Understanding Black Hole Formation in Cygnus X-1

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Background and Purpose

Cygnus X-1 is a luminous X-ray binary, hosting a 14.81 ± 0.98 $M_\odot$ black hole (BH) and a 19.16 ± 1.90 $M_\odot$ O supergiant star in a Keplerian orbit of 5.6 days (Orosz 2011). This system is a persistent X-ray source that emits in two states: low-hard or high-soft state. Although the supergiant is close to filling its Roche-lobe, the observed X-ray emission comes from the partial accretion of the supergiant's stellar wind onto the BH. The purpose of this study is to estimate the mass of the BH immediate progenitor and the magnitude of a possible natal kick imparted to the BH.

Formation scenario of Cygnus X-1

We adopt the simplest formation scenario that can explain all the observations.

- assume both stars, the BH progenitor and the O supergiant were born at the same time
- assume there was no mass transfer at all in the history of Cygnus X-1.
  (This means we can model the O supergiant as a single isolated star.)
- the BH immediate progenitor is a He star.
- during the core-collapse event, the binary orbit was altered by mass loss from the system and the possible natal kick imparted to the BH.
- the BH has accreted negligible amount of mass since its birth.

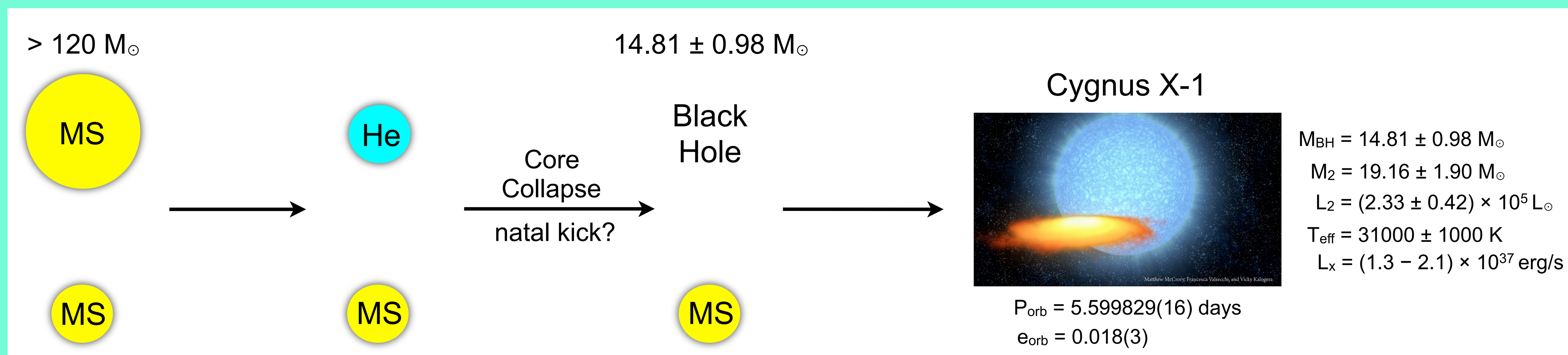

Fig 1. The adopted formation scenario of Cygnus X-1. The notation MS and He stands for main sequence star and helium star, respectively.

Methodology

Step 1: create stellar models that matched all the observed BH companion's properties

- used a modified stellar evolution code, which was originally developed by Paxton (2004)
- computed the X-ray luminosity by Bondi-Hoyle accretion model
- found the companion was a 20 to 23 $M_\odot$ star at zero-age main sequence (ZAMS)
- estimated the BH was born 4.8 to 7.6 million years ago

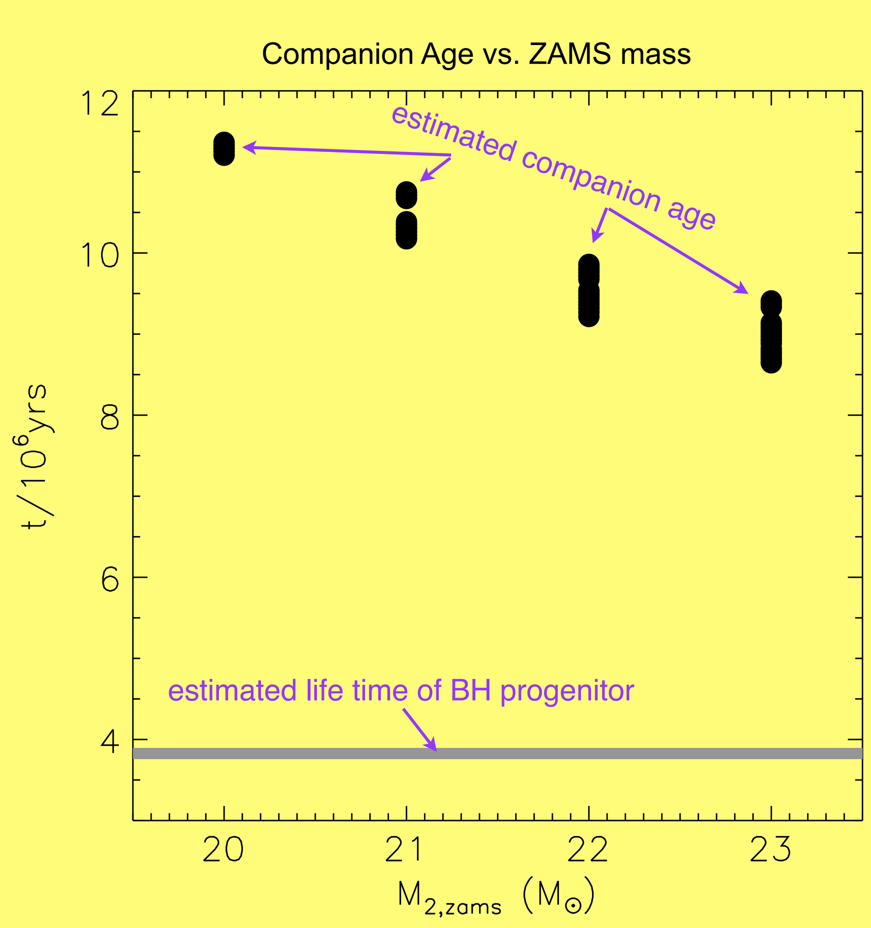

Fig 2. Variations of the estimate companion age against ZAMS mass.

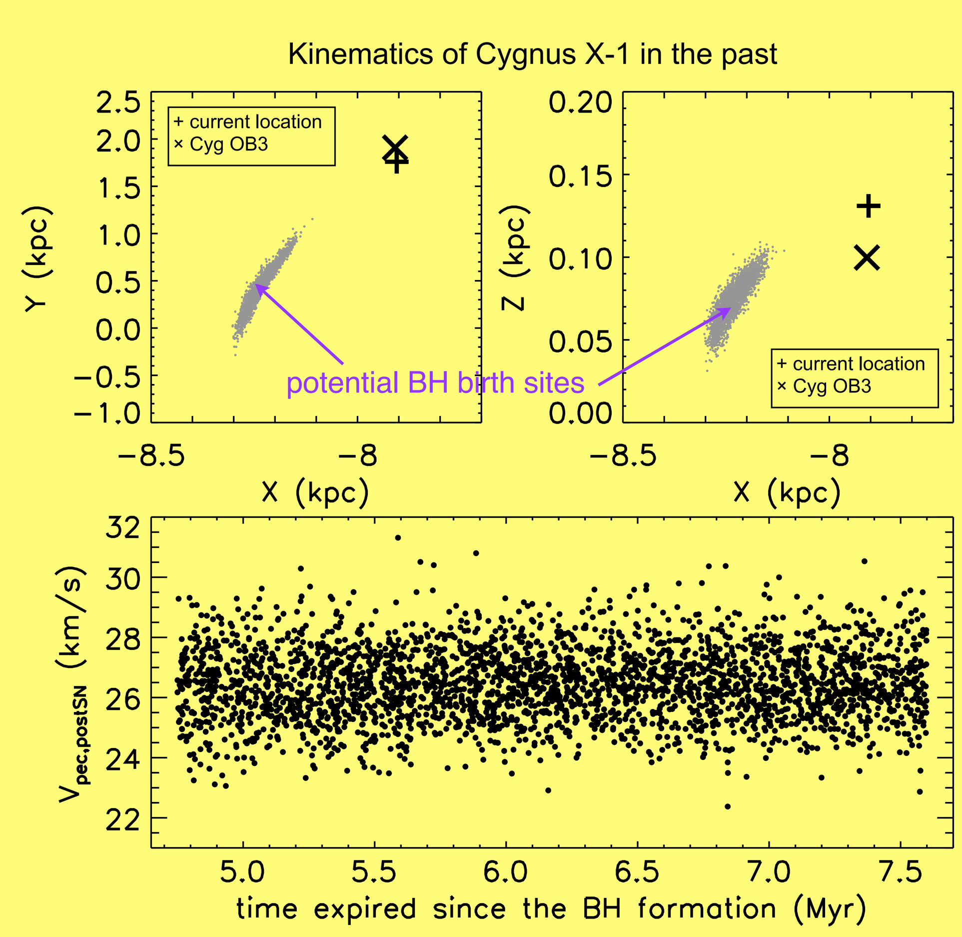

Fig 3. Upper panels: potential birth sites of the BH. Lower panel: the distribution of systemic peculiar velocities against the time expired since the BH formation.

Step 2: find the systemic peculiar velocity (V_{pec_postSN}) right after the BH's formation

- traced the motion of Cygnus X-1 in a galactic potential backwards in time
- derived V_{pec_postSN} = 22 to 32 km/s

Step 3: constrain the binary properties right before the core-collapse event via Monte Carlo simulations

- important free parameters: BH immediate progenitor mass (M_{He}), orbital semi-major axis (A_{preSN}) & eccentricity (e_{preSN}), and natal kick magnitude (V_{kick})
- properties of the companion star was given by stellar models created in Step 1.
- conservation of orbital energy and angular momentum gave the binary parameters right after the core-collapse event
- applied the V_{pec_postSN} = 22 to 32 km/s constraint derived in Step 2
- evolved the binary orbit forward in time to the current epoch
- if the orbital period and eccentricity matched the measured values, we used that data to construct probability distribution functions (PDFs)

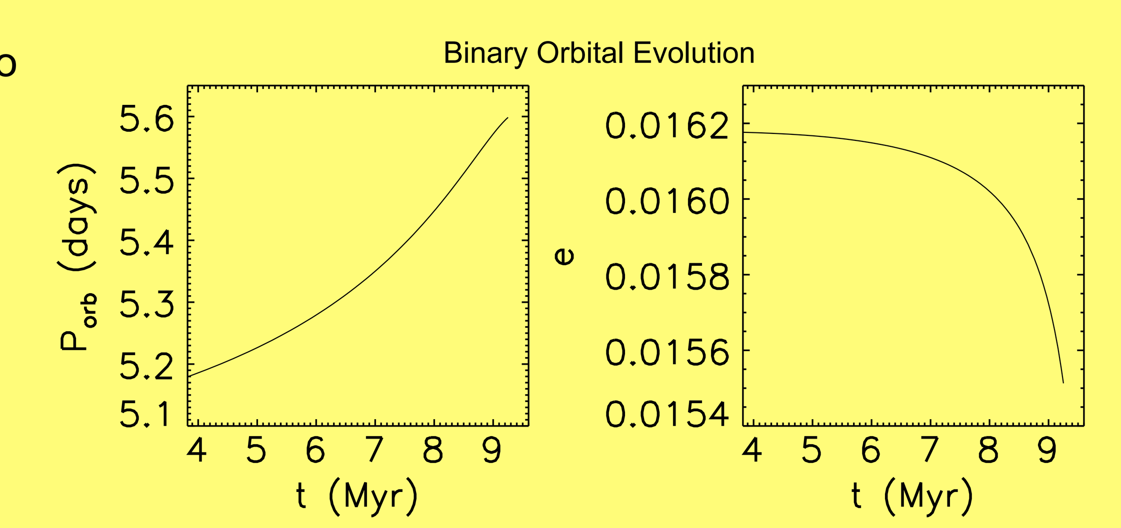

Fig 4. One possible past evolution of Cygnus X-1's orbit. Right after the core-collapse event at t = 3.8 Myr, this binary system consists of a 14.8 $M_\odot$ BH and a 21.7 $M_\odot$ main-sequence companion.

Results and Discussion

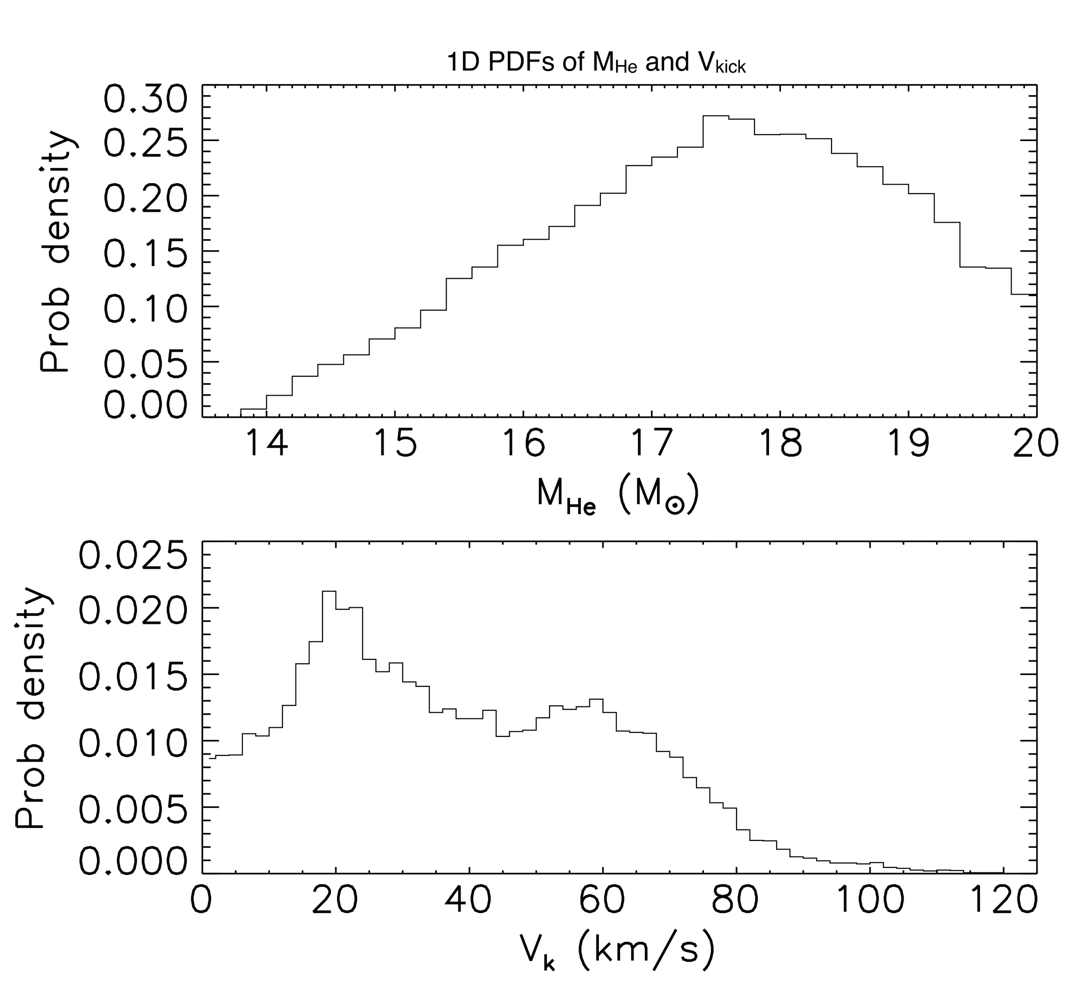

Fig 5. The probability distribution functions of M_{He} and V_{kick}.

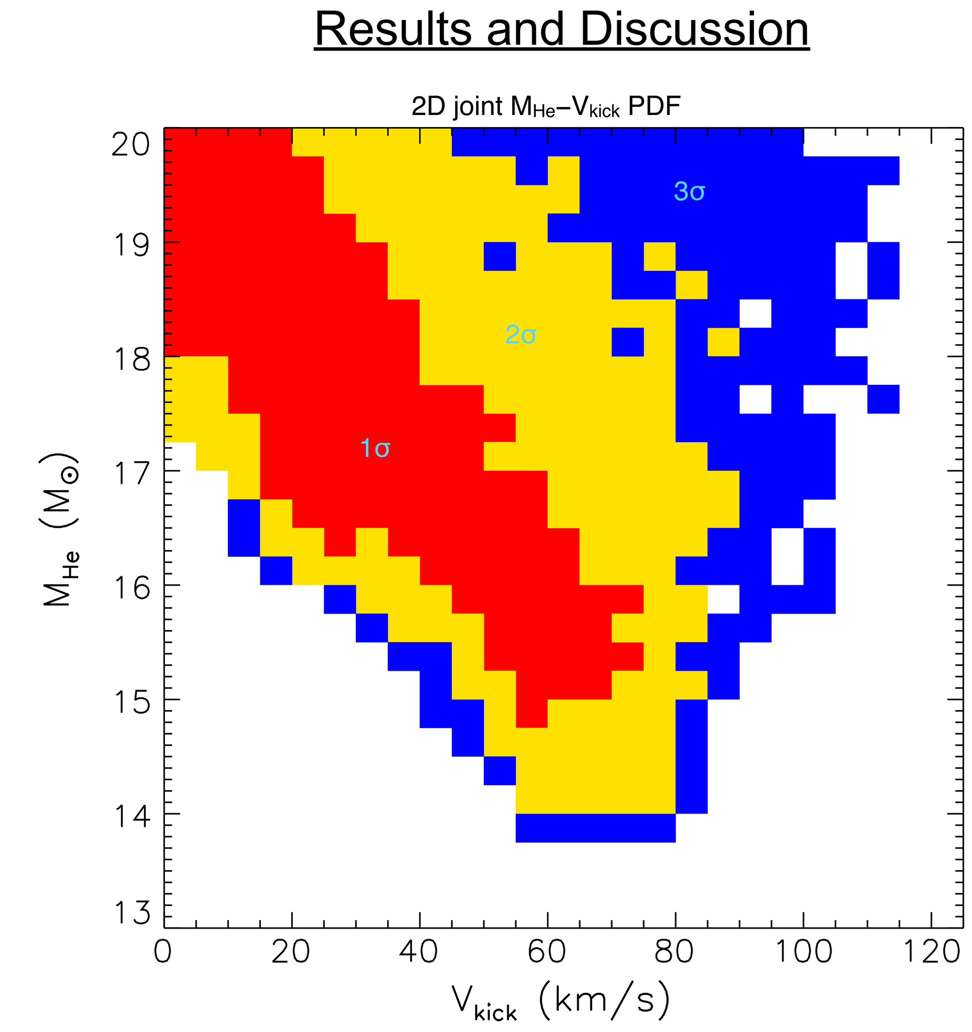

Fig 6. The two dimension joint M_{He}–V_{kick} probability distribution function.

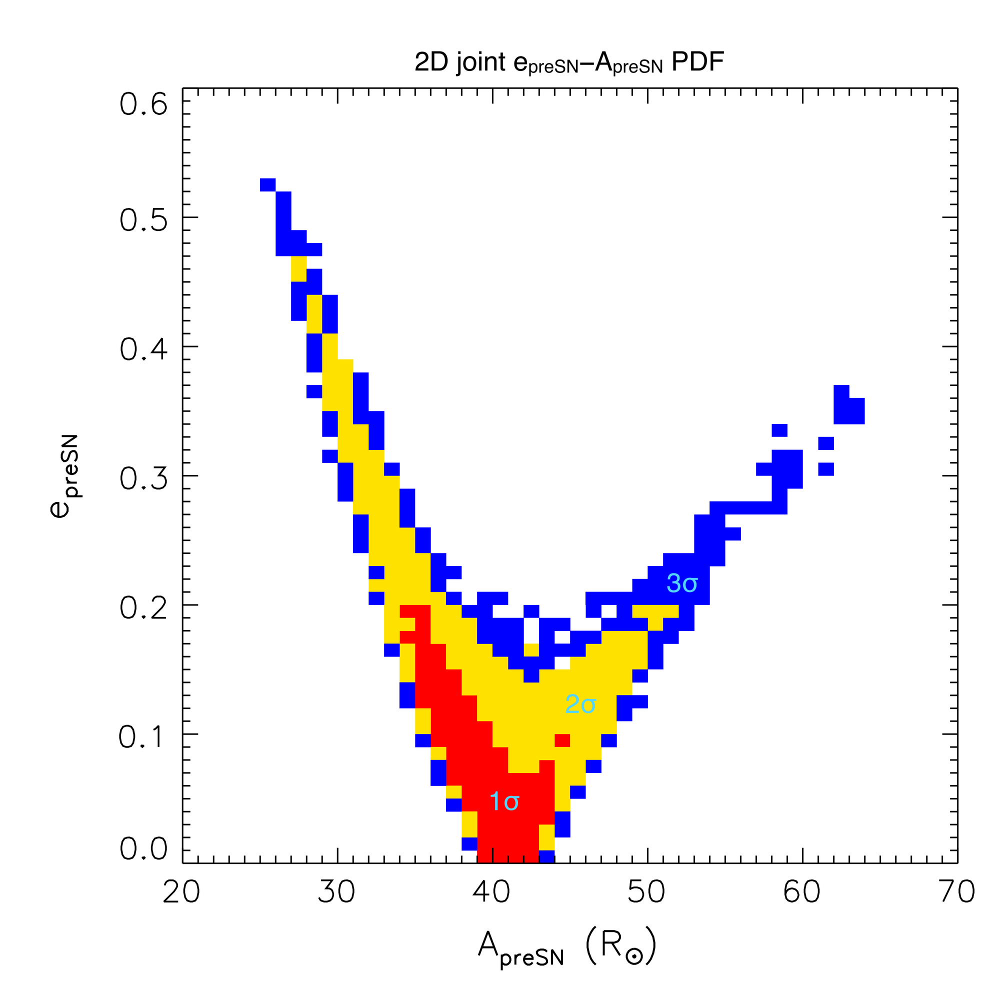

Fig 7. The two dimension joint e_{preSN}–A_{preSN} probability distribution function.

We found that the BH immediate progenitor mass (M_{He}) is between 15 to 20 $M_\odot$, and the natal kick magnitude (V_{kick}) imparted to the BH is ≤ 77 km/s, both at 95% confidence. As shown in the two dimensional joint V_{kick}–M_{He} probability distribution function (see Fig. 6), the BH might probably have received a non zero natal kick at the core collapse event, if M_{He} is < 17 $M_\odot$. For small M_{He}, a minimum V_{kick} of ~55 km/s is necessary to explain all the observed properties of Cygnus X-1. For a more detail presentation of this work, see Wong et al. (2012).

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