Understanding Black Hole Formation and Natal Kicks:
The Case of Cygnus X-1

TsingWai Wong

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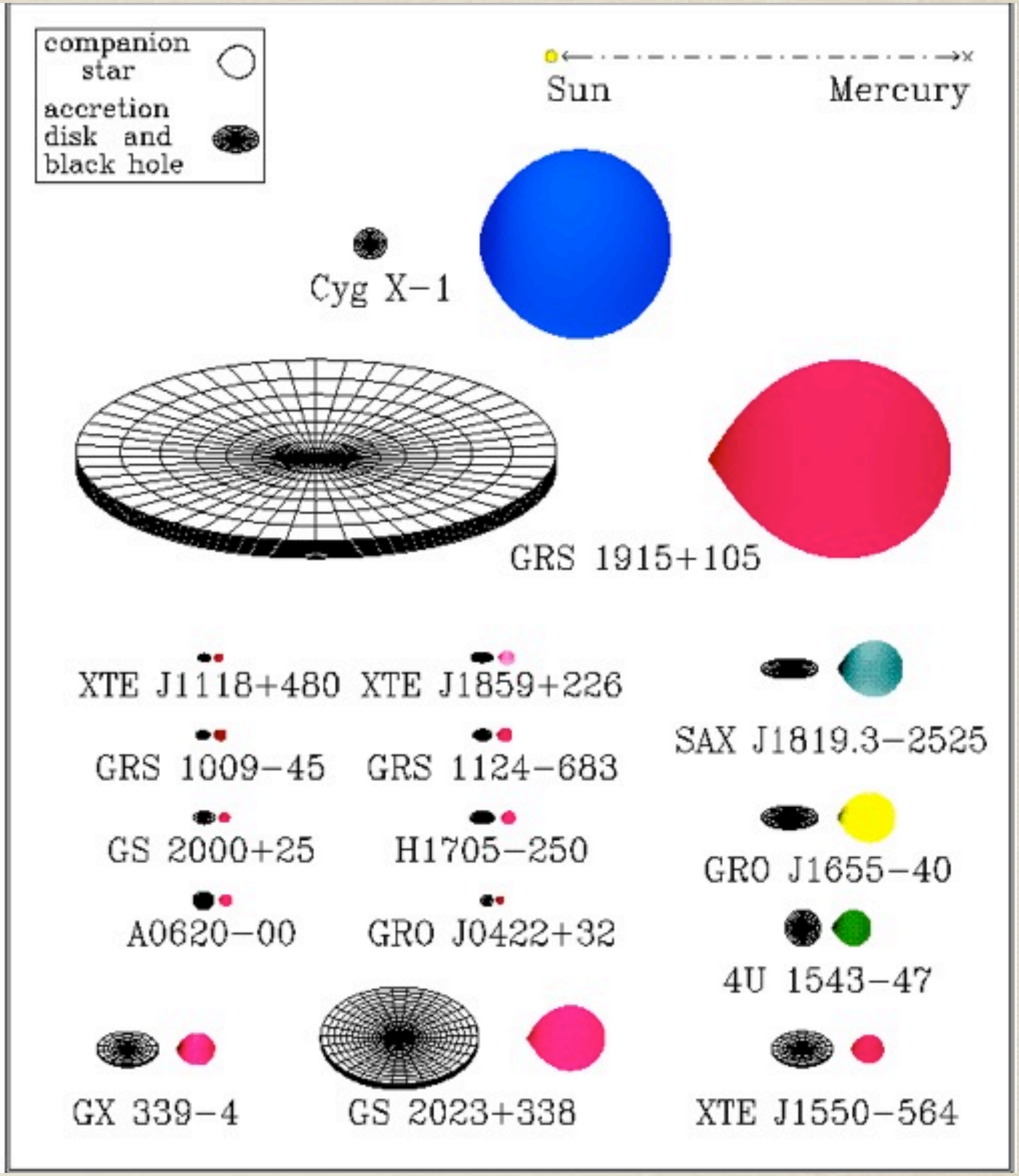
Background & Purpose

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

16 fairly well constrained BH X-ray binaries in Milky way:



(from Charles Bailyn)

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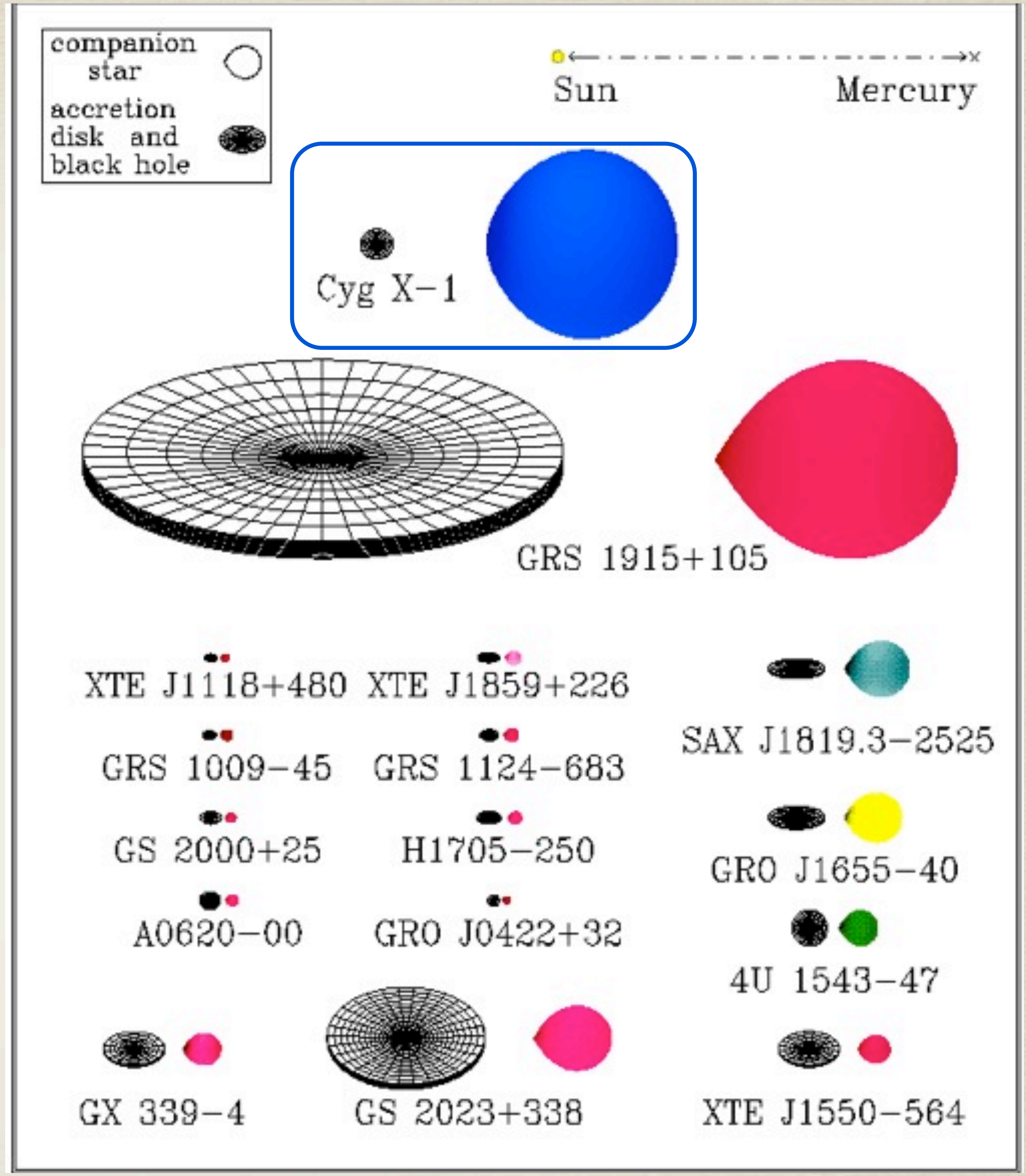
I. wind-fed, high mass



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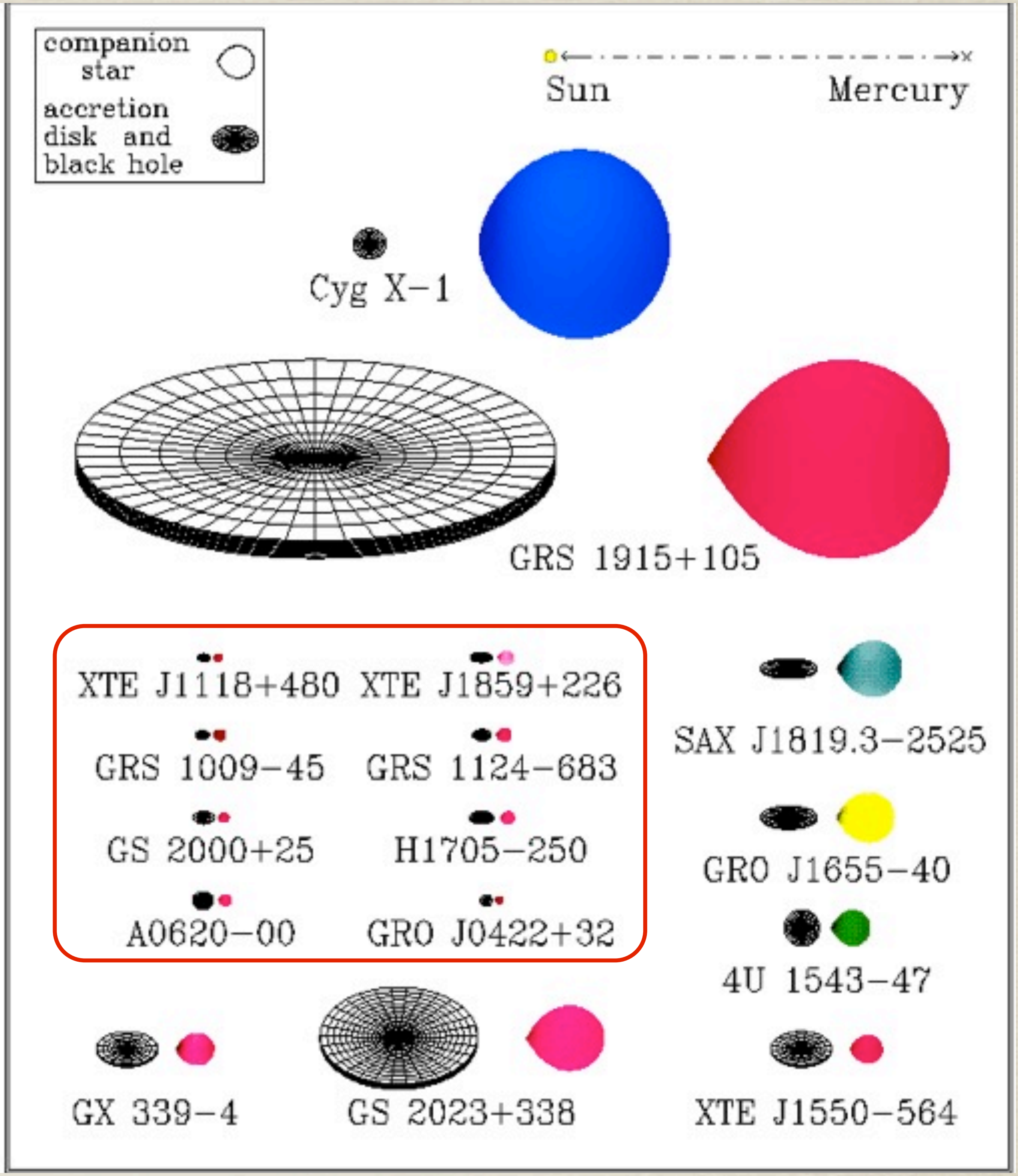
II. late-type, P < 1 day



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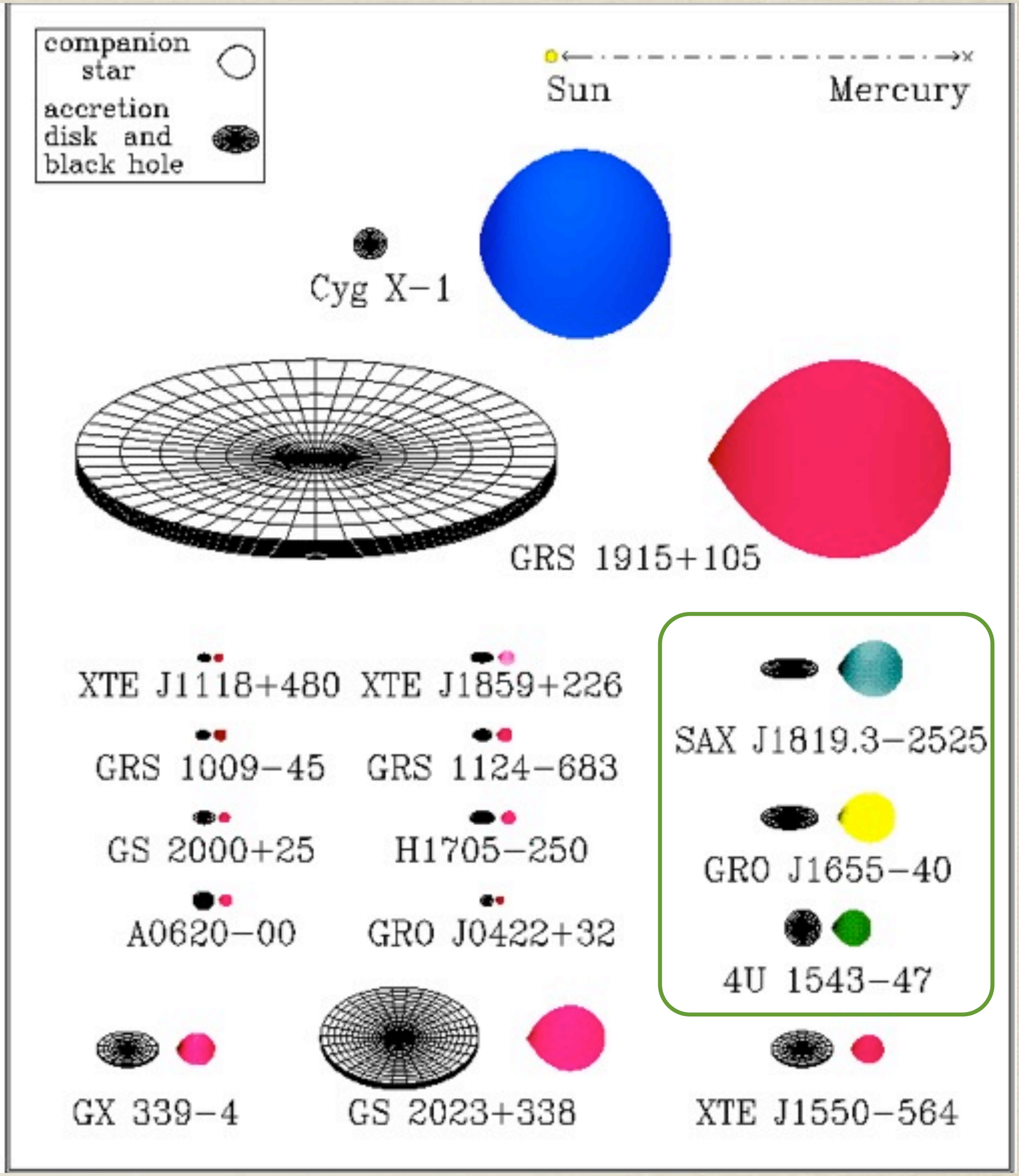

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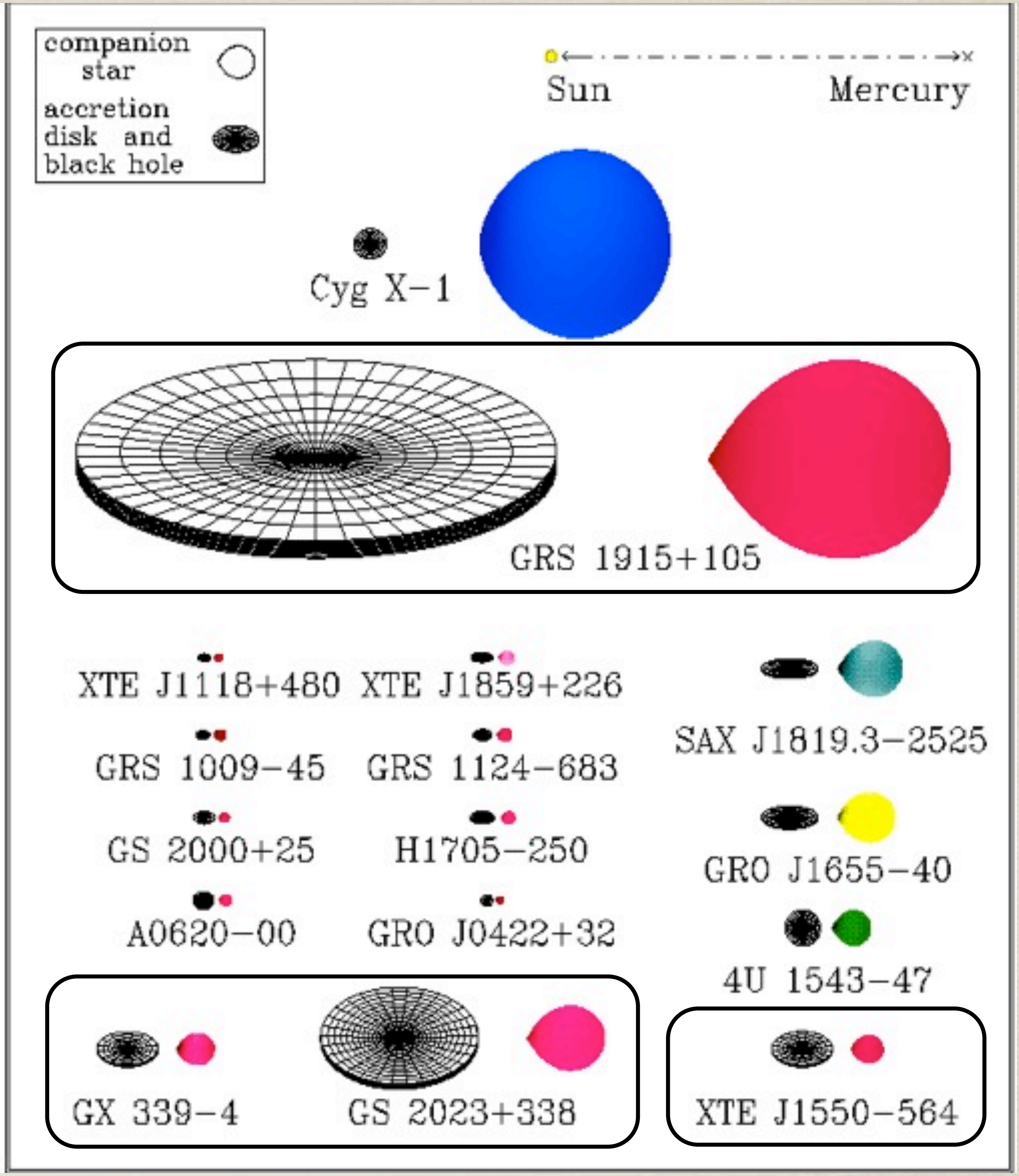
IV. giants, P > 1 day



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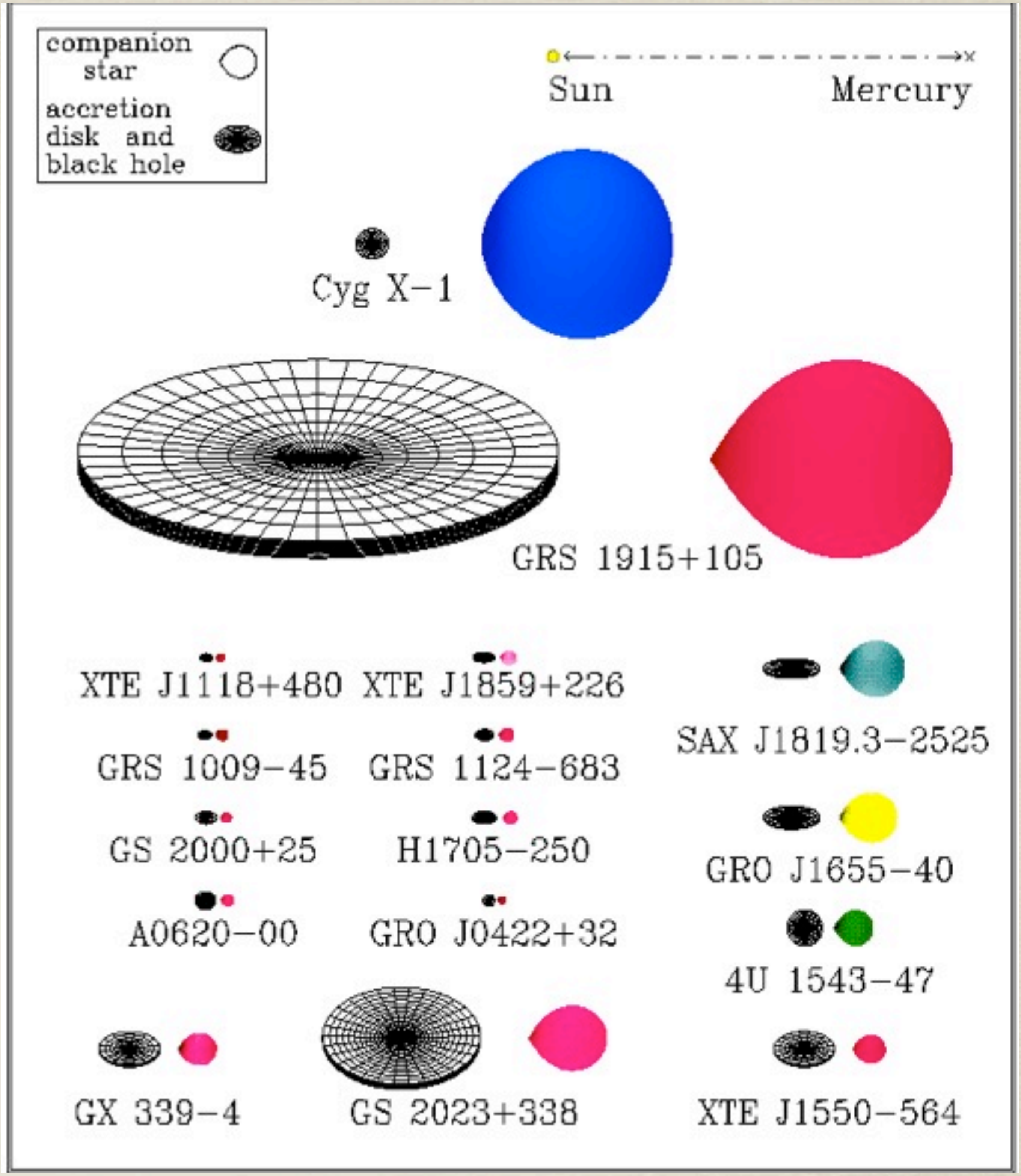
In other galaxies:

M33 X-7, IC 10 X-1, NGC 300 X-1



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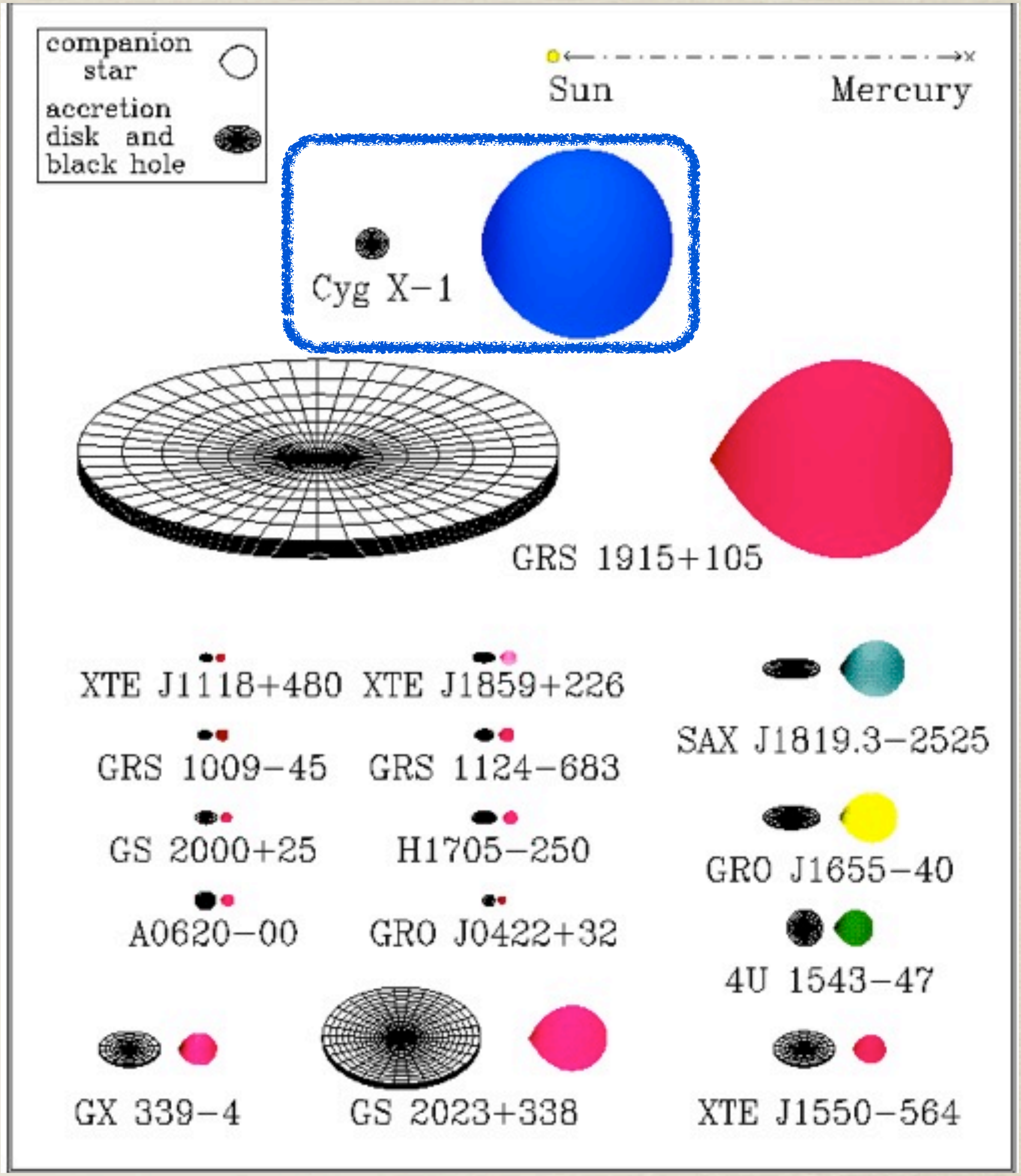

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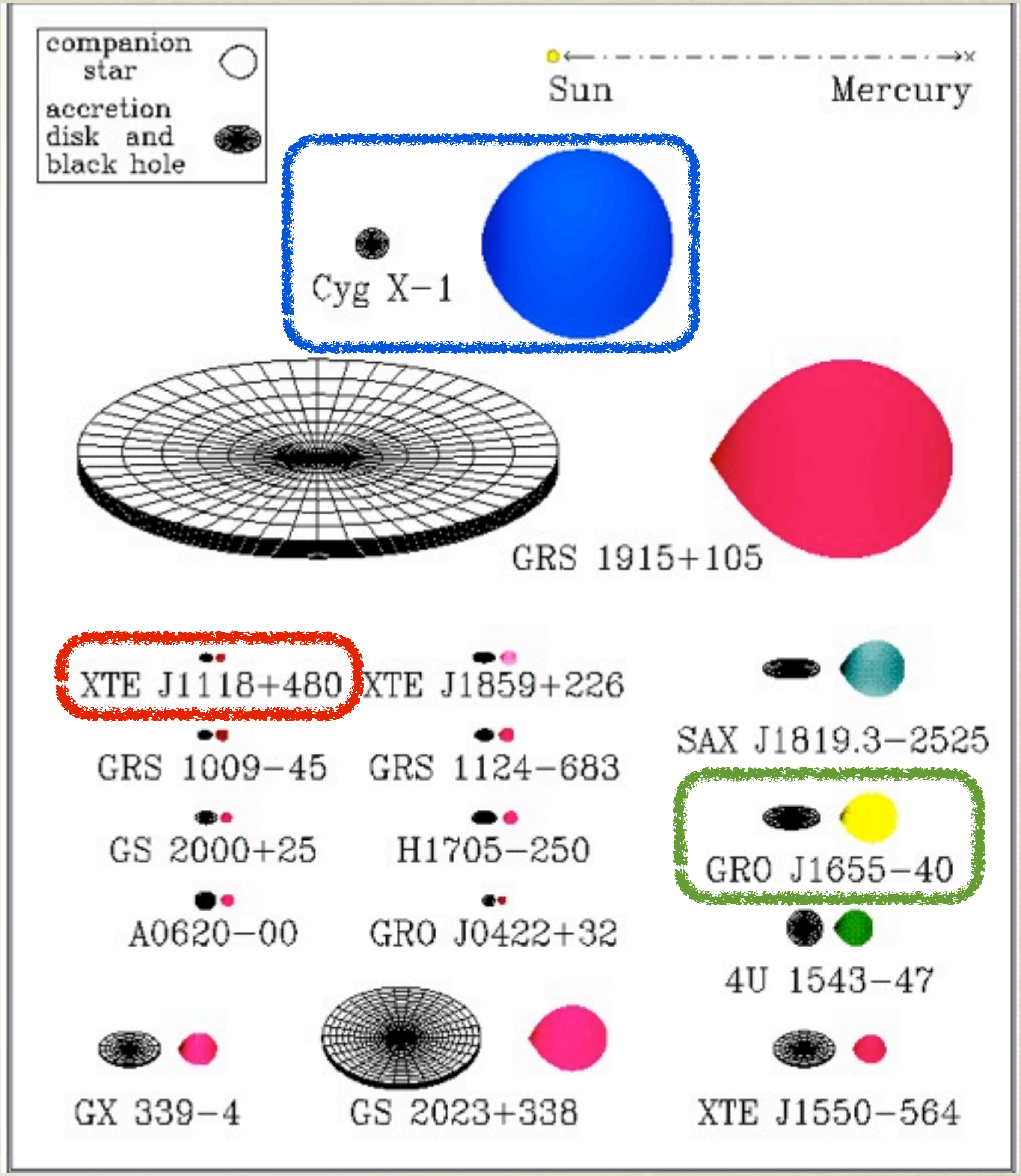

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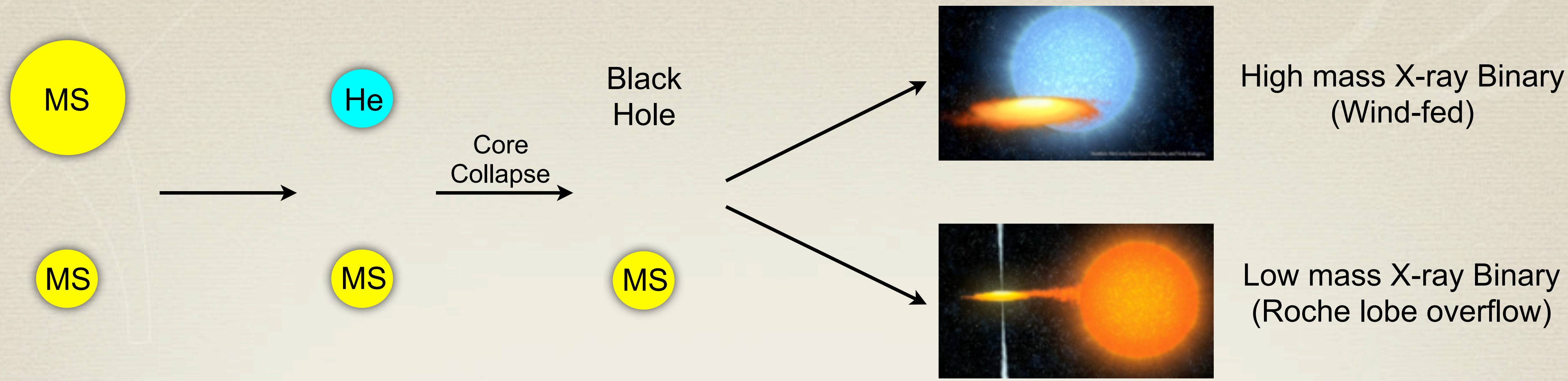


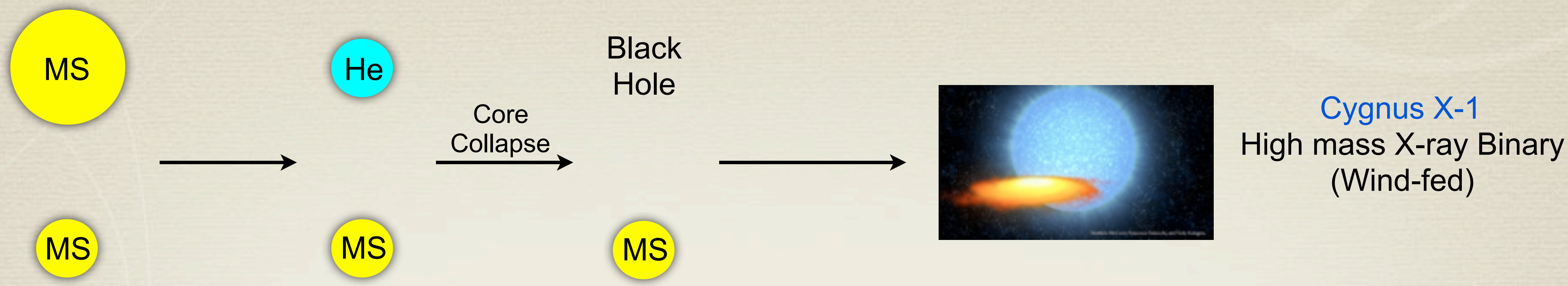
Step 1: Model current observed properties

Step 2: Find the peculiar velocity post BH formation

Step 3: Compute the dynamics involved in core collapse

Step 4: Match the observed orbital period and eccentricity

Derive limits on immediate progenitor mass and natal kicks magnitude



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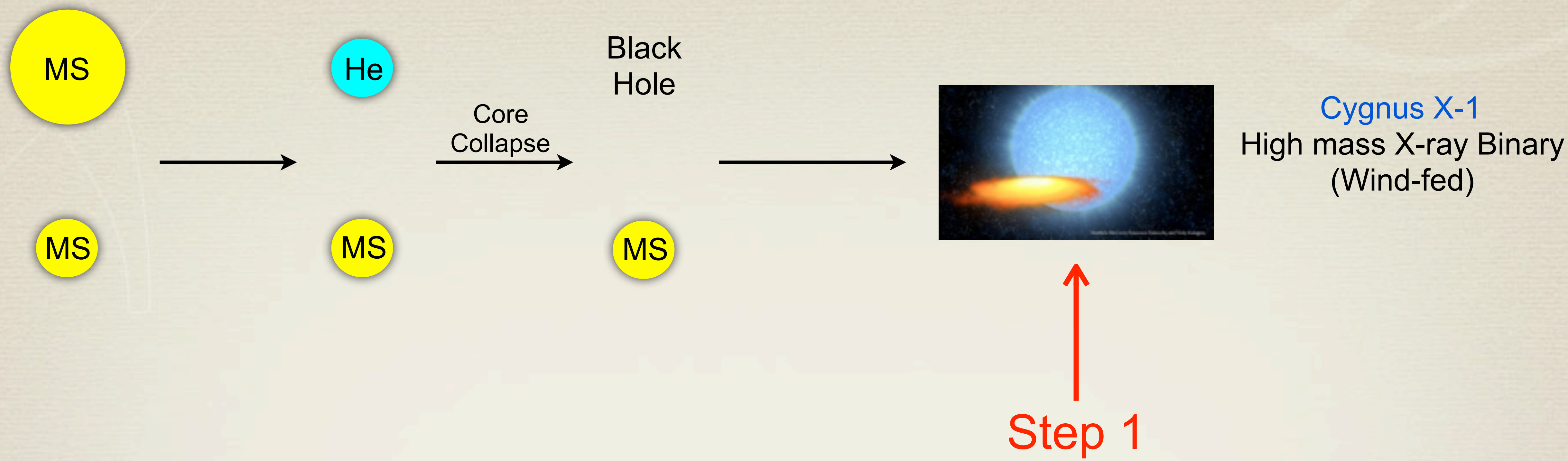

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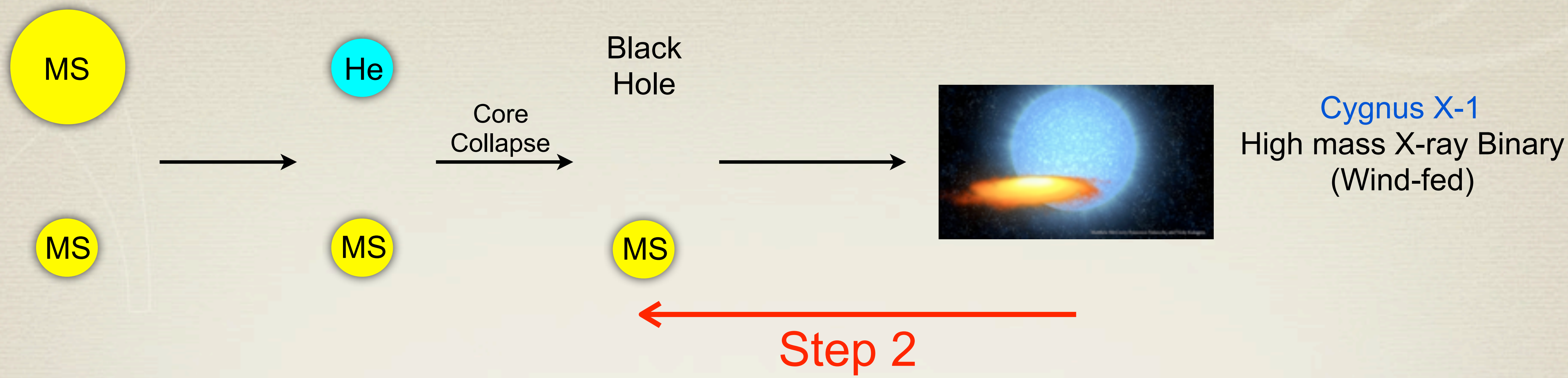

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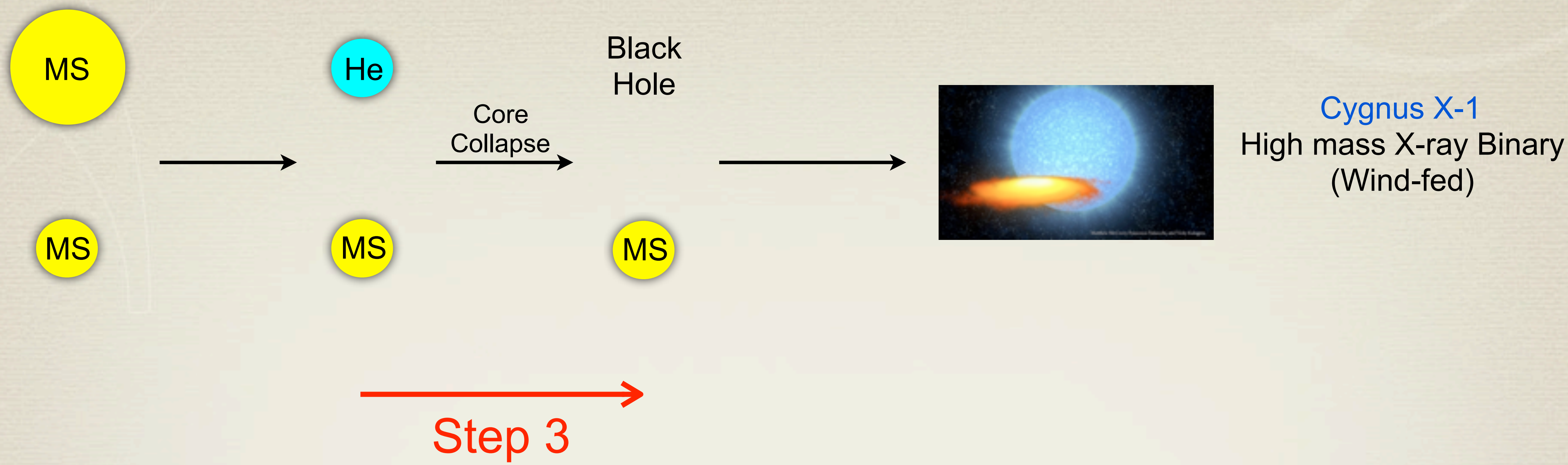

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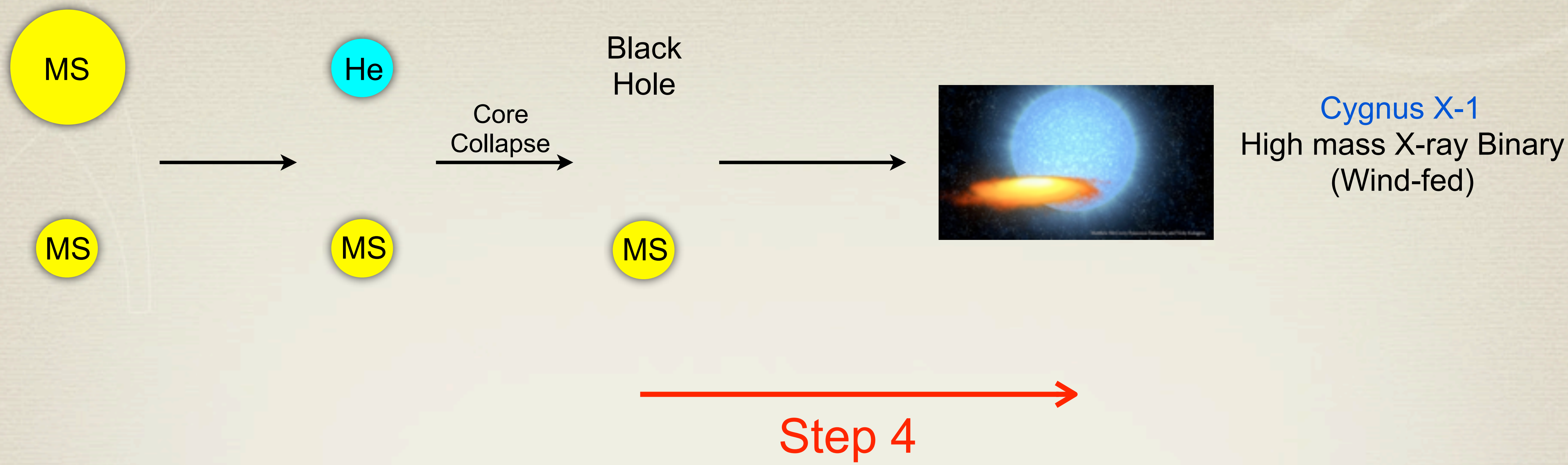

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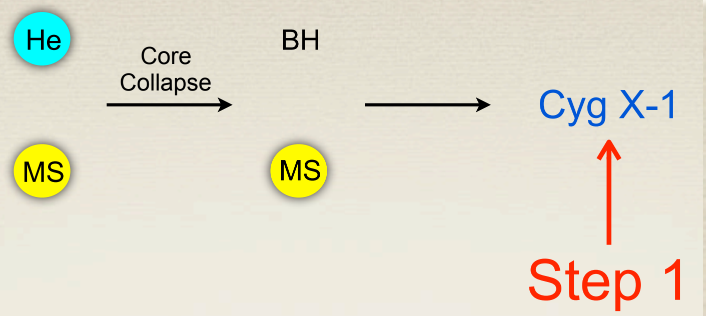

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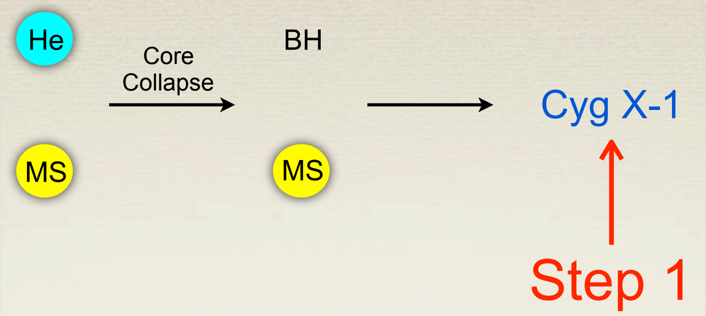

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Parameter	Value	Reference
Inclination angle (deg)	27.06 ± 0.76	Orosz et al. (2011)
Black hole mass ($M_\odot$)	14.81 ± 0.98	Orosz et al. (2011)
Black hole spin	> 0.95	Gou et al. (2011)
Companion mass ($M_\odot$)	19.16 ± 1.90	Orosz et al. (2011)
Companion 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)

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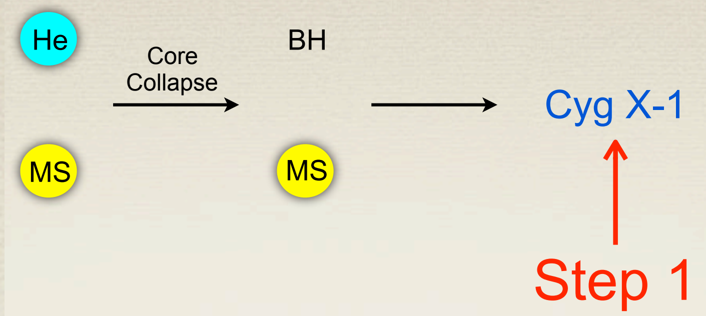

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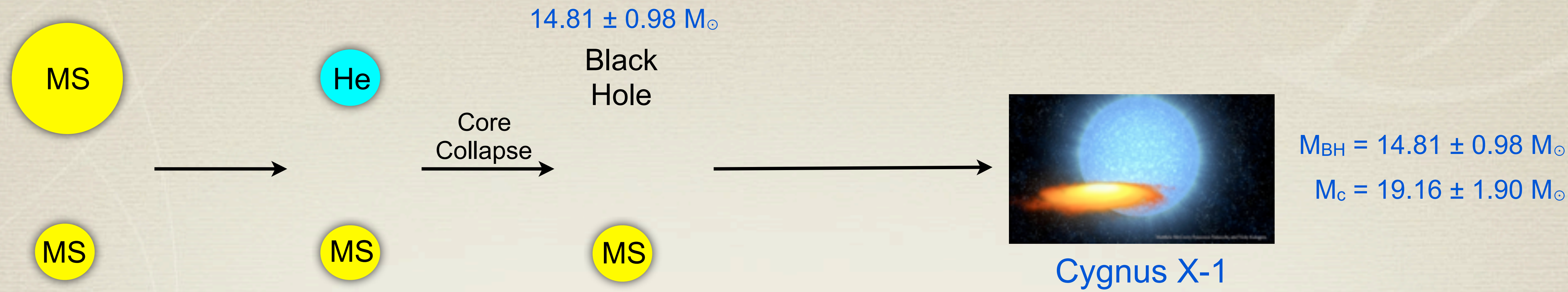
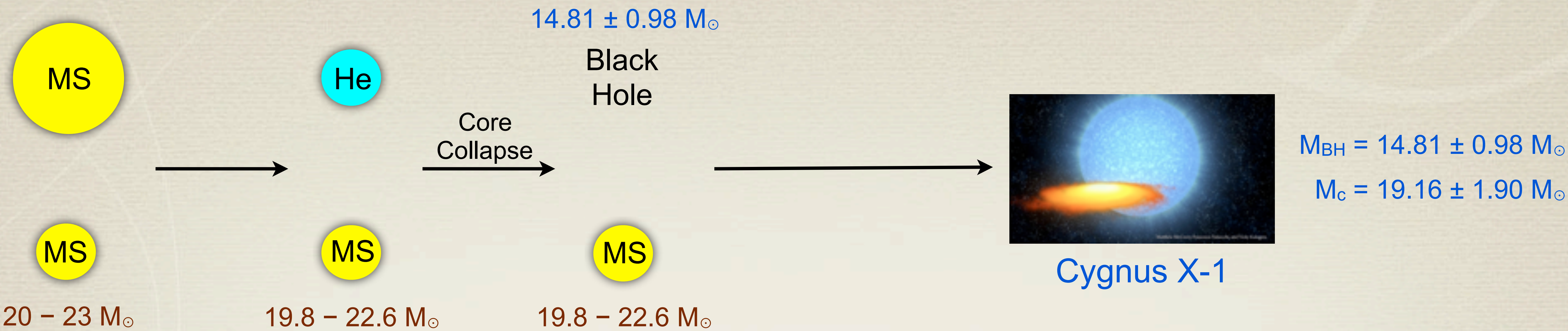

MS
MS
He
MS
Core Collapse
14.81 ± 0.98 M☉
Black Hole
MS
Cygnus X-1
M_BH = 14.81 ± 0.98 M☉
M_c = 19.16 ± 1.90 M☉


MS
MS
20 − 23 $M_\odot$
He
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19.8 − 22.6 $M_\odot$
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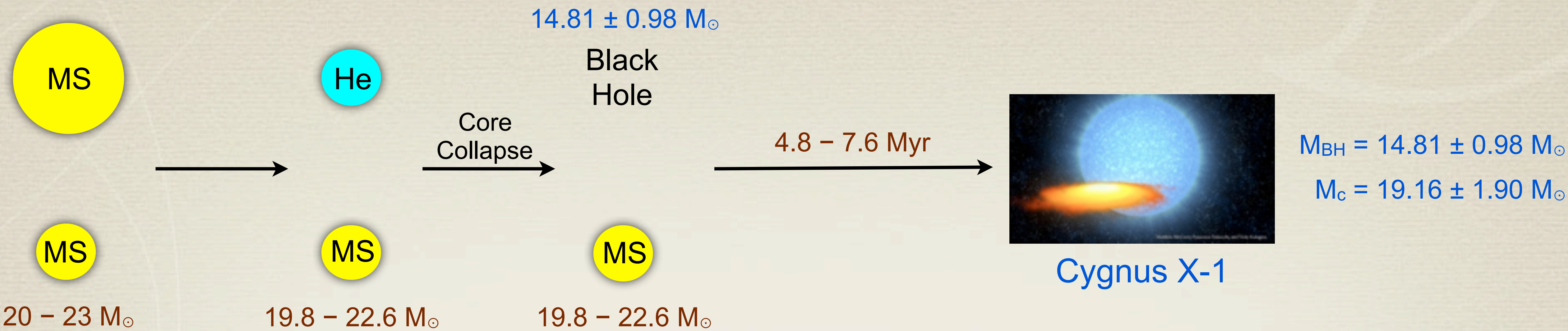
14.81 ± 0.98 M⊙
Black Hole
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4.8 – 7.6 Myr
MS
MS
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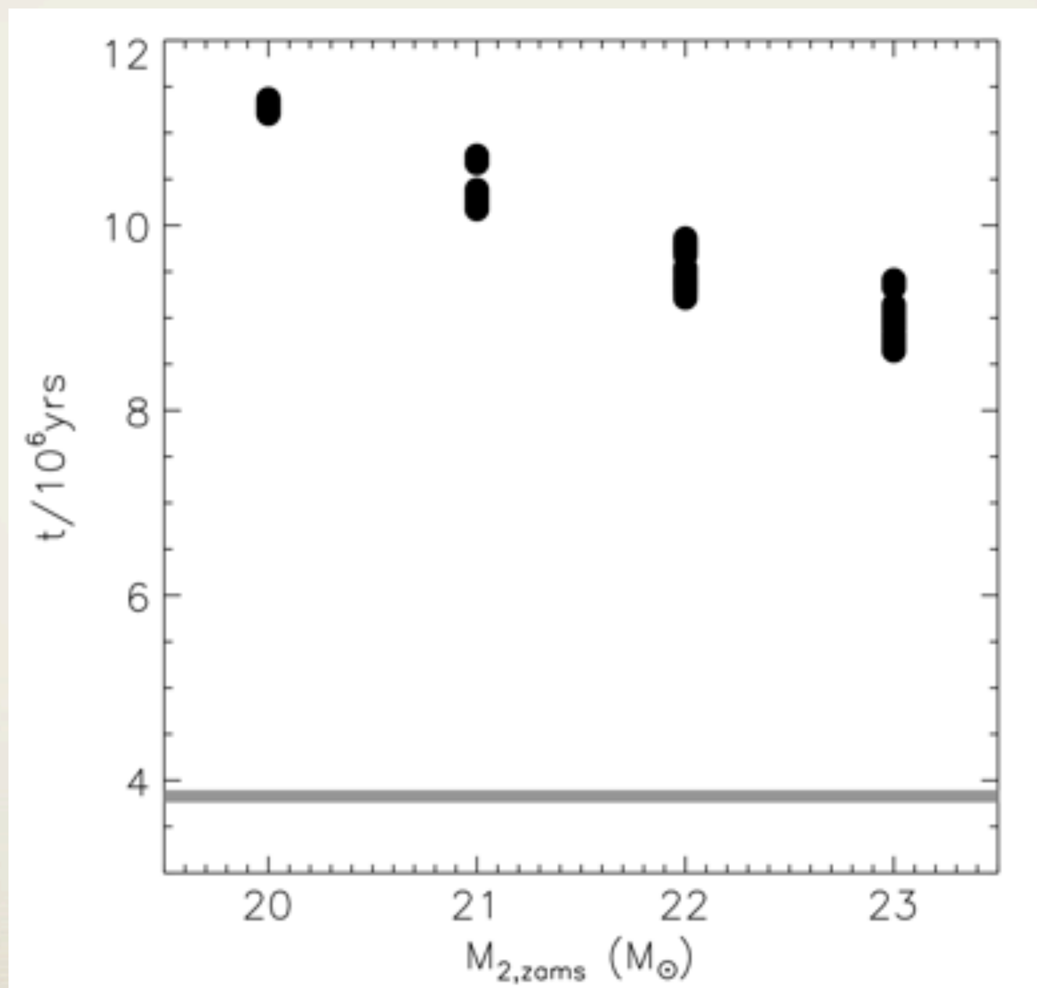
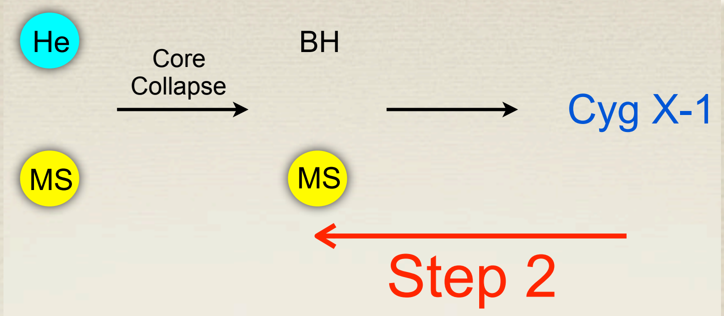
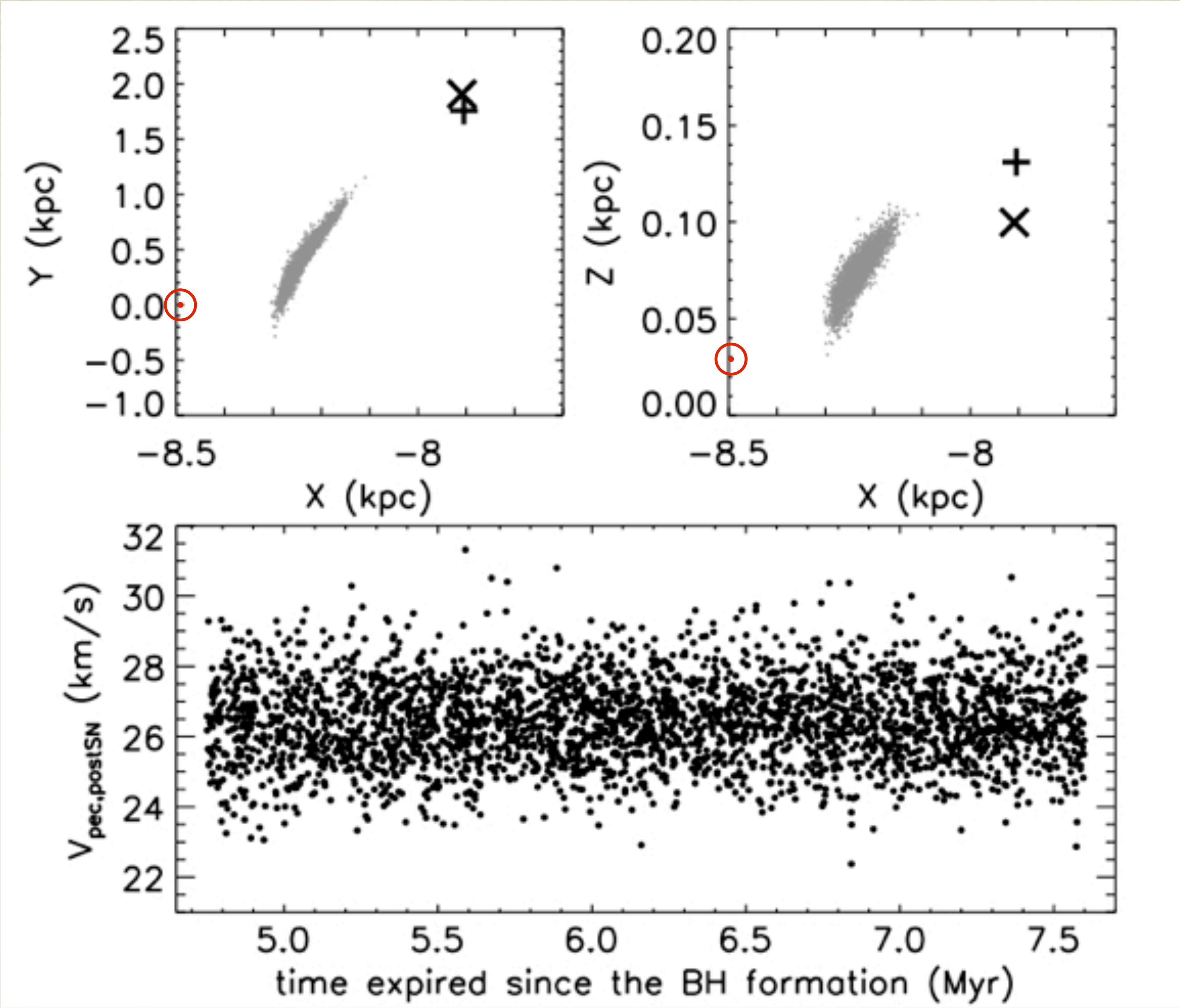

$t/10^6$yrs
12
10
8
6
4
20
21
22
23
$M_{2,zams}$ ($M_\odot$)

Step 2:
Find the peculiar velocity post BH formation



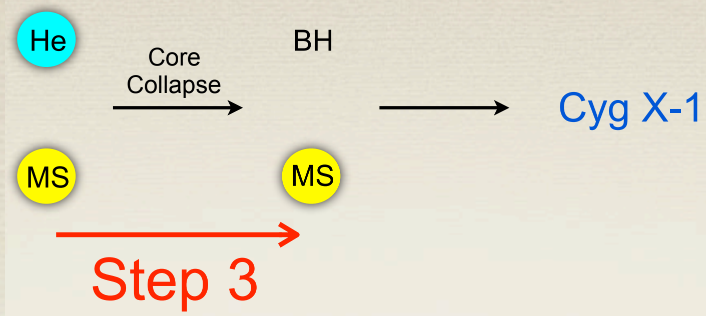
Parameter	Value	Reference
Distance (kpc)	1.86 ± 0.12	Reid et al. (2009)
Galactic longitude (deg)	71.3	Lestrade et al. (1999)
Galactic latitude (deg)	+3.1	Lestrade et al. (1999)
Proper motion in R.A. (mas/yr)	−3.78 ± 0.06	Reid et al. (2009)
Proper motion in decl. (mas/yr)	−6.40 ± 0.12	Reid et al. (2009)

- 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 = 27 ± 5 km/s
- resulted from the collapse core event

Step 3:
Compute the dynamics involved in core collapse



- perform Monte Carlo simulation for the He-MS (pre-SN) binary configuration:
  1) M_{He}
  2) A_{preSN}
  3) e_{preSN}
  4) orbital phase
  5) natal kick (magnitude + direction)

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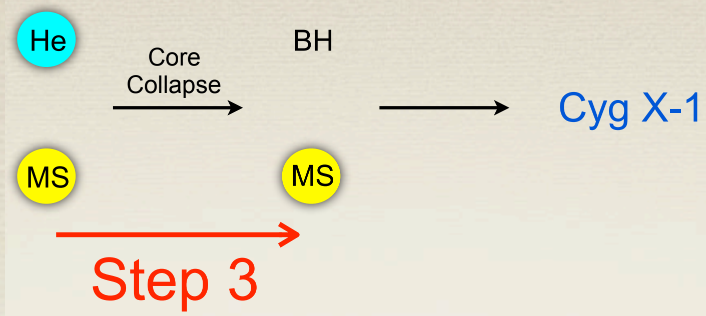

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- constraints:

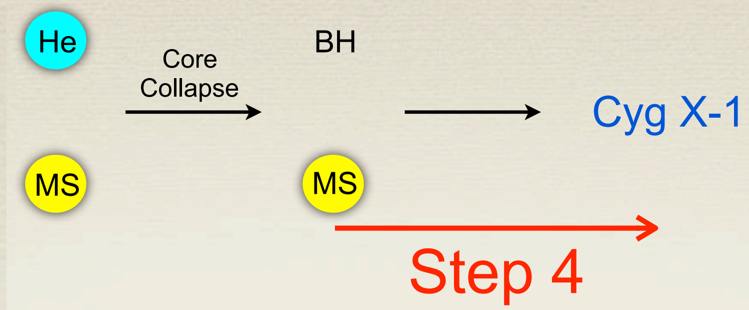
  a) survival of the binary

  b) conservation of orbital energy and angular momentum

  c) peculiar velocity of the post-SN binary

  (from step 2: $V_{pec} = 27 \pm 5$ km/s)

Step 4:
Match the observed orbital period and eccentricity



- 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

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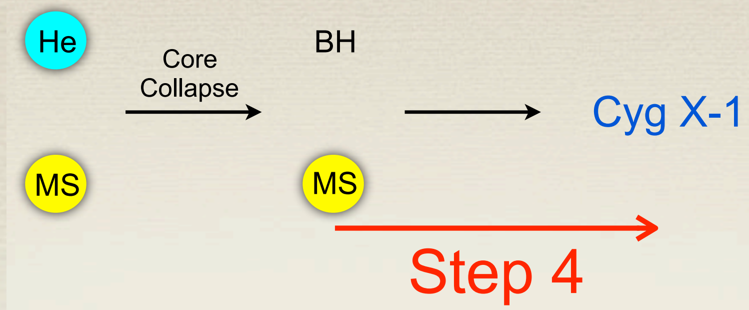

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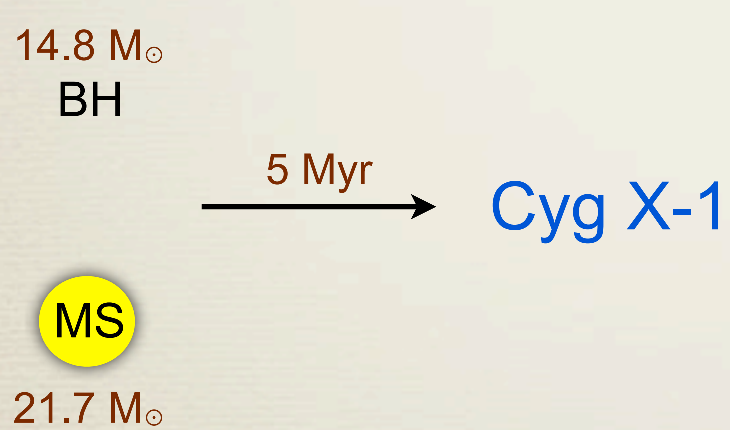
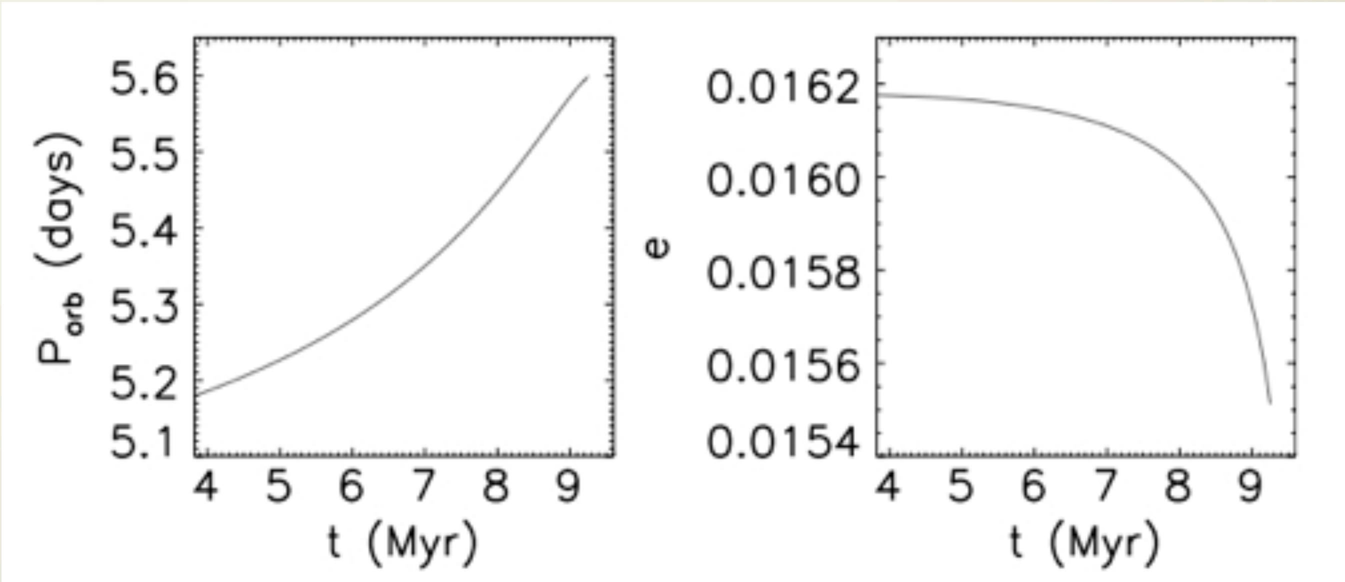




Result

14.81 ± 0.98 $M_\odot$

Black Hole

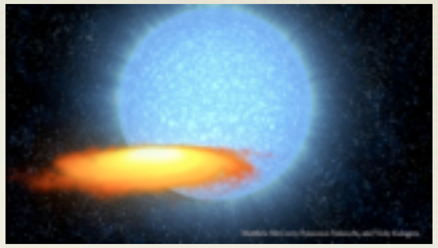
He

Core Collapse →

MS

MS

→



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M_c = 19.16 ± 1.90 $M_\odot$

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MS

19.8 – 22.6 $M_\odot$

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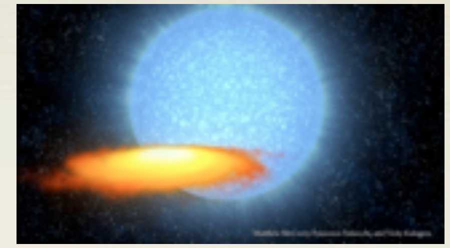
19.8 – 22.6 $M_\odot$

4.8 – 7.6 Myr →



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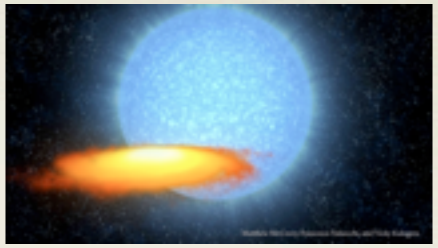
Core Collapse

$V_{pec} = 27 \pm 5$ km/s

4.8 − 7.6 Myr



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MS

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Result

15.0 – 20.0 M$_\odot$

He

MS

19.8 – 22.6 M$_\odot$

Core Collapse

V_{kick} ≲ 77 km/s

14.81 ± 0.98 M$_\odot$

Black Hole

V_{pec} = 27 ± 5 km/s

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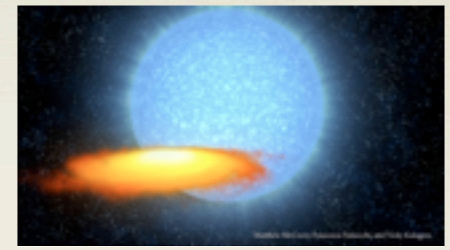
19.8 – 22.6 M$_\odot$

4.8 – 7.6 Myr



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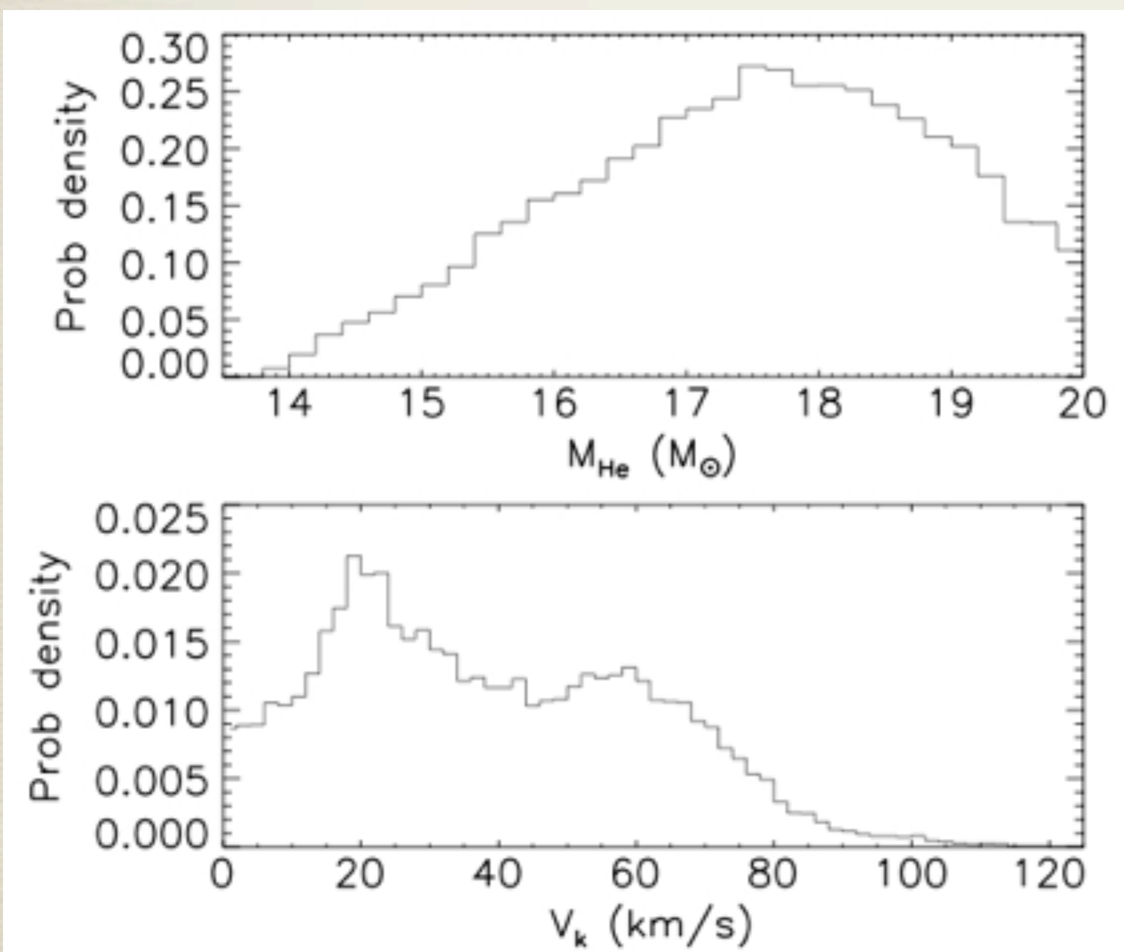

Result

15.0 − 20.0 $M_\odot$

He

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19.8 − 22.6 $M_\odot$

Core Collapse

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

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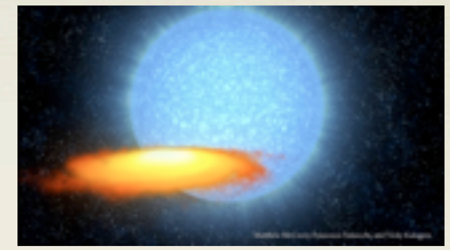

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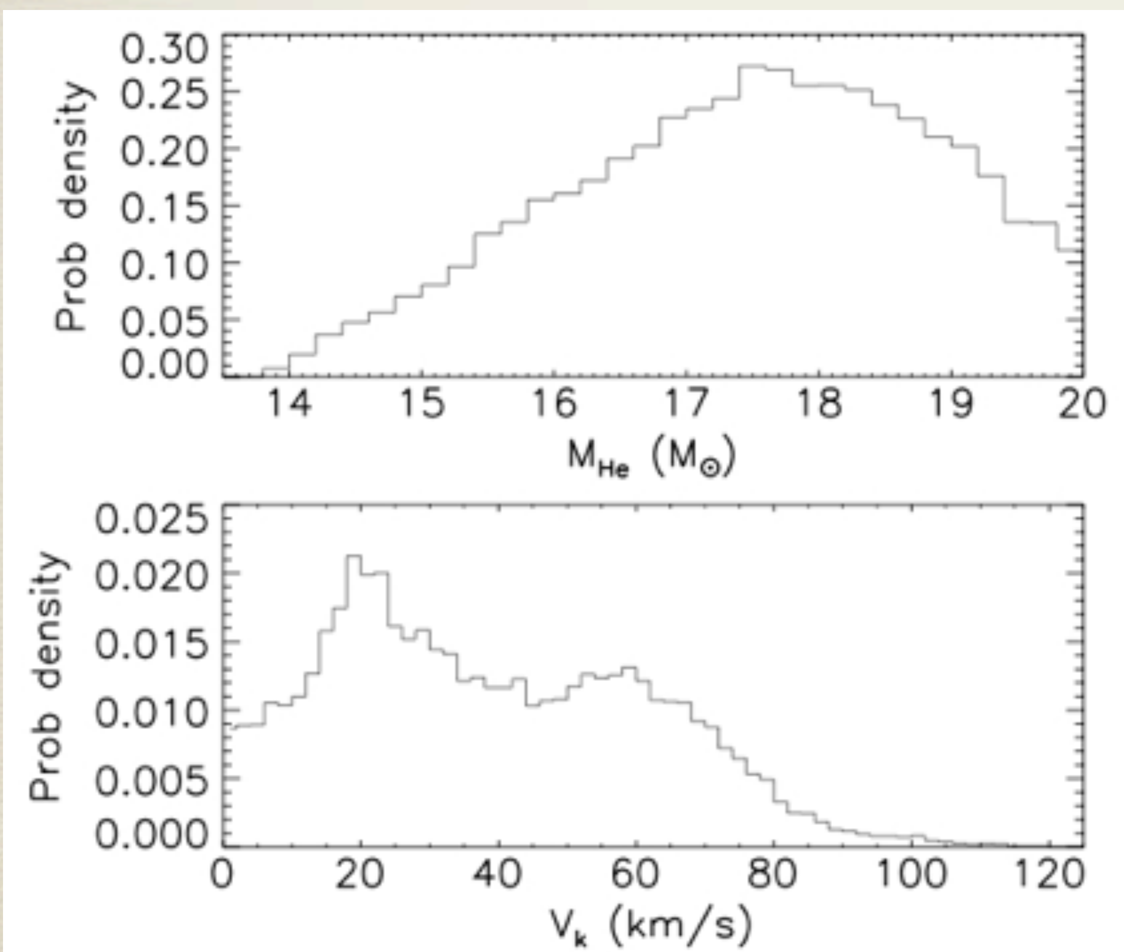

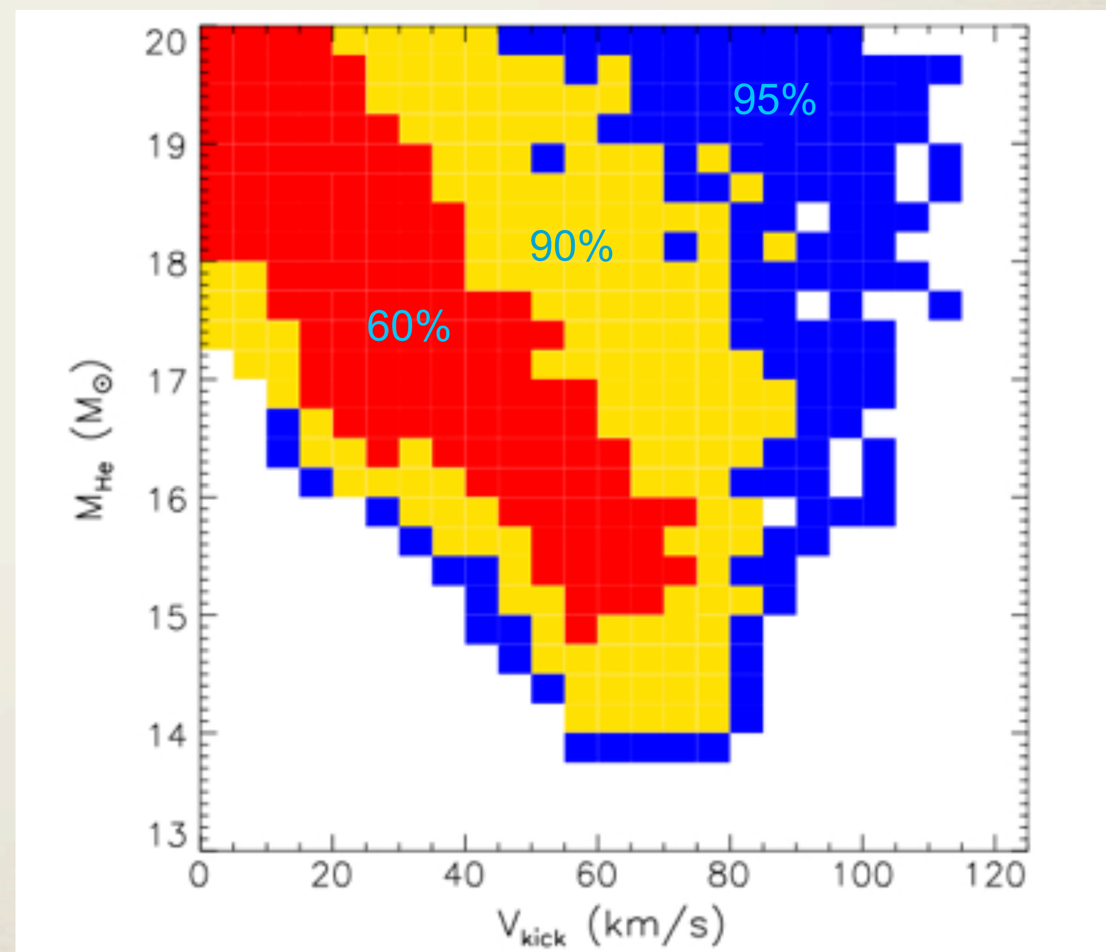

Results

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)

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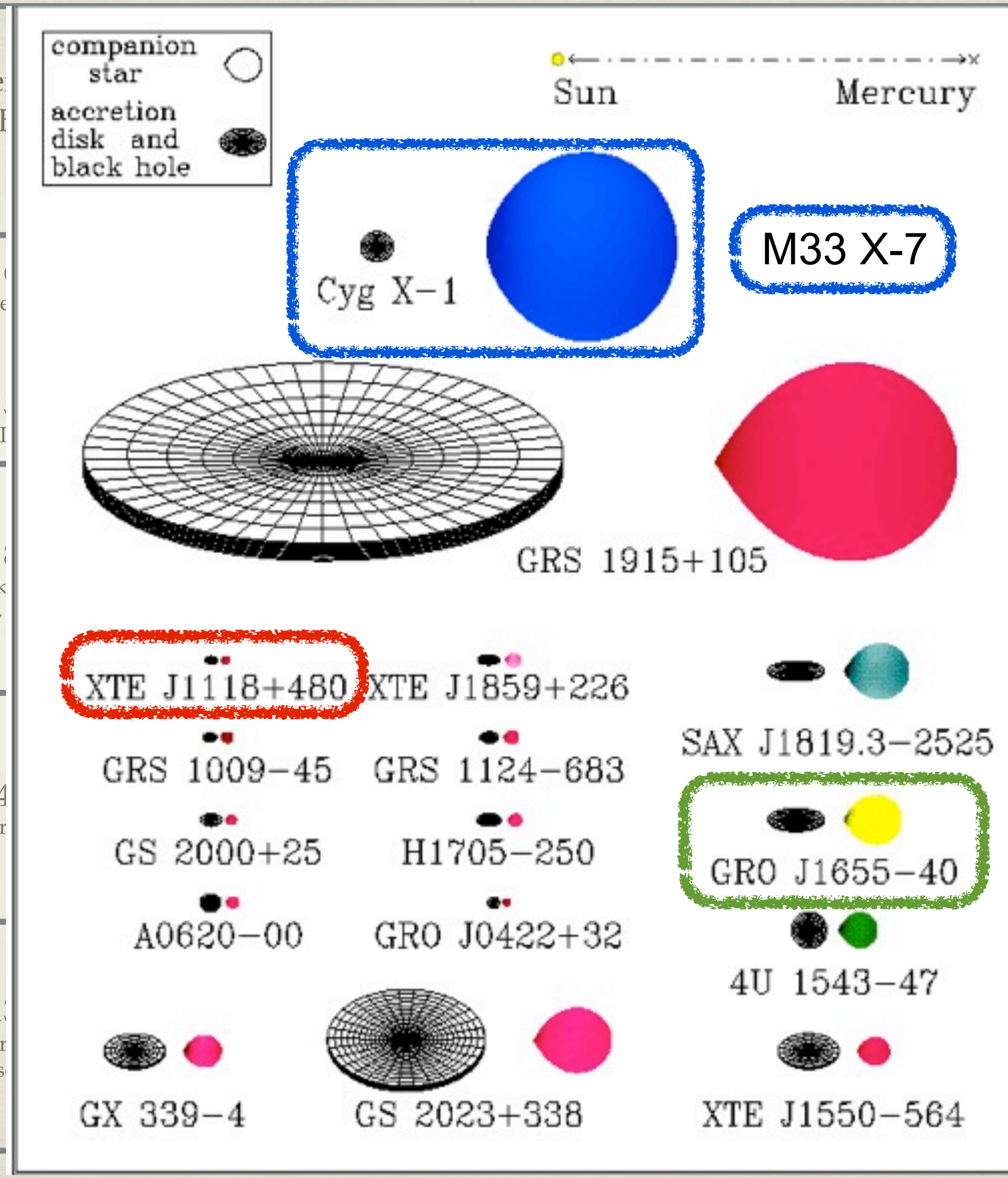

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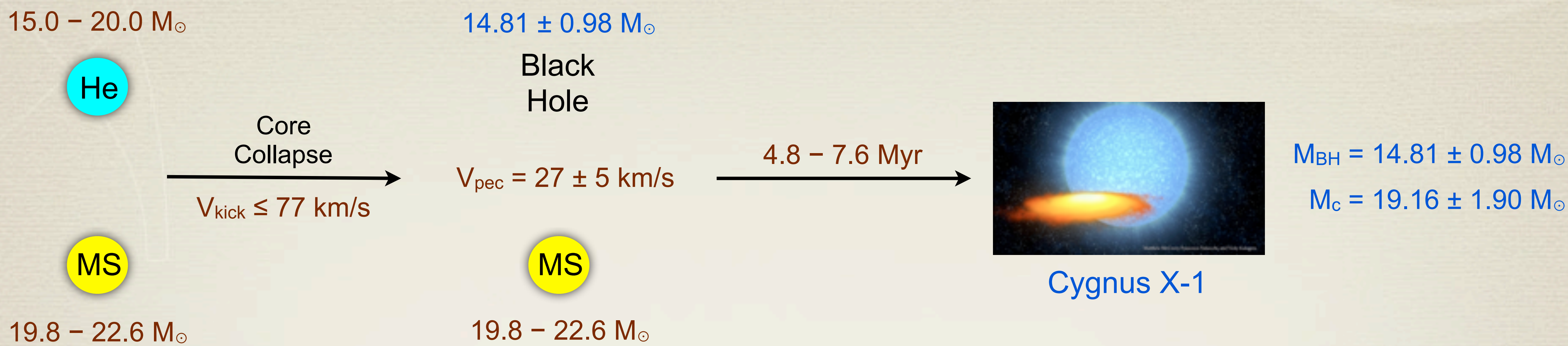
System	Observed Current BH mass ($M_\odot$)	Post-SN BH mass ($M_\odot$)	Immediate Progenitor mass ($M_\odot$)	Natal Kick (km/s)
GRO J1655-40 (early-type, P>1d)	6.3 ± 0.5 (Greene et al. 2001) 5.4 ± 0.3 (Beer & Podsiadlowski 2002)	5.5 – 6.3 (Willems et al. 2005) 3.5 – 5.4 (Willems et al. 2005)	5.5 – 11.0 (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?