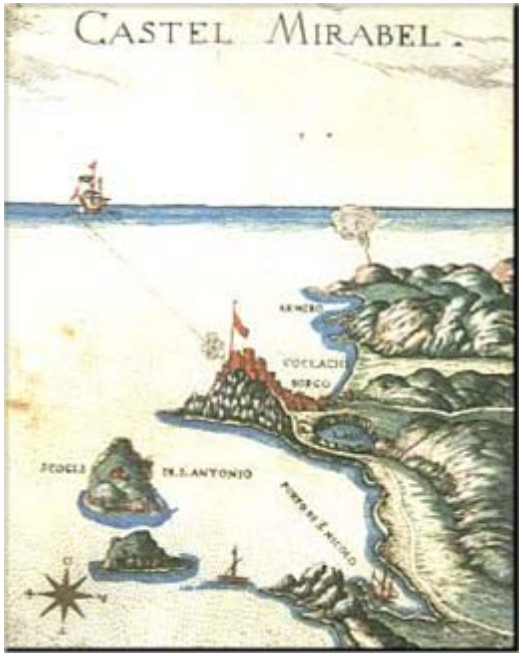
Lithography of XVI century



Chateaux Mirabel

Fortress at the entrance of the Mirabel Bay. Founded in 1579 during the Venetian occupation

In the ancient Venetian dialect:

“Mirabel” = “Belle View”

FORMATION OF BLACK HOLES BY IMPLOSION:

IMPLICATIONS FOR COSMIC EVOLUTION AT THE DAWN OF THE UNIVERSE

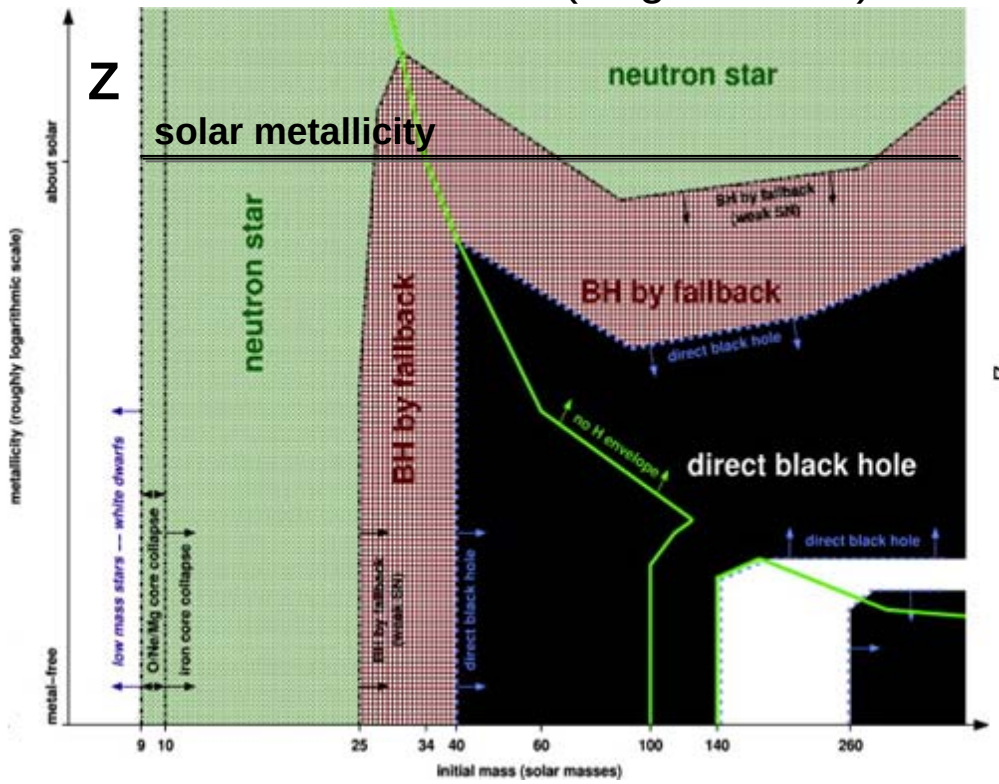
Félix Mirabel
CEA – Saclay (France) & Conicet (Argentina)

Plan of the talk:

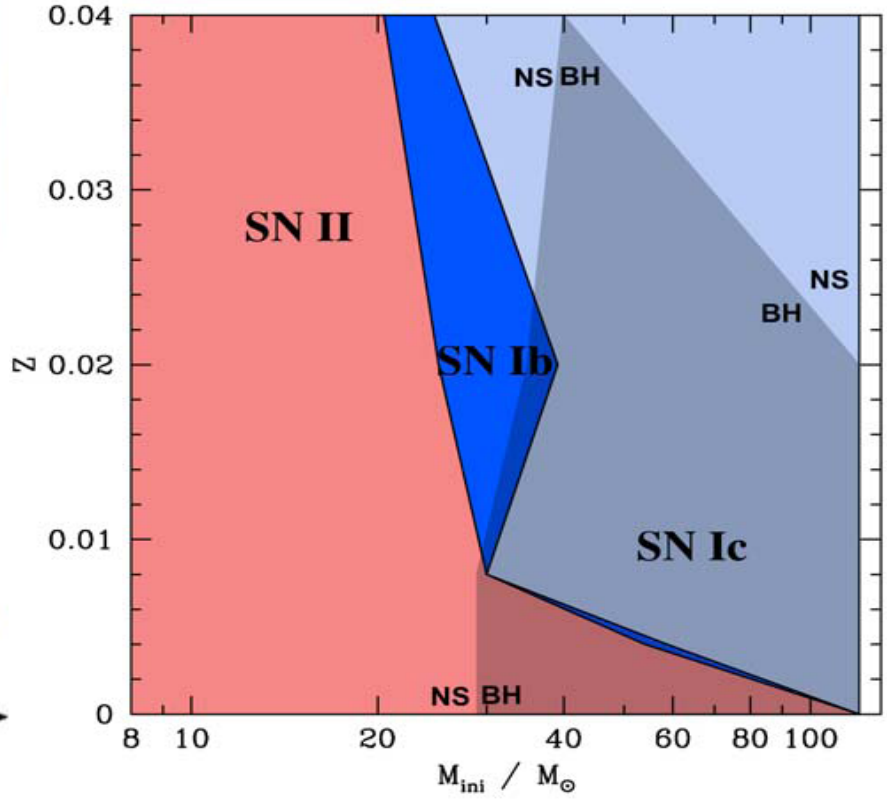
- Review the predictions from theoretical models on the formation of stellar black holes
- Review observations of neutron stars and black holes that may be consistent with the direct formation of black holes (no time…)
- Evidences that the formation of black hole binaries depends on the SFR and Z
- Cosmological implications

FORMATION OF STELLAR BLACK HOLES BY THE COLLAPSE OF MASSIVE STARS

with no rotation (Heger+ 2003)



with rotation (Georgy+ 2009)



Mass of progenitor star

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

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

- **THE MASS OF STELLAR BLACK HOLES**
- **THE FRACTION OF BLACK HOLES / NEUTRON STARS**

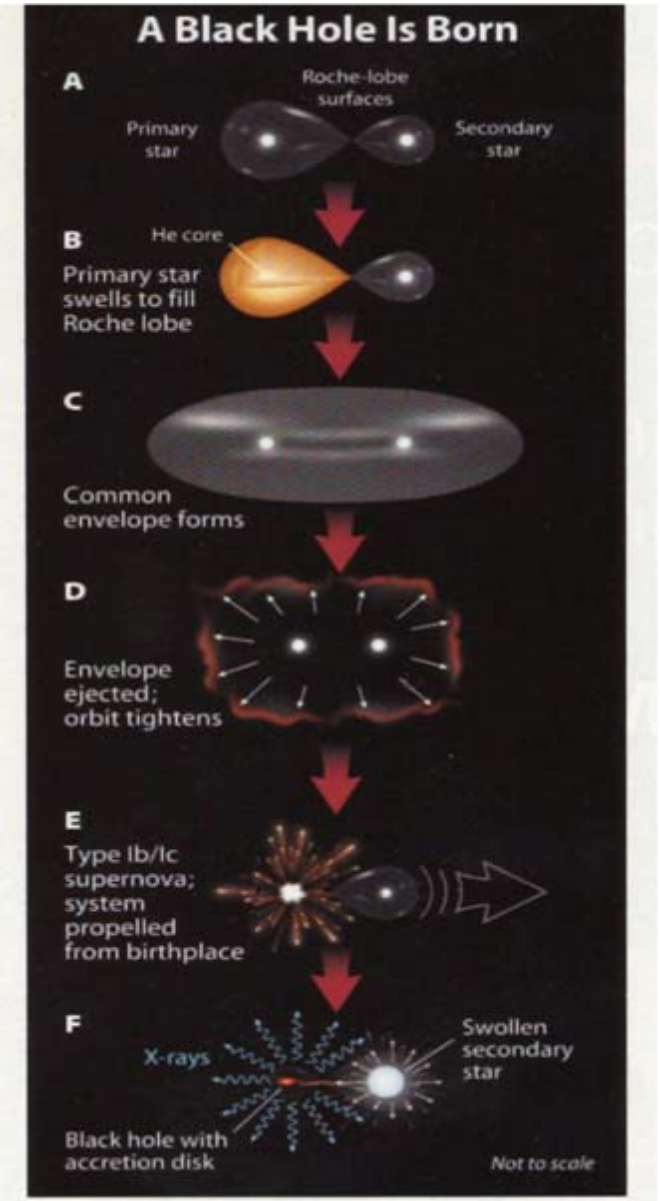
  & because the fraction of binary systems that remain bound increases, also
- **THE FRACTION OF BINARY / SOLITARY BLACK HOLES**

SHOULD INCREASE WITH DECREASING METALLICITY

The following observations of BH-HMXBs, ULXs, SGRs/AXPs & LGRBs are consistent with this theoretical expectation:

1) BHs masses in HMXBs determined dynamically seem to be a decreasing function of the metallicity of the host galaxy. M_{BH} up tp 30 $M_{\odot}$ (Crowther+10)
2) The occurence rate of ULXs increases with the inverse of the host galaxy mass (metallicity). (Soria+; Zampieri & Roberts). The majority of ULXs are BH-HMXBs with BH masses of tens solar (Gladstone, Roberts & Done, 2009)
3) The hosts of LGRBs are small galaxies of relative small metallicity (Le Floc'h, Duc & Mirabel 2003; Fruchter et al. 2006). Caveat: 50% of dark GRBs have A_V>1 mag. But no detection of the hosts with Spitzer (Le Floch+)
4) There are high metallicity progenitors of SGRs and AXPs with M>40 $M_{\odot}$
5) There are evidences for enhanced LGRB rates at z>3 than expected from star formation measurements. Possibly due to evolution in both, IMF and metallicity (Daigne+; Kistler+; Qin+; Wandeman & Piran).
6) Two LGRBs with no luminous SNe (Della Vale+; Fynbo+). Caveats…
7) The kinematics of BHXRBs (Mirabel & Rodrigues)

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



Stellar Forensic:

From the kinematics of the fossils of massive stars we can infer whether they finished as energetic SNe or silently

Mirabel & Irapuan Rodrigues (2001-2009)

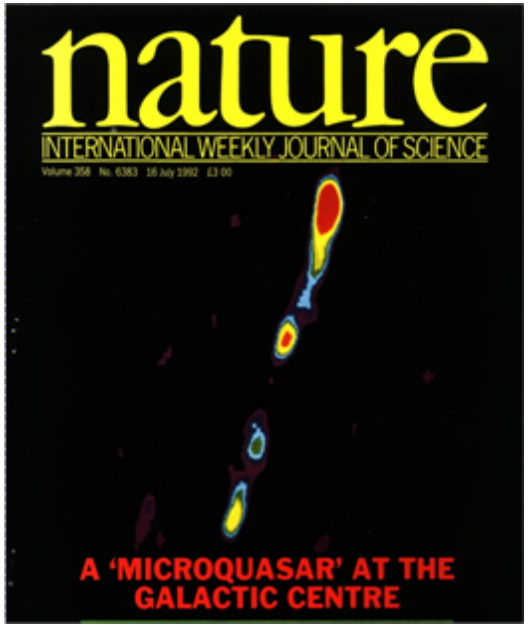
IF THE BH BINARIES HAVE NO ANOMALOUS MOTIONS THE BLACK HOLES MUST HAVE BEEN FORM WITH NO ENERGETIC SNe KICKS

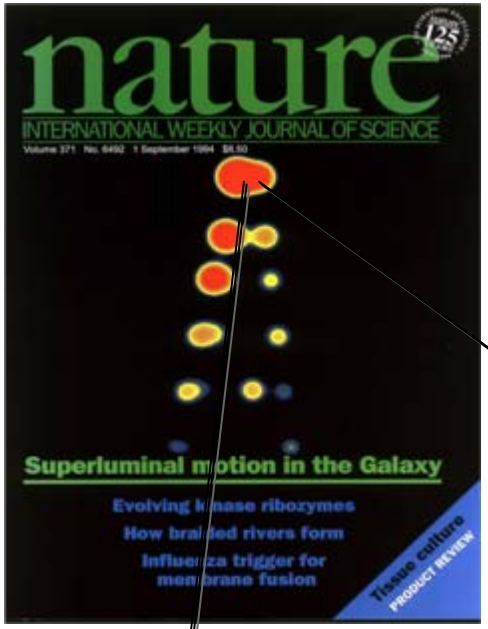
SO FAR DETERMINED THE SPACE VELOCITY (KINEMATICS) FOR 5 BHXRBs WITH M_{BH} = 5-14 $\mathbf{M}_{\odot}$

JETS IN MICROQUASARS

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

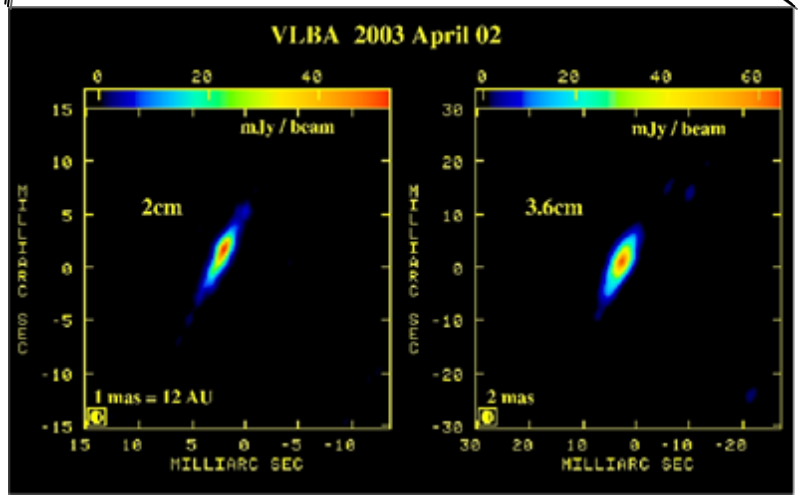
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

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

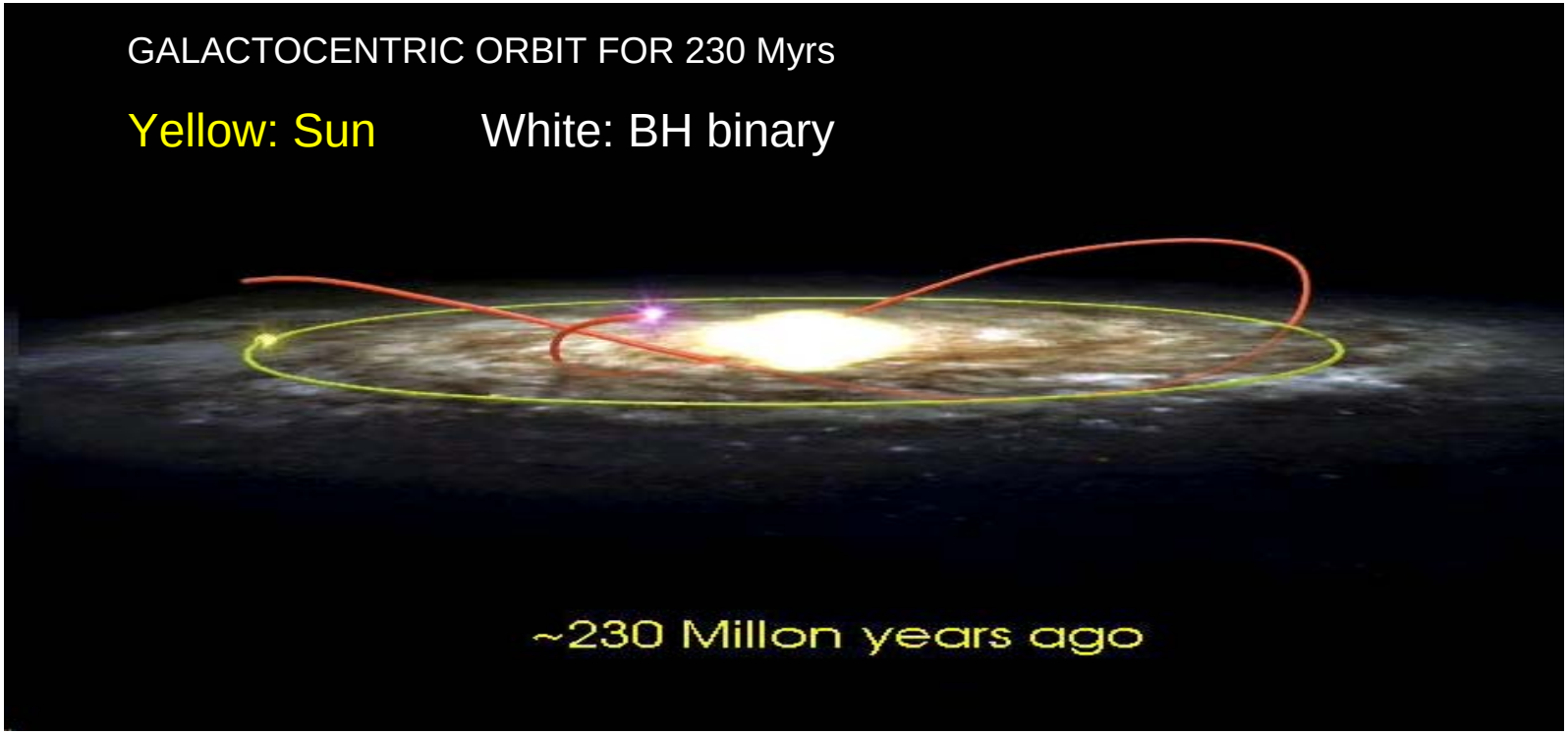
USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

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)



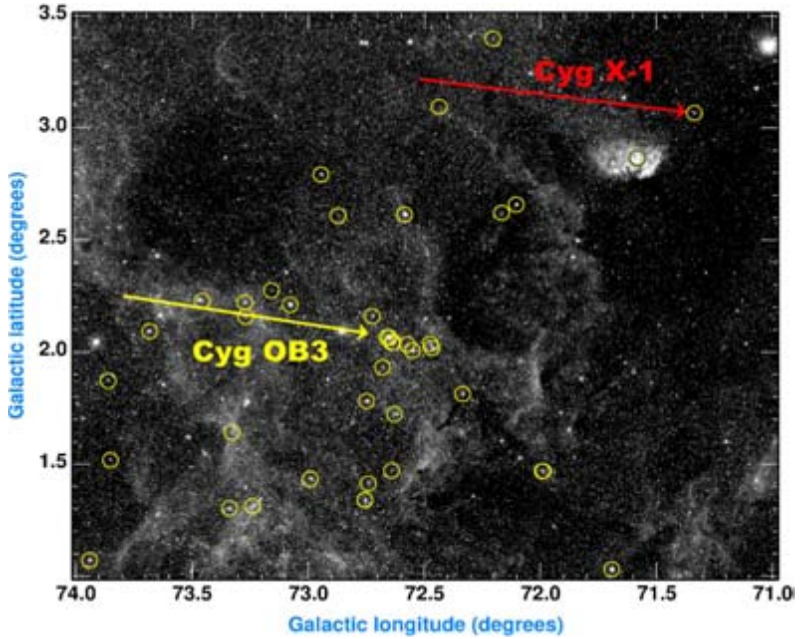
GRO J1655-40: Fossil of a HPN (Israelian et al. Nature 1999)

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

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 $\Rightarrow$

< 1 $M_\odot$ ejected in a 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

GRS 1915+105: **Vp=50-80 km/s & W=7+/-3 km/s** (Dhawan,Mirabel,Rodríguez 01)
V404 Cyg: **Vp= 45-100 km/s & W = 0.2+/-3 km/s** (Miller-Jones et al. 2009)

V_{GC} >10 W. Since kicks have no preferred direction Vp may be due to galactic diffusion. Therefore, these BHs with > 10$M_\odot$ may also have been form directly.

This line of research will be enhanced with GAIA

Because massive stars with low Z end as black holes by direct collapse

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

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

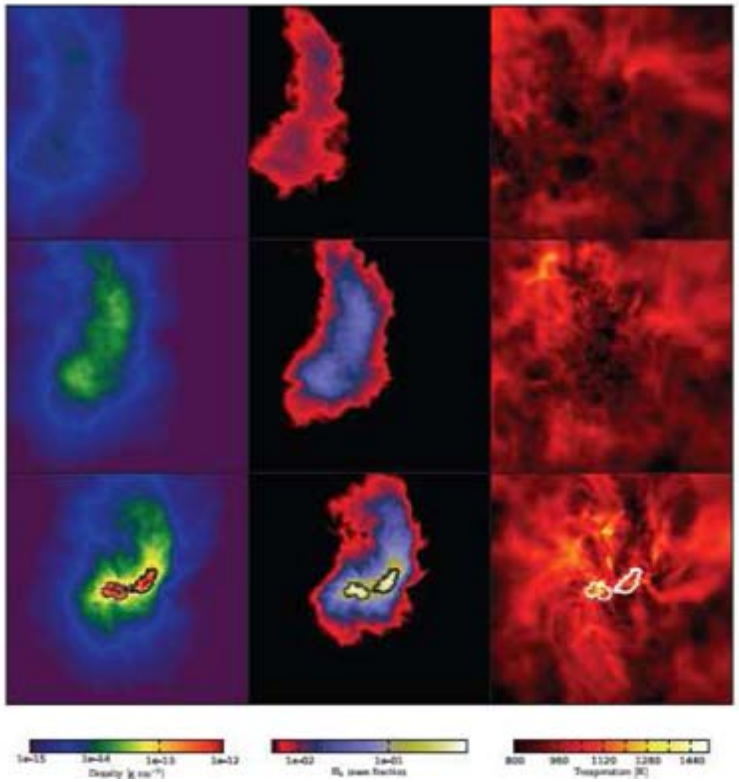
SHOULD INCREASE WITH REDSHIFT

WHAT MAY HAVE BEEN THE COSMOLOGICAL IMPLICATIONS OF XRBs DURING THE DARK AGES: Cold neutral phase of the IGM from 4×10^4 up to 10^9 yr

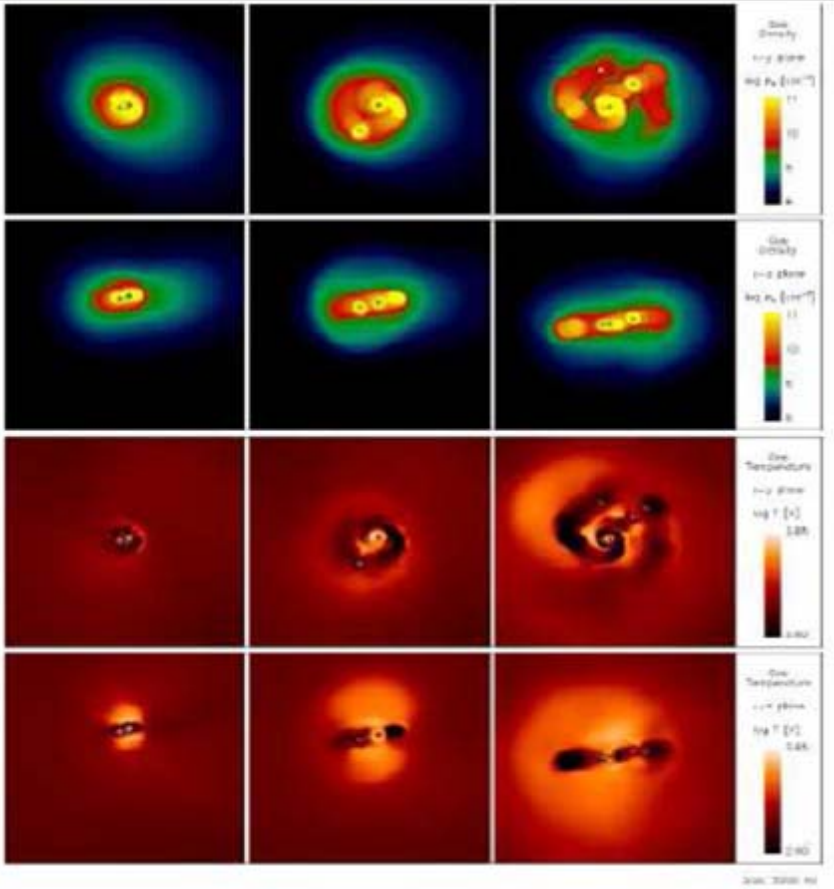
(Question by Sunyaev in VII Microquasar workshop in 2008)

THIS IS A TIMMELY QUESTION BECAUSE…

1) POPULATION III BINARIES



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



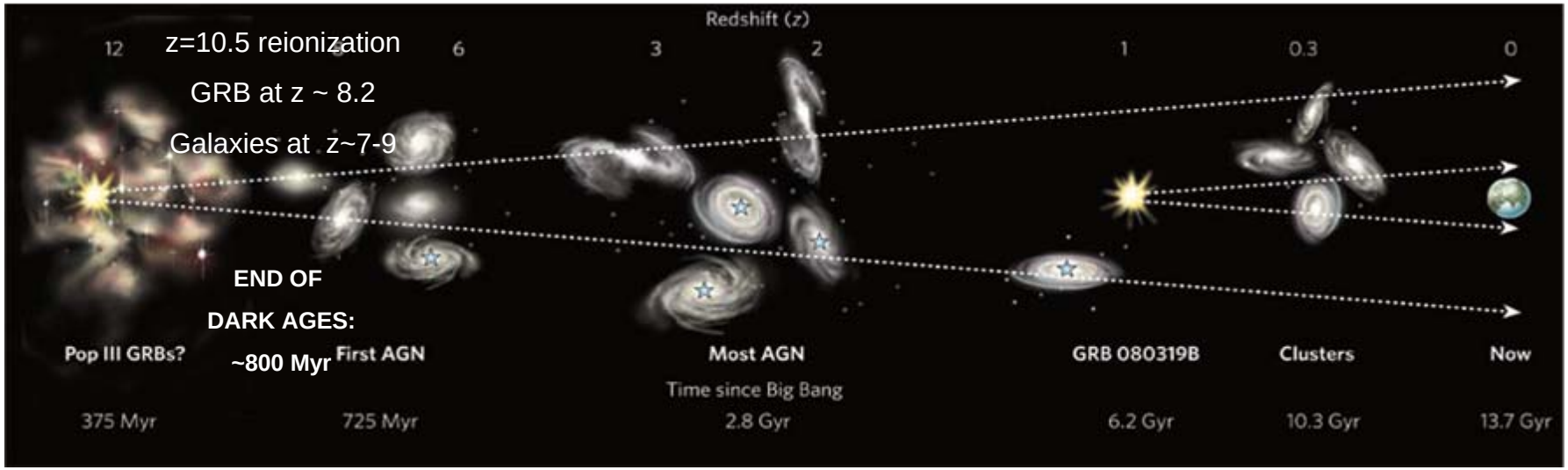
Stacy, Greif & Bromm (ApJ 2010)

- **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 seem "photon starved" to re-ionize the Universe Unless there are

small galaxies below detection, top heavy IMF...(Lorenzoni +; Bouwens+;…(2010)



WHAT MAY HAVE BEEN THE CONSEQUENCES OF FEEDBACK FROM BLACK HOLE X-RAY BINARIES?

Ionizing power of μQSOs versus ionizing power of massive stars

Counting ionizing photons Mirabel,Laurent (Saclay)

. Loeb, Diskra, Pritchard (Harvard)

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

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

In a fully neutral medium **N_{sec*} = 25 (E_γ /1 keV),** where E_γ is the photon energy, but not all stars will be massive and in binaries leading to the formation of HMBHBs

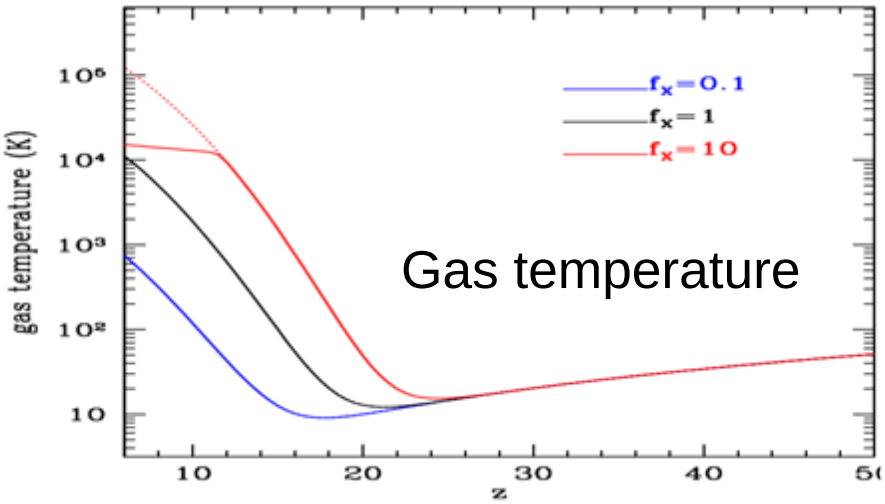
STELLAR BLACK HOLES IN THE DARK AGES

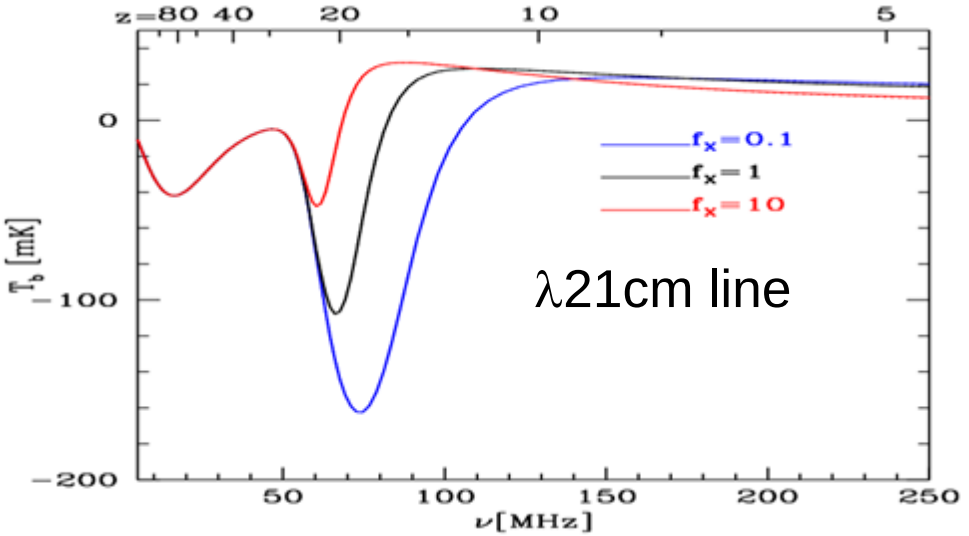
Empirical correlation between X-ray luminosity and SFR. $f_x = 0.2$ at z=0 (Grim, Gilfanov & Sunyaev, 2003)

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

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

4.0 0.5





- HMBHXBs HEATED THE IGM ABOVE 10^4 K OVER LARGE VOLUMES
- DID BH-HMXBs PREVENT THE FORMACION OF LOW MASS DWARFS?

LOW MASS LIMIT FOR GALAXY FORMATION

$$T_{vir} = 1.04 \times 10^4 \, (\mu/0.6) \, (M/10^8 \, M_\odot)^{2/3} \, [(1+z)/10] \, K$$

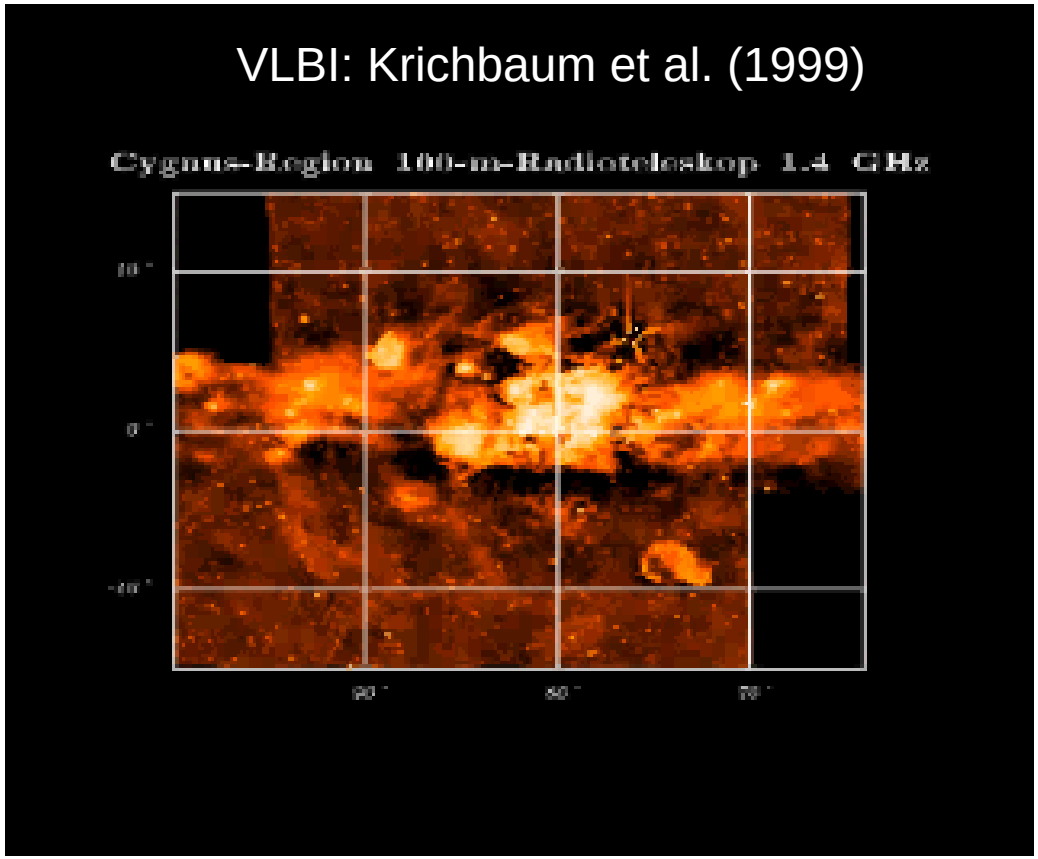
where μ is the mean molecular weight (Loeb, 2010)

X-ray and UV heating of the difusse IGM during reionization resulted in an additional increase of the minimum galaxy mass. Once the IGM was heated to ~10^4 K by the UV and X-rays from BH-HMXBs, dark matter haloes with masses below 10^9 $M_\odot$ could not accrete IGM material because the temperature of the infalling gas increased by an order of magnitude.

The census of dwarf galaxy satellites of the Milky Way requires a suppresion in the abundance of low mass galaxies relative to the low mass dark matter haloes inferred from the Cold Dark Matter Model of the universe.

THE THERMAL HISTORY OF THE IGM HAD A DIRECT IMPACT ON THE PROPERTIES OF THE FAINTEST GALAXIES AT HIGH REDSHIFTS AND THE SMALLEST GALAXIES IN THE LOCAL UNIVERSE

ROLE OF BLACK HOLE FEEDBACK IN GALAXY FORMATION & EVOLUTION



- Feedback from SMBHs shaped the stellar bulges (QSO/high-soft/radiative phase) & prevented the unlimited growth of massive galaxies (radio galaxy/low-hard/jet phase)
- Feedback from the first generations of BHXRBs heated and partially ionized the IGM preventing the formation of very large numbers of dwarf galaxies with $M_{gal}<10^9\ M_\odot$

QUESTIONS ON THE ROLE OF BLACK HOLES IN COSMIC EVOLUTION

Could feedback (radiation & jets) from stellar black holes reconcile the apparent discrepancies of the observations with the predictions of the cold dark matter model of the universe?

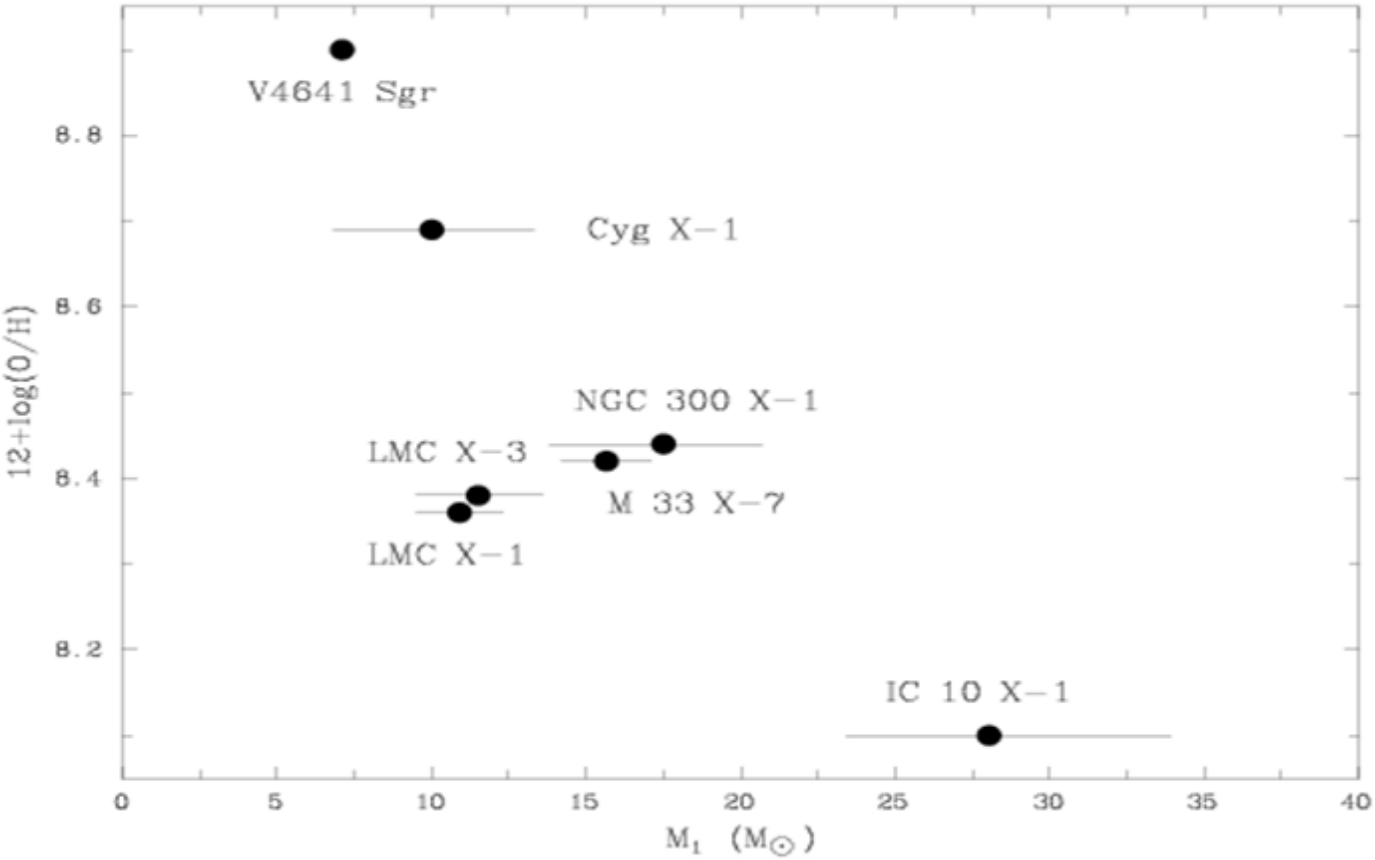
Failed predictions of the Cold Dark Matter Model:

1) A very large number of small mass dwarf galaxies in the Local Group of Galaxies

2) Prominent cusps in the central bulges of galaxies

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

Masses determined dynamically (Crowther et al. 2010)



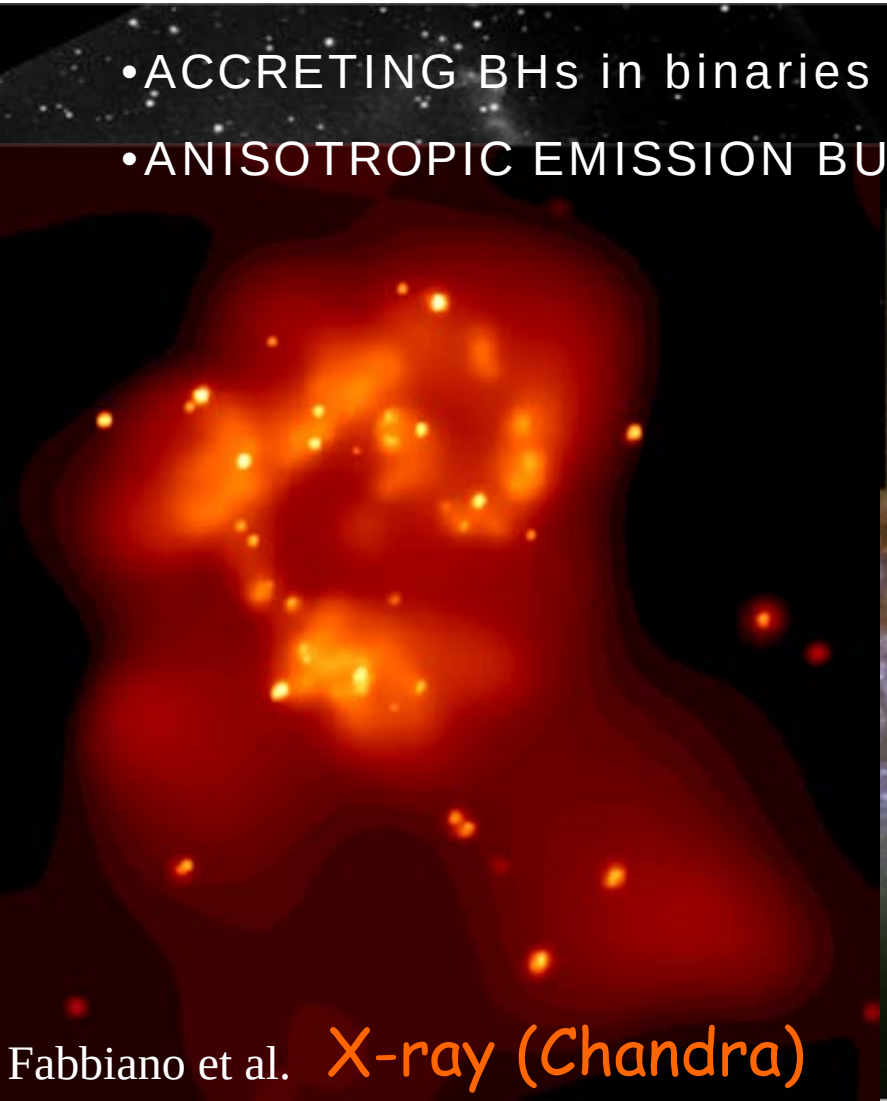
The stellar BHs in M 33 X-7, NGC 300 X-1, IC 10 X-1 have $M_{BH} > 15\ M_{\odot}$ whereas in the Galaxy and M 31 no stellar BH with $M_{BH} > 14\ M_{\odot}$ is known

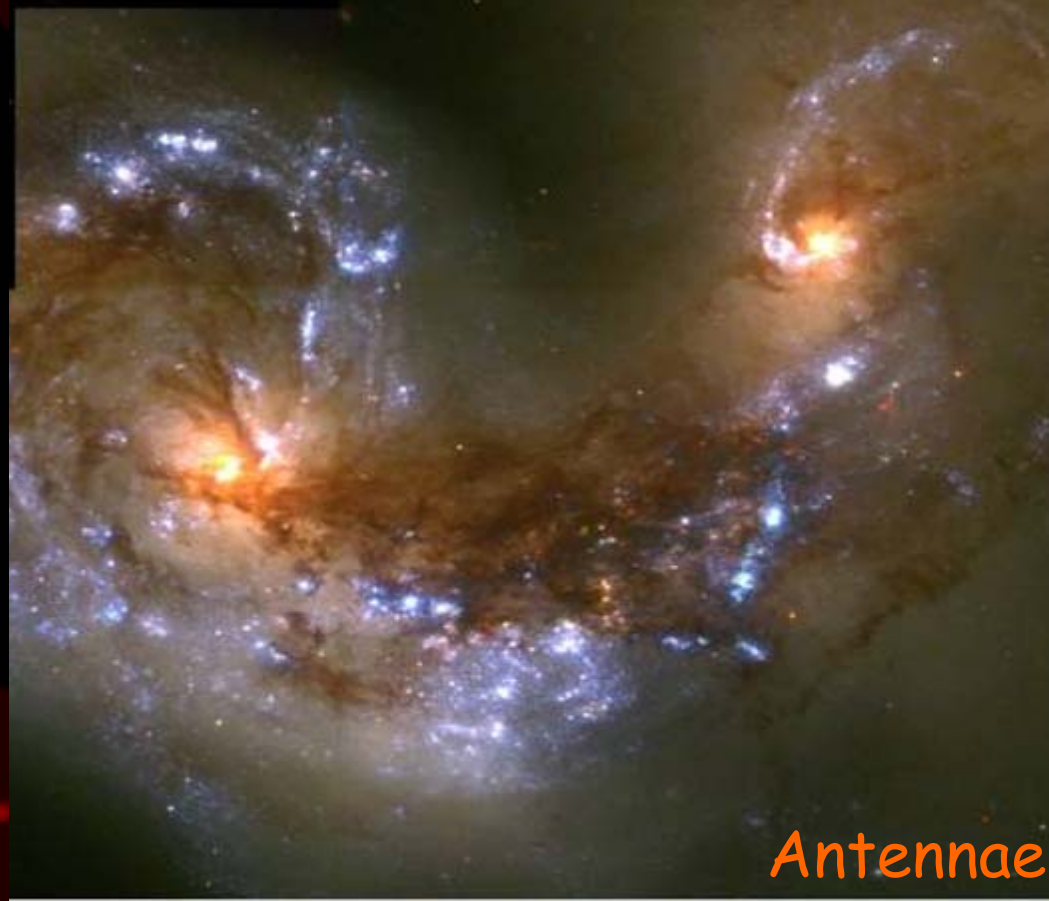
Does the new dynamic mass for NGC 1313 X-2 reveal another black hole of large stellar mass ?

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)

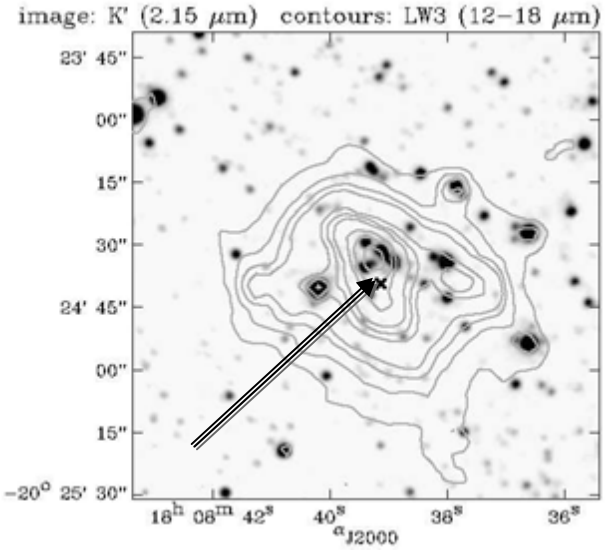




SGRs and AXPs (young neutron stars) found in clusters of massive stars

SGR 1806-20

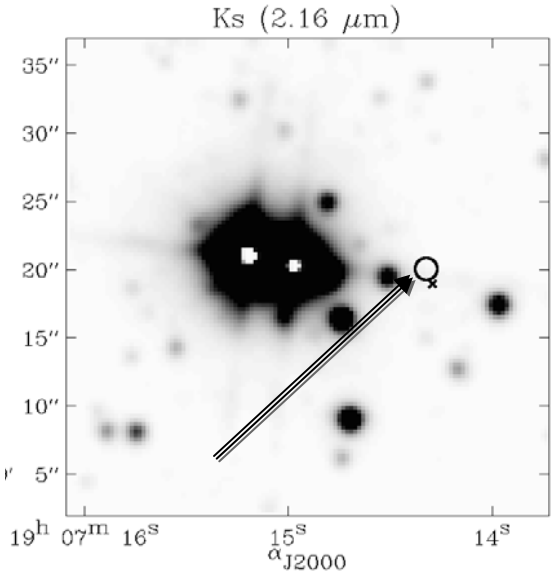
Mirabel et al. (1999)



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

SGR 1900+14

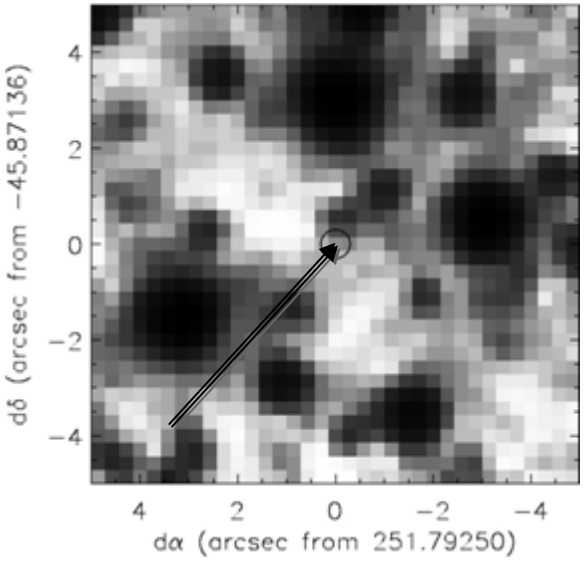
Vrba et al. (2000)



$M_{prog} > 25\ M_{\odot}$

AXP 1647-45

Muno et al. (2006)
in Westerlung 1

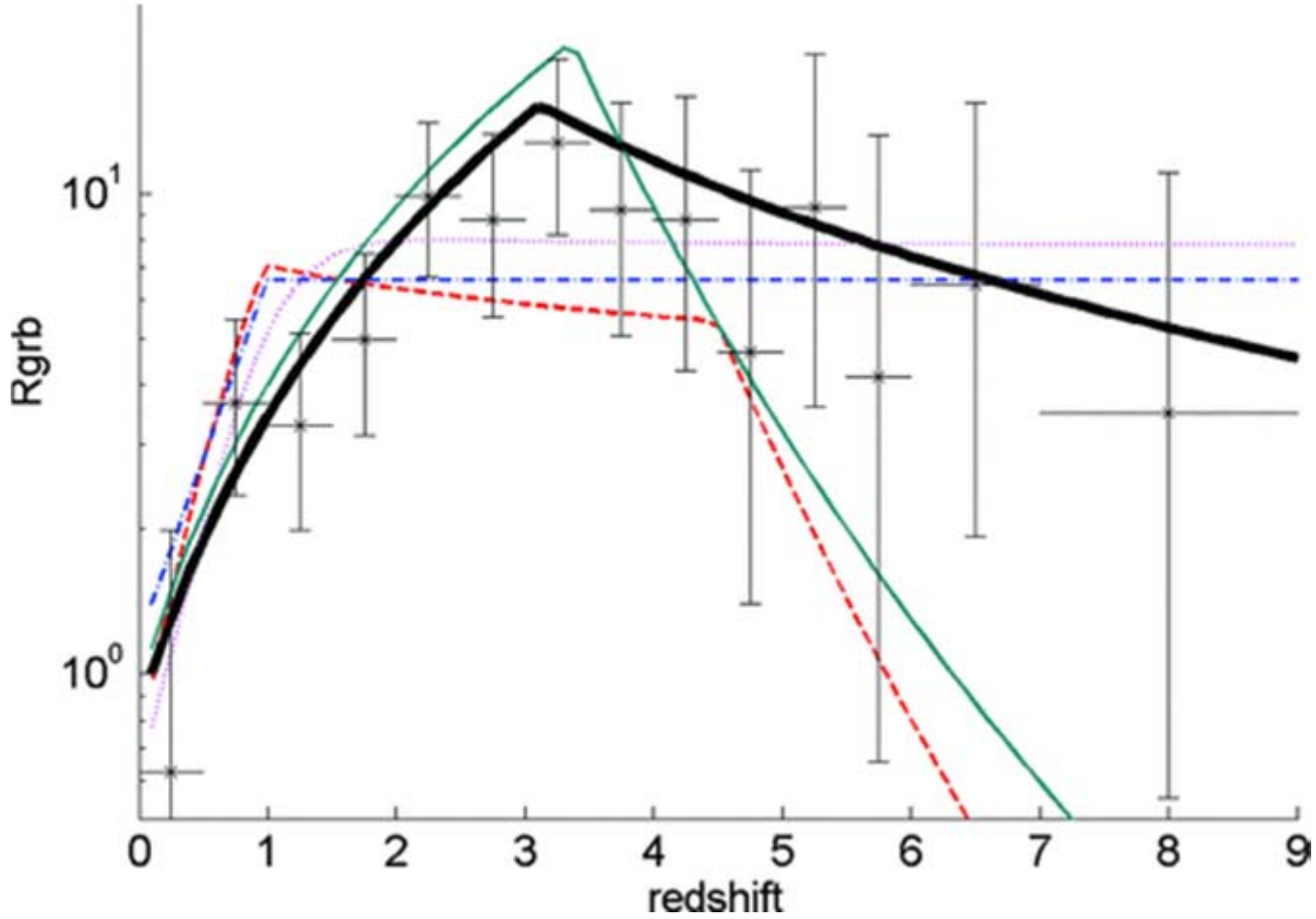


$M_{prog} > 40\ M_{\odot}$

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

The luminosity function and the rate of Swift's GRBs

D. Wanderman and T. Piran (ApJ, 2010)



The results for the rate, in 1/2 unit binning. Best fit for a broken power law - heavy black solid line. Hopkins and Beacom (2006) SFR - red dashed line, Bouwens et al. (2009b) SFR - cyan solid line. SF2 of Porciani and Madau (2001) - magenta dotted line. Rowan-Robinson (1999) SFR – blue dashed dotted line.