THE COSMIC EXPLORER GRAVITATIONAL WAVE OBSERVATORY

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MPSAC whitepapers - CBC populations

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This is an internal working note of the COSMIC EXPLORER project.

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1 Introduction

2 BBHs

We need to generate a population of binary black holes that is somewhat representative of what might be realized in nature. Naturally, large uncertainties exist, especially for redshifts and masses that cannot be probed by current-generation detectors, or by electromagnetic telescopes.

We thus settle for populations of BBHs that are consistent with the LVK measurements in the local universe, and with theoretical and population-synthesis models at high redshifts.

Specifically, for the local populations we use SV:for all of these variables, we will refer to gwpopulation or LVK functions or explain better here what they mean

- **Primary mass**: LVK "power law plus peak" with the following true value of parameters: $\alpha = -3.4$, $m_{min} = 5M_{\odot}$, $m_{max} = 87M_{\odot}$, $\lambda = 0.04$, $\mu_{peak} = 34M_{\odot}$, $\sigma_{peak} = 3.6$, $\delta_m = 4.8M_{\odot}$;
- **Mass ratio**: a simple power law (not conditional on m_1), $p(q) \propto q^{\beta}$ with $\beta = 1.1$;
- **Spin magnitude**: LVK's beta IIDs beta distributions with $\alpha_{\chi} = 2$, $\beta_{\chi} = 5$;
- **Redshift**: We use the Madau-Dickinson star formation rate [1] as a merger rate, since that is still consistent with the latest LVK results. Using the same variables names of gwpopulation, we use $\gamma_z = 2.7$, $z_{peak} = 1.9$, $\kappa = 5.6$;

We also consider a population of high-redshift BBHs, that might be representative of black holes remnants of pop III stars. As no uncontroversial detection of these objects exist, the uncertainty on their parameters is very large. We use:

- **Primary mass**: A fixed value of $20M_{\odot}$
- **Mass ratio**: A fixed value of 0.9
- **Spin magnitude**: LVK's beta IIDs beta distributions with $\alpha_{\chi} = 2$, $\beta_{\chi} = 5$;
- **Redshift**: The distribution introduced in Ref. [2] (their eq C15) with $a_{III} = 0.66$, $b_{III} = 0.3$, $z_{III} = 11.6$. This distribution is consistent with population synthesis studies by Belczynski et al 2016.

Finally, we consider a population of ever higher redshift sources, that could be representative of primordial black holes. For these too, our knowledge is limited. We use:

- **Primary and secondary mass**: The lognormal distribution of Ref. [3] (their Eq 1) with $M_c = 30M_{\odot}$ and $\sigma = 0.3M_{\odot}$;
- **Spin magnitude**: zero spins;
- **Redshift**: A merger rate distribution that increases as the age of the universe decreases (Ref. [3], Eq. 5).

For all other CBC parameters (i.e. sky location, orbital orientation, polarization angle, coalescence time and phase, spin orientation) we use uninformative distributions. We assume all sources are quasi-circular, i.e. we ignore orbital eccentricity.

While the prescriptions above fix the characteristic of each channel, we need three more parameters to fix the relative importance of each each channel. We follow Refs. [2] and [3] and work with $N_{\text{local}} = 96,000$, $N_{\text{III}} = 2,400$ and $N_{\text{pbh}} = 600$ mergers per year in each of the three channels.

3 BNSs

We simulate a single population of BNSs, whose merger rate peaks at cosmic noon, and is consistent with the local merger rate as measured by the LVK.

Specifically we use:

- **Primary and secondary mass**: A double Gaussian distribution, $p(m) = w\mathcal{N}(\mu_L, \sigma_L) + (1-w)\mathcal{N}(\mu_R, \sigma_R)$. We use parameters equal to the medial values of of Ref. [4]: $\mu_L = 1.35M_\odot$, $\sigma_L = 0.08M_\odot$, $\mu_R = 1.8M_\odot$, $\sigma_R = 0.3M_\odot$. Each normal distribution is independently truncated and normalized in the range $[1, 2.3]$ $M_\odot$.
- **Spin magnitude**: Uniform in the range $[0, 0.1]$;
- **Spin orientation**: The spins are aligned the orbital angular momentum;
- **Redshift**: a Madau-Dickinson-like merger rate, with $\gamma_z = 2.7$, $z_{peak} = 1.9$, $\kappa = 5.6$; just as for the local BBHs.

For all other CBC parameters (i.e. sky location, orbital orientation, polarization angle, coalescence time and phase) we use uninformative distributions. We assume all sources are quasi-circular, i.e. we ignore orbital eccentricity.

While there is not yet decisive evidence that the mass distribution of neutron stars in BNS is indeed bimodal, we prefer to have such bi-modality in order to verify if and how precisely it can be characterized by next-generation detectors.

References

[1] Piero Madau and Mark Dickinson. Cosmic Star Formation History. *Ann. Rev. Astron. Astrophys.*, 52:415–486, 2014.

[2] Ken K. Y. Ng, Salvatore Vitale, Will M. Farr, and Carl L. Rodriguez. Probing multiple populations of compact binaries with third-generation gravitational-wave detectors. *Astrophys. J. Lett.*, 913(1):L5, 2021.

[3] Ken K. Y. Ng, Gabriele Franciolini, Emanuele Berti, Paolo Pani, Antonio Riotto, and Salvatore Vitale. Constraining High-redshift Stellar-mass Primordial Black Holes with Next-generation Ground-based Gravitational-wave Detectors. *Astrophys. J. Lett.*, 933(2):L41, 2022.

[4] Will M. Farr and Katerina Chatziioannou. A Population-Informed Mass Estimate for Pulsar J0740+6620. *Research Notes of the American Astronomical Society*, 4(5):65, May 2020.