STELLAR BLACK HOLES

Félix Mirabel
(CEA-Saclay-France & IAFE-Buenos Aires-Argentina)

1) Sources of heat & partial ionization of the Intergalactic Medium during the reionization epoch of the universe

2) Sources of gravitational waves

STELLAR BHs IN THE REIONIZATION EPOCH

THE « SWISS CHEESE » MODEL for the re-ionization of the IGM:

•The IGM was fully ionized by the UV from the first stars (Pop III & II) $\Rightarrow$ HII regions expanding at < 100 Km/s.

- **WHAT WAS THE ROLE OF HIGH ENERGY SOURCES SUCH AS μQSOs, HMXBs, SNe, GRBs?**

Based on recent results from Stellar Evolution and High Energy Astrophysics:

- I proposed that in galaxies at z>6 a large fraction of Pop III-II stars end as **Stellar BHs in HMXBs** $\Rightarrow$ X-rays & Jets
- **X-rays & jets overtake the HII regions ionized by UVs, heat and partially ionize the IGM over large volumes of space.**

ASTROPHYSICAL GROUNDS FOR THE STELLAR BLACK HOLE HYPOTHESIS

THEORETICAL GROUNDS

- **MOST POP III & II STARS WERE FORMED AS MULTIPLE SYSTEMS**
  Turk+Science 2009; Krumholz+ Science 2009; Clark+ Science 2011; Stacy+…etc.

- **STARS OF LOW Z WITH M > 20 $M_\odot$ END AS BHs DIRECTLY**
  Fryer,1999;Heger+2003;Georgy+2009;Woosley+2008;Nomoto+2010; Linden,Kalogera+2011

- **BHs FORM WITH NO ENERGETIC SNe⇒BH & DONOR REMAIN BOUND**
  Mirabel & Rodrigues, Science 2003; Mirabel+ Nature 2008

OBSERVATIONAL GROUNDS

- **MOST ULXs & LGRBs ARE HOSTED IN LOW Z-HIGH-SSFR GALAXIES**
  Feng & Soria,2011;LeFloc'h,Duc,Mirabel;2003;Fruchter+ Nature, 2006; Perley+ 2014

- **IN LOW Z GALAXIES Lx/SFR IS LARGER THAN IN MAIN-S GALAXIES**
  Thuan+ 2004; Kaaret+ 2014; Douna, Pellizza, Mirabel 2015

- **Lx/SFR EVOLUTION WITH z IS DRIVEN BY Z EVOLUTION IN HMXBs**
  Fragos+2012; Basu-Zych+2012; Lehmer, Basu-Zych, Mineo et al. (2016)

$L_{2\text{-}10\ \mathrm{keV}}$ (HMXB)/SFR α $(1 + z)$ up to z~2.5

DUE TO FEEDBACK FROM BH-HMXBs

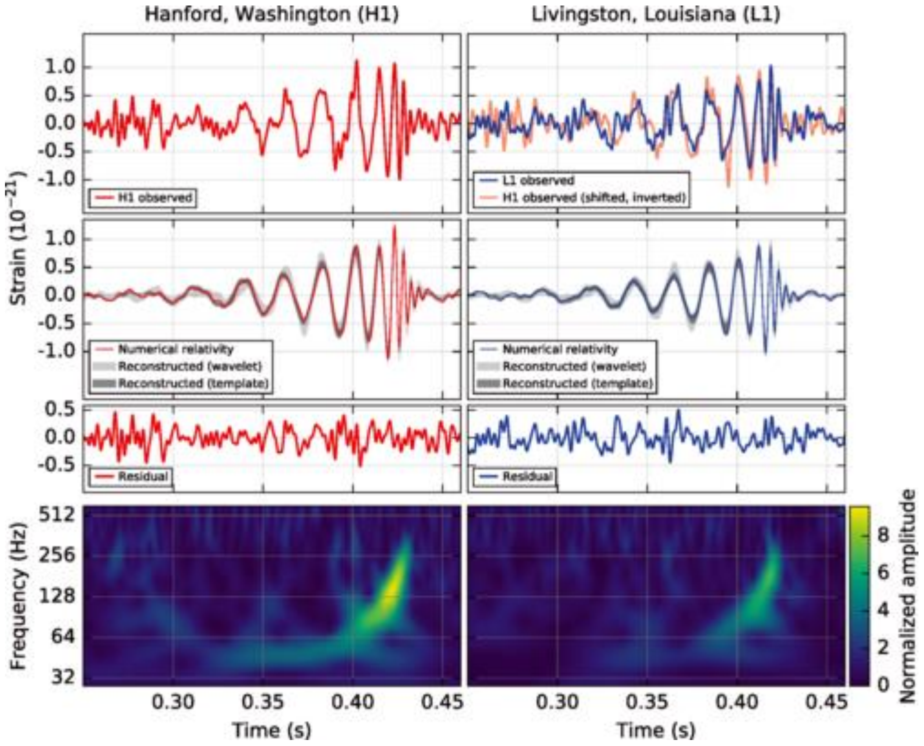
- **I) λ21cm tomography of HI with LOFAR, SKA…will show a smoother end to the dark ages**
- **II) Because of BH-HMXBs heating the λCDM number of dwarf galaxies is reduced**
- **III) There are naked dark matter haloes with M < $10^{8?}$ $M_{\odot}$**
- **IV) BH-BH stellar binaries are the most frequently detected sources of gravitational waves** (Belczynski+ 2011; Ziosi+ 2014)

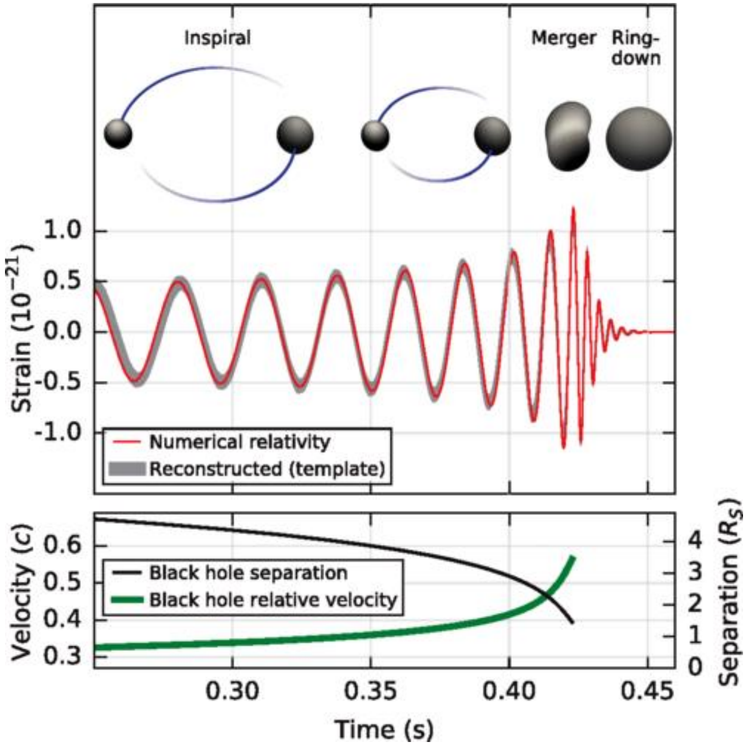
QUESTIONS

- **I) What is the impact of μQSO jets on the IGM?** (Douna, Pellizza, Mirabel, in progress)
- **II) Do X-rays from BH-HMXBs contribute to the ~few % unresolved hard X-ray background?**
- **III) Are BH-HMXBs at z>6 the sources of the radio background discovered with ARCADE 2?** (Fixsen+ 2011; Seiffer+ 2011; Condon+ 2013)

GRAVITATIONAL WAVES FROM BINARY BLACK HOLES

Abbott et al. (LIGO & Virgo collaborations (Physical Review Letters, 11 Feb 2016)





$M = (m_1 \times m_2)^{3/5} / (m_1 + m_2)^{1/5} = c^3 / G \, [5/96 \, \pi^{-8/3} \times f^{-11/3} \, \dot{f} \,]^{3/5}$,

- Luminosity distance of 410 +/- 170 Mpc (z~0.09)
- GW150914 is a merger of a **36 $M_\odot$ & 29 $M_\odot$** BHs with a final BH of 62 $M_\odot$ and 3 $M_\odot$ radiated in GWs
- Peak gravitational wave energy of 3.6 x 10^56 erg/s with no electromagnetic or neutrino counterpart
- This discovery caused surprise because of the rapid detection and large masses of the stellar BHs
- Another detection: GW151226 that would be the result from the fusion of BHs of **14.2 $M_\odot$** & **7.5 $M_\odot$**

BLACK HOLES FORMED IN THE DARK

Working hypothesis:

An binary black hole with components of 30-40 $M_{\odot}$ as GW150914, can be formed from a binary of massive stars if both black holes are formed from low metallicity progenitors by **direct or failed supernova collapse**, namely, with no energetic supernova accompanied by large mass lost that would significantly reduce the mass of the compact objects, and in most cases, unbind the binary system.

Theoretical models predict that those BHs were formed by implosion (Belczynski+ in Nature 2016)

But observations have been elusive and a review of the observational insights of BH formation by direct collapse is of topical interest for Gravitational Wave Astrophysics (Mirabel 2016, in progress)

ARE THERE OBSERVATIONAL EVIDENCES FOR BLACK HOLE FORMATION BY DIRECT COLLAPSE?
ARE THERE OBSERVATIONAL LIMITS FOR THE MASSES OF BH FORMATION WITH NO ENERGETIC SNe?

Important to estimate the BH-BH merger contribution to a stochastic GW background

Observational insights on BH formation by direct collapse

- Kinematics of black hole x-ray binaries to constraint putative natal supernova kicks to BHs

- Search for progenitors of ccSNe in archived images to constraint the progenitor masses

- Identification of massive stars that quietly disappear without optically bright SNe

- Spectroscopy of the nebular emission of SNe to constraint the progenitor masses by the spectral lines from nucleosynthetic products

- Detection of gravitational waves produced by fusion of binary black holes

Conclusion

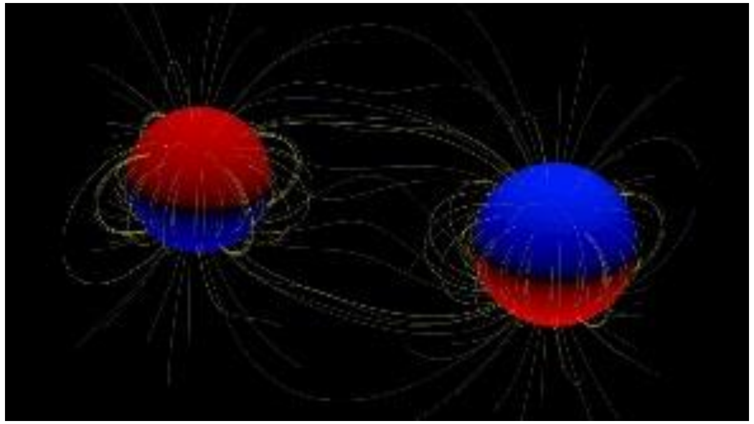
- BHs of ~10 $M_{\odot}$ and lower masses are formed by implosion of stars of > 18 $M_{\odot}$

- A high fraction of massive stars in the universe end as binary black holes

FROM MASSIVE STELLAR BINARIES TO BBHs

MASSIVE STELLAR BINARY

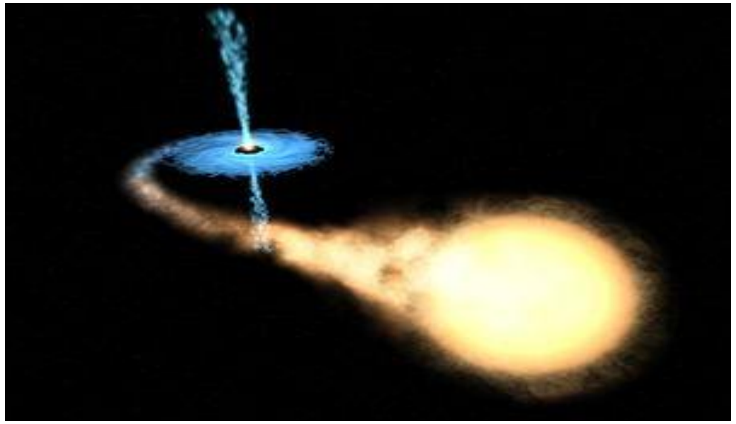
>70% found in multiple systems



BLACK HOLE HIGH MASS X-RAY BINARY

BH-HMXB

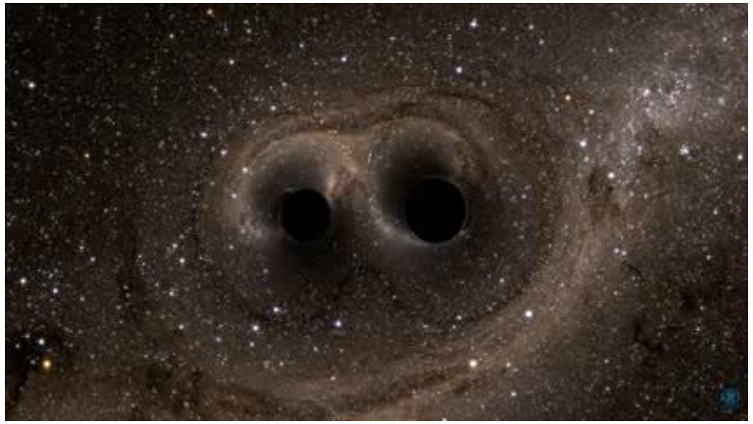
Only 3 known in the Milky Way



BINARY BLACK HOLES

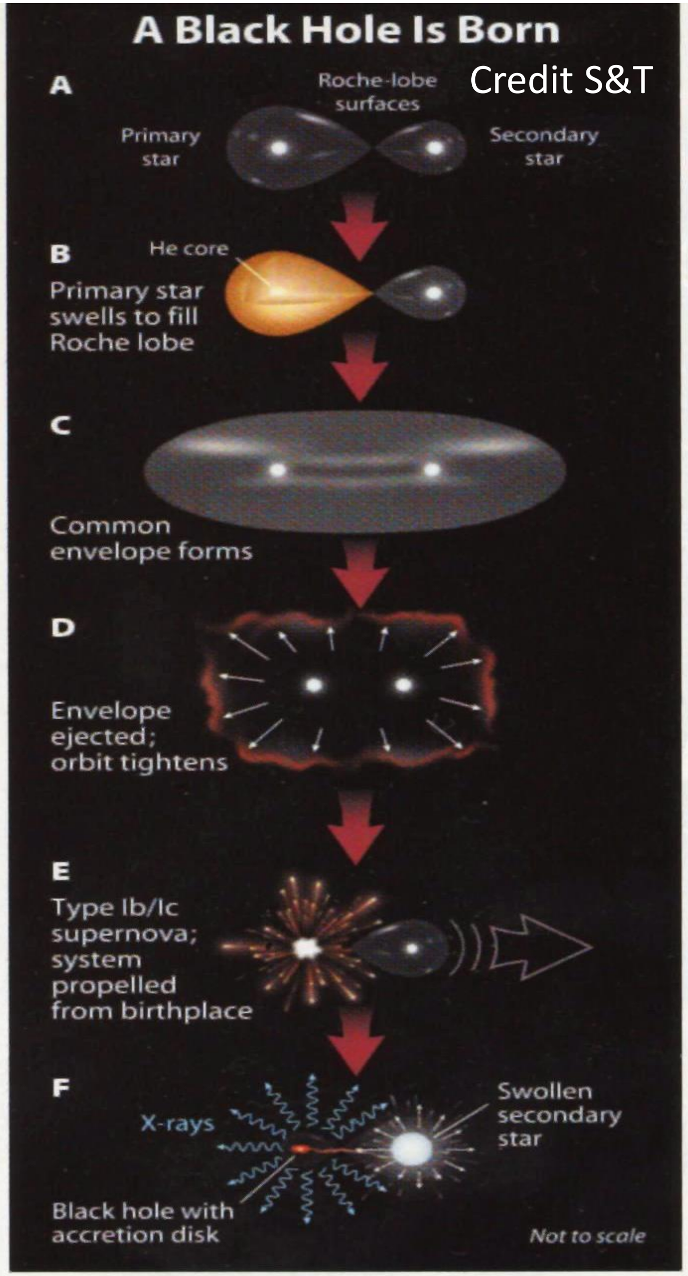
BBHs

GW150914 & GW151226



- In “Stellar black holes at the dawn of the universe” Mirabel et al. A&A 2011 predicted a prolific formation of BH-HMXBs (News & Views in Nature 2011)
- What fraction of massive stellar binaries end as BH-HMXBs, and what fraction end as BBHs?

INSIGHT ON BH FORMATION FROM THE KINEMATICS OF BH-XRBs



CORE COLLAPSE MODELS:

Stellar black holes may form with no SN energetic kicks
(Fryer & Kalogera; Woosley & Heger; Nomoto+; Sukhbold+ 2016...)

- **IS THERE ANY EVIDENCE FOR STELLAR BH FORMATION BY DIRECT COLLAPSE?**
- **IS THERE A RELATION BETWEEN KICK VELOCITIES AND BH MASS?**

TEST OF CORE COLLAPSE MODELS USING THE KINEMATICS IN 3 DIMENSIONS OF 5 μQSOs BHs:

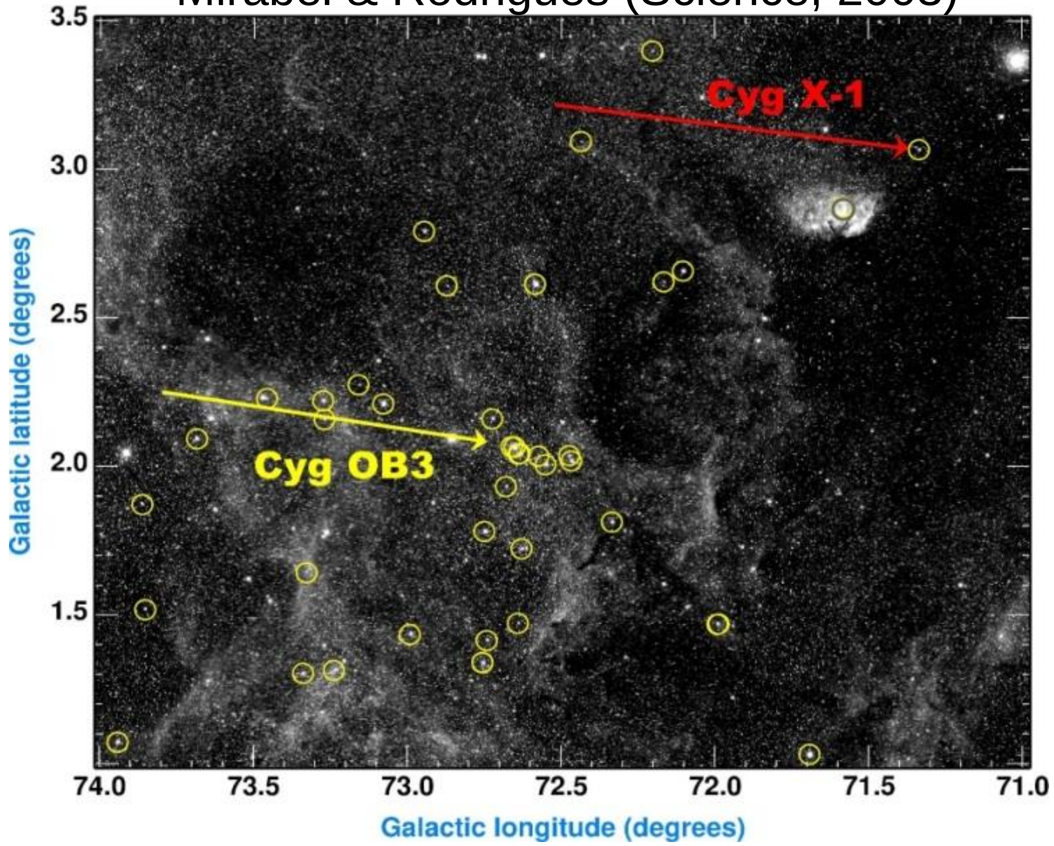
From 3x10^8 BHs in MW, 20 BHXRBs known, 5 BH-μQSOs with spatial Vp

Mirabel et al. (2001-2009)

BLACK HOLES FORMED BY DIRECT COLLAPSE

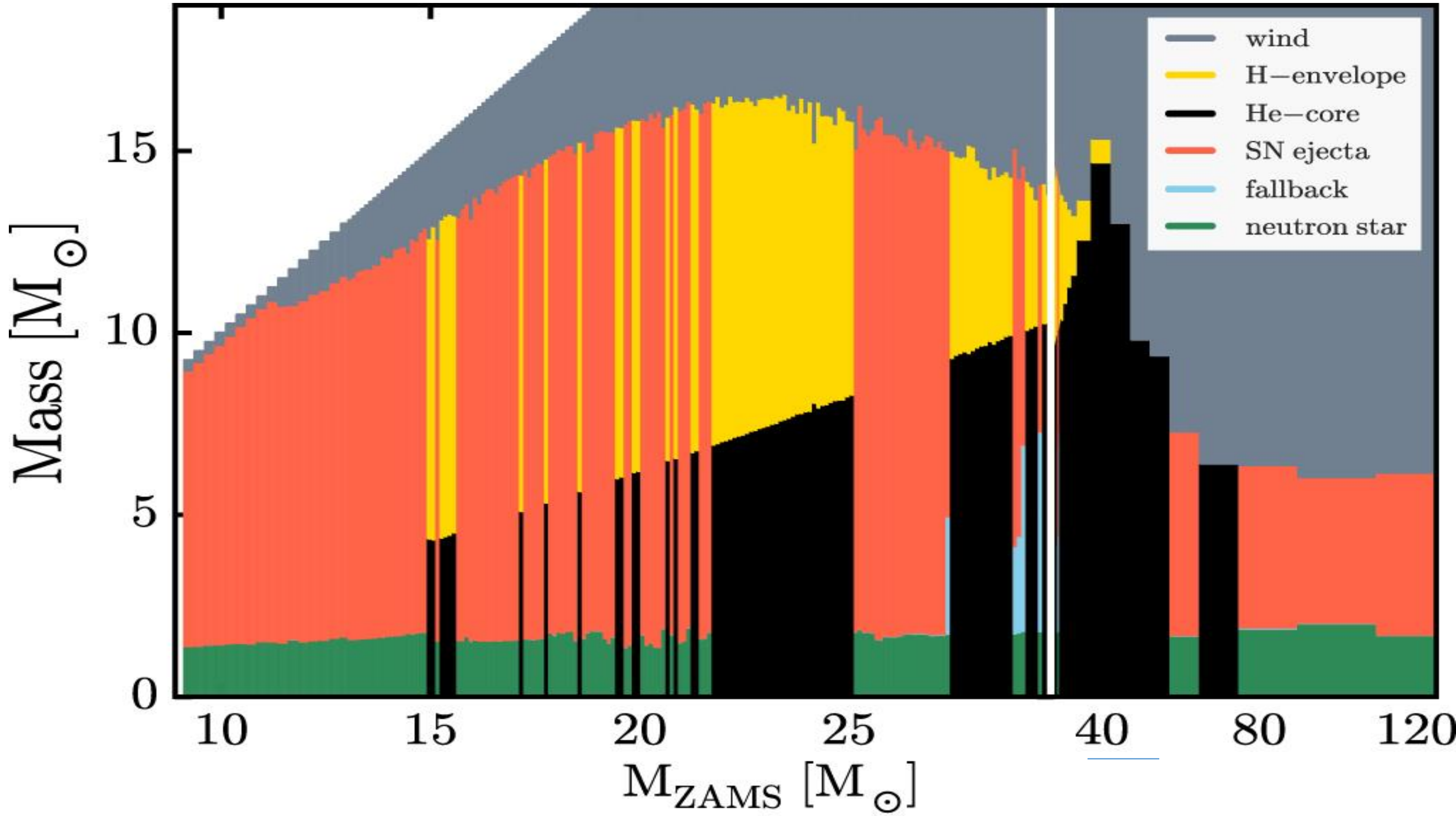
OBSERVATIONS

Mirabel & Rodrigues (Science, 2003)



THEORETICAL MODEL

Islands of exploitability in a sea of BH formation (Sukhbold+ 2016)

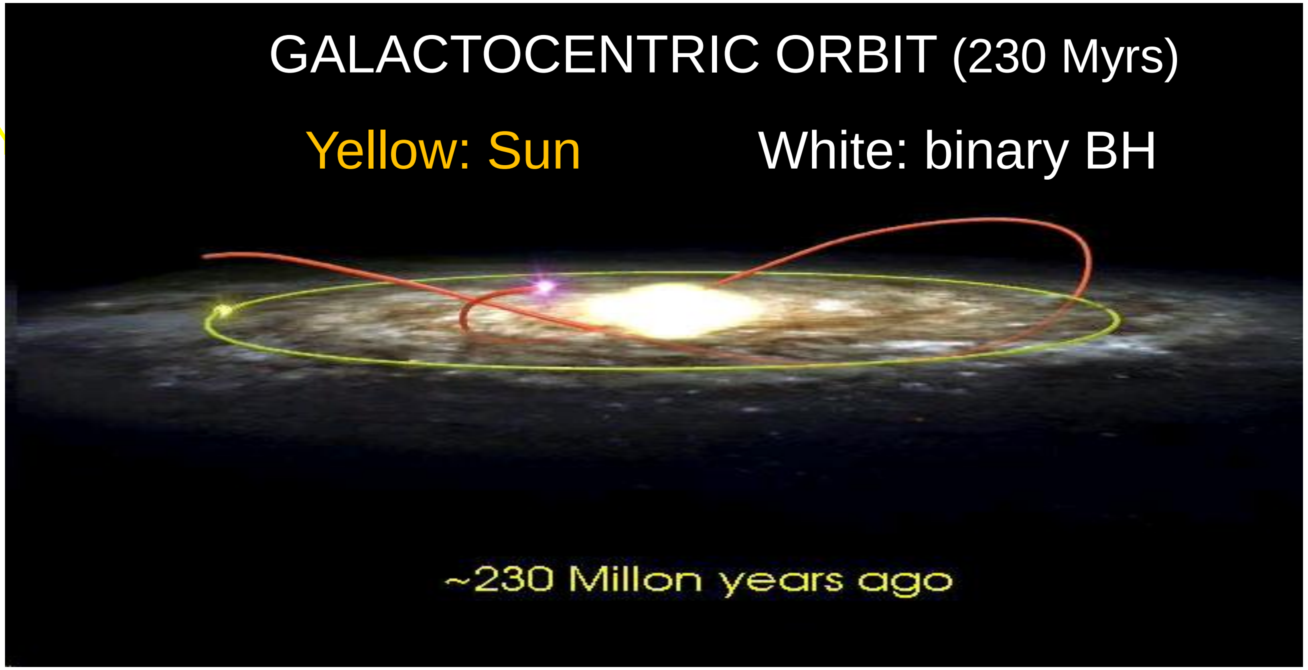


- **Cygnus X-1:** Mbh~15 $M_\odot$; Mdon ~19 $M_\odot$; V_p< 9±2 km/s ⇒ <1 $M_\odot$ in SN; Mprog> 40 $M_\odot$; Mwind ~25 $M_\odot$ in Worf Rayet
- **GRS 1915+105:** Mbh~10 $M_\odot$; V_p=22±24 km/s ⇒ Galactic diffusion; **Mprog > 38 $M_\odot$; < 2 $M_\odot$ in SN**
- **Stars of ~40 $M_\odot$ and Z~$Z_\odot$ may collapse directly to BHs**

THREE RUNAWAY BLACK HOLES

XTE J1118+480 M_{BH}~7 $M_\odot$ M_*~0.4 $M_\odot$; **Vp=145-210 km/s**

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

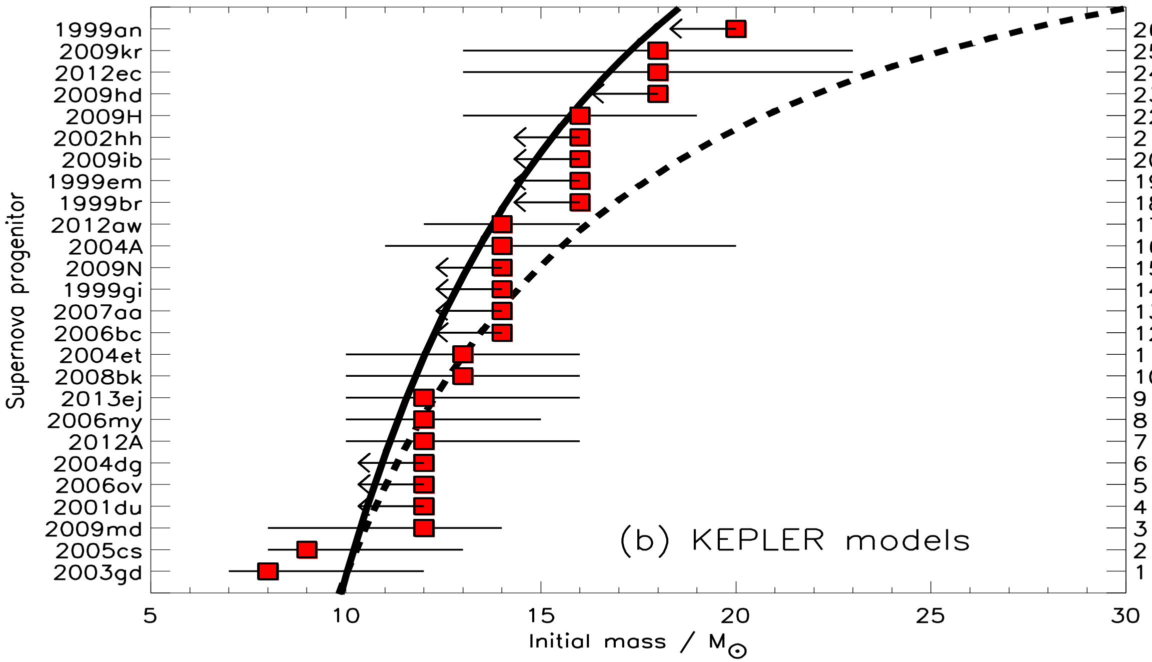


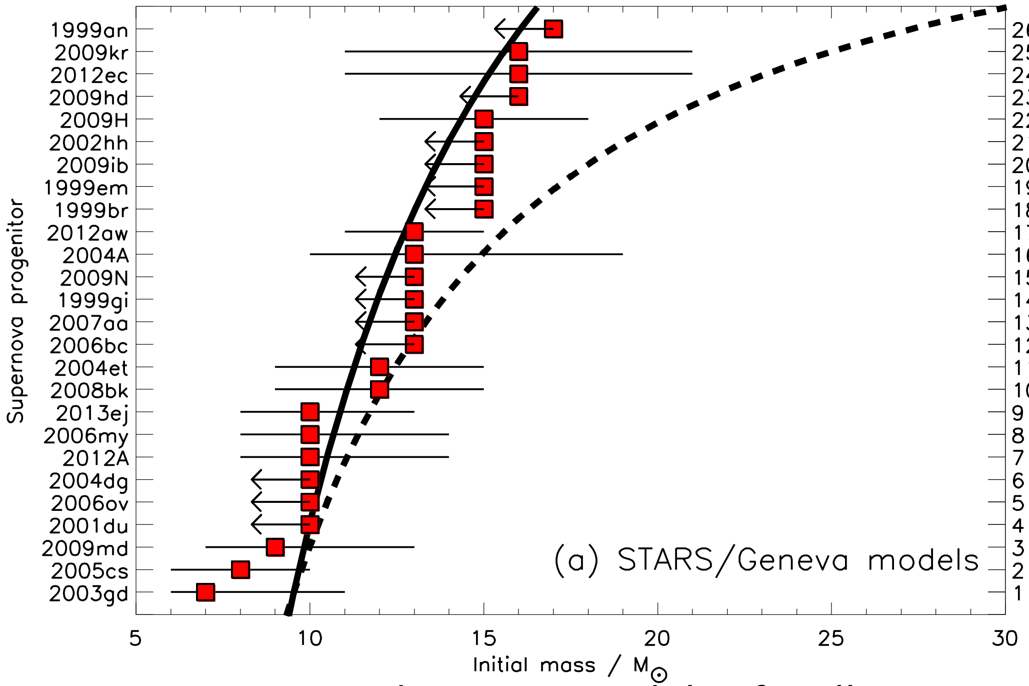
- **GRO J1655-40**: Fossil of a HPN (Israelian et al. Nature 1999)
  M_{BH}~5 $M_\odot$ M_*~2 $M_\odot$; D=1-3 kpc; **V_p=112 km/s** (Mirabel et al. 2002)
- **V404 Cyg** M_{BH} ~9$M_\odot$ M_*~0.8 $M_\odot$ **V_p= 39 km/s** (Miller-Jones et al. 2015)

Not knowing if these runaway x-ray binaries were formed in dense star clusters or from "isolated" binaries, it cannot be excluded the possibility that these BHs of ~5 $M_\odot$, ~7 $M_\odot$ and ~9 $M_\odot$ were formed by implosion.

SEARCH FOR THE PROGENITORS OF BRIGHT SNe

In high resolution images from space and ground (Smartt 2015)





Mass of stellar progenitor of core collapse SNe in the context of the STARS, Geneva, and KEPLER models of stellar evolution. The detections are marked with error bars, the limits with arrows, and the lines extend from the minimum to the maximum masses from cumulative Salpeter IMFs. The mass distribution need to be truncated ~16.5 $M_\odot$ & ~18.5 $M_\odot$.

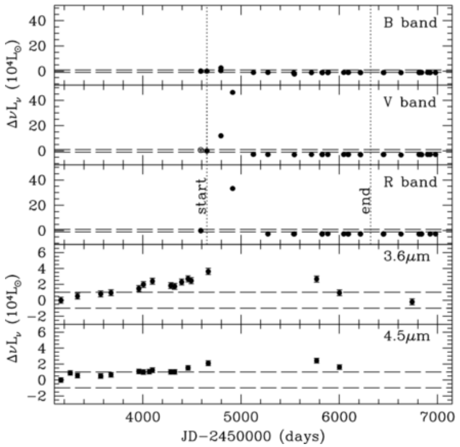
Among 45 SNe with either detected progenitors or upper limits, there is a remarkable deficit of stars above an apparent limit of log $L/L_\odot$ ~5.1 dex ⇒ 16-18 $M_\odot$. II-P SNe are the explosions of red supergiant stars (RSGs) which are believed to have masses in the range of 10 $M_\odot$ to 40 $M_\odot$

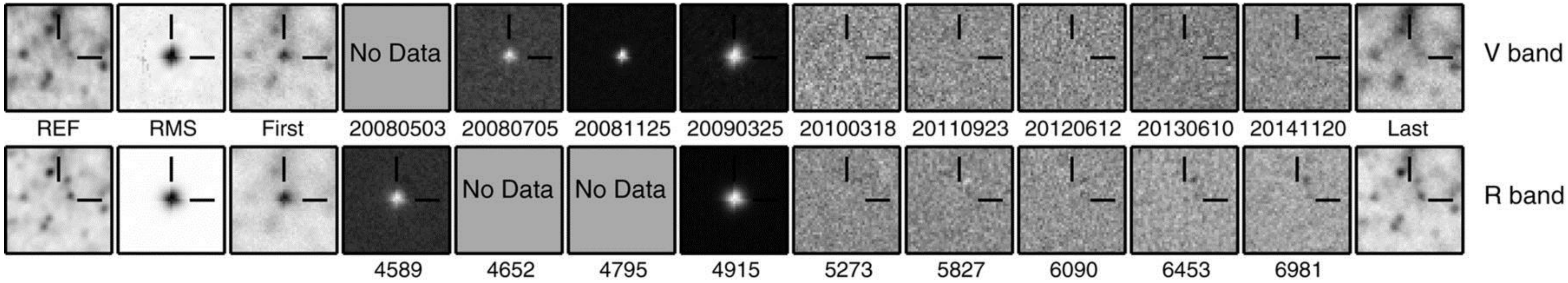
Stars of >20 $M_\odot$ collapse directly to BHs. This may be relevant to all Type II SNe (Smartt, 2015)

SURVEYS FOR FAILED SUPERNOVAE

Repeated observations of nearby galaxies to search for massive stars that disappear without bright supernovae

- **Large Binocular Telescope** Gerke, Kochanek & Stanek (2015) observed 27 nearby galaxies

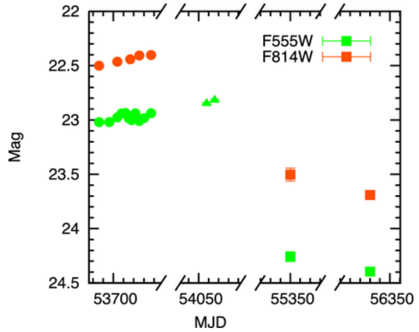


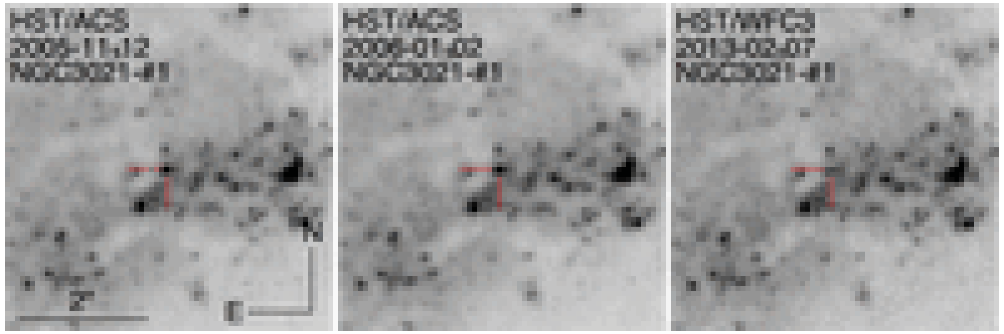


One candidate with 18-25 $M_\odot$ likely associated with a failed SN.

If real ⇒ 30% of CCs are failed SNe **If rejected ⇒ < 40 % of CCs are failed SNe**

- **Systematic analysis of archival HST images** Reynolds, Fraser & Gilmore (2015): 15 targets





One candidate of 25-30 $M_\odot$ that underwent an optically dark core-collapse

Recent models predict a transient display
Lovergrove & Woosley (2013); Sukhbold+(2016)

INDIRECT STRATEGIES

- From HST photometry to generate color-magnitude diagrams of stars within 50 pc of historic ccSNe in galaxies at < 8 Mpc it is concluded that there is no single high-precision progenitor of > 20 $M_\odot$ (Williams+ 2014)
- The spectroscopy of SN nebulae show that the observed evolution of the cooling lines of oxygen cannot reconcile with the expected nucleosynthesis products from Type II SNe with > 20 $M_\odot$ (Jerkstrand+ 2014)

POSSIBLE CAVEATS

Circumstellar dust, luminosity analysis, sample selection, limited number statistics…

It is unlikely that such biases could account for the remarkable stellar mass limit of 18-20 $M_\odot$ for the progenitors of Type II SNe found by different observational methods.

IMPLICATIONS OF BH FORMATION BY DIRECT COLLAPSE FOR GRAVITATIONAL WAVE ASTRONOMY

- If as theoretical models (e.g. Stacy & Bromm 2014) predict that the fraction of massive stellar binaries of $Z < 0.1\ Z_\odot$ is of 36%, have flat frequency mass ratios, and primaries of > 20 $M_\odot$ implode before the primary expands and engulfs the secondary in a common envelope phase (Belczynski+ 2002), they evolve into BH-HMXBs with secondary's that will also implode froming BHs. This implies that ~30% of low metallicity stellar binaries with primaries of > 40 $M_\odot$ end as BBHs, as the source of gravitational waves GW150914. ⇒

A LARGE FRACTION OF LOW Z MASSIVE STARS END AS BINARY BLACK HOLES

the precise fraction depends on the IMF for $Z<0.1\ Z_\odot$ which is believed top heavy (Stacy & Bromm 2014)

- In principle, mergers of stellar black holes should only produce gravitational waves, with no electromagnetic signals. However, if black holes are formed by direct collapse, they will remain in their birth place (e.g. in the disks of galaxies), and electromagnetic signals will be produced by the interaction of the energy release of gravitational waves with the surrounding interstellar medium. ⇒

ELECTROMAGNETIC SIGNALS MAY BE ASSOCIATED TO GWs FROM BH-BH MERGERS

ASTROPHYSICAL IMPLICATION

Merger rate of BBHs based on the assumption of BH formation by direct collapse

Abbott et al. 2016, ApJ 818 L22 A2016

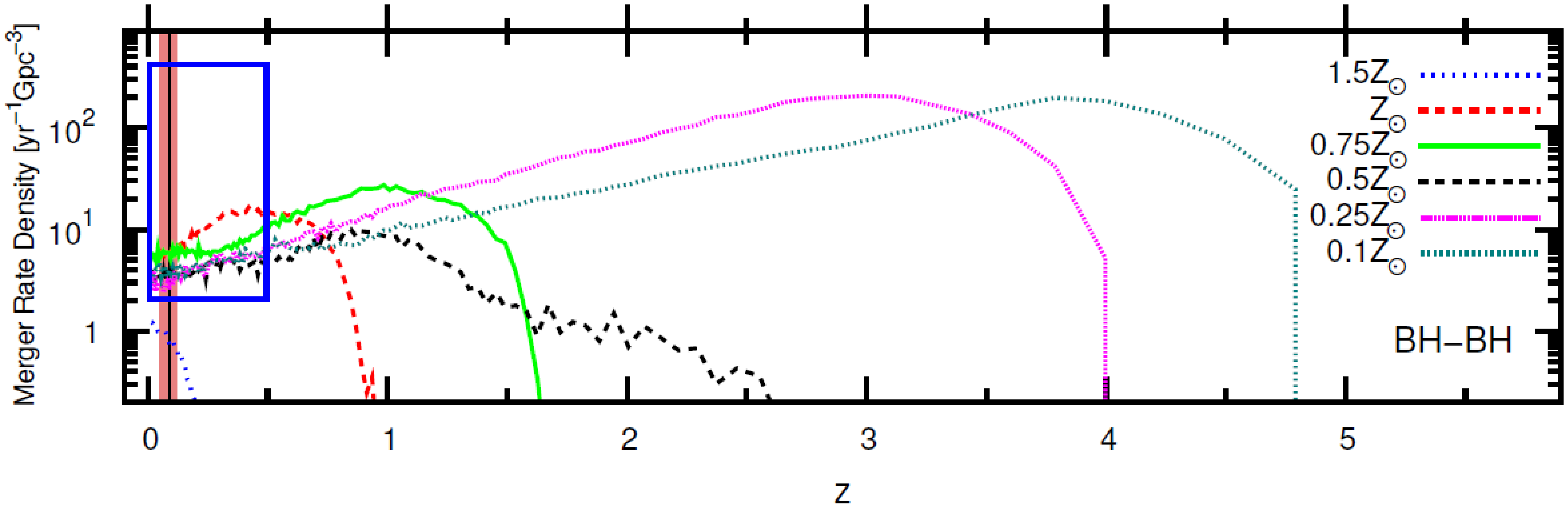


Figure 2. Predictions of BBH merger rate in the comoving frame ($Gpc^{-3}\,yr^{-1}$) from isolated binary evolution as a function of redshift for different metallicity values (adopted from Figure 4 in Dominik et al. 2013). At a given redshift, the total merger rate is the sum over metallicity. The redshift range of GW150914 is indicated by the vertical band; the range of the BBH rate estimates and the redshift out to which a system like GW150914 could have been detected in this observing period are indicated by an open blue rectangular box.

CONCLUSION FROM OBSERVATIONS

- **We don't see peculiar velocities in some BH-HMXBs (e.g. Cygnus X-1), which suggests that black holes with masses as low as ~10 $M_\odot$, and perhaps with even lower masses, as the one of 7.5 $M_\odot$ in GW151226 can be formed by direct collapse without strong kicks.**

- **We don't see in the direct and indirect optical/infrared surveys, progenitors of core collapse supernovae with masses > 18 $M_\odot$ $\Rightarrow$ They may become black holes in the dark.**

- **More than 70% of stars of spectral type O in the Galaxy are in binaries with a flat frequency of the mass ratio (e.g. for 30 $M_\odot$ stars half of the companions have > 15 $M_\odot$)**

- **Caveat: Most evidences are based on what we don't see:** e.g. absence of peculiar velocities in BH-XRBs, absence of progenitors of SNe with >18 $M_\odot$, absence of large masses of oxygen expected in ejecta…

Now, direct signals from black holes have been seen…

Saint Augustine: "Faith is to believe what you do not see, the reward of this faith is to see what you believe."