Black Hole Formation and Natal Kicks

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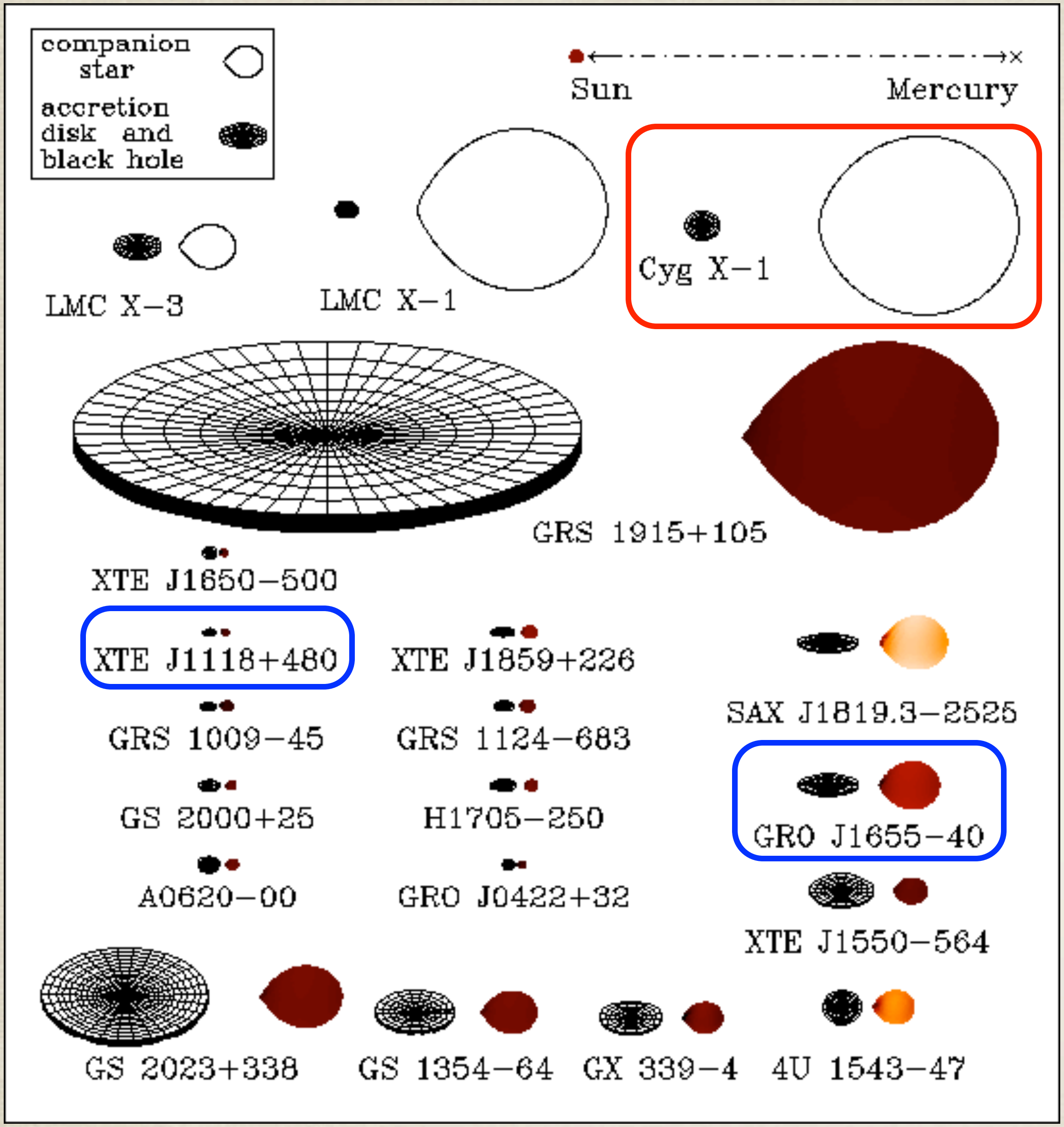
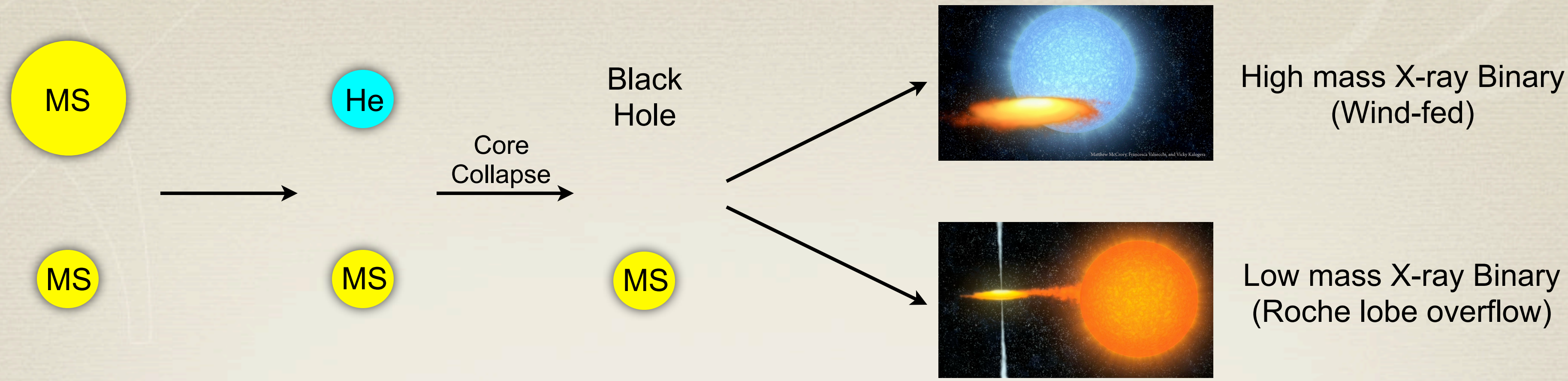


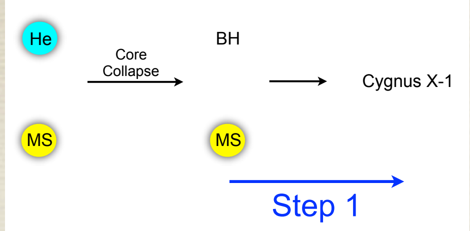
(from Jerome Orosz)

- Find the mass relationship between stellar mass black holes (BH) and their immediate progenitors
- Determine the possible natal kicks magnitude imparted to the black hole
- Shed light on the core collapse mechanism



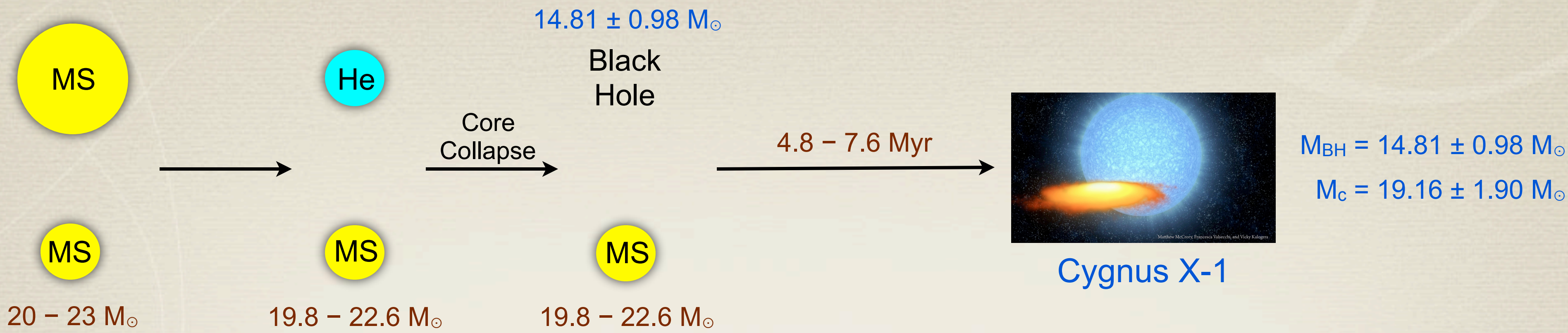
1. uncover the mass transfer history
2. find the systemic peculiar velocity right after the core collapse event
3. derive constraints on the BH immediate progenitor mass and the possible natal kick magnitude

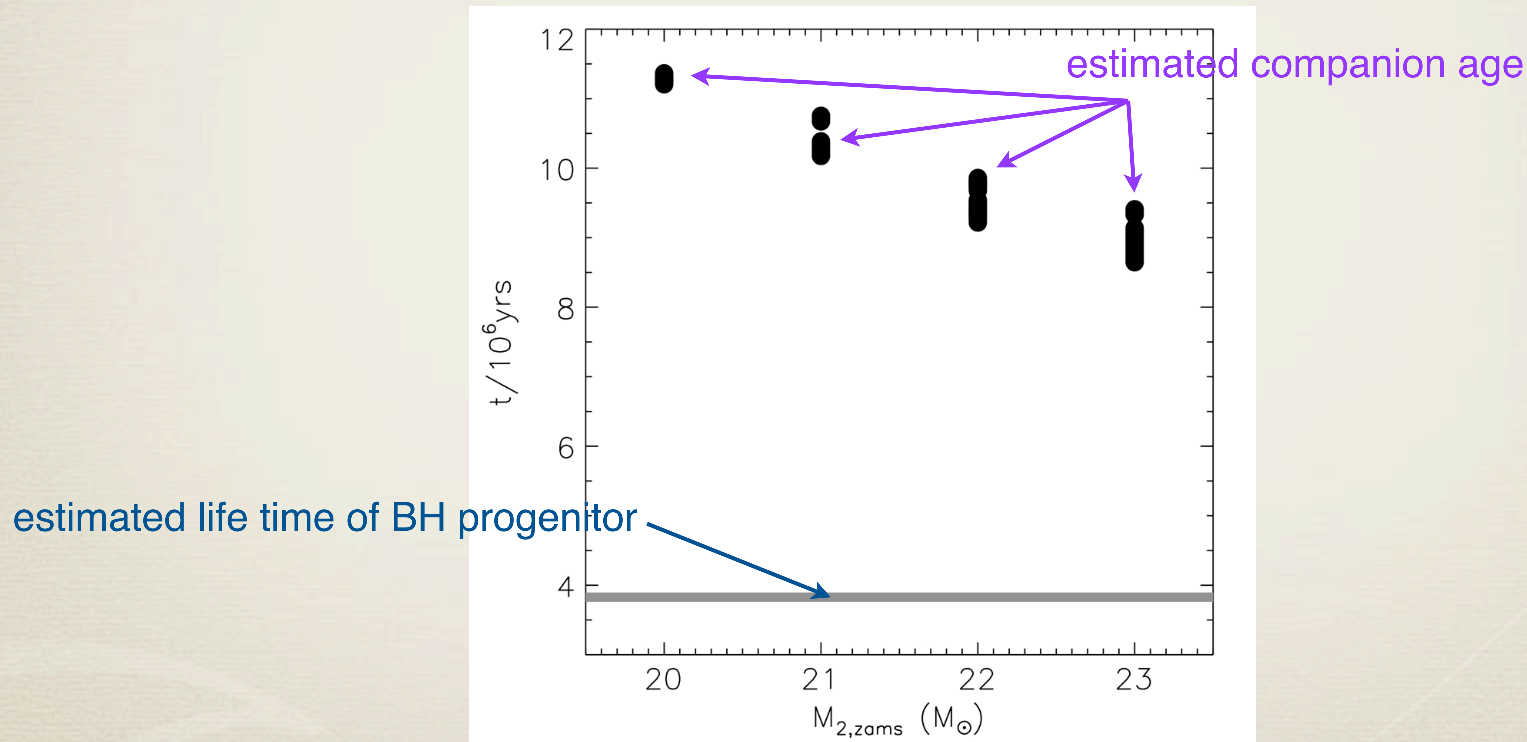
Step 1:
Model current observed properties



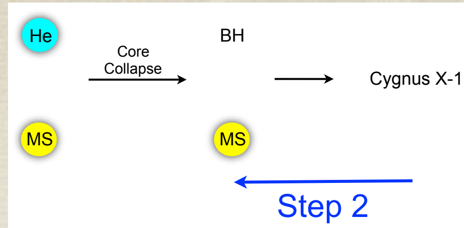
- evolve the companion as an isolated star
- modified version of stellar evolution code EZ (originally developed by Paxton 2004)

Parameter	Value	Reference
Inclination angle (deg)	27.06 ± 0.76	Orosz et al. (2011)
Black hole mass ($M_\odot$)	14.81 ± 0.98	Orosz et al. (2011)
Black hole spin	> 0.95	Gou et al. (2011)
Companion mass ($M_\odot$)	19.16 ± 1.90	Orosz et al. (2011)
Companion radius ($R_\odot$)	16.50 ± 0.84	Orosz et al. (2011)
Companion luminosity (10^5 $L_\odot$)	2.33 ± 0.42	Orosz et al. (2011)
Companion T_{eff} (K)	31000 ± 1000 K	Orosz et al. (2011)
X-ray luminosity (10^{37} erg/s)	$(1.3–2.1)(\frac{d}{1.86\,\mathrm{kpc}})^2$	Frontera et al. (2001), McConnell et al. (2002), Cadolle Bel et al. (2006)


MS
MS
20 – 23 $M_\odot$
He
MS
19.8 – 22.6 $M_\odot$
Core Collapse
14.81 ± 0.98 $M_\odot$
Black Hole
MS
19.8 – 22.6 $M_\odot$
4.8 – 7.6 Myr
Cygnus X-1
M_{BH} = 14.81 ± 0.98 $M_\odot$
M_c = 19.16 ± 1.90 $M_\odot$

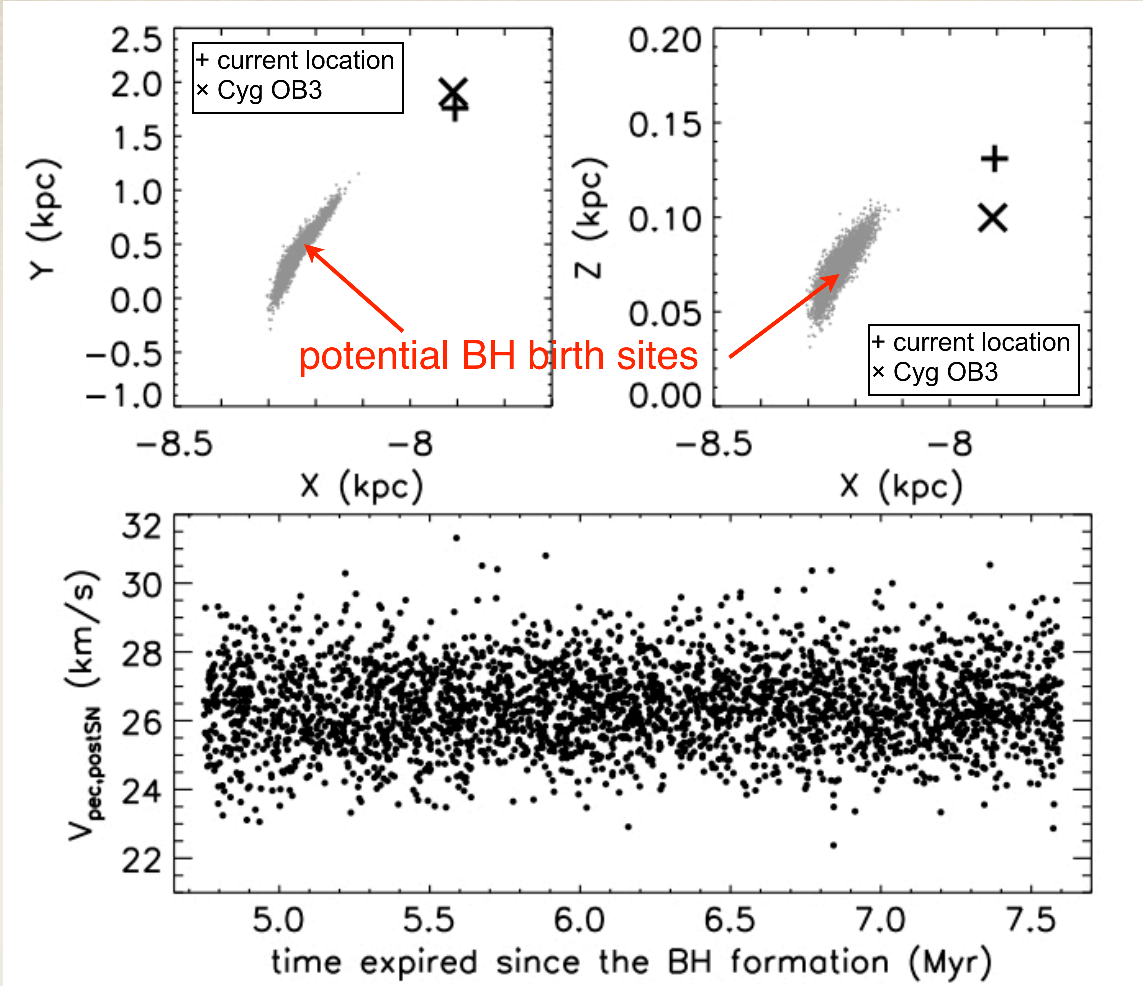

estimated companion age
estimated life time of BH progenitor
$t/10^6$yrs
12
10
8
6
4
20
21
22
23
$M_{2,zams}$ ($M_\odot$)

Step 2:
Find the peculiar velocity post BH formation



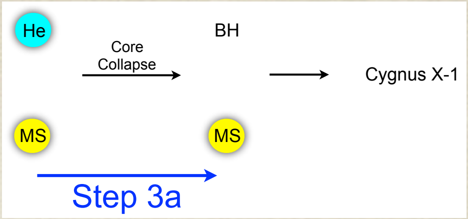
Parameter	Value	Reference
Distance (kpc)	1.86 ± 0.12	Reid et al. (2009)
Galactic longitude (deg)	71.3	Lestrade et al. (1999)
Galactic latitude (deg)	+3.1	Lestrade et al. (1999)
Proper motion in R.A. (mas/yr)	−3.78 ± 0.06	Reid et al. (2009)
Proper motion in decl. (mas/yr)	−6.40 ± 0.12	Reid et al. (2009)

- track the system's motion in a Galactic potential backwards in time
- find the peculiar velocity of the system right after the BH formation



- V_{pec} right after the BH formation = 22 to 32 km/s
- resulted from the collapse core event

Step 3:
Derive constraints on BH immediate progenitor & natal kick magnitude



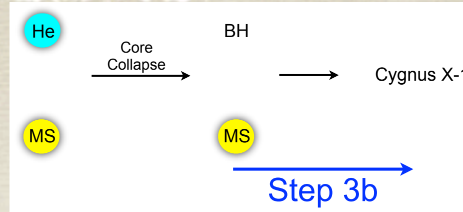
- perform Monte Carlo simulation for the He-MS (pre-SN) binary configuration
    - BH immediate progenitor mass (M_{He})
    - orbital semi-major axis (A_{preSN})
    - orbital eccentricity (e_{preSN})
    - natal kick magnitude (V_{kick})
- constraints:

  a) survival of the binary

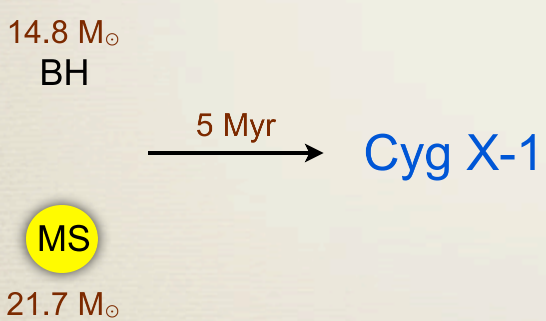
  b) conservation of orbital energy and angular momentum

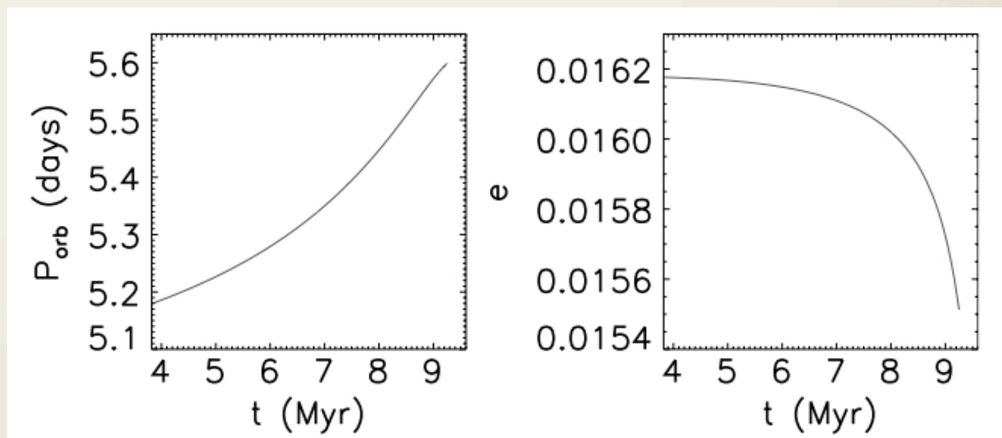
  c) peculiar velocity of the post-SN binary

  (from step 2: V_{pec} = 22 to 32 km/s)



- observed period = 5.599829(16) days
  (Brocksopp et al. 1999)
- observed eccentricity = 0.018(3) (Orosz et al. 2011)
- orbital evolution accounts for:
  1) mass transfer (wind-fed)
  2) tides
  3) gravitation radiation
  4) wind mass loss





Result

15.0 – 20.0 $M_\odot$

He

MS

19.8 – 22.6 $M_\odot$

Core Collapse

$V_{kick} \lesssim 77$ km/s

14.81 ± 0.98 $M_\odot$

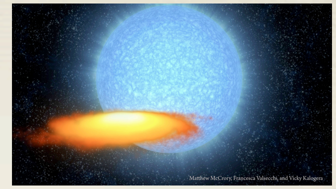
Black Hole

V_{pec} = 27 ± 5 km/s

MS

19.8 – 22.6 $M_\odot$

4.8 – 7.6 Myr

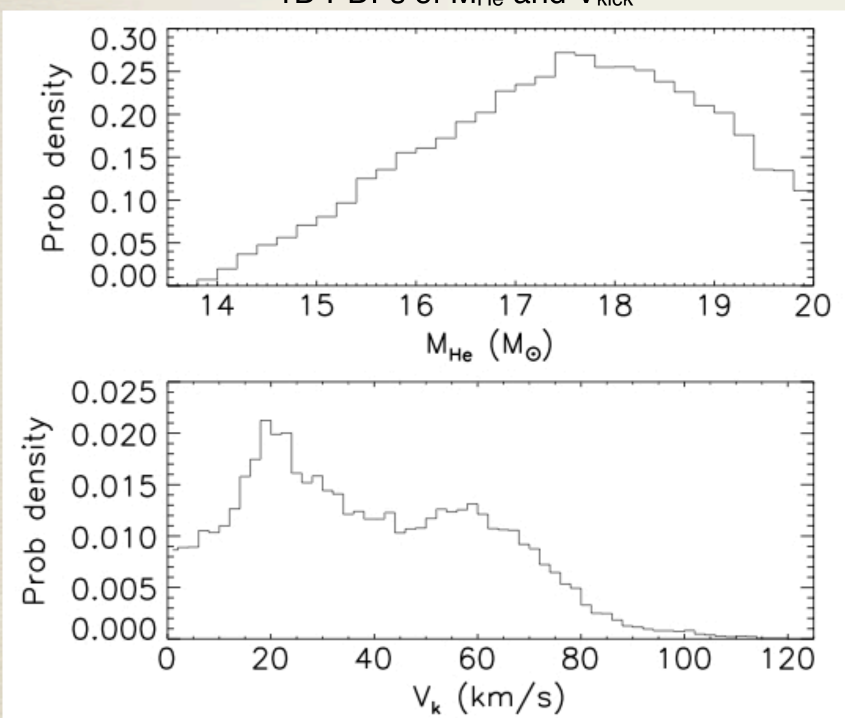


Cygnus X-1

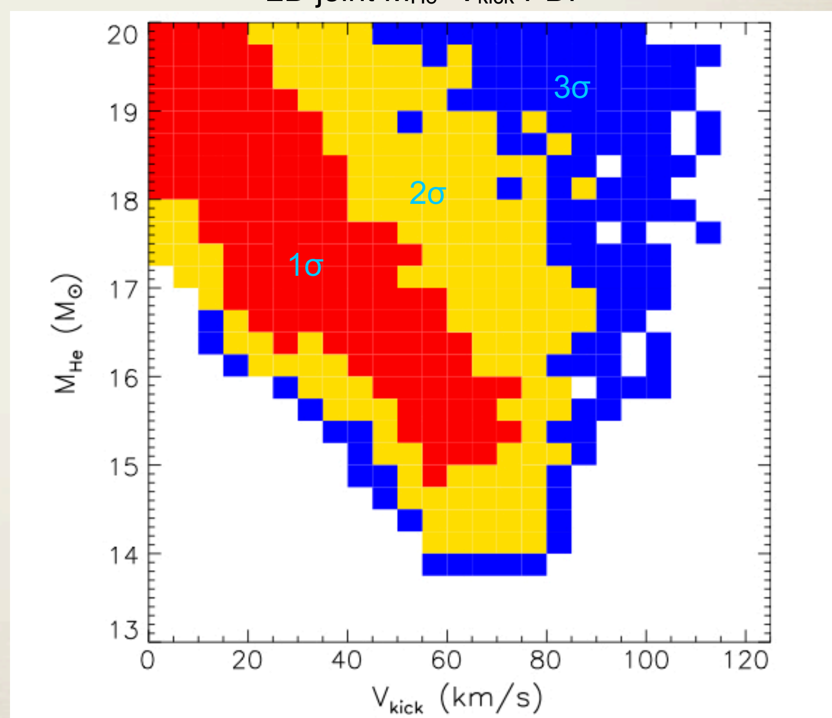
M_{BH} = 14.81 ± 0.98 $M_\odot$

M_c = 19.16 ± 1.90 $M_\odot$

1D PDFs of M_{He} and V_{kick}



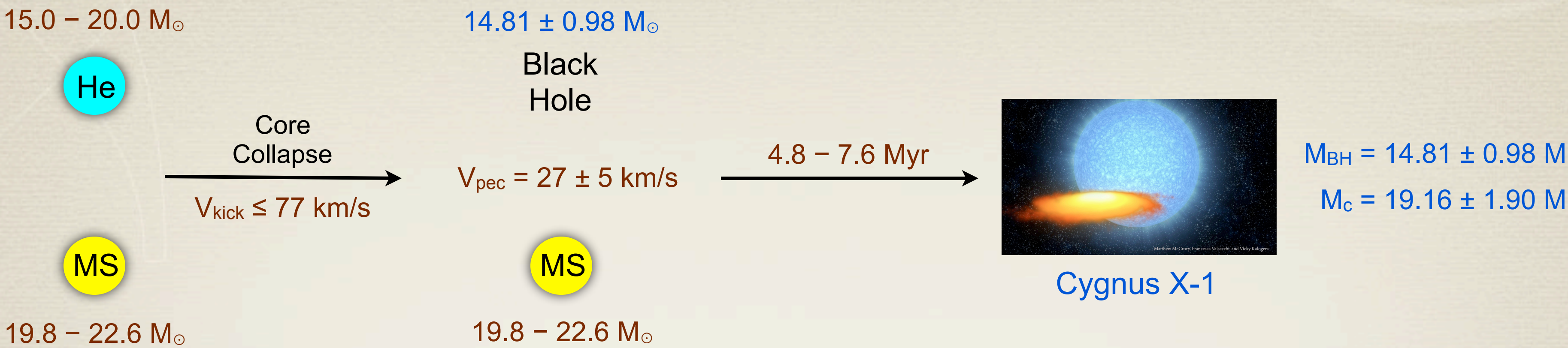
2D joint M_{He}–V_{kick} PDF



Results

System	Observed Current BH mass ($M_\odot$)	Post-SN BH mass ($M_\odot$)	Immediate Progenitor mass ($M_\odot$)	Natal Kick (km/s)
GRO J1655-40 (early-type, P>1d)	6.3 ± 0.5 (Greene et al. 2001) 5.4 ± 0.3 (Beer & Podsiadlowski 2002)	5.5 – 6.3 (Willems et al. 2005) 3.5 – 5.4 (Willems et al. 2005)	5.5 – 11.0 (Willems et al. 2005) 3.5 – 9.0 (Willems et al. 2005)	30 – 160 (Willems et al. 2005) ≤ 210 (Willems et al. 2005)
XTE J1118+480 (late-type, P<1d)	8.0 ± 2.0 (McClintock et al. 2001, Wagner et al. 2001, Gelino et al. 2006)	6.0 – 10.0 (Fragos et al. 2009)	6.5 – 20.0 (Fragos et al. 2009)	80 – 310 (Fragos et al. 2009)
Cygnus X-1 (wind-fed, high mass)	14.81 ± 0.98 (Orosz et al. 2011)	13.8 – 15.8 (Wong et al. 2012)	15.0 – 20.0 (Wong et al. 2012)	≤ 77 (Wong et al. 2012)
M33 X-7 (wind-fed, high mass)	13.5 – 20.0 (Orosz et al. 2007, Valsecchi et al.2010)	13.5 – 14.5 (Valsecchi et al.2010)	15.0 – 16.1 (Valsecchi et al.2010)	10 – 850 (Valsecchi et al.2010)

Conclusion



- Cygnus X-1: M_{He} = 15 - 20 $M_\odot$; $V_{kick} \leq$ 77 km/s (95% CL)

- together with previous studies on GRO J1655-40, XTE J1118+480, M33 X-7, it seems that:
  massive black holes → smaller natal kicks
  low mass black holes → larger natal kicks

- working on supernova hydrodynamics simulations:
  can the asymmetries produce the derived mass loss and natal kicks?