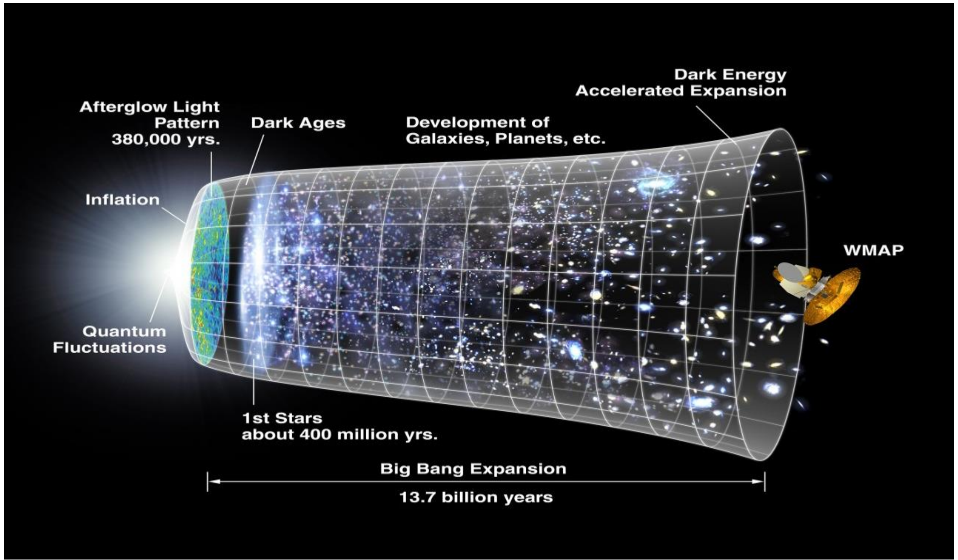
STELLAR BLACK HOLES AT THE DAWN OF THE UNIVERSE

Félix Mirabel

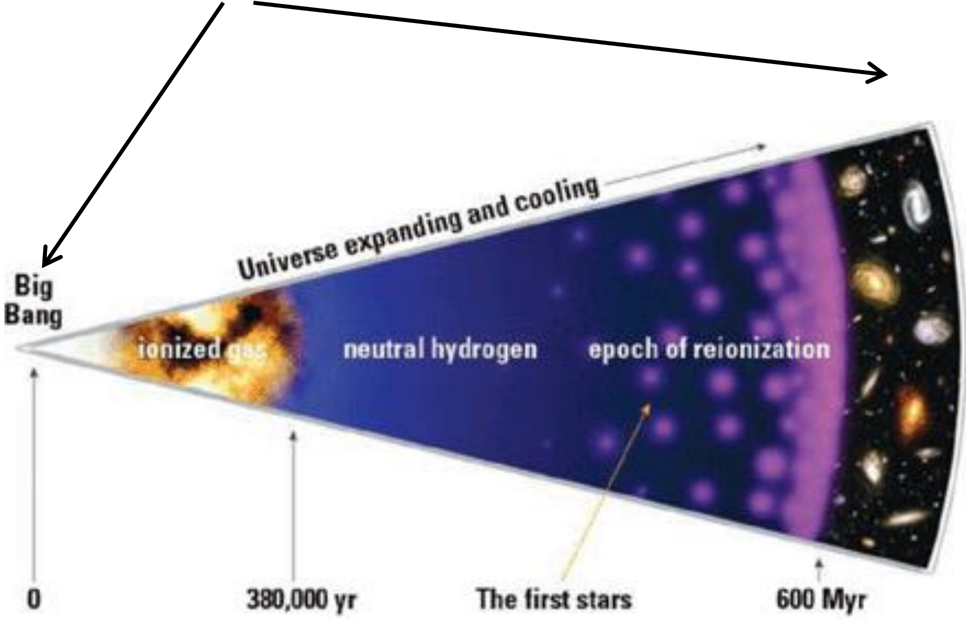
CEA-DSM-IRFU-SAp

RE-IONIZATION EPOCH: A MAJOR FRONTIER IN COSMOLOGY
How the first galaxies re-ionized the IGM ?



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.
- But, the escape fraction of UVs is < 5%

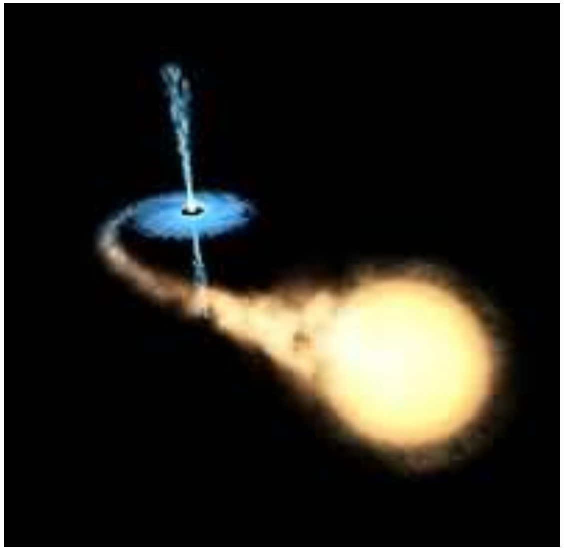


In the first galaxies (z > 10) a large fraction of Pop III-II stars ended as High Mass X-Ray Binaries (HMXBs). The X-rays overtake the HII regions heating and partially ionizing the IGM over large volumes of space.

Mirabel et al. (A&A, 2011)

Haiman (N&V in Nature, 2011)

BECAUSE OF THE COSMIC EVOLUTION OF METALLICITY THERE WAS A COSMIC EVOLUTION OF HIGH MASS X-RAY BINARIES (HMXBs=Accreting stBHs & NSs from massive stars)



In the first galaxies the mass of massive stellar remnants, the numbers of HMXBs, and the frequency of LGRB must have been very large.

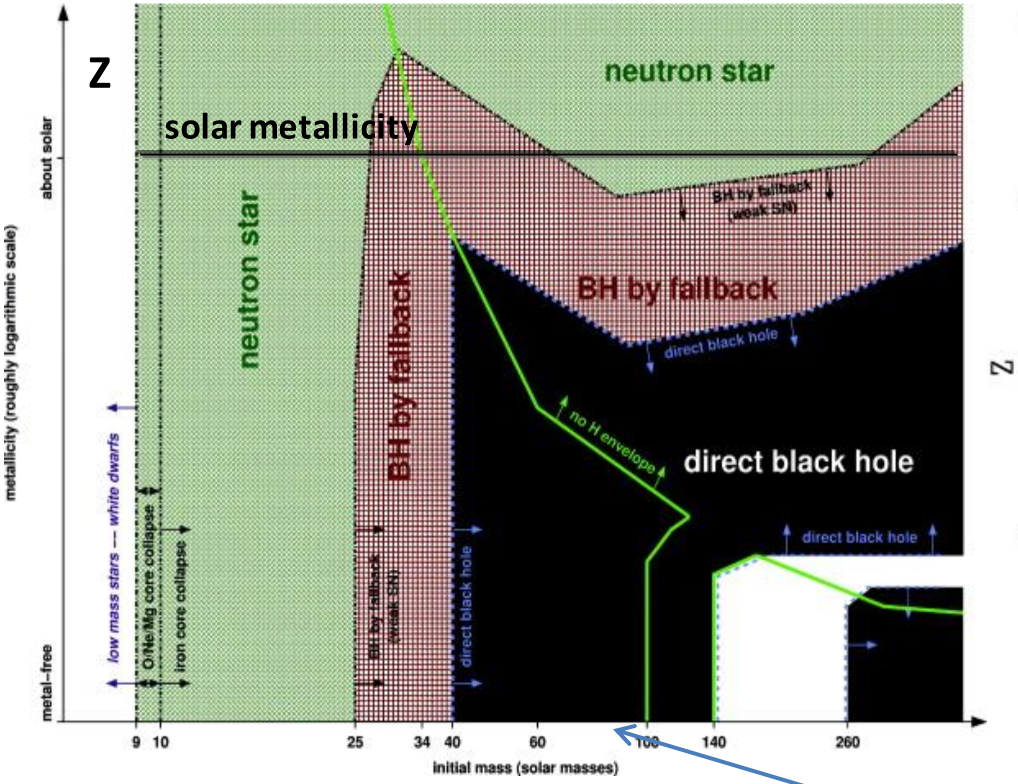
MAIN COSMOLOGICAL IMPLICATIONS

I) X-RAYS HEATED THE GAS AND PARTIALLY IONIZED THE INTERGALACTIC MEDIUM OVER LARGE VOLUMES OF SPACE.

II) FEEDBACK FROM ACCRETING STELLAR BHs & NSs SET LOWER LIMITS TO THE MASS AND UPPER LIMITS TO THE NUMBERS OF DWARF GALAXIES (CONSISTENT WITH λCDM MODEL)

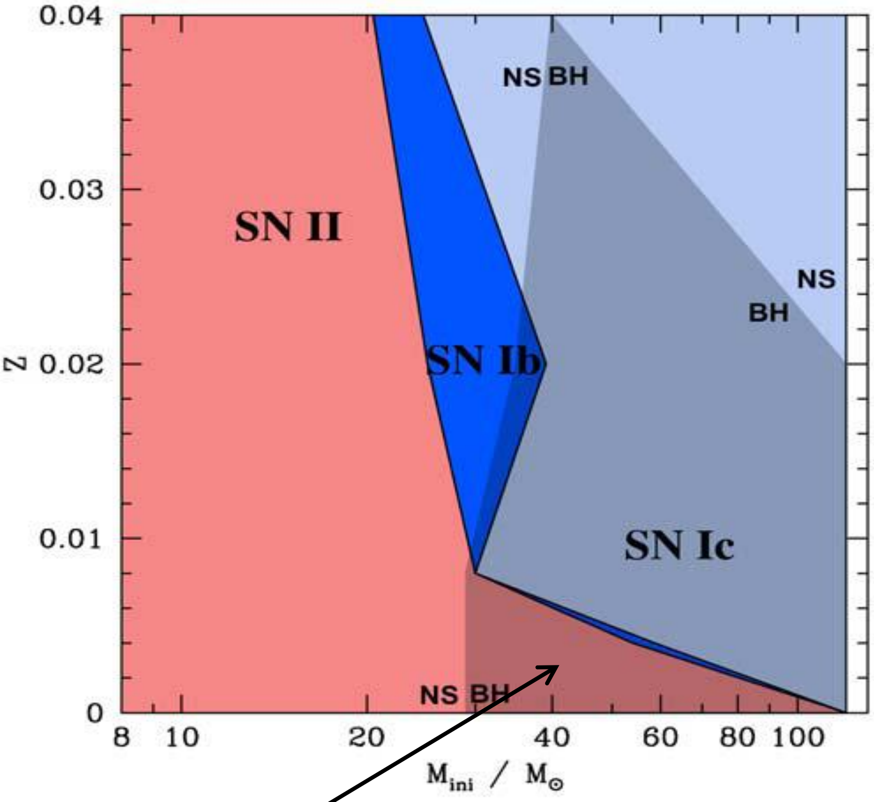
MODELS ON THE FORMATION OF COMPACT OBJECTS BY THE COLLAPSE OF SINGLE STARS

with no rotation (Heger+ 2003)



Mass of progenitor star

with rotation (Georgy+ 2009)



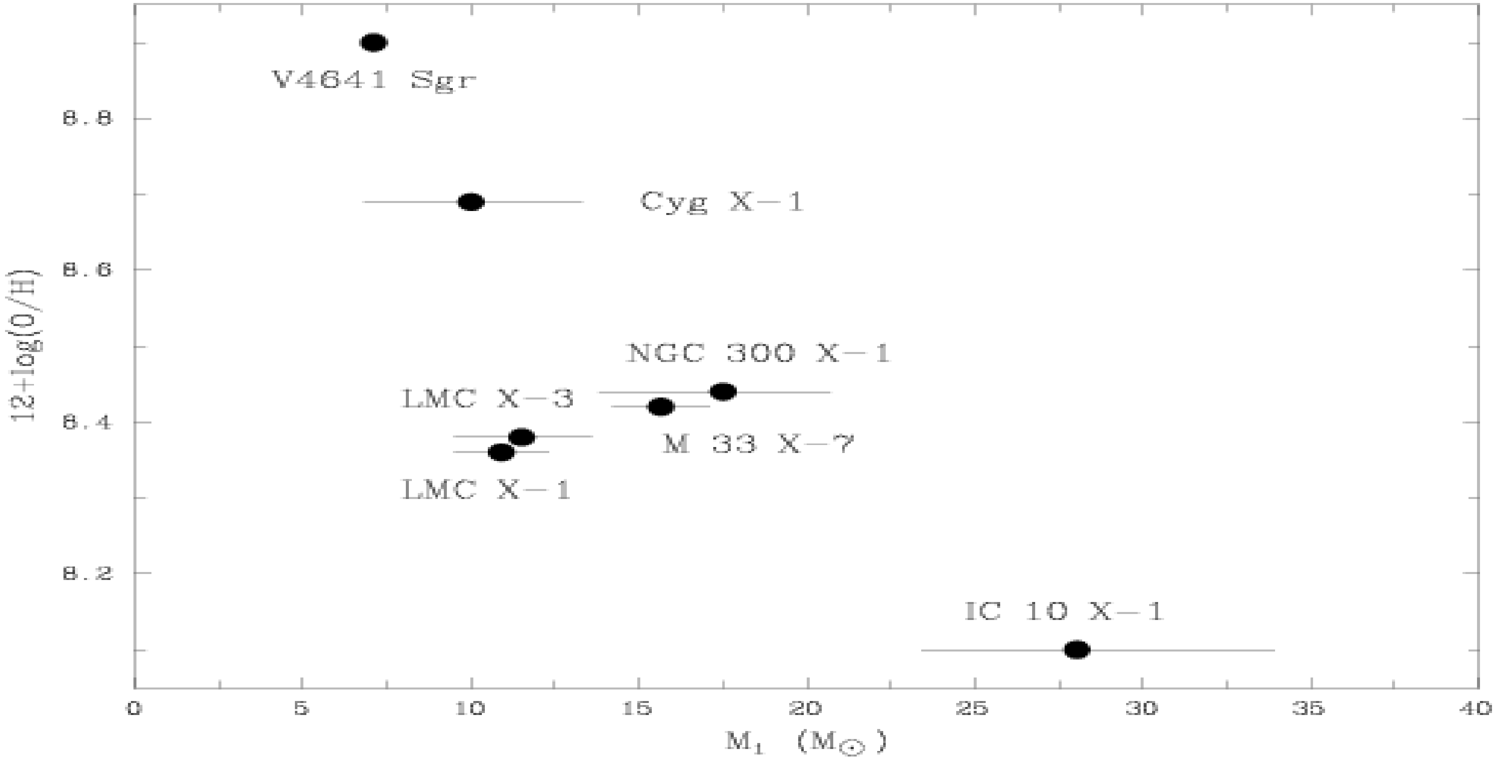
Low metal progenitors form BHs by IMPLOSION (Fryer, 1999)

But following recent results, **binary** is important for the end of massive stars

If the mass lost in low metallicity progenitors is relativelly small, the collapsing cores should be more massive, leading to more massive compact remnants

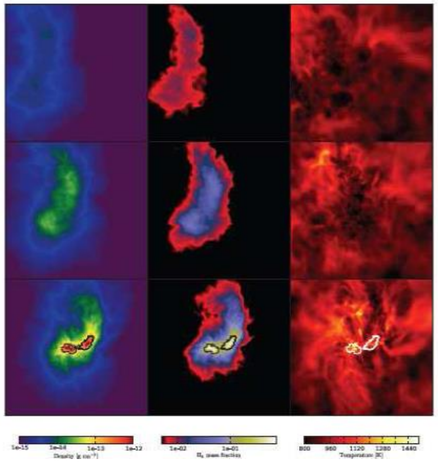
THE MASS OF BHs IN HMXBs SEEMS TO INCREASE WHEN PROGENITORS ARE OF LOW METALLICITIES

Masses determined dynamically (Crowther et al. 2010)

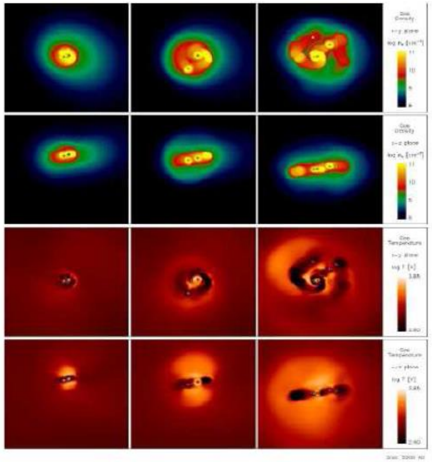


The stellar BHs in the low metallicity galaxies M33 X-7, NGC300 X-1, IC10 X-1 have M_{BH}>15 $M_\odot$ whereas in the Galaxy and M31 all known stellar BHs have M_{BH}<15 $M_\odot$

MASSIVE STARS ARE FORMED IN MULTIPLE SYSTEMS



Turk, Abel & O'Shea (Science 2009)
Krumholz et al. (Science 2009)



Stacy, Greif & Bromm (ApJ 2010)
Fragmentation: Clark+ (Science 2011)

THEORY

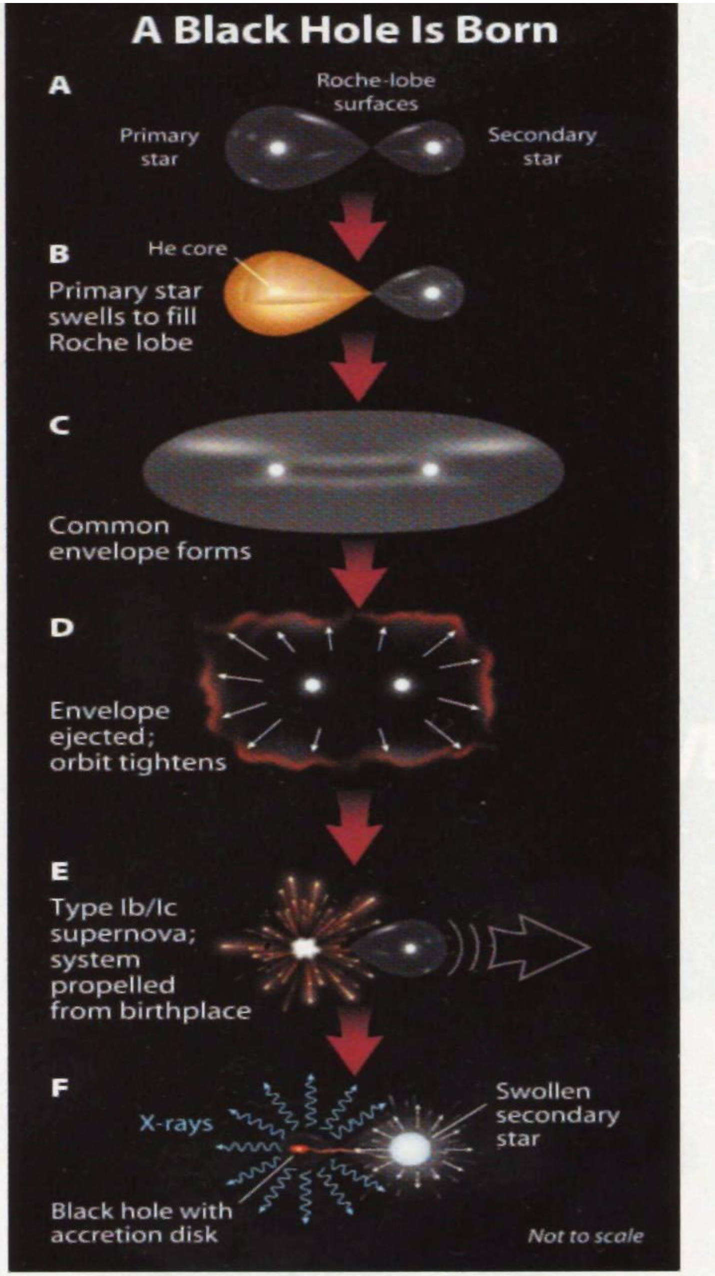
- **Pop III stars were multiple systems dominated by binaries with 10-100 $M_\odot$**
- **This is consistent with no signatures of PISNe** (Becker+ 2011; Frebel, 2011)

OBSERVATIONS

- **In the MW >70% of OB type stars are binaries** (Chini+ 2011; Sana+ Science 2012)

A LARGE FRACTION OF THE Pop III & II STARS END AS BH-HMXBs

HOW ARE BLACK HOLE BINARIES FORM ?



CORE COLLAPSE MODELS:

Massive stellar black holes ($M>10\ M_{\odot}$) should form with no energetic kicks

(Fryer & Kalogera; Woosley & Heger; Nomoto et al.)

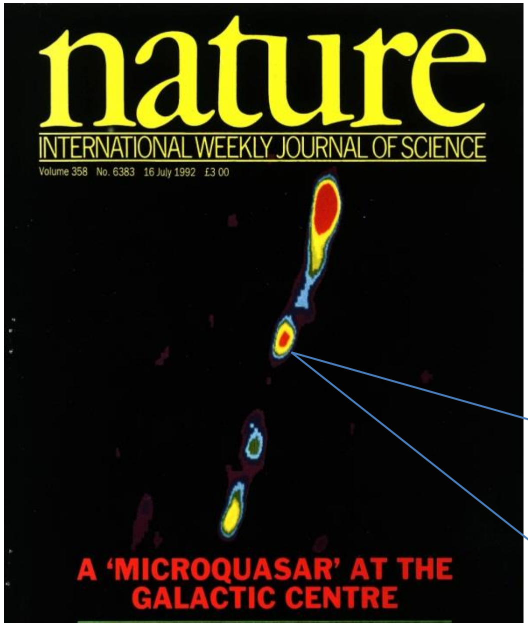
THESE CORE COLLAPSE MODELS CAN BE TESTED USING THE KINEMATICS OF μQSOs

Mirabel & Irapuan Rodrigues (2001-2009)

JETS USED TO PROBE "CORE COLLAPSE IMPLOSION"

STEADY JETS

Mirabel, Rodriguez+ 1992



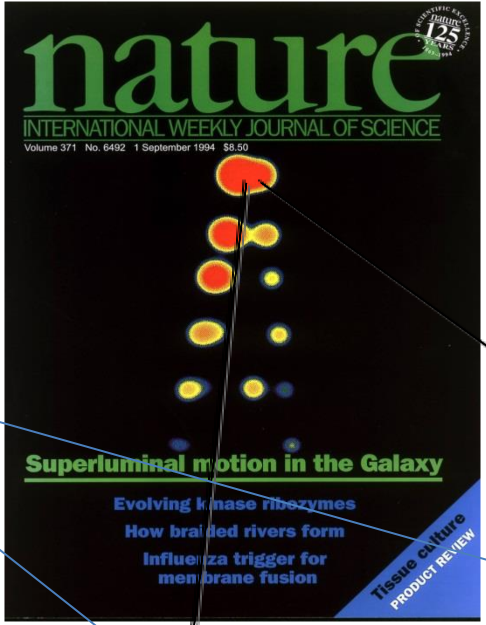
nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 358 No. 6383 16 July 1992 £3 00

A 'MICROQUASAR' AT THE GALACTIC CENTRE

Mirabel & Rodríguez 1994



nature

125 YEARS

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 371 No. 6492 1 September 1994 $8.50

Superluminal motion in the Galaxy

Evolving kinase ribozymes

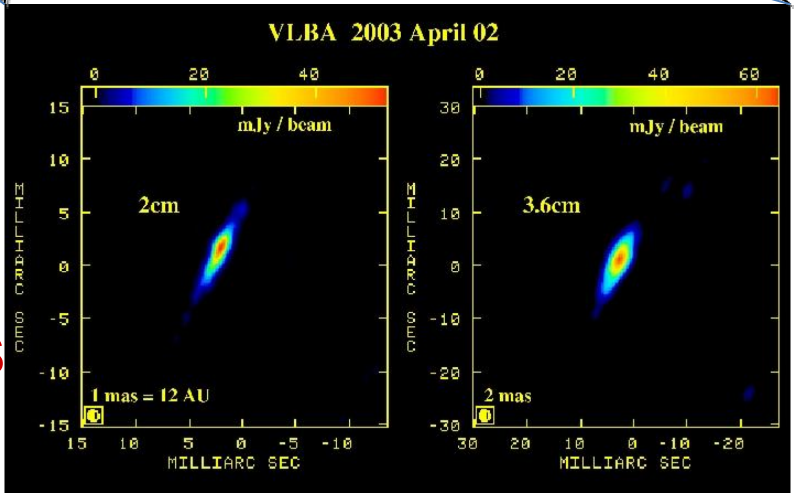
How braided rivers form

Influenza trigger for membrane fusion

Tissue culture PRODUCT REVIEW

TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

In low hard state. Size ~ 100 AU. Same PA

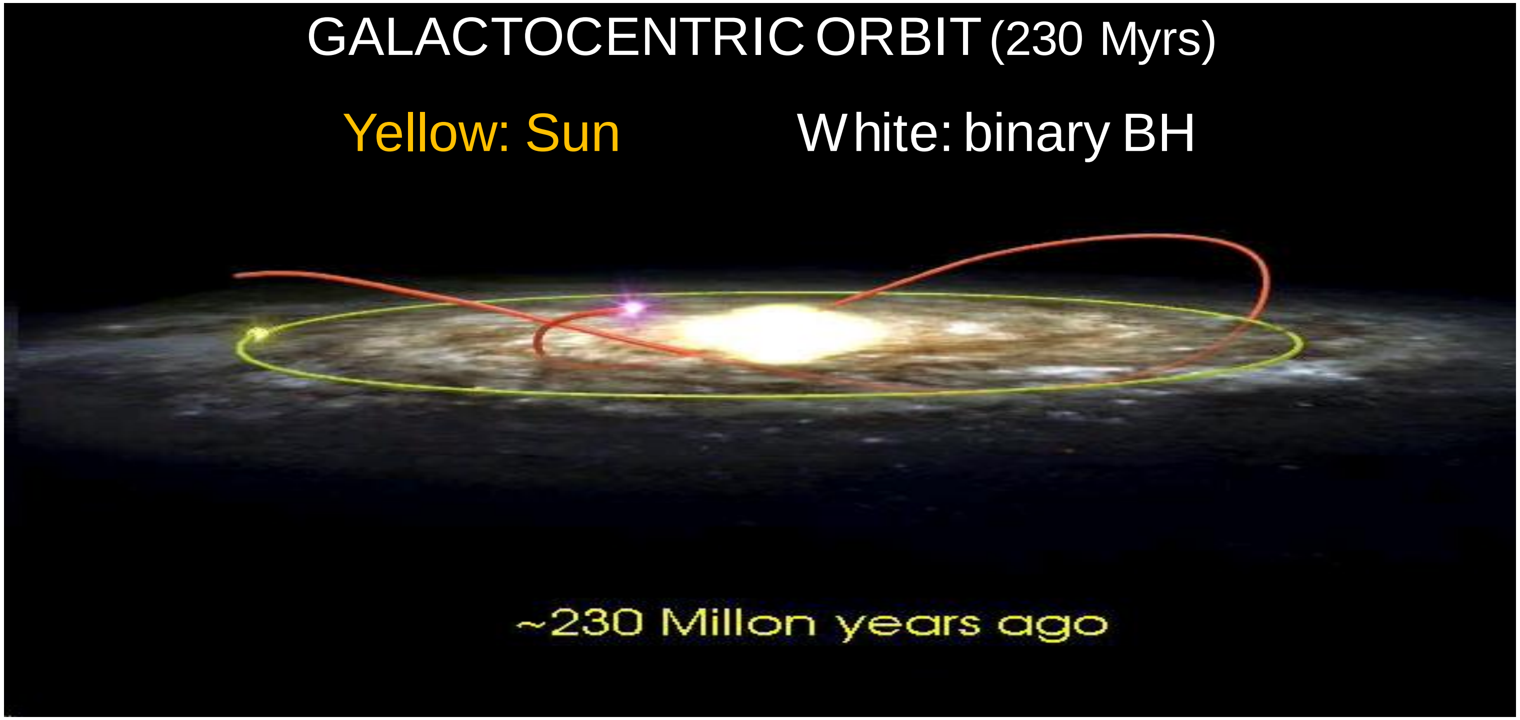
USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

TWO RUNAWAY BLACK HOLES

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

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



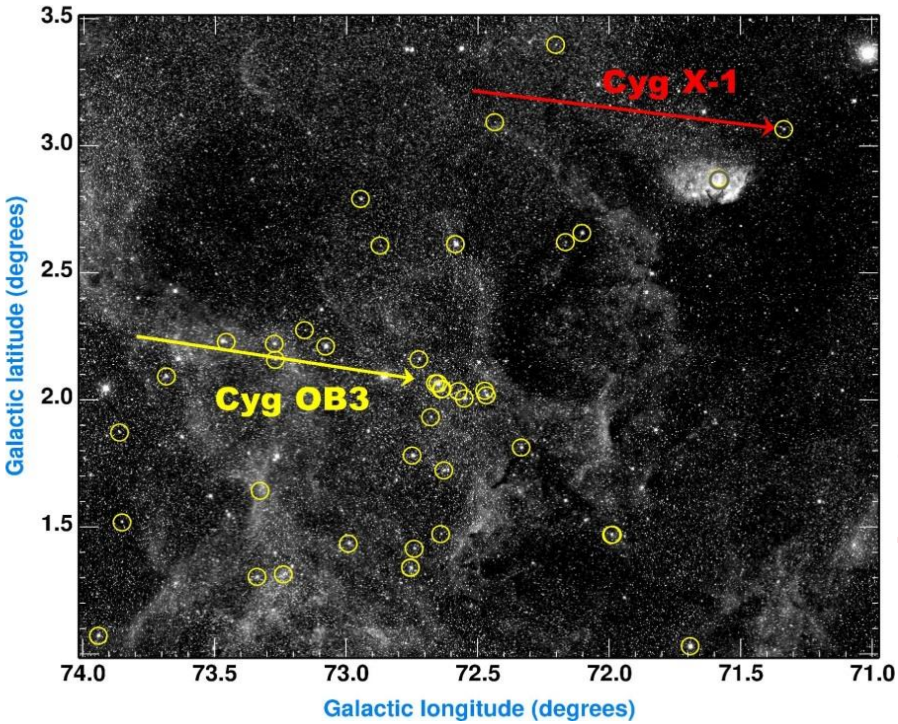
GRO J1655-40: Fossil of a HPN (Israelian et al. Nature 1999)

M_{BH}~5-7 $M_{\odot}$ M_{*}~2 $M_{\odot}$;D=1-3 kpc; **V_p=112+/-18 km/s** (Mirabel et al. 2002)

THE TWO BHs WITH 5-7 $M_{\odot}$ DID NOT REMAIN IN THEIR BIRTH PLACE

BLACK HOLES OF > 10 $M_{\odot}$ FORM BY DIRECT COLLAPSE ("IMPLOSION")

Mirabel & Rodrigues (Science, 2003)



Cygnus X-1

V_p< 9+/-2 km/s $\Rightarrow$ < 1 $M_{\odot}$ ejected in a SN
confirmed by Gou, McClintock+ (2011)

Otherwise it would have been shot out from the parent stellar association

THE ~14 $M_{\odot}$ BH IN Cyg X-1 WAS FORM BY DIRECT COLLAPSE

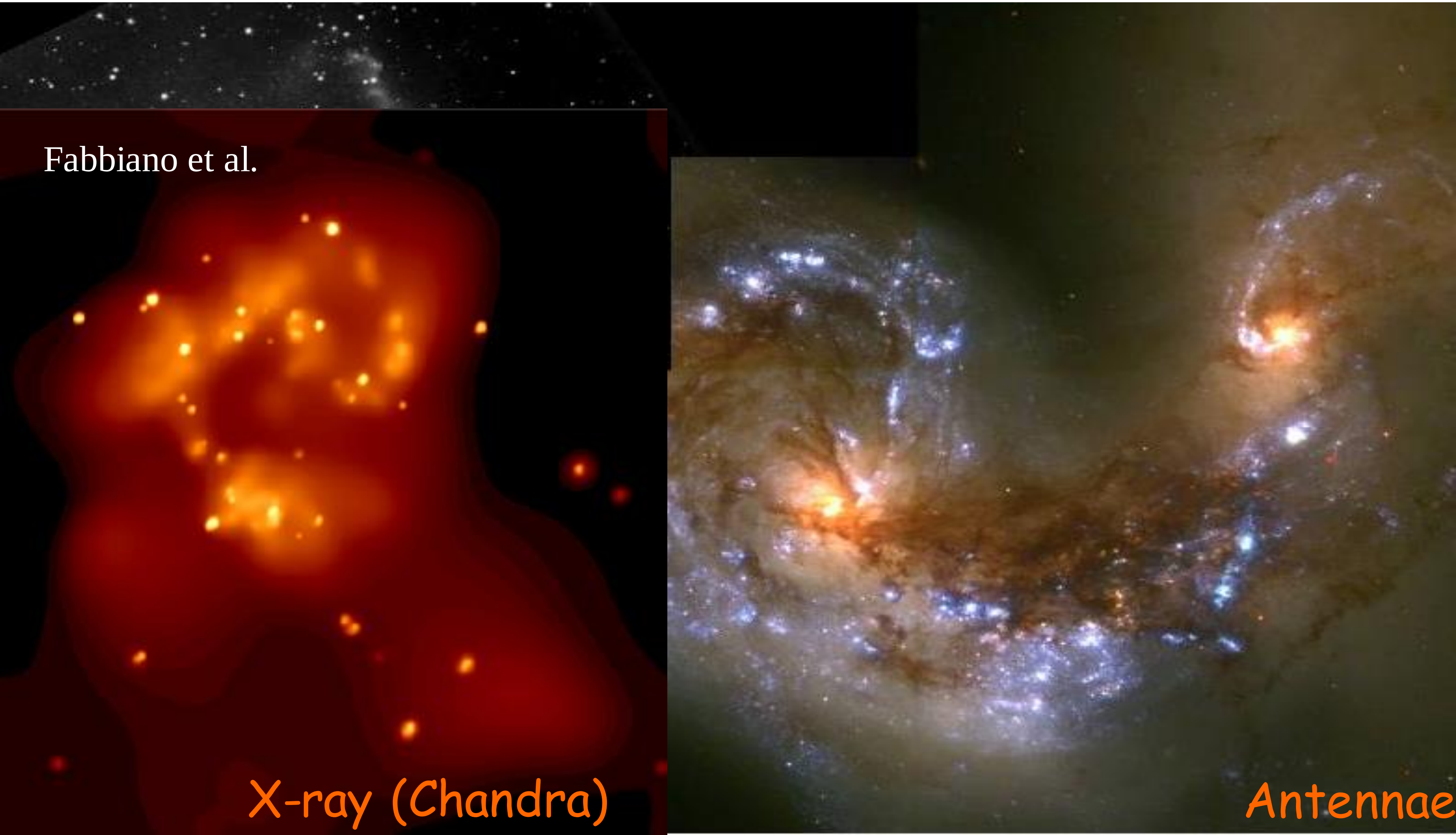
GRS 1915+105: **Vp=50-80 km/s & W=7+/-3 km/s** (Dhawan,Mirabel,Rodríguez 2001)
V404 Cyg: **Vp= 45-100 km/s & W = 0.2+/-3 km/s** (Miller-Jones et al. 2009)

HIGH MASS STELLAR BINARIES END AS BH-HMXBs

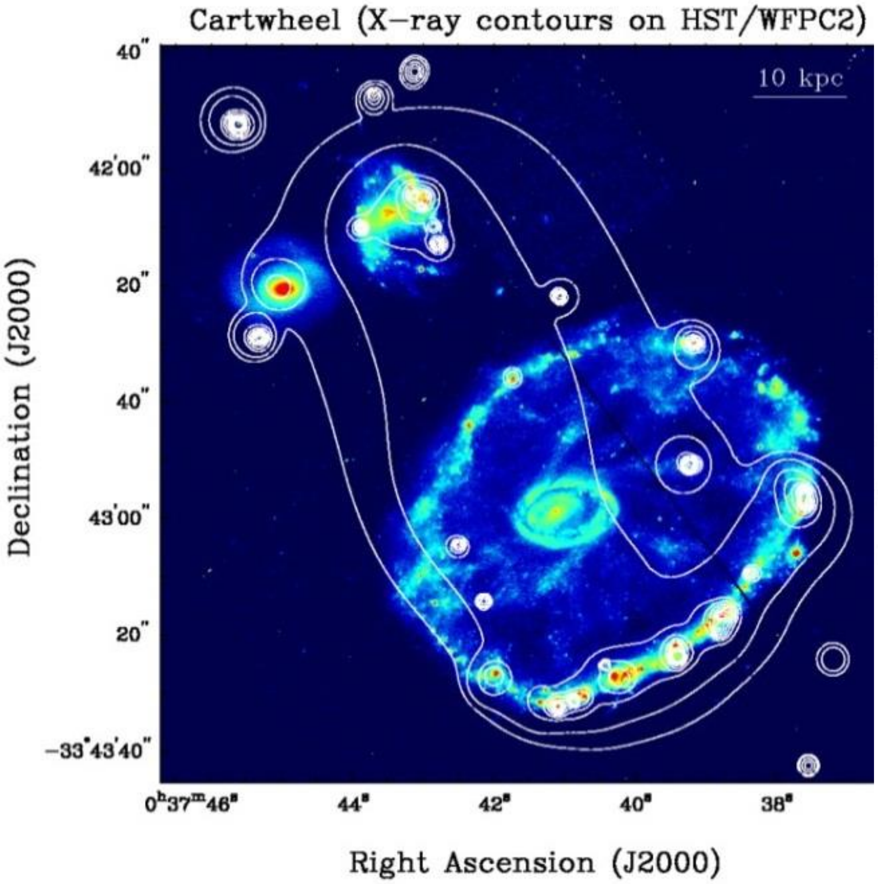
ULTRALUMINOUS X-RAY SOURCES (ULXs)

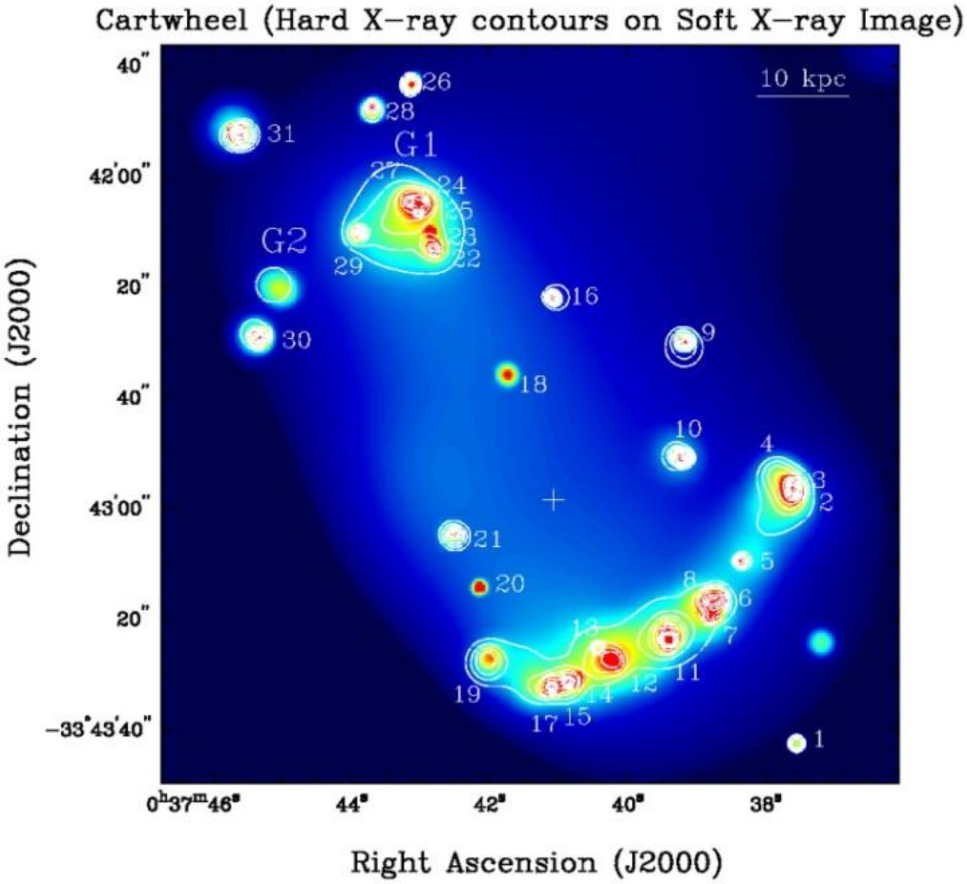
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS IS AN INCREASING FUNCTION OF THE SFR AND A DECREASING FUNCTION OF THE METALLICITY

e.g. Zampieri & Roberts (2009)


Fabbiano et al.

ULXs IN “TEMPLATES” OF HIGH z GALAXIES

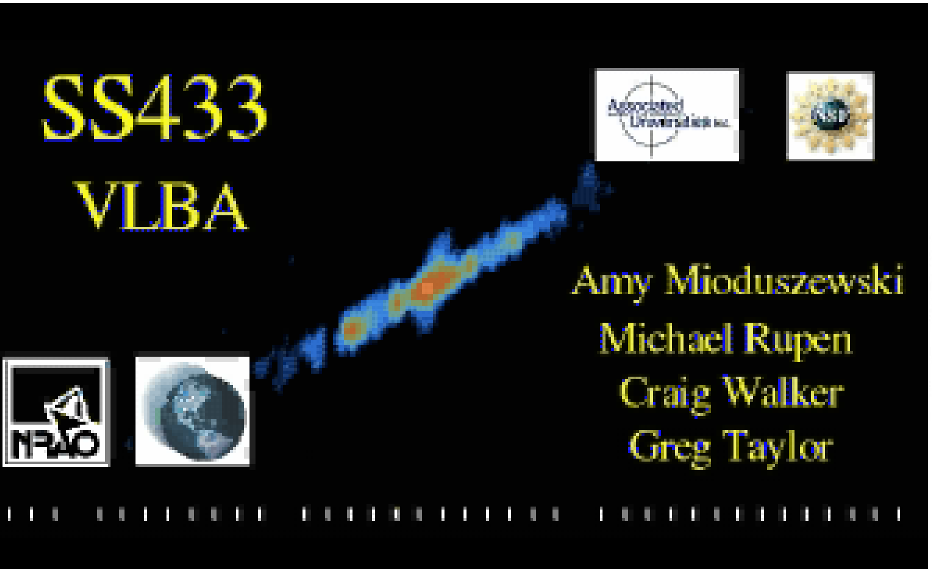




The ULXs luminosity of ~10^{42} erg s^{-1} in the Cartwheel rivals that of AGN

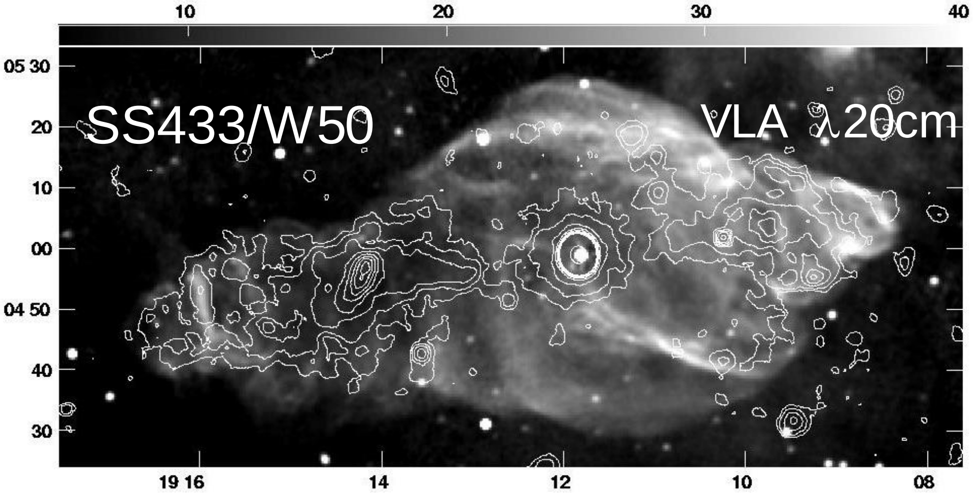
(Gao+ 2003)

POWERFUL JETS FROM BH-HMXBs (μQSOs)



1arcsec

Radio (Dubner et al); X-rays: (Brinkmann et al)

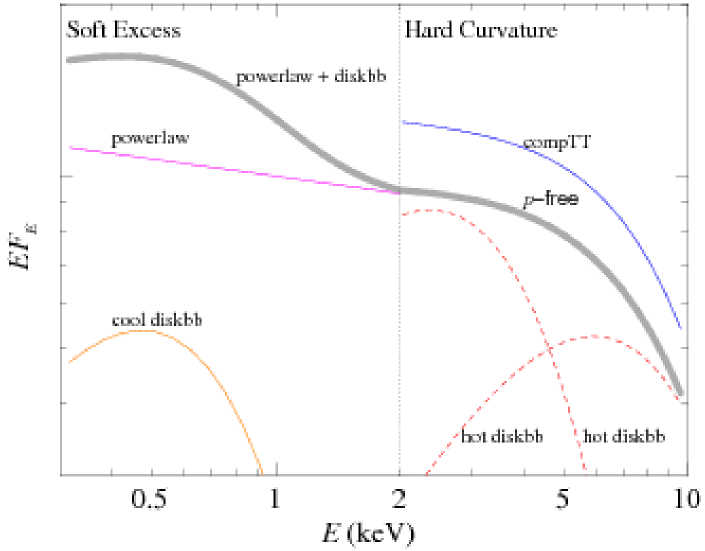


$1^o = 60$ pc

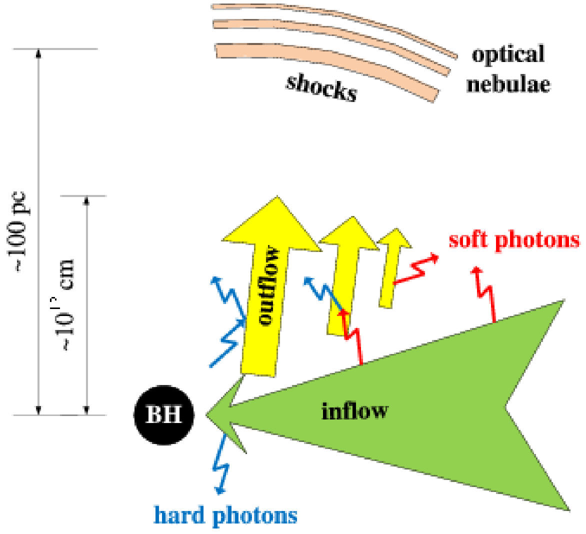
- ATOMIC NUCLEI MOVING AT 0.26c ⇒
- MECHANICAL LUMINOSITY > 10^{39} erg/sec
- NON RADIATIVE JETS = “DARK” JETS
- >50% OF THE ENERGY IS NOT RADIATED

BH-HMXBs IN STAR-FORMING GALAXIES OF LOW METALLICITY

The spectra are soft

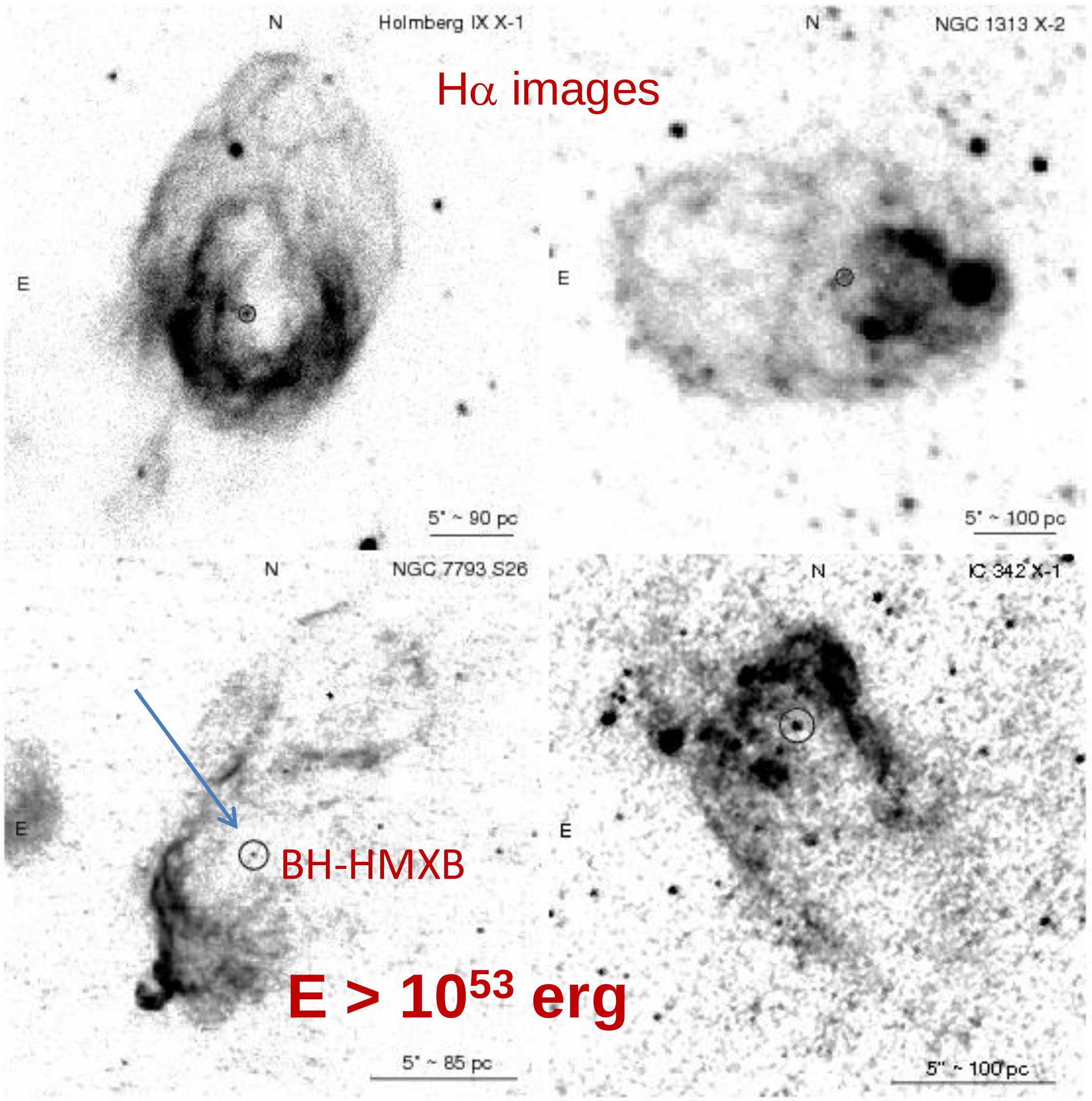


Massive outflows



From Feng & Soria (2011)

shock & photonionized bubbles of > 100 pc size



Hα images

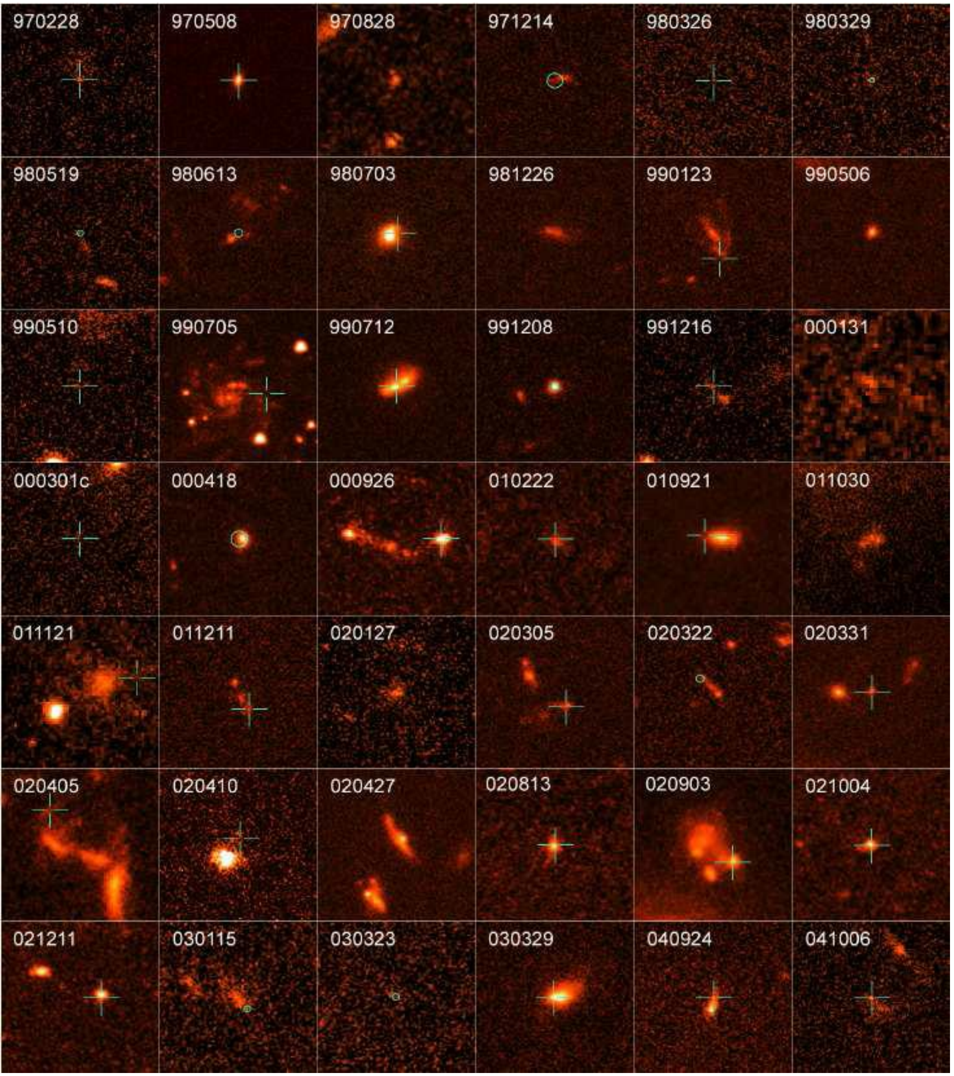
BH-HMXB

E > 10^{53} erg

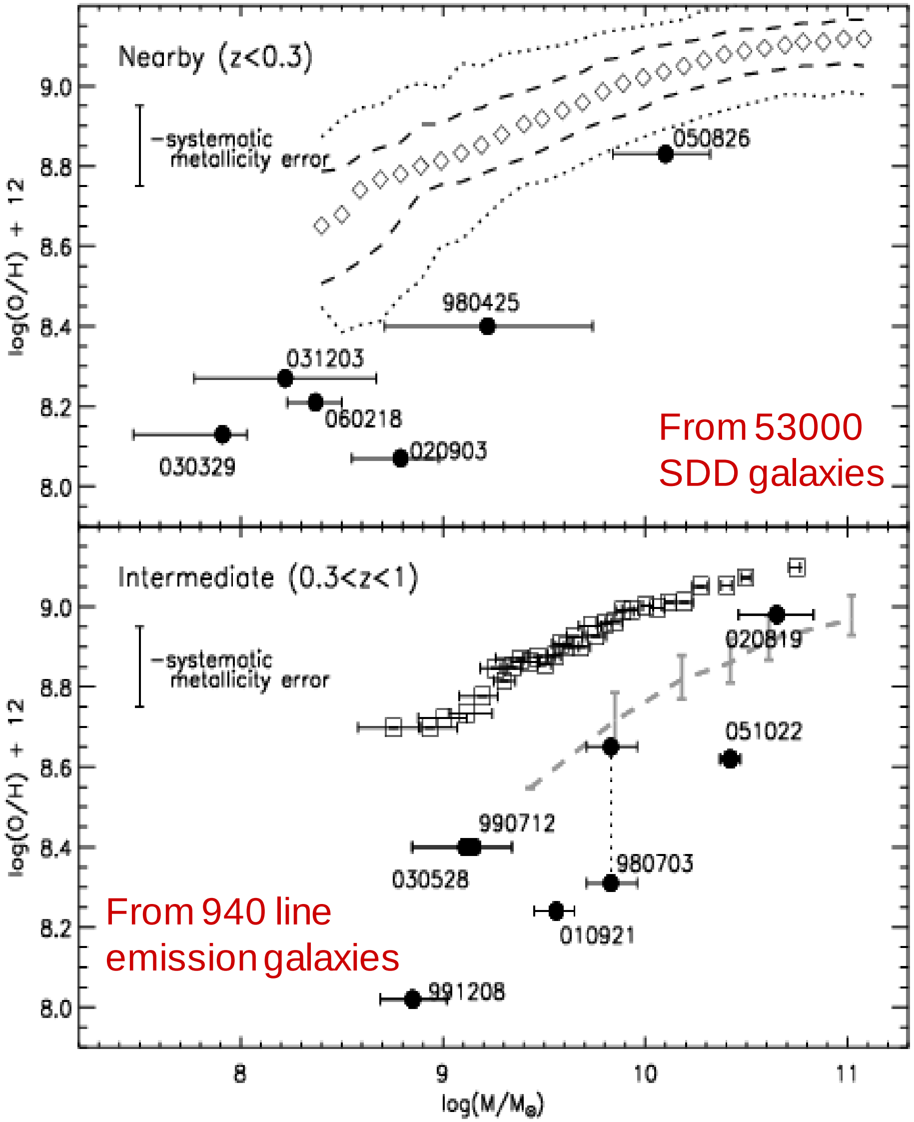
THE HOSTS OF LGRBs ARE SMALL IRR. GALAXIES WITH LOW Z

Le Floc´h, Duc, Mirabel with VLT (2003)

Fruchter + with HST (Nature, 2006)



Levesque et al. (2010)



From 53000 SDD galaxies

From 940 line emission galaxies

CONCLUSION FROM STUDIES OF HMXBs

THE COSMIC EVOLUTION OF METALLICITY ⇒ A COSMIC EVOLUTION OF BH-HMXBs

At low metallicities ($Z < Z^{-5}_{\odot}$) there should be an increase of:

- **the number** of BH-HMXBs since massive stars form BHs by direct collapse
- **the mass** of stellar BHs because the progenitor cores are more massive
- **The X-ray luminosity** of BH-HMXBs because of higher accretion rates (van Paradijs & McClintock, 1995)…an issue to be investigated further.

From a population synthesis study using the Millennium II Cosmological Simulation and the updated galaxy catalog, **Fragos et al. (2012) reach the same conclusions**

Ionizing power of μQSOs versus ionizing power of massive stars

Counting photons Mirabel (CEA), Laurent (CEA), Loeb, Diskra, Pritchard (Harvard)

$$\frac{N_{\gamma,BH}}{N_{\gamma,*}} = 0.6\left(\frac{N_{phot}}{64000}\right)^{-1}\left(\frac{M_{BH}}{M_*}\right)\left(\frac{f_{edd}}{0.1}\right)\left(\frac{t_{acc}}{20\,Myr}\right)\left(\frac{\langle E\rangle_\gamma}{keV}\right)^{-1}\left(\frac{f_{esc,*}}{0.1}\right)^{-1}\left(\frac{f_{esc,BH}}{1.0}\right),$$

f_{edd} = fraction of Eddington luminosity for a time t_{acc}

N_{phot} = number of ionizing photons emitted per atom of H nucleus

$<E>_\gamma$ = mean photon energy emitted by the accreting BH

$f_{esc,*}$ ($f_{esq,BH}$) = fraction of ionizing photons that escape

For fiducial values of the model parameters:

THE ACCRETING BLACK HOLE EMITS A TOTAL NUMBER OF IONIZING PHOTONS THAT IS COMPARABLE TO THAT OF ITS PROGENITOR STAR

- But in a fully neutral medium **N_{sec*} = 25 (E_γ /1 keV),** where E_γ is the photon energy

However, not all stars will be massive and lead to the formation of BH-HMXBs…

TOMOGRAPHY OF THE HI IN THE DARK AGES

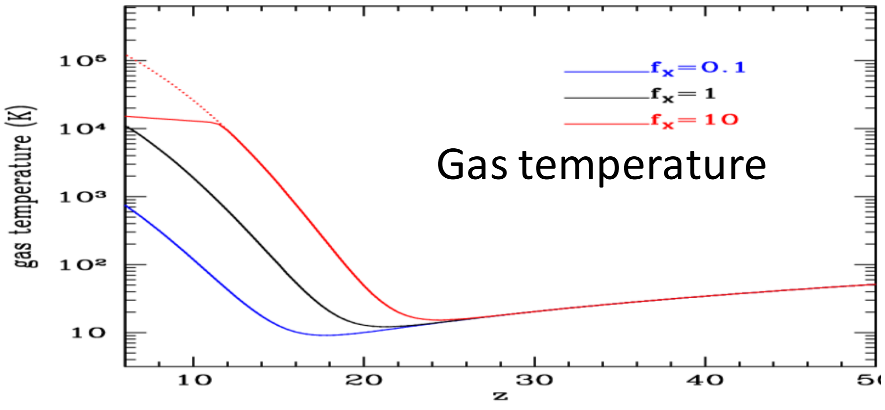
$$L_{2-10} = f_X \times 3.5 \times 10^{40} SFR \quad erg/s$$

f_x does not seem to change up to z=4

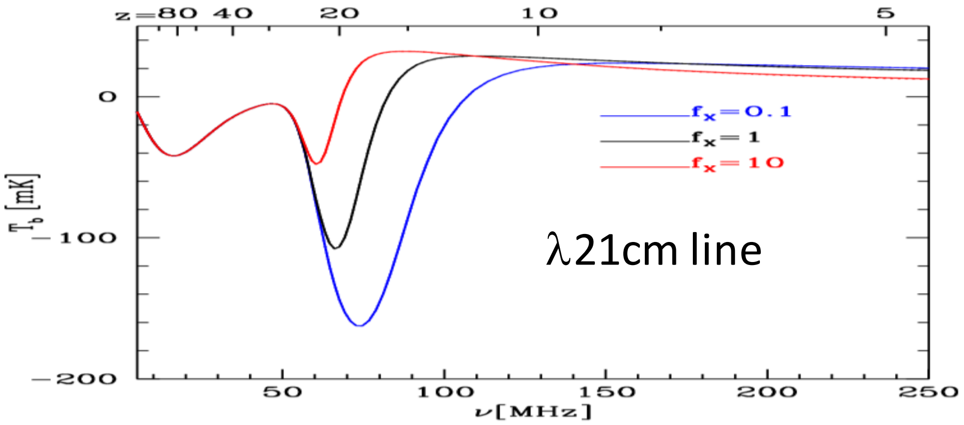
Correlation between X-ray luminosity and SFR. $f_x = 0.2$ at $z<1.3$ (Mineo,Gilfanov, Sunyaev, 2012), but in BCDs $f_x > 10$ times greater than in normal-metallicity star-forming galaxies (Kaaret+ 2011) & in local analogs of Lyman Break Galaxies Lx ~ 10^{42} erg s^{-1} (Jia, Heckman+, 2011)

$$f_X = \frac{f_{2-10} f_{BH} t_{acc} f_{bin} f_{edd} \times 1.5 \times 10^{38}}{3.5 \times 10^{40}} = \underset{4.0}{0.4} \left(\frac{f_{2-10}}{0.1}\right)\left(\frac{f_{BH}}{0.01}\right)\left(\frac{f_{edd}}{0.1}\right)\left(\frac{f_{bin}}{\underset{0.5}{0.05}}\right)\left(\frac{t_{acc}}{20 Myr}\right)$$

At $Z < 10^{-5} Z_\odot$ the IMF is top heavy and flat ⇒ f_x must increase at $z > 6$



Gas temperature



λ21cm line

•BH-HMXBs HEATED THE IGM TO ~10^4 K OVER LARGE VOLUMES

GMRT λ21cm @ z~9 ⇒Was the IGM heated before being fully ionized? (Paciga+ 2012)

BH-HMXBs LIMITED THE MASS OF DWARF GALAXIES

From Loeb (2010): $T_{vir} = 1.04 \text{ x } 10^4 (\mu/0.6) (M/10^8 M_\odot)^{2/3} [(1+z)/10] K$

$$\mathbf{M_{min} \sim 10^9 (\rho/100\rho_c)^{-1/2} (\mu/0.6)^{-3/2} [T(K)/10^4]^{3/2} [(1+z)/10]^{-3/2} M_\odot}$$

ρ_c = critical mass density for a flat universe, r = mass density in the galaxy

μ = mean molecular weight, z = redshift, T = temperature of the IGM

X-ray heating of the diffuse IGM during reionization resulted in an additional increase of the minimum galaxy mass. Once the IGM was heated to ~10^4 K by the X-rays from the first generations of BH-HMXBs, dark matter haloes with masses below a certain mass ($10^x M_\odot$) could not accrete gas from IGM.

- **THE THERMAL HISTORY OF THE IGM DETERMINED BY HMXBs HAD AN IMPACT ON THE PROPERTIES OF THE FAINTEST GALAXIES AT HIGH z AND THE SMALLEST GALAXIES IN THE LOCAL UNIVERSE, REDUCING THE NUMBER OF DWARF GALAXIES PREDICED BY THE λCDM**

CONCLUSIONS FROM HMXBs IN THE $z > 6$ UNIVERSE

I) X-RAYS HAVE LONGER MEAN FREE PATH THAN UVs: THEY HEAT THE GAS FAR FROM THE GALAXIES AND PARTIALLY IONIZE THE BULK OF THE IGM.

II) FEEDBACK FROM BLACK HOLES DETERMINE GALAXY STRUCTURE:
A) SUPERMASSIVE BHs STOP THE UNLIMITED GROWTH OF GALAXIES
B) STELLAR BHs SET A LOWER LIMIT FOR THE MASS AND UPPER LIMIT TO THE NUMBER OF DWARF GALAXIES (CONSISTENT WITH THE λCDM MODEL)

III) SHOULD EXIST NAKED HALOS OF DARK MATTER WITH MASSES $<10^{8-9}$ $M_{\odot}$

IV) BH-BH STELLAR BINARIES MAY BE THE MOST LIKELY SOURCES OF GRAVITATIONAL WAVES (Belczynski et al. 2011)

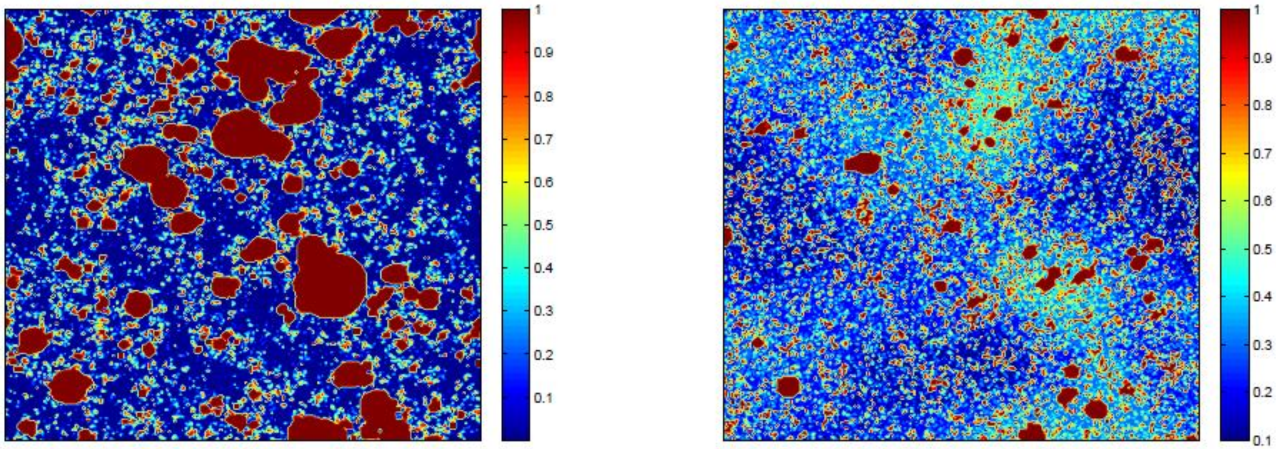
REFERENCES ON THIS WORK

- Mirabel. Review in the Proceedings of IAU Symp. 275 (2011)
  (arXiV:1012.4944v1 [astro-ph.CO] 22 Dec 2010)
- Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 528, A149, 2011)
  Up to date this publication now has ~50 references
- News & Views by Haiman in Nature of 7 April, 2011

OPEN QUESTIONS

I) Will the λ21cm signals from HI at high z (to be measured with LOWFAR, SKA, and single dipole experiments as EDGES), have large amplitudes and be more uniform rather than HII region dominated, having no so patchy “Swiss cheese” topology?

Ionization fractions for 0% and 50% X-rays at z=9 for a slice of $170 \times 170 \times 0.66$ Mpc^3 (Visbal & Loeb, 2011)



II) Are the first HMXBs the cause of the near IR background fluctuations (Yue+2013)?

II) Are the BH-HMXBs with non-thermal emission up to 2 MeV (as in Cyg X-1, that formed at z > 7) the cosmic sources of the unresolved hard X-ray background?

III) Will the mergers of BH-BH stellar binaries be the more likely sources of gravitational waves that will be detected ? (Belczynski et al. 2011)