UNIVERSE@HOME: ULX'S, GR SOURCES, SNIA PROGENITORS

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This proposal aims to create the first database of the simulated stellar content of the Universe, from the earliest stars to the most exotic black hole binaries. This comprehensive stellar library will be a world-wide scientific resource for astronomers, and an educational asset for the public. With a state-of-the-art suite of computational tools, we can calculate the physical properties of individual stars, evolve them in time, and track how they interact with each other as they age. With this library of stellar populations that spans the known range of star formation histories and initial elemental abundances, it is possible to tackle fundamental science questions that have been out of reach in general relativity, astronomy, and cosmology. As a group we will use this database to characterize the population of supernova progenitor stars that have been used to discover the mysterious dark energy that accelerates the expansion of the Universe; we can calculate how (if at all) binary evolution facilitates the formation of ultra-luminous X-ray sources, and we can model the number and physical properties of neutron stars and black holes that strongly emit gravitational waves that are at the heart of research into gamma-ray bursts – the most energetic explosions known-to-date. The data that we create can be mined not only to match current observations, but to predict how the sky will appear to future astronomical observatories as new windows to the Universe open. Altogether, this proposal will allow us to consolidate a strong and highly visible research group; an independent computational center that trains a new cohort of highly educated students, and communicates with the public via innovative science venues, and offer a fresh look at the Universe.

1. OBJECTIVES

1.1. *Context*

Stars are the basic building blocks of galaxies that, in turn, make up the bulk of the baryon content of the Universe. The first stars formed very early—roughly 100 Myr after the Big Bang —out of the primordial hydrogen-helium mix. These stars, referred to as Population III stars, were likely extremely massive ($M \sim 1000 M_{\odot}$) and produced the first heavy elements through nuclear burning and supernova explosions. These first supernovae created black holes with masses between $10-1000 M_{\odot}$ [1,2,3]. Thus, these first stars provided not only the seed black holes for the eventual formation of supermassive black holes ($M_{\rm bh} \sim 10^6 - 10^9 M_{\odot}$), but also the metals that we see in the second generation of stars. These stars, known as Population II stars, began forming after the Population III era from gas that was already polluted with heavy elements [4]. Still, the Sun has 10^4 times more metals than this population ($Z \gtrsim 10^{-4} Z_{\odot}$). Population II stars most likely generated the photons necessary to re-ionize the Universe, and set the chemical composition of the Universe we observe today.

At about 1-2 Gyr after the Big Bang, Population I stars began forming. These stars have metallicities comparable to that of the Sun, and presently dominate the overall star formation in the Universe [5,6]. Although most stars today are in this category, this population is in no way a uniform sample. For example, the metallicity varies widely: about 50% of star formation in the past Gyr occurs at $Z \sim 0.2 Z_{\odot}$, while the remaining half is found at solar composition or higher ($Z \gtrsim Z_{\odot}$) [7]. In the bottom panel of Figure 1, we show a quantitative picture of star formation history with its uncertainties [8].

The environment of Population I stars varries as well. Typically, stars most commonly form as single objects or in binaries, although higher multiplets are known to exist. Even the dynamics of these stars are different: In galaxies, most stars do not directly interact with other stars – these are the field population. However, a small number of stars form in dense stellar clusters, and here dynamical interactions such as collisions are frequent [9,10]. The fact that today's stars form and evolve in such varied circumstances means that they produce a wealth of information that probes an extraordinary range of of physics. Stars emit light across the entire electromagnetic spectrum, from radio to hard gamma rays, and even generate gravitational radiation. Various stages of stellar evolution are connected with explosive events: X-ray flares from magnetic low mass stars [11]; luminous blue variable eruptions from massive single stars [12]; type Ia supernovae from binary white dwarfs [13]; X-ray bursts from binary neutron stars [14]; gravitational radiation bursts from mergers of neutron stars and black holes [15]; long gamma-ray bursts (GRBs) from massive, rapidly rotating stars [16], and short GRBs from double neutron stars and black hole-neutron star mergers [17].

A number of stellar phenomena are still poorly understood and repeatedly defy our attempts to explain them. Our library of models will help us to solve, or at least constrain these mysteries. At the most basic level, astronomers still lack a full description of star formation [18], convection [19], mass loss [20] and supernova explosions [21]. Since the amount of heavy elements released in stellar winds, supernovae and compact object mergers change how stars interact with each other and their environment, these uncertainties propagate into modeling the chemical evolution of the Universe. We will develop physics that models these phenomena which we will publish to facilitate comparisons with current and future observations.

As just one example of the power of this database, consider the following to put things into perspective. Although there is a consensus that the collapse of a massive stellar core powers a long GRB, the issue of why some stars produce GRBs and others do not is still debated [22,23]. Currently, we do not know which stars produce these powerful explosions [24]. The problem is even more pronounced for the case of short GRBs where there are literally tens of alternatives to the favored merger model. Short GRBs are thought to be very distant; one is the most distant object in the Universe [25,26]. It is commonly assumed that these most distant GRBs originate from Population III stars, and yet the debate ensued on whether they were the result of NS-NS/BH-NS mergers or collapsars. Using our synthetic stellar database, we can generate stellar populations at high redshifts and incorporate the uncertainties of primordial star formation, which will provide astrophysically-based answers for the origin and nature of these distant explosions (see Fig. 1, top panel).

1.2. *Project Overview*

We propose to generate synthetic data on stars and stellar remnants. The data will be the result of numerical simulations that will include detailed stellar evolutionary calculations and population synthesis predictions. The data will cover known populations (e.g., high- and low-mass X-ray binaries, double neutron stars) that could be used for calibration and comparisons, as well objects that are yet undetected (e.g., Population III stars and double black holes). The project will be divided into three specific science tasks/categories that will be conducted in parallel, complementing and guiding each other. Each task will be performed with one or more young team members and external advise from a senior scientist from abroad.

In the following section we outline three key issues that will be studied within the framework of the `Synthetic Universe` library during the funding period. Of course, we expect the library to extend well beyond the funding time. The database will be employed by small and large collaborations, that may or may not include the local Warsaw team, and our external collaborators around the world. The data that

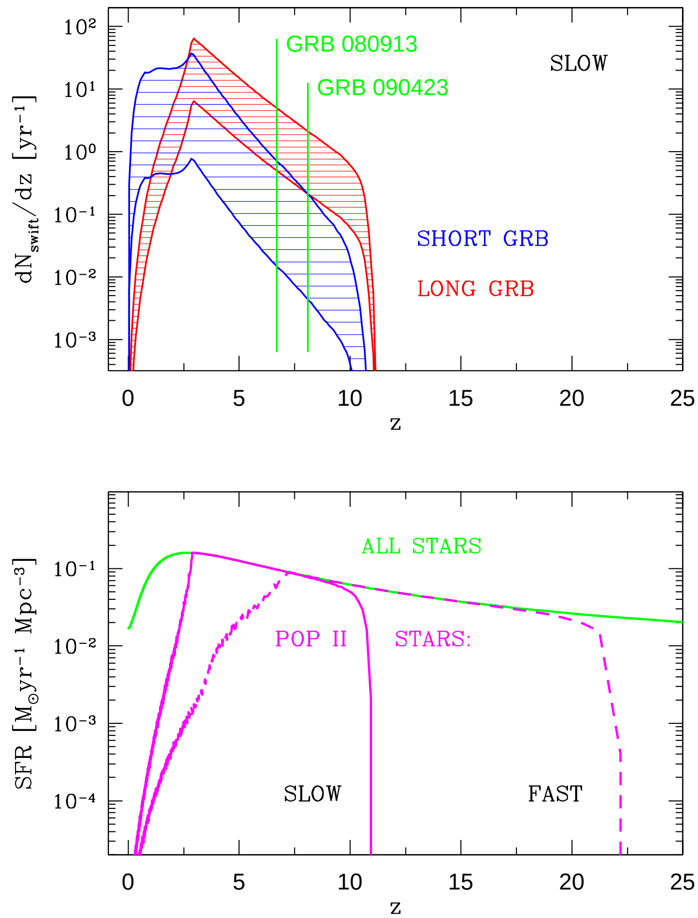

Fig.1 – *Bottom panel:* Overall star formation rate (SFR) history: all stars. We also show the rate we obtained for PopII stars only: the population is rather different for a slow (solid) and fast (dashed line) metallicity evolution model. The models bracket the uncertainty on metal enrichment in the Universe. PopIII (first) stars and PopI (most recent) stars form to the right and left of PopII, respectively. It is clearly seen that independent of the metallicity evolution, the majority of the stars are PopII at $z \lesssim 10$ – this is the redshift of the farthest spectroscopically confirmed objects in the Universe: GRB 080913 ($z = 6.7$) and GRB 090423 ($z = 8.1$). *Top panel:* Predicted *Swift detection* rates of short and long GRBs. Rates are for GRBs originating *exclusively* from PopII stars. GRB 080913 and GRB 090423 have PopII progenitors, and are both long bursts resulting from collapsars *(Belczynski et al. 2010 [8])*.

we will obtain for any of the science projects will be available in the database for any group to perform their own analyses and studies.

The projects within the database will not be, by any means, limited to the list discussed below, but represent specific interests of the team members. At the moment, the initial results from our library are already being used by the *Einstein Telescope* team for mock data challenges (Tania Regimbau, University of Nice, France), to study nucleosynthetic yields and subsequent Galactic metal enrichment from neutron star mergers (Stephan Rosswog, Albanova University, Sweden; Thomas Janka, Max Planck Institute for Astrophysics, Germany) and for studies of Galactic microlensing on black hole binaries (Jeremy Schnittman, NASA, USA).

1.3. *Ultraluminous X-ray Sources*

The ULX is defined as non-nuclear (not a central galactic object) X-ray point source that has an isotropic X-ray luminosity higher than a few times 10^{39} erg/s. This definition has roots in early X-ray observations (Einstein, ROSAT, ASCA) that have revealed a population of unexpectedly bright extragalactic sources [27,28]. Since ULXs are point sources that are not associated with their host galaxy centers, accreting neutron stars or black holes in close binary systems seem to be the most natural candidates. However, the X-ray luminosity of these sources is so high that it exceeds the critical Eddington luminosity of what was believed to be the maximum mass of a stellar origin black hole. The Eddington luminosity can be written as $L_{\rm Edd} = 1.3 \times 10^{38} (M/{\rm M}_{\odot})$ erg/s, and it denotes the maximum bolometric luminosity attained by an accreting object of mass M. For accreting neutron stars and black holes, most of the power comes in the X-ray band and thus X-ray luminosity is a good approximation of bolometric luminosity. The first known stellar black holes were found in our Galaxy and were determined to have masses within the range $5 - 15{\rm M}_{\odot}$ [29]. Therefore, the maximum luminosity that can be provided by an accreting black hole ($15{\rm M}_{\odot}$) of the stellar origin could reach only $L_{\rm Edd} = 2 \times 10^{39}$ erg/s. Any accreting source that exceeds this limit is presently classified as an exceptional source under the ULX category.

Recent years have brought wealth of information. Targeted programs with new generation satellites (Chandra, XMM-Newton, Suzaku, Swift) delivered detailed ULX population X-ray spectral and timing properties and initiated multi-band searches for their counterparts [30]. Recent catalogs contain more than 500 point sources with X-ray luminosities as high as $10^{39} - 10^{42}$ erg/s [31,32,33]. Some ULXs exhibit strong X-ray variations on timescales of minutes confirming their compact nature [34,35]. The combination of the luminosity and the compactness arguments implies that accreting black holes within the mass range $10 - 10{,}000{\rm M}_{\odot}$ are powering ULXs. Although, some small contamination of the ULX catalogs by other sources cannot be excluded without extensive observational follow up. The most likely contamination is expected from background AGNs (can be found in entire ULX luminosity range; [36]), young supernovae (Type IIn may reach 10^{40} erg/s; [37]) and young X-ray pulsars (may slightly exceed 10^{39} erg/s; [38]). That said, most observational time and theoretical effort is dedicated to study the majority of sources that are powered by accreting black holes. On one hand, observers provide luminosity functions [39], host galaxy information [32], correlations between the ULX numbers and star formation/metallicity [40,41] in addition to the multi-wavelength temporal spectral characteristic of sources [42,43,44]. On the other, theorists develop sophisticated models of accreting black holes that include supercritical inflows, beamed emission, and outflows that can interact with the surrounding medium producing shocked nebulae [45,46,47,48]. However, despite the observational and theoretical advances the nature of ULX sources remains unknown.

The most straightforward interpretation of the ultra high X-ray luminosities comes from the Eddington limit. If the limit is in fact not violated it means that ULXs host black holes with masses in the range 10-10,000 ${\rm M}_{\odot}$. If it is further assumed that stellar black holes can only reach mass of $10 - 20{\rm M}_{\odot}$ as observed in the Galaxy, it follows that ULXs host an intermediate mass black hole population of unspecified (most likely dynamical formation) origin [49,50,51]. This idea became very popular, as it would provide the missing link between the stellar mass black holes and supermassive black holes residing in center of various galaxies. There are three major caveats to this interpretation. First, there are models of "leaky" accretion disks with photon bubbles that can violate the Eddington limit by a factor of 10 [52]. Second, the ULX X-ray luminosity may be overestimated by another factor of 10 due to emission anisotropies caused by the beaming expected for high accretion rate binaries [53]. Third, the stellar mass black holes can significantly exceed the typical mass assumed in the above discussion. It was recently demonstrated that if updated wind mass loss rates are employed the stars in low metallicity environment can form black holes as massive as $80{\rm M}_{\odot}$ [54]. This gives another factor of about 10 in potential increase of luminosity for stellar mass black holes. If all the above factors are combined (increase by factor of ~ 1000), it is potentially possible, that stellar mass black holes, can explain even the brightest ULXs ($10^{39} \rightarrow 10^{42}$ erg/s).

Some of the above ideas were already utilized in the ULX studies. It was argued for stellar mass black hole origin combining the beaming and leaky disks to explain the ULX sources with luminosities upto 10^{41} erg/s [55]. They could not reach the most extreme luminosities (10^{42} erg/s), since at the time of their study stellar mass black holes were not known to have masses over $10 - 20\mathrm{M}_{\odot}$. It is worth noting that the same year the so far most massive known stellar black hole ($30\mathrm{M}_{\odot}$) was discovered in low metallicity galaxy IC10 [56,57]. A few years later the formation of this most massive known black hole was explained and used to predict the maximum mass of stellar black holes ($80\mathrm{M}_{\odot}$) by our group [54]. A number of ULX papers followed. In the first approximation, it was postulated that if a very massive stellar origin black hole accretes from a binary companion all (or almost all) ULX sources can be explain without invoking intermediate mass black holes [40,58,59]. However, these results were challenged by the detailed population synthesis calculations implying that the chance for the formation of a ULX source consisting of a very massive stellar origin black hole and a mass transferring companion is close to nil [60,61]. This brings back the heated conundrum: do the most luminous ULX sources have to be powered by intermediate-mass black holes or could they potentially host stellar mass black holes?

Here, we propose the final solution to this issue. We will test whether such evolutionary channels that produce the brightest ULX sources powered by stellar origin black holes exist. We will employ the only population synthesis code (StarTrack [62,63]) that at this moment allows self-consistently for the formation of the very massive stellar origin black holes. We will incorporate the relevant beaming and leaky disk physics into the underlying physical model and test whether it is possible to form a stellar black hole ULX with X-ray luminosity reaching 10^{42} erg/s. The negative answer will indicate that indeed the most luminous ULXs, like 10^{42} erg/s source HLX-1 in ESO234-49 [64], must be powered by an intermediate-mass black hole. The positive answer will allow for the possibility that even the brightest ULXs may be powered by stellar origin black holes. Obviously, our proof-of-principle study will not be able to rule out the intermediate-mass black hole ULX origin. However, if the answer to our hypothesis is positive, we will provide a detailed ULX formation rate estimate. Comparison with the observed number of ULXs in the local Universe with our predicted number of stellar origin ULXs will indicate what fraction (potentially all?) of sources are powered by stellar mass black holes.

The final comment is of somewhat political and of a sensitive nature. However this point needs to be made in order to justify the proposed line of the research. There are claims [60,61] that it is unlikely for a very massive stellar black holes to form a ULX that are based on StarTrack population synthesis calculations. These calculations were performed on a sample of several million massive binaries. Such a sample corresponds to about 10% of the stellar content of a large galaxy (e.g., Milky Way). Such a sample may be considered relevant for most population synthesis studies, provided that a considered population consists of tens of sources per a large galaxy. This is satisfied for most known stellar populations and such an approach is readily justified for such cases. However, this is fundamentally different in the case of ULXs. For one, there is no ULX in our Galaxy, and it takes many galaxies to produce just one. In other words, ULXs are extremely rare objects. Therefore, any population synthesis study that is focused on ULX population, needs to be performed on a very large stellar sample. This is to ensure that, if in fact ULXs form from binary stars, the very rare formation channels are properly identified. One cannot simply perform calculations on a typical population synthesis sample (although it may seem very large), find no bright ULXs (as expected) and then extrapolate the results to the local Universe. This is why PI of this proposal (K.Belczynski) removed his name from the author list of [60]. Here, we propose a suite of massive population synthesis calculations that will encompass a number of large galaxies, and therefore it will be ensured that the conclusions are statistically and scientifically meaningful.

We are also planning to undertake a study of very massive stars within Population I/Population II stars. Recent observations [65,66] demonstrate that stars with significant amount of metals ($30\% Z_{\odot}$; LMC) can reach mass upto $\sim 300\mathrm{M}_{\odot}$. Such a possibility was *never* considered in ULX nor gravitational radiation studies as it defies the current theoretical understanding of star formation (maximum star mass of about $\sim 100\mathrm{M}_{\odot}$). We will extend the Initial Mass Function (IMF) up to (or over) the currently observed limits to study the effects of very massive stars on ULX and double compact object populations. The initial estimates, performed within a large international collaboration (Duncan Brown: co-chair of LIGO coalescence group, Cole Miller: LIGO/VIRGO oversight committee, Chris Fryer: Los Alamos astrophysicist; Alessandra Bunanno: the black hole relativity keyperson + Warsaw Observatory group) indicate that despite the very low numbers (steep IMF) these very massive stars forming intermediate-mass black holes may totally alter the consensus on the impact of the stellar origin of black holes [67].

1.4. *Gravitational Radiation Signature*

Double compact objects, binaries consisting of black holes, neutron stars and white dwarfs in various combinations, are of special interest in context of current ground-based (LIGO/VIRGO) and near future (DECIGO, Einstein Telescope, eLISA) space based gravitational radiation observatories. Double compact objects are the primary sources for ground based interferometers while they will constitute the foreground noise for some space instruments, limiting observations of other objects. In the last decade, several groups were working on rate predictions and characterization of double compact object populations [62,68,69]. Without exception, the gravitational wave predictions were thus far based on observations of stars in our Galaxy. In particular, the predictions were based on stars with solar chemical composition – typical for Milky Way thin disk population. However, even the currently operating instruments can reach far beyond Milky Way. In this local volume, recent deep observations of tens of thousands of nearby galaxies demonstrated that as much as $\sim 50\%$ of local star formation is occurring in low metallicity environments ($\sim 20\% Z_{\odot}$ [7]). This fact is not yet fully recognized in the community, but the implications of this finding are critical. As discussed earlier, metallicity has a strong impact on the final mass of compact objects, especially black holes (see Fig.2). If half of the star forming mass is producing heavy black holes the predicted detection rates can increase by more than an order of magnitude [70] and direct detection of gravitational waves may be much easier than previously believed. This is supported further by empirical estimates of BH-BH merger rates [71] and have rather deep implications the instrument (LIGO/VIRGO) development. Motivated by our estimates [70,71] *Ligo Scientific Collaboration* have already designed and carried out a specific signal search on the last (*S6*) initial LIGO/VIRGO science run [72]. At the moment both observatories are being upgraded to a higher sensitivity, and our results indicate that the engineering runs (ones that are planned before reaching targeted sensitivity) will either result in detections or provide robust constraints on stellar evolution. This calls for a different approach to data analysis for the first advanced LIGO/VIRGO observations.

Our theoretical predictions are supported by recent empirical estimates [71,73,74,75]. At the moment these are the only estimates that take into account a realistic BH/NS mass spectrum, supernovae explosions, common envelope evolution and properly consider the metallicity distribution in the local Universe [76]. Based on our calculations, we argue that the science that can be done with gravitational wave detections shifts toward a new direction and we have already begun providing some very clear-cut examples of what can be learned from the first gravitational wave detections. In particular, we have demonstrated that the detection of a single NS-NS binary within the first 10 detections will put very strong constrains on BH natal kicks [77]. Additionally, the available electromagnetic data on known BH and NS masses is

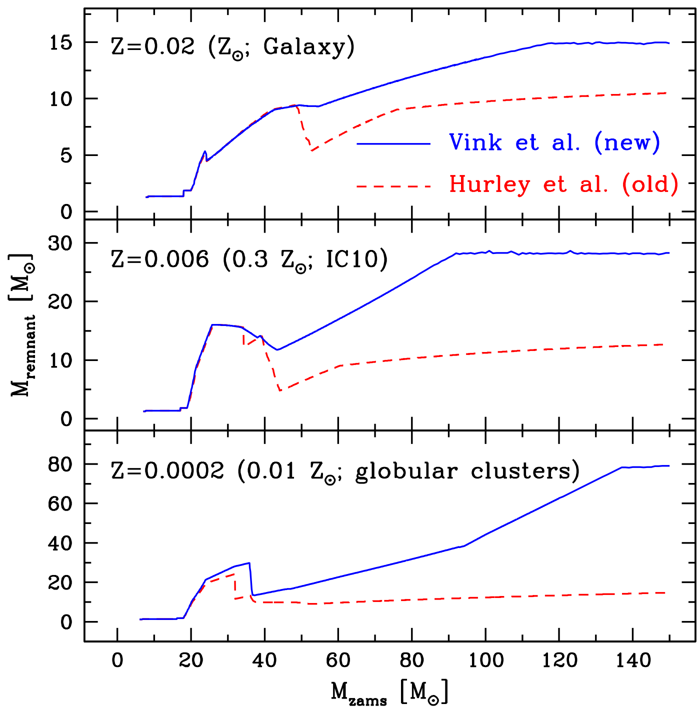

Fig.2 – The initial-remnant mass relation for a `StarTrack` single star evolution for two wind prescriptions: the previously used Hurley et al. winds and newly adopted (modified) Vink et al. winds. *Top panel:* Solar metallicity. This corresponds to the stellar field populations in the Galaxy. The predicted maximum black hole mass $M_{\rm bh,max} \sim 15 M_{\odot}$ for new and $\sim 10 M_{\odot}$ for old winds is consistent with the most massive stellar black holes observed in our Galaxy (e.g., in GRS 1915 $M_{\rm bh} = 14 \pm 4 M_{\odot}$). *Middle panel:* Moderate metallicity. This corresponds to stellar populations in galaxy IC10, which hosts the most massive known stellar black hole ($M_{\rm bh} = 23 - 34 M_{\odot}$). Note that the predicted maximum black hole mass $M_{\rm bh,max} \sim 30 M_{\odot}$ for the new winds is consistent with the measurement in IC10, while $M_{\rm bh,max} \sim 15 M_{\odot}$ obtained for old winds appears to be significantly too small. *Bottom panel:* Very low metallicity. This corresponds to stellar populations of Galactic globular clusters, or protogalaxies. The maximum black hole mass may reach $M_{\rm bh,max} \sim 80 M_{\odot}$ for the newly adopted wind prescriptions *(Belczynski et al. 2010 [54].*)

inconclusive as to the existence of the infamous "mass gap" (the dearth of compact objects in $2-5 M_{\odot}$ mass range). It is not clear whether this gap is the effect of some observational biases or rather reflects on the physics of the supernova explosion engine [78]. In a recent study, we have identified which part of the supernova explosion physics may be responsible for the mass gap and we have indicated that the final answer will be provided by the unbiased gravitational wave measurements of compact object masses [79].

We will provide a qualitatively new description of double compact object populations. The synthetic populations of double compact objects formed at various host galaxy environments (range of galaxy masses, metallicities and star formation histories) will become part of our library. Our model allows for evolution of metal rich stars (Population I and II; [63]) as well as first metal-free stars (Population III; [80,81]). Synthetic data will be provided not only as a function of a given host galaxy type, but also as a function of redshift under an adopted cosmological model that incorporates chemical evolution [8]. The data will include not only basic parameters for double compact objects (component masses or separations/eccentricities at formation) but also very specific parameters (spins: magnitude and their direction [106] or position within the host galaxy [82]) that can allow for a number of applications not only within gravitational wave astronomy but also crucial for gamma-ray burst or X-ray binary studies. At the moment, a number of US-based scientists are using `StarTrack` models to interpret *Chandra* observations [83,84,85,86]. At the same time I am leading efforts together with Harvard (Edo Berger) and Boulder JILA groups (Rosalba Perna) to characterize populations of transients (*Palomar Transient Factory*) and Gamma-ray bursts (*Swift*) with the use of our models.

Our results will allow for rate/parameter estimates specific to a given gravitational wave observatory and will not be limited to LIGO/VIRGO but will be directly applicable to *any* future observatory that is designated to search for double compact objects at arbitrary redshifts. This approach will facilitate the understanding of what science can be done with gravitational radiation detections with existing and planned observatories.

1.5. *Type Ia Supernovae*

Supernova explosions are the fate of all massive stars: these generate the core-collapse supernovae (SNe). SN explosions are also the final stage for a less massive binary system after one of the stars evolves into a carbon-oxygen white dwarf. These generate Type Ia SNe (SNe Ia). All SNe play a critical role in driving the galactic gas ecosystem, in star formation by heating and compressing interstellar gas, and in chemically enriching galaxies. SNe are responsible for releasing radioactive and heavy nuclei into interstellar space and spreading the building blocks of other stars, planets, and ultimately, life. Additionally, observations of SNe Ia have led to the breakthrough discovery that the expansion rate of the Universe is accelerating, due to a mysterious "Dark Energy" [87]. Despite their use as the most important "standard candle" distance indicators, the origin of SNe Ia remains unknown. The long-standing paradigm [88] is that their progenitors consist of a white dwarf that accretes enough matter from its binary companion such that its mass exceeds the Chandrasekhar mass limit ($\sim$1.4 $M_{\odot}$). However, the nature of the companion star, the efficiency of matter accumulation onto the white dwarf, and the explosion mechanism are all thus far unclear [89].

To date, the two most favored scenarios thought to lead to SNe Ia are the Single Degenerate Scenario (stable mass accretion on to a white dwarf from a normal star [90,91]) and the Double Degenerate Scenario (the merger of two massive white dwarf stars [92,93]). However, other promising formation scenarios exist [94], and support for more than one formation scenario is substantiated by recent SNe Ia observations. Several different sub-classes of SNe Ia have been identified [95], and recent advances in theoretical SN modeling indicate that there is likely more than one formation scenario (and explosion mechanism) contributing to the observed sample of SNe Ia [96]. This has far-reaching implications for the theory of Dark Energy: if the explosion mechanism that leads to the formation of a SN Ia is dependent on evolutionary scenario and/or metallicity, this could potentially pose a challenge for cosmological studies by introducing systematic errors [97]. Thus, determining the nature of SN Ia progenitors – both in the local and the most distant Universe – is one of the most important long-standing puzzles in astrophysics that remains to be solved.

The delay time distribution (DTD) is the distribution of times in which SNe Ia explode following a (hypothetical) burst of star formation. Knowing the DTD gives the age of the progenitor, which places strong constraints on the different proposed formation scenarios. If the SN Ia rate is known in addition, then it becomes possible to rule out theoretically-predicted evolutionary channels.

Today, we are uniquely primed to address the question of SN Ia origin. This has already been done to some extent for Local Universe-like stellar populations [13]. Excitingly, now we are poised to determine how well SNe Ia can be considered standard candles [98], and quantify to what degree their rates and delay times vary as a function of *redshift and metallicity*. In order to accomplish this, in the next step we will combine the theoretical rates (quantity) and delay times (feedback timescale) with nucleosynthetic yield predictions for the leading SN Ia formation scenarios as a function of redshift (metallicity). This requires generating a suite of binary evolution models for a grid of stellar metallicities, computing explosion models with the most up-to-date nucleosynthetic yield predictions, and calculating synthetic spectra and light-curves. A complete pipeline is already in place with the collaborators in our existing network: from binary star birth/evolution of SN Ia progenitors (A. Ruiter+K.Belczynski) to explosion modeling (MPA, Wurzburg, Heidelberg) to synthetic spectra calculation (MPA, Mt. Stromlo, LANL). Such a pipeline has already been extensively tested, and shown successful in validating the importance of some of the most promising SNe Ia formation scenarios [99,100].

These efforts will enable us to assess the viability of various explosion models, and gain insight into the origin of different subclasses of SNe Ia: 'normal' SN Ia, sub-luminous and super-luminous SNe Ia, and other peculiar objects (e.g., 2002cx-likes). The `Synthetic Universe` library will contain detailed information on the formation history of the most promising SN Ia progenitors as computed by `StarTrack`. Additionally, delay times and formation histories will also be recorded for core-collapse SNe; some of which are expected to be synonymous with GRBs. The synthetic data on delay times and rates of the various SNe will serve as input for the `NuGrid` collaboration (see 3.2) to obtain estimates of chemical enrichment scenarios for various galaxy types. Such a long-term project would involve convolving theoretical delay times for all stellar explosions with galaxy mass distribution functions as a function of redshift, and imposing a galaxy mass-metallicity dependence [5]. We will thereby provide important input data for chemical evolution models by supplying the relative rates (and DTDs) of various stellar explosions on cosmological scales.

2. DISCIPLINE CONTRIBUTION

We will deliver the first library of synthetic stellar populations to the astro community. At first we will provide the data on the populations of GR sources (NS-NS, BH-NS, BH-BH), ULX binary candidates (BH + stellar type companion) and potential progenitors of Type Ia supernovae (various configurations of accreting white dwarfs in binary systems). The database will be maintained beyond the period of funding and new projects will be added as the need arises. Our contribution will extend beyond the scientific community. We will actively involve the public in our research. We will provide a platform for the public to get involved in our numerical simulations and at the same time we will invest in education and our project advertisement to a wider audience through the Internet.

3. SIGNIFICANCE

We propose to tackle three very specific stellar research projects at the frontier of stellar astrophysics. We will provide a proof-of-principle study of the origin of ultraluminous X-ray sources and we will show whether stellar mass black holes can or cannot explain the observed populations of these objects. We will fully describe the populations of double compact objects (NS-NS, BH-NS, BH-BH) that are the most promising sources for gravitational-wave detectors. LIGO and VIRGO observatories will start taking data around 2015 and we will provide a scientific rationale behind the near-future detection of double compact object mergers and help to guide the signal search techniques. We will study various potential progenitors of Type Ia supernovae in a quest to finally identify which binaries are specifically responsible for these explosions. Our synthetic models will help to eliminate some of the proposed models, while other models will gain in significance, driving progenitor research. We will compare our predictions with the observed supernovae rates, delay times, light curves and spectra.

4. WORK PLAN

4.1. *Database Development*

The database will be placed at a local server maintained by our group, and will be visible and accessible from the outside through the `Synthetic Universe` website. The database will consist of electronic data tables accompanied by detailed descriptions of each table's content. For each simulation from either the evolutionary code or population synthesis code we will post the raw data with a full description of the simulation. A detailed code manual will be placed up front for each code, as well as a general overview of the database and usage instructions. The raw data files will serve as consistency checks and comparisons for groups that prefer to do the post-processing on their own.

Post-processing involves a number of computational tasks that are very often required to present synthetic data in a useful way. For example, it is important to generate a synthetic spectrum to compare to an observed galaxy. To proceed, we will use a population synthesis code to obtain the entire stellar population in this galaxy. For each star, we will then obtain a spectrum from one of the available stellar spectra libraries, and co-add the spectra. These tasks all require extra calculations, and external libraries. These tasks will be performed by analysis codes that we will create and distribute to address our specific data needs. In this example, the final product would be the spectrum of a synthetic galaxy that could be downloaded from our server with the full description of how it was generated.

As the database expands, we will adapt and improve our analysis codes to serve as interactive research tools. In the above example, a need may arise to combine stellar population data to model unforeseen future observations. Since we will have a full library of raw stellar population data within the first years of opening the database, we will also provide interactive software that can allow users to combine the data in novel ways. This can include, but is not limited to: building galaxy models and changing cosmological parameters. Finally, we will provide visualization tools that will specifically work on information contained within the database, requesting time snapshots, imaging, and rapid sampling of the synthetic data. The first pilot project is already available online at: `http://www.syntheticuniverse.org`

4.2. *Specific Schedule*

1) First year. We will start preparations for all three science projects. That will include search of the available literature, contacting other groups that work on the similar subjects and we will establish background for our calculations. We will prepare our physical model (extra input physics, calibrations and updates) for all three projects. In particular, we will use the `MESA` code to updated criteria on common envelope development, we will implement the primary effects of rotation into `StarTrack` based on the Geneva group results, we will add various, less thoroughly-explored though promising SN Ia models (e.g., sub-Chandrasekhar mass merger models [101], violent white dwarf mergers [102], Symbiotic channel [103], double-detonation scenarios [104], thick wind prescription [105]) and we will expand our code for relevant ULX physics (leaky disks, anisotropic emission, very massive stars). We will create and test internal (Warsaw Observatory) computing network within the framework of the `Universe@home` program. We will apply for computer time at various open Polish computational centers.

2) Second year. We will run numerical population synthesis simulations relevant to all three projects. The data will be stored at first on our local disks. At the same time we will work on the development of our websites (`www.syntheticuniverse.org`) and we will get it ready for the arrival of the synthetic data. The simulations will be run at US and Polish Research Institution computer clusters, and (if granted) in Polish open computational centers. And we will launch our `Universe@home` program and open it for the public. We will begin assessing the changes imposed by effects of rotation on relevant stellar populations.

3) Third year. The numerical simulations will continue. We expect that more and more computational resources will be acquired with time via our `Universe@home` program. The first data will be placed in our `www.syntheticuniverse.org` database and made publicly available for other research groups. We will carry out the first analysis of our data for all three projects and write up and submit our initial conclusions to international journals. For practical reasons, the GR papers will be submitted to *Astrophysical Journal*, SN Ia papers to *Monthly Notices of the Royal Astronomical Society* and ULX studies to *Astronomy & Astrophysics*. We will start incorporating `MESA` models into the `StarTrack` code as an optional tool for comparative simulations.

4) Fourth year. The numerical simulations will continue and at the end of this year the simulations will be completed. The full data sets will be placed and described in our library. We will start the final analysis and progress with the three research projects. We will continue incorporating the Geneva models into our population synthesis. Furthermore, we will obtain the first population synthesis simulations that include full effects of rotation from the `MESA` code.

5) Fifth year. Available computer power will be used to obtain extra simulations that we will deem required during our studies or that are requested by the astro community or reviewers of our submitted manuscripts. The entire group will focus on detailed analysis of our results and comparisons of our simulations with (available at this stage) observations. We will also compare our results obtained with rotating and non-rotating stellar models. We will be writing our findings into a series of papers. Students and graduate students will be using these results to progress their theses. At the same time we will be already planning further future extensions of our library. By that time we expect to have major feedback from various groups working on the related subjects and this will help us guide our future database development.

5. METHODOLOGY

5.1. *Stellar Modeling*

Although the theory of stellar evolution is quite a mature subject, it has still to face big questions. Among them: How do massive stars form? How does stellar evolution influence star formation? What was the nature and the characteristics of the first generations of stars in the Universe? What was the role of these first generations in the reionization of the Universe? What physics drives the variations in the stellar populations observed in different environments?

The answers to all these questions require improving stellar models. These improvements are obtained by including important effects, neglected until recently, such as the effects of the stellar winds, the internal transport processes induced by axial rotation or by other instabilities such as the thermohaline mixing, the transport of angular momentum by the gravity waves and/or by a magnetic field. All these effects have been implemented in the Geneva and Bill Paxton stellar models and have been tested by a whole series of observational features. These comparisons all support the view that extra mixing processes do indeed occur in stars, and that models accounting for them can much better reproduce the observations than the models neglecting them. Including these transport mechanisms have deep impacts on the stellar populations expected at a given age and metallicity as well as on the nucleosynthesis of the elements. Many of these effects can be tested using the new windows which are now opening on stellar interiors through astroseismology (e.g., `COROT`, `KEPLER`). Additionally, the huge number of stars that will be observed by the satellite `GAIA` will allow to probe very short evolutionary phases which so far were only in the realm of theory. Heavy mass loss of material by stellar winds, like in the Luminous Blue Variable phase, may be good example of short phenomena that may very deeply affect the end of the stellar life, the nucleosynthetic outputs, the supernova type and the nature of the stellar remnant. `GAIA` observations will lead to strong revisions of the stellar evolution in many parts of the Hertzsprung-Russel diagram.

We will require two type of codes *(i)* population synthesis code and *(ii)* detailed stellar evolutionary code. Though these codes can work independently, ideally they should work together, delivering feedback from one code to another. The end product of such an approach will be a comprehensive and self-consistent picture of stellar populations at a brand new level, both quantitatively in terms the of a data library, and qualitatively in terms of evaluating the input physics.

5.2. *Population Synthesis Models*

We created the comprehensive population synthesis tool `StarTrack` [62,63]. This code uniquely combines rapid stellar evolution with the detailed physics of binary interactions and the formation and evolution of compact stellar remnants. The code is widely used ($\sim$ 100 papers and 3000+ citations on `StarTrack` results), but only in close collaboration with the code PI (K.Belczynski) as the code is not open source software. `StarTrack` is a living code, and its major strength stems from the annual revisions and input physics updates that allow this code to be employed for cutting-edge and innovative research projects. To give an example, in 2008, `StarTrack` was extended to include the evolution of black hole spins [106] (not accounted for in any other synthesis codes), in 2010 the code was updated for the most recent wind mass loss rates [54], in 2011 we have revised supernova explosion model [107] while in 2012 the common envelope evolution was extended [76].

Population synthesis is claimed to lack predictive power. The claim originates from the fact that population synthesis modeling can depend on $\sim$ 30 parameters. These parameters bracket our lack of knowledge of the physics of star formation, evolution, and death. This may be perceived as a major weakness, especially if the method is used “blindly” and there are many examples of population synthesis papers of this sort. This is why `StarTrack` is not an open source code.

However, from another perspective, one can argue that this is the unchallenged strength of population synthesis. By definition, population synthesis allows us to tackle a number of problems that are not approachable by other means—simply because we lack the full physical picture of many phenomena. The predictions can then be contrasted with observations to either lend support for or rule out various models that attempt to describe the unknowns. As a result, population synthesis can guide the development of first-principle-studies, delivering invaluable insights on problems that are at the edge of our understanding. It is an art to provide predictions that are realistic and do not depend (in any significant way) on the method uncertainties – but it is not an impossible art. For example, the revision of wind mass loss rates has led to a very significant increase in the black hole masses that can be formed by stars in the local Universe. Although, the revised winds had been acknowledged for several years, this striking implication was somehow missed. In Figure 2 we show how stellar black holes can reach $\sim 80 M_{\odot}$, up to 8 times larger than commonly believed. This finding does not depend on *any* population synthesis parameters, although it was obtained with the `StarTrack` code.

Population synthesis codes most commonly consist of two major parts; one deals with single stellar evolution and one with physical interactions of two stars in a binary. The `StarTrack` binary physics part is, as mentioned earlier, constantly updated to reflect new advances. As for the stellar evolutionary part, the code employs rapid analytic formulae based on the updated Eggleton stellar evolutionary code [108]. The major update planned for this proposal is to extend `StarTrack` to include rotation in stellar models. Currently, most stellar models exclude the effects of rotation on a star's evolution. Both, the Geneva group and Bill Paxton (MESA) have begun producing the first models with rotation, however the models are still too limited in parameter space to employ them in population synthesis. To probe mass, metallicity, and rotation adequately, we would need approximately 3000 stellar models. At first stage, we plan to use the published Geneva models and use MESA code to generate rotating stellar models to recalibrate our evolutionary formulae within the StarTrack code. Such approach will allow us, for example, to test how the rotation affects the compact object mass. On one hand rotation will increase the star's core mass and on the other the wind mass loss rates are higher for rotating models and it is not clear how these two opposing effects influence the final compact object mass. At the second stage, we will accumulate all available rotating models and we will construct the grid (mass-metallicity-rotation) to be employed as a tool for population synthesis of binary stars with rotating components.

This is high computational cost task. However, such a task is feasible and realistic, and the science profits will by far repay the effort. This is the final step before adopting the full and detailed evolutionary binary models in population synthesis calculations. This effort is cutting-edge: such a symbiosis of population synthesis with rotating stellar models has never been attempted.

5.3. *Detailed Stellar Evolutionary Models*

For a detailed stellar evolutionary code we will adopt and modify an open source MESA code [109] for the database needs. The code will be used to provide single stellar models when an in depth characterization of a single star is required, such as its internal structure, mass profile, or instantaneous composition. The details of stellar evolution are needed to both guide the population synthesis calculations and to characterize populations of single stars or the components of binaries. This is useful to estimate cluster ages, or to predict the existence and range of habitable zones for extrasolar planets, for example.

Similar to Geneva group models [110], MESA allows to include rotation. Rotation is the last major missing parameter in massive stellar evolution modeling. The Geneva group was the first to introduce the effects of rotation on stellar evolution, noting significant changes in mixing and in mass loss rates compared to non-rotating models. Since many stars form either in close binaries where tidal spinup occurs, or with high initial spin, introducing stellar rotation in massive population synthesis calculations is very important and is likely to produce interesting and unexpected results.

To enhance the chemical evolution modeling, we will partner with the NuGrid collaboration (http://forum.astro.keele.ac.uk:8080/nugrid) and help to provide nucleosynthesis yields. As a first science goal, the NuGrid collaboration will generate yields from single stellar models. However, to deliver useful input for chemical evolution of stellar groups and cosmological volumes, more realistic stellar populations will need to be considered. Chris Fryer (Los Alamos), who is participating in both Synthetic Universe and NuGrid projects, will act as the emissary between these groups. On our side we will provide realistic properties of interacting binary stars and double compact objects that feed elements into the interstellar medium quite differently than single stars. We will also provide calibration factors, such as the estimated star formation, supernova and merger rates, that will serve for post-processing of NuGrid calculations.

5.4. *Computational Resources*

The proposed project is overall computationally intensive. We will need thousands of CPU hours for each full simulation. However, each simulation, or say given realization of stellar populations in Universe, will be used to publish at least one paper by our group and will be used by other researchers to conduct their own studies.

Ideally, we would need to have our own computer cluster (500-1000 CPUs), dedicated for this very project. However, such cluster is rather expensive (500,000 PLN or more). Also, it was indicated that our computations could be performed in various Polish open access computer centers. There is a potential issue with applying for CPU time for generally accessible large machines. As it happens architecture of most of such machines is dedicated to perform large parallel simulations (focus is laid on speed of CPUs communication and on short tasks with the use of multi-hundred processors). Our evolutionary and population synthesis simulations do not require parallel computing, but simple sheer CPU force (or large number of single CPUs to run for prolonged time). Therefore, it may be perceived that our application for time on these open-access machines is not justified or is not an optimal use of the available resources.

We will proceed along three different routes to ensure that we have enough CPU time to perform our simulations and we are only asking for minimal (in comparison with the cost of the dedicated computer cluster) funds to purchase 2 laptops for the youngest team members, and the dedicated server with large hard-drive memory and UPS system to host our database (at the moment our initial site is run from a desktop computer).

1) We will apply for time to open-access machines with the science-rationale provided in this proposal.

We have identified the following computational resources to be used: `ICM`, `CYFRONET`, `AstroGridPL`). Predicted success rate: $\sim 50\%$.

2) We will use PI established connections to perform simulations on various (non-open access) computer clusters. We have been given access and permission to perform calculations on 3 machines: `FUTURO` at University of Texas at Brownsville, USA (contact: Matt Benacquista, benacquista@phys.utb.edu), `PSK` at Copernicus Center, PAN, Warsaw, Poland (contact: Zbyszek Loska, zbylo@camk.edu.pl), `SUGAR` at Syracuse University, USA (contact: Duncan Brown, dabrown@physics.syr.edu).

3) We will employ the *Berkeley Open Infrastructure for Network Computing (BOINC)* software to run calculations on personal computers. We will seek volunteers within general public to join our program: `Universe@home` – and allow their home computers to run our software (`StarTrack` set for a small part of a given simulation) at times when a their computers CPUs are idle. This is similar to projects like `Einstein@home` or `Pulsars@home` that are successfully operated to perform data analysis of VIRGO data and search for pulsars in Arecibo data, respectively. At the moment, there are about 40 such programs maintained around the planet. Two of them are based in Poland, but these are run for personal use and mostly dedicated to breaking codes. Our initiative will be the first Polish application of that sort for scientific use. The initial test program will be launched within Warsaw University Observatory. We will use our `Synthetic Universe` server to run the *BOINC* software with the integrated `StarTrack` code. We will request students and graduate students within the Observatory (about 20 desktops, many with dual or quad core CPUs) to join the initial `Universe@home` network and participate in one simulation. At parallel, we will run a control simulation at one of our available clusters (see above). Once we are sure that our initial configuration runs without any problems and delivers correct results, we will launch the main program. To advertise the program and attract the public we will use: *(i)* our websites (both personal and professional), *(ii)* social networks (facebook, twitter) and *(iii)* science venues (conference presentations, departmental talks, research visits). As proven by other programs of that sort, there is abundant public interest to participate in scientific research. However, it is obvious that advertisement is a critical factor to make such a program successful. As indicated above we will follow several routes to advertise. Additionally, we have initiated talks with Copernicus Science Center in Warsaw (contact: Weronika Sliwa,**weronika.sliwa@kopernik.org.pl**) to advertise our program to a broader audience that the Center attracts. This avenue to CPU resources is relatively inexpensive (advertisement costs, website maintenance and broad-band fast network connection) but can offer a great deal of computational power. As a front side seen by public we will run images of X-ray (*Chandra*), gamma-ray (*Swift*) and gravitational-radiation (predicted only at the moment) sky backed-up by popular stories that connect our science goals with the particular calculations performed by the program participants. We hope not only to attract people to participate in our simulations but to make them understand, appreciate and entertain the ideas behind our science project.

6. APPOINTING A NEW SCIENTIFIC TEAM

1) Ashley Ruiter, Ph.D. (Max Planck Institute for Astrophysics, Germany: postdoctoral fellow): supernova type Ia expert, stellar evolution of low and intermediate mass stars, white dwarf physics. Tasks: search for supernova Ia progenitors, expanding the population synthesis with new explosion models. External expertise/advise: Wolfgang Hillebrandt (MPA, Germany).

2) Michal Dominik, M.Sc. (Warsaw Observatory: graduate 3rd year student): expected to be Ph.D. by the time of funding. Gravitational radiation source expert. Tasks: studies of BH-BH, BH-NS, NS-NS binaries and adding rotation to population synthesis model. Science and technical Support of `Synthetic Universe` website. External expertise/advise: Ilya Mandel (University of Birmingham, England)

3) Grzegorz Wiktorowicz, Ms.C. (Warsaw Observatory: graduate 3rd year student): expected to be Ph.D. During first year of funding. X-ray modeling and studies of the formation of High- and Low-mass X-ray binaries. Tasks: Search for ULX stellar sources. Implementation of new ULX physics into the population synthesis code. Science and technical support of `Universe@home`. External expertise/advise: Chris Fryer (Los Alamos National Laboratory, USA).

4) Paulina Karczmarek, Ms.C. (Warsaw Observatory: graduate 1st year student): expected to obtain Ph.D. at the end of the funding period. Currently working with the `MESA` code. Tasks: generating stellar models with rotation and `StarTrack` calibration for low- and intermediate-mass stars. P.Karczmarek will work closely with A.Ruiter and M.Dominik. External expertise/advise: Grzegorz Pietrzynski (Warsaw University, Poland)

5) Marek Walczak (Warsaw Observatory: last year undergraduate student): expected to be Ph.D. student during entire period of funding. Currently working on intermediate-mass black holes. Tasks: study of intermediate-mass BHs as potential sources for LIGO/VIRGO and as alternative explanation to the origin of ULXs. M.Walczak will work closely with M.Dominik and G.Wiktorowicz. External expertise/advise: Cole Miller (University of Maryland, USA)

6) Krzysztof Belczynski, Ph.D. (Warsaw Observatory): primary investigator for this proposal. Expertise in population synthesis, double compact objects, X-ray binaries, gamma-ray burst and supernova progenitors. Tasks: lead of the above group and coordination of the entire project. Also population synthesis code (input physics) development. Lead and development of `Synthetic Universe` website and `Universe@home` program.

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