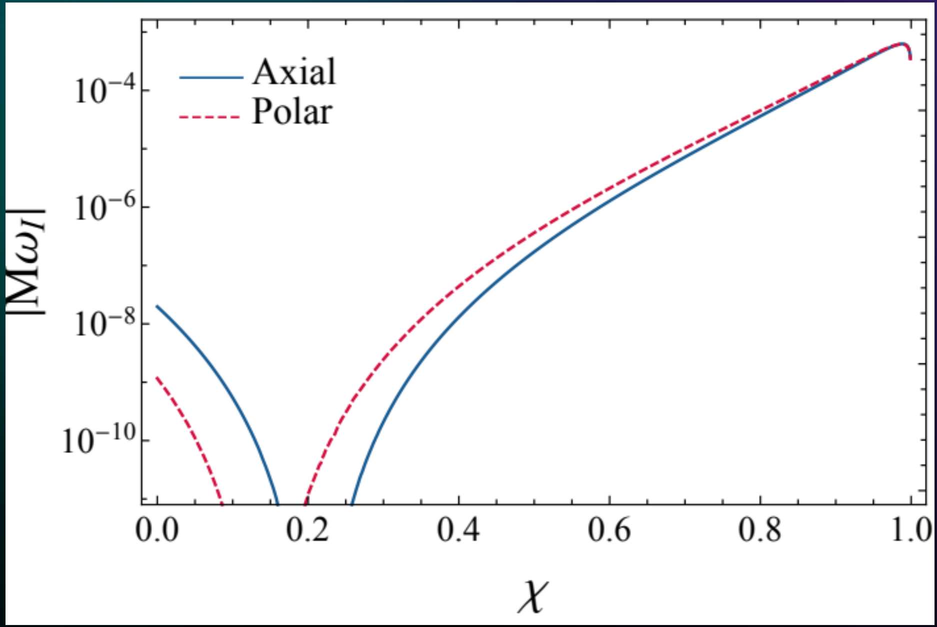
CLASSIFIED BY

Compactness	**Reflectivity**
Inverse of the (possibly effective) **radius**, defined as: $r_0 = r_+(1+\varepsilon)$ With r_+ Kerr horizon, ε **closeness parameter**. **BH limit**: $\varepsilon \to 0$	At **their** (possibly effective) **surface** $\mathcal{R}$ In general complex and frequency dependent. **BH limit**: $\mathcal{R} \to 0$

The ergoregion instability (1/2)

Linear perturbations: $\frac{d^2\Psi(r)}{dr_*^2} + [\omega^2 - V(r)]\Psi(r) = 0$



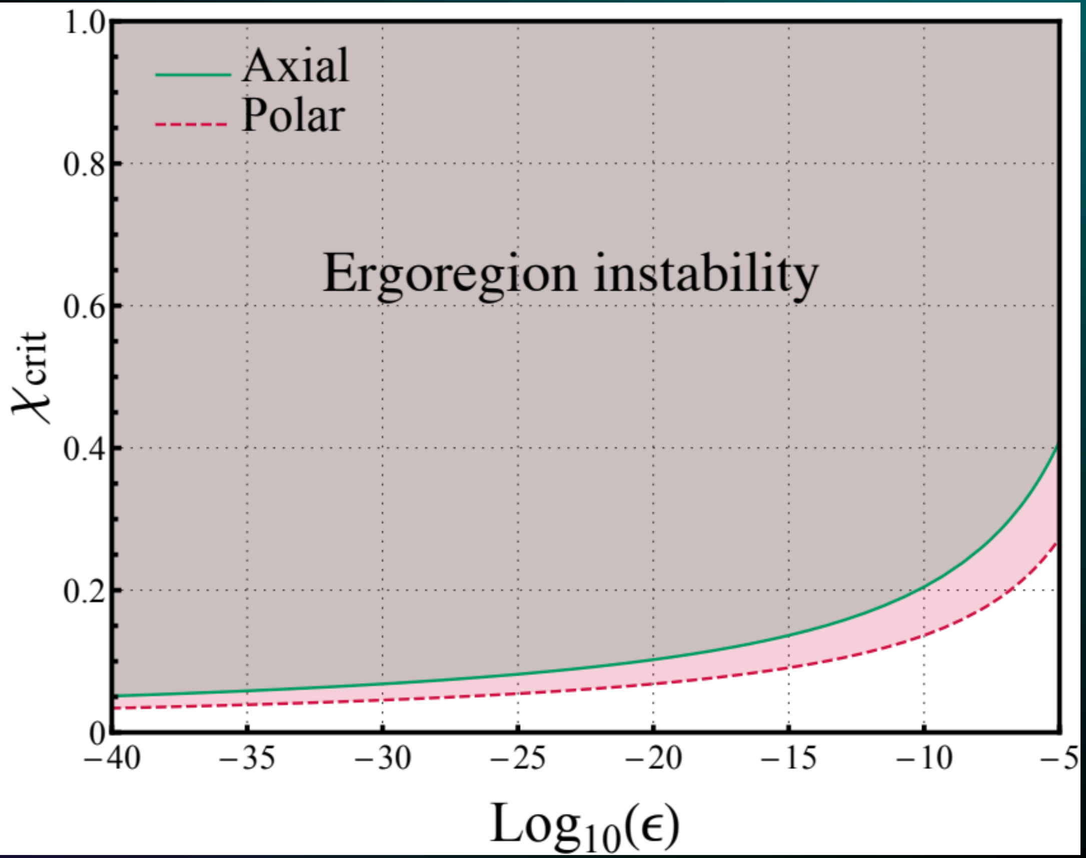


Potential governing the master equation:
In the ECO case, the absence of the horizon at $r_* \to -\infty$ implies a cavity, producing long-lived modes.
Here $\varepsilon = 10^{-6}$.

The imaginary frequency changes sign after a **critical spin** χ_{crit} : *presence* ***of unstable modes***
Here $\varepsilon = 10^{-6}$ *and* $|\mathcal{R}|^2 = 1$

E. Maggio, P. Pani, G. Raposo, Springer (2021)

The ergoregion instability (2/2)



Behaviour of χ_{crit} with the closeness parameter for a perfectly reflecting ECO $|\mathcal{R}|^2 = 1$

Credit: E. Maggio, PhD Thesis, 2022

- ✓ For a **perfectly reflecting ECO** one can find the relation $\chi_{crit}(\varepsilon)$ by **imposing** $\omega_R \simeq \omega_I \simeq 0$:

$$\chi_{crit}(\varepsilon) \propto \frac{1}{\log_{10} \varepsilon}$$

- ✓ The spin **decays** till it reaches the **critical value**

- ✓ The **time** of **instability** is defined as:

$$\tau_{ins} \equiv \frac{1}{\omega_I} \in (5{,}7) \left(\frac{M}{10\ M_\odot} \right) sec$$

Where the **lower** (**upper**) bounds are for **polar** (**axial**) GW perturbations.

Gravitational-wave population inference

If **multiple GWs** from CBC events are **collected**, it's **crucial** to estimate **collective properties** of the **population** of compact objects.
Some of the **frequent questions** one tries to **answer** could be:

- How are distributed the masses/spins of the population of binary black holes/neutron stars? Are there peaks/gaps in the spectrum? Is it what we expect theoretically?
- Are there evidences of different classes of objects (our task)?
- Are we able to handle selection effects, namely the fact we are biased to measuring mainly the most luminous events?

The **framework** employed for these scopes is the **hierarchical Bayesian inference**.

Hierarchical Bayesian inference (1/2)

Main quantities

- GW single-event parameters: $\boldsymbol{\theta}$
- Number of sources for unit $\boldsymbol{\theta}$:
-

$$\frac{dN_s}{d\boldsymbol{\theta}} = N_s \cdot p_{pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})$$

- Pop. Hyperparameters: $\boldsymbol{\Lambda} = \{N_s, \boldsymbol{\lambda}\}$

  N_s: total number of mergers for a given time and volume
  $\boldsymbol{\lambda}$: shape parameters

- $p_{pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})$: fraction of the population with parameters $\boldsymbol{\theta}$, given $\boldsymbol{\lambda}$.

Handling selection effects:

Fraction of detectable events with respect total ones:

$$\frac{N_s^{\uparrow}}{N_s} = \int d\boldsymbol{\theta}\, p_{pop}(\boldsymbol{\theta}|\boldsymbol{\lambda}) p(\rho^{\uparrow}|\boldsymbol{\theta})$$

$p(\rho^{\uparrow}|\boldsymbol{\theta})$**:** probability for a source with $\boldsymbol{\theta}$ to be over detection threshold (like SNR or FAR).

I. Mandel, W. Farr, J. Gair, MNRAS ***486*** *(2019)*
S. Vitale, D. Gerosa, W. Farr, S. Taylor, Springer (2021)

Hierarchical Bayesian inference (2/2)

Further assumptions:

1. N_{tr} source events collected.

2. **Constant** source rate: $\frac{dN_s}{dt} \simeq const$

Final goal

Find the posterior distribution on $\boldsymbol{\Lambda}$ given the set of detected sources $\boldsymbol{D} = \{\mathrm{d}_i\}_{i=1,\ldots,N_{tr}}$:

$$p(\boldsymbol{\lambda}|\mathbf{D}) \propto p(\boldsymbol{D}|\boldsymbol{\lambda})\mathrm{p}(\boldsymbol{\lambda})$$

After **marginalizing** over N_s, assuming a $1/N_s$ prior.

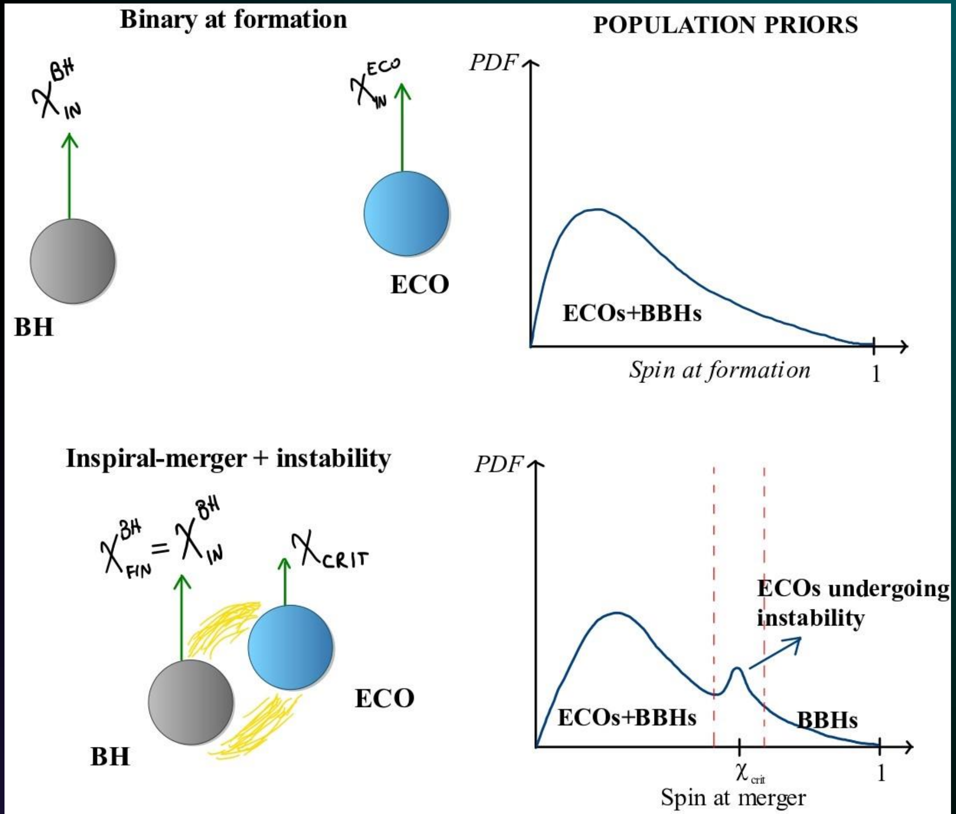
Computing the hyperlikelihood:

$$p(\boldsymbol{D}|\boldsymbol{\lambda}) \propto \prod_{i=1}^{N_{tr}} \frac{\int d\boldsymbol{\theta}\, p_{pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})p(d_i|\boldsymbol{\theta})}{\int d\boldsymbol{\theta}\, p_{pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})p(\rho^{\uparrow}|\boldsymbol{\theta})}$$

GW likelihood

Selection effects act as a **reweighting**

Spin population distribution employed



Since $\mathbf{T(inst)} \ll \boldsymbol{T}\mathbf{(inspiral)}$, we assume that an ECO would reach χ_{crit} almost immediately after formation.

SPINS AT FORMATION

Beta distribution for both ECOs and BBHs

SPIN AT MERGER (THE ONES MEASURED)

- **Beta** with a **gaussian peak** on χ_{crit} for **ECOs**
- **Unchanged** for **BHs** (again Beta)

$$p_{pop}^{tot}(\chi|\Lambda, f_{eco}) = f_{eco}\, p_{pop}^{ECO}(\chi|\Lambda) + (1 - f_{eco})\, p_{pop}^{BBH}(\chi|\Lambda)$$

$$\begin{cases} p_{pop}^{BBH}(\chi|\Lambda) = \beta(\chi|\alpha, \beta) \\ p_{pop}^{ECO}(\chi|\Lambda) = \lambda_{eco}\beta(\chi|\alpha, \beta)\Theta(\chi_{crit} - \chi) + (1 - \lambda_{eco})\mathcal{N}(\chi|\chi_{crit}, \sigma) \end{cases}$$

f_{eco}: fraction of ECOs included in the shape parameters $\boldsymbol{\lambda}$

Simulations and main results

- Simulations carried out with ***ICAROGW*** (S. Mastrogiovanni *et al.* arXiv:2305.17973), a Python software for GW population inference.

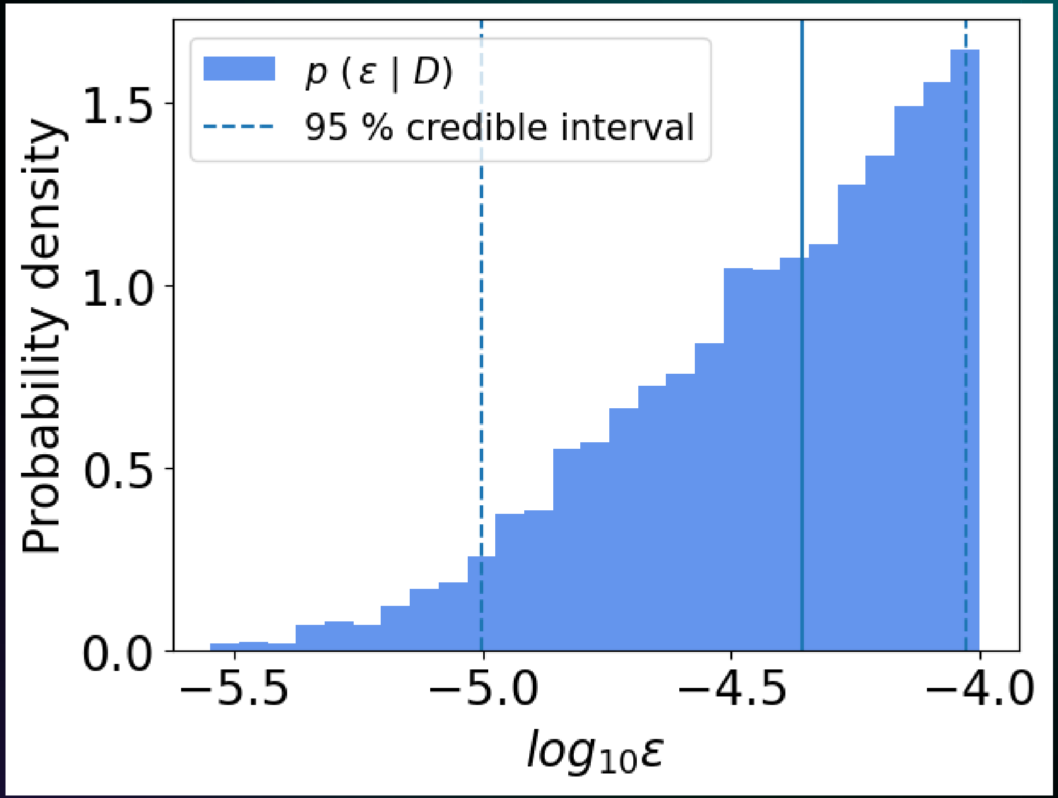
- We performed **three** different simulations on O3 BBH events:
  1. Assuming a population of **100%** ECOs (BHs), namely $f_{eco} = 1$ ($f_{eco} = 0$);
  2. Assuming **mixed** population, f_{eco} free parameter to infer.

- We computed the Bayes factor for the various combinations:

$$K = \frac{p(\boldsymbol{D}|i)}{p(\boldsymbol{D}|j)}, \quad \text{with } i, j \in (BBH, ECO, MIXTURE).$$

$K(mix\ /BBH) = 3.8$ $\qquad K(mix\ /ECO) = 5.4$ $\qquad K(BBH\ /ECO) = 1.4$

Population of 100% ECOs



Marginalized posterior for the closeness parameter ε.

PRIOR FOR ϵ

Log-Uniform in $[\ 10^{-40},\ \ 10^{-4}\ ]$

MAIN MESSAGE

- We can put a **lower limit** on ϵ in the case of $f_{eco} \equiv 1$: this is $\epsilon \simeq 10^{-5}$.
- **Too low values would not explain** some **high-spin events** of the GWTC-3 catalog, if only ECOs are assumed.

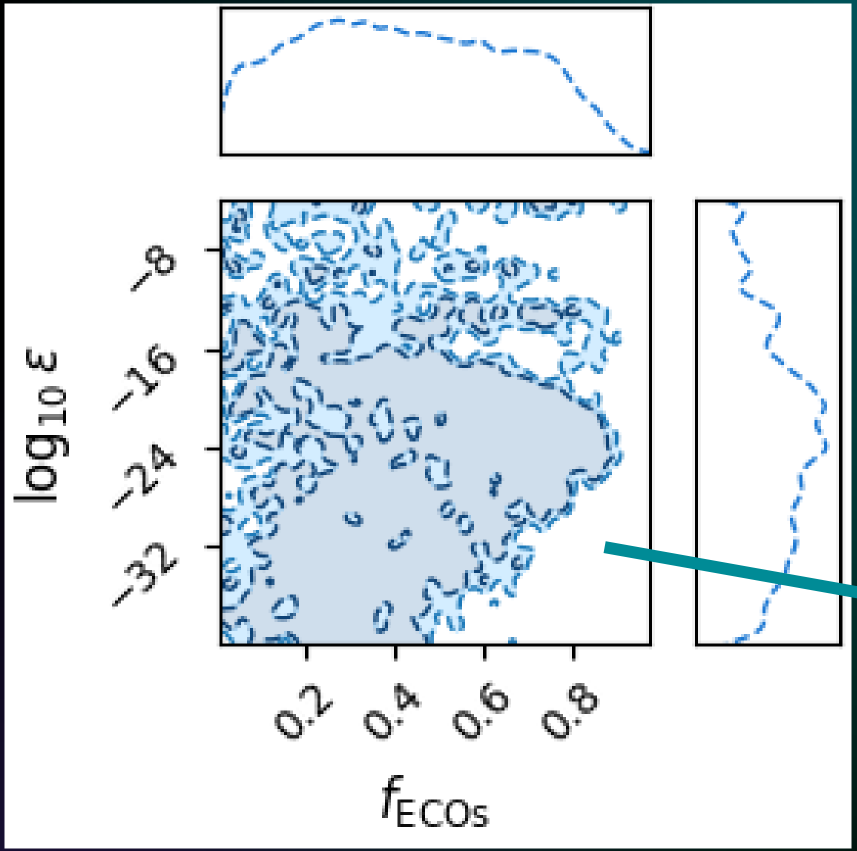
An example of event of the catalog with high spin evidence

Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	$M_{\rm f}$ ($M_\odot$)	$\chi_{\rm f}$	$\Delta\Omega$ (deg^2)	SNR
GW190408_181802	$43.0^{+4.2}_{-3.0}$	$18.3^{+1.9}_{-1.2}$	$24.6^{+5.1}_{-3.4}$	$18.4^{+3.3}_{-3.6}$	$-0.03^{+0.14}_{-0.19}$	$1.55^{+0.40}_{-0.60}$	$0.29^{+0.06}_{-0.10}$	$41.1^{+3.9}_{-2.8}$	$0.67^{+0.06}_{-0.07}$	150	$15.3^{+0.2}_{-0.3}$
GW190412	$38.4^{+3.8}_{-3.7}$	$13.3^{+0.4}_{-0.3}$	$30.1^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$0.25^{+0.08}_{-0.11}$	$0.74^{+0.14}_{-0.17}$	$0.15^{+0.03}_{-0.03}$	$37.3^{+3.9}_{-3.8}$	$0.67^{+0.05}_{-0.06}$	21	$18.9^{+0.2}_{-0.3}$
GW190413_052954	$58.6^{+13.3}_{-9.7}$	$24.6^{+5.5}_{-4.1}$	$34.7^{+12.6}_{-8.1}$	$23.7^{+7.3}_{-6.7}$	$-0.01^{+0.29}_{-0.34}$	$3.55^{+2.27}_{-1.66}$	$0.59^{+0.29}_{-0.24}$	$56.0^{+12.5}_{-9.2}$	$0.68^{+0.12}_{-0.13}$	1500	$8.9^{+0.4}_{-0.7}$
GW190413_134308	$78.8^{+17.4}_{-11.9}$	$33.0^{+8.2}_{-5.4}$	$47.5^{+13.5}_{-10.7}$	$31.8^{+11.7}_{-10.8}$	$-0.03^{+0.25}_{-0.29}$	$4.45^{+2.48}_{-2.12}$	$0.71^{+0.31}_{-0.30}$	$75.5^{+16.4}_{-11.4}$	$0.68^{+0.10}_{-0.12}$	730	$10.0^{+0.4}_{-0.5}$
GW190421_213856	$72.9^{+13.4}_{-9.2}$	$31.2^{+5.9}_{-4.2}$	$41.3^{+10.4}_{-6.9}$	$31.9^{+8.0}_{-8.8}$	$-0.06^{+0.22}_{-0.27}$	$2.88^{+1.37}_{-1.38}$	$0.49^{+0.19}_{-0.21}$	$69.7^{+12.5}_{-8.7}$	$0.67^{+0.10}_{-0.11}$	1200	$10.7^{+0.2}_{-0.4}$
GW190424_180648	$72.6^{+13.3}_{-10.7}$	$31.0^{+5.8}_{-4.6}$	$40.5^{+11.1}_{-7.3}$	$31.8^{+7.6}_{-7.7}$	$0.13^{+0.22}_{-0.22}$	$2.20^{+1.58}_{-1.16}$	$0.39^{+0.23}_{-0.19}$	$68.9^{+12.4}_{-10.1}$	$0.74^{+0.09}_{-0.09}$	28000	$10.4^{+0.2}_{-0.4}$
GW190425	$3.4^{+0.3}_{-0.1}$	$1.44^{+0.02}_{-0.02}$	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	$0.06^{+0.11}_{-0.05}$	$0.16^{+0.07}_{-0.07}$	$0.03^{+0.01}_{-0.02}$	–	–	10000	$12.4^{+0.3}_{-0.4}$
GW190426_152155	$7.2^{+3.5}_{-1.5}$	$2.41^{+0.08}_{-0.08}$	$5.7^{+3.9}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.32}_{-0.30}$	$0.37^{+0.18}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	–	–	1300	$8.7^{+0.5}_{-0.6}$
GW190503_185404	$71.7^{+9.4}_{-8.3}$	$30.2^{+4.2}_{-4.2}$	$43.3^{+9.2}_{-8.1}$	$28.4^{+7.7}_{-8.0}$	$-0.03^{+0.20}_{-0.26}$	$1.45^{+0.69}_{-0.63}$	$0.27^{+0.11}_{-0.11}$	$68.6^{+8.8}_{-7.7}$	$0.66^{+0.09}_{-0.12}$	94	$12.4^{+0.2}_{-0.3}$
GW190512_180714	$35.9^{+3.8}_{-3.5}$	$14.6^{+1.3}_{-1.0}$	$23.3^{+5.3}_{-5.8}$	$12.6^{+3.6}_{-2.5}$	$0.03^{+0.12}_{-0.13}$	$1.43^{+0.55}_{-0.55}$	$0.27^{+0.09}_{-0.10}$	$34.5^{+3.8}_{-3.5}$	$0.65^{+0.07}_{-0.07}$	220	$12.2^{+0.2}_{-0.4}$
GW190513_205428	$53.9^{+8.6}_{-5.9}$	$21.6^{+3.8}_{-1.9}$	$35.7^{+9.5}_{-9.2}$	$18.0^{+7.7}_{-4.1}$	$0.11^{+0.28}_{-0.17}$	$2.06^{+0.88}_{-0.80}$	$0.37^{+0.13}_{-0.13}$	$51.6^{+8.2}_{-5.8}$	$0.68^{+0.14}_{-0.12}$	520	$12.9^{+0.3}_{-0.4}$
GW190514_065416	$67.2^{+18.7}_{-10.8}$	$28.5^{+7.9}_{-4.8}$	$39.0^{+14.7}_{-8.2}$	$28.4^{+9.3}_{-8.8}$	$-0.19^{+0.29}_{-0.32}$	$4.13^{+2.65}_{-2.17}$	$0.67^{+0.33}_{-0.31}$	$64.5^{+17.9}_{-10.4}$	$0.63^{+0.11}_{-0.15}$	3000	$8.2^{+0.3}_{-0.6}$
GW190517_055101	$63.5^{+9.6}_{-9.6}$	$26.6^{+4.0}_{-4.0}$	$37.4^{+11.7}_{-7.6}$	$25.3^{+7.0}_{-7.3}$	$0.52^{+0.19}_{-0.19}$	$1.86^{+1.62}_{-0.84}$	$0.34^{+0.24}_{-0.14}$	$59.3^{+9.1}_{-8.9}$	$0.87^{+0.05}_{-0.07}$	470	$10.7^{+0.4}_{-0.6}$
GW190519_153544	$106.6^{+13.5}_{-14.8}$	$44.5^{+6.4}_{-7.1}$	$66.0^{+10.7}_{-12.0}$	$40.5^{+11.0}_{-11.1}$	$0.31^{+0.20}_{-0.22}$	$2.53^{+1.83}_{-0.92}$	$0.44^{+0.25}_{-0.14}$	$101.0^{+12.4}_{-13.8}$	$0.79^{+0.07}_{-0.13}$	860	$15.6^{+0.2}_{-0.3}$
GW190521	$163.9^{+39.2}_{-23.5}$	$69.2^{+17.0}_{-10.6}$	$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$	$0.03^{+0.32}_{-0.39}$	$3.92^{+2.19}_{-1.95}$	$0.64^{+0.28}_{-0.28}$	$156.3^{+36.8}_{-22.4}$	$0.71^{+0.12}_{-0.16}$	1000	$14.2^{+0.3}_{-0.3}$
GW190521_074359	$74.7^{+7.0}_{-4.8}$	$32.1^{+3.2}_{-2.5}$	$42.2^{+5.9}_{-4.8}$	$32.8^{+5.4}_{-6.4}$	$0.09^{+0.10}_{-0.13}$	$1.24^{+0.40}_{-0.57}$	$0.24^{+0.07}_{-0.10}$	$71.0^{+6.5}_{-4.4}$	$0.72^{+0.05}_{-0.07}$	550	$25.8^{+0.1}_{-0.2}$
GW190527_092055	$59.1^{+21.3}_{-9.8}$	$24.3^{+9.1}_{-4.2}$	$36.5^{+16.4}_{-9.0}$	$22.6^{+10.5}_{-8.1}$	$0.11^{+0.28}_{-0.28}$	$2.49^{+2.48}_{-1.24}$	$0.44^{+0.34}_{-0.20}$	$56.4^{+20.2}_{-9.3}$	$0.71^{+0.12}_{-0.16}$	3700	$8.1^{+0.3}_{-0.9}$
GW190602_175927	$116.3^{+19.0}_{-15.6}$	$49.1^{+9.1}_{-8.5}$	$69.1^{+15.7}_{-13.0}$	$47.8^{+14.3}_{-17.4}$	$0.07^{+0.25}_{-0.24}$	$2.69^{+1.79}_{-1.12}$	$0.47^{+0.25}_{-0.17}$	$110.9^{+17.7}_{-14.9}$	$0.70^{+0.10}_{-0.14}$	690	$12.8^{+0.2}_{-0.3}$
GW190620_030421	$92.1^{+18.5}_{-13.1}$	$38.3^{+8.3}_{-6.5}$	$57.1^{+16.0}_{-12.7}$	$35.5^{+12.2}_{-12.3}$	$0.33^{+0.22}_{-0.25}$	$2.81^{+1.68}_{-1.31}$	$0.49^{+0.23}_{-0.20}$	$87.2^{+16.8}_{-12.1}$	$0.79^{+0.08}_{-0.15}$	7200	$12.1^{+0.3}_{-0.4}$
GW190630_185205	$59.1^{+4.6}_{-4.8}$	$24.9^{+2.1}_{-2.1}$	$35.1^{+6.9}_{-5.6}$	$23.7^{+5.2}_{-5.1}$	$0.10^{+0.12}_{-0.13}$	$0.89^{+0.56}_{-0.37}$	$0.18^{+0.10}_{-0.07}$	$56.4^{+4.4}_{-4.6}$	$0.70^{+0.05}_{-0.07}$	1200	$15.6^{+0.2}_{-0.3}$
GW190701_203306	$94.3^{+12.1}_{-9.5}$	$40.3^{+5.4}_{-4.9}$	$53.9^{+11.8}_{-8.0}$	$40.8^{+8.7}_{-12.0}$	$-0.07^{+0.23}_{-0.29}$	$2.06^{+0.76}_{-0.73}$	$0.37^{+0.11}_{-0.12}$	$90.2^{+11.3}_{-8.9}$	$0.66^{+0.09}_{-0.13}$	46	$11.3^{+0.2}_{-0.3}$
GW190706_222641	$104.1^{+20.2}_{-13.9}$	$42.7^{+10.0}_{-7.0}$	$67.0^{+14.6}_{-16.2}$	$38.2^{+14.6}_{-13.3}$	$0.28^{+0.26}_{-0.29}$	$4.42^{+2.59}_{-1.93}$	$0.71^{+0.32}_{-0.27}$	$99.0^{+18.3}_{-13.5}$	$0.78^{+0.09}_{-0.18}$	650	$12.6^{+0.2}_{-0.4}$
GW190707_093326	$20.1^{+1.9}_{-1.3}$	$8.5^{+0.6}_{-0.5}$	$11.6^{+3.3}_{-1.7}$	$8.4^{+1.4}_{-1.7}$	$-0.05^{+0.10}_{-0.08}$	$0.77^{+0.38}_{-0.37}$	$0.16^{+0.07}_{-0.07}$	$19.2^{+1.9}_{-1.3}$	$0.66^{+0.03}_{-0.04}$	1300	$13.3^{+0.2}_{-0.4}$
GW190708_232457	$30.9^{+2.5}_{-1.8}$	$13.2^{+0.9}_{-0.6}$	$17.6^{+4.7}_{-2.3}$	$13.2^{+2.0}_{-2.7}$	$0.02^{+0.10}_{-0.08}$	$0.88^{+0.33}_{-0.39}$	$0.18^{+0.06}_{-0.07}$	$29.5^{+2.5}_{-1.8}$	$0.69^{+0.04}_{-0.04}$	14000	$13.1^{+0.2}_{-0.3}$

CREDIT

R. Abbot et al. Phys.Rev.X ***11*** *(2021) 021053*

Mixture model



Marginalized bidimensional posterior for the closeness parameter ε and the fraction of ECOs, for a mixed population

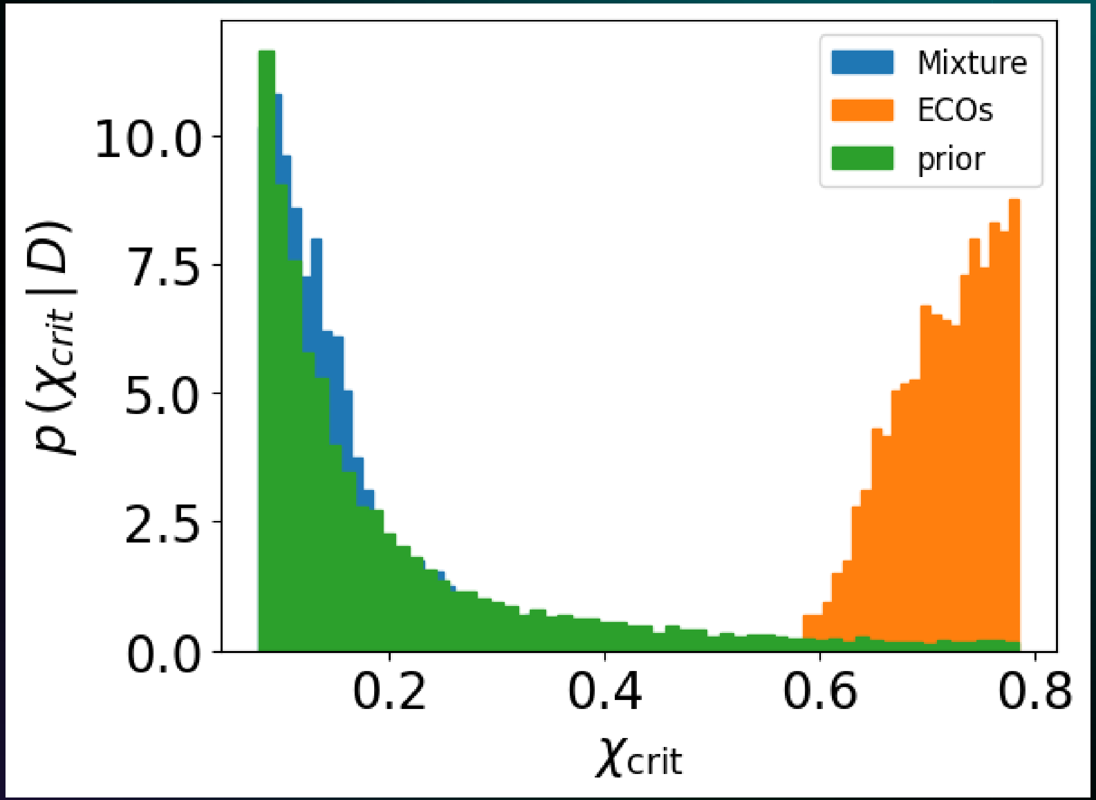
GOAL

- We keep f_{eco} as a free parameter to infer to.
- Which **constraints** can we put on f_{eco} and ϵ ?

We can **exclude** the **region** of **high-fraction**, **ultra-compact** ECOs ($f_{eco} \simeq 1, \varepsilon \ll 1$):

Particularly, no **more** than 60% of objects can be ECOs in the **ultra-compact region** ($\varepsilon < 10^{-30}$)

Implied distribution on χ_{crit}



Posterior distribution mapped on $\chi_{crit}(\epsilon)$ for the two models, compared with the prior, that reflects the log-uniform prior on ϵ.

- **ONLY ECOs**: **shifted toward higher** values, recover high spin events
- **MIXTURE**: **dominated** by **prior** on ϵ. High-spin events are handled by the possibility of being a BH.

Probability of being a certain object (1/2)

- **Suppose** we have a new astrophysical event: what is the probability that this is an ECO (BBH)?
- What we know? The previous events with which we computed the posterior on population parameters
- We basically want to compute the following:

$$P(ECO|\boldsymbol{D}, d) = \int P(\boldsymbol{\lambda}|\boldsymbol{D}) \left[\int P(ECO|\chi, \boldsymbol{\lambda}) P(\chi|d, \boldsymbol{\lambda})\, d\chi \right] d\boldsymbol{\lambda}$$

$\boldsymbol{D}$: all the previous data containing CBC events, used to compute the hyperposterior on $\boldsymbol{\lambda}$

d: data containing the new event

We compute it for all the events of the catalog used for the analysis

Probability of being a certain object (2/2)

Probability of being an ECO for each of the two objects of the O3 binaries

Event ID	$p_1(\text{ECO}\|\boldsymbol{D}, d)$	$p_2(\text{ECO}\|\boldsymbol{D}, d)$
GW190408_181802	$0.41^{+0.51}_{-0.40}$	$0.40^{+0.51}_{-0.39}$
GW190412	$0.25^{+0.43}_{-0.24}$	$0.32^{+0.41}_{-0.31}$
GW190413_134308	$0.35^{+0.43}_{-0.34}$	$0.39^{+0.47}_{-0.38}$
GW190421_213856	$0.38^{+0.48}_{-0.37}$	$0.39^{+0.47}_{-0.38}$
GW190503_185404	$0.39^{+0.50}_{-0.38}$	$0.39^{+0.46}_{-0.38}$
GW190512_180714	$0.44^{+0.52}_{-0.43}$	$0.40^{+0.51}_{-0.39}$
GW190513_205428	$0.41^{+0.50}_{-0.39}$	$0.38^{+0.47}_{-0.37}$
GW190517_055101	$0.02^{+0.03}_{-0.02}$	$0.33^{+0.42}_{-0.32}$
GW190519_153544	$0.23^{+0.29}_{-0.22}$	$0.32^{+0.39}_{-0.31}$
GW190521	$0.28^{+0.37}_{-0.28}$	$0.34^{+0.42}_{-0.33}$
GW190521_074359	$0.40^{+0.50}_{-0.39}$	$0.37^{+0.48}_{-0.36}$
GW190527_092055	$0.37^{+0.48}_{-0.36}$	$0.38^{+0.46}_{-0.37}$
GW190602_175927	$0.39^{+0.49}_{-0.38}$	$0.37^{+0.45}_{-0.36}$
GW191105_143521	$0.44^{+0.52}_{-0.42}$	$0.42^{+0.51}_{-0.40}$
GW191109_010717	$0.16^{+0.21}_{-0.16}$	$0.30^{+0.37}_{-0.29}$
GW191127_050227	$0.29^{+0.37}_{-0.29}$	$0.36^{+0.43}_{-0.35}$
GW191129_134029	$0.43^{+0.52}_{-0.42}$	$0.42^{+0.50}_{-0.40}$
GW191204_171526	$0.36^{+0.51}_{-0.35}$	$0.36^{+0.47}_{-0.36}$
GW191204_171526	$0.36^{+0.51}_{-0.35}$	$0.36^{+0.47}_{-0.36}$
GW191215_223052	$0.38^{+0.48}_{-0.37}$	$0.40^{+0.48}_{-0.39}$
GW191216_213338	$0.43^{+0.54}_{-0.42}$	$0.42^{+0.51}_{-0.40}$
GW191222_033537	$0.41^{+0.50}_{-0.39}$	$0.40^{+0.49}_{-0.39}$
GW191230_180458	$0.39^{+0.46}_{-0.38}$	$0.37^{+0.47}_{-0.36}$
GW200112_155838	$0.41^{+0.51}_{-0.40}$	$0.41^{+0.49}_{-0.40}$
GW200128_022011	$0.34^{+0.43}_{-0.33}$	$0.37^{+0.46}_{-0.36}$
GW200129_065458	$0.36^{+0.48}_{-0.36}$	$0.38^{+0.49}_{-0.37}$
GW200202_154313	$0.44^{+0.52}_{-0.43}$	$0.41^{+0.51}_{-0.40}$

The two prbabilities p_1 and p_2 are referred to the two objects of the binary. The **high-spin events** of the catalog **can be recognized as black holes** (at least the primary object). The **heaviest** object of GW190517_055101 is ~ 100% a black hole.

Conclusions

- If **all** the compact objects are **ECOs**, epsilon **cannot be** lower than 10^{-5} at 95% credible interval. We **exclude** a population of ultra-compact exotic objects;
- If **mixed population**: no more than 60% of ECOs can be present if $\varepsilon < 10^{-30}$ (namely ultra-compact objects);
- The **heaviest object of the GW190517_055101** binary is ~100% a BH with all the models we tried.

What's next?

- Employ a **reflectivity-dependent** model.
- Analyse **simulated signals** from a mixed population, and study future **forecast**.
- **FOLLOW-UP PROJECT**: Check the presence of biases due to potential difference among BBH and ECO waveforms.

Thanks for the attention !

Adriano Frattale Mascioli

Contact: adriano.frattalemascioli@uniroma1.it

Sapienza University of Rome & INFN-Roma1

GraSP, 25/10/2023
Pisa