THE FORMATION OF STELLAR BLACK HOLES

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**IMPACT OF STELLAR BHs:**

- First in the context of cosmology
  Mirabel+ (2011) & N&V in Nature (Haiman)

- Now in the context of GW astrophysics
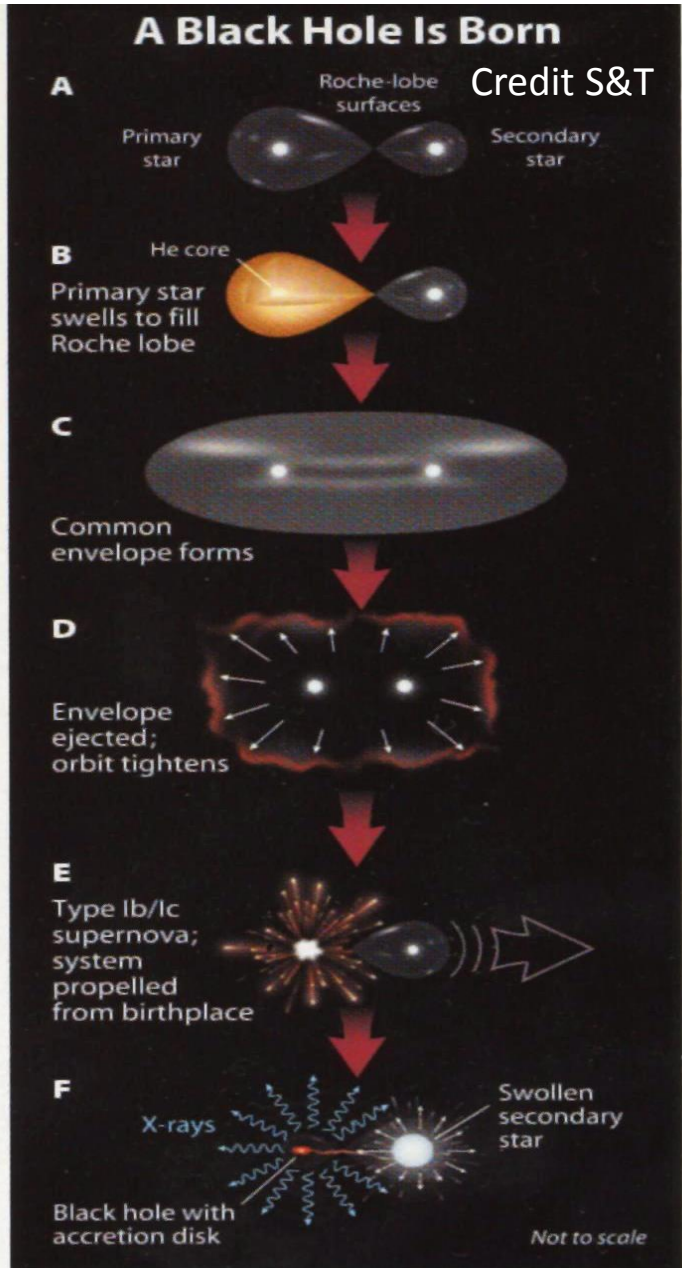 Invited review in New Astronomy Reviews (in press)

  http://dx.doi.org/10.1016/j.newar.2017.04.002
  http://arxiv.org/abs/1609.08411

SYNERGY BETWEEN X-RAY AND GWs STUDIES

The first detection of GWs produced surprise because of the high BH masses and BH-BH merger rates
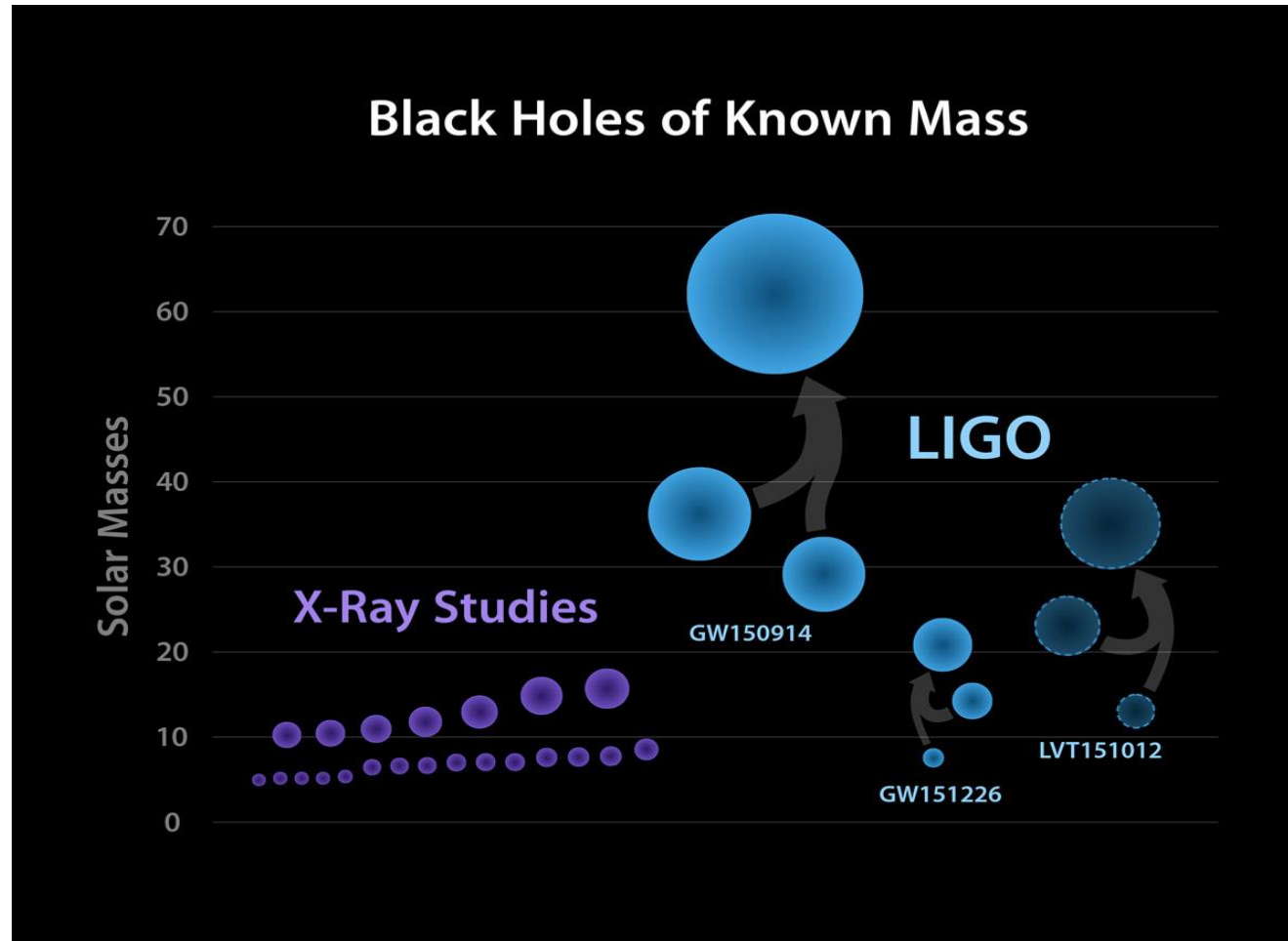
I will show that what we know from X-ray studies, in particular, from the BH kinematics & metallicity dependence, the estimated BH masses & BH merger rates inferred from GWs should be large

INSIGHTS ON BH FORMATION FROM THE KINEMATICS OF BH-XRBs

A Black Hole Is Born

Credit S&T

A — Roche-lobe surfaces. Primary star. Secondary star.

B — He core. Primary star swells to fill Roche lobe

C — Common envelope forms

D — Envelope ejected; orbit tightens

E — Type Ib/Ic supernova; system propelled from birthplace

F — X-rays. Swollen secondary star. Black hole with accretion disk. Not to scale

CORE COLLAPSE MODELS OF NSs and BHs FORMATION:

Are stellar black holes formed with similar Natal Kicks as NSs?
(Fryer & Kalogera 2001; Woosley & Heger; Nomoto+; Sukhbold+ 2016...

Important question because

If BHs were born with the same kick distribution as neutron stars the merger rate of BBHs would decrease by a factor of ~20 relative to BHs being born with no energetic SNe and Natal kicks

(Dominik, Belczynski, Fryer 2012)

TO DETERMINE NATAL KICKS OF BHs THE VELOCITIES OF BH-XRBs IN 3 DIMENSIONS ARE REQUIRED (Mandel 2016)
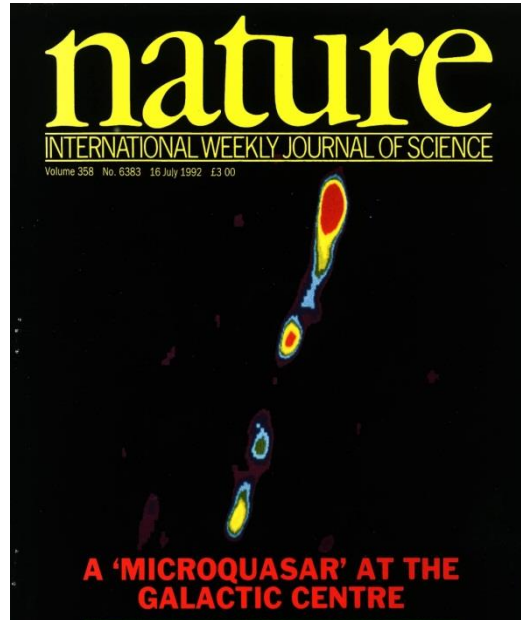
From 3×10^8 BHs in MW, 20 BHXRBs known, 5 BH-μQSOs with 3D velocities
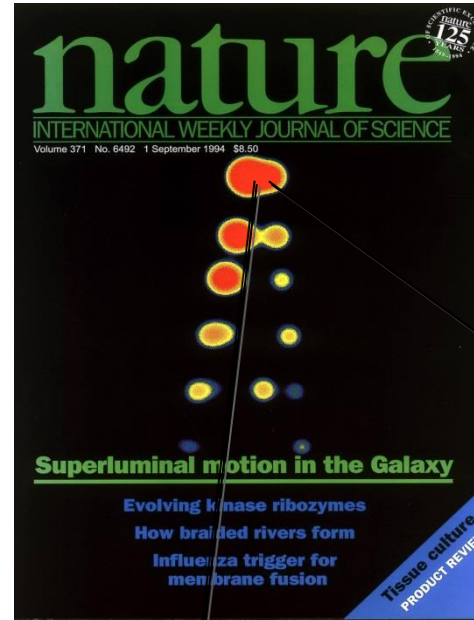
Mirabel, Irapuan Rodrigues et al. (2001-2009)

JETS IN ``MICROQUASARS''

Mirabel, Rodriguez+ 1992   Mirabel & Rodríguez 1994
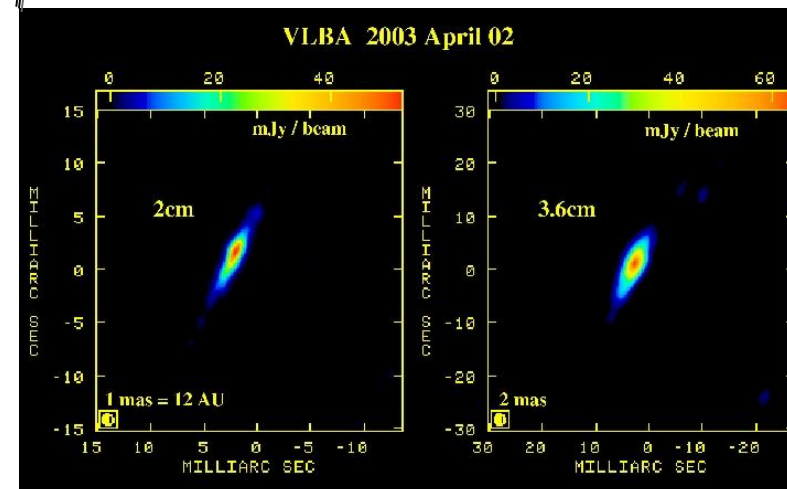
STEADY

JETS

TRANSIENT

JETS

COMPACT JETS

Dhawan, Mirabel, Rodríguez (2007)

**DISTANCES & PROPER MOTIONS
OF BH-XRBs ARE DETERMINED
WITH VLBI OF COMPACT JETS TO
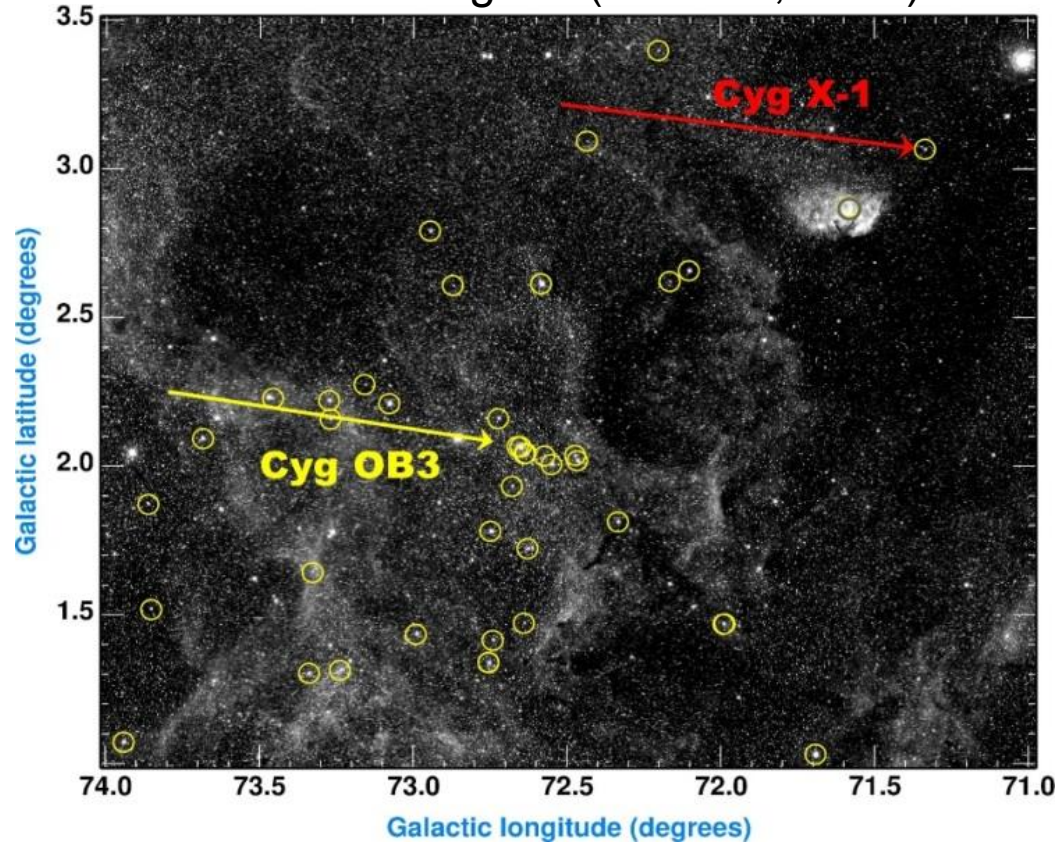GET SUB-MILLIARC SEC PRECISION**

TWO BLACK HOLES FORMED BY DIRECT COLLAPSE

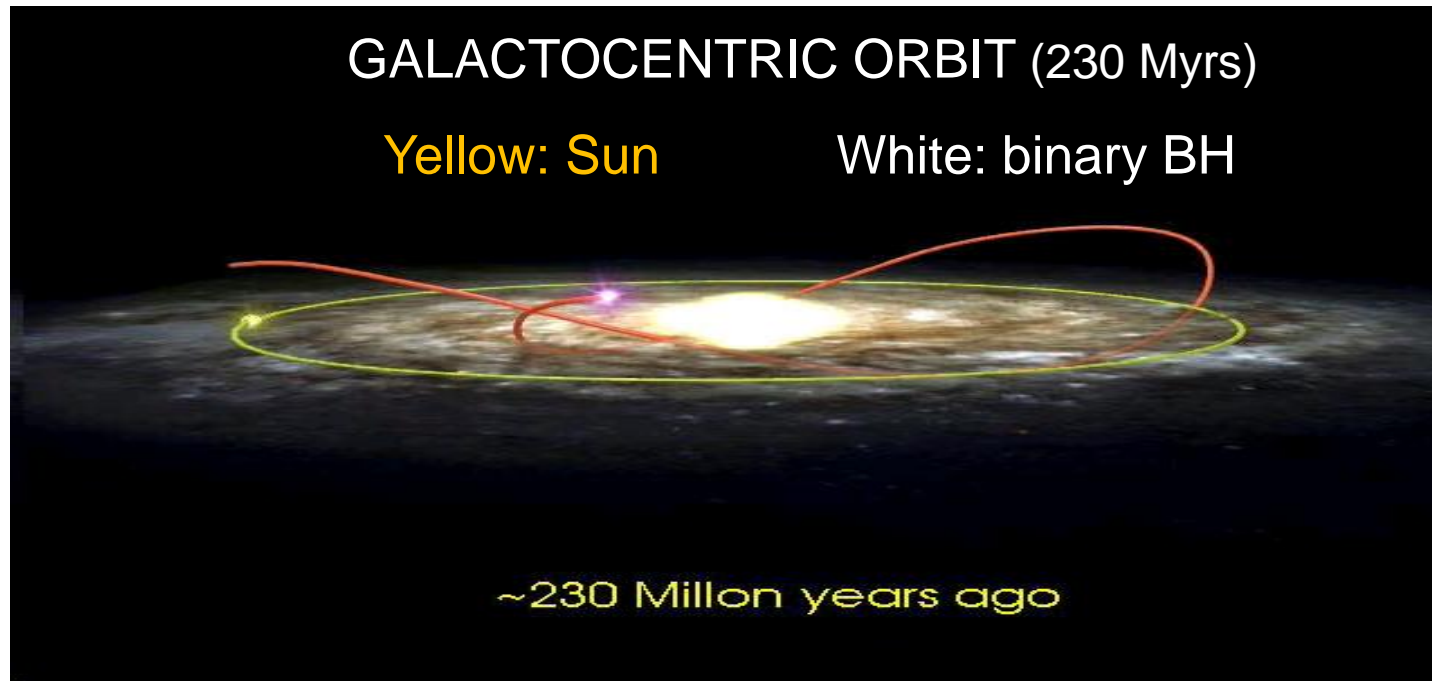**OBSERVATIONS**
Mirabel & Rodrigues (Science, 2003)

- **Cygnus X-1:** $M_{bh} \sim 15\ M_{\odot}$; $M_{don} \sim 19\ M_{\odot}$; $V_p < 9 \pm 2$ km/s $\Rightarrow <1\ M_{\odot}$ in SN; $M_{prog} > 40\ M_{\odot}$; $M_{lost} \sim 25\ M_{\odot}$ in Wolf Rayet

- **GRS 1915+105:** $M_{bh} \sim 10\ M_{\odot}$; $V_p = 22 \pm 24$ km/s $\Rightarrow$ Galactic diffusion

- **Stars of ~40 $M_{\odot}$ and Z~Z$_{\odot}$ may collapse directly as BHs**
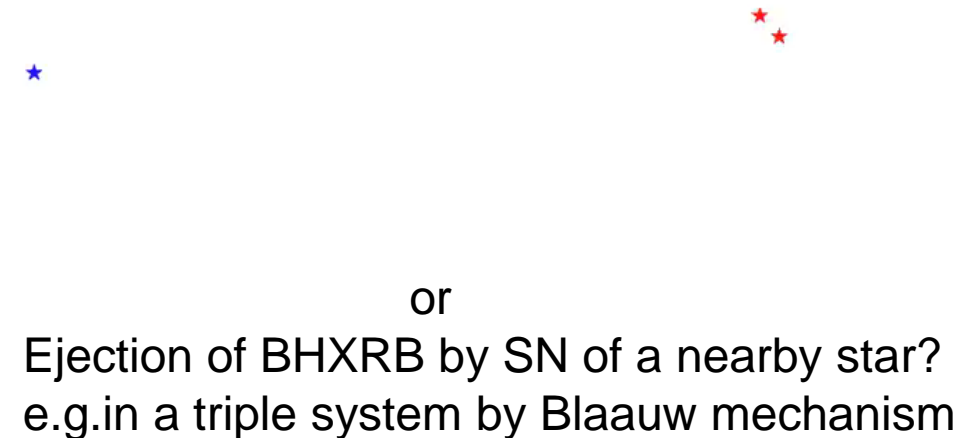
THREE RUNAWAY BLACK HOLES

XTE J1118+480: $M_{BH} \sim 7.6 \pm 0.7\, M_\odot$ $M_* \sim 0.5 \pm 0.3\, M_\odot$ (b = 62.3°; z = 1.5 kpc); **Vp=183±31 km/s**

Mirabel, Dhawan, Rodrigues et al. (Nature 2001)

Binary & single star interaction in a cluster?
Dynamical mechanism. Credit: Carl Rodriguez

GALACTOCENTRIC ORBIT (230 Myrs)

Yellow: Sun   White: binary BH

~230 Millon years ago

or
Ejection of BHXRB by SN of a nearby star?
e.g.in a triple system by Blaauw mechanism

GRO J1655-40: $M_{BH} \sim 5.3 \pm 0.7\, M_\odot$ $M_* \sim 2.4 \pm 0.7\, M_\odot$; D=1-3 kpc; V_p=**112±18 km/s** (Mirabel 2002)

V404 Cyg: $M_{BH} \sim 9.0 \pm 0.6\, M_\odot$ $M_* \sim 0.75 \pm 0.25\, M_\odot$; V_p= **39.9±5.5 km/s** (Miller-Jones+ 2015)

HOWEVER, THE RUNAWAY VELOCITIES CAN BE TRIGGERED BY DIFFERENT MECHANISMS

RUNAWAY VELOCITIES OF BH-XRBs vs BH MASS
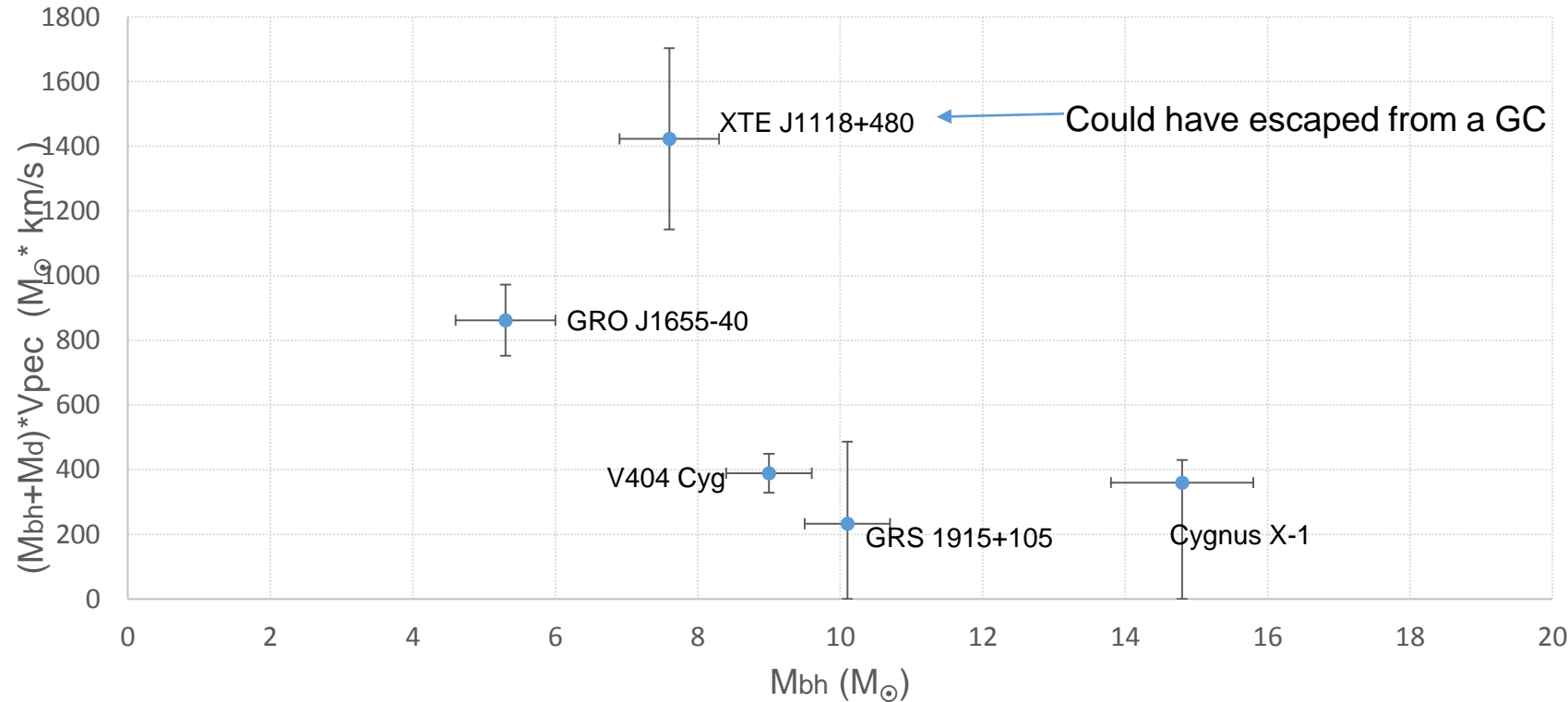
- Expected from current models of BH formation

- XTE J1118+480 is at b = 62° and z=1.5 kpc from the disk

- If born with SN kicks or NKs, it is intriguing that except XTE J1118+480, the components of the runaway velocities perpendicular to the Galactic disk are 2.1±1, 4±1, 6±2, and 6±1 km s^{-1}. For GRO J1655-40 Vp=112±18 km s^{-1} and 2.1±1 km s^{-1}. **Why should be a runaway preferential direction?**

- **BHs of M_{BH}>10 $M_\odot$ are formed by direct collapse, but it is uncertain how BHs of M_{BH}<10 $M_\odot$ are formed. This result from BH-XRBs observations would be qualitatively consistent with high BBH merger rates inferred from GWs.**

BH FORMATION AS FUNCTION OF Z & z HAS BEEN OBSERVATIONLLY CONFIRMED

- In the Local Universe, HMXBs are ~10 times more numerous per unit star formation in galaxies with $Z < 0.2\ Z_\odot$ than in solar-metallicity galaxies (Douna, Pellizza & Mirabel 2016)

- From the Chandra Deep Field South, due to the declining Z with increasing redshift, the X-ray luminosity due to HMXBs in galaxies out to z=2.5 is: $L_{2\text{-}10\ keV}$ **(HMXB)/SFR** $\propto$ **(1 + z)** (Lehmer+ 2016)

- The CIB-CXB coherence require that at least 10%–15% of the CIB sources are accreting BHs (Cappelluti+2013; Kashlinsky 2016) which suggests that **BH-XRBs formed prolifically during re-ionization** (Mirabel+ 2011)

- A recent model predicts substantially larger BH masses of ~25, 60 and 130 $M_\odot$ for metallicity progenitors of $Z/Z_\odot$ = 2 x 10^{-2}, 2 x 10^{-3} and 2 x 10^{-4} (Spera+ 2015)

MASSIVE STARS, THE PROGENITORS OF BBs ARE FORMED IN MULTIPLE SYSTEMS

- >70% of MW O stars are binaries and the frequency of the mass ratio distribution is flat (Sana+ 2012)

- Theoretical models indicate that ~36% of stars in primordial galaxies are formed in small groups, with a high incidence of binaries of several tens of solar masses and (Krumholz,+ 2009; Turk+ 2009; Stacy & Bromm 2014).
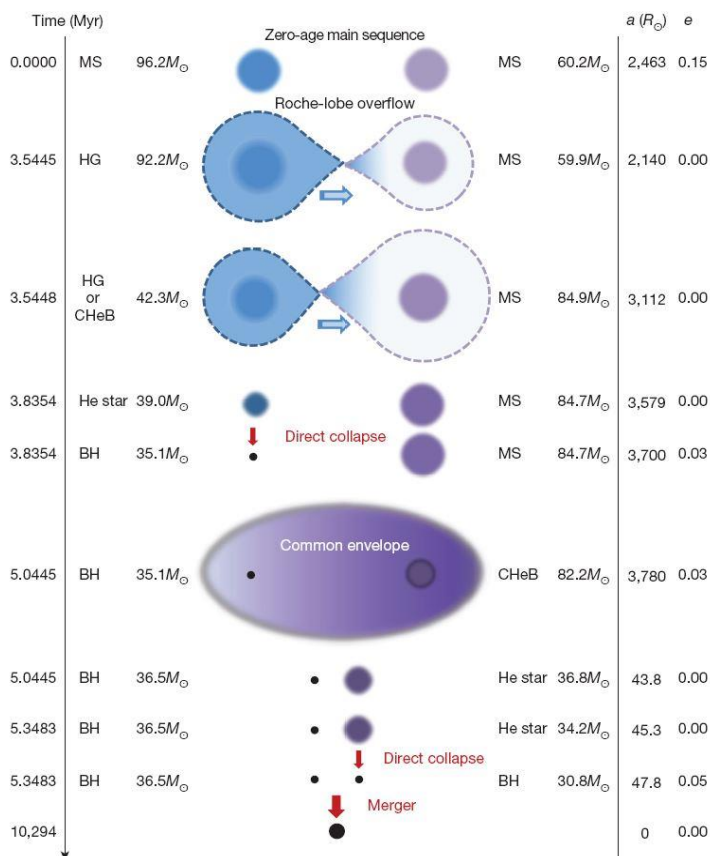
The chemical evolution of the universe $\Rightarrow$ a large fraction of binary massive stars in the early universe end as BH-HMXBs and as BBHs
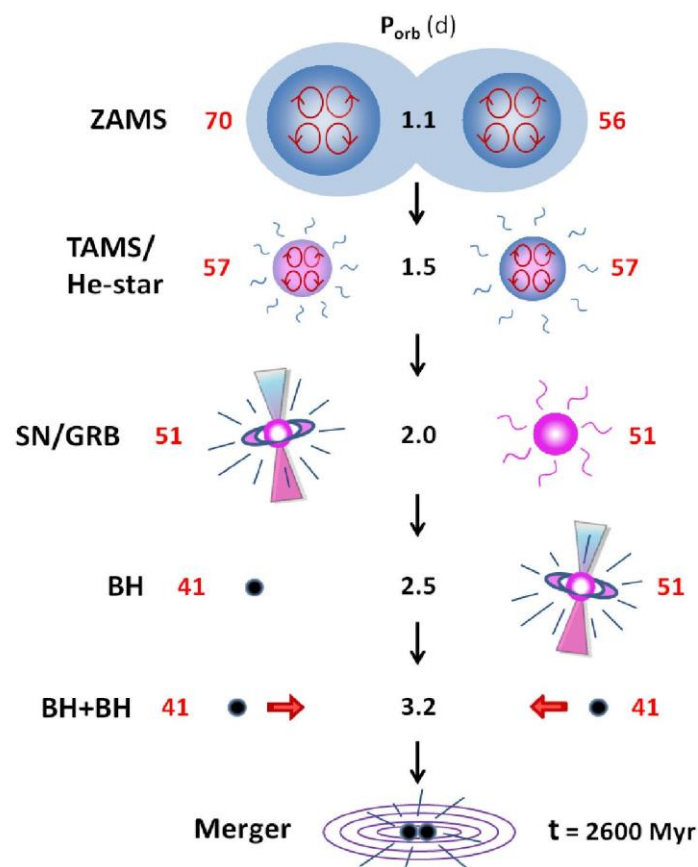
Mirabel et al. (2011) for impact of BH-HMXBs in cosmology

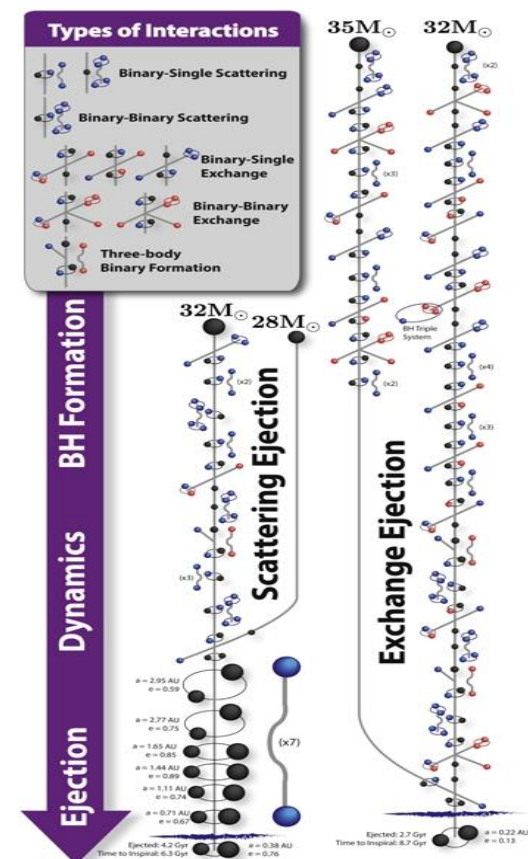# FORMATION OF THE BBHs IN GW150914 FROM BINARY MASSIVE STARS

GW150914 formed from a massive binary star (Belczynski+ Nature 2016)

Massive contact binary (MOB) that remain chemically homogeneous
De Mink+ (2016) & Marchant+ (2016)

GW150914 formed by dynamical interactions in nuclear Clusters
(Rodriguez+ 2016) & Antonini & Rasio 2016)

- **Two stellar models of GW150914 implicitly assume that both BHs of ~30 $M_\odot$ were formed by direct collapse**
- **Could the BHs in GW150914 be primordial?** (Bird+2016; Kashlinsky+2016; Clesse+2016; 2017; Ali-Haimoud & Kamionkowski 2016)

CONCLUSION FROM OBSERVATIONAL STUDIES OF BH-XRBs

- Stars of solar metallicity and >40 $M_\odot$ collapse directly to form BHs by implosion, without energetic SNe and Natal Kicks (e.g. Cygnus X-1) $\Rightarrow$ **BHs may be formed by complet implosion. Does this formation mechanism depends on the BH mass? The mass distribution of BH-BH merger rates from GWs will help answer this question**

- From the kinematics of BH-XRBs there is evidence for BH formation by direct collapse, but BH formation with SNe/Natal kicks is uncertain $\Rightarrow$ **This would be qualitatively consistent with a large estimated BBH merger rate that may be inferred from LIGO/VIRGO observations**

- The theoretically expected metallicity and redshift dependence for the formation of BH-XRBs has now been confirmed by observations $\Rightarrow$ **BHs of ~30 $M_\odot$ up to ~100 $M_\odot$ would naturally be of stellar origin**