How Did We Get Here? Retracing the Lives of Binary Stars with POSYDON

A collection of work regarding the channels of binary star evolution

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Abstract

This poster serves as an introduction to **POSYDON** (**PO**pulation **SY**nthesis with **D**etailed binary-evolution simulati**ON**s), a binary population synthesis tool [1][2]. Additionally, it is a collection of finished and work-in-progress projects which utilize POSYDON as the backbone of the research process.

Previous Work

This previous work was completed during the fall 2025 semester at the College of DuPage as a part of an honors independent study. It served as a general introduction to POSYDON, its general data structure, and the various processes driving binary evolution. To prevent the scope of the project from becoming too constrained, I broke it down into simplified 'states' of binary evolution, which I defined to be detached, semi-detached, and contact systems, then comparing simulated populations with the 'poster children' of said stage. These reference stars included Vela X-1, V404 Cygni, and W Ursae Majoris respectively. From this comparison I found that these systems are largely outsiders in their respective stages, and furthermore present evidence that V404 Cygni must have evolved as a tertiary system with all three stars playing critical roles in the evolution.

Current Work

It is known that the progenitors of stellar mass BHs are high mass stars, with many of these stars being in binaries with solar-type stars. However, there is a large amount of uncertainty when it comes to formation and survival rate of these systems. As seen in [3], the 'quiet' nature of these systems makes visual detection and observation difficult. Currently, I am hoping to find a formation rate and common evolutionary channel of low P_{orb} black hole sun-like star (henceforth 'BH-Sol') binary systems via population synthesis with POSYDON.

Introduction

Why Does Binary Star Evolution Matter?

Binary star evolution is a complicated and nuanced field of investigation that is deeply critical to our understanding of the universe. Binaries are critical for our understanding of cosmology due to Type Ia SN and BH mergers driving our understanding of general relativity. Furthermore, these binary systems make up the majority of the stars in our galaxy, with an estimated 60%-80% of all massive stars in our MW being in a binary. While a large portion of those will evolve with a wide enough separation to evolve independently, there is a sizable fraction which do interact. Due to the already moderately complicated process of single star evolution, the possibility for binary evolution in interacting systems is extremely large and nuanced (see fig 1). This process poses a great problem when it comes to accurately modeling these systems from formation to end, something that POSYDON hopes to mitigate.

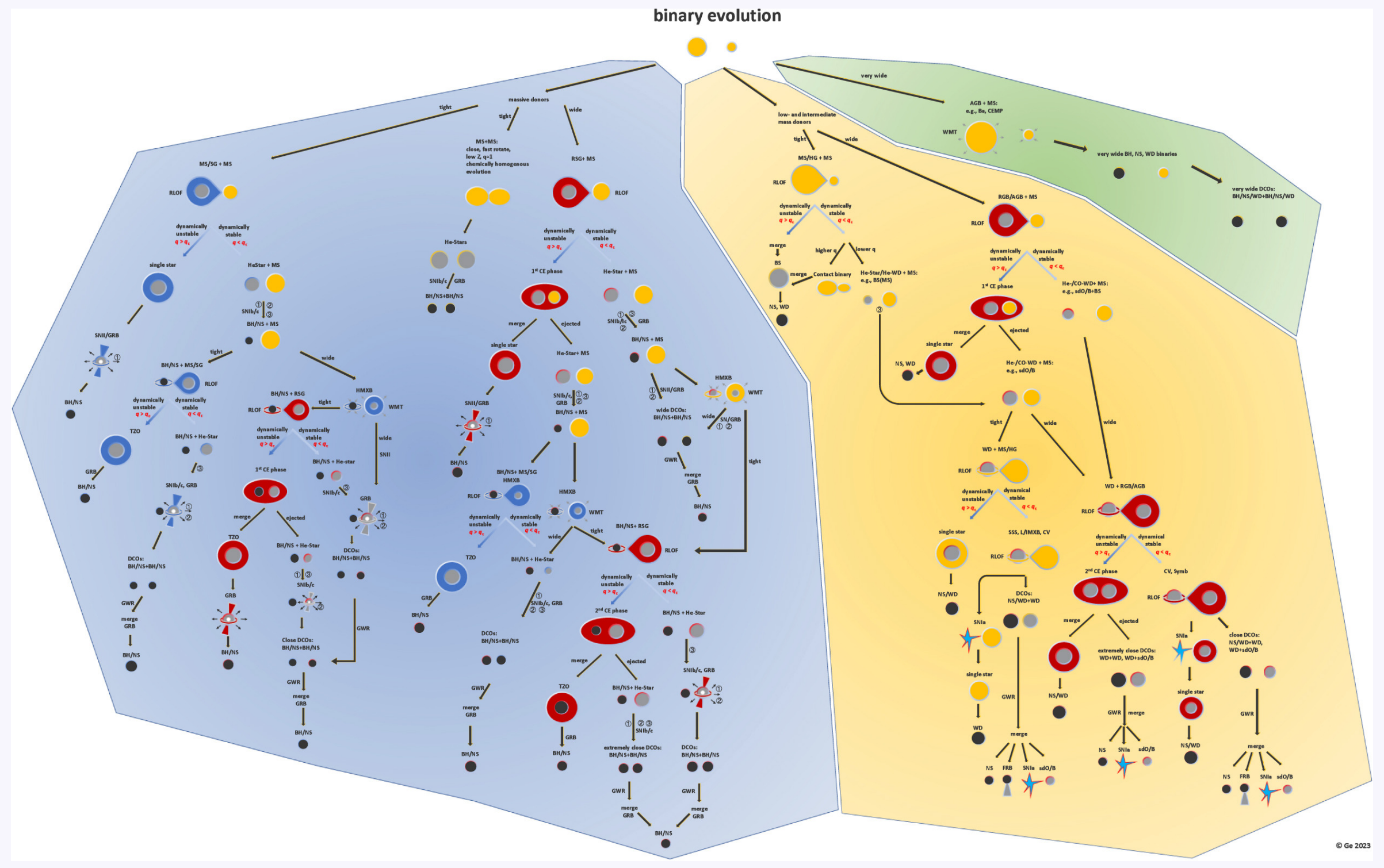

Figure 1: Detailed flowchart of binary star evolution. Reprint from [4].

What is POSYDON?

POSYDON is an open-source tool for simulation, interpretation, and analysis of binary system populations. POSYDON first takes a user-configurable population of initial zero-age main sequence (ZAMS) systems and evolves them through a series of MESA grids and solvers, recording their properties at the start and end of each stage. By taking this approach, it allows for systems with vast, complicated evolutionary paths to be evolved from start to end in a computationally efficient manner. POSYDON provides the framework to do this process in a high-performance computing environment, allowing massive and rapid analysis [2]. (See table 1 for an example of data structure.) In practical use, this allows for much broader and more accurate inquiry.

Binary ID	System State	Orbital Period (days)	$\log_{10}$ Mass Transfer Rate	Donor State	Donor Mass $M_\odot$	Accretor State	Accretor Mass $M_\odot$
54	Detached	0.047520	−99.000	NS	1.196033	stripped He Core He burning	≈ 1.002
183	Detached	0.0429883	≈ −80.8	NS	1.196033	stripped He Core He burning	≈ 0.9957

Table 1: Example of POSYDON data, heavily modified for readability

Previous Work

The goal with this piece of work was to compare how the properties of well-known observed systems differed from the 'true' distributions within their respective populations.

My process for analyzing these systems consisted of first finding said 'poster children' for the systems, and then comparing said systems to their simulated population counterparts. To select my reference systems, I mainly relied on historical literature, picking the systems that helped drive the research forward in their respective categories. From this initial process I settled on Vela X-1, V404 Cygni, and W Ursae Majoris.

For my reference population it was essential to get an accurate distribution of binary systems. In order to do this, I sourced an evolved $1Z_\odot$ POSYDON grid of a million systems where all the systems were initially ZAMS binaries with MW-based mass ratio, eccentricity, and period distributions. This allowed for a dataset which contained binaries in all stages of evolution, at a wide range of masses, allowing for more detailed analysis.

Current Work

As outlined in [3], the formation rate and evolutionary channels of BH-Sol binaries are useful for deeper understanding of XrBs. However, these systems pose great difficulty when trying to use observational methods. This is because, in contrast to XrBs, they are 'quiet,' with the only sign of a BH companion being in slight variations to the sun-like stars' spectra. Due to this, [3] is only able to put an upper limit via non-detection of the formation rate of these systems at 1 in 10^5.

Because of the difficulty of visual observation, I hope to take a largely different approach, instead utilizing POSYDON. This methodology will (ideally) allow proposing an expected formation (and possibly detection rate) of BH-Sol systems, as well as an investigation of the evolutionary channels of BH-Sol systems.

Even when investigating a very specific type of system, it is best practice to start with as generalized of a grid as possible. In this case, I started with a grid which utilized initial mass distributions from [5], with the initial masses being constrained to $4 < M_{1,\odot} < 150$, $0.1 < M_{2,\odot} < 150$. This 'wide net' approach is crucial, as the evolutionary channels can be very diverse, with many 'paths' leading to the same 'destination.'

Methods

Previous Work

My general workflow for analysis relied on a custom-written HR Diagram script, which allowed easy graphing of the donor star within the evolved population. Furthermore, this script utilized the Python package Bokeh, which allowed for interactive HTML plots, allowing for more efficient analysis. A simple use example can be found at `https://piersonlip.github.io/Posydon_HR_Graphing_Script/` This script was then applied to each observed system (see fig 2, 3, 5).

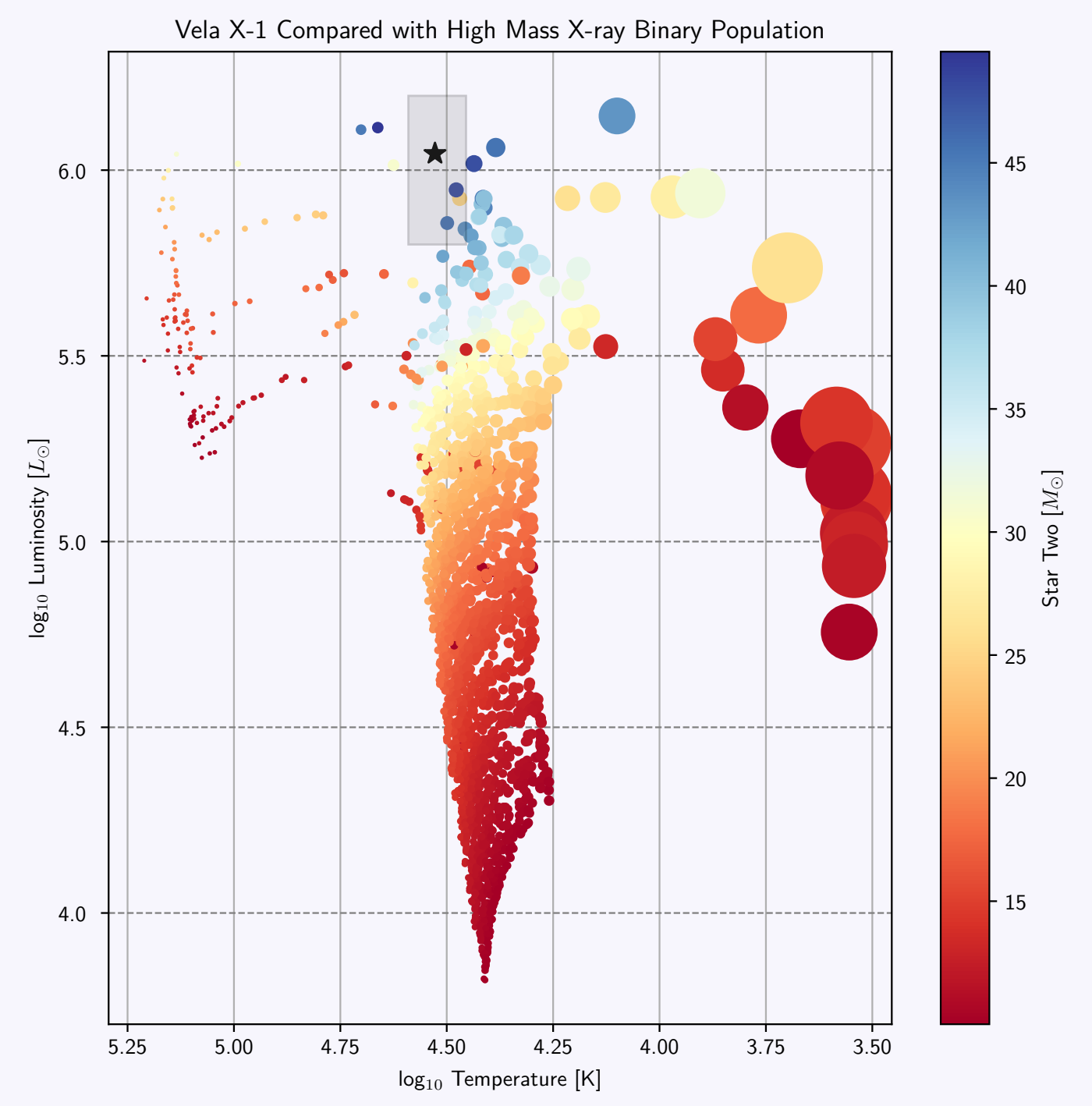

Figure 2: Vela X-1's observed temperature and luminosity in comparison to similar detached HMXBs. Note that the 'black box' is a representation of the error range

From this process it quickly became clear that both Vela X-1 and W UMa were extremes in their respective populations. This is predictable, as the more extreme nature is directly correlated to ease of observation.

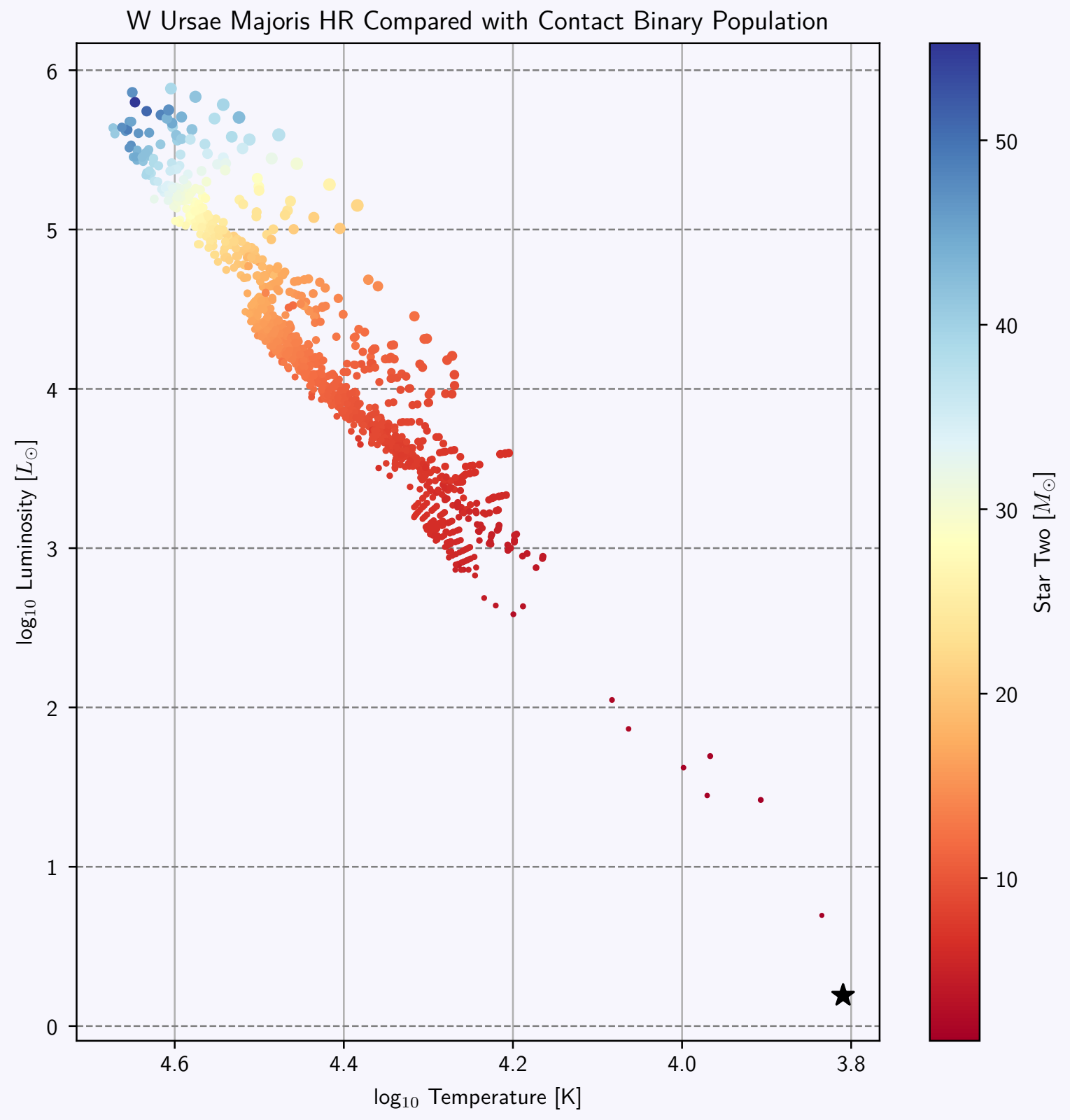

Figure 3: W Ursae Majoris observed temperature and luminosity in comparison to evolved contact binaries.

However, it quickly became clear that V404 Cygni was more than just an extreme case, it was radically different from the evolved population. This is discussed further in results.

Current Work

After evolving the initial grid I found a dominant channel of evolution in BH-Sol systems emerged, this being `ZAMS_oCE1_CC1_oRLO2_CC2`. Via inspection of the evolution history, it became evident that the systems evolve detached, then into post-MS unstable RLO via S1 → S2. This period decrease leads to common envelope, which then *greatly* decreases the orbital period. The envelope is then ejected, leaving a depleted stripped He core. The core then collapses in a couple of thousand years, leaving the system in a BH-Sol state with low p_{orb}/separation. Furthermore, I found that the systems were quite constrained with their initial properties (see table 2).

	orbital_period_i
count	6.000000
mean	4022.716197
std	151.522384
min	3873.118288
25%	3908.300983
50%	3978.305326
75%	4124.397101
max	4248.507680

	S1_mass_i
count	6.000000
mean	17.515761
std	0.520269
min	16.815111
25%	17.190036
50%	17.510176
75%	17.818155
max	18.254965

	S2_mass_i
count	6.000000
mean	2.296788
std	0.320702
min	1.797809
25%	2.120753
50%	2.353828
75%	2.547210
max	2.620529

Table 2: Distributions of initial conditions in BH-Sol progenitors in Grid 1.

After the discovery of this channel in the initial population, I decided to focus on trying to understand it more in depth. From this I moderately constrained the initial grids to the distribution of previously evolved BH-Sol systems. This allowed for a much greater quantity of BH-Sol systems to be evolved, allowing for further analysis. Previous work from [3] placed an upper limit on the orbital period of these systems when filtering, however, when investigating the population, it became clear that the period of the systems was dependent on the stage of CE evolution, with little distinction between systems with $P_{orb} < 300$d. As a side effect of the evolutionary channel of BH-Sol systems it has become key to understand the survivability of the CE stage, which can start to be seen in fig 4.

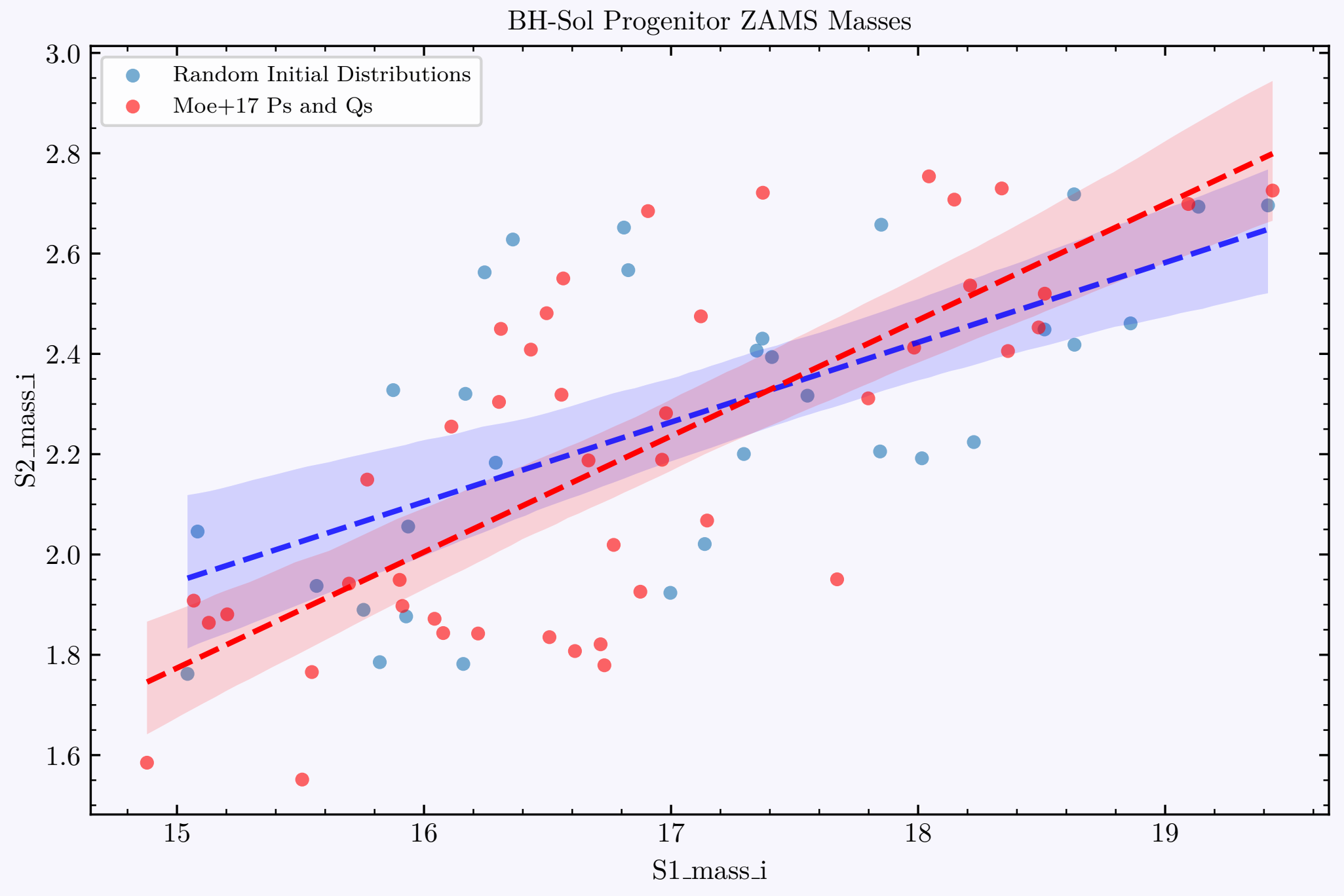

Figure 4: Plot of the initial properties in BH-Sol progenitors. Includes a grid using a mass distribution from [5] and a sampled distribution.

As of now, 5 more grids have been simulated with various initial properties and metallicities. These grids are all still in the process of investigation.

Previous Results and Current Questions

Previous Work

With W UMa and Vela X-1 the results, while on the more extreme side, were expected, however, with V404 Cygni the results seemed to hint at a much larger phenomenon. After consulting literature, it became clear that recent papers (namely [6]) had discovered that V404 Cygni was in fact *not* a binary system, instead being a tertiary system, with a third star orbiting around the giant and BH's COM. The property comparison between V404 Cygni and the simulated population greatly supports the work proposed in [6], where they suggest the tertiary star played a key role in the evolution of the central binary.

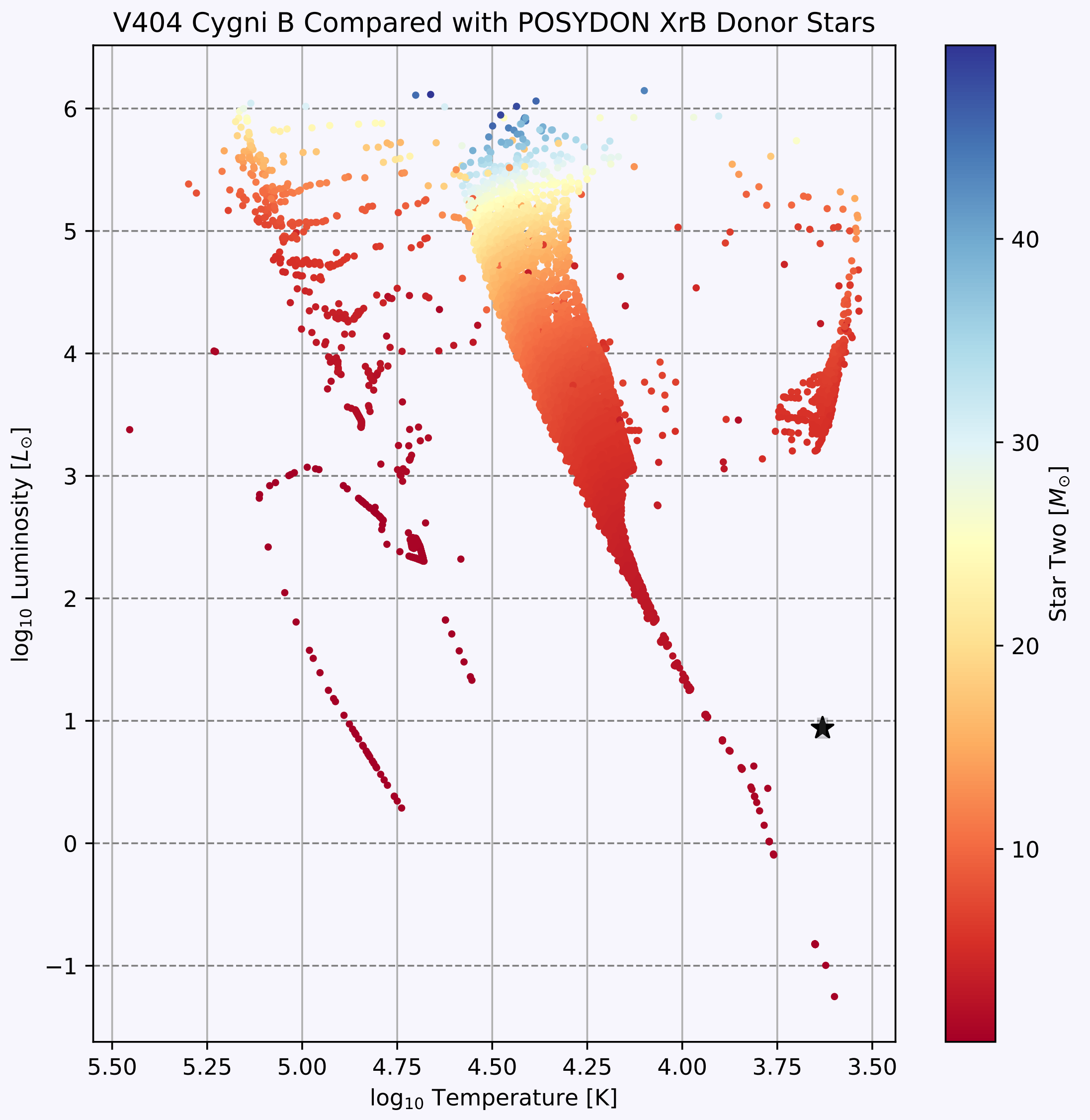

Figure 5: V404 Cygni plotted against evolved XrB binaries.

Next Steps and Current Questions

With my current work, there are a number of current goals and open questions, a large majority of which revolve around CE evolution. Currently, I hope to investigate the CE evolution channel of BH-Sol formation through various metallicity channels, and once that is adequately mapped, move on to analyzing the channels present at lower metallicities.

Discussion

All LaTeX and code for this poster, as well as various reports and papers, can be found at `https://github.com/PiersonLip/`.

While the previous work comparing observed binaries to POSYDON evolved populations did little in terms of actual 'depth,' it was nevertheless a fascinating introduction to the research experience, and figuring out what was happening with V404 Cygni was a really awesome experience.

Acknowledgments

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