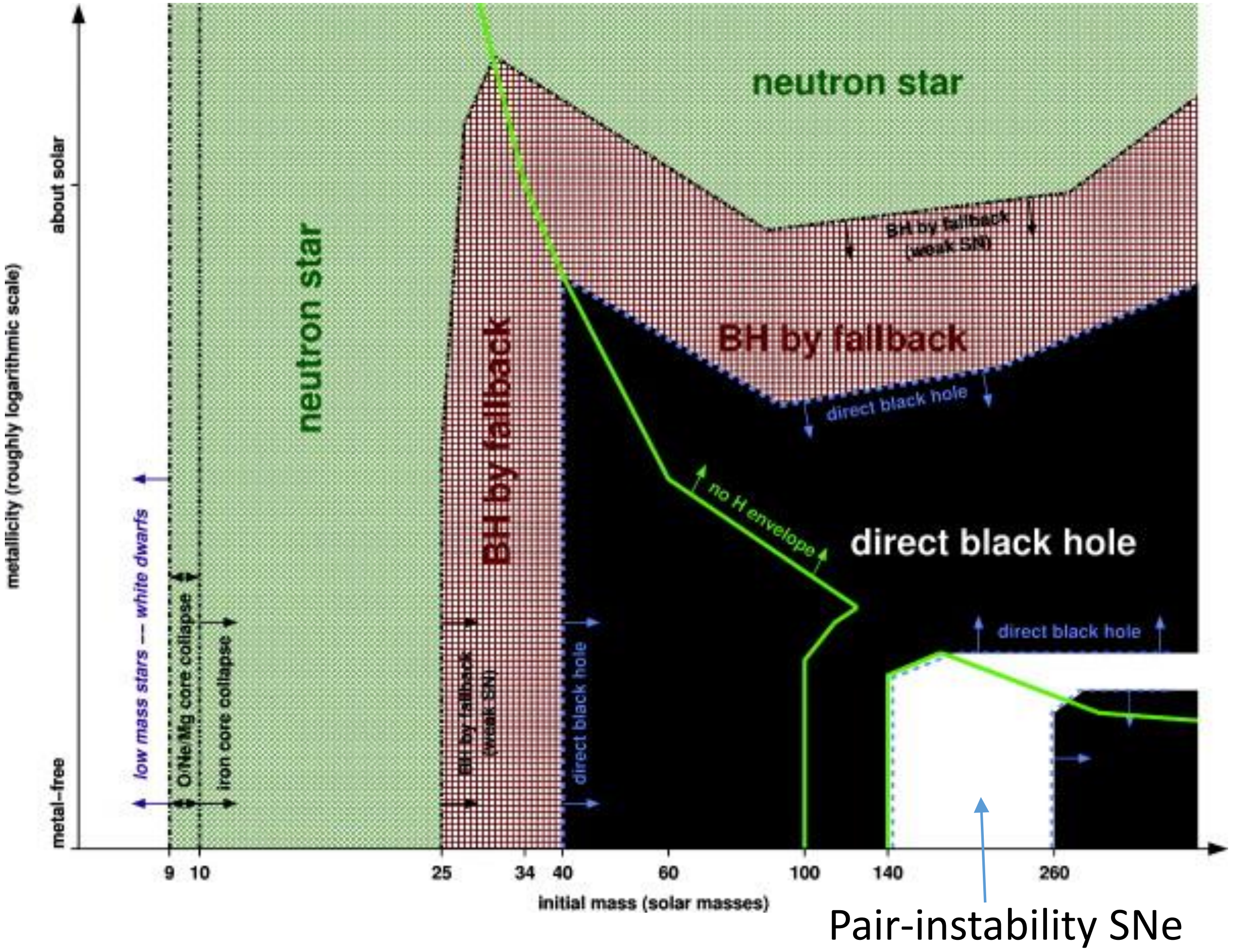
COMPACT JETS AND THE FORMATION OF STELLAR BLACK HOLES

Credit: J.P. Luminet

Félix Mirabel
Saclay-Paris-France & IAFE-BsAs-Argentina

THEORY: THE FORMATION OF StBHs DEPENDS ON MASS & METALLICITY

Model for the evolution of **single stars** (Heger+ 2003)…



BHs can be formed in two different ways:

- by **direct collapse** without a SN or NKs (“in situ”)

or

- by **failed SN** leading to the **delayed formation of a BH by fallback** e.g. Fryer & Kalogera (2001)

Are BHs born with kicks as NSs or by implosion?

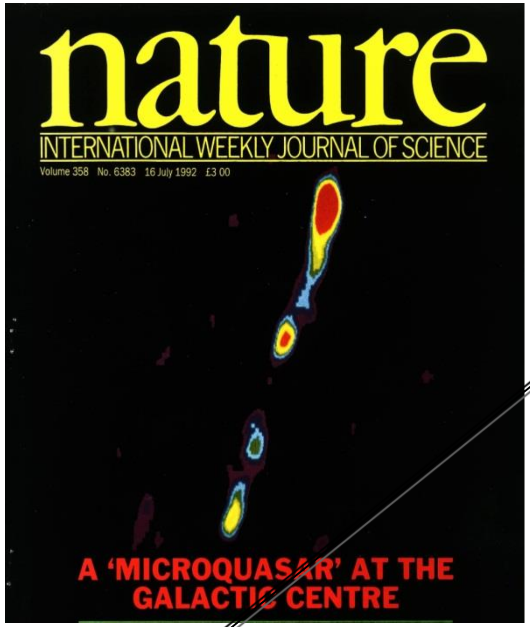
ARE THERE OBSERVATIONAL EVIDENCES FOR BH FORMATION BY IMPLOSION AND Z DEPENDENCE?

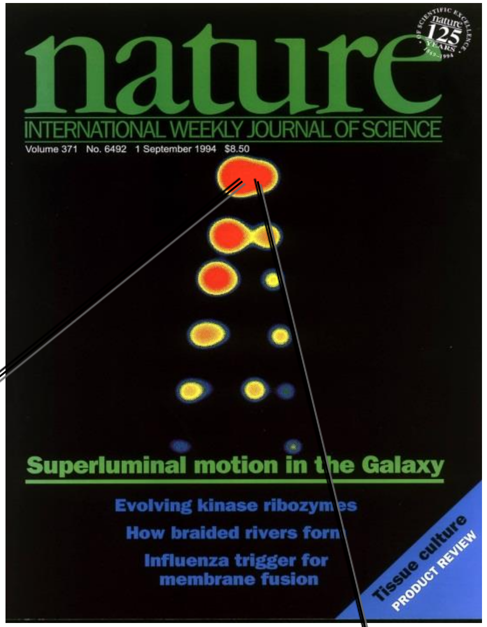
3D KINEMATICS OF BHXBs USING COMPACT μQSO JETS

Mirabel, L.F. Rodríguez+ 1992 Mirabel & L.F. Rodríguez 1994

STEADY JET SOURCES

e.g. 1E 1740-2942





TRANSIENT JET SOURCES

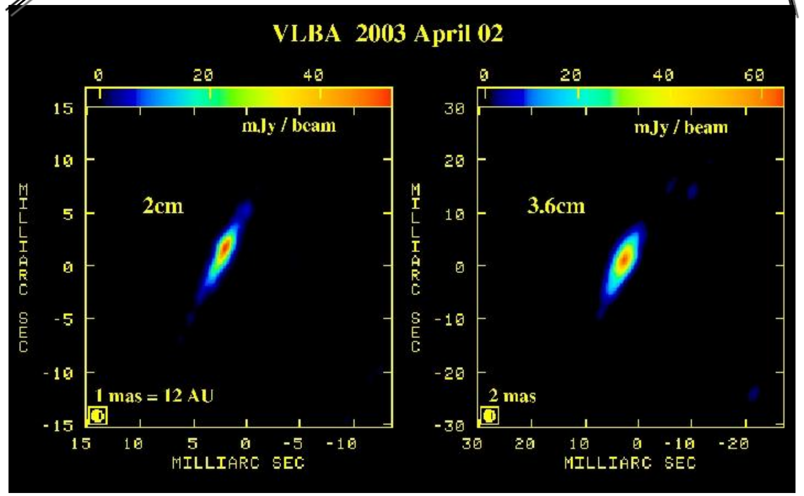
e.g. GRS 1915+105

Accretion disk instabilities & mini-jets in GRS 1915+105 during 1h. Time delays consisten with (van der Laan, Nature 1966)

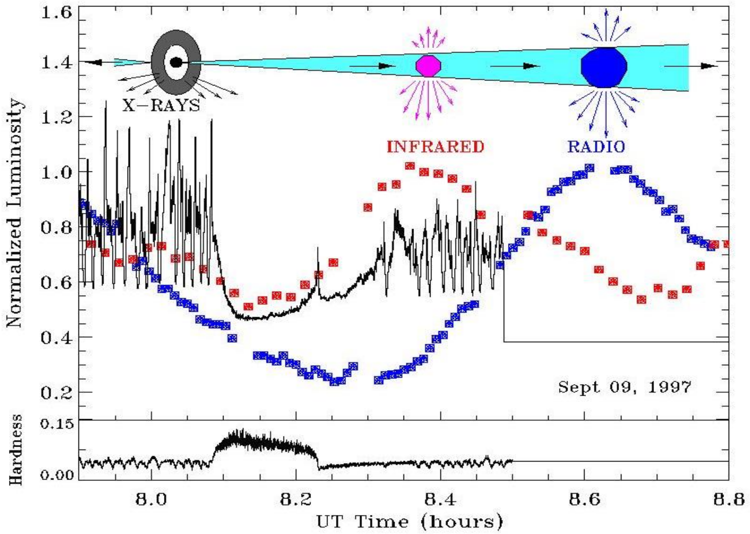
COMPACT JETS

Dhawan, Mirabel, Rodríguez (1997)

VLBI OF COMPACT JETS: Trigonometric parallaxes & proper motions…& GAIA…

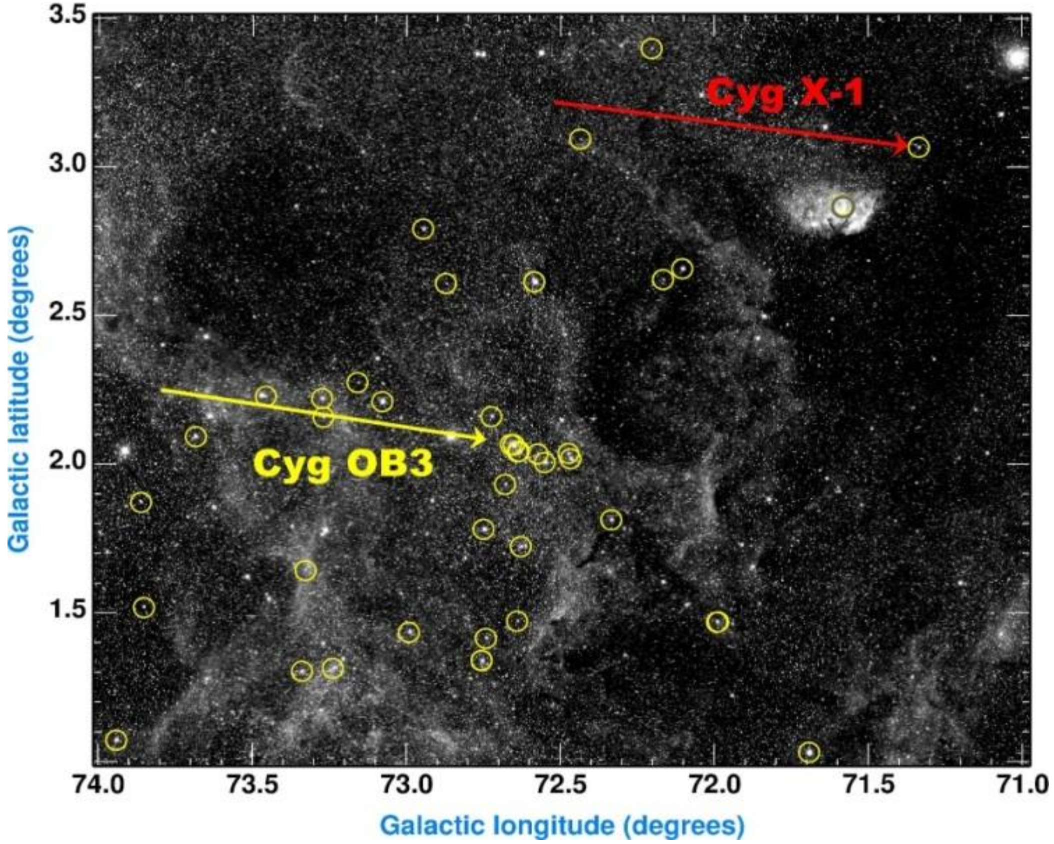


Mirabel & Rodríguez (Nature 1998)



BLACK HOLES FORMED BY DIRECT COLLAPSE

Mirabel & Rodrigues (Science 2003)………



Cygnus X-1

8 years later confirmed and improved by Reid+ (ApJ 2011)

Cygnus X-1: D~1.9 kpc; Mbh~15 $M_\odot$; Mdon ~19 $M_\odot$; V_p<9±2 km/s ⇒ <1 $M_\odot$ in SN; Mprog> 40 $M_\odot$; Mlost ~25 $M_\odot$

GRS 1915+105

Dhawan, Mirabel & Rodríguez+ 2007….Reid+ 2014

GRS 1915+105: D~8.6 kpc; Mbh~10 $M_\odot$; Mdon ~0,5 $M_\odot$; V_p=22±24 km/s ⇒ Galactic diffusion in an old system

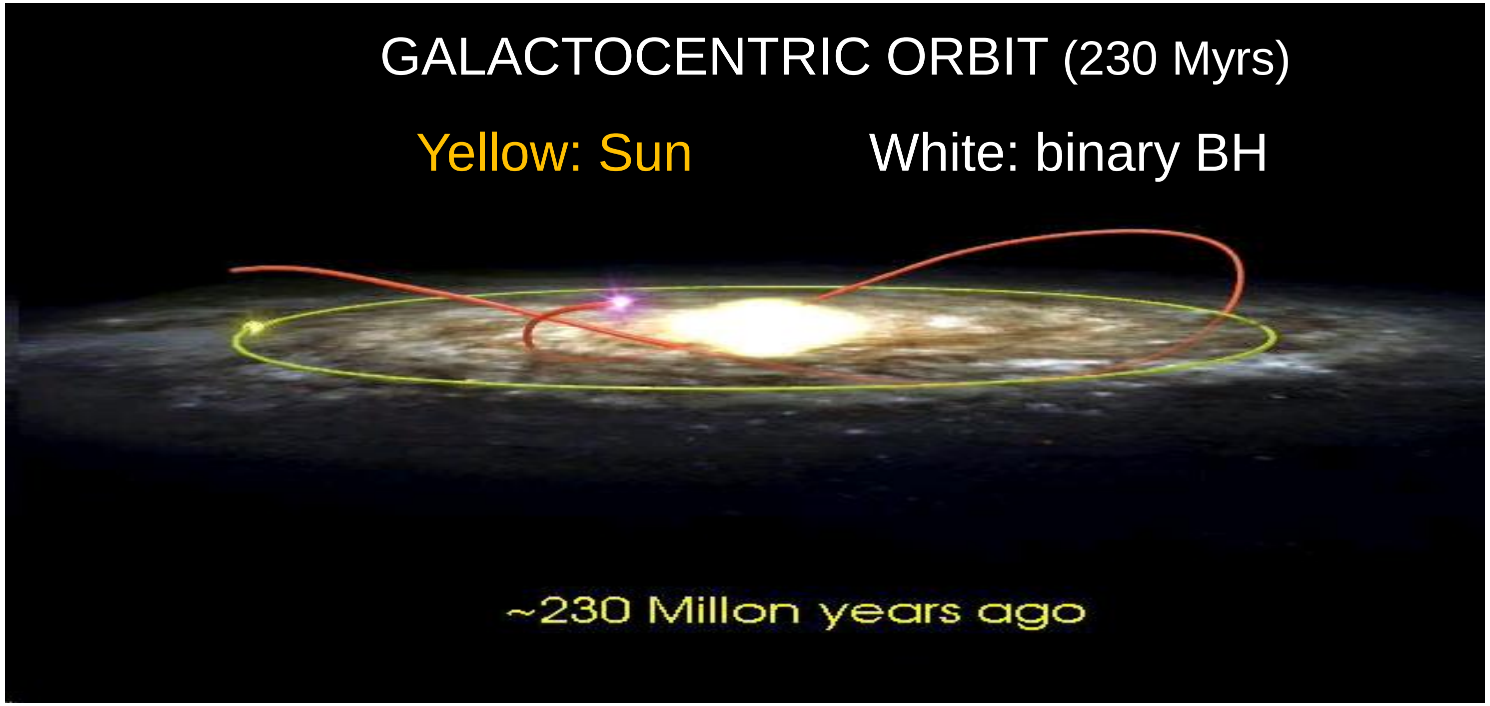
Stars of ~40 $M_\odot$ and Z~$Z_\odot$ may collapse directly and end as BHs

⇒ The BHs remain bound to donor stars, accrete mass & inject X-rays & jets

RUNWAY BLACK HOLES

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

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



Triggered to the Galactic halo from the Galactic disk by a natal SN/kick, or formed by dynamical interaction in a GC & escaped from it with few tens km/s?

GRO J1655-40: M_{BH}~5.3±0.7 $M_\odot$ **M_*~2.4±0.7 $M_\odot$;** **V_p=112±18 km/s** (Mirabel, Mignani+ 2002)

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

ARE THE RUNWAY BH-XRBs TRIGGERED BY NATAL KICKS ON THE BH IN THE X-RAY BINARY?

THE FORMATION OF StBHs DEPENDS ON METALLICITY & REDSHIFT

- In **the Local Universe**, BH-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, Laurent, Mirabel 2016 & 2017)

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

- **The specific ULXs frequency in spirals** increases with the increase in specific star formation rate and the decrease in metallicity (Walton+ 2011 & references therein).

- A **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** (e.g. Mirabel+ 2011)

MASSIVE STARS: THE PROGENITORS OF BH-XRBs & BBs ARE FORMED IN MULTIPLE SYSTEMS

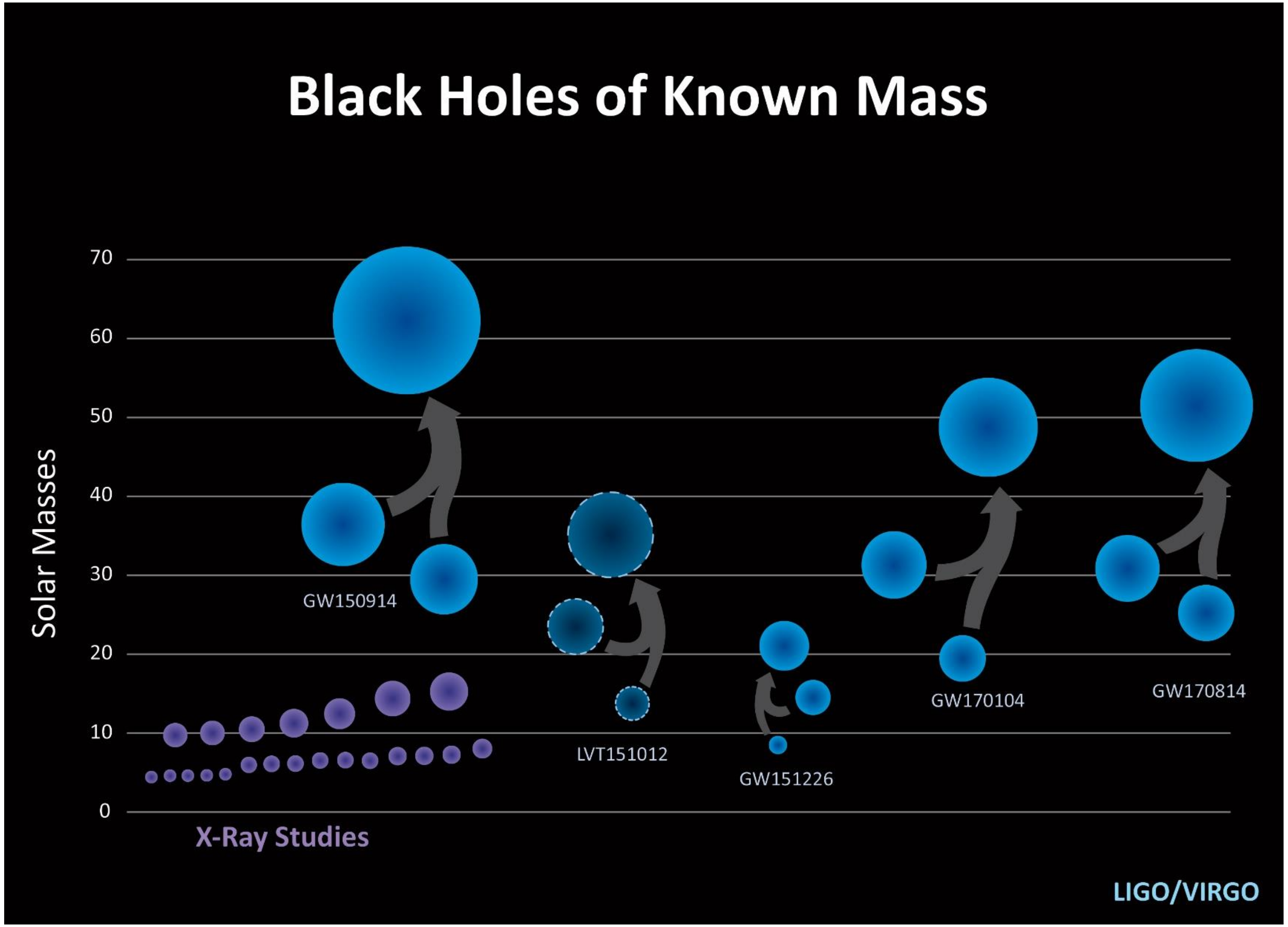
- >70% of MW O stars are binaries and the frequency of the mass ratio distribution is flat (Sana+ 2012)

⇒

If BHs are formed by implosion a large fraction of massive stars in the early universe end as BH-HMXBs and BBHs

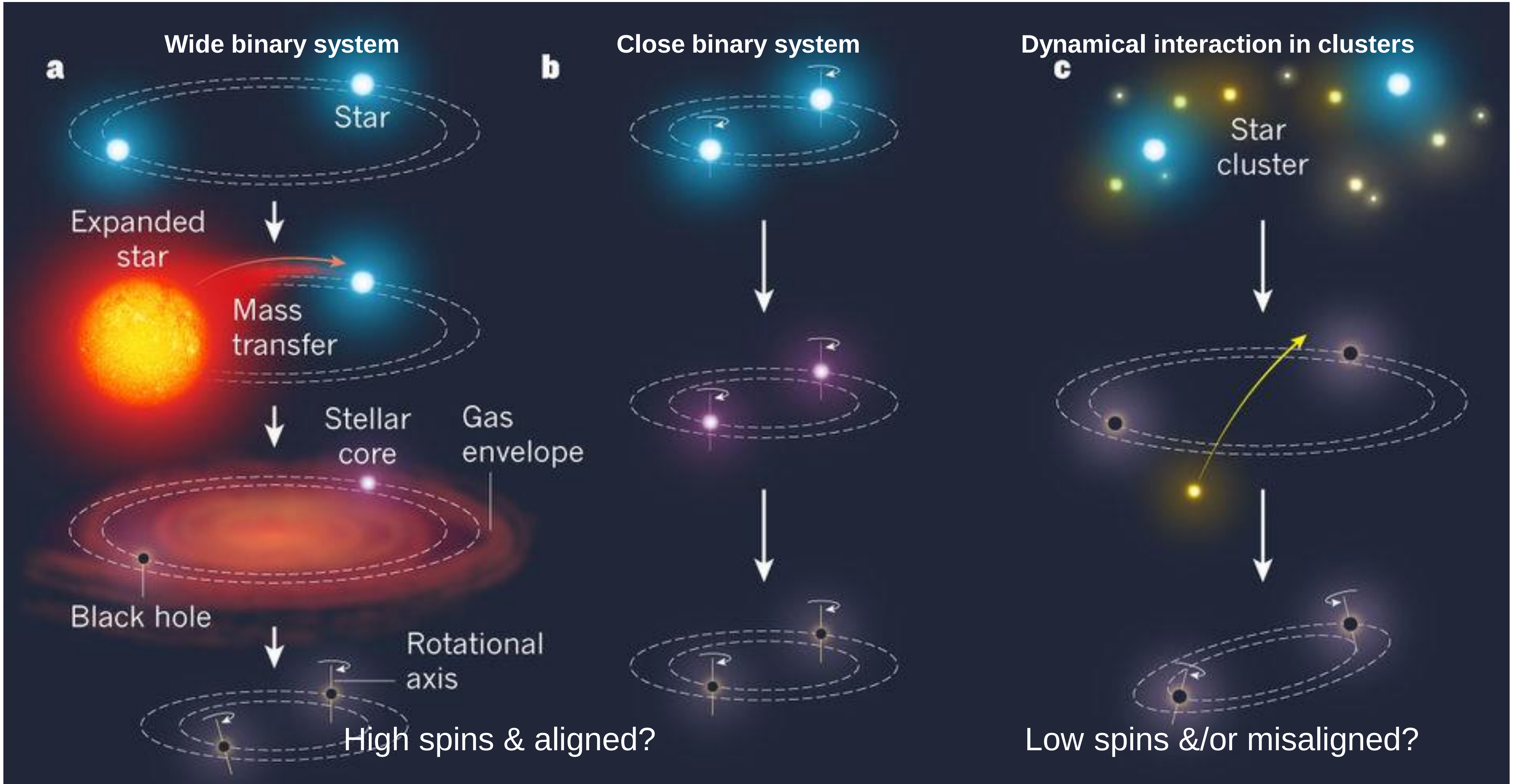
Mirabel, Dijkstra, Laurent, Loeb, Pritchard (2011) for cosmological implications

STELLAR BLACK HOLES IN GRAVITATIONAL WAVE ASTROPHYSICS



Different masses & possibly different spins of StBHs $\Rightarrow$ different formation channels?

FORMATION CHANNELS OF THE BINARY BHs SOURCES OF GWs



High spins & aligned?

Low spins &/or misaligned?

Mandel & Farmer (N&V in Nature 2017)

Summary and conclusions: Formation of Stellar Black Holes

New Astronomy Reviews: http://dx.doi.org/10.1016/j.newar.2017.04.002

• From the kinematics of Galactic BH X-ray binaries in three di-mensions of space it is found that stars of solar metallicity and > 40 M may collapse directly to form BHs by implosion, without energetic SN explosions and Natal Kicks (NKs). In fact, from the kinematics of Cygnus X-1 it is inferred that the BH of ∼15 M was formed in situ with no NK, by the implosion of a progenitor of ∼40 M , that probably went through a Wolf Rayet phase with a total mass loss of ∼25 M .The kinematics of GRS 1915 + 105 suggests that the BH of ∼10 M in this X-ray binary was also formed by implosion with no trigger from a NK. These observations are consistent with core-collapse models based on neutrino-powered explosions of massive stars (Sections 2.1 and 2.4).

• The linear momentum of BH X-ray binaries determined from velocities in three dimensions increases with decreasing BH mass, as expected from core-collapse models. However, this possible trend is inferred from low numbers statistics (only five sources) and its interpretation in terms of kick velocities im-parted to the compact object in the runaway binary is uncertain without knowledge of the binary's origin. X-ray binaries may be formed in different environments and their runaway velocities be caused by a diversity of physical mechanisms (Sections 2.2 and 2.3).

• XTE J1118 + 480 is in the Galactic Halo and if interpreted as a field binary formed in the disk would have received a natal kick > 80 km s −1 , but if formed by dynamical interaction in a globular cluster the BH could have been formed with no energetic trigger. The BH X-ray binaries GRO J1655-40, V404 Cyg, GRS 1915 + 105 and Cygnus X-1 are in the Galactic disk and have relatively low motions in directions perpendicular to the disk. They are respectively 2.1 ±1, 4 ±1, 6 ±2, and 6 ±1 km s −1 . If the BHs in those X-ray binaries would have been born with energetic kicks, it would be intriguing that their motions in di-rections perpendicular to the Galactic disk are so small, unless there is a preference of BH natal kicks in directions along the Galactic disk…The most striking case is that of the runaway BH X-ray binary GRO J1655-40, which has a velocity component on the Galactic plane of ∼112 ±18 km s −1 whereas its velocity component perpendicular to the Galactic plane is 2.1 ±1 km s −1 (Section 2.3).

• It is expected that parallax distances and proper motions of BH-XRBs determined from VLBI observations at radio wavelengths, and with GAIA at optical wavelengths, will allow to determine the velocities in three dimensions accurately enough and for larger samples of BHXRBs, to track their paths to the sites of birth, and better constrain models on stellar BH formation.

• BH-XRB candidates have been identified in globular clusters, and their confirmation would provide evidence for BH forma-tion by either direct collapse and/or sufficiently low natal kicks, since they would not have been ejected from the clusters. It is expected that low mass BHs accreting at low rates could still be present in large numbers far from the globular cluster's central cusps. A way to identify those quiescent BH X-ray binaries in Milky Way globular clusters is by the observation of the characteristic radio continuum self-absorbed synchrotron emission of stellar BHs at low mass accretion rates. he recent possible identification of a dormant intermediate-mass BH candidate in the globular cluster 47 Tucanae inferred from the dynamical state of the cluster, opens a new way to identify these elusive objects, which could have been seeds for the formation of supermassive BHs. (Section 2.6).

• The theoretically expected metallicity and redshift dependence of the formation of BH-XRBs has now been confirmed by observations. From a large set of data of high mass X-ray binaries (mostly containing accreting BHs) in nearby galaxies, it is found that they are typically ten times more numerous per unit star formation in low-metallicity galaxies (< 20% solar) than in solar-metallicity galaxies. The expected redshift dependence of high mass X-ray binaries on metallicity has also been confirmed by observations in the Chandra Deep Field South survey. The X-ray luminosity normalized by the star formation rate due to BH-HMXBs in normal galaxies show out to redshift $z = 2.5$ an evolution that is proportional to redshift, which is due to the declining metallicity of the progenitors of BH-HMXBs with in-creasing redshift, which is consistent with the indications of significant populations of high redshift BHs among the Cosmic Infrared Background sources (Section 3). It is expected that the future X-ray satellite Athena will allow to extend the study of BH-XRBs to higher redshifts.

• A large fraction of stars above some mass limit subject to de-bate (between 17 and 25 M) implode in the dark without lu-minous SNe, most likely ending as BHs. This is inferred from searchers for SN progenitors in optical and infrared archived images, from massive stars that quietly disappear in the dark, from the largest stellar masses in the young stellar populations that host historic supernova remnants, and from the absence of nucleosynthetic products of very massive stars in the nebular spectra of core-collapse supernovae. The detection of accreting BHs at the position of failed SNe by follow up observations in X-rays and radio wavelengths, offers the possibility to find the first observational evidence of BH formation in real time. The enhanced capabilities of the future Athena X-ray satellite and the upgraded VLA and future SKA radio interferometers will play an important role in this area of research (Section 4).

• Three main evolutionary channels have been proposed for Bi-nary Black hole (BBH) formation: (1) BBHs formed by isolated evolution of massive stellar binaries, (2) BBHs formed from tight binaries with fully mixed chemistry, and (3) BBHs formed by dynamical interaction in dense stellar clusters. In model (1) the BH members of BBHs are formed by direct collapse and with no BH natal kicks that would unbind the stellar binary. In model (3) it is tacitly assumed that the members of BBHs are also formed with no BH natal triggers that would eject the BHs from the stellar cluster before BBH formation. Model (2) avoids the physics uncertainties in mass transfer, common envelope mass ejection events, and the still unconstrained BH kicks. However, model (2) assumes massive tight binary pro-genitors of BBHs and has preference for BBHs with large masses as in GW150914, but the relative low BH masses in GW151226 are difficult to reproduce. In principle the formation of the BBH in GW151226 can be accounted by models (1) and (3). (Section 5).

• BBHs formed from relatively isolated massive stellar binaries (channel 1) or contact massive binaries (channel 2) by either direct collapse and sufficiently low natal kicks, will remain in situ and ultimately merge in galactic disks. BBHs formed by dy-namical interactions in the cusps of globular clusters, may be ejected from their birth place and ultimately merge in galactic haloes, like the sources of short gamma-ray bursts.

• The detection by the LIGO-Virgo collaboration of GWs from the fusion of stellar BBHs has open new horizons for BH as-trophysics. Virgo will soon come into operations, and together with LIGO and other future GW detectors will make possible to narrow down the origin of the GWs, allowing the detection of possible electromagnetic radiation coming from the same GW source or its immediate environment, and the identification of its astronomical host. It is expected that in a more distant fu-ture the GW space mission LISA, besides detecting GWs from the fusion of supermassive BHs, will be able to anticipate the time at which the final fusion of stellar BHs will take place, al-lowing extraordinary progresses in the frontiers of physics and astrophysics.

• Most astrophysical insights on the formation of stellar BHs by implosion of massive stars had been based on what we don't see: e.g. the absence of runaway motions in BH-XRBs, the absence of progenitors of core-collapse SNe above some mass limit, the absence of luminous SNe associated to massive stars that suddenly disappear, the absence in the nebular spectra of core-collapse SNe of the expected nucleosynthetic elements from very massive stars … Thanks to the faith on scientific research and technological cre-ativity that made possible the detection of the first sources of gravitational waves, now we have seen direct signals from BHs. Perhaps Saint Augustine was right when in another context he stated: "Faith is to believe what you do not see, the reward of this faith is to see what you believe."

SOME OF THE CONCLUSIONS

- BHs may be formed by complete/almost complete implosion of massive stars $\Rightarrow$ BHs may remain in the progenitor environment

- BBHs of 10-30 $M_\odot$ must have been formed prolifically in the early universe $\Rightarrow$ The large numbers of dwarf galaxies predicted by the λCDM could not form $\Rightarrow$ should exist naked dark matter haloes...

- The results from the studies of BH-XRBs are qualitatively consistent with the high merging rates of BBHs estimated by LIGO-Virgo colla…

- IF IMBHs are formed by mergers of StBHs, GWs may kick them out from the low potentials of globular clusters and dwarf galaxies $\Rightarrow$ Most IMBHs would be naked and swirling around in galactic haloes