COSMIC EVOLUTION OF STELLAR BLACK HOLES AND THE END OF THE DARK AGES

DARK AGES: FROM ~400.000 TO < 10^9 YEARS

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REIONIZATION OF THE UNIVERSE?

- Motivated by first results of WMAP it was proposed a very early ionization of the IGM by IMBHs (Madau, Rees, Volonteri, et al. 2004).
- The ionization may have been produced by the first galaxies, namely, by the UV radiation from stars of Population III & II (Loeb et al. and many others).
- However from

a) the theoretical models of the formation and collapse of massive stars

b) the multiple observations of the remnants of massive stars

I PROPOSE AS WORKING HYPOTHESIS THAT STELLAR BLACK HOLE HIGH MASS X-RAY BINARIES (BH-HMXBs) MAY HAVE PLAYED AN IMPORTANT, COMPLEMENTARY ROLE, TO THAT OF THEIR MASSIVE STELLAR PROGENITORS IN THE PROCESS OF REIONIZATION OF THE UNIVERSE

Is this hypothesis consistent with the following observational results ?

1) a LGRB at $z \sim 8.2$,

2) galaxies at $z = 7\text{-}9$ with HST/WFC3

3) Recent results from WMAP that date the reionization epoch at $z \sim 10.5$?

Plan of the talk

- Short review of the theoretical models that predict the direct collapse of massive stars
- Review the diversity of observations of the fossils (neutron stars and black holes) in the near and far universe from which can be inferred that black holes can be form by direct collapse
- Review how the formation of black hole binaries depends on the SFR of the host galaxy and Z
- Cosmological implications (in progress)

STELLAR BLACK HOLES PLAYED AN IMPORTANT ROLE IN COSMOLOGY IF THEY CAN FORM BY THE IMPLOSION OF MASSIVE STARS (WITH NO SNe)

It is difficult to prove observationally the direct formation (with no SNe) of stellar black holes since one should prove the “inexistence” of SNe…

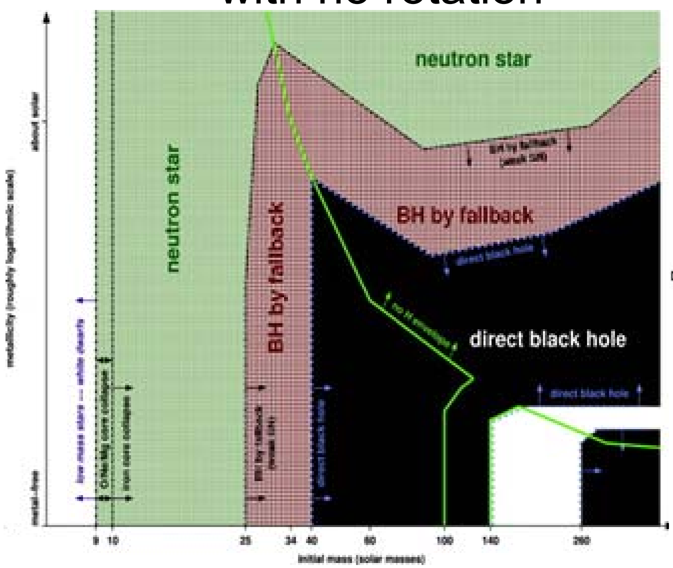
“A Survey About Nothing: Monitoring a Million Supergiants…”

From the fossils can be inferred whether massive stars finish with energetic explosions or silently

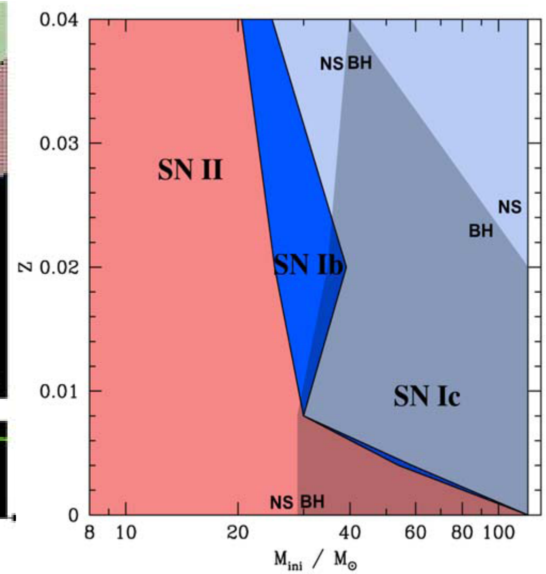
“Stellar Forensics”

MODELS FOR THE COLLAPSE OF SINGLE MASSIVE STARS

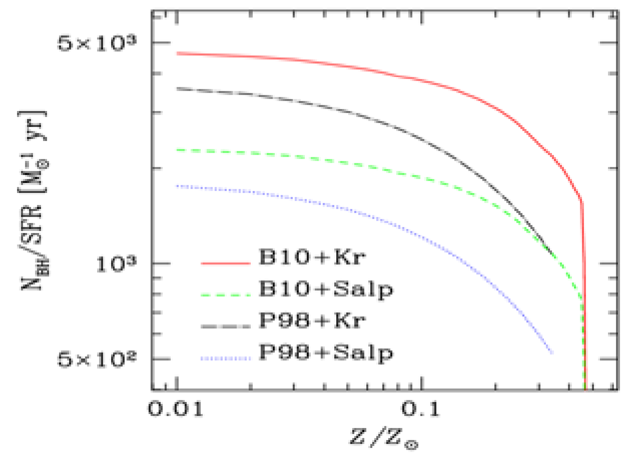
Heger et al. (2003)
with no rotation



Georgy et al (2009)
with rotation



Mapelli et al. (2010)
Number of expected massive BHs per galaxy normalized to the SFR as a function of Z



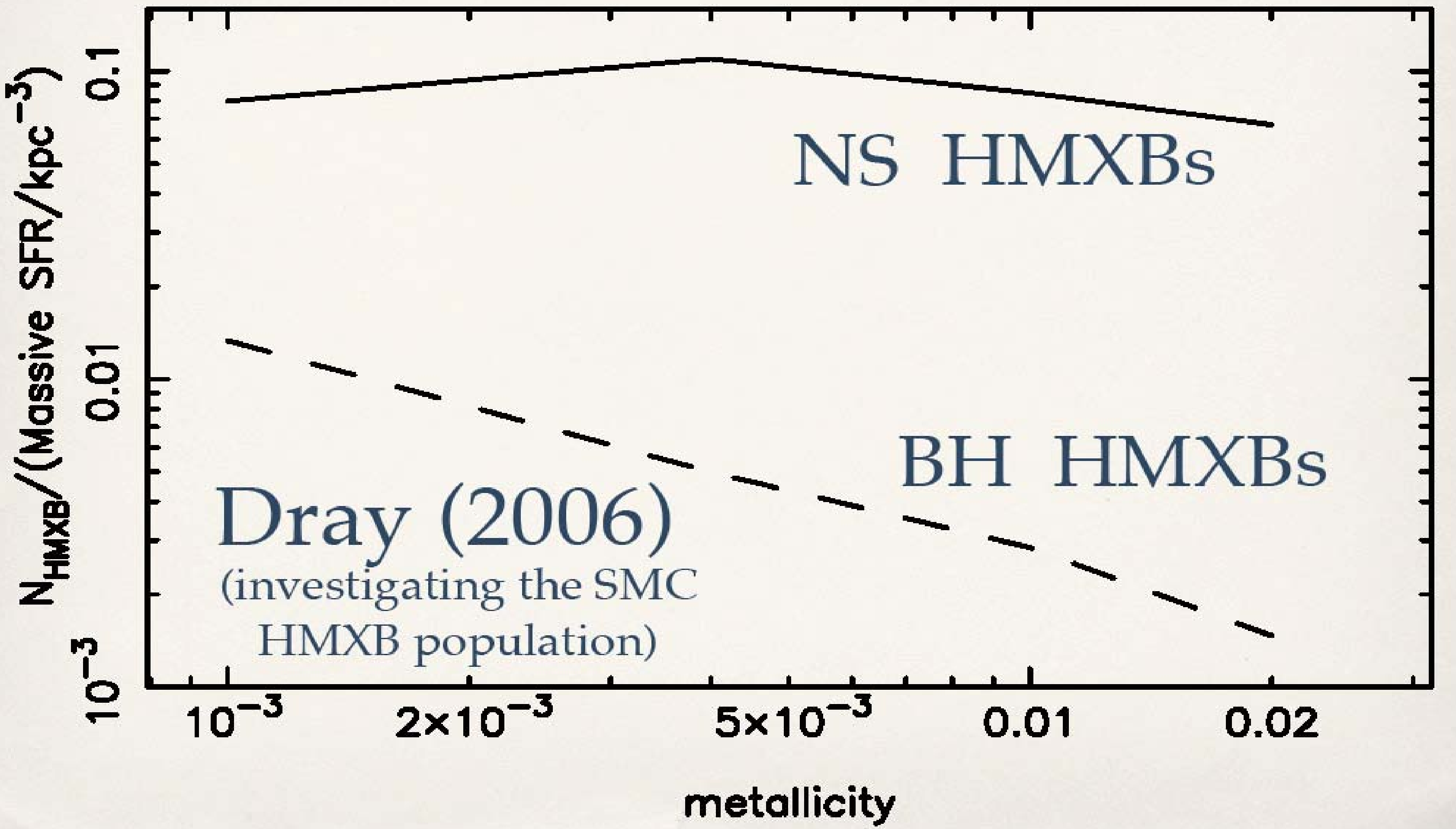
•Low metal progenitors may form BHs by implosion (Fryer, 1999)

•There is a threshold effect: BHs form with $Z<0.5Z_{\odot}$ (Mapelli+2010)

But the destiny of massive stars also depends on magnetism & **binarity**

MODELS OF BH HMXBs FORMATION AS A FUNCTION OF SFR & Z

For early studies of BH-binary Z-dependence, see Belczynski et al. (2004) & Dray (2006)



Current models on the evolution of massive stars imply:

- THE MASS OF STELLAR BLACK HOLES
- THE FRACTION OF BLACK HOLES / NEUTRON STARS
- THE FRACTION OF BINARY / SOLITARY BLACK HOLES

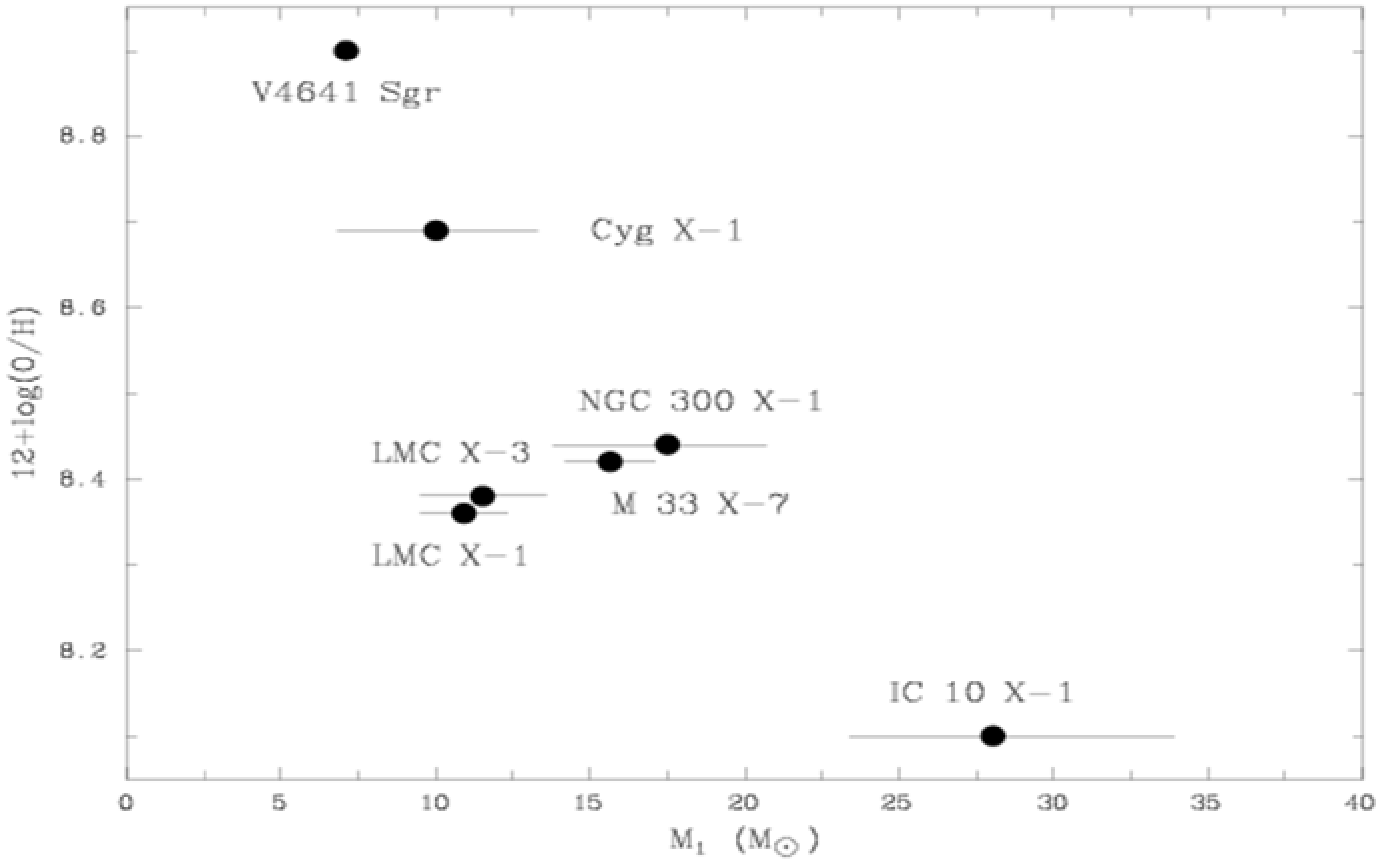
SHOULD INCREASE WITH DECREASING METALLICITY OF THE PROGENITORS:

Because the fraction of binary systems that remain bound increases, from a theoretical point of view one expects that

THE FRACTION OF BLACK HOLE HIGH MASS X-RAY BINARIES SHOULD INCREASE WITH THE DECREASING METALLICITY OF THE PROGENITORS

THE MASS OF BHs IN HMXBs SEEMS TO BE A DECREASING FUNCTION OF METALLICITY

Masses determined dynamically (Crowther et al. 2010)



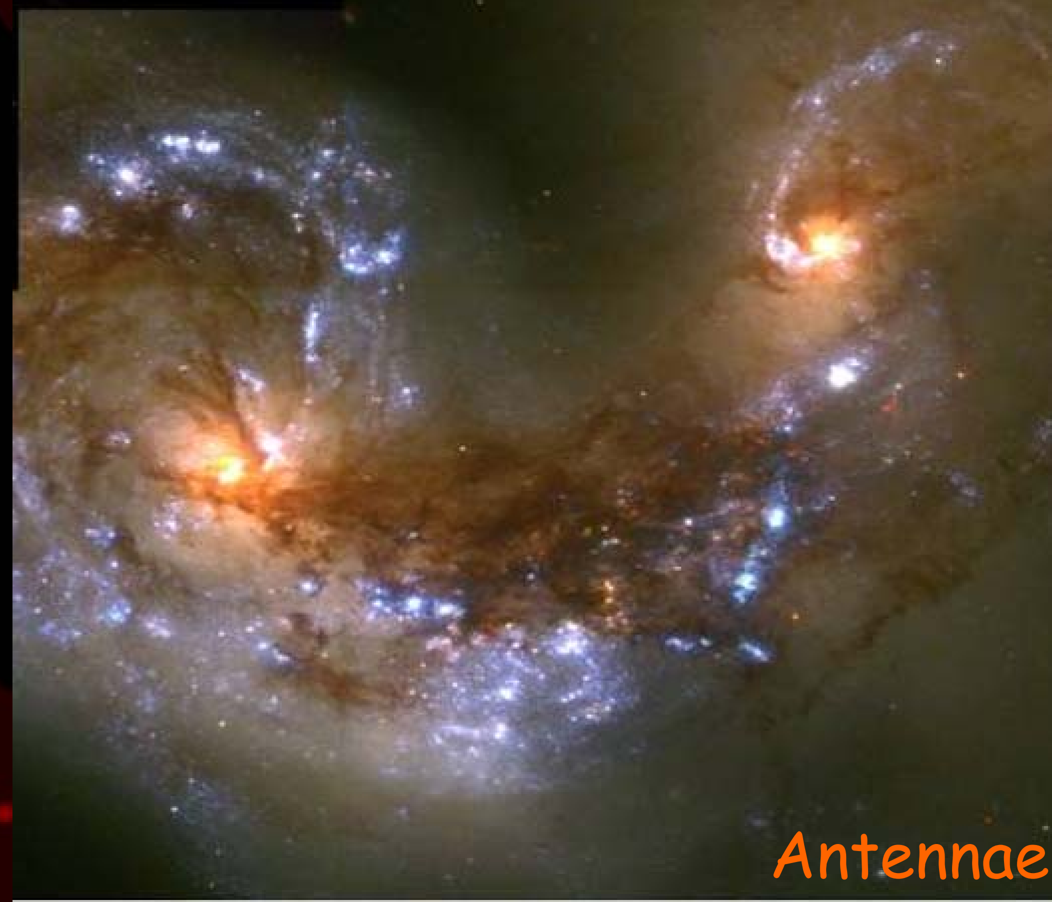
The stellar BHs in M 33 X-7, NGC 300 X-1, IC 10 X-1 have $M_{BH} > 15\ M_{\odot}$ whereas in the Galaxy and M 31 no stellar BH with $M_{BH} > 14\ M_{\odot}$ is known

Besides, a new dynamic mass for NGC 1313 X-2 may reveal another black hole of large stellar mass

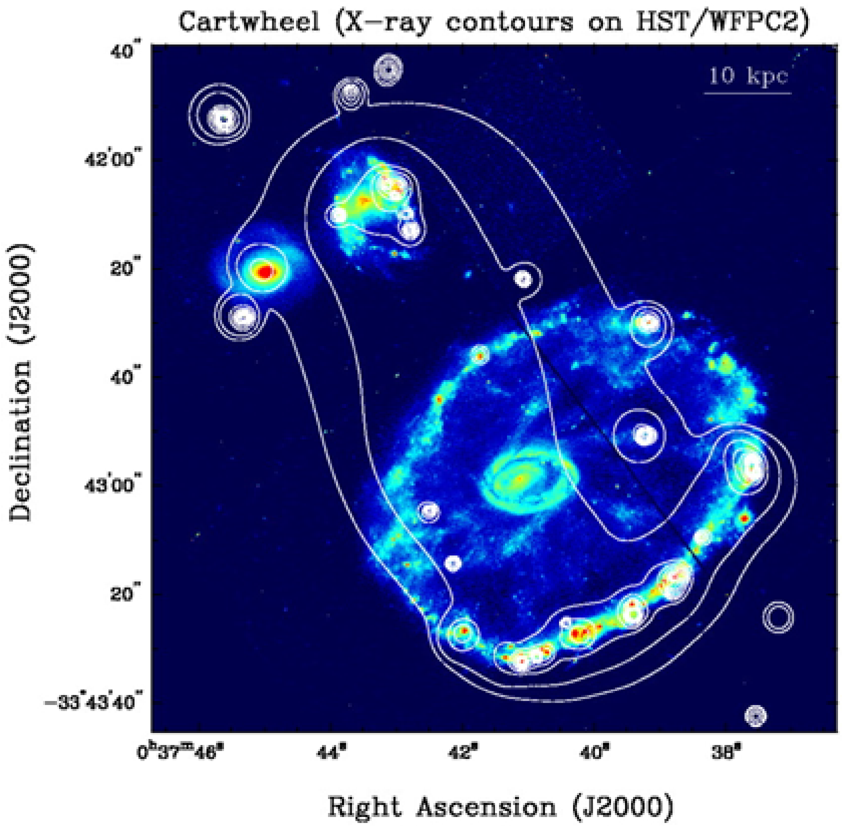
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS IN STARBURST GALAXIES IS A DECREASING FUNCTION OF THE METALLICITY OF THE HOST GALAXY

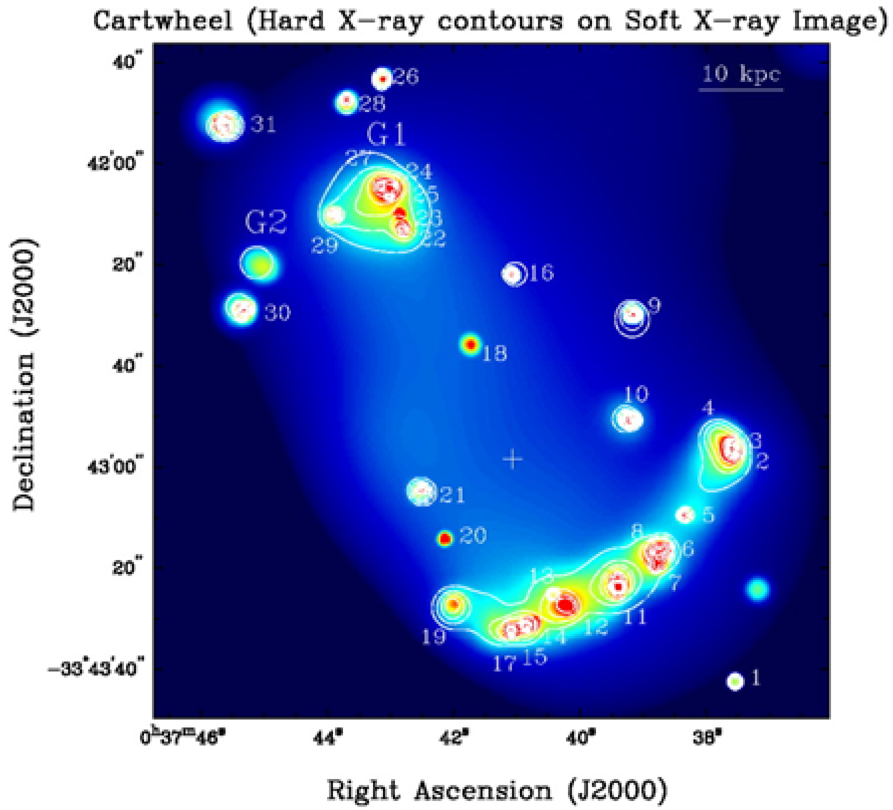
e.g. Zampieri & Roberts (2009)

- ACCRETING BHs in binaries with $M_{BH} > 30\ M_{\odot}$ (Pakull et al. 2002)
- ANISOTROPIC EMISSION BUT NOT BEAMED (King et al. 2001)



ULXs in the Cartwheel



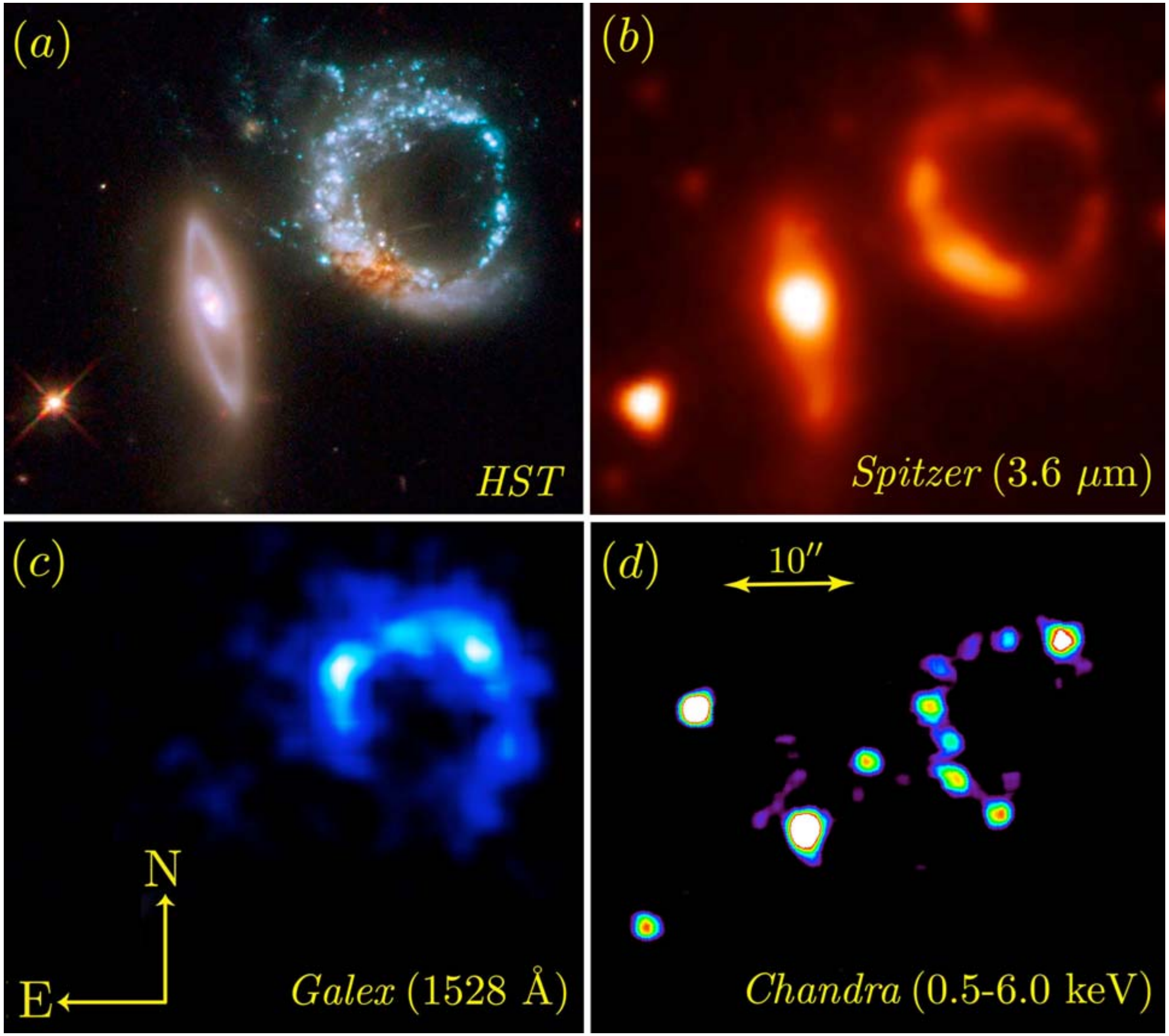


Rival the X-ray luminosities usually associated with active galactic nuclei

Total X-ray luminosity ~ 10^{42} erg s^{-1} (Gao et al. 2007)

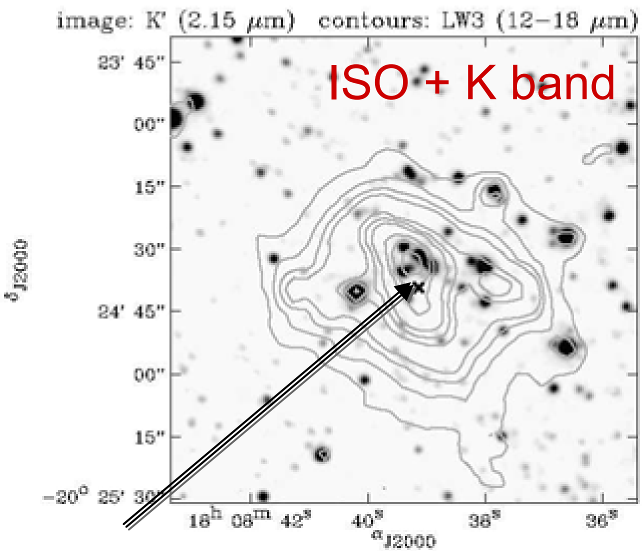
ULXs in Arp 147

Rappaport et al. 2010



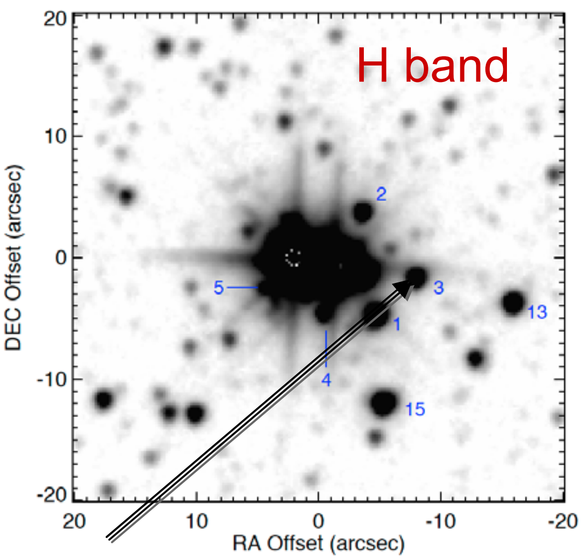
SGRs and AXPs (young neutron stars) found in clusters of massive stars

SGR 1806-20
Mirabel et al. (1999)



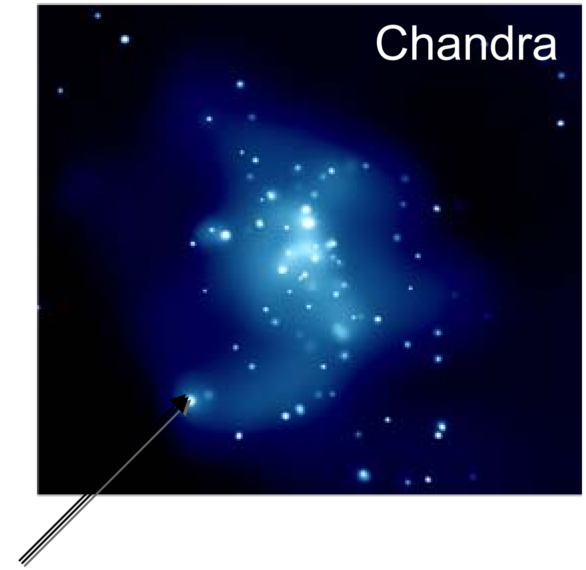
$M_{prog} > 40\ M_\odot$

SGR 1900+14
Vrba+ 2000; Davies+ 2009



$M_{prog} \sim 20\ M_\odot$

AXP 1647-45
Muno et al. (2006)
in Westerlung 1



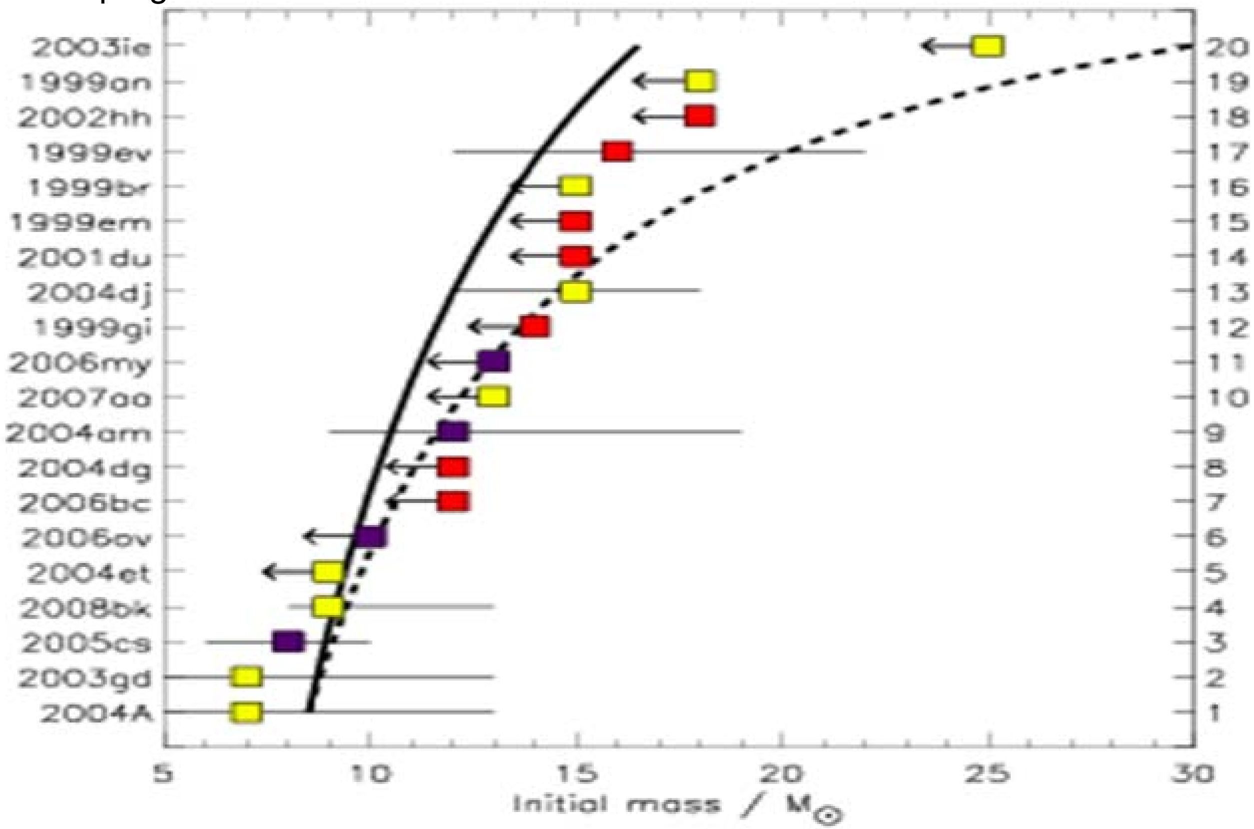
$M_{prog} \sim 40\ M_\odot$

These mass estimates were confirmed by recent studies (Davies et al. 2009)

MASSIVE STARS OF HIGH METALLICITY END AS NEUTRON STARS RATHER THAN BLACK HOLES

PROGENITORS OF CORE-COLLAPSE SNe HAVE MASSES < 20 $M_\odot$

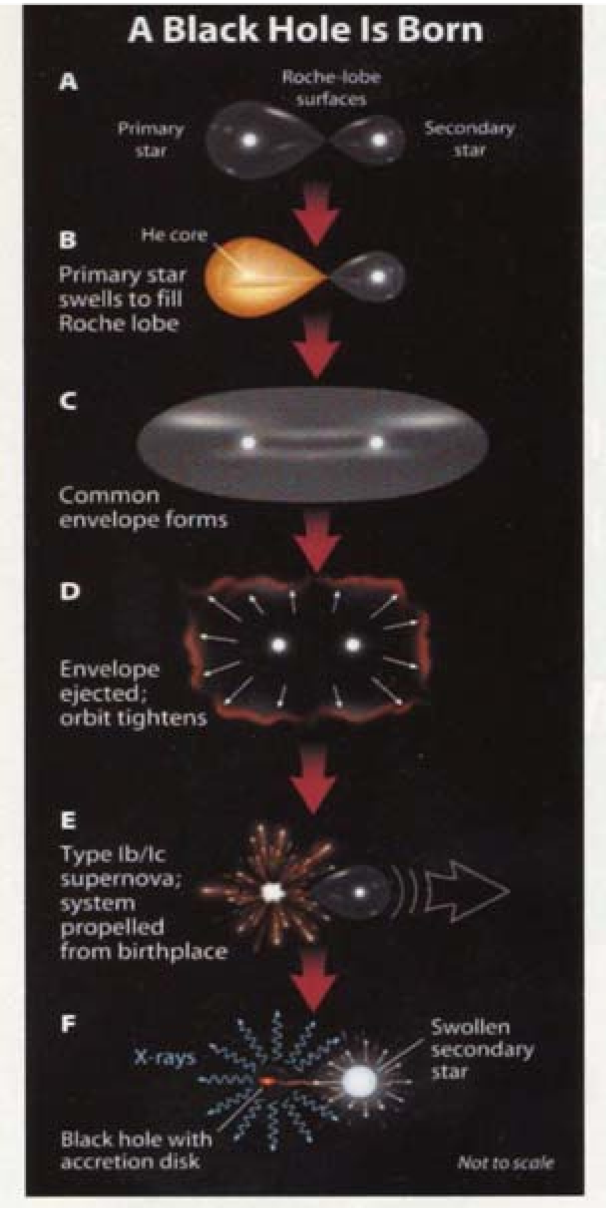
M_{prog} ~ 8-20 $M_\odot$ from II-P SNe (Smartt + ARAA, 2009)



"Progenitors with M>20 $M_\odot$ may collapse quietly"

However, contested on stellar evolution (RSGs may evolve) & statistical grounds by Smith + (2010)

THE KINEMATICS OF μQSOs ⇒ BLACK HOLES MAY FORM WITH NO ENERGETIC SNe



Mirabel & Irapuan Rodrigues (2001-2009)

Used their kinematics to test whether stellar black holes may form directly

IF THE BH BINARIES HAVE NO ANOMALOUS MOTIONS THEY MUST HAVE BEEN FORM WITH NO ENERGETIC SNe KICKS

SO FAR DETERMINED THE

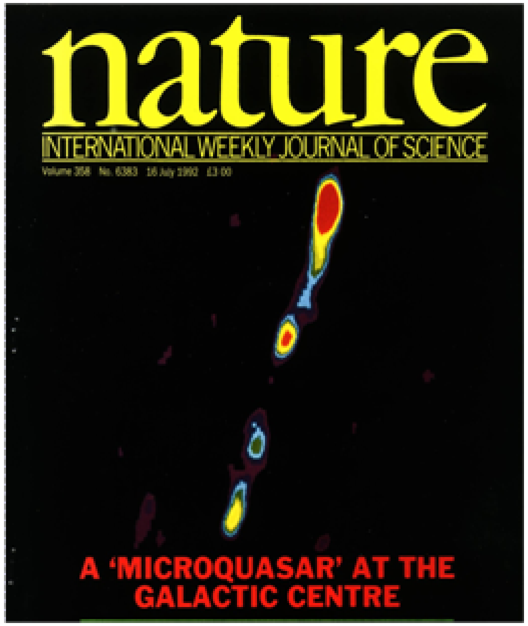
SPACE VELOCITY (KINEMATICS)

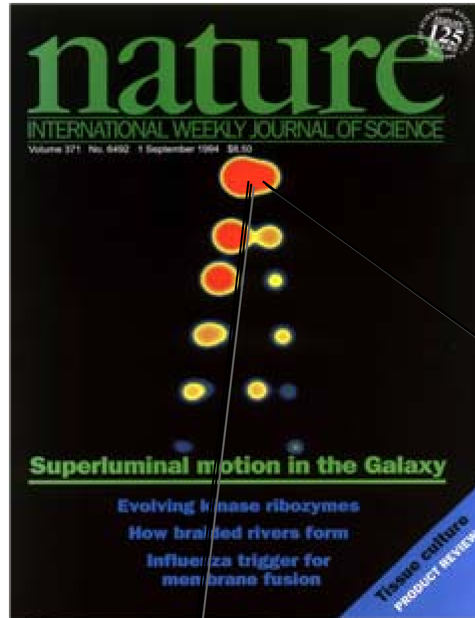
FOR 5 BHXRBs WITH 5-14 $\mathbf{M_\odot}$

JETS IN MICROQUASARS

Mirabel et al. (1992) Mirabel & Rodríguez (1994)

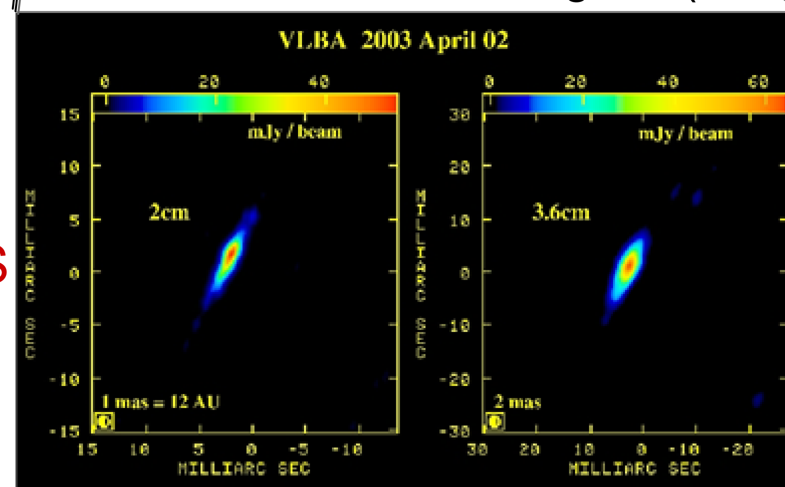
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

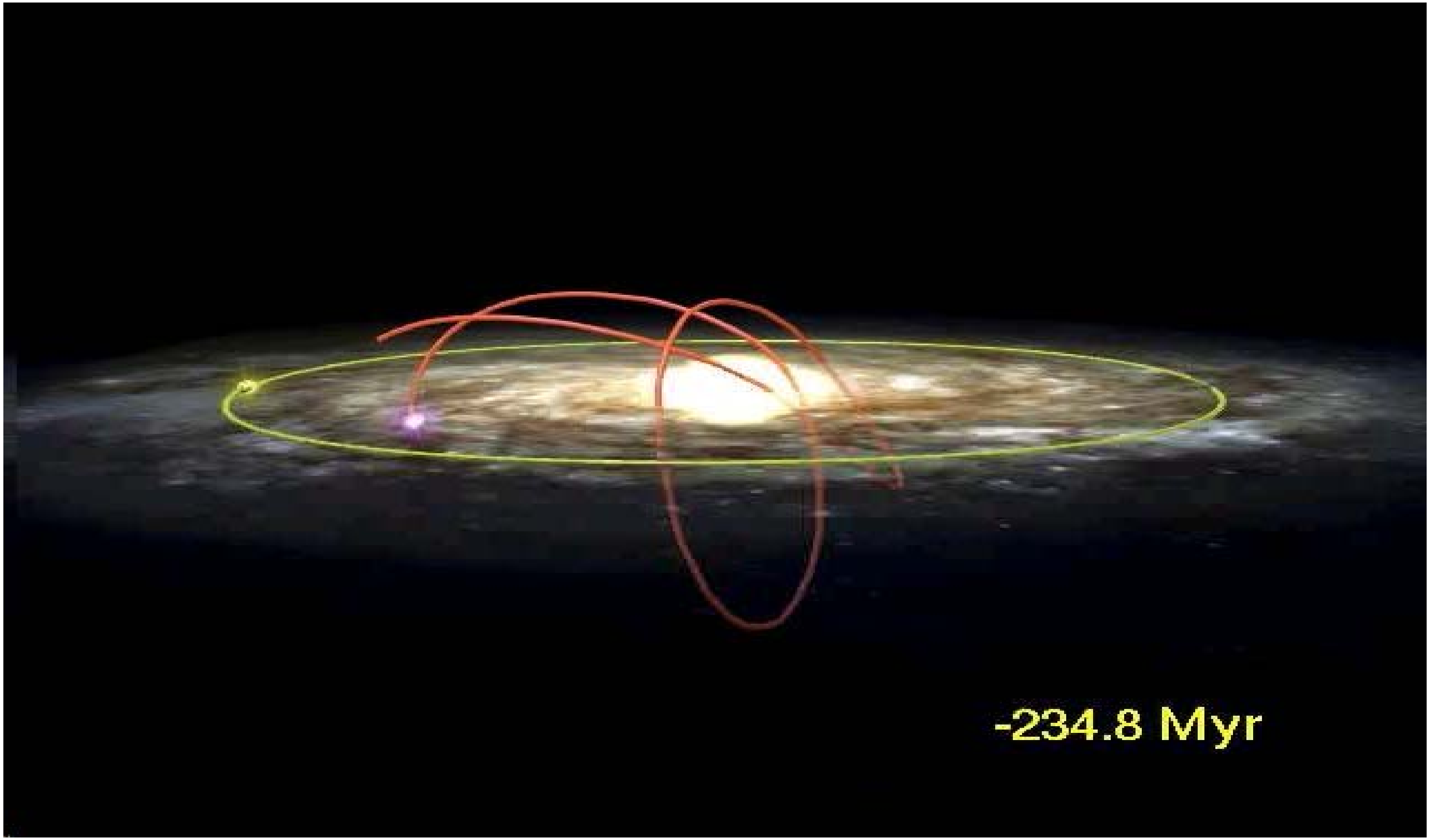
In low hard state. Size ~ 100 AU. Same PA

USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

THE GALACTIC TRIP OF SCORPIUS X-1

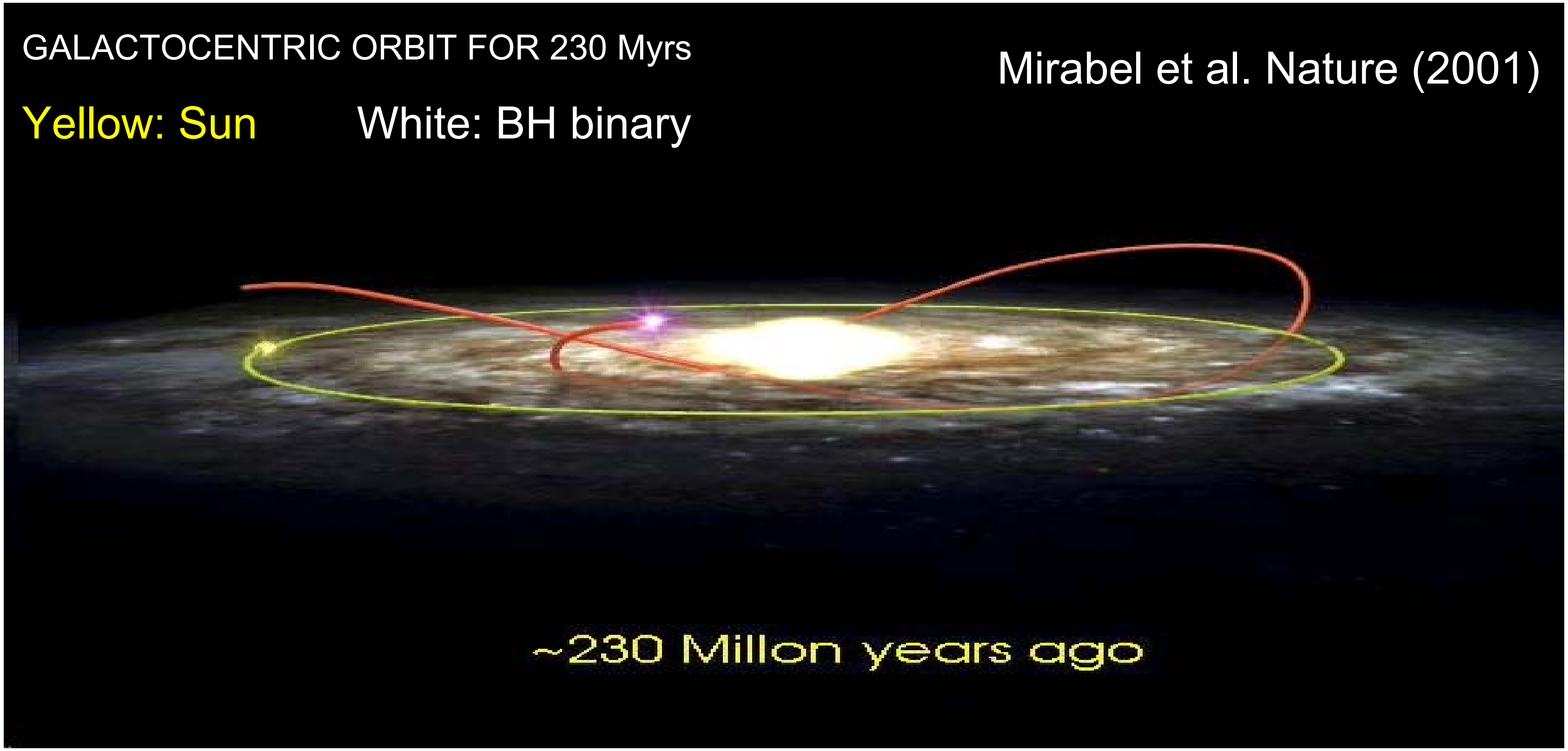
Parallax ⇒ the best determined space velocity (Mirabel & Rodrigues, 2003)



SCORPIUS X-1 WAS SHOT OUT FROM THE GALACTIC BULGE OR SCAPED FROM A GLOBULAR CLUSTER

TWO RUNAWAY BLACK HOLES

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



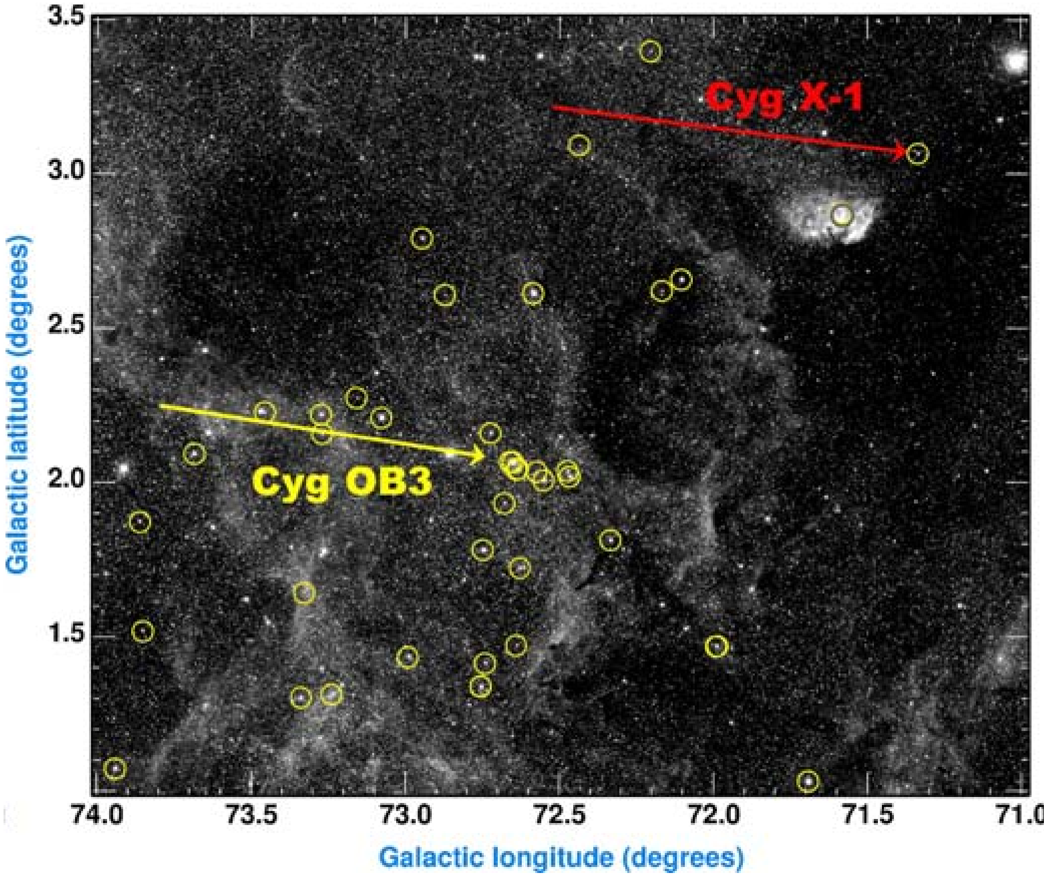
GRO J1655-40: Fossil of a HPN (Israelian et al. Nature 1999)

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

THE ~10 $M_\odot$ BLACK HOLE IN Cyg X-1 WAS BORN IN THE DARK

Mirabel & Rodrigues (Science, 2003)



V_p < 9 +/- 2 km/s ⇒

< 1 $M_\odot$ ejected in SN

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

THE ~10 $M_\odot$ BH IN Cyg X-1 WAS FORM BY DIRECT COLLAPSE

TWO OTHER BHs WITH $M > 10\ M_{\odot}$

- GRS 1915+105 (Dhawan, Mirabel & L.F. Rodríguez, 2001)

$M_{BH} \sim 14 +/- 4\ M_{\odot}$; $M^* \sim 1.2\ M_{\odot}$; D=9+/-2 kpc: **V_p= 50-80 km/s & W = 7+/-3 km/s**

- V404 Cyg (Miller-Jones, Jonker, Nelemans et al., 2009)

$M_{BH} \sim 12 +/- 2\ M_{\odot}$; $M^* \sim 0.7\ M_{\odot}$; D=4+/-2 kpc: **V_p= 45-100 km/s & W = 0.2+/-3 km/s**

- **THE TWO PECULIAR SPACE MOTIONS ARE DIRECTED TOWARDS THE GALACTIC CENTRE AND HAVE SMALL W COMPONENTS** ($V_{GC} > 10$ W).

HOWEVER, THE PECULIAR VELOCITY DISPERSION OF PULSARS SHOW THAT KICKS HAVE NO PREFERENTIAL DIRECTION.

- **THE PECULIAR MOTIONS OF GRS 1915+105 AND V404 Cyg ARE CONSISTENT WITH THE GALACTIC DIFFUSION OF THE OLD STELLAR POPULATION** (Prantzos), **AND DO NOT REQUIRE ENERGETIC NATAL KICKS.**

THE THREE GALACTIC BHs WITH $M_{BH} > 10\ M_{\odot}$ HAVE BEEN FORM DIRECTLY OR WITH FAINT SNe

However, this is a very small, biased, sample of the 10^8 BHs in the Galaxy

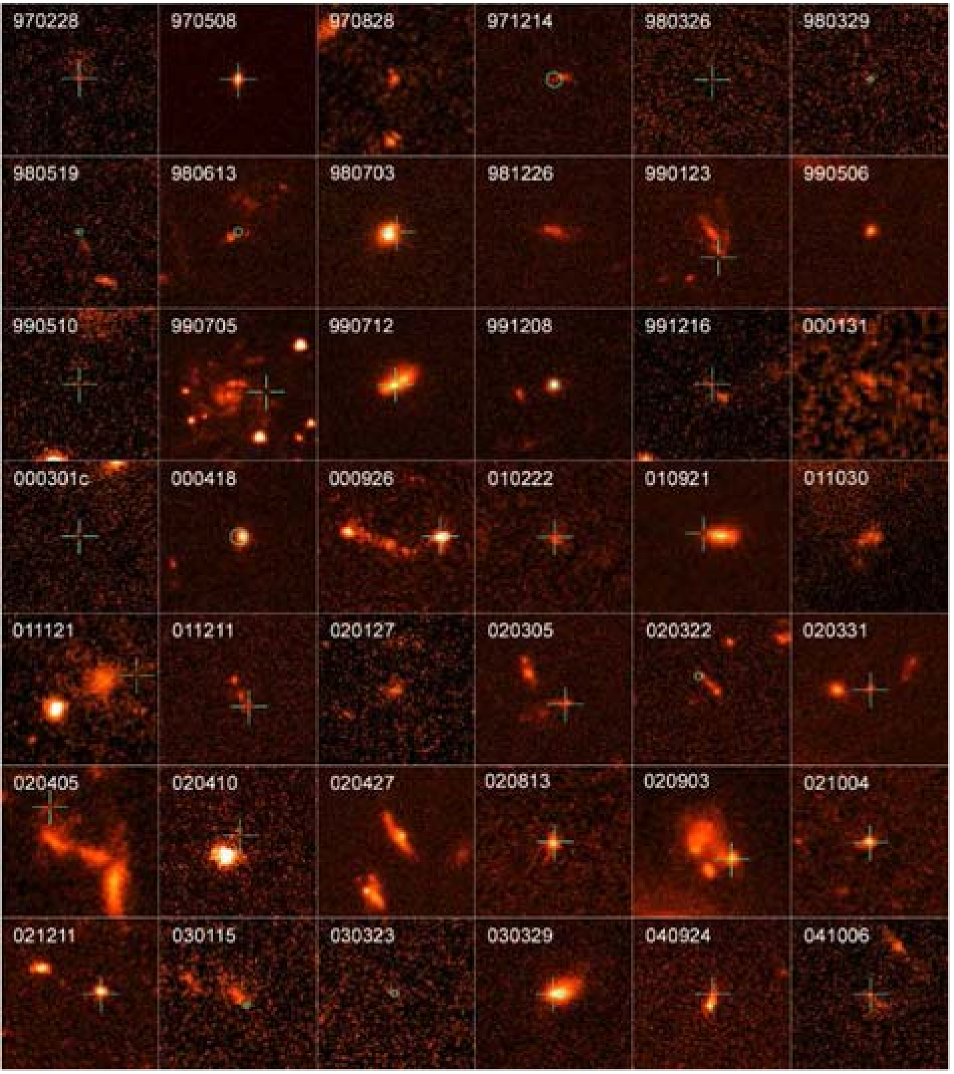
Bright future with GAIA: precise determination of proper motions and parallaxes

HOSTS OF LGRBs ARE SMALL IRR. GALAXIES

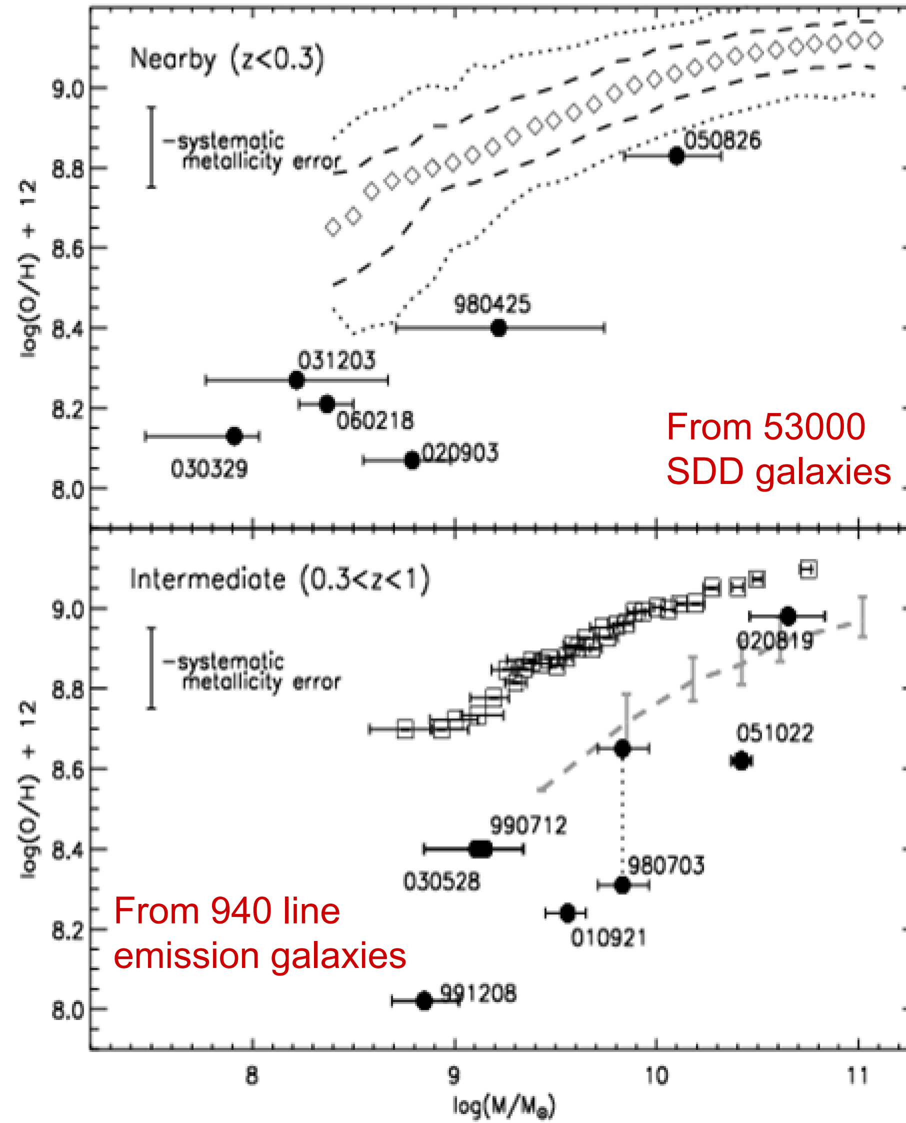
Le Floc´h, Duc, Mirabel with VLT (2003)

OF RELATIVE LOW METALLICITY

Fruchter + with HST (Nature, 2006)



Levesque et al. (2010)



Other possible indications of direct black hole formation

1) No high mass progenitors > 18 $M_\odot$ of core collapse SNe (Smartt, ARAA 2009)

2) Most galaxy hosts of LGRBs are small, irregular galaxies of low metallicity (Le Floc´h, Duc, Mirabel 2003; Fruchter + 2006; Savaglio + 2009).

3) Core collapse SNe prefer higher metallicity spiral galaxy hosts than LGRBs (Graham, Fruchter et al. 2010, Svenson et al. 2010)

4) Faint core collapse SNe II with extremely low V_{exp} of the ejecta & extraordinarily low ^{56}Ni in the ejecta (Zampieri et al. 2003; Valenti et al. 2009 ⇒ formation of black holes by implosion ?

5) No luminous SNe found associated with GRB 060505 & GRB 060614. Caveat: alternative interpretations: e.g. possibility of low ^{56}Ni production.

6) Does the rate of LGRBs increases with redshift ? YES (Daigne+ 2006; Kistler+ 2009); ? (Podsiadlowski)

THE BOTOM-UP GALAXY FORMATION & THE COSMIC EVOLUTION OF METALLICITY $\Rightarrow$ A COSMIC EVOLUTION OF HMBHBs

- THE MASS OF STELLAR BLACK HOLES
- THE FRACTION OF BLACK HOLES/NEUTRON STARS
- THE FRACTION OF BINARY/SINGLE BLACK HOLES

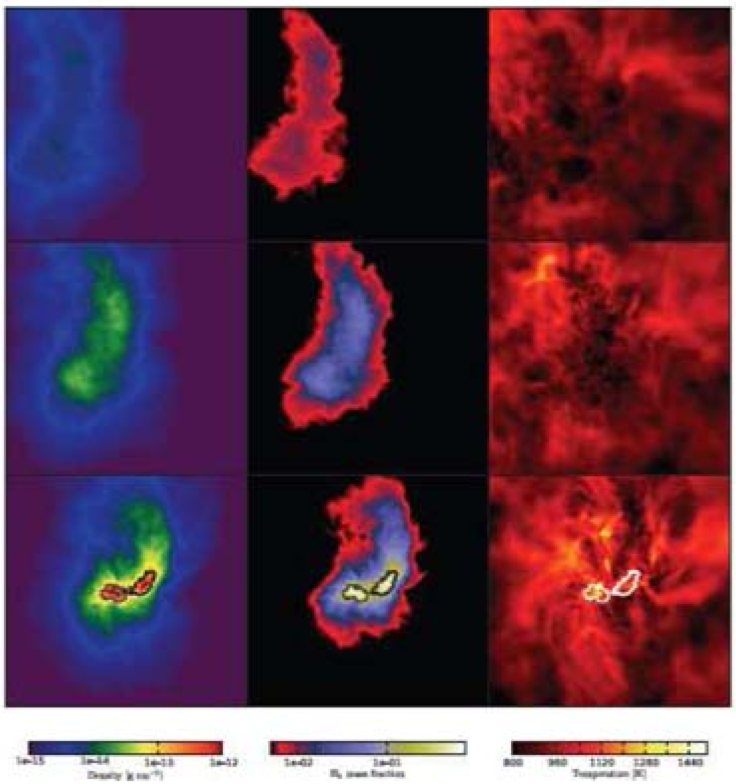
SHOULD INCREASE WITH REDSHIFT

WHAT MAY HAVE BEEN THE COSMOLOGICAL IMPLICATIONS OF A LARGE POPULATION OF HMBHBs (MICROQUASARS) AT HIGH z ?

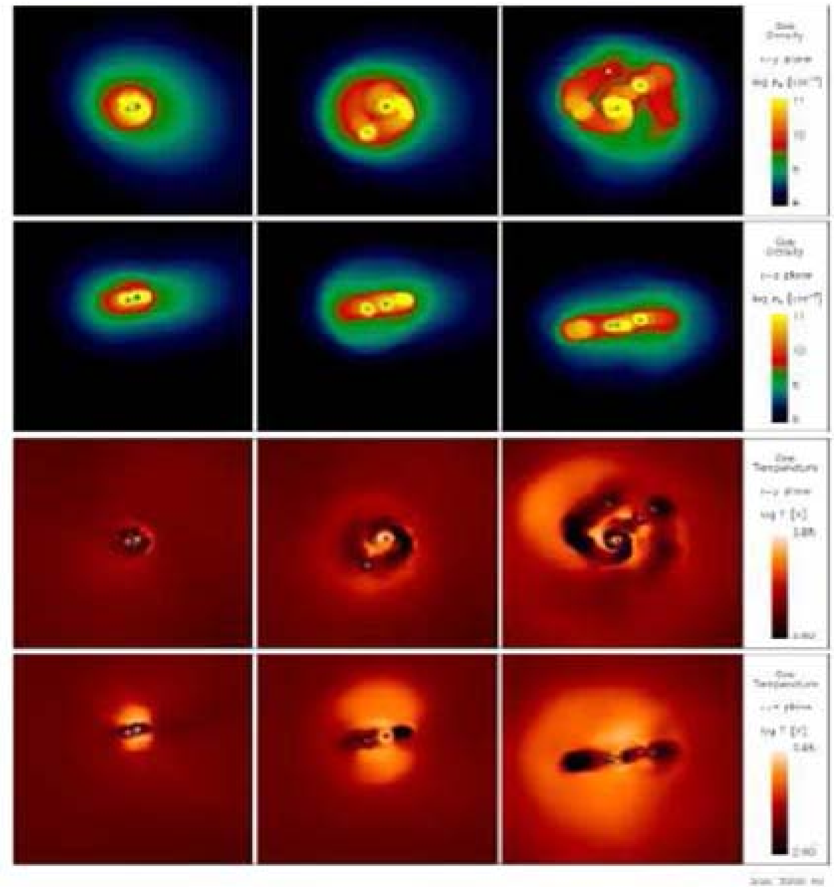
(Sunyaev in VII Microquasar workshop in Turkey)
(Next as IAU Symp. In Buenos Aires 13-17 Sept 2010)

THIS IS A TIMMELY QUESTION BECAUSE…

1) POPULATION III BINARIES



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

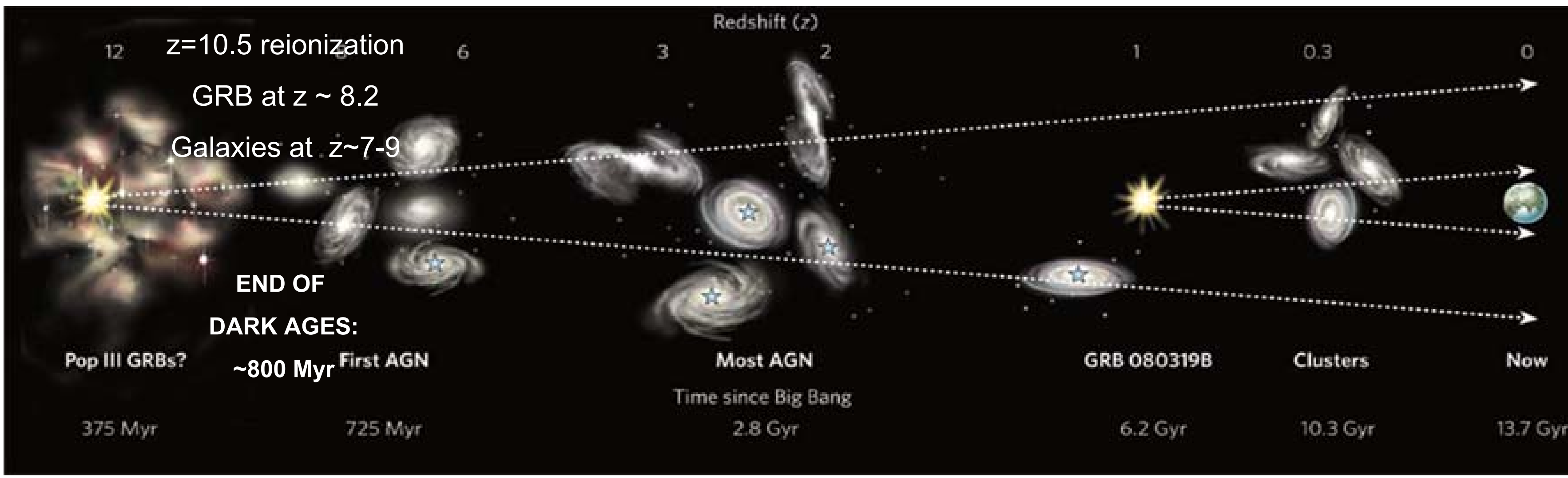


Stacy, Greif & Bromm (ApJ 2010)

- **Pop III stars were multiple systems dominated by binaries with 10-100 $M_{\odot}$**

2) A LGRB at z~8.2 has similar properties to LGRBs at lower redshifts (Salvaterra+ Nature 2009)

3) HST/WFC3 z=8-9 galaxies are "photon starved" to re-ionize the Universe Unless there are small galaxies below detection, top heavy IMF...(Lorenzoni +; Bouwens+;…(2010)



COULD BLACK HOLE HIGH MASS BINARIES BE COMPLEMENTARY RE-IONIZATION SOURCES ?

Ionizing power of μQSOs versus ionizing power of massive stars

Counting ionizing photons (Mirabel, Loeb, Diskra, Laurent; in progress)

BH-HMXBs (e.g. Cyg X-1) are persistent UV/X-ray sources with spectra characterized by two components: 1) a UV-soft x-ray thermal bump from the disk & 2) a non-thermal power law component of hard X-rays from the corona and/or jet described by $S(E) = E^{-\alpha} e^{-E/Eo}$ with $\alpha \sim 2.0$.

1) If $\alpha > 1.0$ microquasars do not overproduce the soft X-ray unresolved background

2) From Monte Carlo simulations the ionization power by hard x-rays and jets is < 10% that of the thermal component from the accretion disk

Number of ionizing photons from μQSO:

$$N_{ion} = 1.7\ 10^{62}\ (M_{BH}/10M_{\odot})\ (f_{edd}/0.1)\ (t_{\mu QSO}/10\ Myr)$$

Number of ionizing photons from the progenitor star:

$$N_{ion,*} = 5\ 10^{61}\ (M_{*}/10M_{\odot})^{-1}\ (nion/4000)^{-1}$$

Ionizing power of µQSOs versus ionizing power of massive stars

Counting ionizing photons (Mirabel, Loeb, Diskra, Laurent; in progress)

$$N_{ion}/N_{ion,*} = 3\,(M_{BH}/10M_\odot)\,(f_{edd}/0.1)\,(t_{\mu QSO}/10\text{ Myr})\,(M_*/10M_\odot)^{-1}\,(n_{ion}/4000)^{-1}$$

f_{edd}=flux in Eddington units; $t_{\mu QSO}$=lifetime of µQSO; n_{ion}=number of ionizations/baryon

Microquasars cause a number of 'secondary ionizations' N_{sec} due to energetic electrons created by X-Ray photons that ionize a hydrogen atom. Then

$$N_{ion}/N_{ion,*} = 3\,(1+N_{sec})\,(M_{BH}/10M_\odot)\,(f_{edd}/0.1)\,(t_{\mu QSO}/10\text{ Myr})\,(M_*/10M_\odot)^{-1}\,(n_{ion}/4000)^{-1}$$

In a **highly ionized medium** the high energy electrons loose their energy by Coulomb interactions and heat the gas. Therefore N_{sec} = 0 and

µQSQs heat the gas and $N_{ion}/N_{ion,*} \sim 3$

But, **in a fully neutral medium** a 1 keV secondary electron can by collisions produce a number of ionizations N_{sec} = 25 ($E_{ionizing\ photon}$/1 keV). Therefore, for typical parameters

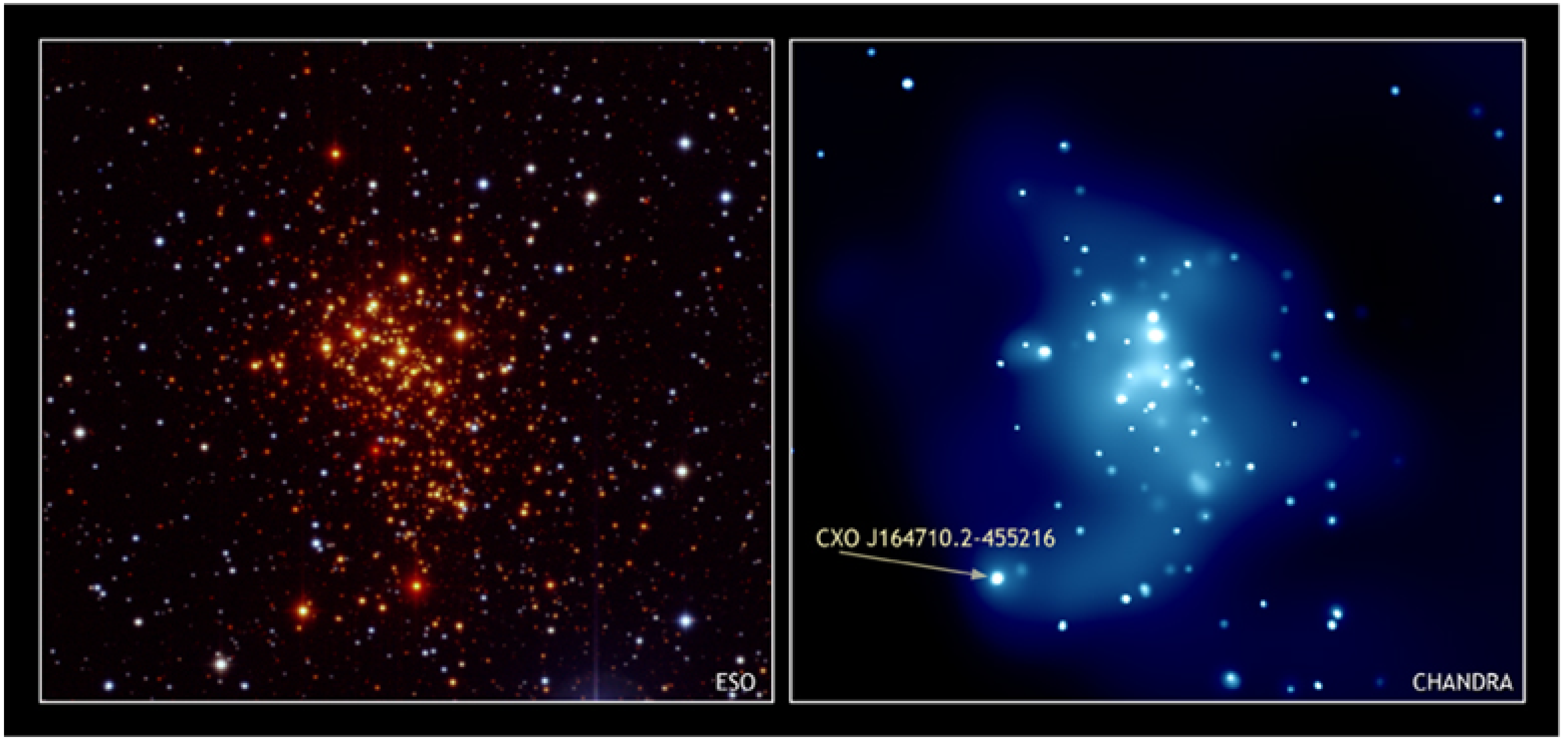
in a fully neutral medium $N_{ion}/N_{ion,*}$=10-100

CONCLUSION

A LARGE POPULATION OF STELLAR BLACK HOLE HIGH MASS X-RAY BINARIES AT HIGH REDSHIFTS WOULD BE IMPORTANT AS SOURCES OF PHOTONS FOR THE VERY EARLY PHASES OF RE-IONIZATION

(Calculations in progress)

A young neutron star in Westerlung 1



Wd 1: The most massive compact young cluster in the MW

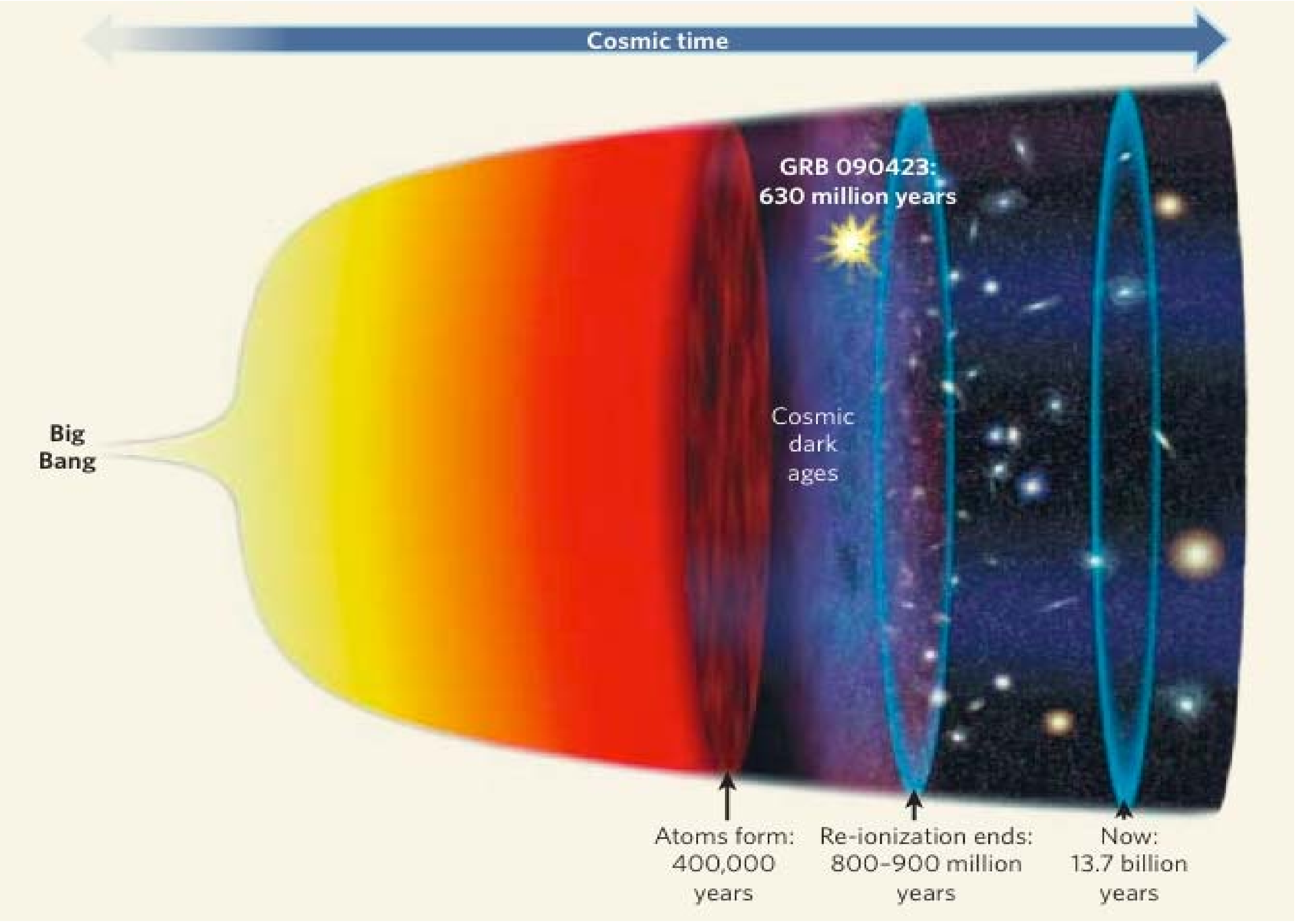
Total mass > 1.5 $10^3\ M_\odot$, perhaps > $10^5\ M_\odot$

No stellar black hole found so far in Wd 1

As predicted by models on the metallicity dependence of the formation of black holes,

this severely limits the range of stellar masses that lead to the formation of black holes.

How rotation and binarity of the progenitor would add further constraints ?


Cosmic time
GRB 090423:
630 million years
Big
Bang
Cosmic
dark
ages
Atoms form:
400,000
years
Re-ionization ends:
800–900 million
years
Now:
13.7 billion
years