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# Gravitational Wave Background for LISA from Synthetic Populations of White Dwarf Binaries in the Local Universe

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# Introduction

In the context of the gravitational waves study, there are mainly two possible paths: the first is the **analysis of existing data** from experiments like Ligo, Virgo and Kagra, with the goal of detecting and characterizing the observable sources within their relative frequency bands; the second approach is the **forecasting approach**, which aims to characterize future experiments in order to better understand what types of sources they could detect and how well.

One of the most important future detectors is the European *Laser Interferometer Space Antenna* (LISA), the first space-based gravitational wave detector. LISA will be arranged as an equilateral triangle with 2.5 million kilometers long arms, placed in a heliocentric orbit, and will operate within the frequency range from approximately 0.1mHz to 1Hz. Among the typical sources that emit gravitational wave signal in this range are the **compact binaries**, and in our particular case we are interested in **double white dwarf binaries** (WDBs).

The goal of this work is to estimate the gravitational wave background produced by the extragalactic WDBs in the local universe, by using the **COSMIC** code to generate synthetic astrophysical populations to represent the galaxies listed in the **Gravitational Wave Galaxy Catalog** (GWGC).

In **Chapter 1** we will introduce the theoretical foundations of gravitational waves, derive the amplitude of the signal generated by a binary system, and define the most important parameters. Finally, we discuss how to combine the signals from multiple sources, to find a cumulative background.

In **Chapter 2** we will give a brief overview of how gravitational wave detectors work, trying to better understand what kinds of sources LISA will be able to see, what resolution and what sensitivity it will have and why in particular we are interested in WDBs.

In **Chapter 3** we introduce the concept of stellar population synthesis and the code COSMIC used for this purpose. We will introduce its features, main parameters, and pipeline, and explain how it is used to generate full-size astrophysical populations of WDBs.

In **Chapter 4** we introduce the GWGC, list the key information it provides and explain how we move from there to infer the remaining parameters that we need.

In **Chapter 5** we use the obtained information to compute the total gravitational wave signal summing the contribution from all the simulated sources, taking into account their spatial distribution, LISA's frequency resolution, and the *zone of avoidance* caused by the milky way.

In **Chapter 6** we plot the total resulting signal on the LISA sensitivity curve, and discuss the results and their possible implications.

Finally, in **Chapter 7** we will draw some conclusions from the work as a whole, discussing its limitations, assumptions and its possible extensions and follow-ups.

# Chapter 1

## Gravitational Waves Theory

After considering, in 1905, the problem of the apparently *instantaneous* propagation of light, with the theory of Special Relativity, in 1916 Albert Einstein considered the problem of the apparently *instantaneous* propagation of gravity through *long distances*, in his theory of General Relativity. Einstein showed that long-distance interaction arises from the deformation of spacetime caused by massive objects. Hence, in the "static case", the deviated motion apparently caused by the interaction between two distant masses really is, in fact, a manifestation of spacetime curvature nearby, generated by the presence of the two objects. The "static case" just depicted, though, treats the curvature as if it had always been there, and doesn't take into account of any variation in the masses, positions or velocities of the two objects, that would induce an evolution to the curvature itself. In truth, after a change in the mass-energy distribution, the corresponding curvature variation requires its time to reach far distances, and a fascinating prediction of General Relativity is that it propagates in the form of a wave, that travels at the speed of light.

### 1.1 Gravitational Waves as Perturbations

The typical approach to the study of gravitational waves is to derive them as small perturbations of the background from the Einstein's equations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R, \quad (1.1)$$

which can be conveniently written as

$$R_{\mu\nu} = \frac{8\pi G}{c^4} \left( T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T \right), \quad (1.2)$$

where  $G_{\mu\nu}$  is the Einstein tensor,  $R_{\mu\nu}$  is the Ricci tensor,  $R$  is the Ricci scalar,  $g_{\mu\nu}$  is the metric of spacetime, and  $T_{\mu\nu}$  is the stress-energy tensor. As a background solution we can consider the flat spacetime described by the metric  $\eta_{\mu\nu}$ , to which the perturbation term appears as a fluctuation in the metric  $|h_{\mu\nu}| \ll |\eta_{\mu\nu}|$ , known

as *weak field* approximation. Thus, the perturbed spacetime can be written as:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll |\eta_{\mu\nu}|.$$

With this metric, the equations 1.2 becomes

$$\{\square_F h_{\mu\nu} - \left[ \frac{\partial^2}{\partial x^\lambda \partial x^\mu} h_\nu^\lambda + \frac{\partial^2}{\partial x^\lambda \partial x^\nu} h_\mu^\lambda + \frac{\partial^2}{\partial x^\nu \partial x^\mu} h_\lambda^\lambda \right]\} = -\frac{16\pi G}{c^4} \left( T_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} T \right).$$

Now, by requiring that the *weak-field* approximation remains satisfied for infinitesimal diffeomorphisms, and by choosing a coordinate system in which the *harmonic gauge condition*<sup>1</sup> is satisfied, we can find that, up to first order in  $h_{\mu\nu}$ , the harmonic gauge condition is equivalent to

$$\frac{\partial}{\partial x^\mu} h_\rho^\mu = \frac{1}{2} \frac{\partial}{\partial x^\rho} h, \quad h = \eta^{\mu\nu} h_{\mu\nu} \equiv h_\nu^\nu, \quad (1.3)$$

and after defining the tensor<sup>2</sup>

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} h,$$

we can finally write the linearized Einstein equations as

$$\begin{cases} \square \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}, \\ \partial^\mu \bar{h}_{\mu\nu} = 0. \end{cases}$$

This form, and its twin with  $T_{\mu\nu} = 0$ , where the first equation becomes the D'Alembert equation, are relevant because they show that *a perturbation of a flat spacetime propagates as a wave travelling at the speed of light*.

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<sup>1</sup>It is an arbitrary coordinate condition which makes it possible to solve the Einstein field equations. It can be found by requiring that the linearized Einstein equations satisfy the D'Alembert equation.

<sup>2</sup>Also known as *trace-reversed* perturbation tensor, since  $\bar{h} = \eta^{\mu\nu} \bar{h}_{\mu\nu} = -h$ .



### 1.1.1 Harmonic gauge

### 1.1.2 The TT gauge

## 1.2 Motion and geodesics

### 1.2.1 The motion deviation

### 1.2.2 The geodesic deviation

## 1.3 The Quadrupole Approximation

### 1.3.1 The weak-field, slow-motion approximation

### 1.3.2 The quadrupole formula

### 1.3.3 Transform to the TT gauge

## 1.4 Gravitational waves from a binary system

### 1.4.1 General solution for circular orbits

Up to 13.86/7 at page 255 of the book.

## 1.5 Energy carried by a gravitational wave

### 1.5.1 Stress-energy pseudo-tensor

### 1.5.2 Gravitational wave luminosity

## 1.6 Evolution of a compact binary system

### 1.6.1 Signal from inspiralling compact objects

Here we get to the actual amplitude we used, and the parameters involved.

### 1.6.2 ASD and multiple sources



# Chapter 2

## LISA

### 2.1 interferometers

- Instrument description (what is an interferometer, why in space, how it will be made, orbit) - frequency band - what will it see? - frequency resolution - sensibility curve and ASD meaning - Why WD choice in particular?



## Chapter 3

# COSMIC and Stellar Populations Synthesis

The abundance of information of the electromagnetic spectrum allowed us to build highly detailed models of various celestial objects such as stars, both on their individual internal structure and on how this is influenced by the interaction with other bodies, for instance in binary systems. In the pursuit of reaching a greater sensitivity in the gravitational counterpart too, which could potentially reveal new information, or place better constraints on the existing models, these stellar models, when combined with a good theory of gravity, can be used to construct synthetic populations that reproduce observable features like luminosity, color, and chemical composition, which could enable us to predict what their gravitational signal would look like. In gravitational waves research, our observational capabilities are still very limited, and the signals are still comparatively very weak relative to their electromagnetic counterpart. Therefore, methods that rely on simulations can be very useful both to explore how different sources could look like in the gravitational wave domain, and how effectively they could be detected with current or future instruments.

### 3.1 Stellar populations synthesis codes

Generating a synthetic population of stars is a very complex task, that involves multiple steps, each involving important choices. *First*, we need to choose a starting point: we could start from the very beginning of stars formation and simulate all the process from the birth onward, or we could select a later phase in the stars evolution, shared from the most, in order to reduce unnecessary computational power and time consumption. If we want to simulate entire stellar populations choosing a starting point also implies selecting appropriate distributions for the main parameters that characterize the "starting point population", like masses, metallicities, but also orbital parameters for the stars that are in binary systems, like orbital period, distance, and eccentricity. *Second*, we must choose how the stars

will evolve from the starting point, and this involves the single star evolution but also the effects that interaction with other stars in binary systems have on it. *Finally*, we have to decide when we want to stop the simulation, choosing an endpoint that aligns with the needs of this study.

### 3.1.1 The starting point

As we know, in the Hertzsprung-Russel diagram, which plots the *luminosity* of the stars vs their *color index*, most of the stars appear distributed in the **main sequence (MS)**, a continuous and distinctive band. A star's position on this band is determined by its initial mass, and a good rule of thumb is that the most massive stars are hotter, more luminous, and evolve more quickly, while the lower-mass stars burn their fuel more slowly, and remain on the MS longer.

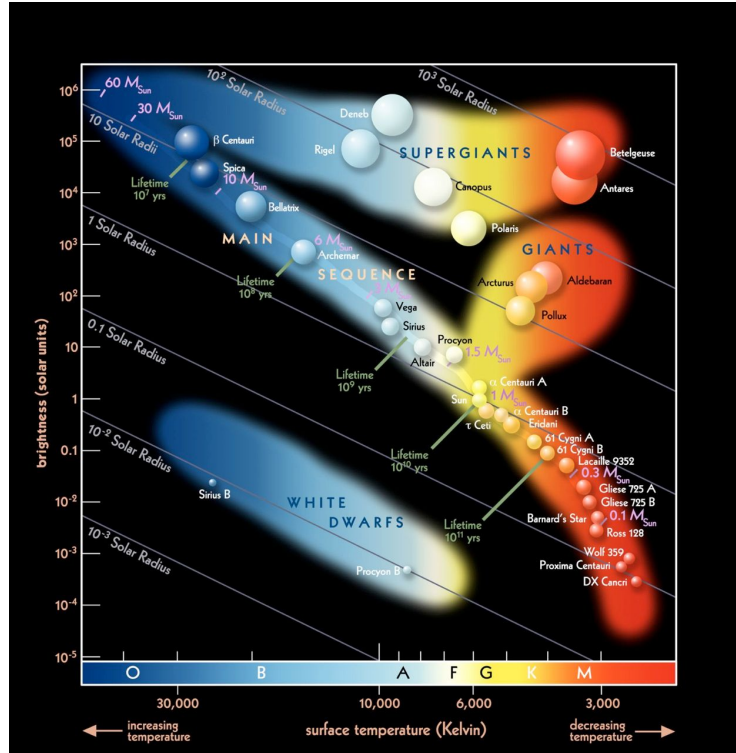


Figure 3.1: WRITE CAPTION, INSERT REFERENCE

Since almost all stars go through a phase in the MS, and evolve from there differently, in this work, the chosen starting point for stellar evolution is the Zero Age Main Sequence (ZAMS). At this stage, stars have just begun hydrogen burning in their cores, marking the start of their stable main sequence phase. This allows to bypass the early phases of star formation, which are much less relevant to the gravitational wave sources of interest, while still capturing the essential evolutionary processes that lead to the formation of compact objects.

### 3.1.2 Single star evolution

Simulating the evolution of a single star is in itself a very complex matter, and the only way to make it computationally feasible in the context of large-scale population synthesis is to approximate the evolution for a wide range of mass  $M$  and metallicity  $Z$ . In fact, detailed evolution codes can require substantial computational time even for the evolution of a single star, which is not practical when generating a full-scale astrophysical population containing millions of stars. Also, in order to make population synthesis statistically robust a large enough number of stars of a certain type must be evolved in order to overcome stochastic noise (in particular, the Poisson noise for  $n$  simulations of a particular type of star, implies an error that grows as  $\sqrt{n}$ ). A winning strategy, adopted by several population synthesis frameworks, is to pre-generate a large grid of detailed stellar evolution models, and use them to derive a number of interpolation formulae as functions that approximate stellar properties as a function of age, mass and metallicity. In Hurley et al. [2000b] this method is implemented through the development of a set of **Single Star Evolution (SSE)** formulae, with the result of a very compact, efficient and adaptable code, which makes it perfect for the integration of binary-star interactions. The work presented in Hurley et al. [2000b] therefore serves as the theoretical and computational foundation for many complex stellar population synthesis codes, including the one used in this thesis. It takes care of the single-star evolution of stars from ZAMS through all the possible evolutionary outcomes, depending on the star's initial conditions.

### 3.1.3 Binary stars evolution

While the evolution of single stars already represents a challenge, the inclusion of binary interactions introduces a much higher level of complexity. In such systems, the evolution of each star is strongly influenced by its companion through a variety of processes, such as mass transfer and accretion, common envelope evolution, collisions, supernova kicks, tidal effects, angular momentum loss, and mergers. These interactions can drastically alter the final outcomes, and are essential for modeling the formation of compact binaries that are potential gravitational wave targets for LISA. To efficiently model binary evolution within the framework of stellar population synthesis, the work of Hurley et al. [2002b] extends the SSE formalism by introducing a set of prescriptions for binary interactions, and updating the treatment of processes such as Roche lobe overflow, common envelope evolution and coalescence by collision, leading to the development of the **Binary Star Evolution (BSE)** algorithm. This code includes the interpolation-based approach used in SSE for single-star evolution, but adds a comprehensive treatment of binary-specific processes, enabling the simulation of a wide range of binary configurations but keeping the affordable computational requirements of SSE. The BSE algorithm tracks the joint evolution of both stars in a binary system, taking into account their initial parameters, such as masses, orbital period, eccentricity, and metallicity, and updates these properties dynamically as the system evolves. The flexibility and speed of the

BSE code make it a key component in many modern population synthesis tools, including the one used in this thesis, which we will now introduce.

## 3.2 COSMIC

For the purposes of this work, we employ a community-developed binary population synthesis (BPS) python-based code, called the **Compact Object Synthesis and Monte Carlo Investigation Code (COSMIC)**, whose «*primary purpose is to generate synthetic populations with an adaptive size based on how the shape of binary parameter distributions change as the number of simulated binaries increases*»<sup>1</sup>. COSMIC's binary evolution is built upon BSE, incorporating extensive modifications in order to include updated physical prescriptions. It includes all necessary tools to generate a population, from the generation of initial conditions, to scaling the simulated systems to full-scale astrophysical populations. The code is presented in Breivik et al. [2020], where it is described in full detail and used, as a proof of concept, to simulate the Galactic population of compact binaries and their associated gravitational wave signal. In the following section we will see the main features of the code, and explain what makes it the right choice for this thesis work.

### 3.2.1 Fixed population

A fundamental concept in COSMIC, which is the key to the code's efficiency, is the idea of *fixed population*. This refers to a relatively small sample<sup>2</sup> of just enough binaries to capture, in a statistically meaningful way, the underlying shape of the parameter distribution functions of the target population, as determined by the user specified Star Formation History (SFH) and evolution model. This is achieved following an iterative process designed to reach a convergence with respect to a defined matching condition, and consists of five key steps:

1. The user selects a binary evolution model and SFH;
2. Based on the SFH and the chosen initial parameter distribution, an initial population is generated;
3. The population evolves for a user specified number of steps, according to the selected evolution model;
4. If it is the first iteration, half of the simulated systems is compared with the total population. In the following steps, the population from the previous one gets compared to the population containing both the current and previous

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<sup>1</sup><https://cosmic-popsynth.github.io/docs/stable/pages/about.html>

<sup>2</sup>Note that, from now on, every time we talk about sampling, that is where the "M" of COSMIC comes into play: this code uses proficiently the Monte Carlo Markov Chain methods to sample populations and parameter distributions, as will follow in this section.



iterations. In any case, the comparison is done in order to check if the matching condition has been achieved;

5. Once the parameter distributions of the population have converged, the corresponding population is called *fixed population*, which represents the statistical features of a binary evolution model.

In practice, the fixed population is the converged, computationally efficient representation of the systems that we want to simulate, embedded in a complete small-scale synthetic galaxy that also contains other stellar components. The output is stored in a data frame, which separates the full galaxy properties from the fixed population ones. The last step required to construct a full size galaxy is to scale the fixed population (by mass or by number of stars) with a re-sampling approach with replacement, allowing to extrapolate a larger final population that preserves the statistical properties encoded in the fixed population.

### Initialization

The fixed population is generated from an initial collection of binaries sampled from distribution functions to assign to each binary an initial value of metallicity ( $Z$ ), primary star mass ( $m$ ), mass ratio ( $q$ ), orbital separation ( $a$ ), eccentricity ( $e$ ), and birth time ( $T_0$ ) according to the selected SFH. In COSMIC the user can choose between different binary parameter distributions, and different parameters can be treated independently. Moreover, COSMIC allows a complete personalization of the initial population through a number of other parameters, including different time-steps to control the binary physics, metallicity, stellar winds, common envelope phase, natal kicks, remnant mass, remnant spin, gravitational wave orbital decay, mass transfer, tides, and particular specifications for different kinds of stellar objects, mixing variables, and magnetic braking. In this work all the parameters were left default, but one: we tweaked the metallicity value, in order to differentiate fixed populations describing the parameter distributions for galaxies of different types. We will go more into detail on this topic in the next chapters.

### Convergence

The number of simulated systems in the fixed population ideally describes the final parameter distribution functions while being low enough to keep the code efficient. Since every population depends on a different binary evolution model, to quantify this number a *discrete match criteria* is developed, based on the work Chatziioannou et al. [2017]. Independently generated histograms for each parameter are used to track their distribution as successive populations are generated and cumulatively added to the fixed population. The physical limits of the simulated systems are

then enforced by taking the logistic transform, and finally the match is defined as:

$$match = \frac{\sum_{k=1}^N P_{k,i} P_{k,i+1}}{\sqrt{\sum_{k=1}^N (P_{k,i} P_{k,i}) \sum_{k=1}^N (P_{k,i} P_{k,i+1})}},$$

where  $P_{k,i}$  is the probability for the  $k$ th bin, for the  $i$ th iteration. For how it is defined, the match value shifts between 0 and 1, and tends to unity as the parameter distributions converge to a distinct shape.

### 3.2.2 The output

- population's parameters (the ones COSMIC gives to user)
  - parameter distribution graphs

## 3.3 Astrophysical population

- Scaling to astrophysical population, what is needed (refer to next chapter)

## Chapter 4

# GWGC and Galaxy Properties

- Catalog introduction and description (what it has - what we need) - How we'll get what we need (brief description of how we use catalog info to get what we want) - T value to Class - Class to Mass-Luminosity relation -> Mass (Faber & Gallagher)
- Finding each galaxy's metallicity from the mass (Tremonti - Allende Prieto) - Metallicity bins for GWGC galaxies



## Chapter 5

# Total Gravitational Wave Signal

- For each galaxy: - Compute right  $N_{astro}$  - compute each binary's GW signal; - bin it to LISA's frequency sensibility bins - Plot it on LISA's sensibility curve - Zone of avoidance: how to consider all the sky



# Chapter 6

## Results

- Plot of spectral distribution of the computed signal - Analysis of the distribution of the sources - Eventual implications (none, since it shouldn't be visible)





## Chapter 7

# Conclusions and Future Perspectives

Recap of the whole Work - Limits of the Work, assumptions and approximations used - Possible extensions



# Appendix A

## Appendix

Dettagli tecnici sul codice.

Tabelle di parametri.

Ulteriori grafici.

Script di calcolo, se rilevante.



# Bibliography

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese , K. Ackley, C. Adams, T. Adams, P. Addesso , R. X. Adhikari, V. B. Adya, C. Affeldt, M. Afrough, B. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain , P. Ajith, B. Allen, G. Allen, A. Allocca, P. A. Altin, A. Amato, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, D. V. Atallah, P. Aufmuth, C. Aulbert, K. AultONeal, C. Austin, A. Avila-Alvarez, S. Babak, P. Bacon, M. K. M. Bader, S. Bae, M. Bailes, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, S. Banagiri, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, S. D. Barthelmy, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, J. C. Batch, M. Bawaj, J. C. Bayley, M. Bazzan, B. Bécsy, C. Beer, M. Bejger, I. Belahcene, A. S. Bell, B. K. Berger, G. Bergmann, S. Bernuzzi, J. J. Bero, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, S. Bhagwat, R. Bhandare, I. A. Bilenko, G. Billingsley, C. R. Billman, J. Birch, R. Birney, O. Birnholtz, S. Biscans, S. Biscoveanu, A. Bisht, M. Bitossi, C. Biwer, M. A. Bizouard, J. K. Blackburn, J. Blackman, C. D. Blair, D. G. Blair, R. M. Blair, S. Bloemen, O. Bock, N. Bode, M. Boer, G. Bogaert, A. Bohe, F. Bondu, E. Bonilla, R. Bonnand, B. A. Boom, R. Bork, V. Boschi, S. Bose, K. Bossie, Y. Bouffanais, A. Bozzi, C. Bradaschia, P. R. Brady, M. Branchesi, J. E. Brau, T. Briant, A. Brillet, M. Brinkmann, V. Brisson, P. Brockill, J. E. Broida, A. F. Brooks, D. A. Brown, D. D. Brown, S. Brunett, C. C. Buchanan, A. Buikema, T. Bulik, H. J. Bulten, A. Buonanno, D. Buskulic, C. Buy, R. L. Byer, M. Cabero, L. Cadonati, G. Cagnoli, C. Cahillane, J. Calderón Bustillo, T. A. Callister, E. Calloni, J. B. Camp, M. Canepa, P. Canizares, K. C. Cannon, H. Cao, J. Cao, C. D. Capano, E. Capocasa, F. Carbognani, S. Caride, M. F. Carney, G. Carullo, J. Casanueva Diaz, C. Casentini, S. Caudill, M. Cavaglià, F. Cavalier, R. Cavalieri, G. Cella, C. B. Cepeda, P. Cerdá -Durán, G. Cerretani, E. Cesarini, S. J. Chamberlin, M. Chan, S. Chao, P. Charlton, E. Chase, E. Chassande-Mottin, D. Chatterjee, K. Chatziioannou, B. D. Cheeseboro, H. Y. Chen, X. Chen, Y. Chen, H. P. Cheng, H. Chia, A. Chincarini, A. Chiummo, T. Chmiel, H. S. Cho, M. Cho, J. H. Chow, N. Christensen, Q. Chu, A. J. K. Chua, and S. Chua. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, October 2017.

doi: 10.1103/PhysRevLett.119.161101.

B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P. Aufmuth, K. AultONeal, C. Austin, V. Avendano, A. Avila-Alvarez, S. Babak, P. Bacon, F. Badaracco, M. K. M. Bader, S. Bae, P. T. Baker, F. Baldaccini, G. Ballardín, S. W. Ballmer, S. Banagiri, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, S. Barnum, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, M. Bawaj, J. C. Bayley, M. Bazzan, B. Bécsy, M. Bejger, I. Belahcene, A. S. Bell, D. Beniwal, B. K. Berger, G. Bergmann, S. Bernuzzi, J. J. Bero, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, R. Bhandare, J. Bidler, I. A. Bilenko, S. A. Bilgili, G. Billingsley, J. Birch, R. Birney, O. Birnholtz, S. Biscans, S. Biscoveanu, A. Bisht, M. Bitossi, M. A. Bizouard, J. K. Blackburn, J. Blackman, C. D. Blair, D. G. Blair, R. M. Blair, S. Bloemen, N. Bode, M. Boer, Y. Boetzel, G. Bogaert, F. Bondu, E. Bonilla, R. Bonnand, P. Booker, B. A. Boom, C. D. Booth, R. Bork, V. Boschi, S. Bose, K. Bossie, V. Bossilkov, J. Bosveld, Y. Bouffanais, A. Bozzi, C. Bradaschia, P. R. Brady, A. Bramley, M. Branchesi, J. E. Brau, T. Briant, J. H. Briggs, F. Brighenti, A. Brillet, M. Brinkmann, V. Brissou, P. Brockill, A. F. Brooks, D. D. Brown, S. Brunett, A. Buikema, T. Bulik, H. J. Bulten, A. Buonanno, D. Buskulic, M. J. Bustamante Rosell, C. Buy, R. L. Byer, M. Cabero, L. Cadonati, G. Cagnoli, C. Cahillane, J. Calderón Bustillo, T. A. Callister, E. Calloni, J. B. Camp, W. A. Campbell, M. Canepa, K. C. Cannon, H. Cao, J. Cao, E. Capocasa, F. Carbognani, S. Caride, M. F. Carney, G. Carullo, J. Casanueva Diaz, C. Casentini, S. Caudill, M. Cavaglià, F. Cavalier, R. Cavalieri, G. Cella, P. Cerdá-Durán, G. Cerretani, E. Cesarini, O. Chaibi, K. Chakravarti, S. J. Chamberlin, M. Chan, S. Chao, P. Charlton, E. A. Chase, E. Chassande-Mottin, D. Chatterjee, M. Chaturvedi, K. Chatziioannou, B. D. Cheeseboro, H. Y. Chen, X. Chen, Y. Chen, H. P. Cheng, C. K. Cheong, H. Y. Chia, A. Chincarini, A. Chiummo, G. Cho, H. S. Cho, M. Cho, N. Christensen, Q. Chu, S. Chua, and K. W. Chung. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Physical Review X*, 9(3):031040, July 2019. doi: 10.1103/PhysRevX.9.031040.

Jeff J. Andrews, W. M. Farr, V. Kalogera, and B. Willems. Evolutionary Channels for the Formation of Double Neutron Stars. *ApJ*, 801(1):32, March 2015. doi: 10.1088/0004-637X/801/1/32.

Jeff J. Andrews, Andreas Zezas, and Tassos Fragos. `dart_board`: Binary Population

- Synthesis with Markov Chain Monte Carlo. *ApJS*, 237(1):1, July 2018. doi: 10.3847/1538-4365/aaca30.
- Jeff J. Andrews, Katelyn Breivik, Chris Pankow, Daniel J. D’Orazio, and Mohammadtaher Safarzadeh. LISA and the Existence of a Fast-merging Double Neutron Star Formation Channel. *ApJ*, 892(1):L9, March 2020. doi: 10.3847/2041-8213/ab5b9a.
- Astropy Collaboration, Thomas P. Robitaille, Erik J. Tollerud, Perry Greenfield, Michael Droettboom, Erik Bray, Tom Aldcroft, Matt Davis, Adam Ginsburg, Adrian M. Price-Whelan, Wolfgang E. Kerzendorf, Alexander Conley, Neil Crighton, Kyle Barbary, Dimitri Muna, Henry Ferguson, Frédéric Grollier, Madhura M. Parikh, Prasanth H. Nair, Hans M. Unther, Christoph Deil, Julien Woillez, Simon Conseil, Roban Kramer, James E. H. Turner, Leo Singer, Ryan Fox, Benjamin A. Weaver, Victor Zabalza, Zachary I. Edwards, K. Azalee Bostroem, D. J. Burke, Andrew R. Casey, Steven M. Crawford, Nadia Dencheva, Justin Ely, Tim Jenness, Kathleen Labrie, Pey Lian Lim, Francesco Pierfederici, Andrew Pontzen, Andy Ptak, Brian Refsdal, Mathieu Servillat, and Ole Streicher. Astropy: A community Python package for astronomy. *A&A*, 558:A33, October 2013. doi: 10.1051/0004-6361/201322068.
- D. Bacon, S. Sigurdsson, and M. B. Davies. Close approach during hard binary-binary scattering. *MNRAS*, 281(3):830–846, August 1996. doi: 10.1093/mnras/281.3.830.
- Leor Barack and Curt Cutler. LISA capture sources: Approximate waveforms, signal-to-noise ratios, and parameter estimation accuracy. *Phys. Rev. D*, 69(8):082005, April 2004. doi: 10.1103/PhysRevD.69.082005.
- Jim W. Barrett, Ilya Mandel, Coenraad J. Neijssel, Simon Stevenson, and Alejandro Vigna-Gómez. Exploring the Parameter Space of Compact Binary Population Synthesis. In Massimo Brescia, S. G. Djorgovski, Eric D. Feigelson, Giuseppe Longo, and Stefano Cavioti, editors, *Astroinformatics*, volume 325 of *IAU Symposium*, pages 46–50, June 2017. doi: 10.1017/S1743921317000059.
- Jim W. Barrett, Sebastian M. Gaebel, Coenraad J. Neijssel, Alejandro Vigna-Gómez, Simon Stevenson, Christopher P. L. Berry, Will M. Farr, and Ilya Mandel. Accuracy of inference on the physics of binary evolution from gravitational-wave observations. *MNRAS*, 477(4):4685–4695, July 2018. doi: 10.1093/mnras/sty908.
- K. Belczynski, A. Heger, W. Gladysz, A. J. Ruiter, S. Woosley, G. Wiktorowicz, H. Y. Chen, T. Bulik, R. O’Shaughnessy, D. E. Holz, C. L. Fryer, and E. Berti. The effect of pair-instability mass loss on black-hole mergers. *A&A*, 594:A97, October 2016. doi: 10.1051/0004-6361/201628980.

- K. Belczynski, J. Klencki, C. E. Fields, A. Olejak, E. Berti, G. Meynet, C. L. Fryer, D. E. Holz, R. O’Shaughnessy, D. A. Brown, T. Bulik, S. C. Leung, K. Nomoto, P. Madau, R. Hirschi, E. Kaiser, S. Jones, S. Mondal, M. Chruslinska, P. Drozda, D. Gerosa, Z. Doctor, M. Giersz, S. Ekstrom, C. Georgy, A. Askar, V. Baibhav, D. Wysocki, T. Natan, W. M. Farr, G. Wiktorowicz, M. Coleman Miller, B. Farr, and J. P. Lasota. Evolutionary roads leading to low effective spins, high black hole masses, and O1/O2 rates for LIGO/Virgo binary black holes. *A&A*, 636: A104, April 2020. doi: 10.1051/0004-6361/201936528.
- Krzysztof Belczynski, Vassiliki Kalogera, and Tomasz Bulik. A Comprehensive Study of Binary Compact Objects as Gravitational Wave Sources: Evolutionary Channels, Rates, and Physical Properties. *ApJ*, 572(1):407–431, June 2002. doi: 10.1086/340304.
- Krzysztof Belczynski, Vassiliki Kalogera, Frederic A. Rasio, Ronald E. Taam, Andreas Zezas, Tomasz Bulik, Thomas J. Maccarone, and Natalia Ivanova. Compact Object Modeling with the StarTrack Population Synthesis Code. *ApJS*, 174(1): 223–260, January 2008. doi: 10.1086/521026.
- Krzysztof Belczynski, Tomasz Bulik, Chris L. Fryer, Ashley Ruiter, Francesca Valsecchi, Jorick S. Vink, and Jarrod R. Hurley. On the Maximum Mass of Stellar Black Holes. *ApJ*, 714(2):1217–1226, May 2010. doi: 10.1088/0004-637X/714/2/1217.
- M. Benacquista and K. Holley-Bockelmann. Consequences of Disk Scale Height on LISA Confusion Noise from Close White Dwarf Binaries. *ApJ*, 645(1):589–596, July 2006. doi: 10.1086/504024.
- D. Bhattacharya and E. P. J. van den Heuvel. Formation and evolution of binary and millisecond radio pulsars. *Phys. Rep.*, 203(1-2):1–124, January 1991. doi: 10.1016/0370-1573(91)90064-S.
- H. Bondi and F. Hoyle. On the mechanism of accretion by stars. *MNRAS*, 104:273, January 1944. doi: 10.1093/mnras/104.5.273.
- Katelyn Breivik, Kyle Kremer, Michael Bueno, Shane L. Larson, Scott Coughlin, and Vassiliki Kalogera. Characterizing Accreting Double White Dwarf Binaries with the Laser Interferometer Space Antenna and Gaia. *ApJ*, 854(1):L1, February 2018. doi: 10.3847/2041-8213/aaa23.
- Katelyn Breivik, Scott Coughlin, Michael Zevin, Carl L. Rodriguez, Kyle Kremer, Claire S. Ye, Jeff J. Andrews, Michael Kurkowski, Matthew C. Digman, Shane L. Larson, and Frederic A. Rasio. COSMIC Variance in Binary Population Synthesis. *ApJ*, 898(1):71, July 2020. doi: 10.3847/1538-4357/ab9d85.



- Katie Breivik, Scott Coughlin, Michael Zevin, Carl Rodriguez, Jeff Andrews, Chase Kimball, Medigman, and Inhtran. COSMIC-PopSynth/COSMIC: COSMIC, December 2019.
- Floor S. Broekgaarden, Stephen Justham, Selma E. de Mink, Jonathan Gair, Ilya Mandel, Simon Stevenson, Jim W. Barrett, Alejandro Vigna-Gómez, and Coenraad J. Neijssel. STROOPWAFEL: simulating rare outcomes from astrophysical populations, with application to gravitational-wave sources. *MNRAS*, 490(4): 5228–5248, December 2019. doi: 10.1093/mnras/stz2558.
- Judit Camacho, Santiago Torres, Enrique García-Berro, Mónica Zorotovic, Matthias R. Schreiber, Alberto Rebassa-Mansergas, Ada Nebot Gómez-Morán, and Boris T. Gänsicke. Monte Carlo simulations of post-common-envelope white dwarf + main sequence binaries: comparison with the SDSS DR7 observed sample. *A&A*, 566:A86, June 2014. doi: 10.1051/0004-6361/201323052.
- Sourav Chatterjee, Frederic A. Rasio, Alison Sills, and Evert Glebbeek. Stellar Collisions and Blue Straggler Stars in Dense Globular Clusters. *ApJ*, 777(2):106, November 2013. doi: 10.1088/0004-637X/777/2/106.
- Katerina Chatziioannou, James Alexander Clark, Andreas Bauswein, Margaret Millhouse, Tyson B. Littenberg, and Neil Cornish. Inferring the post-merger gravitational wave emission from binary neutron star coalescences. *Phys. Rev. D*, 96(12):124035, December 2017. doi: 10.1103/PhysRevD.96.124035.
- Yang Chen, Alessandro Bressan, Léo Girardi, Paola Marigo, Xu Kong, and Antonio Lanza. PARSEC evolutionary tracks of massive stars up to  $350 M_{\odot}$  at metallicities  $0.0001 \leq Z \leq 0.04$ . *MNRAS*, 452(1):1068–1080, September 2015. doi: 10.1093/mnras/stv1281.
- J. S. W. Claeys, O. R. Pols, R. G. Izzard, J. Vink, and F. W. M. Verbunt. Theoretical uncertainties of the Type Ia supernova rate. *A&A*, 563:A83, March 2014. doi: 10.1051/0004-6361/201322714.
- Erwin De Donder and Dany Vanbeveren. The influence of binaries on galactic chemical evolution. *New A Rev.*, 48(10):861–975, September 2004. doi: 10.1016/j.newar.2004.07.001.
- M. de Kool. Common Envelope Evolution and Double Cores of Planetary Nebulae. *ApJ*, 358:189, July 1990. doi: 10.1086/168974.
- S. E. de Mink and K. Belczynski. Merger Rates of Double Neutron Stars and Stellar Origin Black Holes: The Impact of Initial Conditions on Binary Evolution Predictions. *ApJ*, 814(1):58, November 2015. doi: 10.1088/0004-637X/814/1/58.
- S. E. de Mink, O. R. Pols, and R. W. Hilditch. Efficiency of mass transfer in massive close binaries. Tests from double-lined eclipsing binaries in the SMC. *A&A*, 467(3):1181–1196, June 2007. doi: 10.1051/0004-6361:20067007.

- Christopher J. Deloye and Ronald E. Taam. Adiabatic Mass Loss and the Outcome of the Common Envelope Phase of Binary Evolution. *ApJ*, 719(1):L28–L31, August 2010. doi: 10.1088/2041-8205/719/1/L28.
- R. J. Dewey and J. M. Cordes. Monte Carlo Simulations of Radio Pulsars and Their Progenitors. *ApJ*, 321:780, October 1987. doi: 10.1086/165671.
- Michał Dominik, Krzysztof Belczynski, Christopher Fryer, Daniel E. Holz, Emanuele Berti, Tomasz Bulik, Ilya Mandel, and Richard O’Shaughnessy. Double Compact Objects. I. The Significance of the Common Envelope on Merger Rates. *ApJ*, 759(1):52, November 2012. doi: 10.1088/0004-637X/759/1/52.
- Michał Dominik, Krzysztof Belczynski, Christopher Fryer, Daniel E. Holz, Emanuele Berti, Tomasz Bulik, Ilya Mandel, and Richard O’Shaughnessy. Double Compact Objects. II. Cosmological Merger Rates. *ApJ*, 779(1):72, December 2013. doi: 10.1088/0004-637X/779/1/72.
- P. Eggenberger, G. Meynet, A. Maeder, R. Hirschi, C. Charbonnel, S. Talon, and S. Ekström. The Geneva stellar evolution code. *Ap&SS*, 316(1-4):43–54, August 2008. doi: 10.1007/s10509-007-9511-y.
- J. J. Eldridge and E. R. Stanway. BPASS predictions for binary black hole mergers. *MNRAS*, 462(3):3302–3313, November 2016. doi: 10.1093/mnras/stw1772.
- J. J. Eldridge, E. R. Stanway, L. Xiao, L. A. S. McClelland, G. Taylor, M. Ng, S. M. L. Greis, and J. C. Bray. Binary Population and Spectral Synthesis Version 2.1: Construction, Observational Verification, and New Results. *PASA*, 34:e058, November 2017. doi: 10.1017/pasa.2017.51.
- A. V. Fedorova, A. V. Tutukov, and L. R. Yungelson. Type-Ia Supernovae in Semidetached Binaries. *Astronomy Letters*, 30:73–85, February 2004. doi: 10.1134/1.1646692.
- Tassos Fragos, Jeff J. Andrews, Enrico Ramirez-Ruiz, Georges Meynet, Vicky Kalogera, Ronald E. Taam, and Andreas Zezas. The Complete Evolution of a Neutron-star Binary through a Common Envelope Phase Using 1D Hydrodynamic Simulations. *ApJ*, 883(2):L45, October 2019. doi: 10.3847/2041-8213/ab40d1.
- John M. Fregeau and Frederic A. Rasio. Monte Carlo Simulations of Globular Cluster Evolution. IV. Direct Integration of Strong Interactions. *ApJ*, 658(2):1047–1061, April 2007. doi: 10.1086/511809.
- Chris L. Fryer, Krzysztof Belczynski, Grzegorz Wiktorowicz, Michał Dominik, Vicky Kalogera, and Daniel E. Holz. Compact Remnant Mass Function: Dependence on the Explosion Mechanism and Metallicity. *ApJ*, 749(1):91, April 2012. doi: 10.1088/0004-637X/749/1/91.

- Jim Fuller and Linhao Ma. Most Black Holes Are Born Very Slowly Rotating. *ApJ*, 881(1):L1, August 2019. doi: 10.3847/2041-8213/ab339b.
- Aaron M. Geller, Nathan W. C. Leigh, Mirek Giersz, Kyle Kremer, and Frederic A. Rasio. In Search of the Thermal Eccentricity Distribution. *ApJ*, 872(2):165, February 2019. doi: 10.3847/1538-4357/ab0214.
- Nicola Giacobbo and Michela Mapelli. The progenitors of compact-object binaries: impact of metallicity, common envelope and natal kicks. *MNRAS*, 480(2):2011–2030, October 2018. doi: 10.1093/mnras/sty1999.
- Nicola Giacobbo, Michela Mapelli, and Mario Spera. Merging black hole binaries: the effects of progenitor’s metallicity, mass-loss rate and Eddington factor. *MNRAS*, 474(3):2959–2974, March 2018. doi: 10.1093/mnras/stx2933.
- D. Goldberg and T. Mazeh. The mass-ratio distribution of the spectroscopic binaries in the Pleiades. *A&A*, 282:801–803, February 1994.
- G. Gräfener and W. R. Hamann. Mass loss from late-type WN stars and its Z-dependence. Very massive stars approaching the Eddington limit. *A&A*, 482(3):945–960, May 2008. doi: 10.1051/0004-6361:20066176.
- M. Atakan Gürkan, Marc Freitag, and Frederic A. Rasio. Formation of Massive Black Holes in Dense Star Clusters. I. Mass Segregation and Core Collapse. *ApJ*, 604(2):632–652, April 2004. doi: 10.1086/381968.
- D. C. Heggie. Binary evolution in stellar dynamics. *MNRAS*, 173:729–787, December 1975. doi: 10.1093/mnras/173.3.729.
- J. G. Hills and C. A. Day. Stellar Collisions in Globular Clusters. *Astrophys. Lett.*, 17:87, February 1976.
- D. Hils, P. L. Bender, and R. F. Webbink. Gravitational Radiation from the Galaxy. *ApJ*, 360:75, September 1990. doi: 10.1086/169098.
- G. Hobbs, D. R. Lorimer, A. G. Lyne, and M. Kramer. A statistical study of 233 pulsar proper motions. *MNRAS*, 360(3):974–992, July 2005. doi: 10.1111/j.1365-2966.2005.09087.x.
- Jarrold R. Hurley, Onno R. Pols, and Christopher A. Tout. Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity. *MNRAS*, 315(3):543–569, July 2000a. doi: 10.1046/j.1365-8711.2000.03426.x.
- Jarrold R. Hurley, Onno R. Pols, and Christopher A. Tout. Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity. *MNRAS*, 315(3):543–569, July 2000b. doi: 10.1046/j.1365-8711.2000.03426.x.

- Jarrold R. Hurley, Christopher A. Tout, and Onno R. Pols. Evolution of binary stars and the effect of tides on binary populations. *MNRAS*, 329(4):897–928, February 2002a. doi: 10.1046/j.1365-8711.2002.05038.x.
- Jarrold R. Hurley, Christopher A. Tout, and Onno R. Pols. Evolution of binary stars and the effect of tides on binary populations. *MNRAS*, 329(4):897–928, February 2002b. doi: 10.1046/j.1365-8711.2002.05038.x.
- Icko Iben, Jr., Alexander V. Tutukov, and Lev R. Yungelson. A Model of the Galactic X-Ray Binary Population. I. High-Mass X-Ray Binaries. *ApJS*, 100:217, September 1995a. doi: 10.1086/192217.
- Icko Iben, Jr., Alexander V. Tutukov, and Lev R. Yungelson. A Model of the Galactic X-Ray Binary Population. II. Low-Mass X-Ray Binaries in the Galactic Disk. *ApJS*, 100:233, September 1995b. doi: 10.1086/192218.
- Icko Iben, Jr., Alexander V. Tutukov, and Lev R. Yungelson. On the Origin of Hydrogen-deficient Supergiants and Their Relation to R Coronae Borealis Stars and Non-DA White Dwarfs. *ApJ*, 456:750, January 1996. doi: 10.1086/176694.
- Icko Iben, Jr., Alexander V. Tutukov, and Lev R. Yungelson. Helium and Carbon-Oxygen White Dwarfs in Close Binaries. *ApJ*, 475(1):291–299, January 1997. doi: 10.1086/303525.
- N. Ivanova, K. Belczynski, V. Kalogera, F. A. Rasio, and R. E. Taam. The Role of Helium Stars in the Formation of Double Neutron Stars. *ApJ*, 592(1):475–485, July 2003. doi: 10.1086/375578.
- N. Ivanova, C. O. Heinke, F. A. Rasio, K. Belczynski, and J. M. Fregeau. Formation and evolution of compact binaries in globular clusters - II. Binaries with neutron stars. *MNRAS*, 386(1):553–576, May 2008. doi: 10.1111/j.1365-2966.2008.13064.x.
- Natalia Ivanova and Ronald E. Taam. Thermal Timescale Mass Transfer and the Evolution of White Dwarf Binaries. *ApJ*, 601(2):1058–1066, February 2004. doi: 10.1086/380561.
- R. G. Izzard, L. M. Dray, A. I. Karakas, M. Lugaro, and C. A. Tout. Population nucleosynthesis in single and binary stars. I. Model. *A&A*, 460(2):565–572, December 2006. doi: 10.1051/0004-6361:20066129.
- R. G. Izzard, E. Glebbeek, R. J. Stancliffe, and O. R. Pols. Population synthesis of binary carbon-enhanced metal-poor stars. *A&A*, 508(3):1359–1374, December 2009. doi: 10.1051/0004-6361/200912827.
- Robert G. Izzard, Christopher A. Tout, Amanda I. Karakas, and Onno R. Pols. A new synthetic model for asymptotic giant branch stars. *MNRAS*, 350(2):407–426, May 2004. doi: 10.1111/j.1365-2966.2004.07446.x.

- D. L. Kaplan, S. Chatterjee, B. M. Gaensler, and J. Anderson. A Precise Proper Motion for the Crab Pulsar, and the Difficulty of Testing Spin-Kick Alignment for Young Neutron Stars. *ApJ*, 677(2):1201–1215, April 2008. doi: 10.1086/529026.
- Paul D. Kiel, Jarrod R. Hurley, Matthew Bailes, and James R. Murray. Populating the Galaxy with pulsars - I. Stellar and binary evolution. *MNRAS*, 388(1):393–415, July 2008. doi: 10.1111/j.1365-2966.2008.13402.x.
- J. Klencki, M. Moe, W. Gladysz, M. Chruslinska, D. E. Holz, and K. Belczynski. Impact of inter-correlated initial binary parameters on double black hole and neutron star mergers. *A&A*, 619:A77, November 2018. doi: 10.1051/0004-6361/201833025.
- Kevin H. Knuth. Optimal Data-Based Binning for Histograms. *arXiv e-prints*, art. physics/0605197, May 2006. doi: 10.48550/arXiv.physics/0605197.
- Valeriya Korol, Elena M. Rossi, Paul J. Groot, Gijs Nelemans, Silvia Toonen, and Anthony G. A. Brown. Prospects for detection of detached double white dwarf binaries with Gaia, LSST and LISA. *MNRAS*, 470(2):1894–1910, September 2017. doi: 10.1093/mnras/stx1285.
- Kyle Kremer, Katelyn Breivik, Shane L. Larson, and Vassiliki Kalogera. Accreting Double White Dwarf Binaries: Implications for LISA. *ApJ*, 846(2):95, September 2017. doi: 10.3847/1538-4357/aa8557.
- Kyle Kremer, Carl L. Rodriguez, Pau Amaro-Seoane, Katelyn Breivik, Sourav Chatterjee, Michael L. Katz, Shane L. Larson, Frederic A. Rasio, Johan Samsing, Claire S. Ye, and Michael Zevin. Post-Newtonian dynamics in dense star clusters: Binary black holes in the LISA band. *Phys. Rev. D*, 99(6):063003, March 2019. doi: 10.1103/PhysRevD.99.063003.
- Kyle Kremer, Claire S. Ye, Nicholas Z. Rui, Newlin C. Weatherford, Sourav Chatterjee, Giacomo Fragione, Carl L. Rodriguez, Mario Spera, and Frederic A. Rasio. Modeling Dense Star Clusters in the Milky Way and Beyond with the CMC Cluster Catalog. *ApJS*, 247(2):48, April 2020. doi: 10.3847/1538-4365/ab7919.
- Pavel Kroupa. On the variation of the initial mass function. *MNRAS*, 322(2): 231–246, April 2001. doi: 10.1046/j.1365-8711.2001.04022.x.
- Pavel Kroupa, Christopher A. Tout, and Gerard Gilmore. The Distribution of Low-Mass Stars in the Galactic Disc. *MNRAS*, 262:545–587, June 1993. doi: 10.1093/mnras/262.3.545.
- Matthias U. Kruckow, Thomas M. Tauris, Norbert Langer, Michael Kramer, and Robert G. Izzard. Progenitors of gravitational wave mergers: binary evolution with the stellar grid-based code COMBINE. *MNRAS*, 481(2):1908–1949, December 2018. doi: 10.1093/mnras/sty2190.

- A. Lamberts, S. Garrison-Kimmel, P. F. Hopkins, E. Quataert, J. S. Bullock, C. A. Faucher-Giguère, A. Wetzel, D. Kereš, K. Drango, and R. E. Sanderson. Predicting the binary black hole population of the Milky Way with cosmological simulations. *MNRAS*, 480(2):2704–2718, October 2018. doi: 10.1093/mnras/sty2035.
- Astrid Lamberts, Sarah Blunt, Tyson B. Littenberg, Shea Garrison-Kimmel, Thomas Kupfer, and Robyn E. Sanderson. Predicting the LISA white dwarf binary population in the Milky Way with cosmological simulations. *MNRAS*, 490(4):5888–5903, December 2019. doi: 10.1093/mnras/stz2834.
- Mike Y. M. Lau, Ilya Mandel, Alejandro Vigna-Gómez, Coenraad J. Neijssel, Simon Stevenson, and Alberto Sesana. Detecting double neutron stars with LISA. *MNRAS*, 492(3):3061–3072, March 2020. doi: 10.1093/mnras/staa002.
- Nathan Leigh, Alison Sills, and Christian Knigge. An analytic model for blue straggler formation in globular clusters. *MNRAS*, 416(2):1410–1418, September 2011. doi: 10.1111/j.1365-2966.2011.19136.x.
- V. M. Lipunov and K. A. Postnov. Spectrum of Gravitational Radiation of Binary Systems. *Soviet Ast.*, 31:228, April 1987.
- V. M. Lipunov, L. M. Ozernoy, S. B. Popov, K. A. Postnov, and M. E. Prokhorov. Population Synthesis of X-Ray Sources at the Galactic Center. *ApJ*, 466:234, July 1996a. doi: 10.1086/177505.
- V. M. Lipunov, K. A. Postnov, and M. E. Prokhorov. The Scenario Machine: restrictions on key parameters of binary evolution. *A&A*, 310:489–507, June 1996b.
- V. M. Lipunov, K. A. Postnov, M. E. Prokhorov, and A. I. Bogomazov. Description of the “Scenario Machine”. *Astronomy Reports*, 53(10):915–940, October 2009. doi: 10.1134/S1063772909100047.
- T. B. Littenberg, S. L. Larson, G. Nelemans, and N. J. Cornish. Prospects for observing ultracompact binaries with space-based gravitational wave interferometers and optical telescopes. *MNRAS*, 429(3):2361–2365, March 2013. doi: 10.1093/mnras/sts507.
- Jinzhong Liu and Yu Zhang. Gravitational-wave radiation from double compact objects with eLISA in the Galaxy. *PASP*, 126(937):211, March 2014. doi: 10.1086/675721.
- James C. Lombardi, Jr., Jessica S. Warren, Frederic A. Rasio, Alison Sills, and Aaron R. Warren. Stellar Collisions and the Interior Structure of Blue Stragglers. *ApJ*, 568(2):939–953, April 2002. doi: 10.1086/339060.
- R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs. The Australia Telescope National Facility Pulsar Catalogue. *AJ*, 129(4):1993–2006, April 2005. doi: 10.1086/428488.

- M. Mapelli, M. Colpi, and L. Zampieri. Low metallicity and ultra-luminous X-ray sources in the Cartwheel galaxy. *MNRAS*, 395(1):L71–L75, May 2009. doi: 10.1111/j.1745-3933.2009.00645.x.
- Michela Mapelli and Nicola Giacobbo. The cosmic merger rate of neutron stars and black holes. *MNRAS*, 479(4):4391–4398, October 2018. doi: 10.1093/mnras/sty1613.
- Pablo Marchant, Mathieu Renzo, Robert Farmer, Kaliroe M. W. Pappas, Ronald E. Taam, Selma E. de Mink, and Vassiliki Kalogera. Pulsational Pair-instability Supernovae in Very Close Binaries. *ApJ*, 882(1):36, September 2019. doi: 10.3847/1538-4357/ab3426.
- Tsevi Mazeh, Dorit Goldberg, Antoine Duquennoy, and Michel Mayor. On the Mass-Ratio Distribution of Spectroscopic Binaries with Solar-Type Primaries. *ApJ*, 401: 265, December 1992. doi: 10.1086/172058.
- Paul J. McMillan. Mass models of the Milky Way. *MNRAS*, 414(3):2446–2457, July 2011. doi: 10.1111/j.1365-2966.2011.18564.x.
- G. Meynet and A. Maeder. Stellar evolution with rotation. XI. Wolf-Rayet star populations at different metallicities. *A&A*, 429:581–598, January 2005. doi: 10.1051/0004-6361:20047106.
- S. Miyaji, K. Nomoto, K. Yokoi, and D. Sugimoto. Supernova triggered by electron captures. *PASJ*, 32:303–329, January 1980.
- Maxwell Moe and Rosanne Di Stefano. Mind Your Ps and Qs: The Interrelation between Period (P) and Mass-ratio (Q) Distributions of Binary Stars. *ApJS*, 230 (2):15, June 2017. doi: 10.3847/1538-4365/aa6fb6.
- C. J. Moore, R. H. Cole, and C. P. L. Berry. Gravitational-wave sensitivity curves. *Classical and Quantum Gravity*, 32(1):015014, January 2015. doi: 10.1088/0264-9381/32/1/015014.
- G. Nelemans, L. R. Yungelson, and S. F. Portegies Zwart. The gravitational wave signal from the Galactic disk population of binaries containing two compact objects. *A&A*, 375:890–898, September 2001a. doi: 10.1051/0004-6361:20010683.
- G. Nelemans, L. R. Yungelson, S. F. Portegies Zwart, and F. Verbunt. Population synthesis for double white dwarfs . I. Close detached systems. *A&A*, 365:491–507, January 2001b. doi: 10.1051/0004-6361:20000147.
- C. A. Nelson and P. P. Eggleton. A Complete Survey of Case A Binary Evolution with Comparison to Observed Algol-type Systems. *ApJ*, 552(2):664–678, May 2001. doi: 10.1086/320560.

- C. Y. Ng and Roger W. Romani. Birth Kick Distributions and the Spin-Kick Correlation of Young Pulsars. *ApJ*, 660(2):1357–1374, May 2007. doi: 10.1086/513597.
- Samaya Nissanke, Michele Vallisneri, Gijs Nelemans, and Thomas A. Prince. Gravitational-wave Emission from Compact Galactic Binaries. *ApJ*, 758(2):131, October 2012. doi: 10.1088/0004-637X/758/2/131.
- K. Nomoto. Evolution of 8-10 solar mass stars toward electron capture supernovae. I - Formation of electron-degenerate O + NE + MG cores. *ApJ*, 277:791–805, February 1984. doi: 10.1086/161749.
- Ken’ichi Nomoto. Evolution of 8–10  $M_{\text{sun}}$  Stars toward Electron Capture Supernovae. II. Collapse of an O + NE + MG Core. *ApJ*, 322:206, November 1987. doi: 10.1086/165716.
- Ken’ichi Nomoto and Yoji Kondo. Conditions for Accretion-induced Collapse of White Dwarfs. *ApJ*, 367:L19, January 1991. doi: 10.1086/185922.
- Bill Paxton, Lars Bildsten, Aaron Dotter, Falk Herwig, Pierre Lesaffre, and Frank Timmes. Modules for Experiments in Stellar Astrophysics (MESA). *ApJS*, 192(1):3, January 2011. doi: 10.1088/0067-0049/192/1/3.
- Bill Paxton, Matteo Cantiello, Phil Arras, Lars Bildsten, Edward F. Brown, Aaron Dotter, Christopher Mankovich, M. H. Montgomery, Dennis Stello, F. X. Timmes, and Richard Townsend. Modules for Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive Stars. *ApJS*, 208(1):4, September 2013. doi: 10.1088/0067-0049/208/1/4.
- Bill Paxton, Pablo Marchant, Josiah Schwab, Evan B. Bauer, Lars Bildsten, Matteo Cantiello, Luc Dessart, R. Farmer, H. Hu, N. Langer, R. H. D. Townsend, Dean M. Townsley, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and Explosions. *ApJS*, 220(1):15, September 2015. doi: 10.1088/0067-0049/220/1/15.
- Bill Paxton, Josiah Schwab, Evan B. Bauer, Lars Bildsten, Sergei Blinnikov, Paul Duffell, R. Farmer, Jared A. Goldberg, Pablo Marchant, Elena Sorokina, Anne Thoul, Richard H. D. Townsend, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions. *ApJS*, 234(2):34, February 2018. doi: 10.3847/1538-4365/aaa5a8.
- Bill Paxton, R. Smolec, Josiah Schwab, A. Gaudy, Lars Bildsten, Matteo Cantiello, Aaron Dotter, R. Farmer, Jared A. Goldberg, Adam S. Jermyn, S. M. Kanbur, Pablo Marchant, Anne Thoul, Richard H. D. Townsend, William M. Wolf, Michael Zhang, and F. X. Timmes. Modules for Experiments in Stellar Astrophysics (MESA): Pulsating Variable Stars, Rotation, Convective Boundaries,



- and Energy Conservation. *ApJS*, 243(1):10, July 2019. doi: 10.3847/1538-4365/ab2241.
- P. C. Peters and J. Mathews. Gravitational Radiation from Point Masses in a Keplerian Orbit. *Physical Review*, 131(1):435–440, July 1963. doi: 10.1103/PhysRev.131.435.
- Ph. Podsiadlowski, N. Langer, A. J. T. Poelarends, S. Rappaport, A. Heger, and E. Pfahl. The Effects of Binary Evolution on the Dynamics of Core Collapse and Neutron Star Kicks. *ApJ*, 612(2):1044–1051, September 2004. doi: 10.1086/421713.
- Onno R. Pols, Christopher A. Tout, Peter P. Eggleton, and Zhanwen Han. Approximate input physics for stellar modelling. *MNRAS*, 274(3):964–974, June 1995. doi: 10.1093/mnras/274.3.964.
- Onno R. Pols, Klaus-Peter Schröder, Jarrod R. Hurley, Christopher A. Tout, and Peter P. Eggleton. Stellar evolution models for  $Z = 0.0001$  to  $0.03$ . *MNRAS*, 298(2):525–536, August 1998. doi: 10.1046/j.1365-8711.1998.01658.x.
- S. F. Portegies Zwart and F. Verbunt. Population synthesis of high-mass binaries. *A&A*, 309:179–196, May 1996.
- Simon F. Portegies Zwart and Stephen L. W. McMillan. The Runaway Growth of Intermediate-Mass Black Holes in Dense Star Clusters. *ApJ*, 576(2):899–907, September 2002. doi: 10.1086/341798.
- S. Rappaport, Ph. Podsiadlowski, P. C. Joss, R. Di Stefano, and Z. Han. The relation between white dwarf mass and orbital period in wide binary radio pulsars. *MNRAS*, 273(3):731–741, April 1995. doi: 10.1093/mnras/273.3.731.
- Hans Ritter, Michael Politano, Mario Livio, and Ronald F. Webbink. The White Dwarf Mass Distribution in Classical Nova Systems. *ApJ*, 376:177, July 1991. doi: 10.1086/170265.
- Travis Robson, Neil J. Cornish, and Chang Liu. The construction and use of LISA sensitivity curves. *Classical and Quantum Gravity*, 36(10):105011, May 2019. doi: 10.1088/1361-6382/ab1101.
- Carl L. Rodriguez, Sourav Chatterjee, and Frederic A. Rasio. Binary black hole mergers from globular clusters: Masses, merger rates, and the impact of stellar evolution. *Phys. Rev. D*, 93(8):084029, April 2016. doi: 10.1103/PhysRevD.93.084029.
- Ashley J. Ruiter, Krzysztof Belczynski, Matthew Benacquista, Shane L. Larson, and Gabriel Williams. The LISA Gravitational Wave Foreground: A Study of Double White Dwarfs. *ApJ*, 717(2):1006–1021, July 2010. doi: 10.1088/0004-637X/717/2/1006.

- Hideyuki Saio and Ken'ichi Nomoto. Off-Center Carbon Ignition in Rapidly Rotating, Accreting Carbon-Oxygen White Dwarfs. *ApJ*, 615(1):444–449, November 2004. doi: 10.1086/423976.
- Edwin E. Salpeter. The Luminosity Function and Stellar Evolution. *ApJ*, 121:161, January 1955. doi: 10.1086/145971.
- A. R. Sandage. The color-magnitude diagram for the globular cluster M 3. *AJ*, 58: 61–75, January 1953. doi: 10.1086/106822.
- L. Siess, R. G. Izzard, P. J. Davis, and R. Deschamps. BINSTAR: a new binary stellar evolution code. Tidal interactions. *A&A*, 550:A100, February 2013. doi: 10.1051/0004-6361/201220327.
- Tristan L. Smith and Robert R. Caldwell. LISA for cosmologists: Calculating the signal-to-noise ratio for stochastic and deterministic sources. *Phys. Rev. D*, 100 (10):104055, November 2019. doi: 10.1103/PhysRevD.100.104055.
- Mario Spera and Michela Mapelli. Very massive stars, pair-instability supernovae and intermediate-mass black holes with the *sevn* code. *MNRAS*, 470(4):4739–4749, October 2017. doi: 10.1093/mnras/stx1576.
- Mario Spera, Michela Mapelli, and Alessandro Bressan. The mass spectrum of compact remnants from the PARSEC stellar evolution tracks. *MNRAS*, 451(4): 4086–4103, August 2015. doi: 10.1093/mnras/stv1161.
- Mario Spera, Michela Mapelli, Nicola Giacobbo, Alessandro A. Trani, Alessandro Bressan, and Guglielmo Costa. Merging black hole binaries with the SEVN code. *MNRAS*, 485(1):889–907, May 2019. doi: 10.1093/mnras/stz359.
- E. R. Stanway and J. J. Eldridge. Re-evaluating old stellar populations. *MNRAS*, 479(1):75–93, September 2018. doi: 10.1093/mnras/sty1353.
- Elizabeth R. Stanway, J. J. Eldridge, and George D. Becker. Stellar population effects on the inferred photon density at reionization. *MNRAS*, 456(1):485–499, February 2016. doi: 10.1093/mnras/stv2661.
- Simon Stevenson, Christopher P. L. Berry, and Ilya Mandel. Hierarchical analysis of gravitational-wave measurements of binary black hole spin-orbit misalignments. *MNRAS*, 471(3):2801–2811, November 2017. doi: 10.1093/mnras/stx1764.
- Simon Stevenson, Matthew Sampson, Jade Powell, Alejandro Vigna-Gómez, Coenraad J. Neijssel, Dorottya Szécsi, and Ilya Mandel. The Impact of Pair-instability Mass Loss on the Binary Black Hole Mass Distribution. *ApJ*, 882(2):121, September 2019. doi: 10.3847/1538-4357/ab3981.

- T. M. Tauris, N. Langer, and M. Kramer. Formation of millisecond pulsars with CO white dwarf companions - II. Accretion, spin-up, true ages and comparison to MSPs with He white dwarf companions. *MNRAS*, 425(3):1601–1627, September 2012. doi: 10.1111/j.1365-2966.2012.21446.x.
- T. M. Tauris, N. Langer, T. J. Moriya, Ph. Podsiadlowski, S. C. Yoon, and S. I. Blinnikov. Ultra-stripped Type Ic Supernovae from Close Binary Evolution. *ApJ*, 778(2):L23, December 2013. doi: 10.1088/2041-8205/778/2/L23.
- Thomas M. Tauris, Norbert Langer, and Philipp Podsiadlowski. Ultra-stripped supernovae: progenitors and fate. *MNRAS*, 451(2):2123–2144, August 2015. doi: 10.1093/mnras/stv990.
- Stephen R. Taylor and Davide Gerosa. Mining gravitational-wave catalogs to understand binary stellar evolution: A new hierarchical Bayesian framework. *Phys. Rev. D*, 98(8):083017, October 2018. doi: 10.1103/PhysRevD.98.083017.
- S. Toonen and G. Nelemans. The effect of common-envelope evolution on the visible population of post-common-envelope binaries. *A&A*, 557:A87, September 2013. doi: 10.1051/0004-6361/201321753.
- S. Toonen, G. Nelemans, and S. Portegies Zwart. Supernova Type Ia progenitors from merging double white dwarfs. Using a new population synthesis model. *A&A*, 546:A70, October 2012. doi: 10.1051/0004-6361/201218966.
- S. Toonen, J. S. W. Claeys, N. Mennekens, and A. J. Ruiter. PopCORN: Hunting down the differences between binary population synthesis codes. *A&A*, 562:A14, February 2014. doi: 10.1051/0004-6361/201321576.
- A. Tutukov and L. Yungelson. Double-degenerate semidetached binaries with helium secondaries: cataclysmic variables, supersoft X-ray sources, supernovae and accretion-induced collapses. *MNRAS*, 280(4):1035–1045, June 1996. doi: 10.1093/mnras/280.4.1035.
- A. V. Tutukov and L. R. Yungelson. Degenerate Dwarfs in Binary Systems. *Soviet Ast.*, 36:266, June 1992.
- A. V. Tutukov and L. R. Yungelson. A Model for the Population of Binary Stars in the Galaxy. *Astronomy Reports*, 46(8):667–683, August 2002. doi: 10.1134/1.1502227.
- Aleksandr V. Tutukov, Lev R. Yungelson, and Icko Iben, Jr. The Frequencies of Supernovae in Binaries. *ApJ*, 386:197, February 1992. doi: 10.1086/171005.
- L. M. van Haaften, G. Nelemans, R. Voss, S. Toonen, S. F. Portegies Zwart, L. R. Yungelson, and M. V. van der Sluys. Population synthesis of ultracompact X-ray binaries in the Galactic bulge. *A&A*, 552:A69, April 2013. doi: 10.1051/0004-6361/201220552.

- Alejandro Vigna-Gómez, Coenraad J. Neijssel, Simon Stevenson, Jim W. Barrett, Krzysztof Belczynski, Stephen Justham, Selma E. de Mink, Bernhard Müller, Philipp Podsiadlowski, Mathieu Renzo, Dorottya Szécsi, and Ilya Mandel. On the formation history of Galactic double neutron stars. *MNRAS*, 481(3):4009–4029, December 2018. doi: 10.1093/mnras/sty2463.
- Jorick S. Vink and A. de Koter. On the metallicity dependence of Wolf-Rayet winds. *A&A*, 442(2):587–596, November 2005. doi: 10.1051/0004-6361:20052862.
- Jorick S. Vink, A. de Koter, and H. J. G. L. M. Lamers. Mass-loss predictions for O and B stars as a function of metallicity. *A&A*, 369:574–588, April 2001. doi: 10.1051/0004-6361:20010127.
- Jorick S. Vink, L. E. Muijres, B. Anthonisse, A. de Koter, G. Gräfener, and N. Langer. Wind modelling of very massive stars up to 300 solar masses. *A&A*, 531:A132, July 2011. doi: 10.1051/0004-6361/201116614.
- Chen Wang, Dong Lai, and J. L. Han. Neutron Star Kicks in Isolated and Binary Pulsars: Observational Constraints and Implications for Kick Mechanisms. *ApJ*, 639(2):1007–1017, March 2006. doi: 10.1086/499397.
- C. A. Whyte and P. P. Eggleton. A simple model for binary star evolution. *MNRAS*, 214:357–378, June 1985. doi: 10.1093/mnras/214.3.357.
- S. E. Woosley. Pulsational Pair-instability Supernovae. *ApJ*, 836(2):244, February 2017. doi: 10.3847/1538-4357/836/2/244.
- S. E. Woosley. The Evolution of Massive Helium Stars, Including Mass Loss. *ApJ*, 878(1):49, June 2019. doi: 10.3847/1538-4357/ab1b41.
- Stan. E. Woosley and Alexander Heger. The Deaths of Very Massive Stars. In Jorick S. Vink, editor, *Very Massive Stars in the Local Universe*, volume 412 of *Astrophysics and Space Science Library*, page 199, January 2015. doi: 10.1007/978-3-319-09596-7\_7.
- Claire S. Ye, Kyle Kremer, Sourav Chatterjee, Carl L. Rodriguez, and Frederic A. Rasio. Millisecond Pulsars and Black Holes in Globular Clusters. *ApJ*, 877(2):122, June 2019. doi: 10.3847/1538-4357/ab1b21.
- S. Yu and C. S. Jeffery. The gravitational wave signal from diverse populations of double white dwarf binaries in the Galaxy. *A&A*, 521:A85, October 2010. doi: 10.1051/0004-6361/201014827.
- Shenghua Yu and C. Simon Jeffery. The gravitational-wave signal generated by a galactic population of double neutron-star binaries. *MNRAS*, 448(2):1078–1098, April 2015. doi: 10.1093/mnras/stv059.

- L. Yungelson, M. Livio, A. Tutukov, and S. J. Kenyon. A Model for the Galactic Population of Symbiotic Stars with White Dwarf Accretors. *ApJ*, 447:656, July 1995. doi: 10.1086/175908.
- L. R. Yungelson, J. P. Lasota, G. Nelemans, G. Dubus, E. P. J. van den Heuvel, J. Dewi, and S. Portegies Zwart. The origin and fate of short-period low-mass black-hole binaries. *A&A*, 454(2):559–569, August 2006. doi: 10.1051/0004-6361:20064984.
- Michael Zevin, Kyle Kremer, Daniel M. Siegel, Scott Coughlin, Benny T. H. Tsang, Christopher P. L. Berry, and Vicky Kalogera. Can Neutron-star Mergers Explain the r-process Enrichment in Globular Clusters? *ApJ*, 886(1):4, November 2019. doi: 10.3847/1538-4357/ab498b.
- M. Zorotovic, M. R. Schreiber, B. T. Gänsicke, and A. Nebot Gómez-Morán. Post-common-envelope binaries from SDSS. IX: Constraining the common-envelope efficiency. *A&A*, 520:A86, September 2010. doi: 10.1051/0004-6361/200913658.