GTT WORK ON THE COLLISION OF HVCs WITH GALACTIC DISKS

Astron. Astrophys. 170, 107–113 (1986)

ASTRONOMY AND ASTROPHYSICS

The collision of high-velocity clouds with a galactic disk

G. Tenorio-Tagle[1,2], P. Bodenheimer[1,2], M. Różyczka[1,3], and J. Franco[4]

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Received May 26, accepted July 22, 1986

THE ASTROPHYSICAL JOURNAL, 256:112-119, 1982 May 1

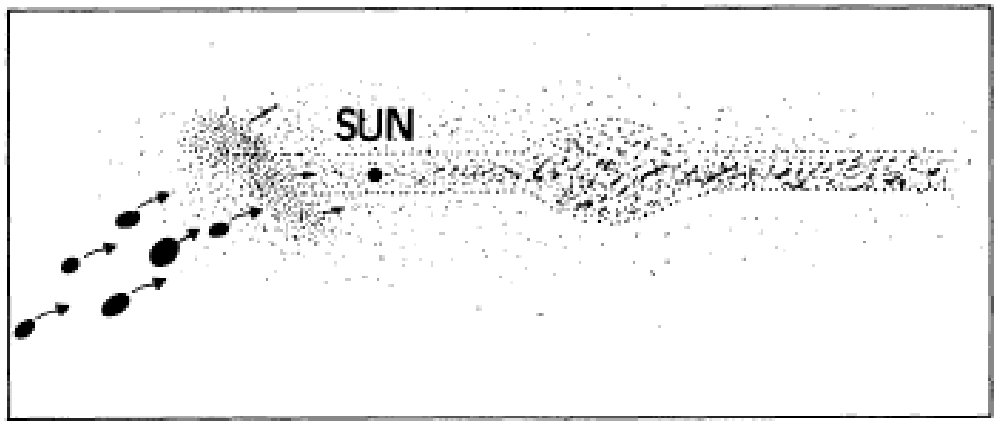


FIG. 3.—Sketch of the model proposed for the impinging stream of very high velocity clouds producing a Galactic splatter in the anticenter of the Galaxy.

INFALLING CLOUDS WITH VERY HIGH VELOCITIES: A COLLISION WITH THE MILKY WAY IN THE ANTICENTER

I. F. MIRABEL
Department of Physics, University of Puerto Rico
Received 1981 August 25; accepted 1981 November 11

THE ASTROPHYSICAL JOURNAL, 333:826–839, 1988 October 15

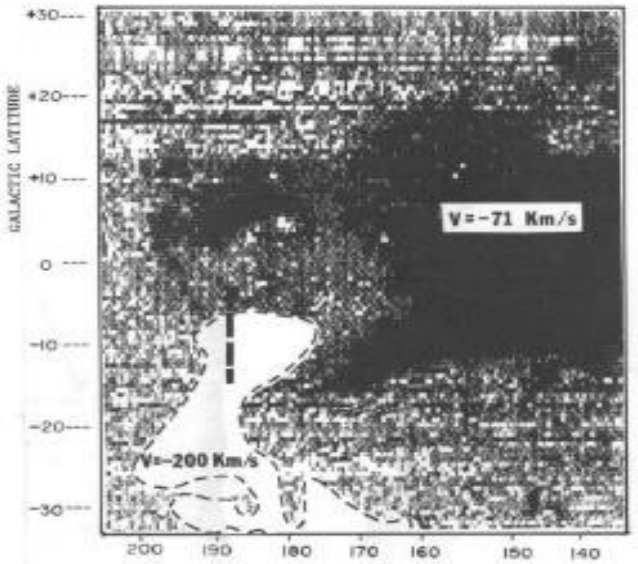


FIG. 1.—Twenty-one centimeter line emission contour of the colliding very high velocity cloud ($v = -200$ km s^{-1}) represented in white (data from Hulsbosch and Wakker 1988), superposed on a gray-scale representation of the H I anticenter supershell centered at $v = -71$ km s^{-1} (Heiles 1984). The broken line represents the extent of the high-resolution position-velocity maps shown in Fig. 2.

ON THE ORIGIN OF THE ORION AND MONOCEROS MOLECULAR CLOUD COMPLEXES

J. FRANCO,[1,2] G. TENORIO-TAGLE,[1,2] P. BODENHEIMER,[2,3] M. RÓŻYCZKA,[2,4] AND I. F. MIRABEL[5]
Received 1988 January 4; accepted 1988 April 12

1) From surveys of HVCs of HI in the center and anticenter of the Galaxy it was inferred an infall of 1 $M_\odot$/yr
2) A stream of HVCs in the anticenter impact the disk at ~300 km/s triggering an hiper-shell of 10^{54} ergs = 10^3 SNe
3) The SNe overall injection of energy on the disk >> than infalling HVCs but HVCs can inject larger energies in small regions

HIGH MASS STARS THAT DO NOT EXPLODE AND END AS BLACK HOLES

Félix Mirabel

CEA-Paris-France & IAFE-BsAs-Argentina

IMPACT OF STELLAR BHs:

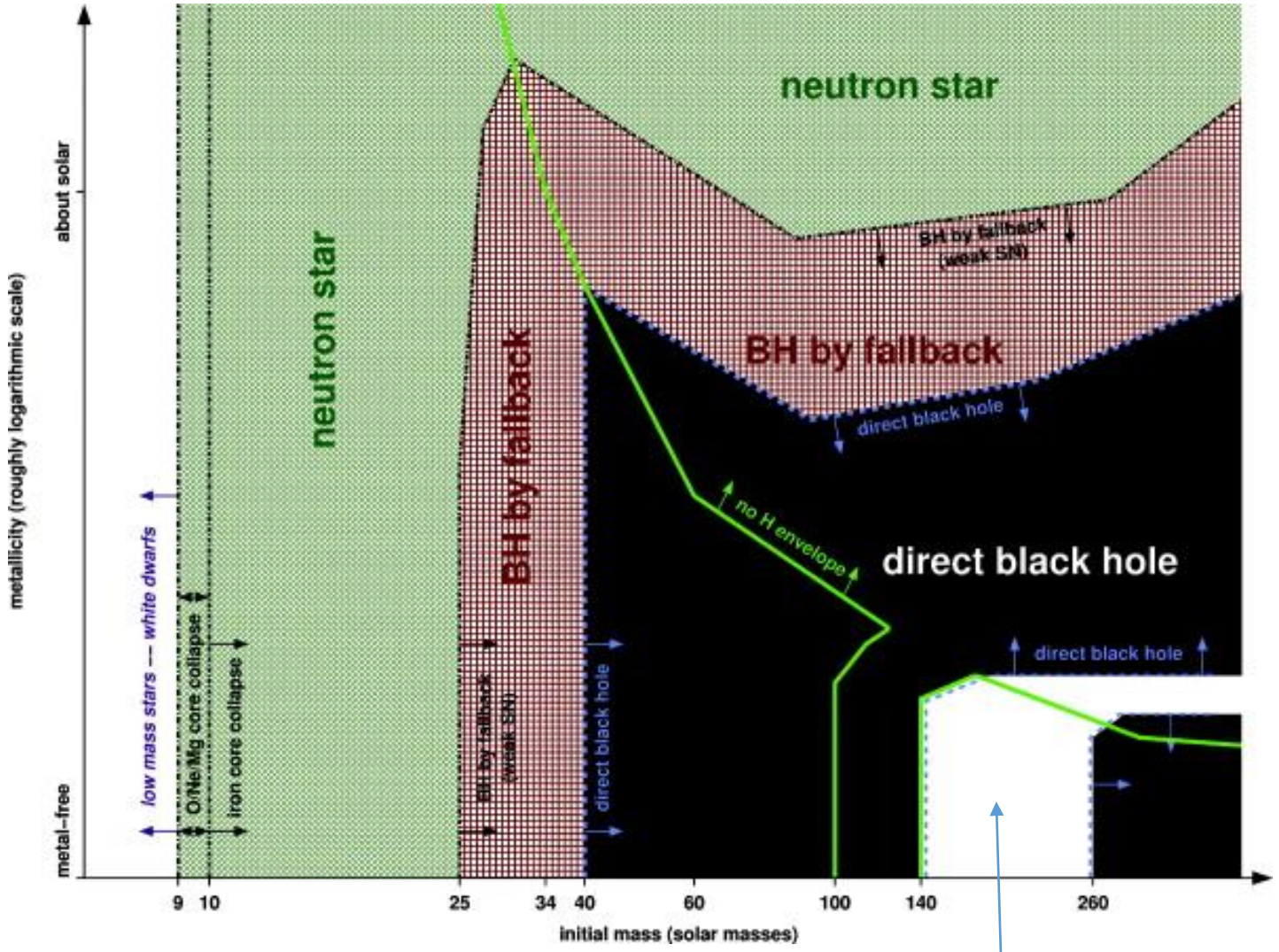
- First in the context of cosmology
  Mirabel+ (2011) & N&V in Nature (Haiman)

- 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

THE EVOLUTION OF MASSIVE STARS DEPENDS ON MASS & METALLICITY

Model for the evolution of **single stars** (Heger, Fryer, Woosley + 2003)

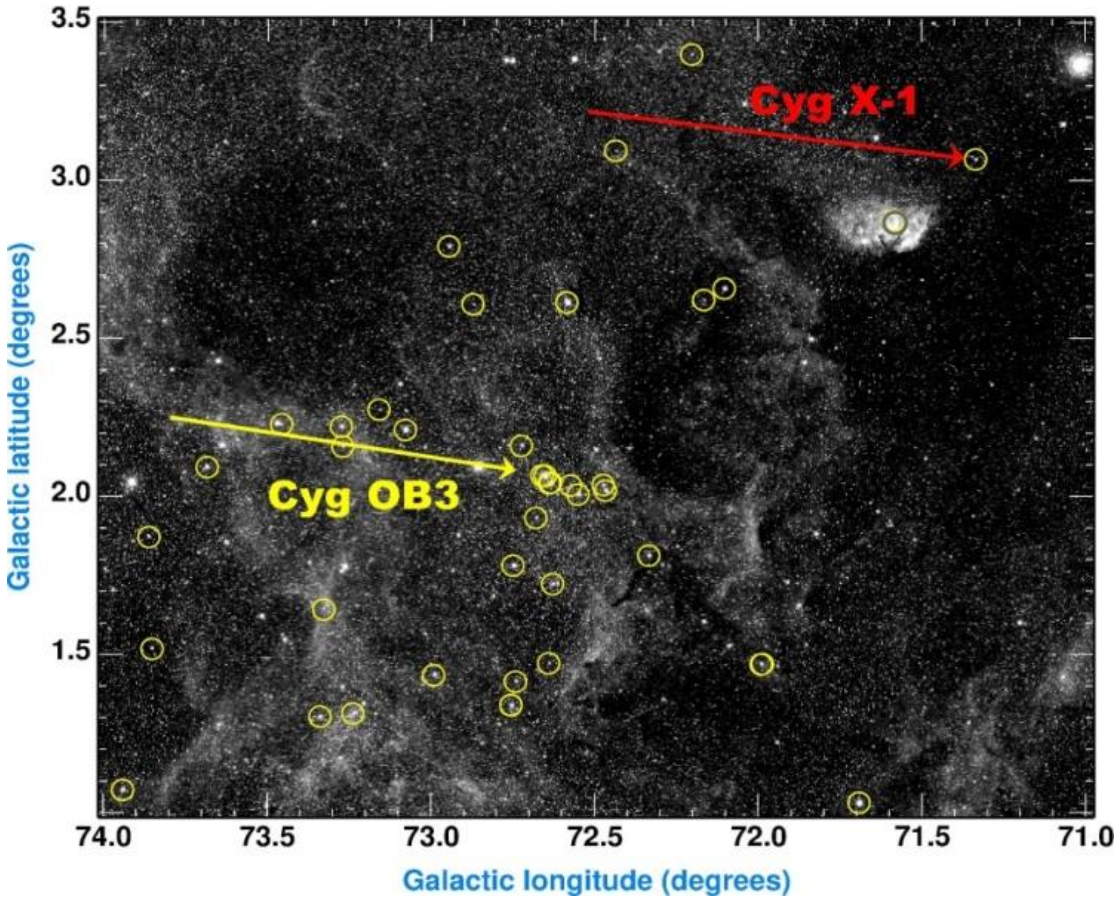


Pair-instability SNe

- Massive stars die as BHs depending on their mass and metallicity in two ways:
- by **direct collapse** without a SN or NKs
  or
- by **failed SN:** an explosion occurs in a proto-NS but the energy is too low to completely unbind the stellar envelope, and a large fraction of it falls back onto the NS, leading to the **delayed formation of a BH.**

- **ARE THERE EVIDENCES OF BH FORMATION BY IMPLOSION?**

TWO BLACK HOLES FORMED BY DIRECT COLLAPSE



Observations of Cygnus X-1

Mirabel & Rodrigues (Science, 2003); Reid + (2011)

Cygnus X-1: D~1.9 kpc; M_{bh}~15 $M_\odot$; M_{don} ~19 $M_\odot$; V_p<9±2 km/s ⇒ <1 $M_\odot$ in SN; M_{prog}> 40 $M_\odot$; M_{lost} ~25 $M_\odot$

Observations of GRS 1915+105

Dhawan, Mirabel, Ribo+ (2007); Reid+ (2014)

GRS 1915+105: D~8.6 kpc; M_{bh}~10 $M_\odot$; M_{don} ~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

BLACK HOLE FORMATION AS FUNCTION OF Z & z

- 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: $\mathbf{L_{2\text{-}10\ keV}\ (HMXB)/SFR \propto (1 + z)}$ (Lehmer+ 2016)

- 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** (Mirabel+ 2011)

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)

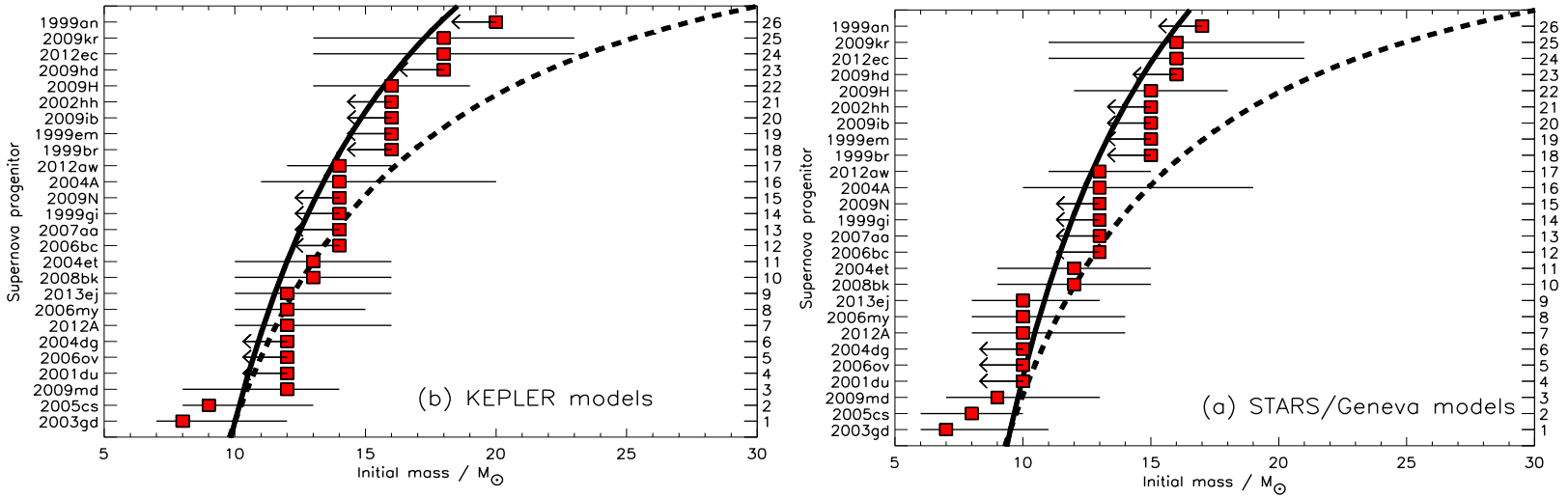
$\Rightarrow$

The chemical evolution of the universe $\Rightarrow$ a large fraction of binary massive stars in the early universe end as BH-HMXBs and BBHs

Impact of BH-HMXBs in cosmology and galaxy evolution (Mirabel et al. 2011)

NO PROGENITORS OF BRIGHT SN-II WITH >18-25 $M_\odot$

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



RSG stars more massive than 18 $M_\odot$ do not explode as ccSN II (Smartt 2015)

Mass of stellar progenitor of core collapse SNe in the context of different models of stellar evolution.
The mass distribution would need to be truncated ~16.5 $M_\odot$ & ~18.5 $M_\odot$. (Smartt 2015)

- **Among 45 SNe II 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 ⇒18 $M_\odot$**

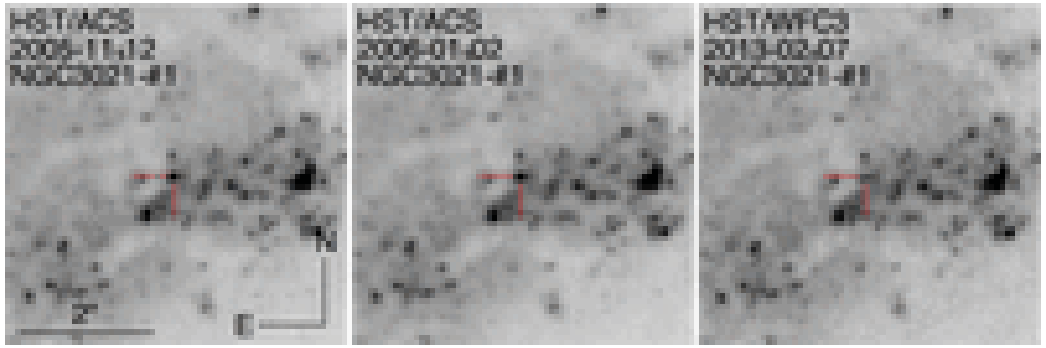
⇒

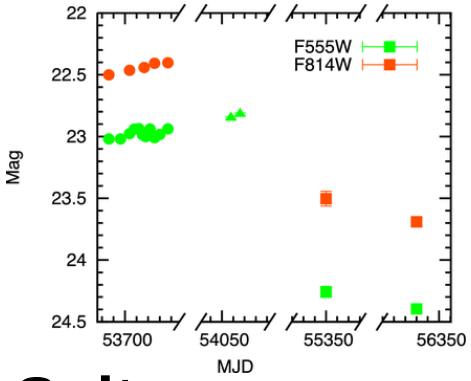
- **Stars of >25 $M_\odot$ implode to form BHs, and is relevant to all Type II SNe** (Smartt, 2015)
- **Absorption ⇒ the limit increases to the theoretical > 25 $M_\odot$** Beasor & Davies (2016)

BHs FORMED IN THE DARK BY FAILED SN COLLAPSE?

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

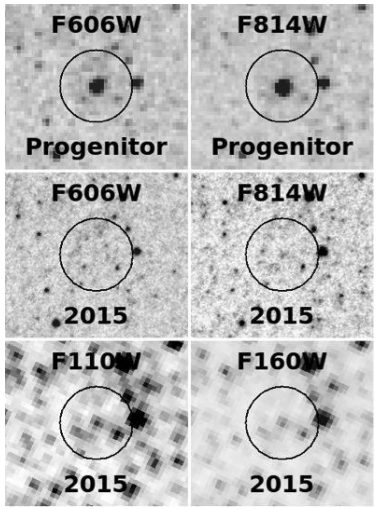
- **Systematic analysis of archival HST images:** 15 targets Reynolds+ 2015):

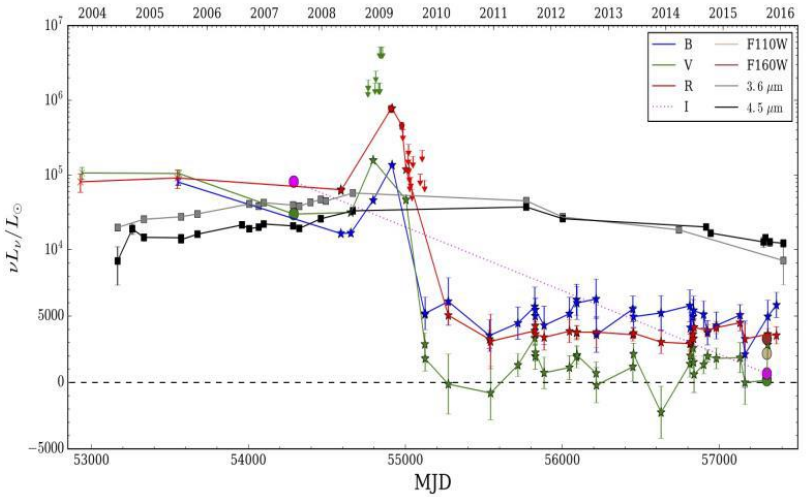




One yellow Supergiant candidate of 25-30 $M_{\odot}$ that underwent an optically dark core-collapse in a cluster of massive stars

- **Large Binocular Telescope + HST + Spitzer:** 27 nearby galaxies Gerke+ (2015)





- One red Supergiant candidate of 25 $M_{\odot}$ confirmed as a failed SN (Adams+ arXiv:1609.01283v1)
- **If real ⇒ 30% of CCs are failed SNe.**
  If rejected ⇒ < 40 % of CCs are failed SNe
- Recent models propose a "**transient display**" Lovergrove & Woosley (2013); Sukhbold+(2016)

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) ⇒ HII regions expanding at < 100 Km/s.

Based on above mentioned results from different areas of astrophysics:

- **I proposed that in galaxies at z>10 a large fraction of Pop III-II stars end as StBHs in HMXBs ⇒ prolific sources of X-rays & jets**
- **X-rays & jets overtake the HII regions produced by UVs, pre-heating and ionizing the IGM over large volumes of the IGM**

IMPACT ON COSMOLOGY & GALAXY EVOLUTION

Mirabel, Dijkstra, Laurent, Loeab, Pritchard (2011) that motivated a Nature N&V by Haiman (2011)

- **I) X-rays & jets from BH-HMXBs pre-heated the ISM**

$\Rightarrow$

- **II) λ21cm tomography of HI with LOFAR, SKA…may show a smoother end to the dark ages**

- **III) Feedback from stellar BHs reduce the λCDM predicted number of dwarf galaxies**

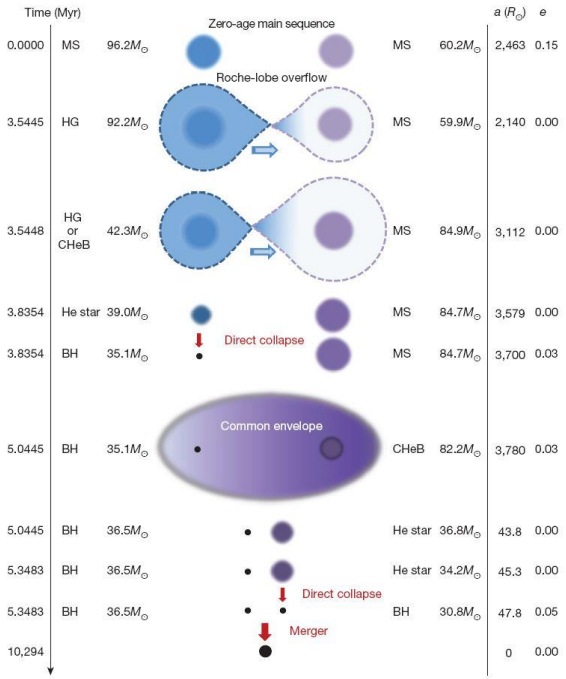
- **IV) There are naked dark matter haloes with M $<10^8$ $M_\odot$**

- **V) It is not surprising that BHs of 20-30 $M_\odot$ are found as sources of gravitational waves…**

IMPACT ON GW ASTROPHYSICS

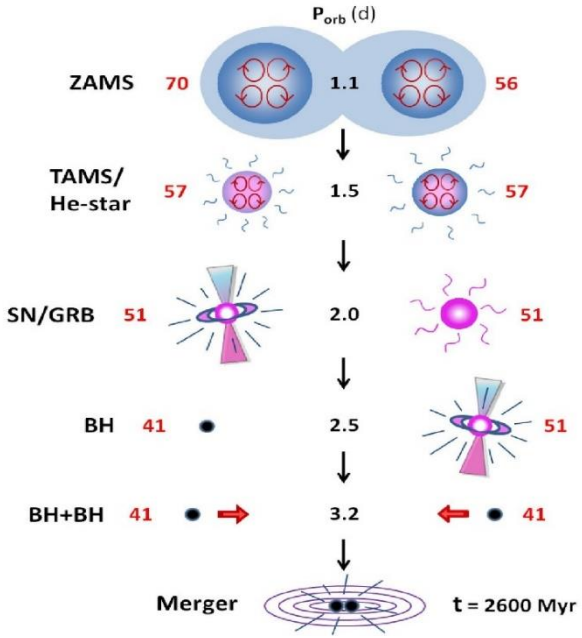
MODELS FOR THE FORMATION OF BBHs OF STELLAR ORIGIN

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

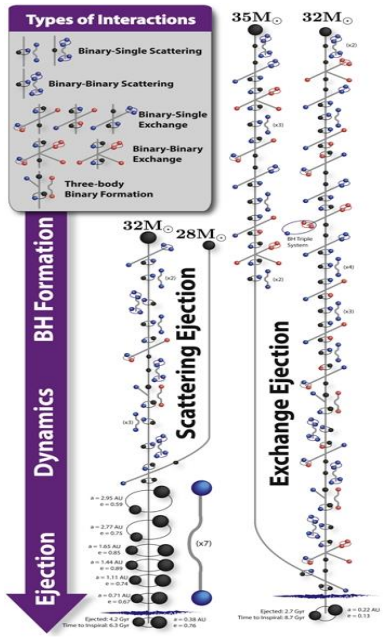


BBH formed from a massive contact binary (MOB) that remain chemically homogeneous

De Mink+ (2016) & Marchant+ (2016)



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



- **Two of these models assume that BHs of 20-30 $M_\odot$ can be formed by direct collapse and kicks that will not disrupt the stellar binaries or eject the BHs from the cluster before BBH formation.**

CONCLUSION FROM 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 & GRS 1915+105) $\Rightarrow$ **BHs may be formed by complete implosion of massive stars.**

- The theoretically expected metallicity and redshift dependence for the formation of BH-XRBs has now been confirmed by observations $\Rightarrow$ **BBHs of 20-30 $M_\odot$ can be formed out of massive stars of low metallicity.**

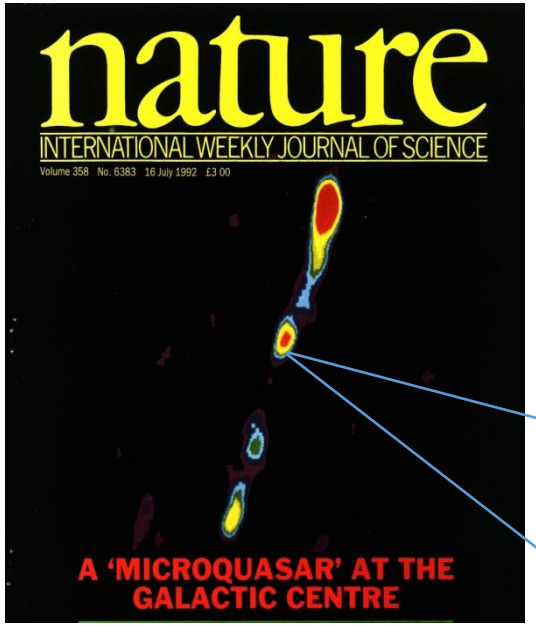
New Astronomy Reviews, in press: http://dx.doi.org/10.1016/j.newar.2017.04.002

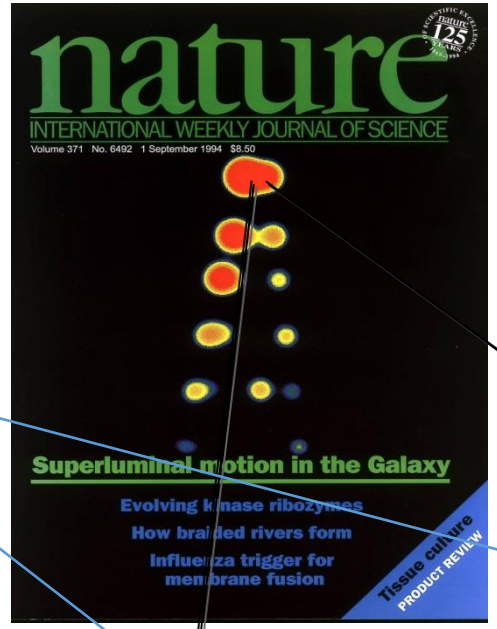
KINEMATICS USING JETS FROM MICROQUASARS

Mirabel, L.F. Rodríguez+ 1992

Mirabel & L.F. Rodríguez 1994

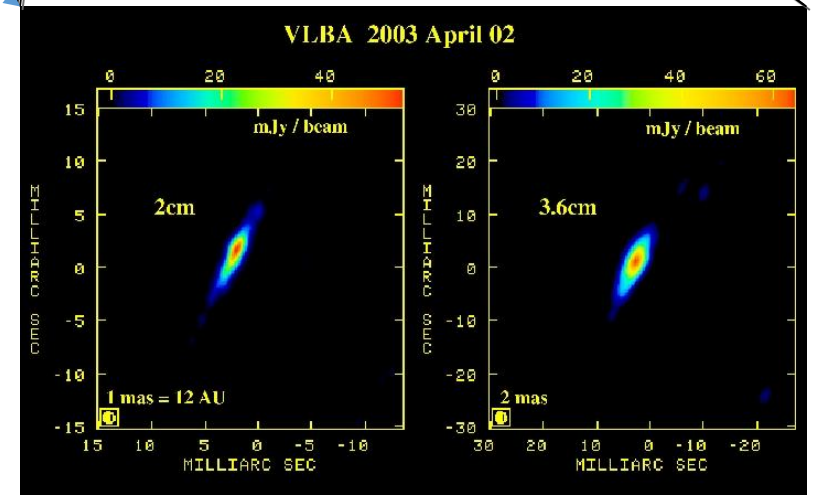
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

- **VLBI:** DISTANCES & PROPER MOTIONS OF BH-XRBs DETERMINED WITH SUB-MILLIARC SEC PRECISION
- **GAIA:** FOR OPTICALLY BRIGHT DONORS

From studies of the kinematics in 3D of 5 BH-XRBs…

THE FORMATION OF STELLAR BLACK HOLES

A subject of topical interest in several areas of Astrophysics:

- **Stellar Evolution** because the most massive stars end as stellar BHs
- **Galaxy Evolution & Cosmology** because StBHs are possible seeds of Supermassive BHs, may have determined limits for dwarf galaxy formation, and pre-heated the IGM during the re-ionization of the universe
- **High Energy Astrophysics** because BBHs are the sources of the most energetic phenomena observed so far (e.g. GWs by fusion of BHs)

HOW STELLAR BLACK HOLES ARE FORMED?

THE RUNAWAY VELOCITY OF A COMPACT BINARY WITH A NS or BH MAY BE DUE TO:

- **Blaauw kick**: The sudden baryonic mass-loss in the SN explosion of the primary star of a binary. In this case the ejected matter will continue to move with the orbital velocity of the progenitor, and to conserve momentum the resulting compact binary will move in the opposite direction. The binary will be unbinded when more than half the binary's total mass is instantaneously lost, which is not expected (Blaauw 1961; Nelemans 1999)

- **Natal kick by anisotropic emission of neutrinos in a SN** (Fryer & Kusenko 2006)

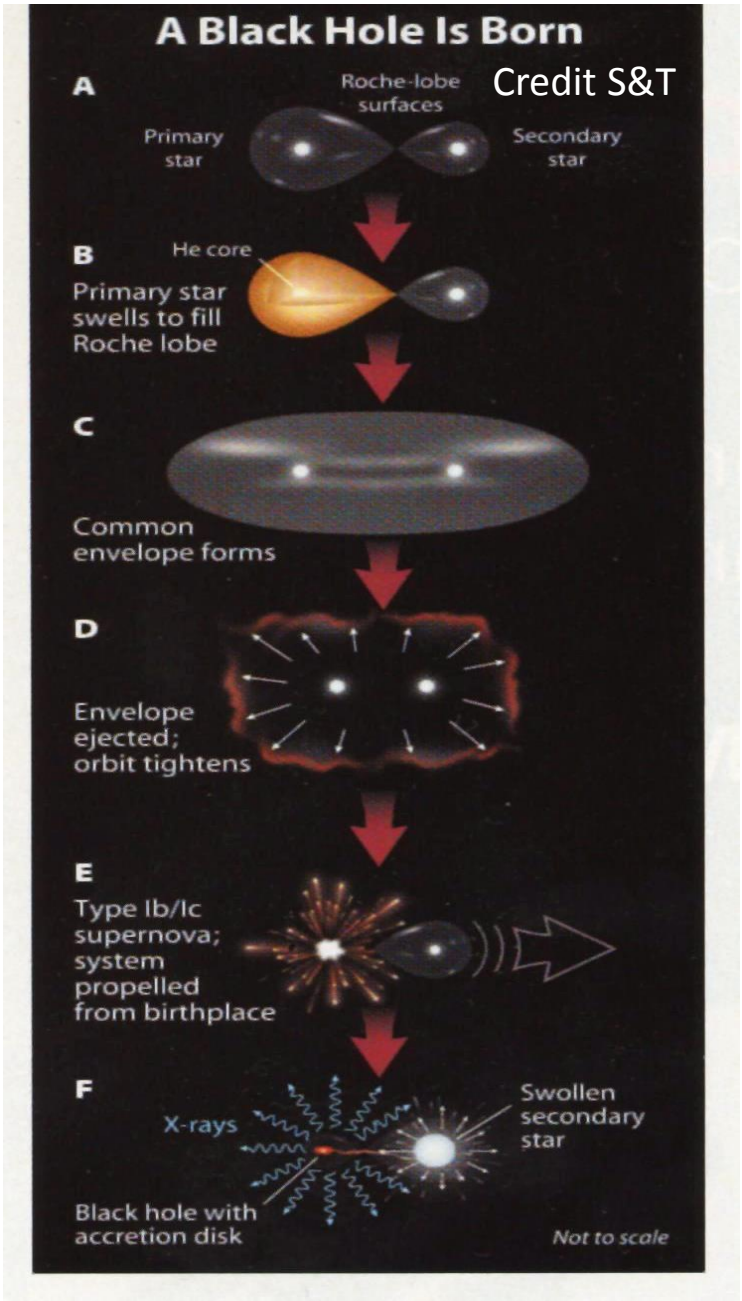
- **Natal kick by anisotropic emission of Gravitational Waves in a SN** (Bonnell & Pringle 1995)

- **If formed in a dense stellar cluster by dynamical interactions** (Poveda+ 1967; Rodriguez+ 2013)

- **If formed in a dense stellar cluster by the SN explosion of a massive star that formed a multiple bound system with the runaway compact binary** (Mirabel 2017)

KINEMATICS OF BLACK HOLE X-RAY BINARIES IN THE MILKY WAY GALAXY

INSIGHTS ON BH FORMATION FROM THE KINEMATICS OF BH-XRBs



CORE COLLAPSE MODELS:

Stellar black holes may be formed with no SN explosions
(Fryer & Kalogera 2001; Woosley & Heger; Nomoto+; Sukhbold+ 2016...)

From statistical analysis of the positions of BHs, (Reppeto+ 2012; Belczynski, Repetto+ 2016) concluded that BHs are formed with same kicks as NSs. However,

Mandel (2016) shows that **"it is not possible to confidently infer BH SN kicks"**

$\Rightarrow$

THE VELOCITIES OF BH-XRBs IN 3D ARE REQUIRED !

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

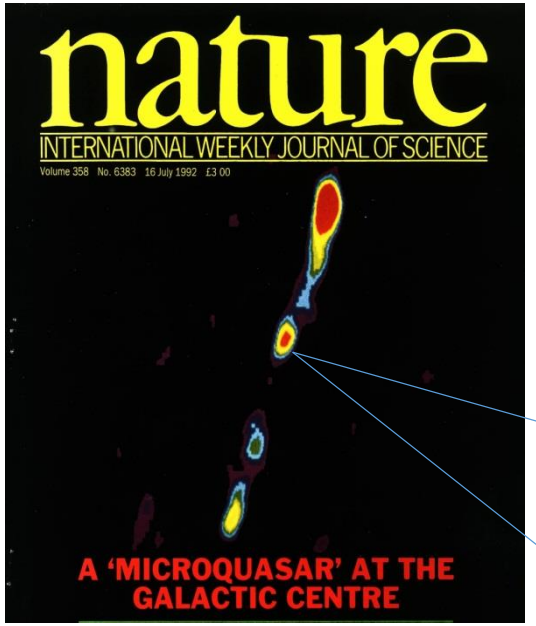
From 3×10^8 BHs in MW, 20 BHXRBs known, 5 BH-μQSOs with 3D velocities

Mirabel, Rodrigues et al. (2001-2009)

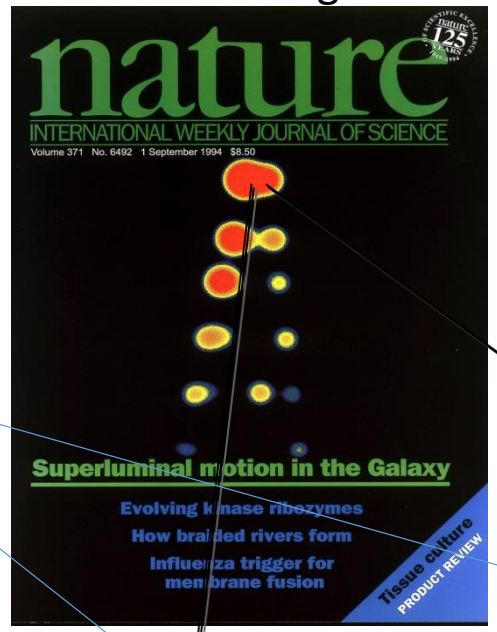
PARALLAX DISTANCES & PROPER MOTIONS BY VLBI

STEADY JETS

Mirabel, Rodriguez+ 1992

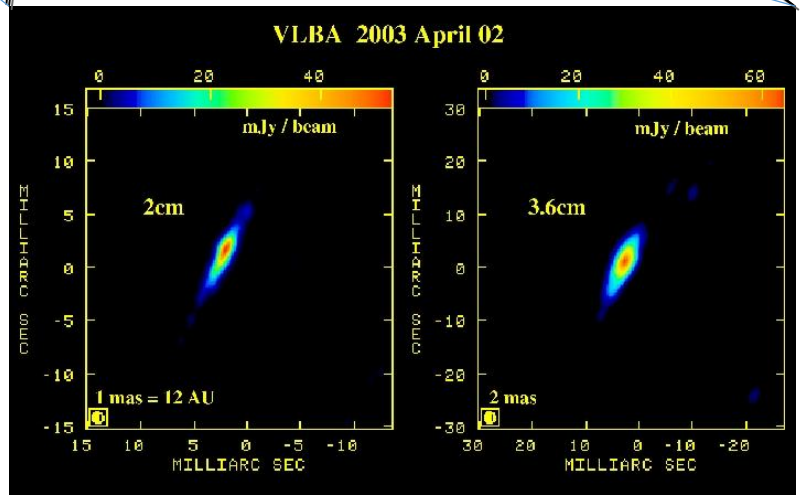


Mirabel & Rodríguez 1994



TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

In low hard state. Size ~ 100 AU with same PAs

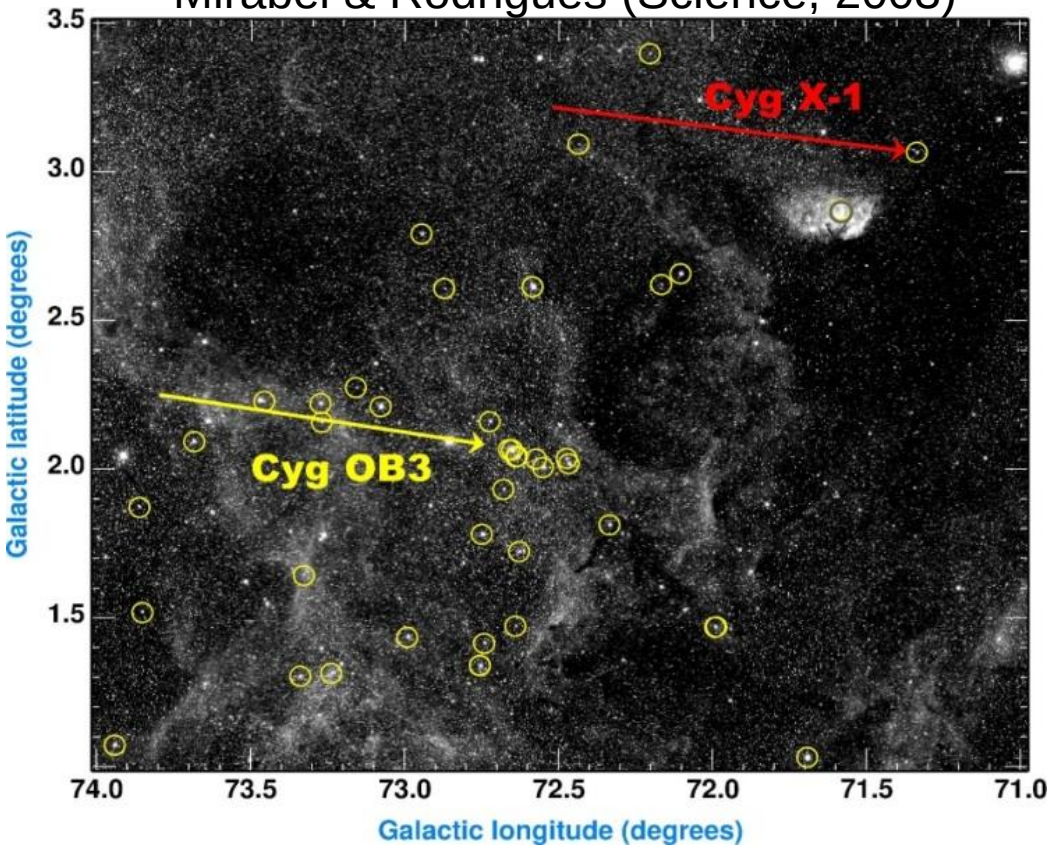
DETERMINE PARALLAXES & PROPER MOTIONS

(with VLBI can obtain sub-miliarc-sec precision)

BLACK HOLES FORMED BY DIRECT COLLAPSE

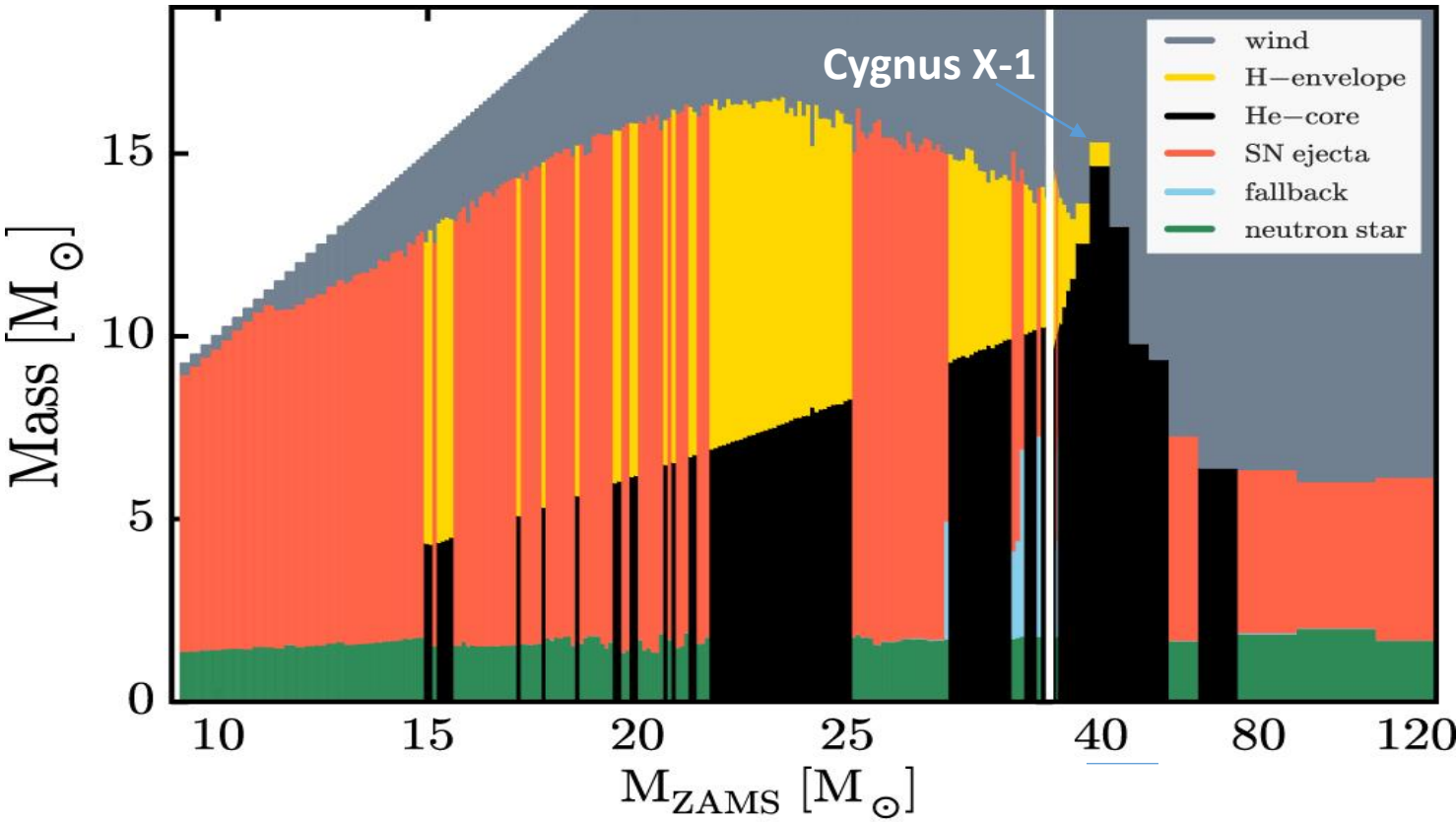
OBSERVATIONS

Mirabel & Rodrigues (Science, 2003)



MODEL FOR SINGLE STARS OF $Z_\odot$ (consistent with Cyg X-1 !)

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

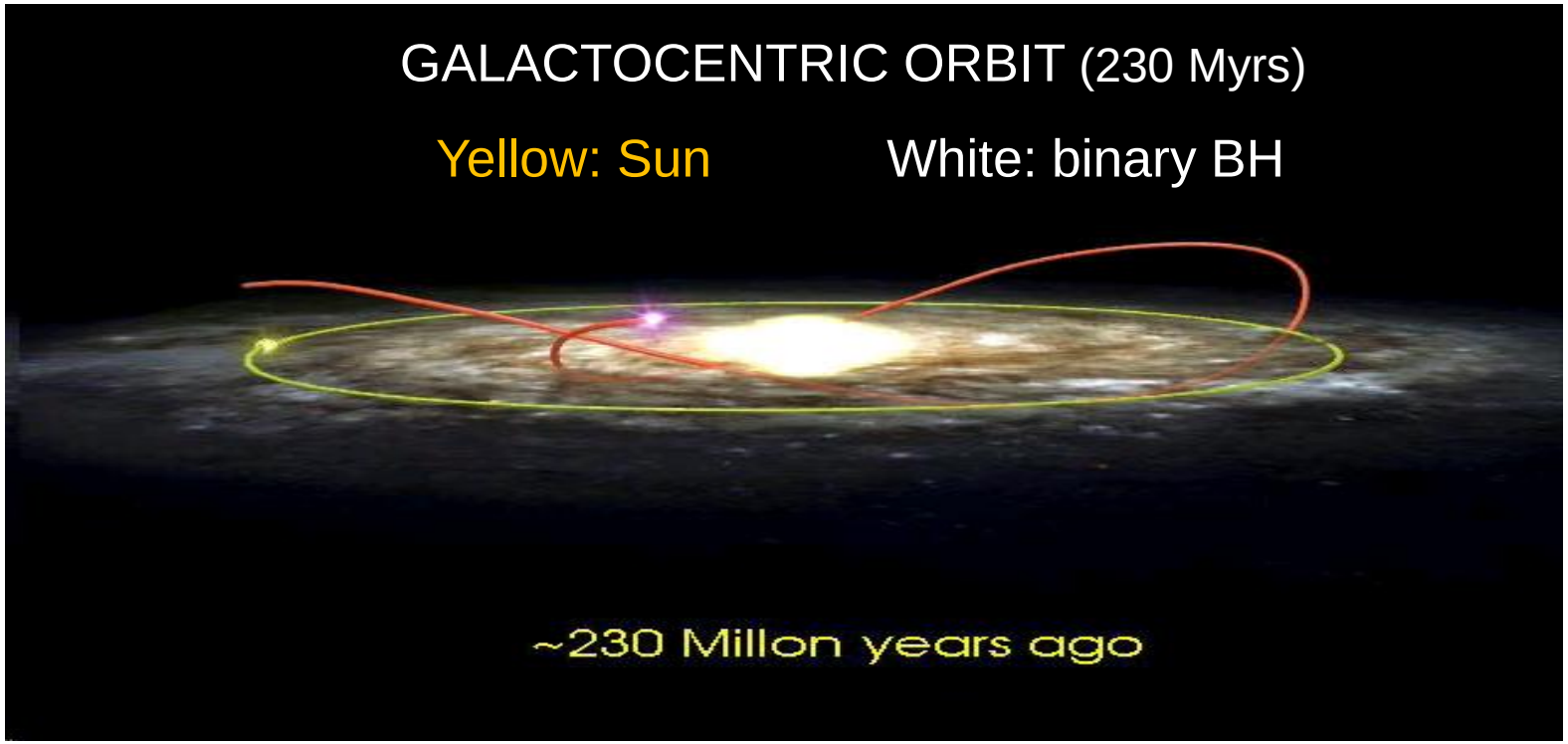


- **Cygnus X-1:** M_{bh}~15 $M_\odot$; M_{don} ~19 $M_\odot$; V_p< 9±2 km/s ⇒ <1 $M_\odot$ in SN; M_{prog}> 40 $M_\odot$; M_{lost} ~25 $M_\odot$ in Wolf Rayet
- **GRS 1915+105:** M_{bh}~10 $M_\odot$; V_p=22±24 km/s ⇒ Galactic diffusion
- **Stars of ~40 $M_\odot$ and Z~$Z_\odot$ may collapse directly as BHs**

THREE RUNAWAY BLACK HOLES

XTE J1118+480: M_{BH}~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)

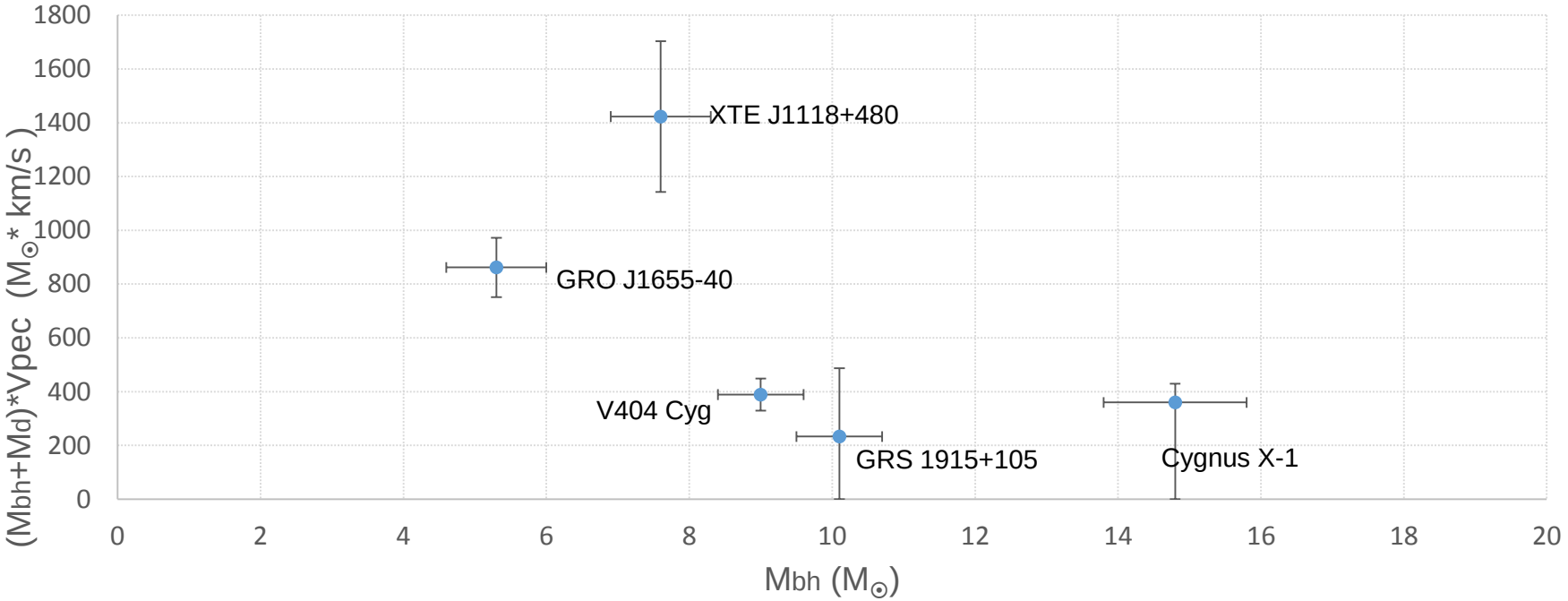


Binary & single star interaction in a cluster?
Dynamical mechanism. Credit: Carl Rodriguez

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

- **GRO J1655-40:** Fossil of a HPN (Israelian+ Nature 1999) ?
  M_{BH}~5.3±0.7 $M_\odot$ M_*~2.4±0.7 $M_\odot$; D=1-3 kpc; **V_p=112±18 km/s** (Mirabel+ 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)

LINEAR MOMENTUM OF BHXRBs 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

Does the energy of SNe and/or natal kicks increase with decreasing BH mass?

CAVEATS

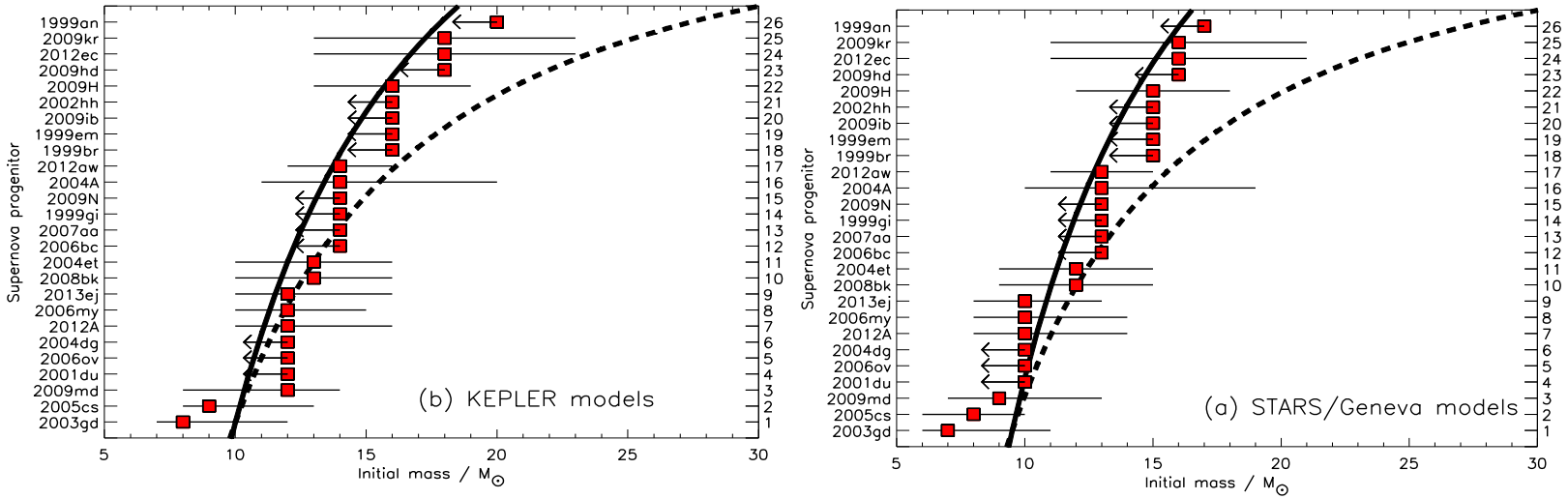
- Vp is usually interpreted as a Vkick. But if formed in a dense star cluster, Vp could be due to other mechanisms.
- If born with Blaauw kicks or NKs, it is intriguing that except XTE J1118+480, the components Vp perpendicular to the Galactic disk are 2.1±1, 4±1, 6±2, and 6±1 km s^{-1}. For GRO J1655-40 Vp=112±18 km s^{-1} and 2.1±1 km s^{-1}

Are the runaway velocities of BHs of 5-9 $M_\odot$ due to SN/Natal Kicks to the BHs?

MASSIVE STARS GONE WITHOUT BANG

NO PROGENITORS OF BRIGHT SN-II WITH 18-25 $M_\odot$

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



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$\Rightarrow$

- **Stars of >18 $M_\odot$ implode to form BHs, and is relevant to all Type II SNe** (Smartt, 2015)
- **Absorption $\Rightarrow$ the limit increases to the theoretical > 25 $M_\odot$** Beasor & Davies (2016)

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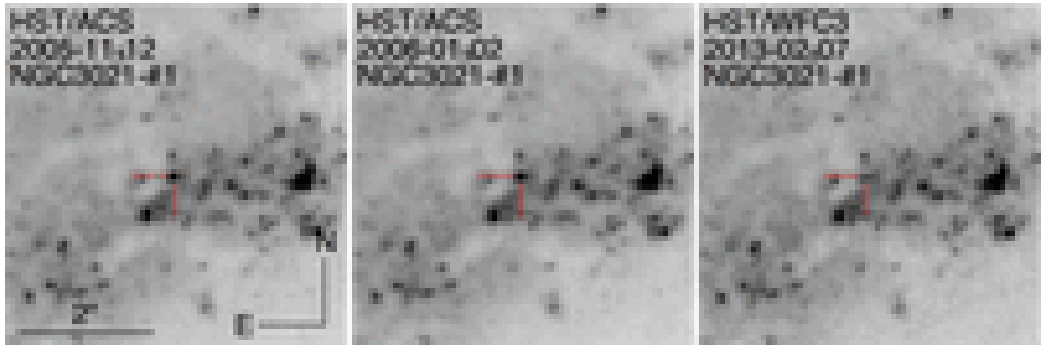
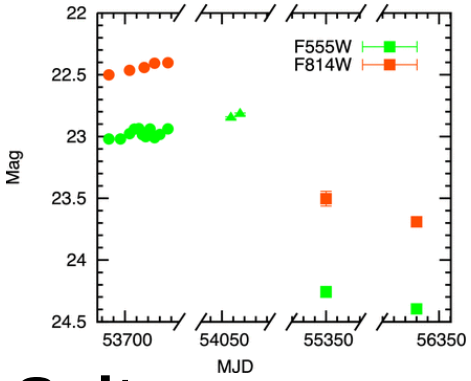
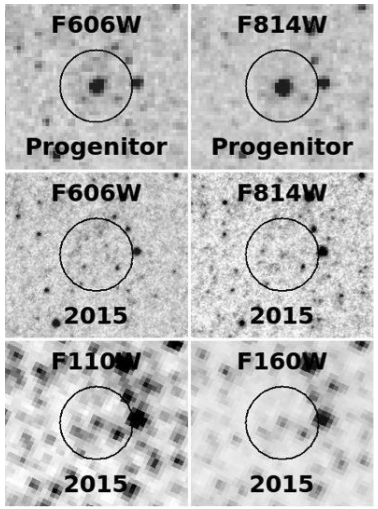
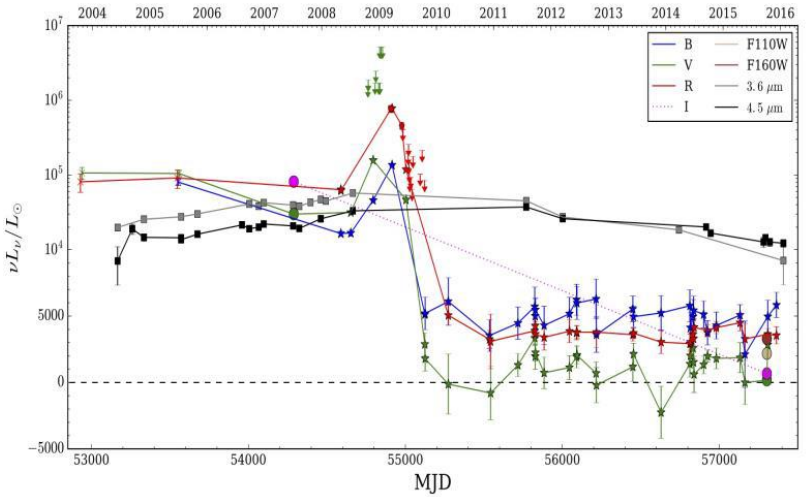




One yellow Supergiant candidate of 25-30 $M_{\odot}$ that underwent an optically dark core-collapse in a cluster of massive stars

- **Large Binocular Telescope + HST + Spitzer:** 27 nearby galaxies Gerke+ (2015)





- One red Supergiant candidate of 25 $M_{\odot}$ confirmed as a failed SN (Adams+ arXiv:1609.01283v1)
- **If real ⇒ 30% of CCs are failed SNe.**
  If rejected ⇒ < 40 % of CCs are failed SNe
- Recent models propose a "**transient display**" Lovergrove & Woosley (2013); Sukhbold+(2016)

INDIRECT INSIGHTS FOR LOW MASS LIMITS OF SNe

- The spectroscopy of SN nebulae show that the observed evolution of the cooling lines of oxygen cannot be reconciled with the expected nucleosynthesis products from Type II SNe if they are the explosions of stellar progenitors of >20 $M_{\odot}$ (Jerkstrand+ 2014)

- 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 ccSNe of > 20 $M_{\odot}$ (Williams+ 2014)

POSSIBLE CAVEATS IN THE UPPER MASS LIMIT OF ccSNe

- Circumstellar dust, luminosity analysis, sample selection, limited number statistic, variable stars (e.g. Mira variables, R Coronae Borealis, eclipsing binaries, etc.), and the rate of ccSNe extrapolated to z~2.5 may not be supportive of an upper mass limit for progenitors at ~20 $M_{\odot}$

- It was found an increase of circumstellar extinction through the RSG lifetime, implying that in the more evolved stars the progenitor's initial mass could be underestimated by up to 9 $M_{\odot}$, in which case the observational upper mass limits of 16-20 $M_{\odot}$ for the progenitors of Type IIP SNe when corrected by absorption, would be consistent with the theoretical mass limit of 25 $M_{\odot}$, and the "RSG problem" solved (Beasor & Davies 2016)

- **NO EVIDENCE THAT STARS OF >25 $M_{\odot}$ EXPLODE AS SNe**
- **DO ALL STARS WITH >25 $M_{\odot}$END AS BHs WITH NO SNe?**

BH FORMATION AS FUNCTION OF METALLICITY & REDSHIFT

- 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 $Z/Z_{\odot} = 2 \times 10^{-2}$, 2×10^{-3} and 2×10^{-4} (Spera+ 2015)

FALTAN TRABAJOS SOBRE FONDO DIFUSO EN I y EN X

MASSIVE STARS 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 flat frequency mass ratios (Krumholz,+ 2009; Turk+ 2009; Stacy & Bromm 2014).

Therefore, it is expected that a large fraction of binary massive stars in the early universe end as BH-HMXBs & BBHs

STELLAR BLACK HOLES IN THE RE-IONIZATION EPOCH OF THE UNIVERSE

HOW WAS THE IGM RE-IONIZED?

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) ⇒ HII regions expanding at < 100 Km/s.

Based on above mentioned results from Stellar evolution and high energy astrophysics:

- **I proposed that in galaxies at z>10 a large fraction of Pop III-II stars end as StBHs in HMXBs ⇒ prolific sources of X-rays & jets**
- **X-rays & jets overtake the HII regions produced by UVs, pre-heating and partially ionizing the IGM over large volumes**

CONCLUSIONS FROM THIS HYPOTHESIS

Mirabel, Dijkstra, Laurent, Loeab, Pritchard (2011) that motivated a Nature N&V by Haiman (2011)

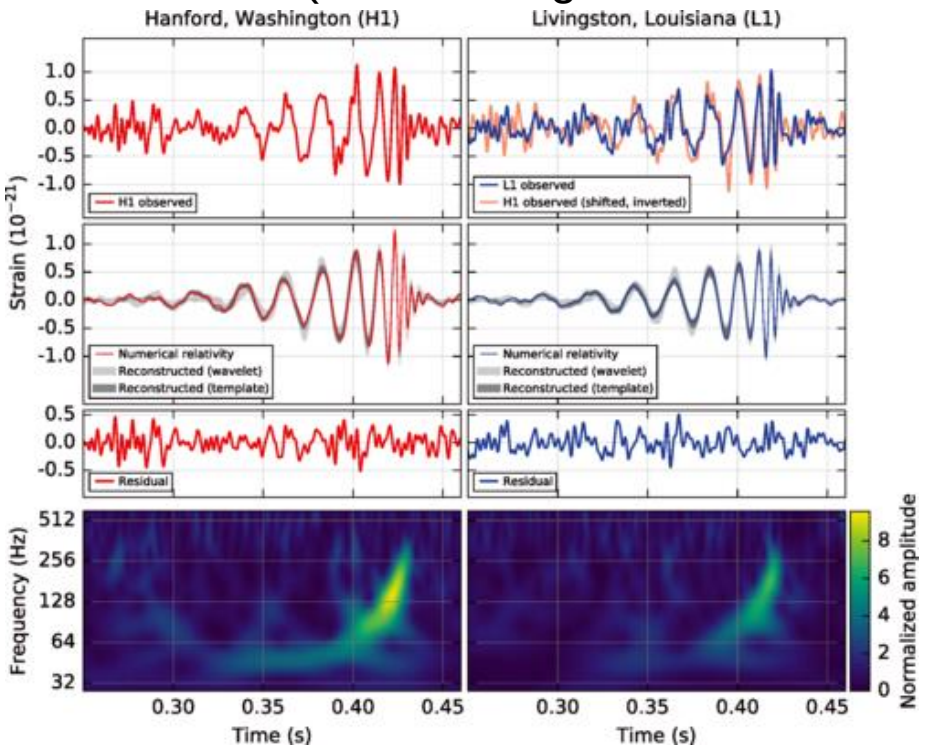
- **I) λ21cm tomography of HI with LOFAR, SKA…may show a smoother end to the dark ages**
- **II) The X-rays from BH-HMXBs may contribute to the 10-20% unresolved hard X-ray background**
- **III) Feedback from stellar BHs reduce the λCDM predicted number of dwarf galaxies**
- **IV) There are naked dark matter haloes with M $<10^9$ $M_\odot$**
- **V) BH-BH stellar binaries may be the more likely detected sources of gravitational waves**

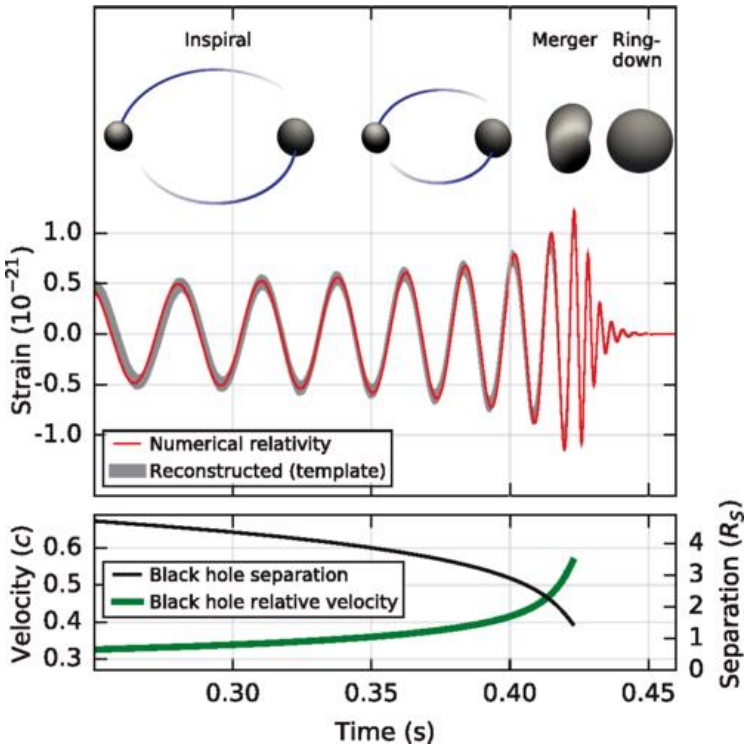
After 100 years were detected….

GRAVITATIONAL WAVES FROM THE FUSION OF BLACK HOLES

GRAVITATIONAL WAVES FROM BINARY BLACK HOLES

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

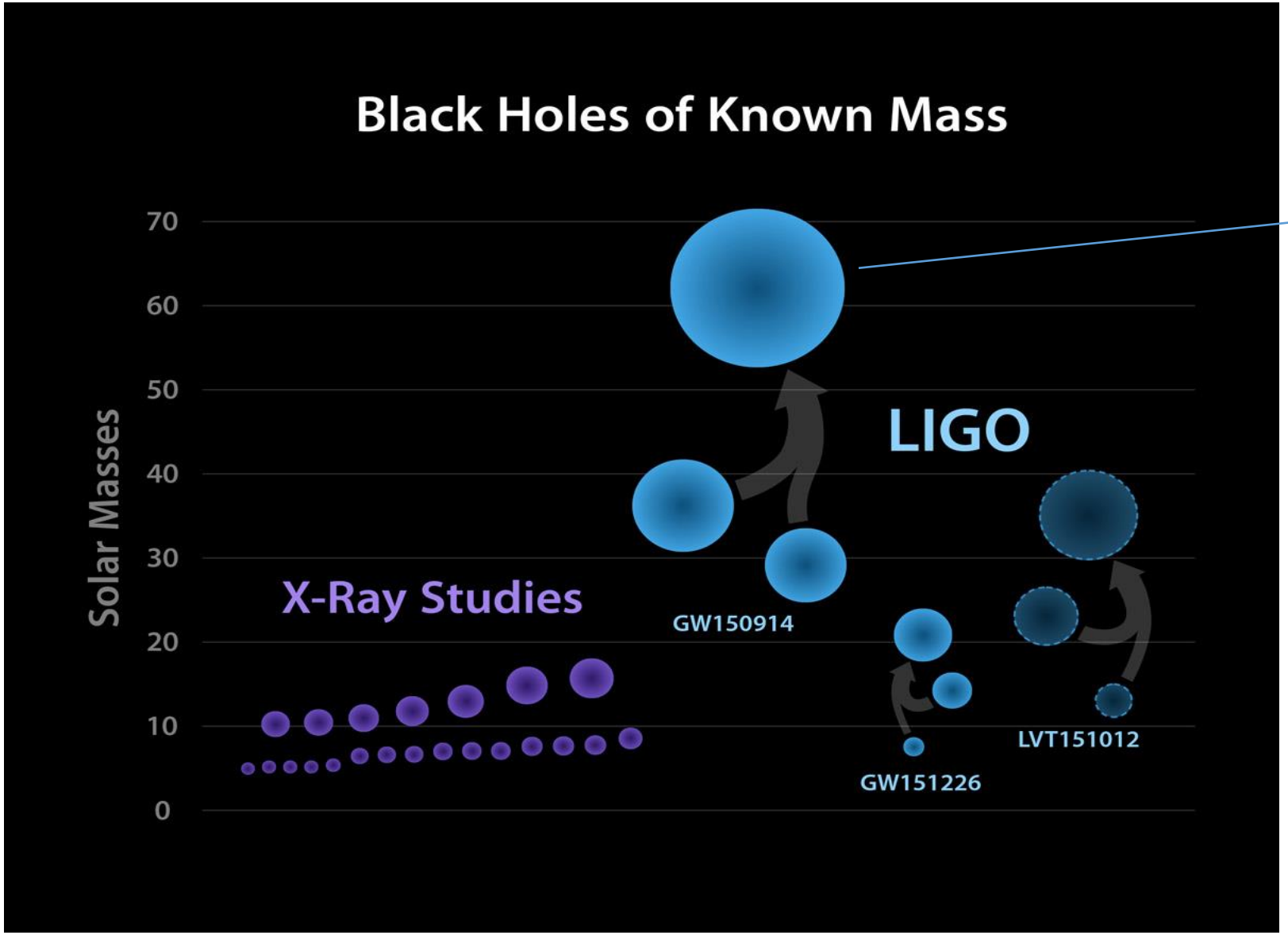




$$M=(m1 \times m2)^{3/5} /(m1 + m 2)^{1/5} = c^3 /G \, [5/96 \, \pi^{-8/3} \times f^{-11/3} \dot{f} \,]^{3/5} ,$$

- 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 $M_\odot$**

The detection of GW150914 produced surprise because of: (1) the BH large masses of 30-40 $M_{\odot}$ and, (2) the prompt detection of GWs from BH mergers



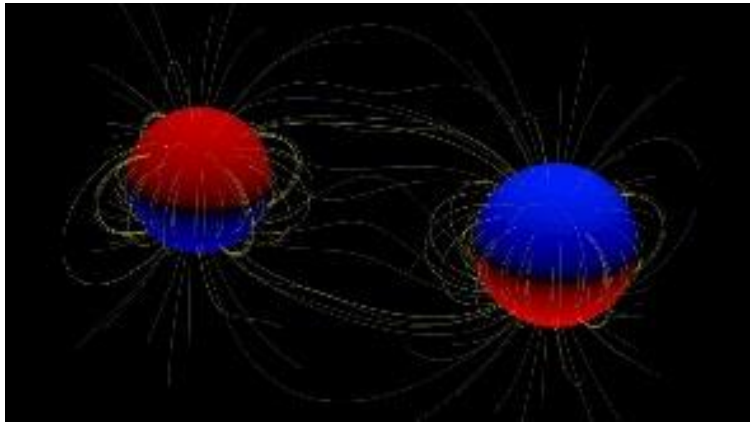
Peak gravitational wave energy of 3.6 x 10^56 erg/s

~100.000 ccSNe ⇒

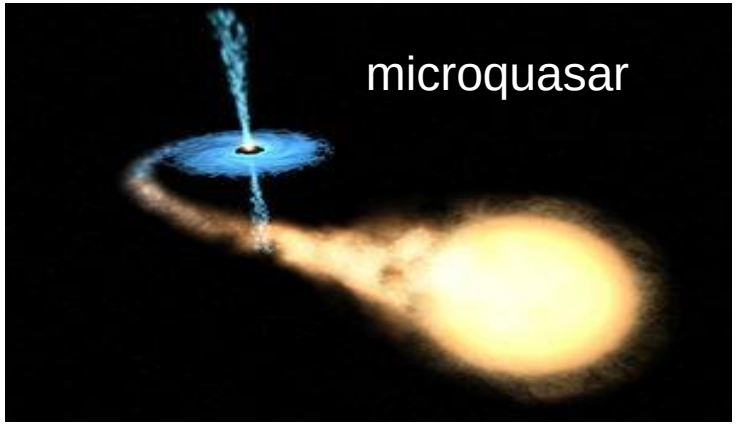
The detected most energetic event after the Big Bang

BBHs FORMED FROM MASSIVE STELLAR BINARIES IN THE FIELD

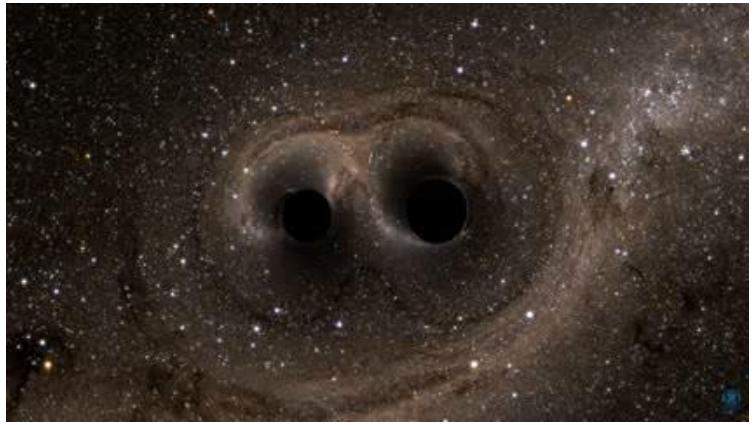
MASSIVE STELLAR BINARY
>70% found in multiple systems



BH-HMXRB
~3 known in the Milky Way (e.g.Cyg X-1)



BINARY BLACK HOLES
BBHs: GW150914 & GW151226

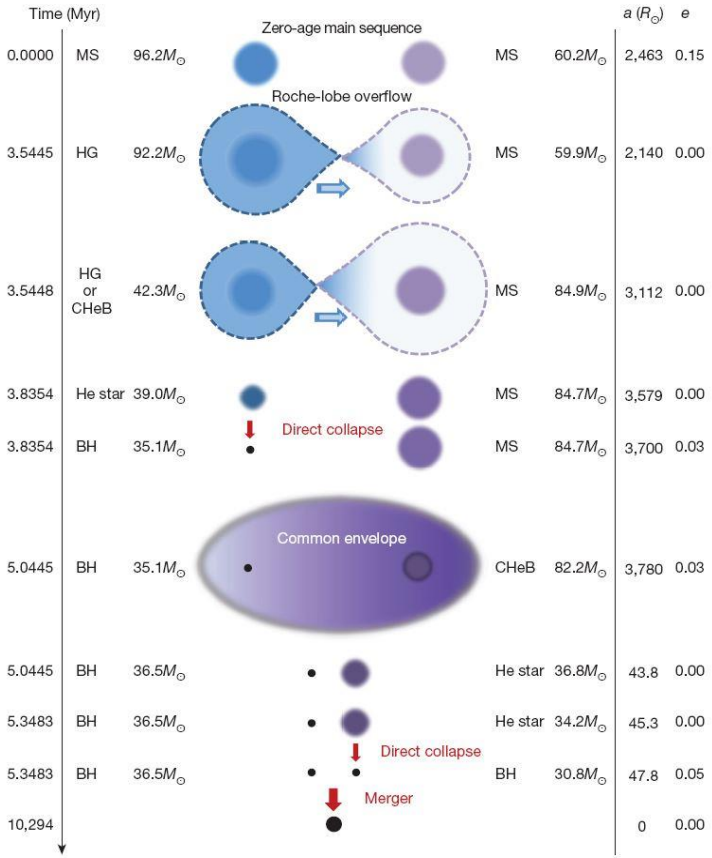


- The kinematics of BH-XRBs in 3D may encode the formation mechanism of BHs

Observations of μQSOs provide insigths on BH formation by implosion

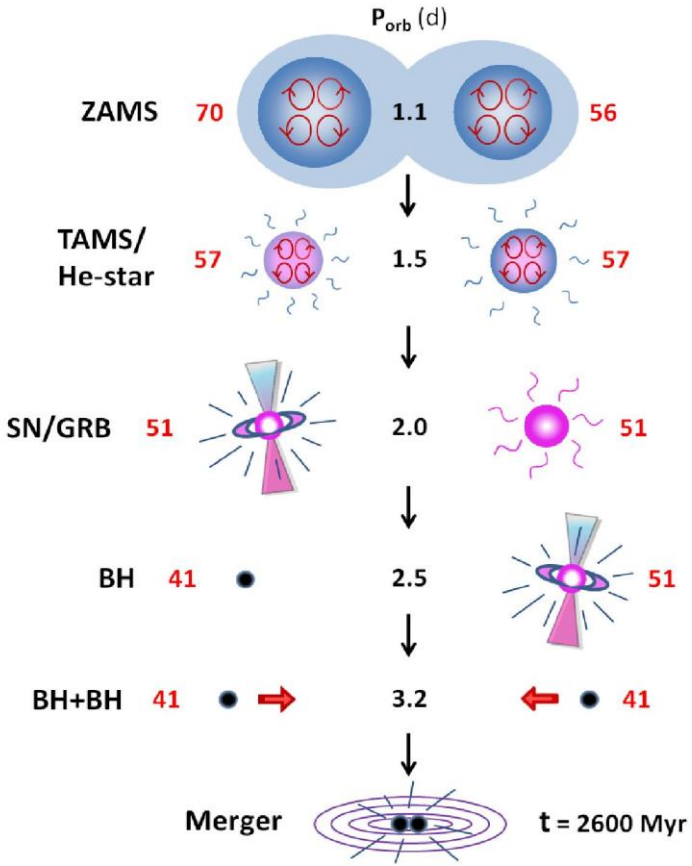
FORMATION OF THE BBHs IN GW150914 FROM BINARY MASSIVE STARS

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



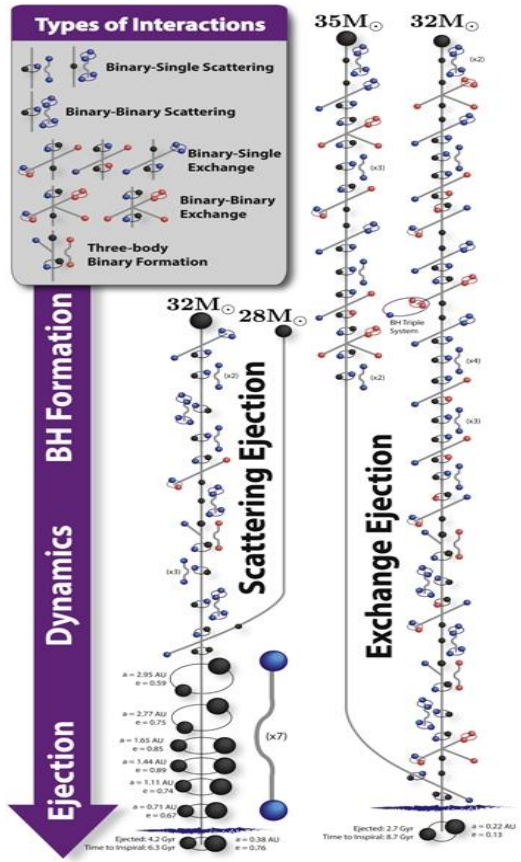
Massive contact binary (MOB) that remain chemically homogeneous

De Mink+ (2016) & Marchant+ (2016)



GW150914 formed by dynamical interactions in nuclear Clusters

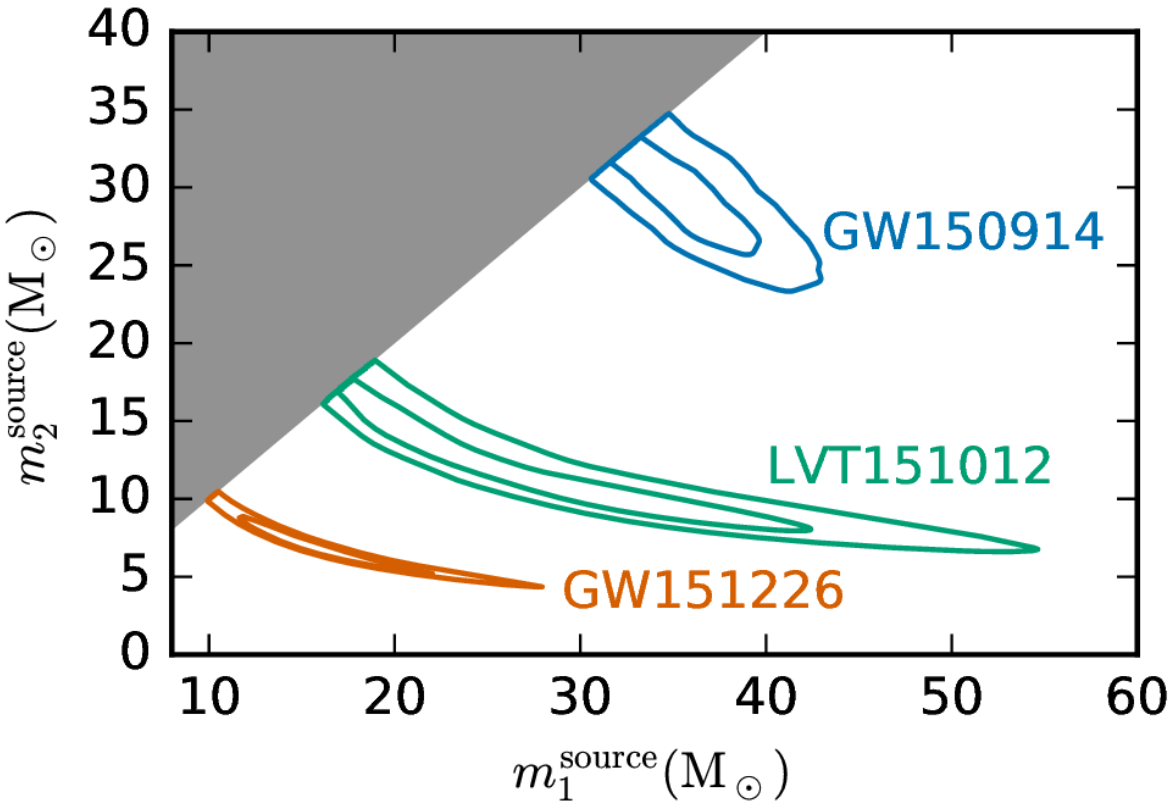
(Rodriguez+ 2016) & Antonini & Rasio 2016)



- **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-Haımoud & Kamionkowski 2016)

GRAVITATIONAL WAVE EVENTS

Probabilities densities of masses for three GW events (LIG0-VIRGO coll.)



- **GW150914: BHs of 30-40 $M_\odot$**
- **GW151226: BHs of ~7$M_\odot$ & ~14$M_\odot$**
- Can BHs of ~10 $M_\odot$ and lower masses be formed by implosion?
- Important to estimate the BH-BH merger contribution to a stochastic GW background
- **BBH merger rate: 2-400 $Gpc^{-3}\,yr^{-1}$**

- **COULD BHs CONSTITUTE A LARGE FRACTION OF DARK MATTER?**

(Bird+2016; Clesse+2016; 2017; Ali-Haımoud & Kamionkowski 2016)

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

GRACIAS!