STELLAR BLACK HOLES AT THE DAWN OF THE UNIVERE

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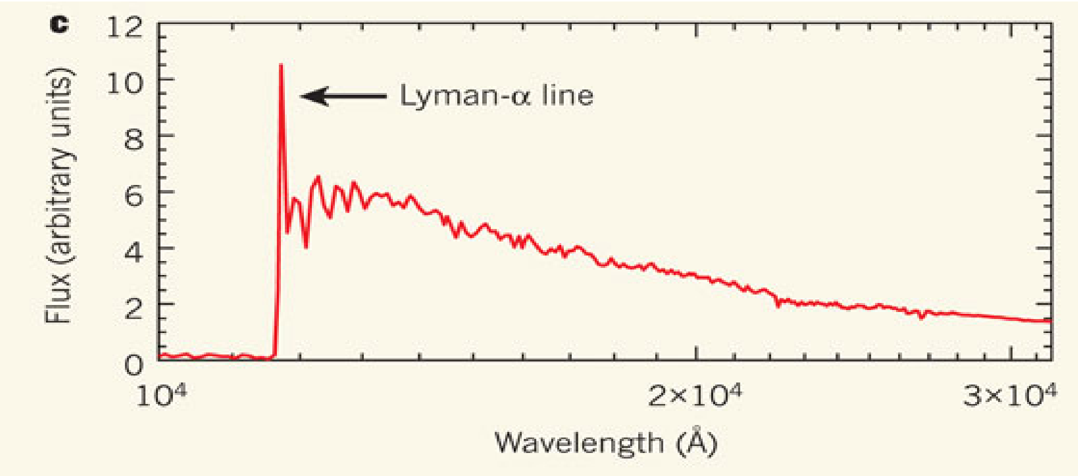
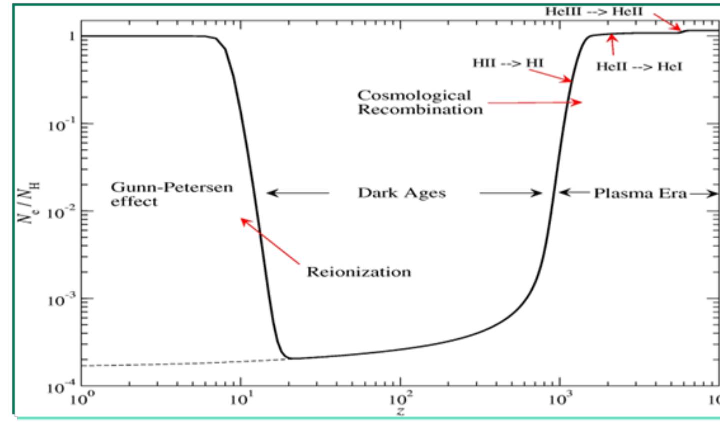
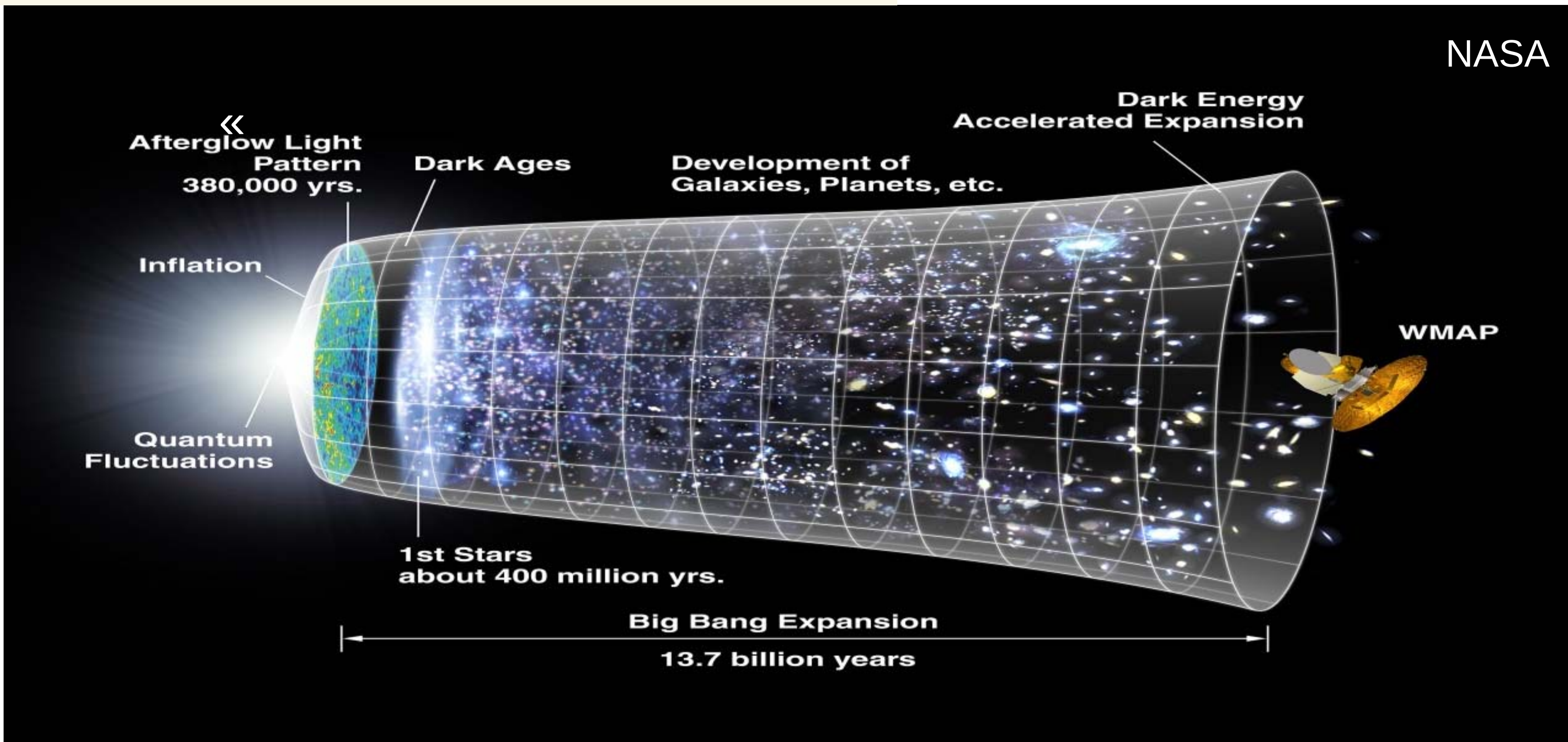
Because of astrophysical reasons, irrespect of WDM or CDM, the large numbers of dwarf galaxies are not observed because they could not form

THE DARK AGES OF THE UNIVERSE

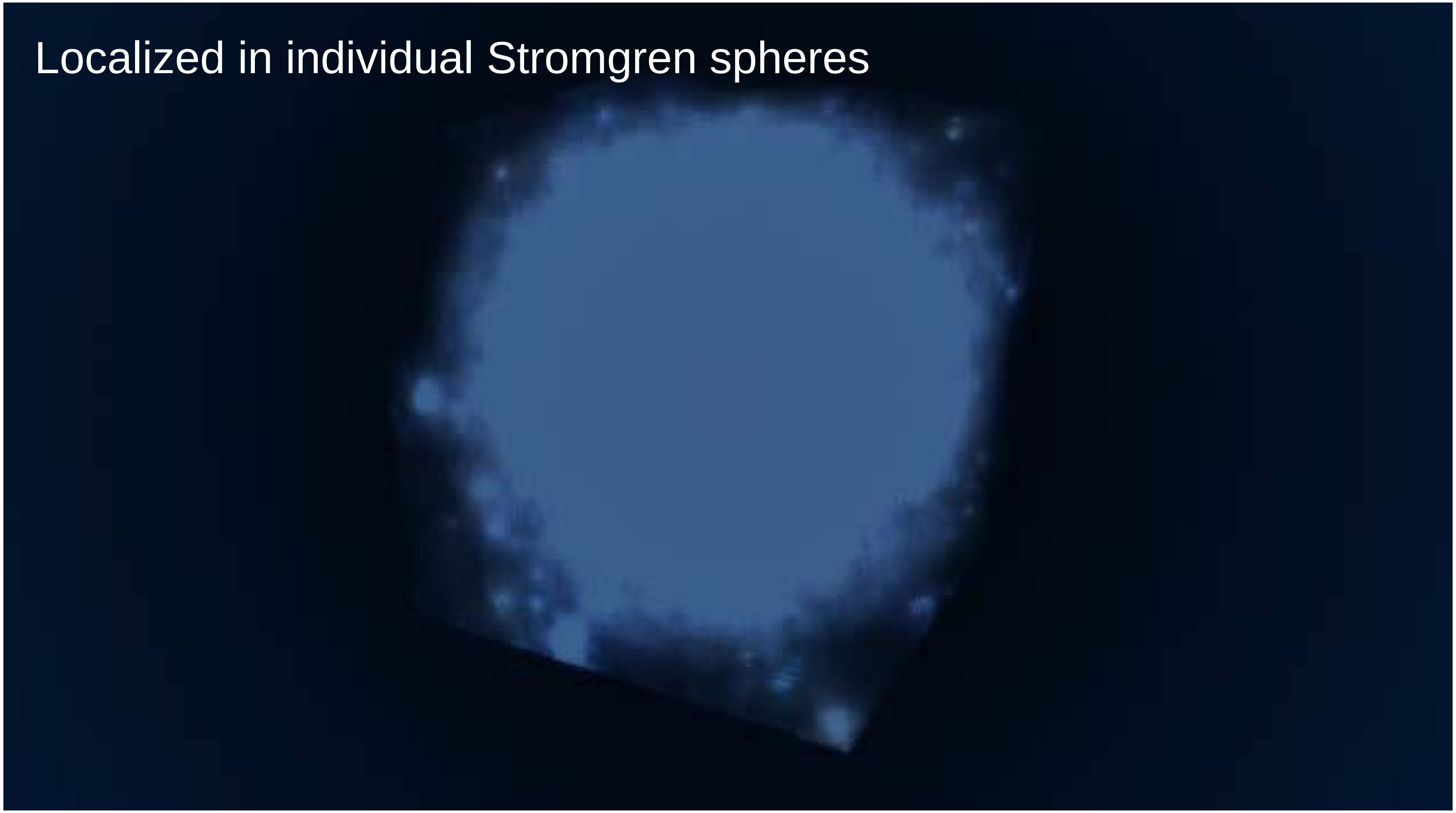




10^1 10^3 z



THE « SWISS CHEESE » MODEL



The cosmology community assumes that the IGM was **fully** ionized by the UV from the first massive stars (e.g. Roberston, Ellis+ Nature 2010), and that the remnants from those massive stars (BHs) did not play an important role. However, Power+ (2009) proposed the role of Bhs from the existence of GCs with ages of 13 billion yr..

The role of accreting stellar BHs has so far been overlooked

Plan of the talk

I. Astrophysics of stellar black holes

- **Theoretical models** on the formation of BH-HMXBs
- **Observations** of stellar black hole binaries

$\Rightarrow$

An historic cosmic evolution of BH-HMXBs

Mirabel: Invited review at the IAU Symp "Jets at all Scales" (Feb, 2011)

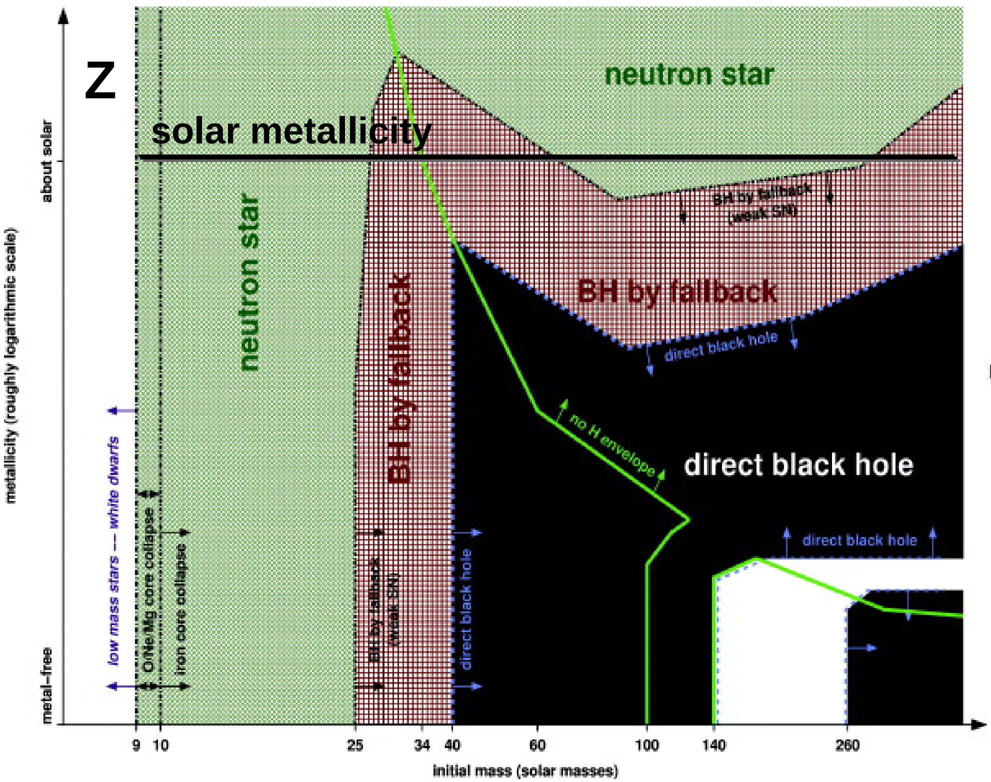
II. Implications for cosmology:

- **A smooth & rapid end of the dark ages?** (N&V in Nature)
- **A high low mass limit for dwarf galaxies $\Rightarrow$ DMMs**
- **Polarization of the CMB?**
- **BH stellar binaries as gravitational wave sources**

Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 528, A149, 2011)
News & Views by Haiman in Nature of 7 April, 2011

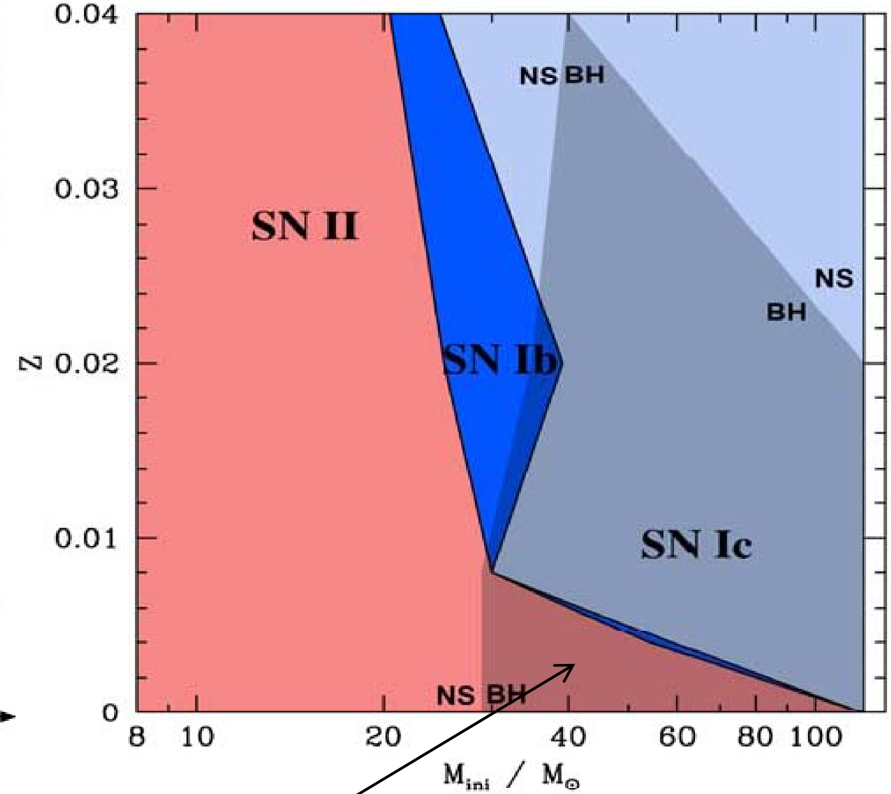
MODELS ON THE FORMATION OF COMPACT OBJECTS BY THE COLLAPSE OF SINGLE STARS

with no rotation (Heger+ 2003)



Mass of progenitor star

with rotation (Georgy+ 2009)

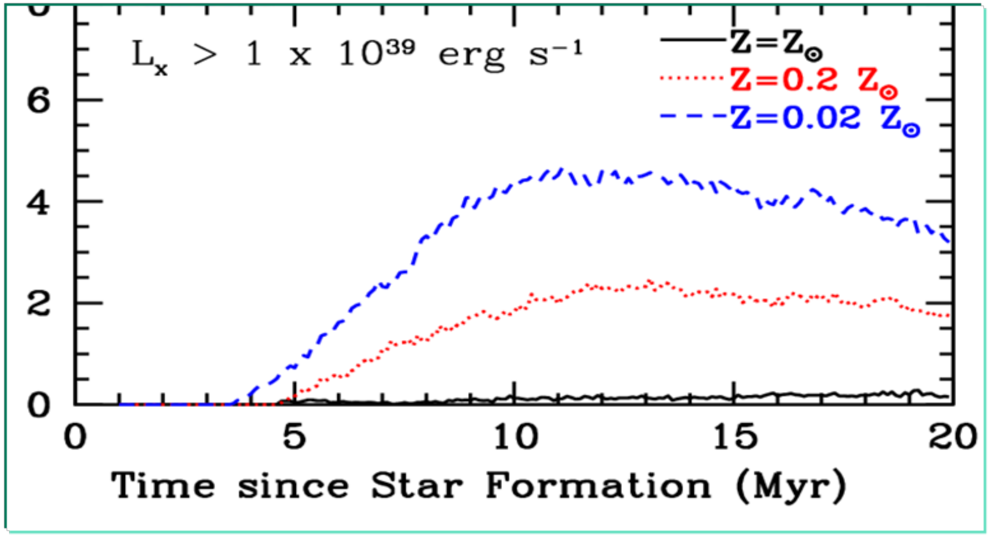


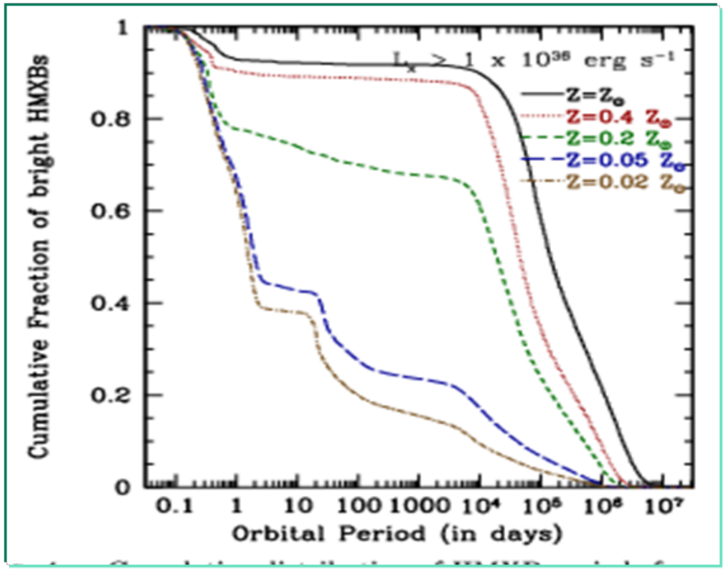
Low metal progenitors form BHs by IMPLOSION (Fryer, 1999)

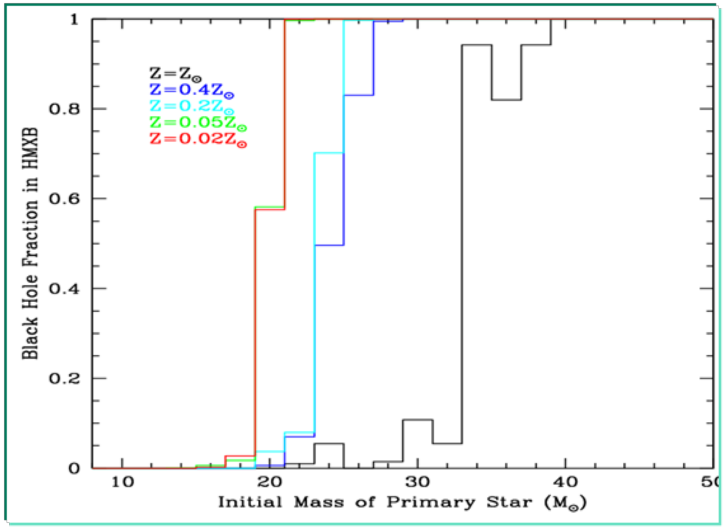
But the destiny of massive stars also depends on **binarity & magnetism**

THE FORMATION OF HMXBs IS STRONGLY METALLICITY DEPENDENT (Linden, Kalogera+ 2011)

Number of HMXBs per starburst of 10^6 $M_\odot$







AT LOW Z

- the number of HMXBs increases
- the orbital period decreases
- progenitors of > 20 $M_\odot$ end as BHs

FROM CURRENT MODELS OF STELLAR EVOLUTION

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

SHOULD INCREASE WITH DECREASING METALLICITY OF THE PROGENITORS

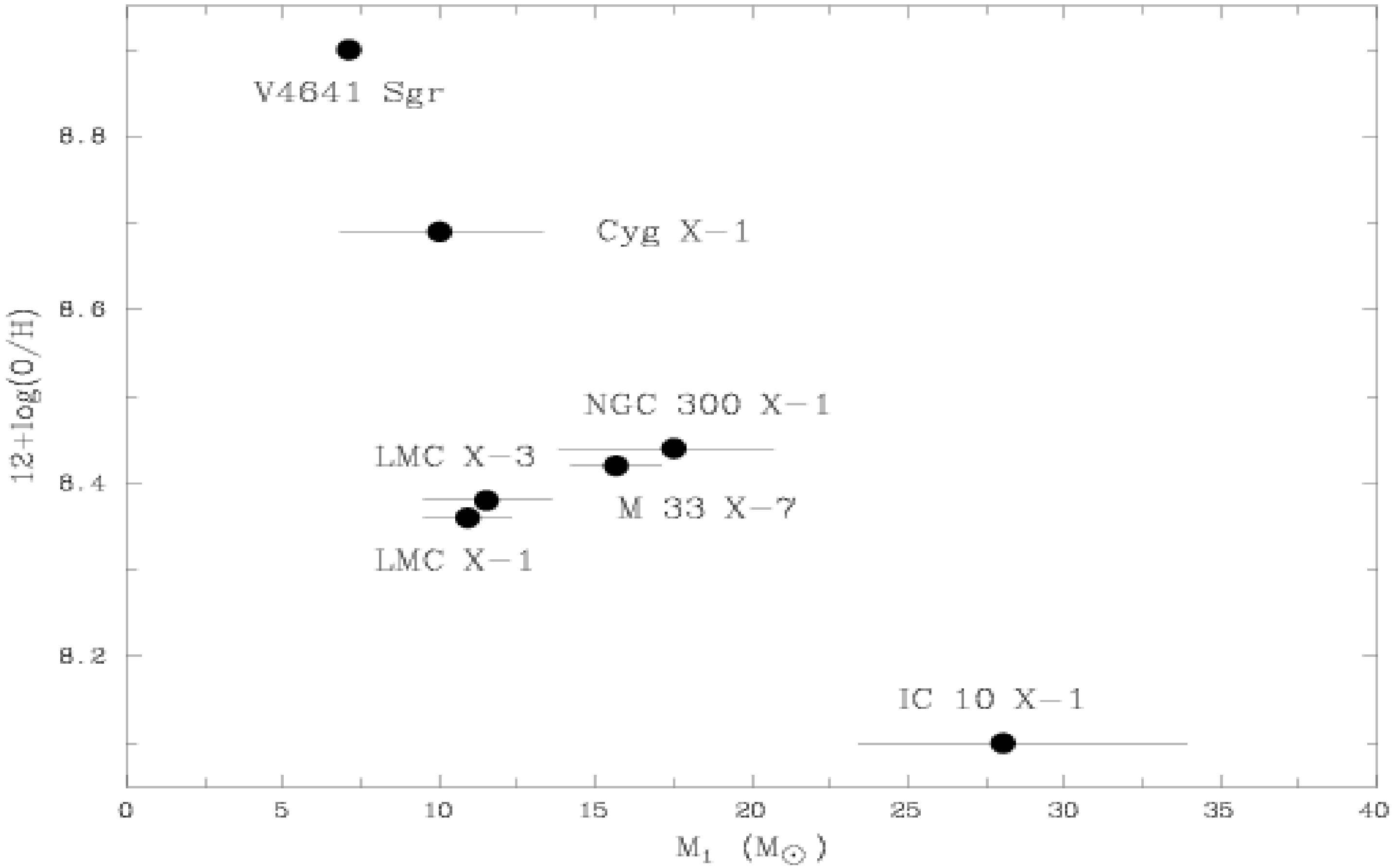
Because the fraction of binary systems that remain gravitationally bound increases, from a theoretical point of view one expects that

THE BH-HMXBs FRACTION INCREASES WITH THE INVERSE OF THE METALLICITY

WHAT OBSERVATIONS CAN TEST THESE THEORETICAL PREDICTIONS?

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

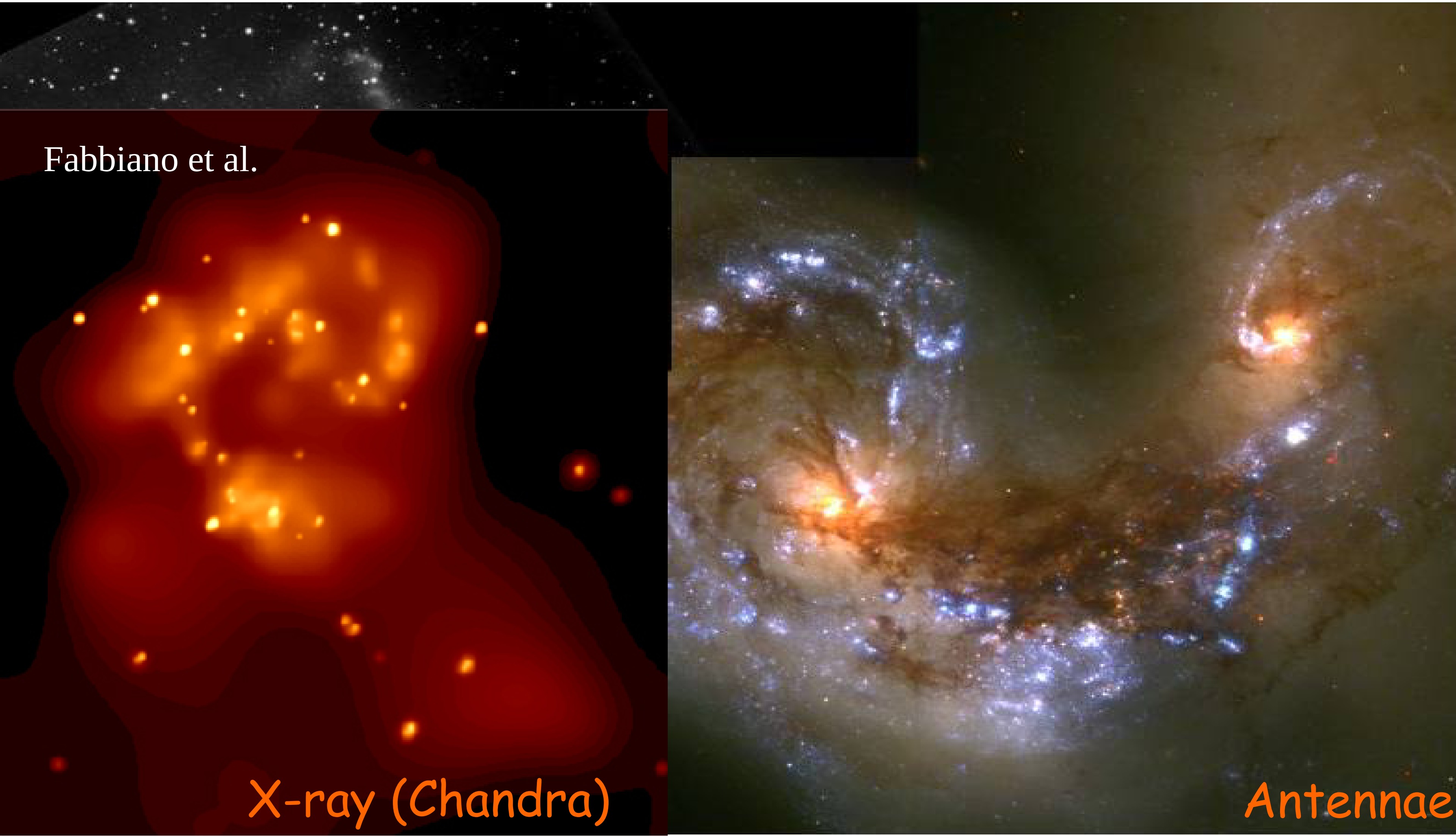
Masses determined dynamically (Crowther et al. 2010)



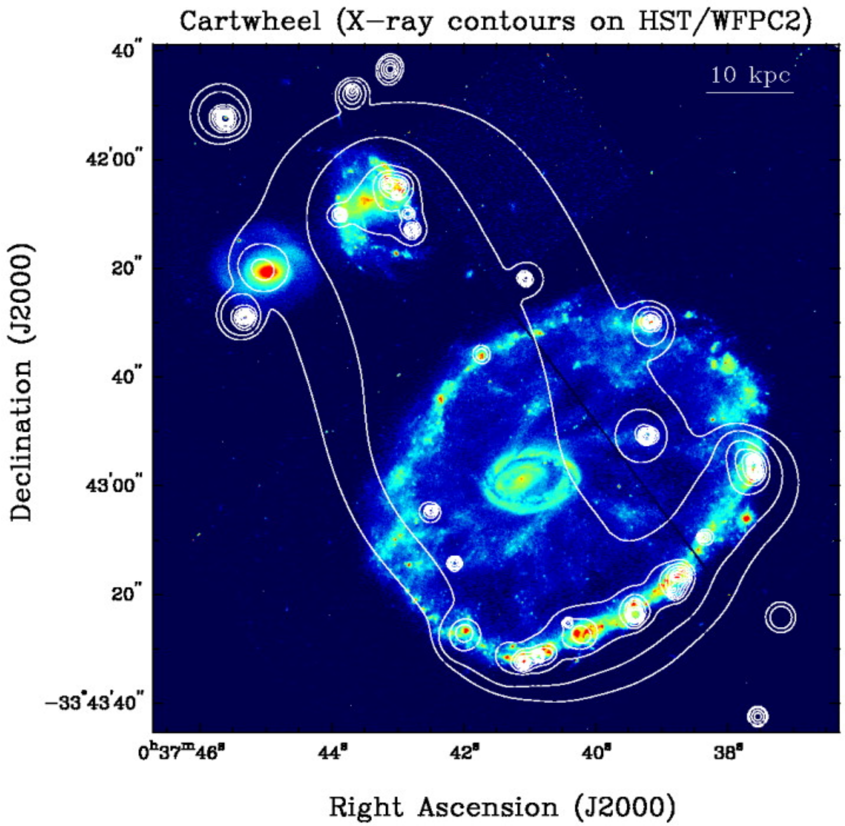
The stellar BHs in M 33 X-7, NGC 300 X-1, IC 10 X-1 have M_{BH} > 15 $M_\odot$ whereas in the Galaxy and M 31 no stellar BH with M_{BH} > 14 $M_\odot$ is known

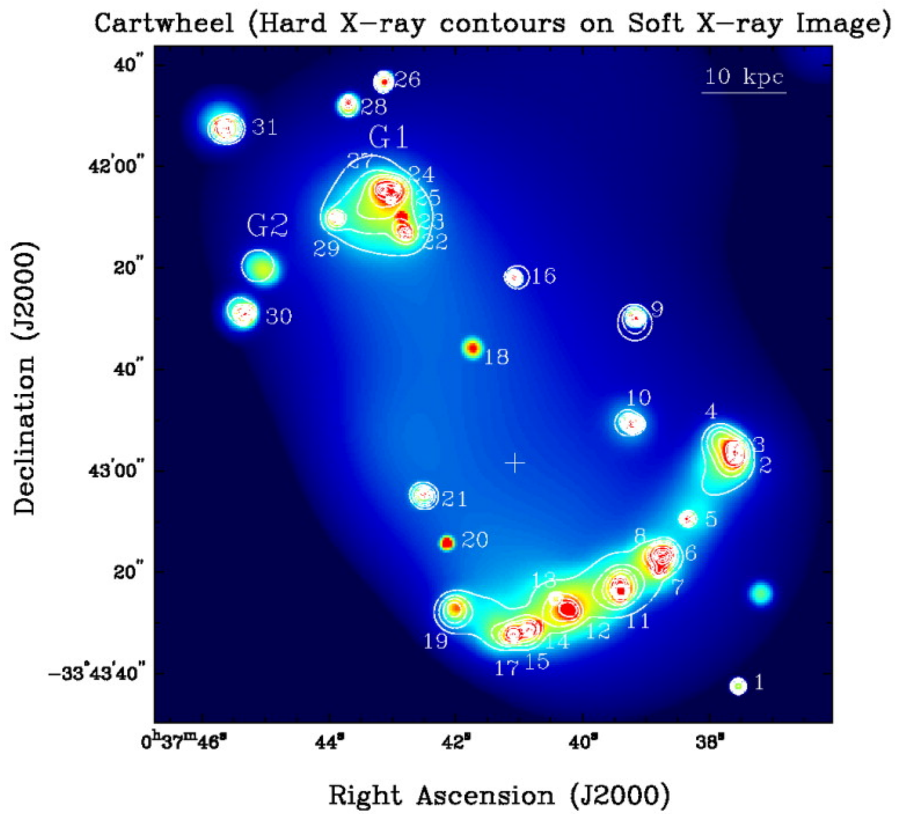
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS IS AN INCREASING FUNCTION OF THE SSFR AND A DECREASING FUNCTION OF THE METALLICITY OF THE HOST GALAXY

e.g. Zampieri & Roberts (2009)



ULXs in the low metallicity Cartwheel galaxy (template for high z galaxies)

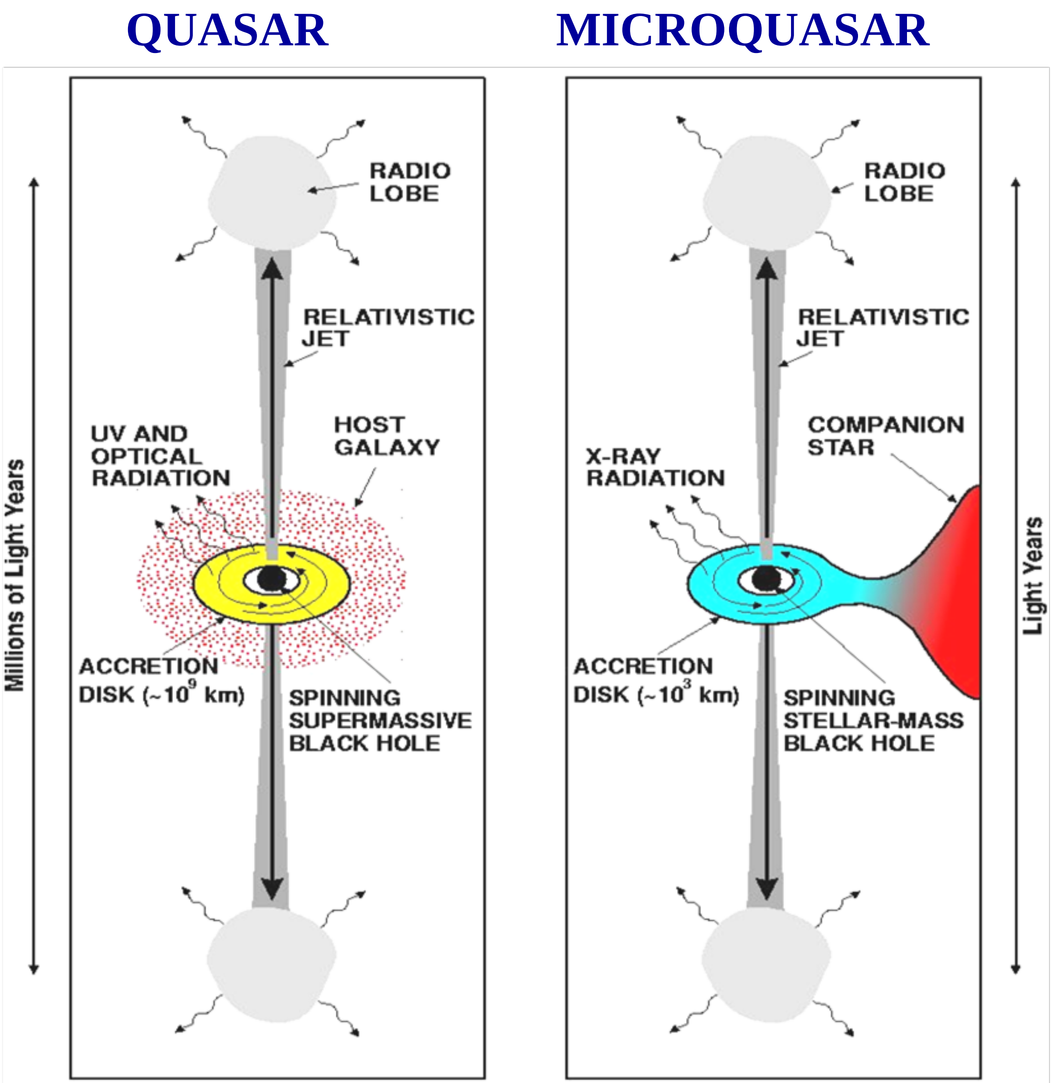




Total X-ray luminosity ~ 10^{42} erg s^{-1} (Gao et al. 2003)

The total X-ray luminosity rivals that of low luminosity AGN

ULX's ARE MICROQUASARS



$E_{BH} \sim 0.1\ (m_{acc}\ C^2)$ (Lynden-Bell, 1970)

Mirabel & Rodríguez; Nature 1998

The scales of length and time are proportional to M_{BH}

$R_{sh} = 2GM_{BH}/c^2$; $\Delta T \ \alpha \ M_{BH}$

Unique system of equations:

The maximum color temperature of the accretion disk is:

$$T_{col} \ \alpha \ (M/\ 10M_{\odot})^{-1/4}$$

(Shakura & Sunyaev, 1976)

Waited era of space astronomy

For a given accretion rate:

$L_{Bol} \ \alpha \ M_{BH}$; $l_{jet} \ \alpha \ M_{BH}$;

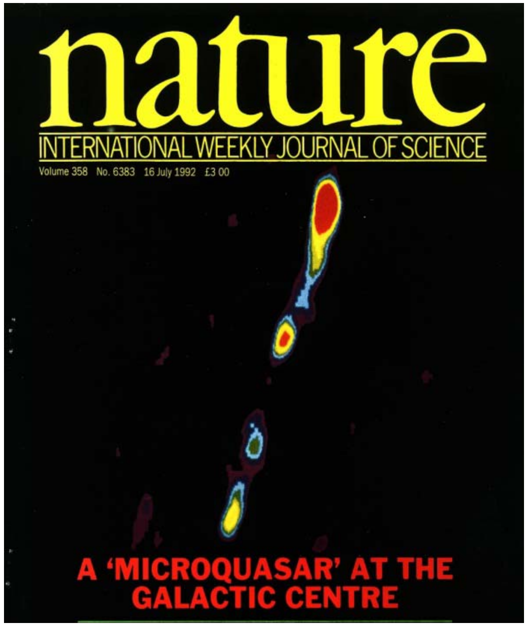
$\varphi \ \alpha \ M_{BH}^{-1}$; $B \ \alpha \ M_{BH}^{-1/2}$

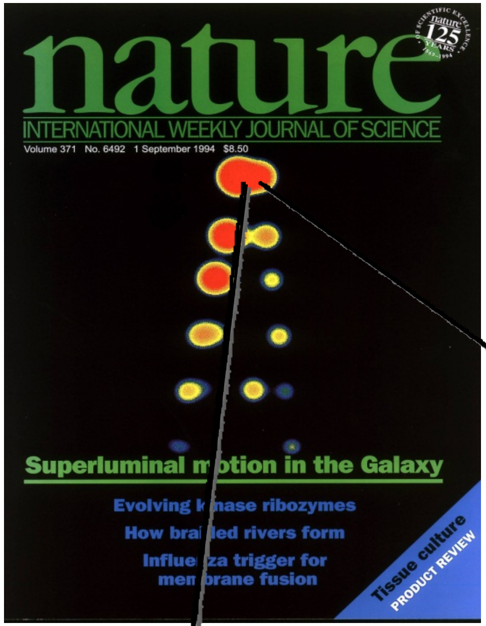
(Sams, Eckart, Sunyaev, 96; Rees 04)

JETS IN MICROQUASARS

Mirabel, Rodríguez+(1992) Mirabel & Rodríguez (1994)

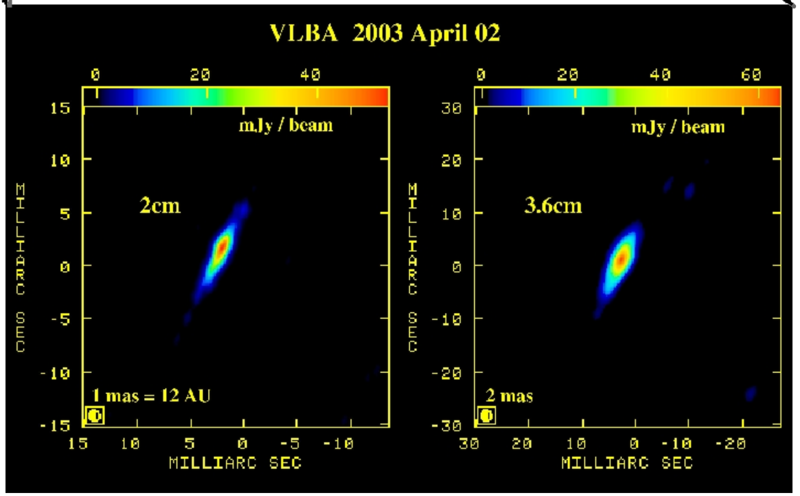
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



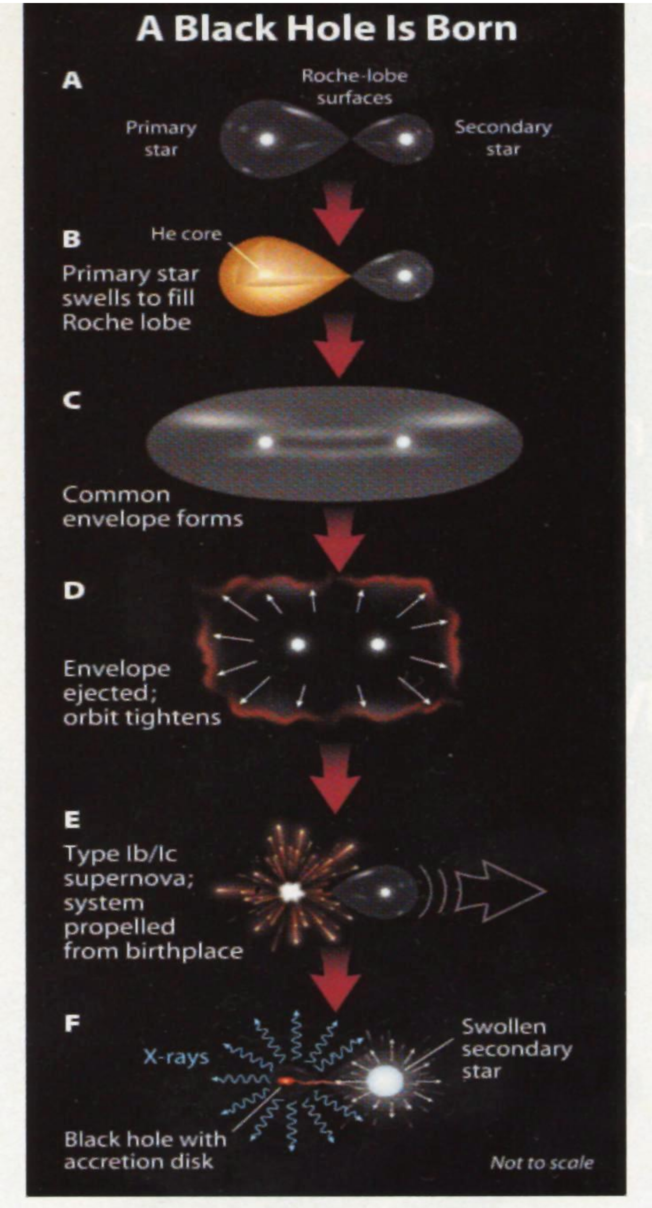
COMPACT JETS

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

USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

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



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)

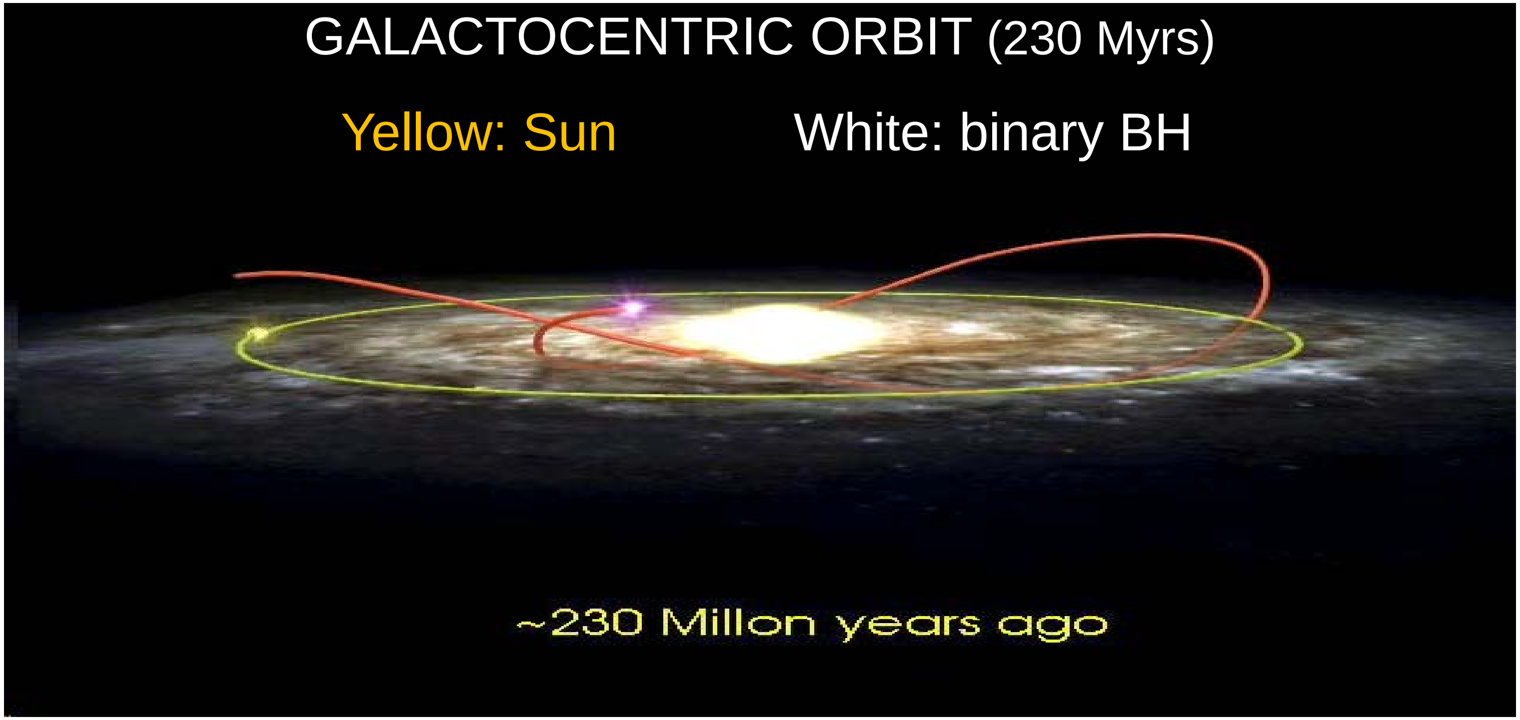
IF THE BH BINARIES HAVE NO ANOMALOUS MOTIONS THE BLACK HOLES MUST HAVE BEEN FORM WITH NO ENERGETIC SNe KICKS

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

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)



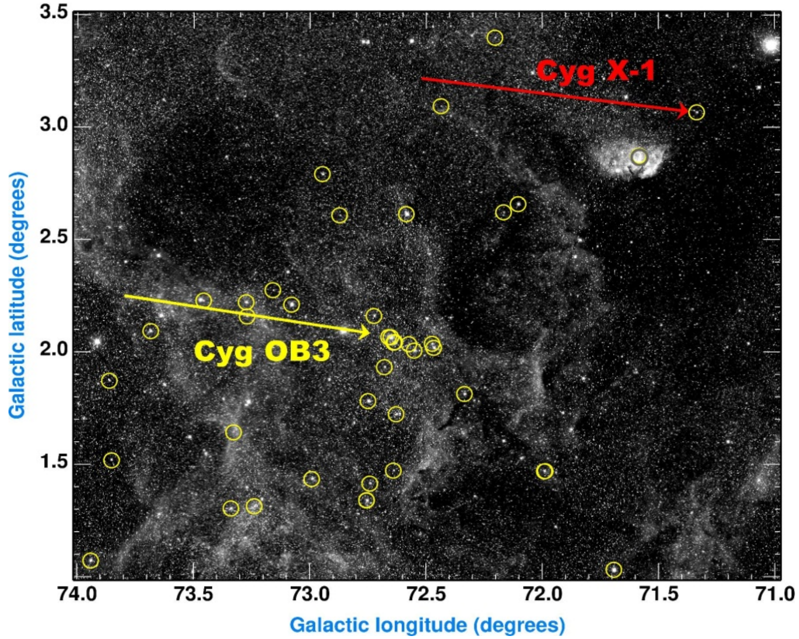
GRO J1655-40: Fossil of a HPN (Israelian et al. Nature 1999)

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 REMAINED IN ITS BIRTH PLACE

Mirabel & Rodrigues (Science, 2003) now confirmed by Gou, McClintock+ (2011)



V_p < 9 +/- 2 km/s ⇒

< 1 $M_\odot$ ejected in a SN

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

THE ~14 $M_\odot$ BH (Orosz+2011) **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)

BHs with >10 $M_\odot$ are form by direct collapse

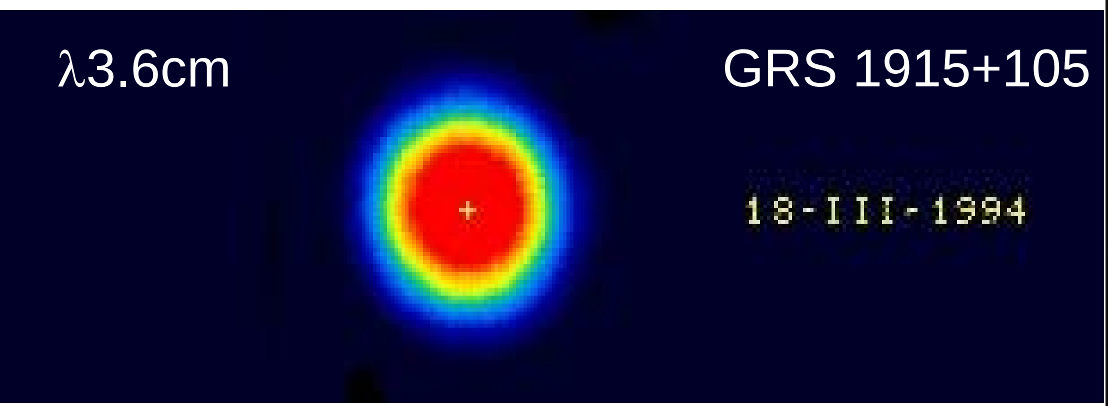
This line of research will be enhanced with GAIA

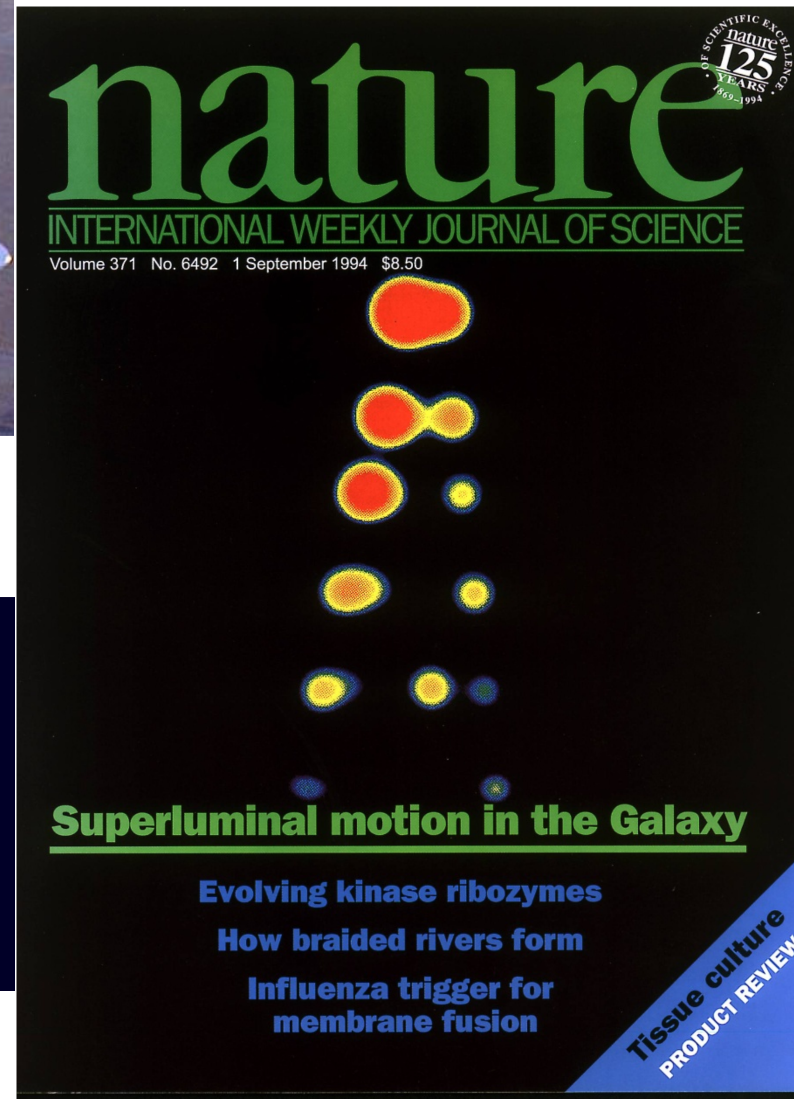
POWERFUL SUPERLUMINAL EJECTIONS IN μQSOs

The mass of the Moon at v = 0.98c

Mirabel & Rodriguez, 1994

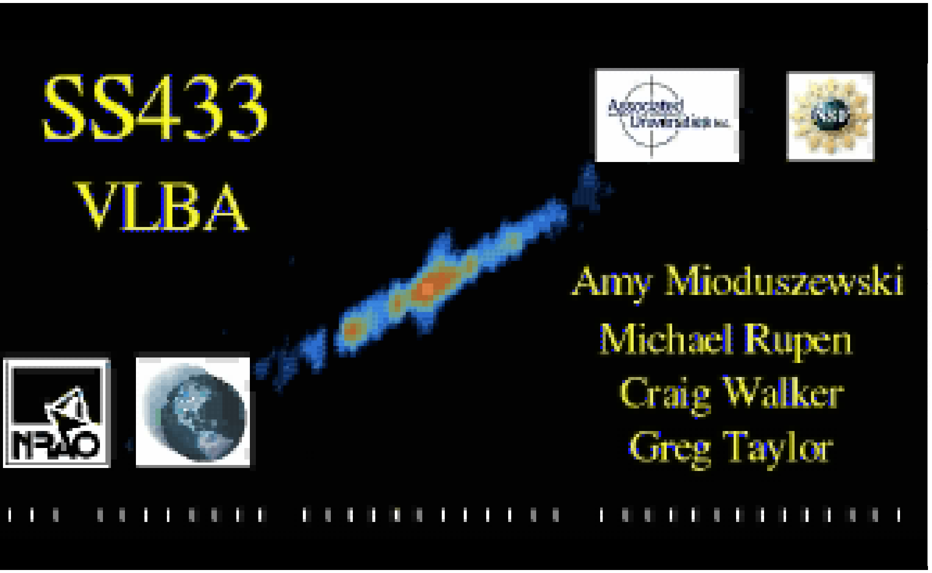
1 arcsec





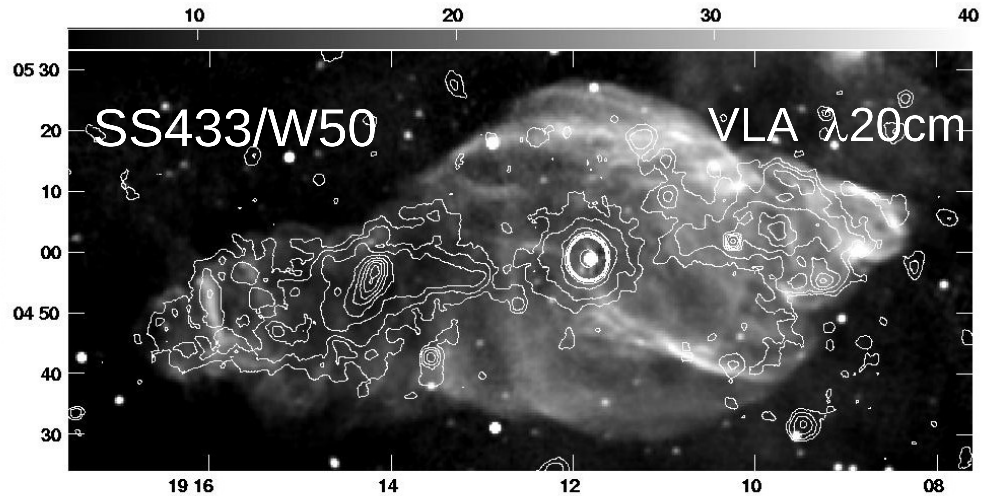
V_{app} > C AT A DISTANCE > 8 Kpc

POWERFUL JETS FROM μQSOs



1arcsec

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

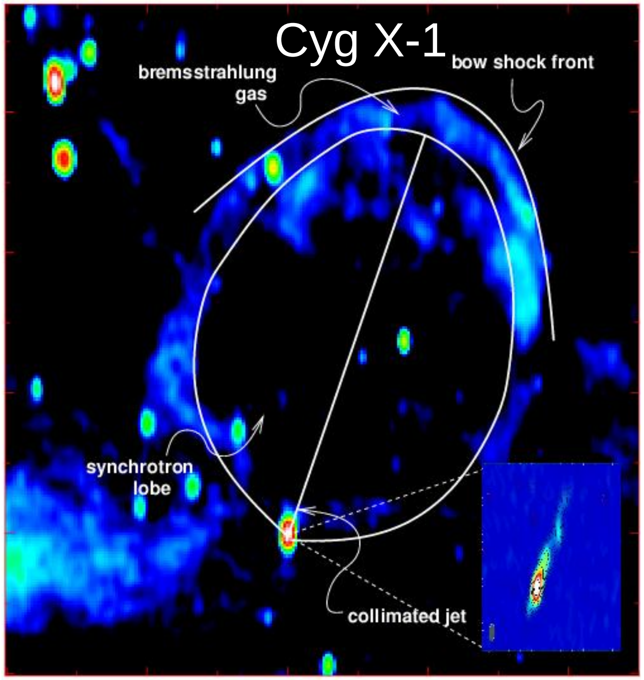


$1^o = 60$ pc

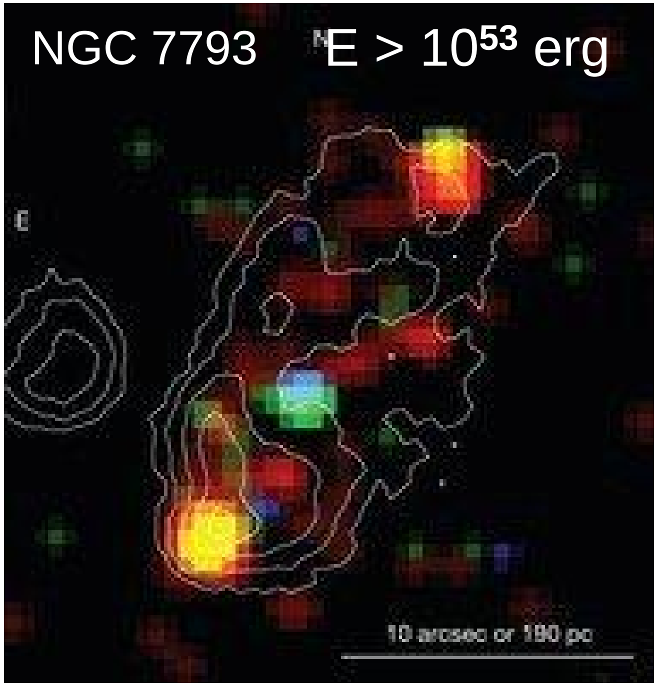
- ATOMIC NUCLEI MOVING AT 0.26c ⇒
- MECHANICAL LUMINOSITY > 10^{39} erg/sec
- NON RADIATIVE JETS = "DARK" JETS
- >50% OF THE ENERGY IS NOT RADIATED

FEEDBACK FROM BH-HMXBs (μQSOs)

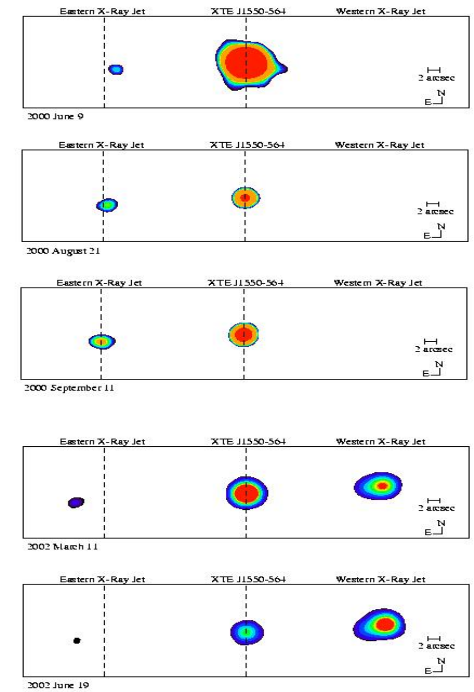
Gallo et al. (Nature, 2005)



Pakull et al. (Nature, 2010)



Corbel+ (Science 2002,05)



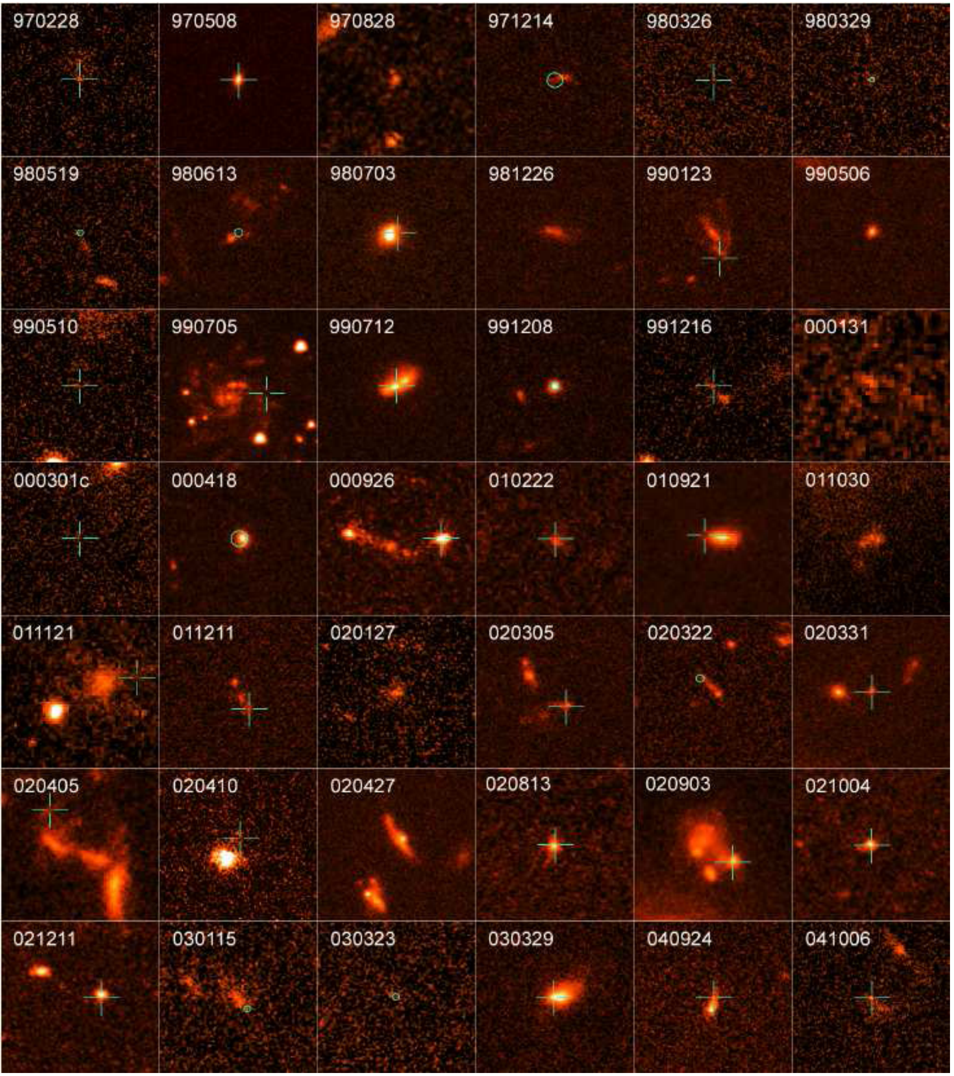
Moving X-ray jets in XTE J1550-564 & H1743-322 (Corbel et al. Science) ⟹

- **Formation of a double-lobe X-ray/radio source in real time**
- **The energy from a BH-HMXB may be 100 times that of the baryonic and photonic energy from typical core collapse SNe**

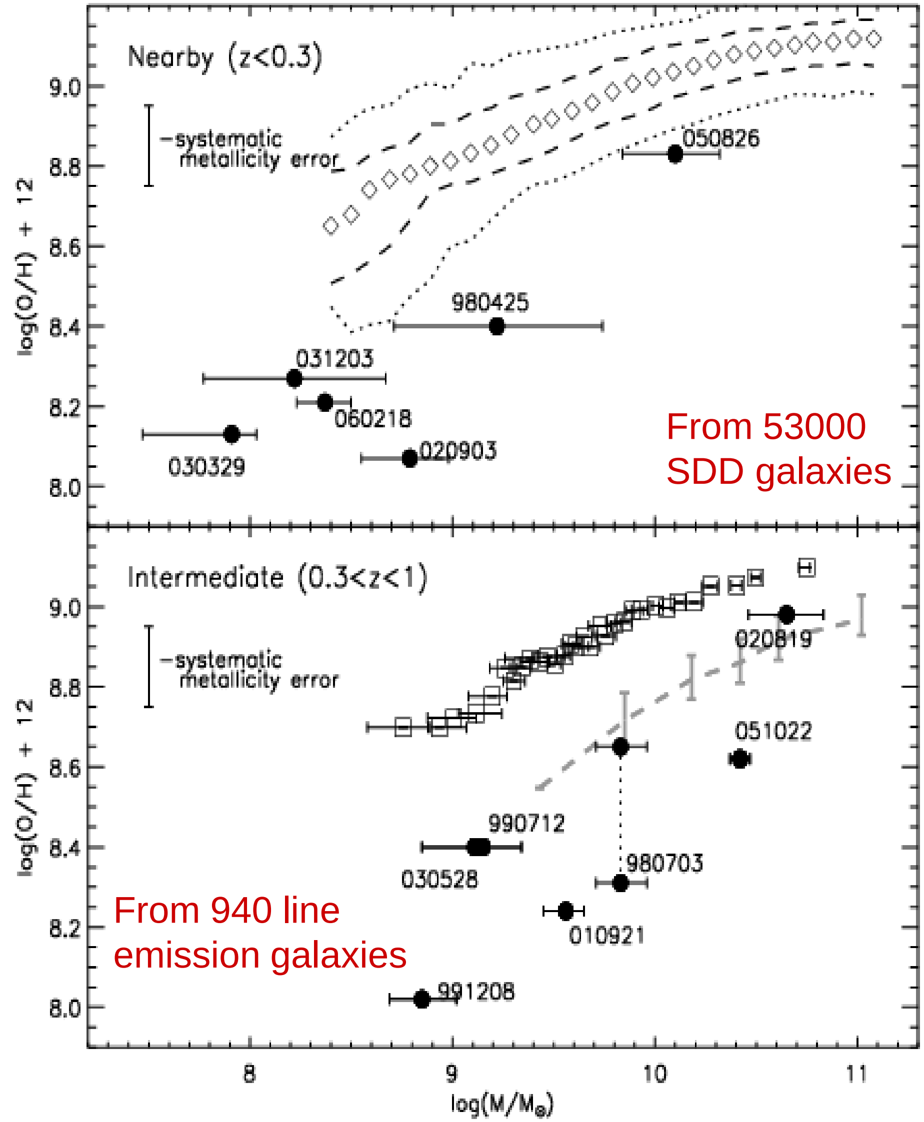
HOSTS OF LGRBs ARE SMALL IRR. GALAXIES WITH HIGH SSFR & RELATIVE LOW METALLICITY

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

Fruchter + with HST (Nature, 2006)



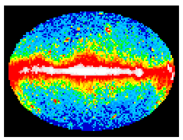
Levesque et al. (2010)

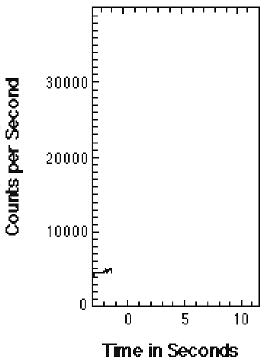


LGRBs MARK THE FORMATION OF BLACK HOLES

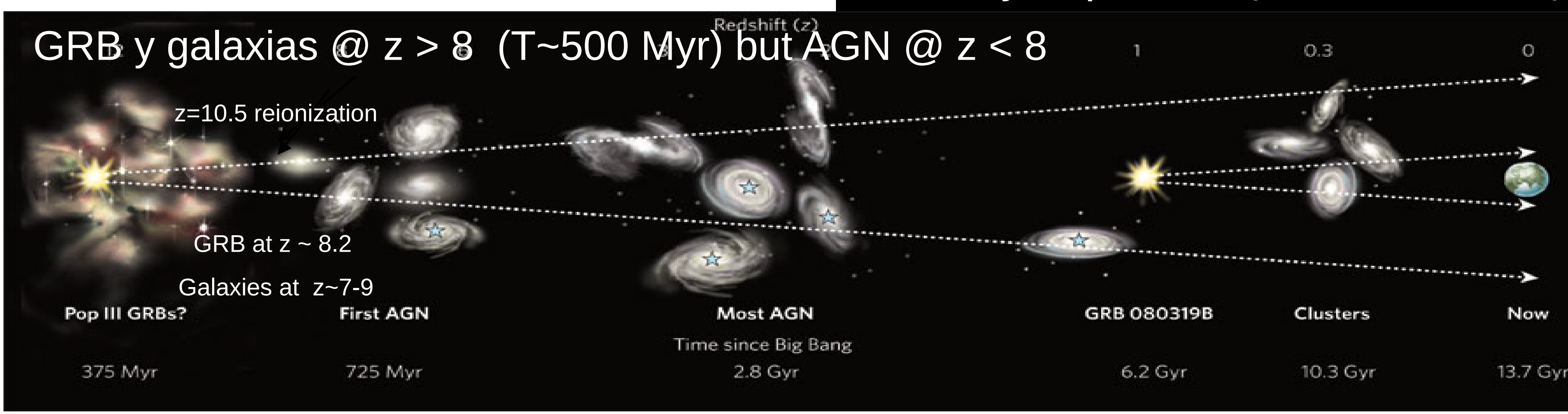
stellar collapse & super-relativistic jets

Hiper-nova explosion (SN Ic)





Also by implosion (Mirabel,Science)



HST/WFC3 z=7-9 galaxies seem “photon starved” Bouwens+; 2010)

RECENT DEVELOPEMENTS

X-RAY OBSERVATIONS IN TEMPLATES OF GALAXIES AT z>6

- X-ray emission from distant galaxies reveals a hidden population of "supermassive" BHs (Trestier+ Nature 2011)...or large collection of stellar BH?
- X-ray luminosities of ~10^{42} erg s^{-1} in local analogs of Lyman Break Galaxies

$\Rightarrow$ « SMBH growth » (Jia, Heckman+, 2011)…or large collection of stellar BH?

No detection of prominent Fe emission line at 6.4 keV typical of Type 2 AGN !

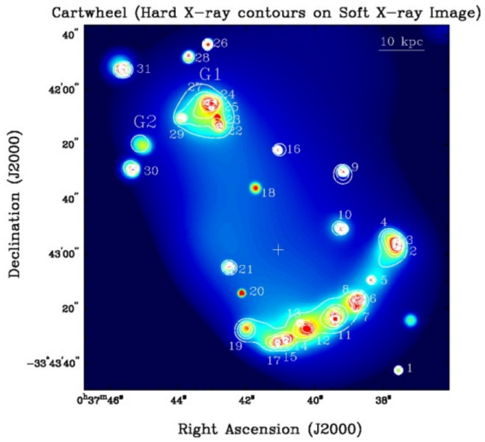
SOLITARY STELLAR BLACK HOLES IN YOUNG GALAXIES

- ~10^6 stellar BHs in a high density ISM produce ~10^{61} ergs over billon years.

10^8 stellar BHs of 10 $M_\odot$ can rival a single central BH of 10^9 $M_\odot$ (Wheeler+)

However, because of feedback Bondi accretion may not be that efficient…

BEYONG ARGUMENTS WE KNOW THAT MOST ULXs ARE BLACK HOLE BINARIES AND THAT THEIR GALACTIC HOSTS ARE THE CLOSEST NEARBY TEMPLATES OF THE HIGH z GALAXIES



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

THE COSMIC EVOLUTION OF METALLICITY

$\Rightarrow$ A COSMIC EVOLUTION OF BH-HMXBs

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

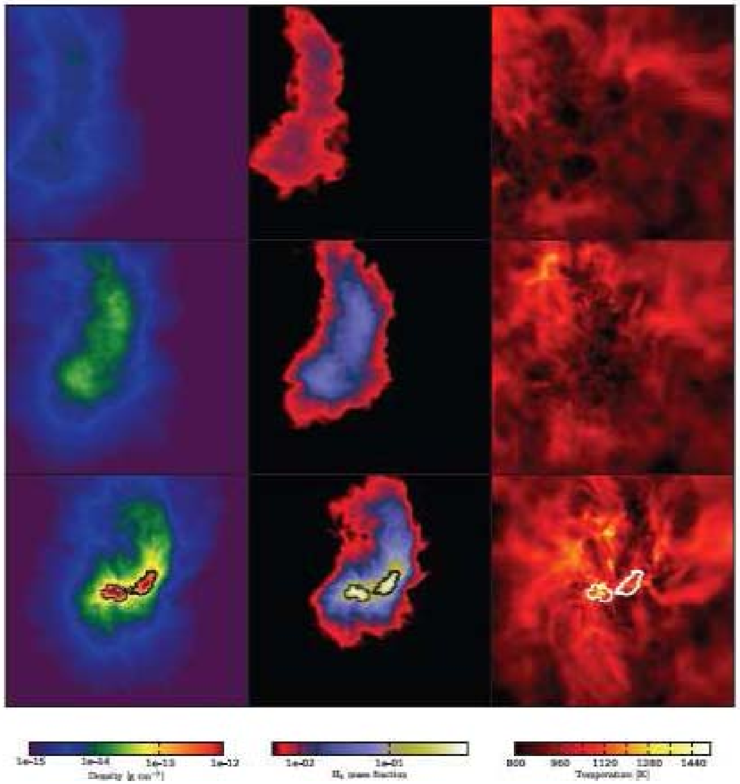
SHOULD INCREASE WITH REDSHIFT

In the VII Microquasar workshop in 2008 Sunyaev asked the question on

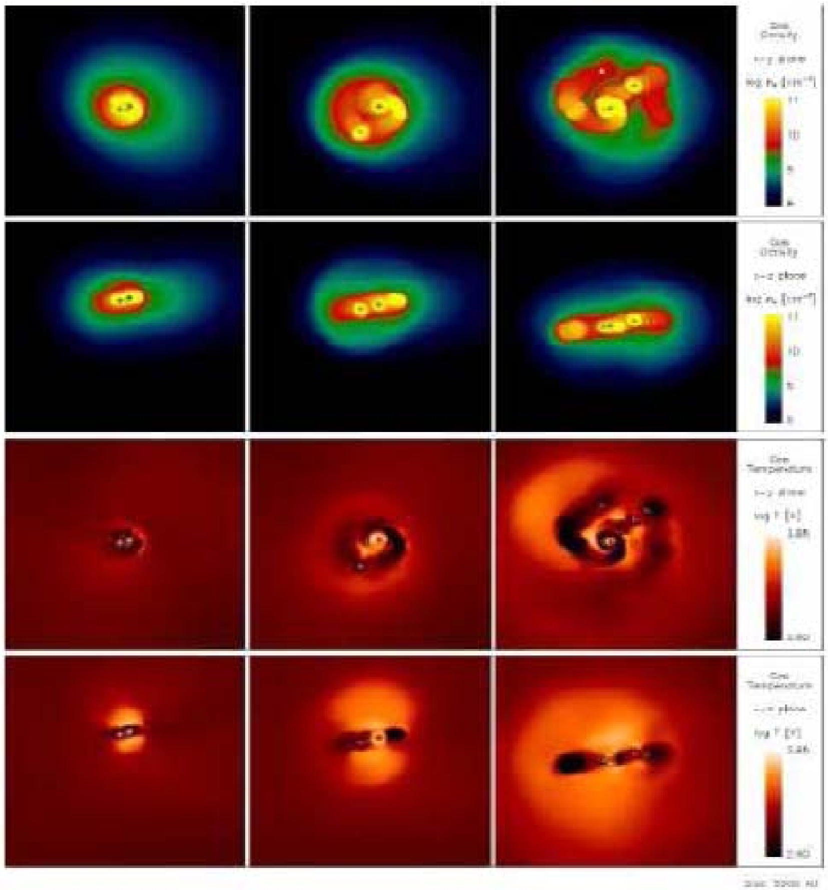
WHAT MAY HAVE BEEN THE COSMOLOGICAL IMPLICATIONS OF XRBs DURING THE DARK AGES THAT LASTES FROM $4x10^4$ up to 10^9 yrs ?

NOW THIS IS HAS BECOME A TIMMELY QUESTION BECAUSE…

POPULATION III STARS



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



Stacy, Greif & Bromm (ApJ 2010)

1) **Pop III stars were multiple systems dominated by binaries with 10-100 $M_\odot$ that should end as BH-HMXBs**

2) **>70% of OB type stars are binaries** (Clark+, 2011; Chini+, 2011)

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

- 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

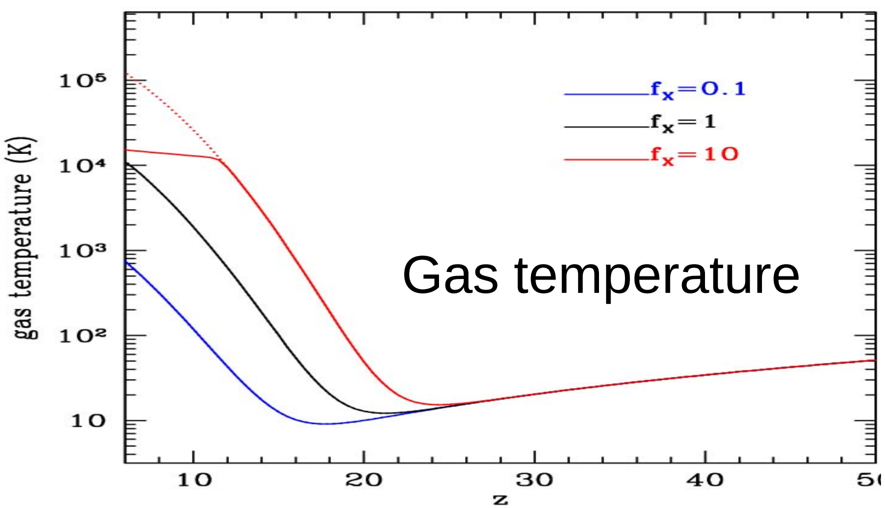
STELLAR BLACK HOLES IN THE DARK AGES

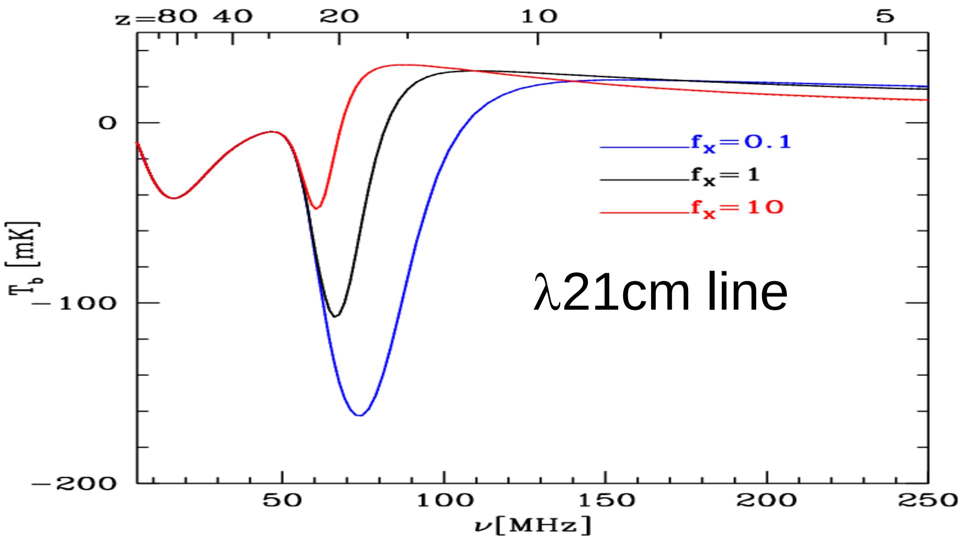
Empirical correlation between X-ray luminosity and SFR. f_x = 0.2 at z=0 (Grim, Gilfanov & Sunyaev, 2003)

$$L_{2-10} = f_X \times 3.5\times10^{40}\, SFR \qquad erg/s$$

$$f_X = \frac{f_{2-10}\, f_{BH}\, t_{acc}\, f_{bin}\, f_{edd} \times 1.5\times10^{38}}{3.5\times10^{40}} = 0.4\left(\frac{f_{2-10}}{0.1}\right)\left(\frac{f_{BH}}{0.01}\right)\left(\frac{f_{edd}}{0.1}\right)\left(\frac{f_{bin}}{0.05}\right)\left(\frac{t_{acc}}{20\,Myr}\right)$$

4.0 0.5





- BH-HMXBs 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

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

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

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

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

X-ray and UV 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 UV and X-rays from BH-HMXBs, dark matter haloes with masses below 10^9 $M_\odot$ could not accrete gas from IGM.

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

II. COSMOLOGICAL IMPLICATIONS

1) Because X-rays and relativistic jets penetrate beyond the UVs, BH-HMXBs determined the early thermal history of the IGM ($T \sim 10^4$ K), and played an important, and complementary role in the re-ionization of the universe at large distance scales.

2) Predictions: a) No Swiss cheese topology in the λ21cm signals from HI to be measured with LOWFAR, SKA, and single dipole experiments (e.g. EDGES)? Will it have larger amplitudes and uniform, rather than HII region dominated?
   b) Synchrotron emission from relativistic jets and inverse Compton processes?
   c) Polarization of the CMB with Planck?

3) Are BH-HMXBs at z>7 the sources of the unresolved hard X-ray background?

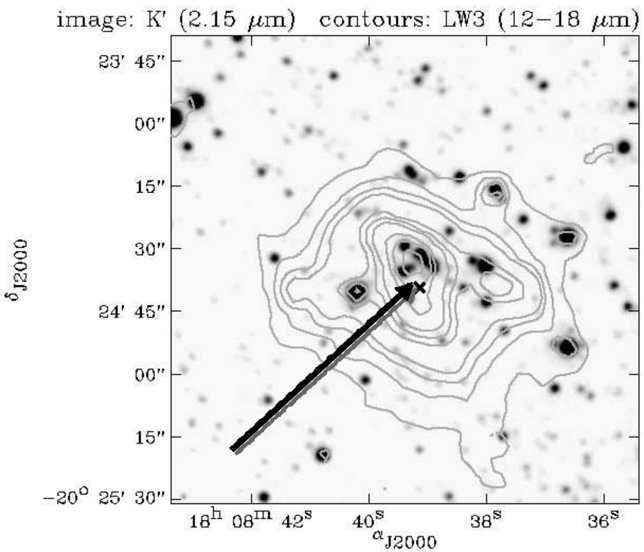
4) Because of the feedback (radiation & jets) from BH-HMXBs in the early universe dwarf galaxies of low mass could not form. This is why we do not observe them.

5) Will BH-BH stellar binaries may be the more likely sources of gravitational waves? (Belczynski et al. 2011)

- Mirabel: Invited review at the IAU Symp "Jets at all Scales" (October, 2010)
- Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A **528**, A149, 2011)
- News & Views by Haiman in Nature of 7 April, 2011

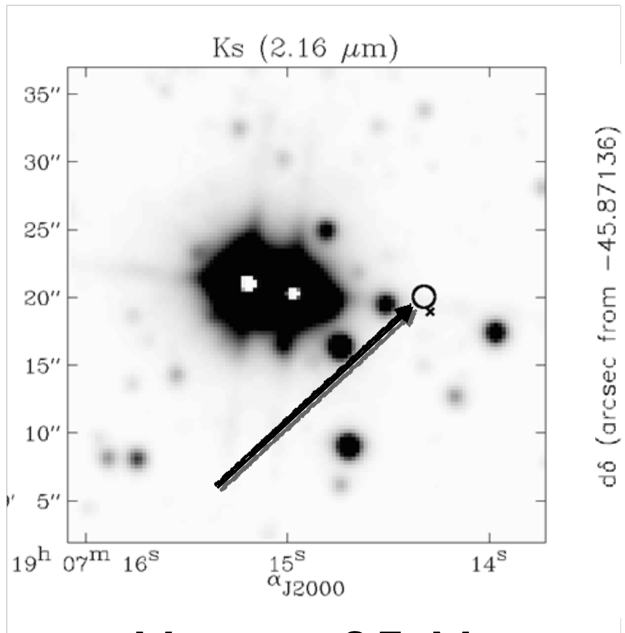
SGRs and AXPs (young neutron stars) found in clusters of massive stars

SGR 1806-20
Mirabel et al. (1999)



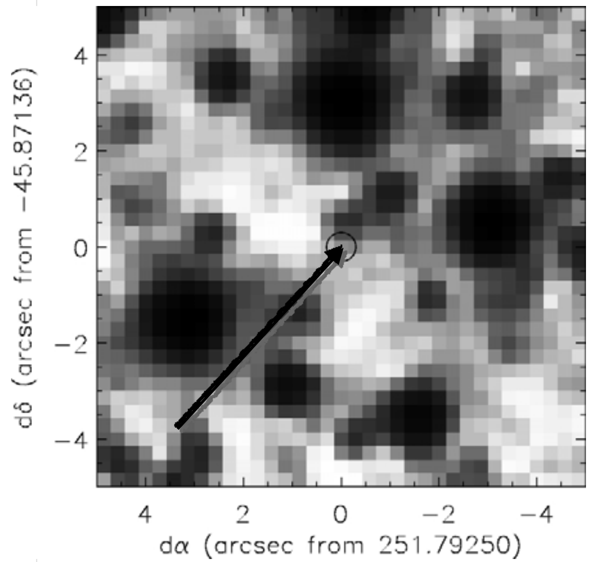
$M_{prog} > 40\ M_\odot$

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

HEATING AND REIONIZATION

BY X-RAYS AND RELATIVISTIC JETS

(that propagate more rapidly than their associated ionization fronts)

- X-ray thermal emission from SNe (Oh, ApJ 2001)
- Inverse Compton on CMB photons with $\rho \propto (1 + z)^4$
- X-rays from microquasars produce $N_{ion} \sim (E_{phot} / 37)$ eV
- (Secondary ionizations of HI dominate over direct photoionization)
- X-ray $\rightarrow$ He I $\rightarrow$ e- $\longrightarrow$ 30 HII $\longrightarrow$ H_2 (Venkatesan et al. ApJ 2001)

II. COSMOLOGICAL IMPLICATIONS

1) Because X-rays and relativistic jets penetrate beyond the UVs, BH-HMXBs determined the early thermal history of the IGM ($T \sim 10^4$ K), and played an important complementary role in the re-ionization of the universe at large distance scales.

2) Predictions: a) No Swiss cheese topology of the λ21cm signals from HI to be measured with LOWFAR, SKA, and the single dipole experiments (e.g. EDGES). Will have larger amplitudes and will be uniform rather than HII region dominated.
b) Synchrotron emission from relativistic jets and inverse Compton processes
c) Polarization of the cosmic microwave background with Planck?

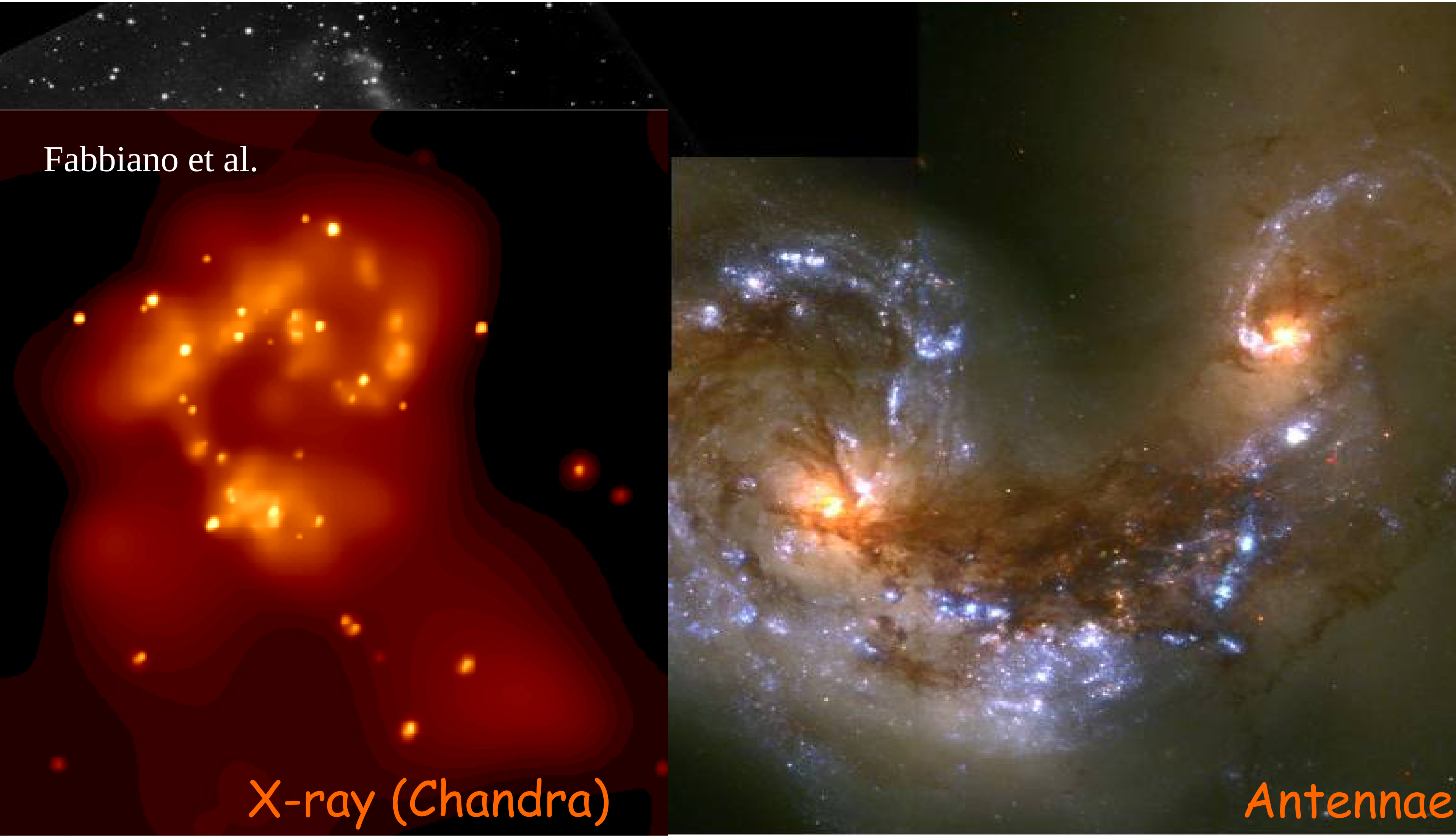
3) BH-HMXBs at z > 7 may be the sources of the unresolved X-ray background

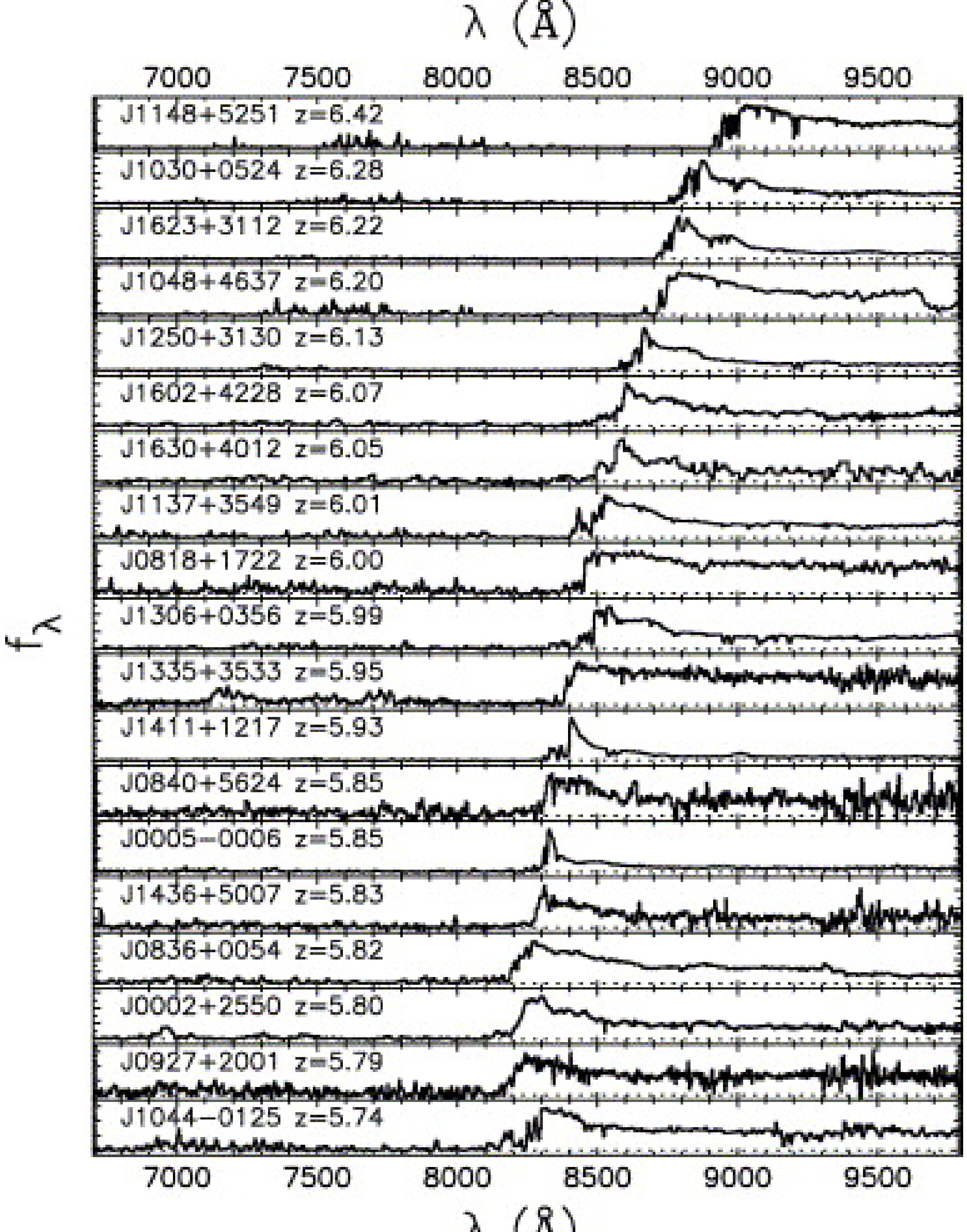
4) Feedback (radiation & jets) from BH-HMXBs in the early universe provide a framework to reconcile the apparent discrepancies of the observed number of dwarf galaxies with the predicted numbers from the CDM.

6) BH-BH binaries may be the more likely sources of gravitational waves

- Mirabel: Invited review at the IAU Symp "Jets at all Scales" (October, 2010)
- Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 528, A149, 2011)
- News & Views by Haiman in Nature of 7 April, 2011

BEYOND THE UNCERTANTIES, LOW METALLICITY GALAXIES IN THE LOCAL UNIVERSE, WHICH SERVE AS TEMPLATES, SHOW THAT THE OCCURRENCE RATE OF BH-HMXBs IS A DECREASING FUNCTION OF METALLICITY



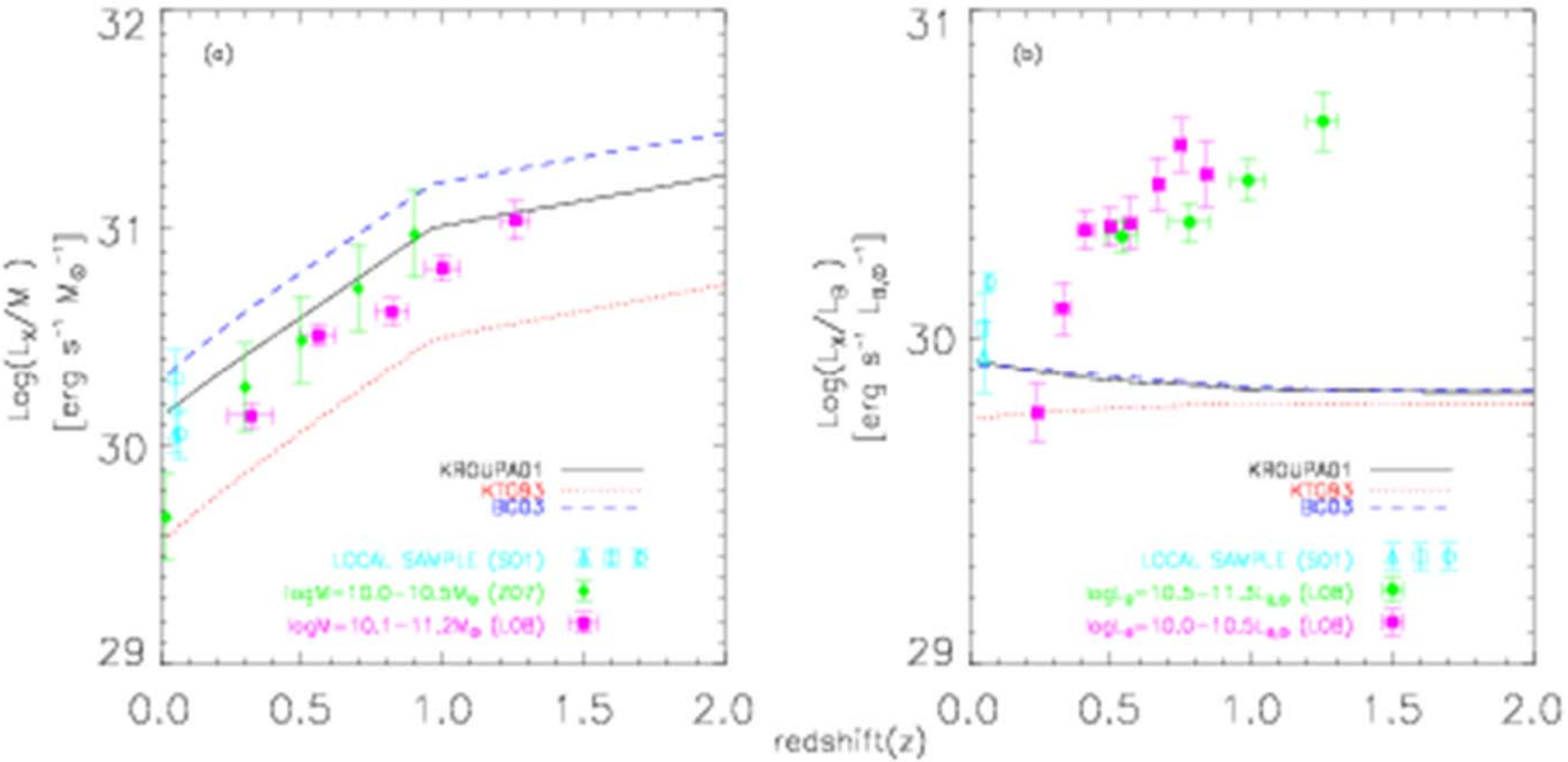


Fan et al 2006

L_X/L_B for late type galaxies as a function of z

Late type galaxy sample within the Chandra Deep Field with HST morphology

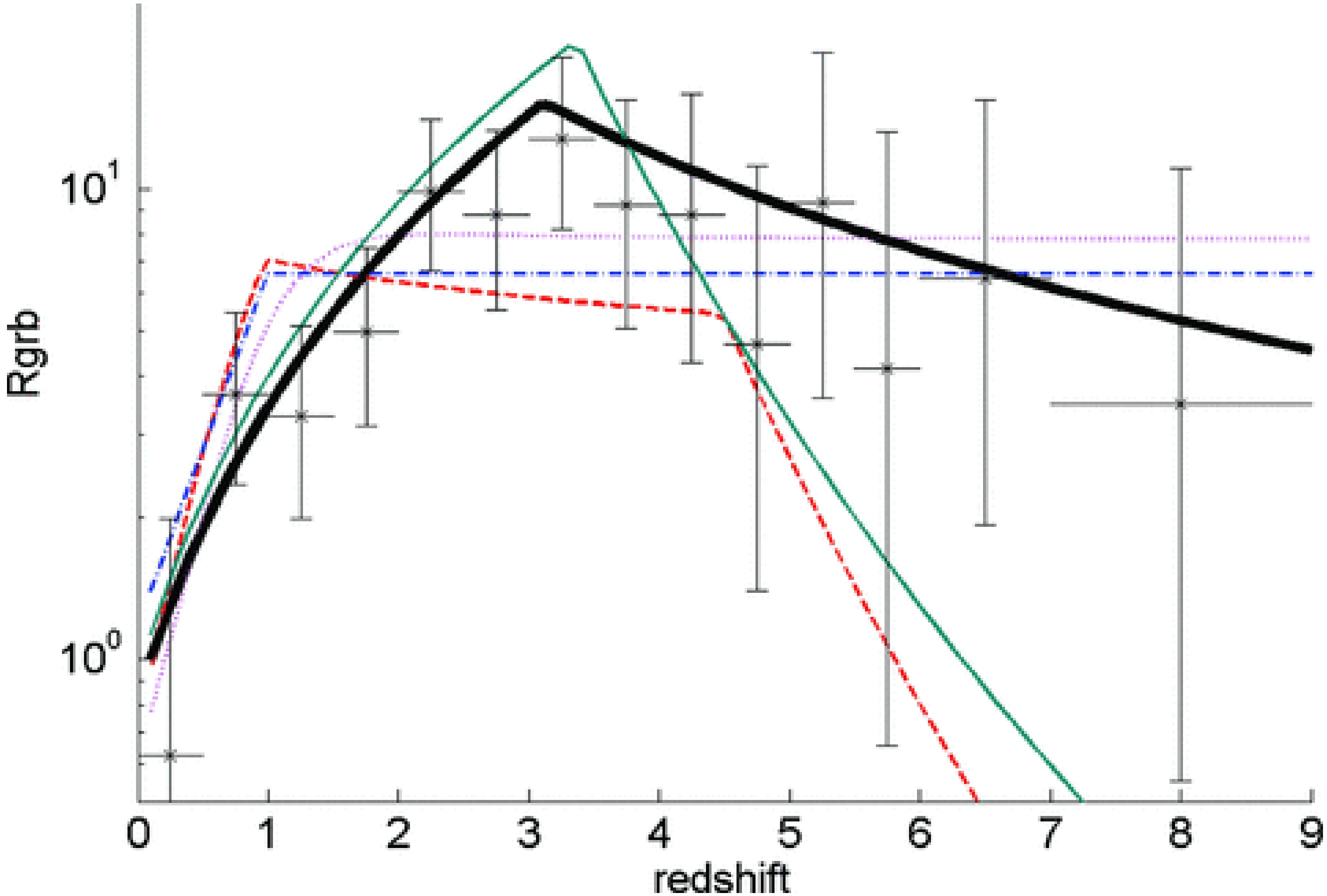
Zuo et al. (2010)



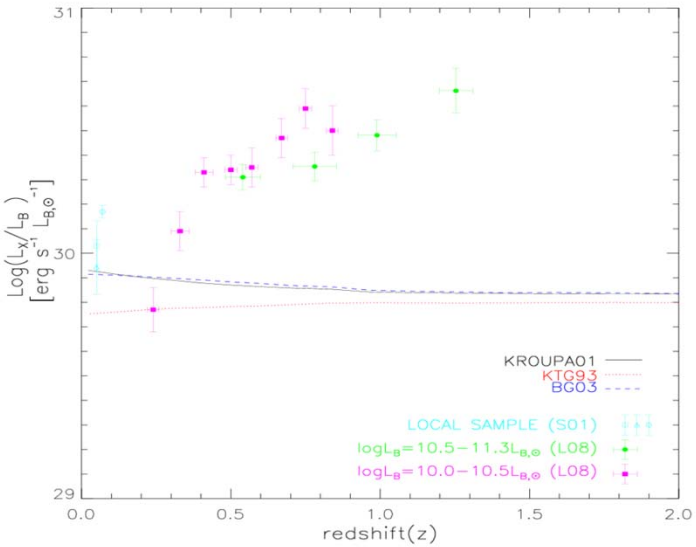
Due to dust absorption or to evolution of metallicity & SFR?

There are evidences for enhanced LGRB rates at z>3 than expected from star formation measurements

(e.g. Daigne+ 2006; Kistler+ 2008; Wanderman & Piran, 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.



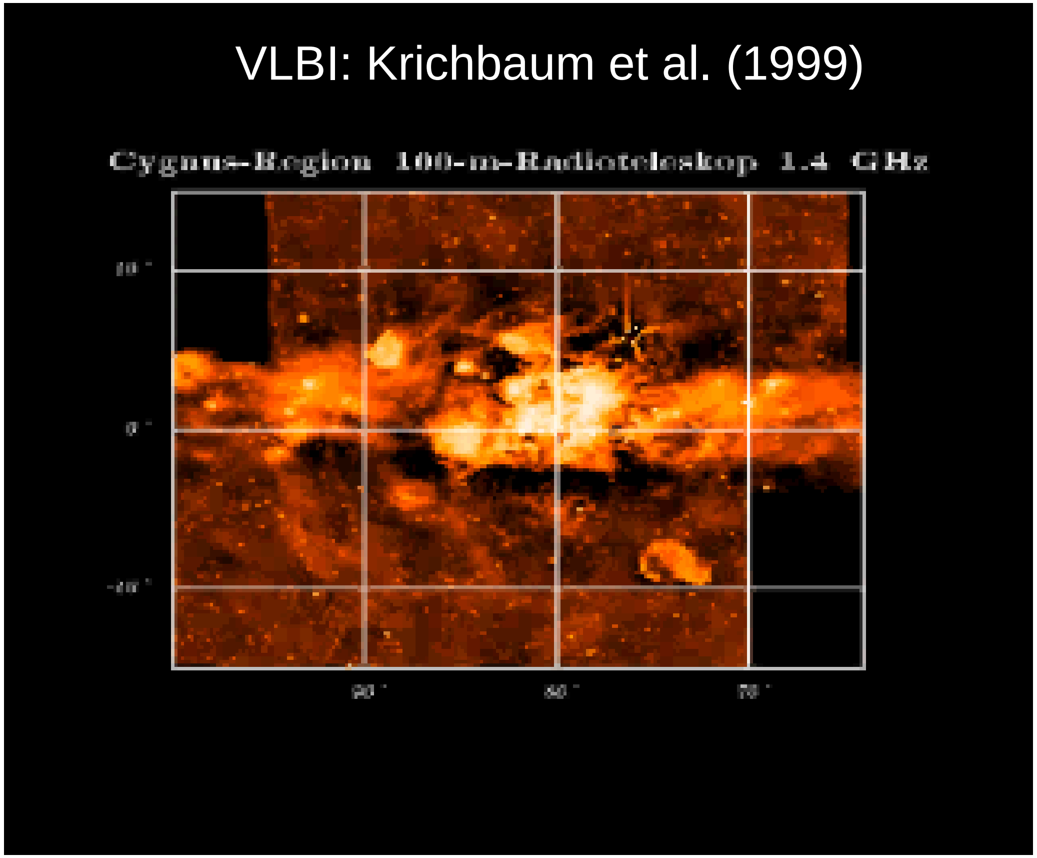
Magnetic Fields in Massive Stars, their Winds, and their Nebulae

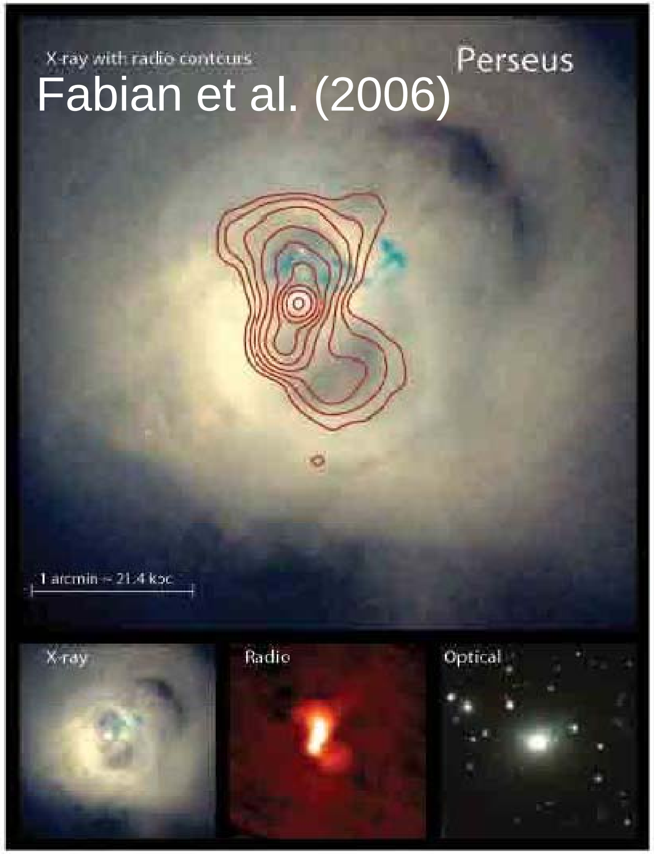
Rolf Walder · Doris Folini · Georges Meynet

« Surface metallicities may

become enhanced, thus affecting the mass-loss rates.”

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

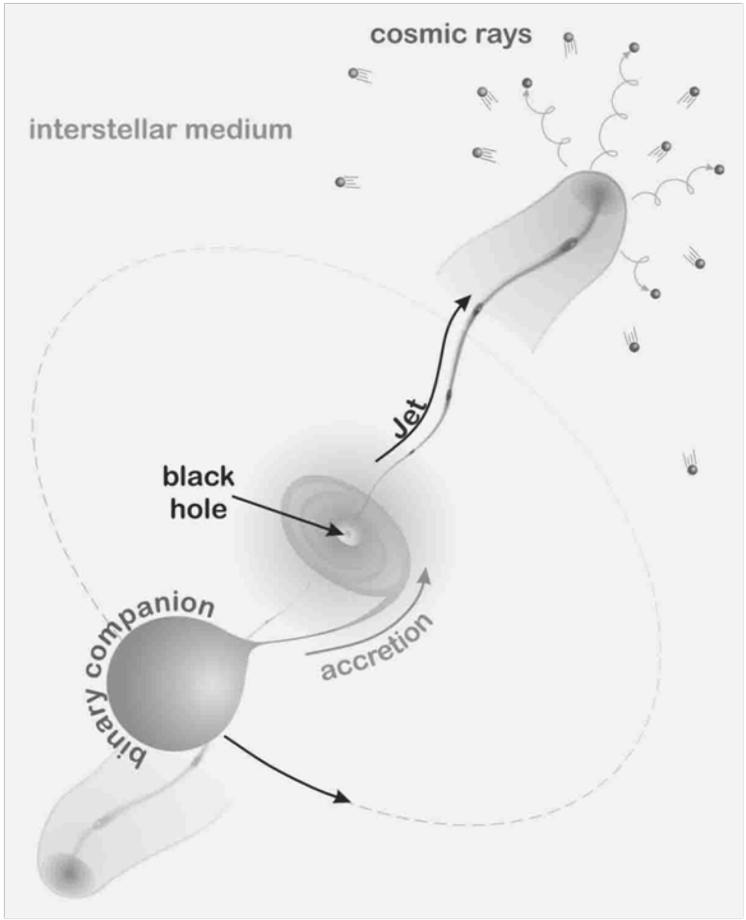
Could feedback (radiation & jets) from stellar black holes reconcile the apparent discrepancies of the observations with the predictions of the CDM?

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

IN ADDITION:
COULD THIS LARGE POPULATION OF BH-BINARIES BE IMPORTANT SOURCES OF GRAVITATIONAL WAVES ?


cosmic rays
interstellar medium
Jet
black
hole
binary companion
accretion