HIGH ENERGY SOURCES IN THE RE-IONIZATION EPOCH:

Stellar Black Holes: Microquasars

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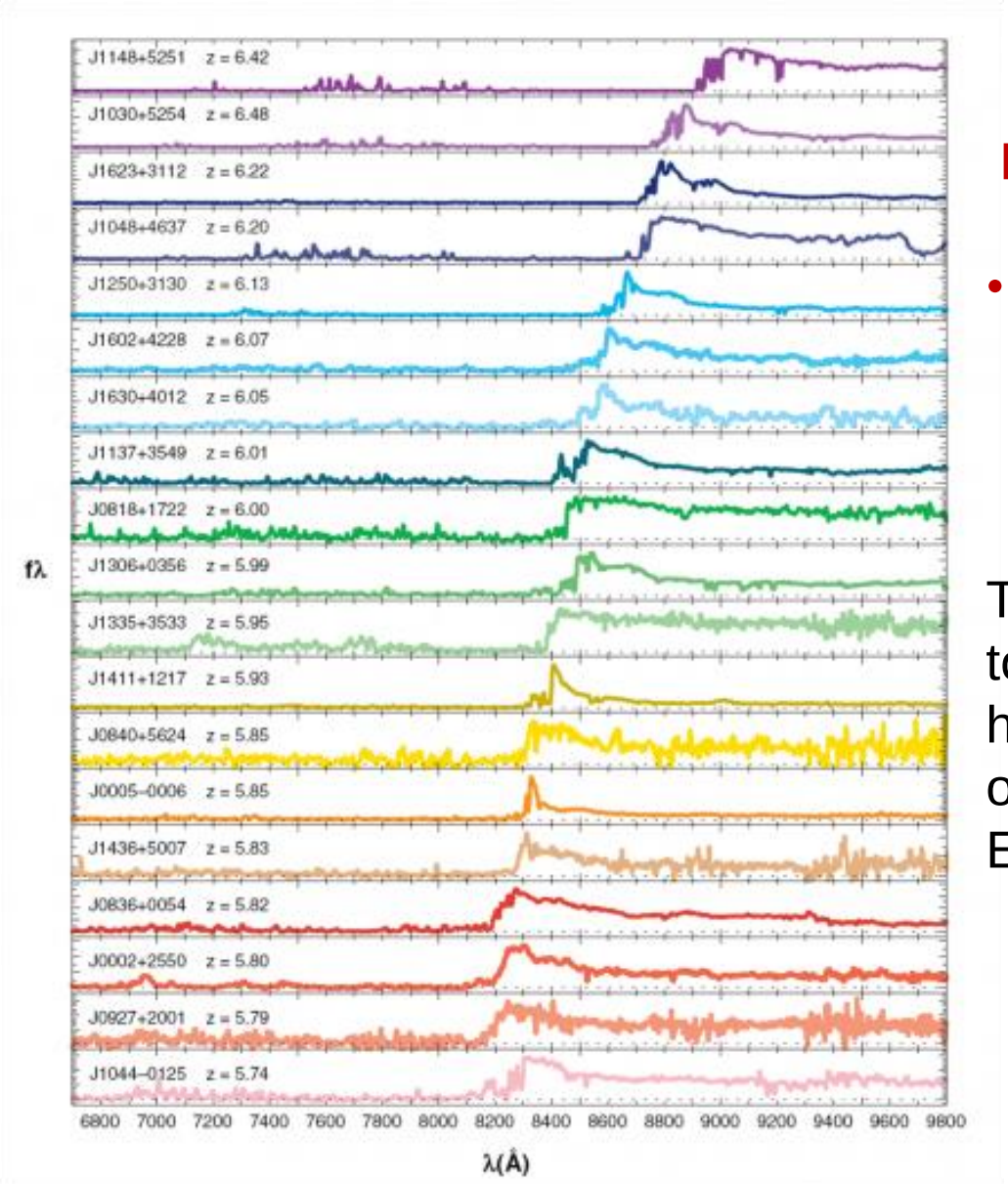
At the crossroads of Stellar Evolution, High Energy Astrophysics & Cosmology

Gunn-Peterson effect



EVIDENCE FOR THE DARK AGES

- **No light (continuum radiation) is observed at wavelengths less than Lα because it is fully absorbed by atomic hydrogen.**

The **Gunn–Peterson trough** is due to the presence of neutral hydrogen in the IGM. This effect was originally predicted in 1965 by James E. Gunn and Bruce Peterson

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.

- **ROLE OF HIGH ENERGY SOURCES (AGN, SNe, LGRBs, XRBs)?**

  Based on recent results from stellar evolution and high energy astrophysics:

- **Proposal: In galaxies at z>10 a large fraction of Pop III-II stars end as StBHs in HMXBs ⇒ important feedback in the form of X-rays & jets**

- **X-rays overtake the HII regions produced by UVs, heating and partially ionizing the IGM over large volumes of space.**

ASTROPHYSICAL GROUNDS FOR THE STELLAR BLACK HOLE HYPOTHESIS

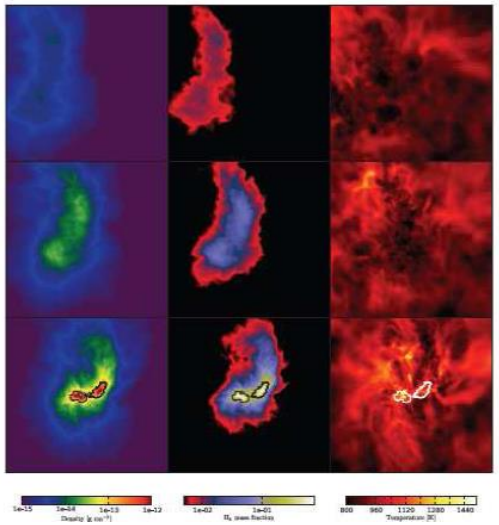
THEORETICAL GROUNDS

- **MOST POP III & II STARS WERE FORMED AS MULTIPLE SYSTEMS**
  Turk+Science 2009; Krumholz+ Science 2009; Clark+ Science 2011; Stacy+…etc.
- **STARS OF LOW Z WITH M > 20 $M_{\odot}$ END AS BHs DIRECTLY**
  Fryer,1999;Heger+2003;Georgy+2009;Woosley+2008;Nomoto+2010; Linden,Kalogera+2011
- **NO ENERGETIC SNe ⇒ STELLAR BHs REMAIN BOUND TO DONORS**
  Mirabel & Rodrigues, Science 2003; Mirabel+ Nature 2008

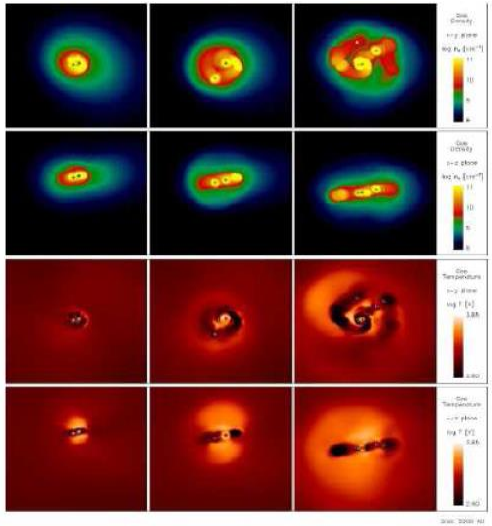
OBSERVATIONAL GROUNDS

- **MOST ULXs & LGRBs ARE HOSTED IN LOW Z-HIGH-SSFR GALAXIES**
  Feng & Soria,2011;LeFloc'h,Duc,Mirabel;2003;Fruchter+ Nature, 2006; Perley+ 2014
- **Lx/SFR EVOLUTION WITH z IS DRIVEN BY Z EVOLUTION IN HMXBs**
  Fragos+2012; Basu-Zych+2012
- **IN LOW Z GALAXIES Lx/SFR IS LARGER THAN IN MAIN-S GALAXIES**
  Thuan+ 2004; Kaaret+ 2014; Douna, Pellizza, Mirabel, 2014 (in progress)

MOST POP III & II WERE FORMED AS 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 $M_\odot$**

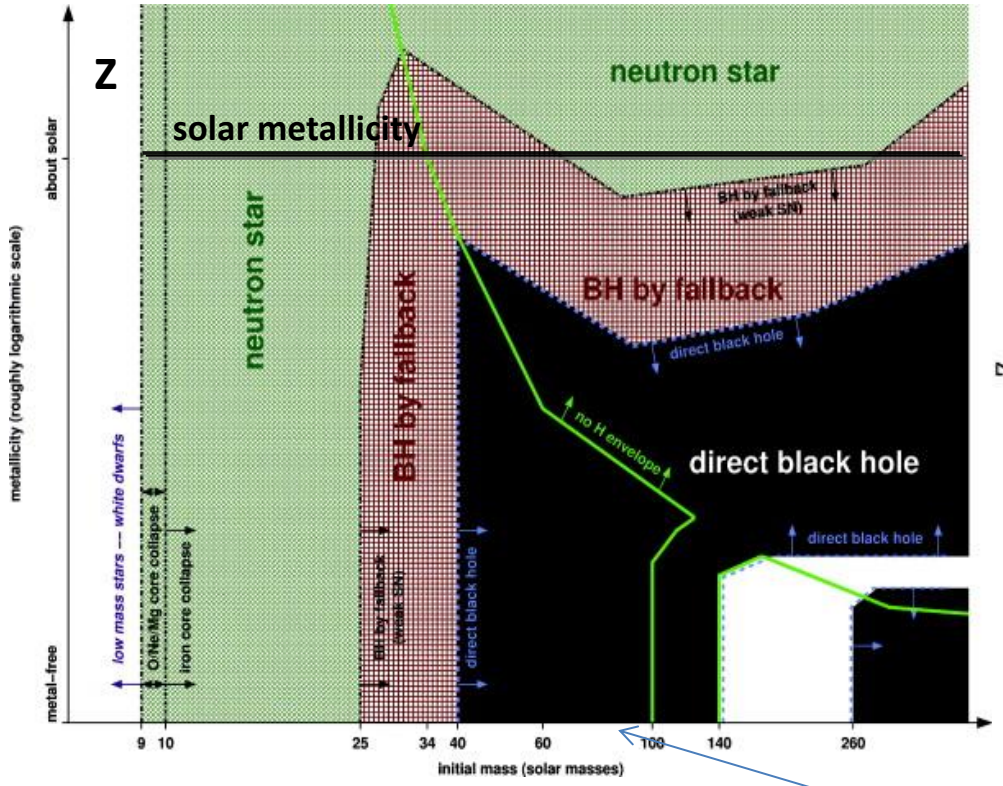
OBSERVATIONS

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

DID A LARGE FRACTION OF Pop III & II BINARIES END AS BH-HMXBs?

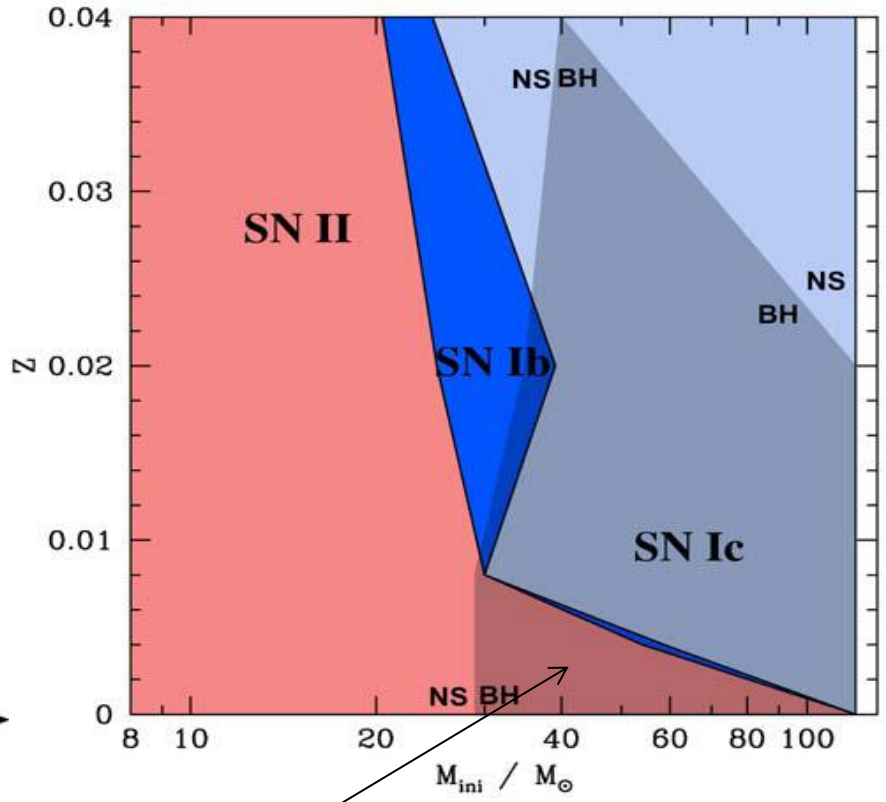
MASSIVE STARS OF LOW Z END DIRECTLY AS BHs

with no rotation (Heger+ 2003)



Mass of progenitor star

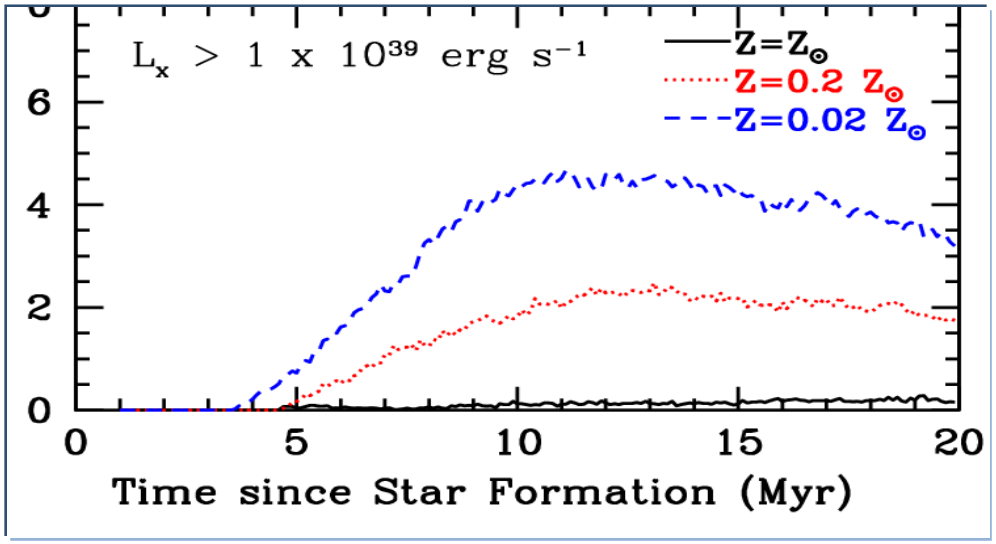
with rotation (Georgy+ 2009)

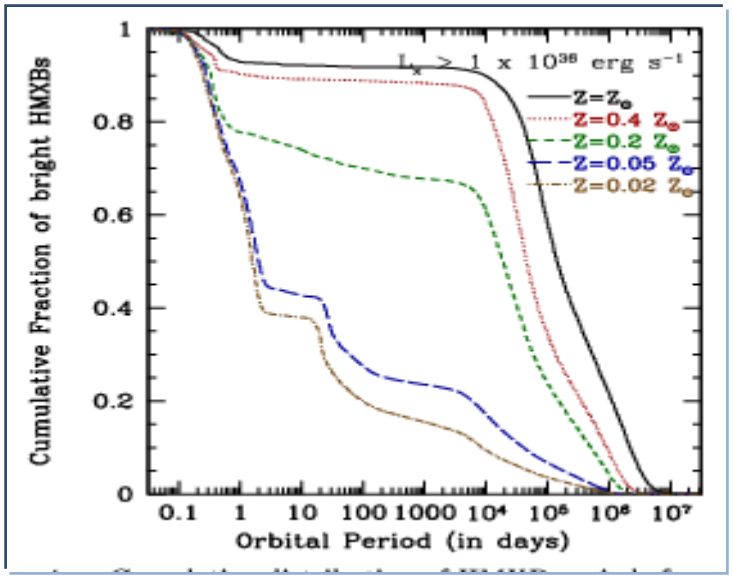


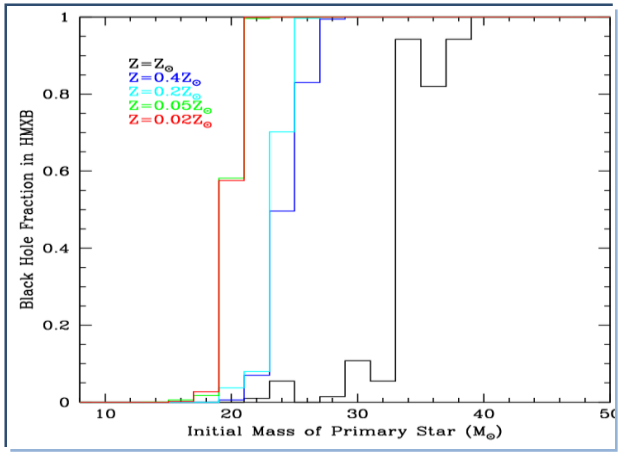
- Low metal progenitors form BHs by IMPLOSION (e.g. Fryer, 1999)
- The formation of BHs in binaries is metallicity dependent (Linden, Kalogera+ 2011)

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

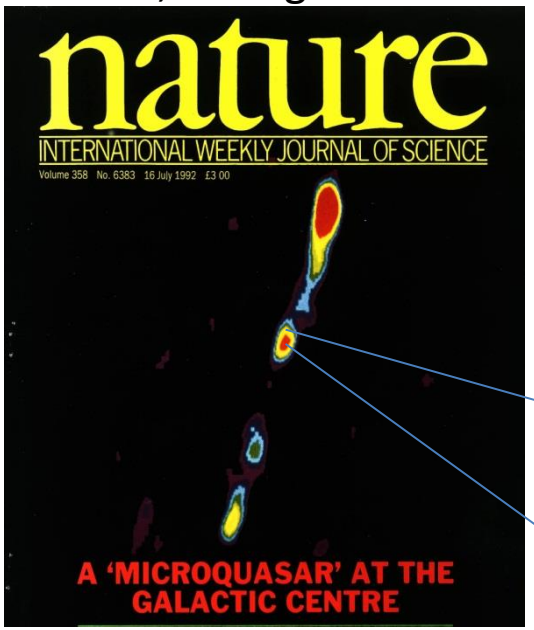
What observations can be used to test these theoretical predictions?

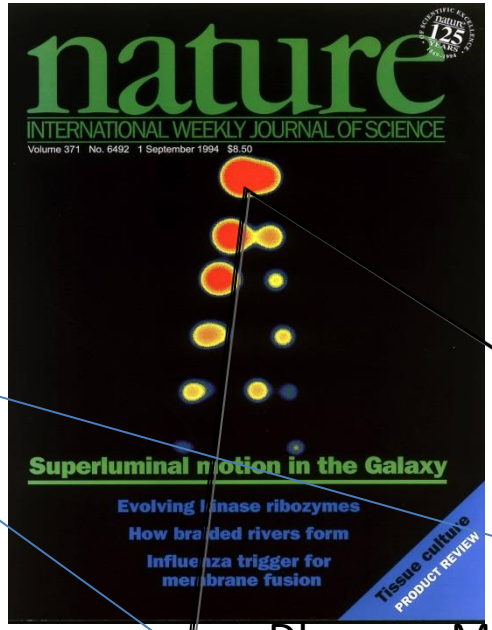
KINEMATICS OF BLACK HOLE μQSOs to test the direct formation of StBHs

Mirabel, Rodriguez+ 1992

Mirabel & Rodríguez 1994

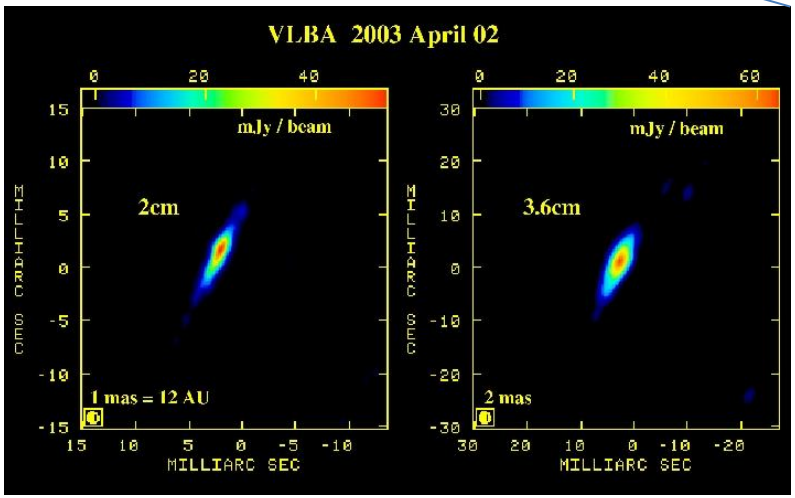
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

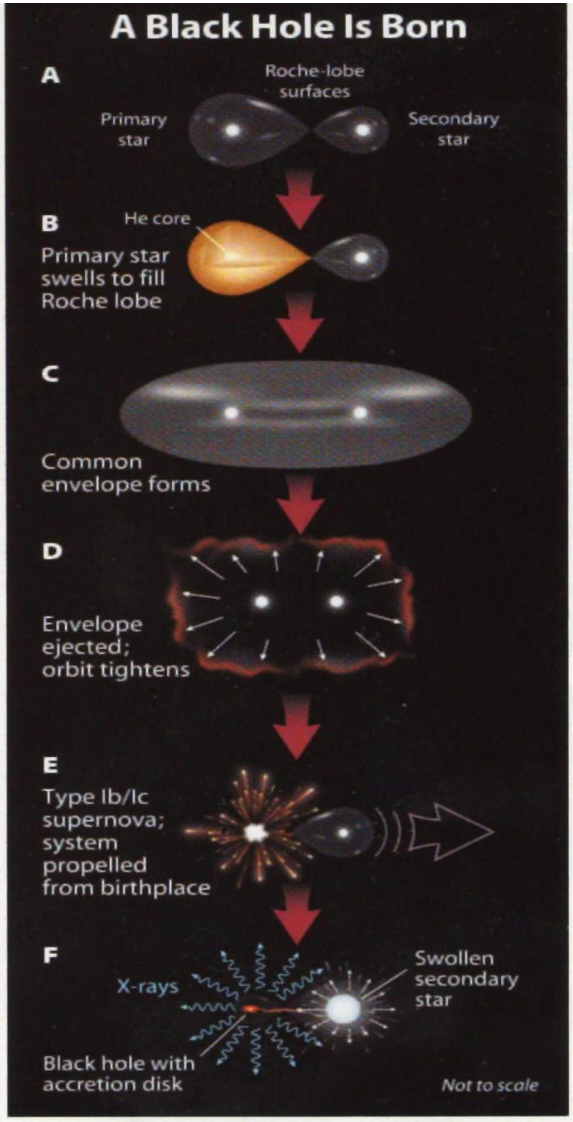
In low hard state. Size ~ 100 AU. Same PA

USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

BHs OF >10 $M_\odot$ FORM BY DIRECT COLLAPSE

APPROACH BASED ON THE KINEMATICS (Mirabel & Irapuan Rodrigues 2001-2009)

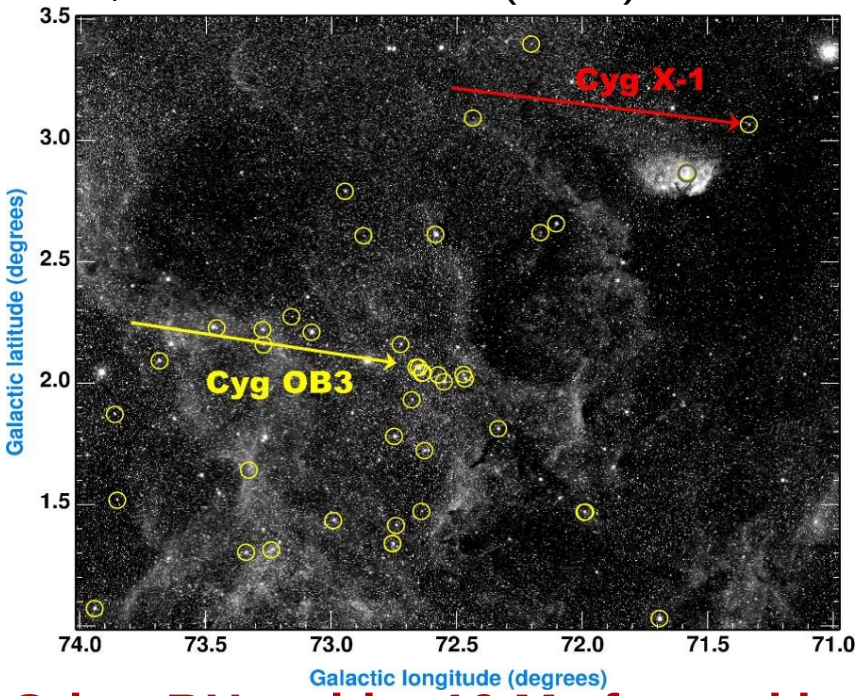


Sky & Telescope

THE BH IN Cyg X-1 WAS FORMED IN THE DARK

Mirabel & Rodrigues (Science, 2003)

Gou, McClintock et al. (2012) confirmed this result



Cyg X-1 remained in its birth place

V_p < 9 +/- 2 km/s

$\Rightarrow$ < 1 $M_\odot$ in SN

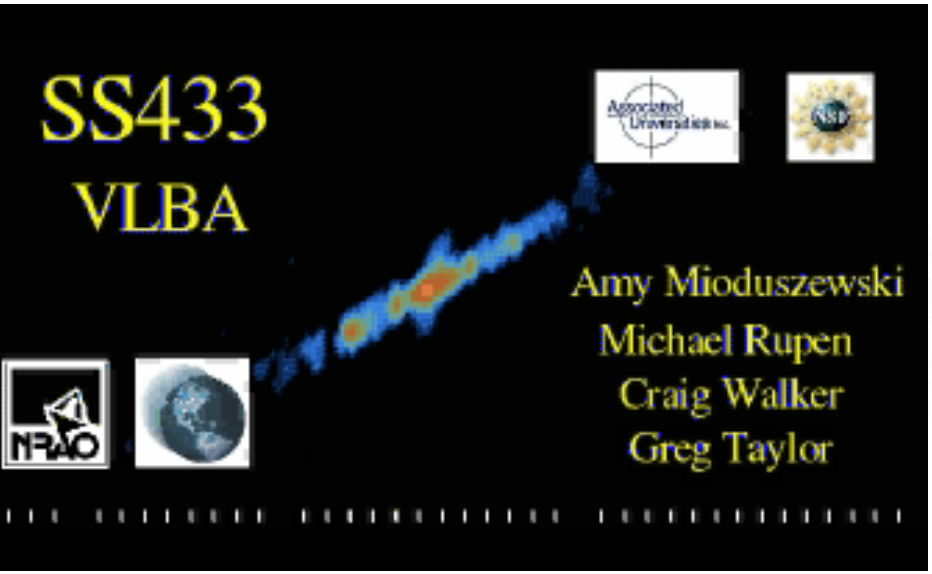
Other BHs with >10 $M_\odot$ formed by direct collapse:

GRS 1915:**W=7+/-3 km/s** (Dhawan,Mirabel,Rodríguez,01)

V404 Cyg:**W=0.2+/-3 km/s** (Miller-Jones et al. 2009)

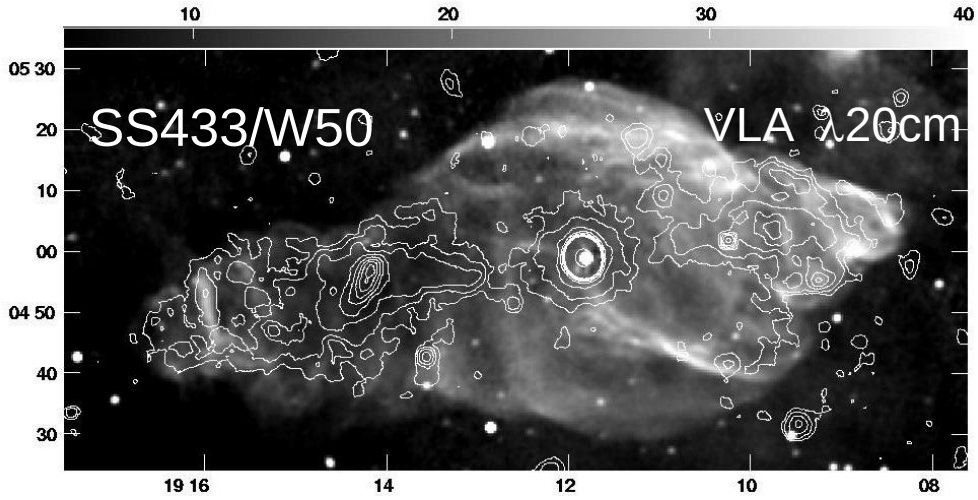
The BHs remain bound to donors

POWERFUL JETS FROM HMXBs (μQSOs)



1arcsec

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



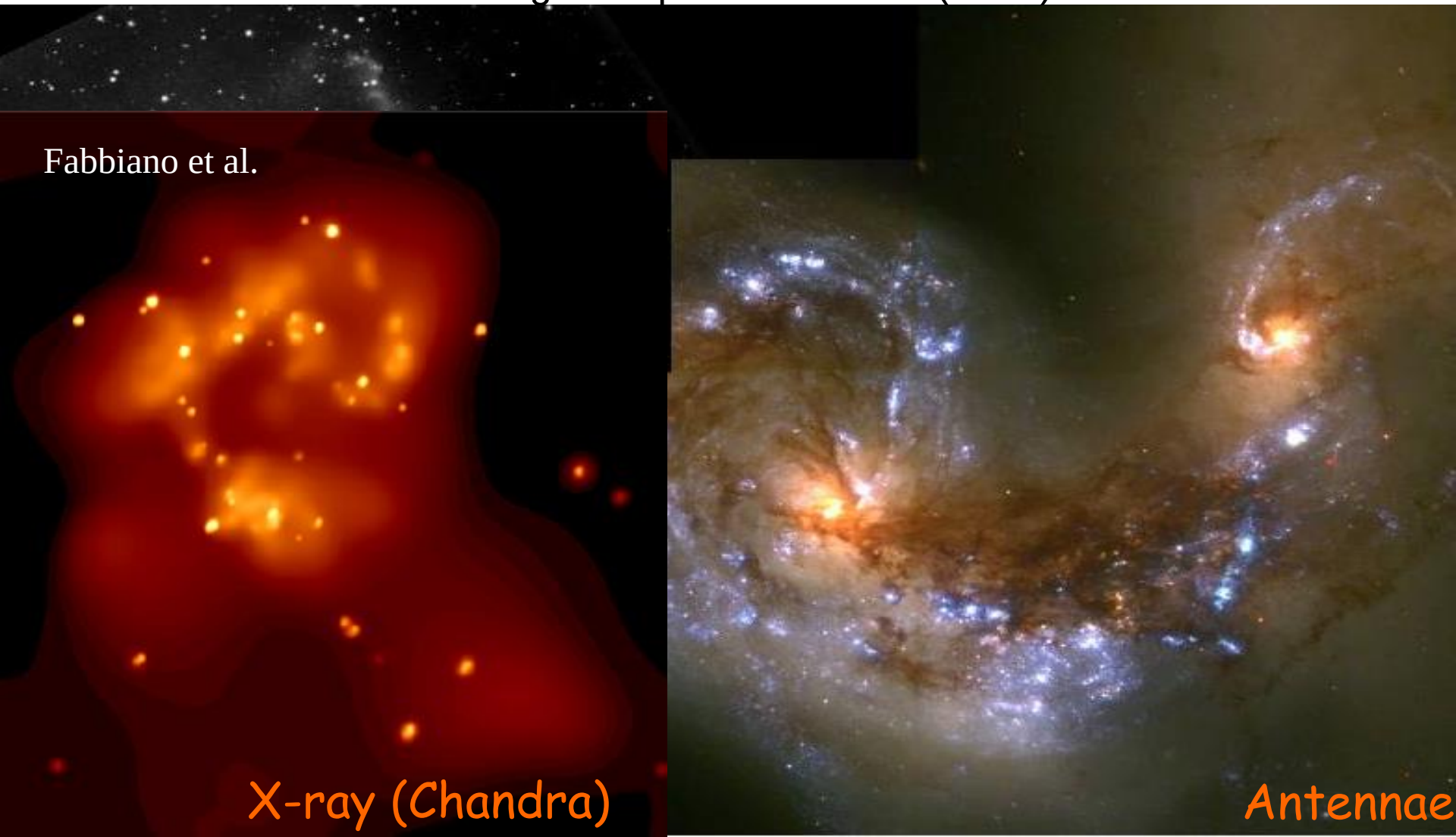
1^{o} = 60 pc

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

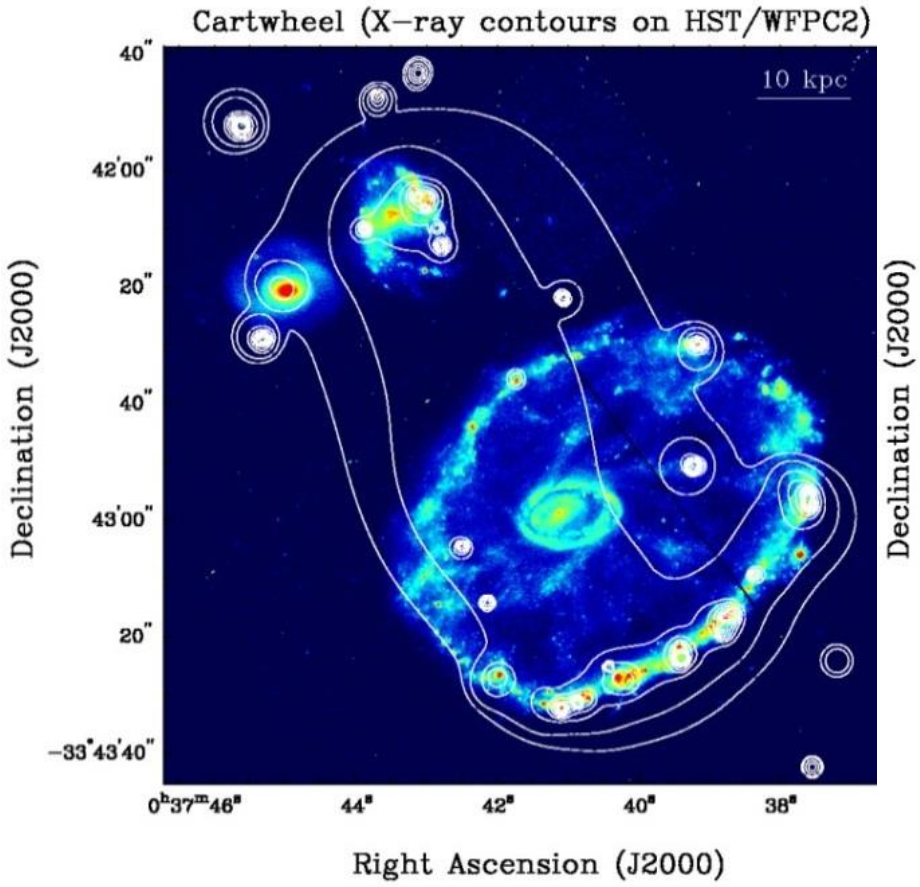
ULTRALUMINOUS X-RAY SOURCES (ULXs=HMXBs)

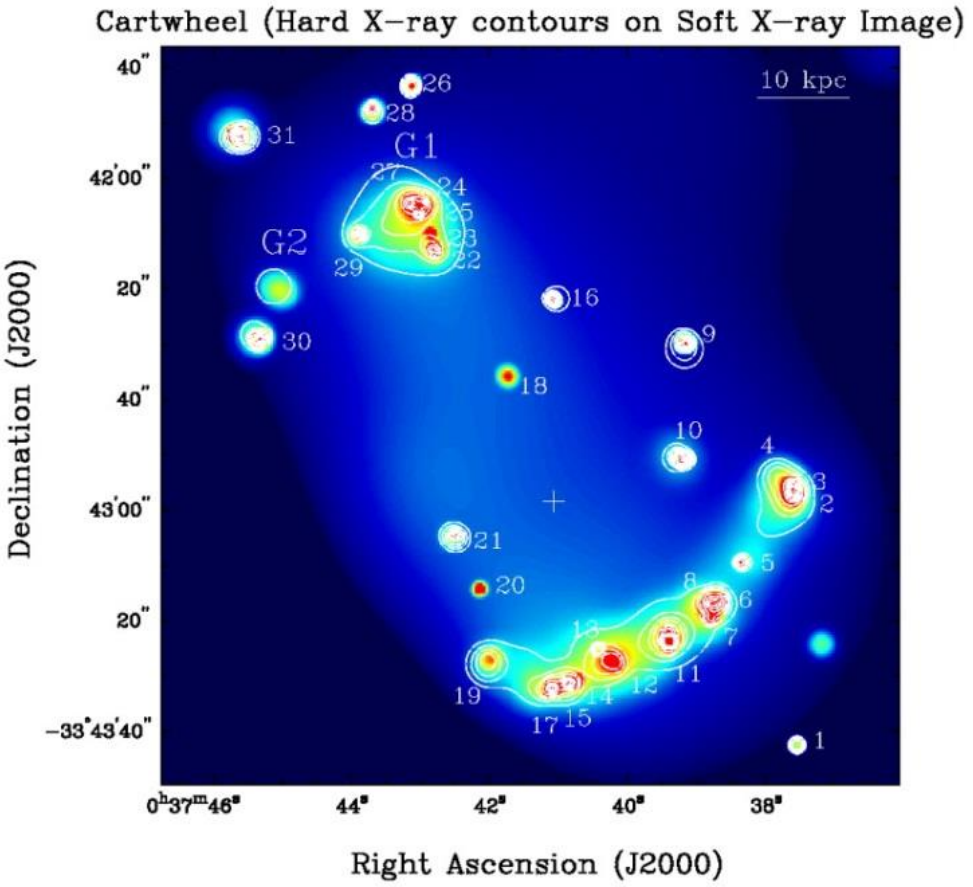
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS INCREASES WITH THE SFR AND DECREASES WITH METALLICITY

e.g. Zampieri & Roberts (2009)



ULXs IN “TEMPLATES” OF z>6 GALAXIES





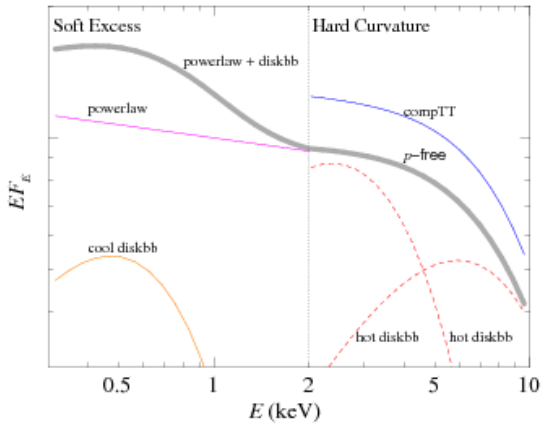
The integrated ULXs luminosity of ~10^{42} erg s^{-1} rivals that of AGN

(Gao+ 2003)

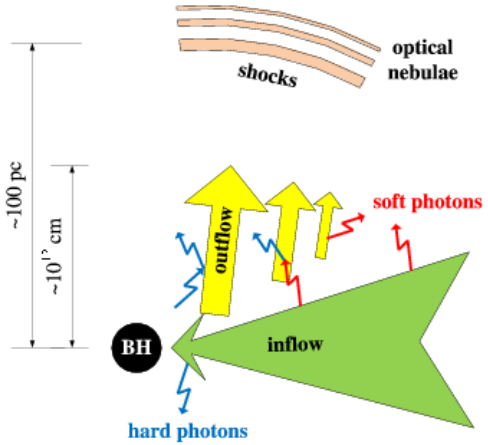
ULXs ARE FOUND IN LOW Z GALAXIES

MOST ULXs ARE BH-HMXBs SOMETIMES WITH HII BUBBLES

e.g. In the best local templates of primeval galaxies the specific BH-HMXBs formation is high

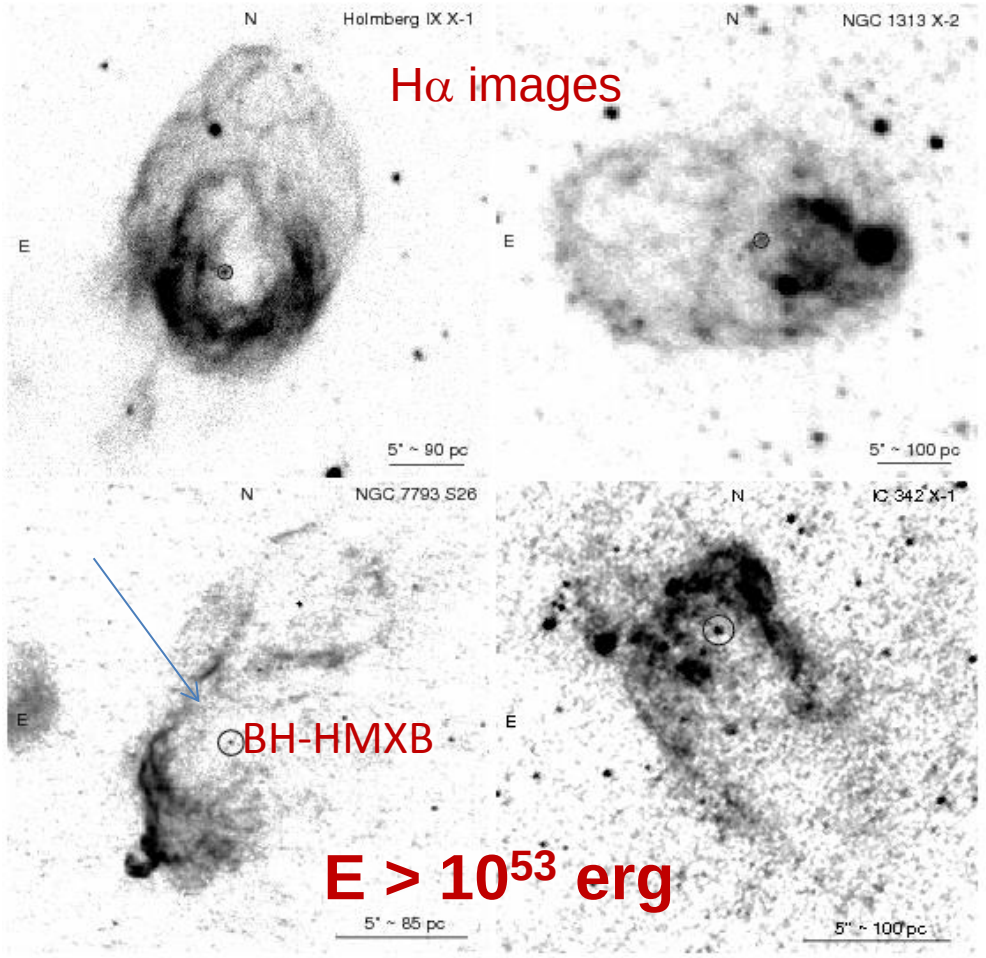


Massive outflows



From Feng & Soria (2011)

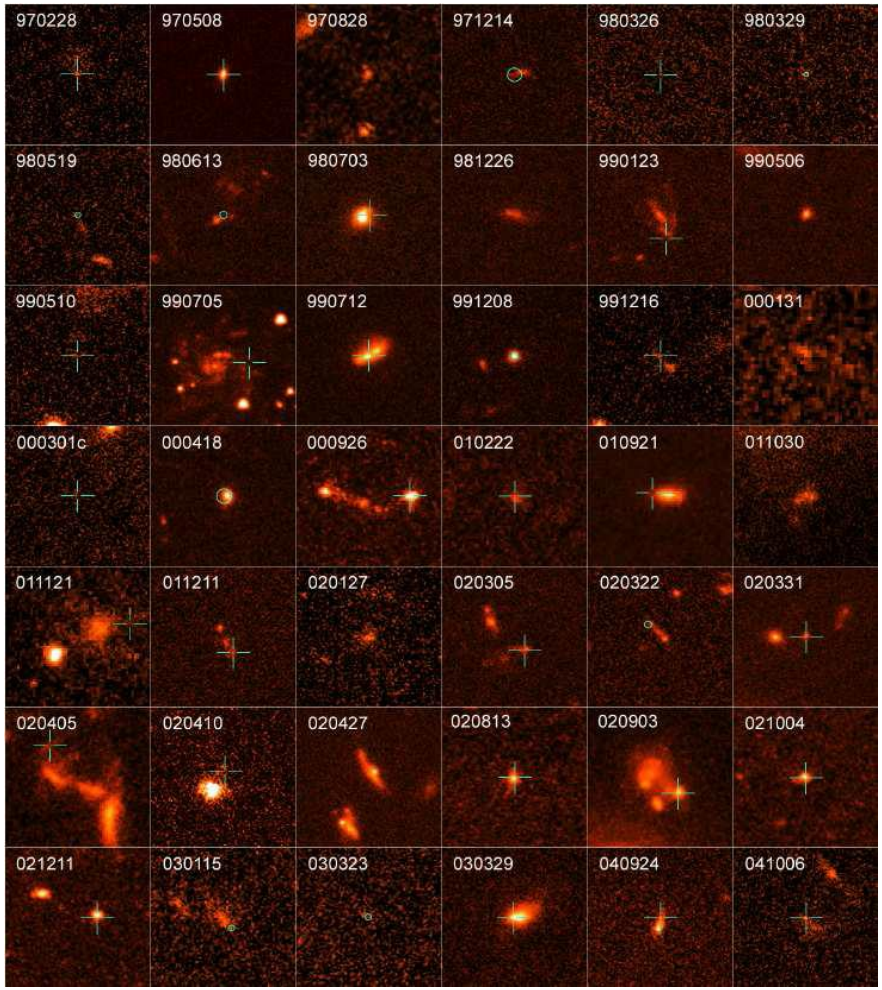
shock & photonionized bubbles of > 100 pc size



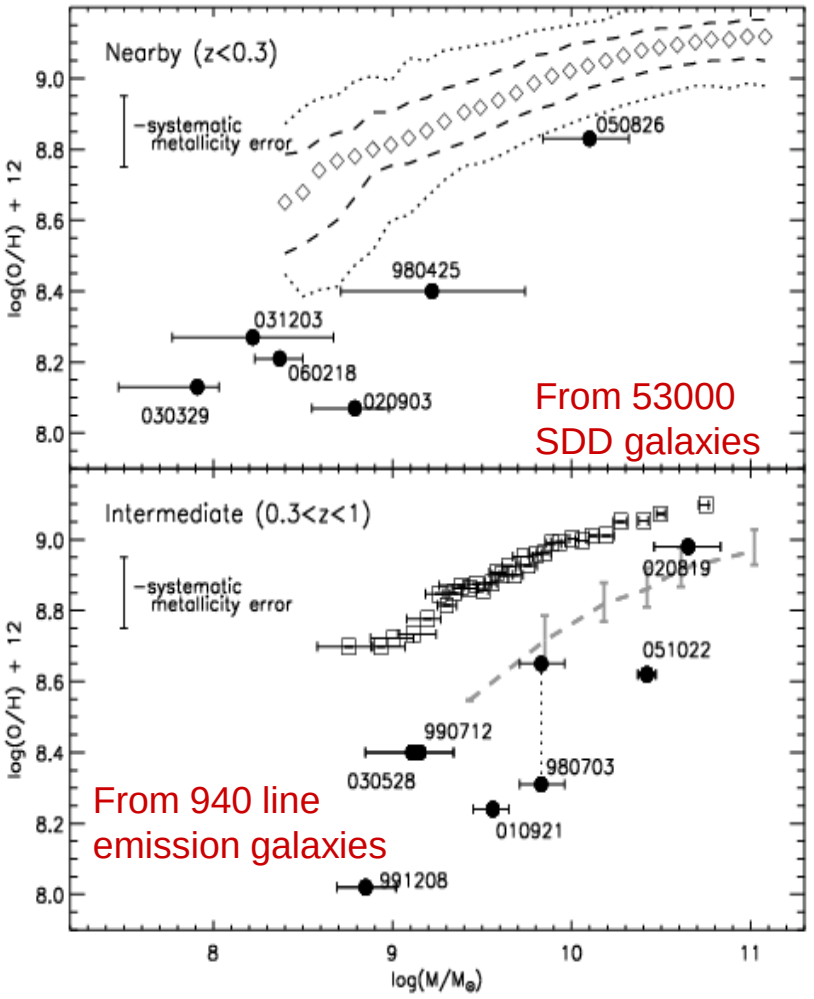
THE HOSTS OF LGRBs WITH OPTICAL AFTERGLOWS ARE SMALL IRREGULAR GALAXIES OF LOW Z

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

Fruchter + with HST (Nature, 2006)



Levesque et al. (2010)



However, dark LGRBs may pose some caveats & controversy

FROM STUDIES OF HMXBs IN LOCAL UNIVERSE IT IS INFERRED

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 mass** of stellar BHs because the progenitor cores are more massive
- **The number** of BH-HMXBs since massive stars form BHs by direct collapse
- **The X-ray luminosity** of BH-HMXBs…an issue to be investigated further.

Mirabel. Invited Review. Proceedings of IAU Symp. 275 (2011)
(arXiV:1012.4944v1 [astro-ph.CO] 22 Dec 2010)

Ionization by BH-HMXB vs massive star

Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 2011) ⇒ N&V in Nature (2011)

Counting photons

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

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

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

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

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

For fiducially values of the model parameters:

AN ACCRETING STELLAR BLACK HOLE EMITS A NUMBER OF X-RAY PHOTONS COMPARABLE TO THE UV PHOTONS FROM ITS PROGENITOR STAR

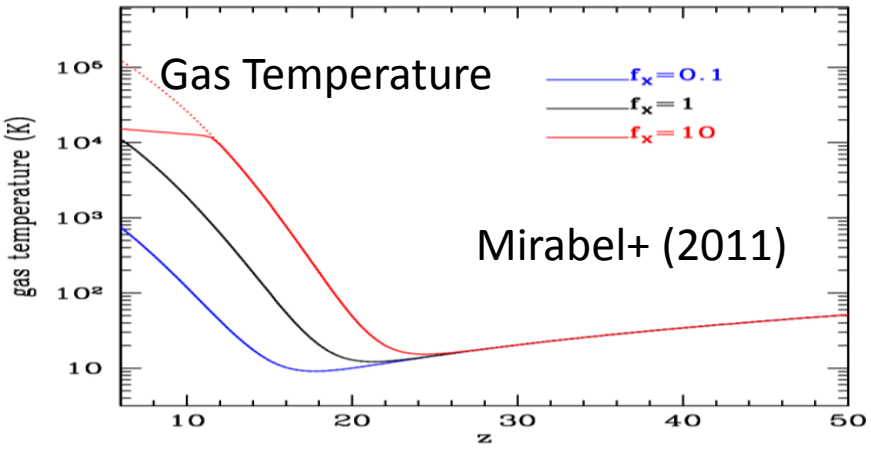
- But in a fully neutral medium **N_{sec*} = 25 (E_γ /1 keV),** where E_γ is the photon energy

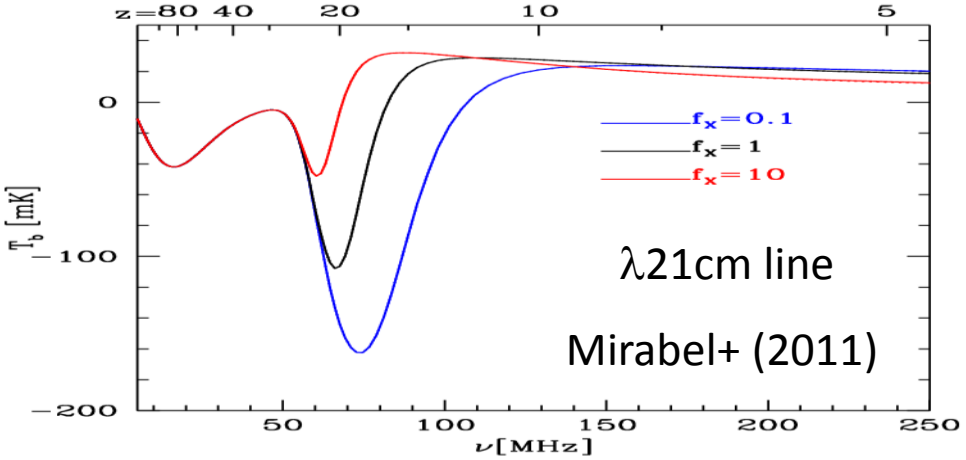
However, not all stars will be massive and lead to the formation of BH-HMXBs…

HMXBs & HI TOMOGRAPHY DURING THE EoR

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

f_x at z > 6 must increase as $Z < 10^{-5}\ Z_\odot$

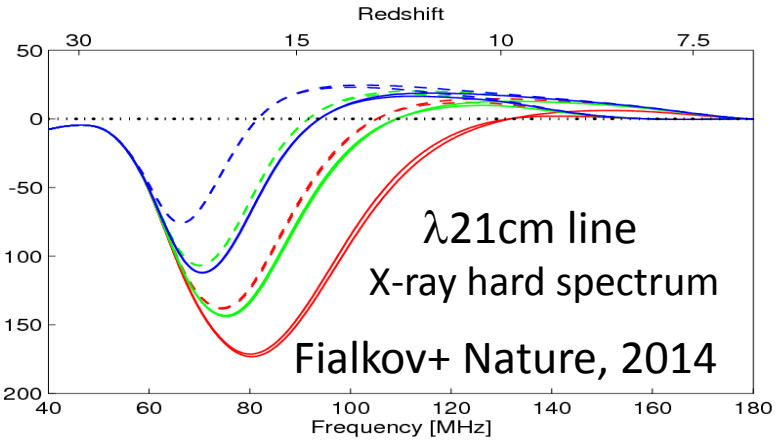




BH-HMXBs HEATED THE IGM TO ~10^4 K OVER LARGE VOLUMES

CONCLUSION:

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.

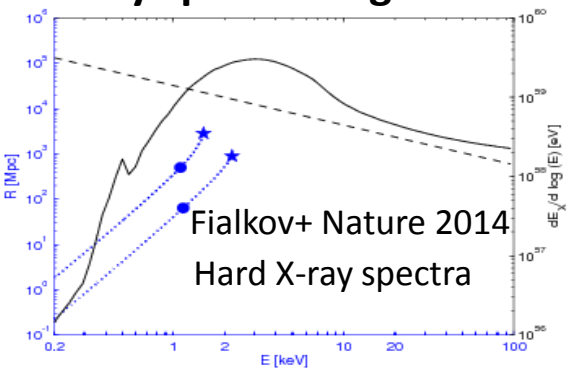


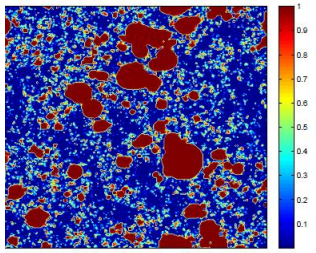
The λ21cm tomography of HI with LOFAR, SKA, etc. may reveal a smoother end to the dark ages depending on the SED of HMXBs

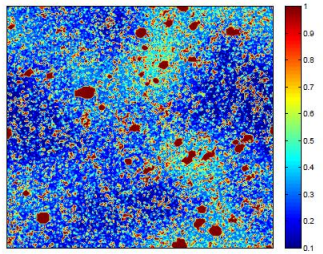
X-rays=0 ⇒ large fluctuations. X-rays=50% ⇒ lower fluctuations but at shorter λs

(Visbal & Loeb, 2011; Fialkov+ Nature 2014)

X-ray spectra of galaxies



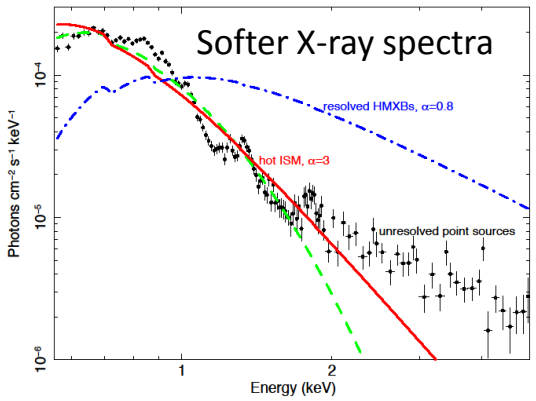


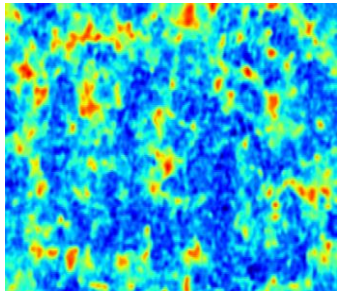


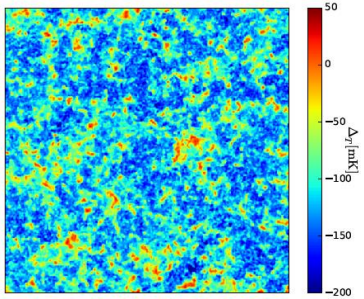
UVs vs UVs+X-rays.
HMXBs with hard spectra

Slice of 170×170×0.66 Mpc^3

Pacucci et al., 20014







HMXBs + soft X-rays ⇒
Larger fluctuations

Slice 1.5 Mpc at z_{peak} = 16

hard (right) and soft (left) X-ray SED

X-RAY IMPACT ON FIRST STARS & GALAXIES

- **THE DOMINANT POP III STARS HAVE MASSES OF 3-30 $M_\odot$**

  (Hummel, Stacy, Jeon, Oliveri, Bromm, 2014)

  For n < 1 cm^{-3} X-ray heating dominates & enhance the formation of H2

  For n > 100 cm^{-3} H2 accelerates cooling, collapse & fragmentation

- **DWARF GALAXIES WITH <10^9 $M_\odot$ COULD NOT FORM**

  Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 2011)

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

  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

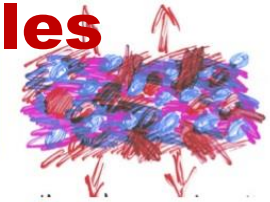
- **THE THERMAL HISTORY OF THE IGM DETERMINED BY X-RAYS FROM HMXBs LIMITED THE MASS OF POP III-II STARS & THE NUMBERS OF DWARF GALAXIES RELATIVE TO THE NUMBERS PREDICTED BY THE λCDM**

BLACK HOLES CONSTRAINT THE MASS OF GALAXIES

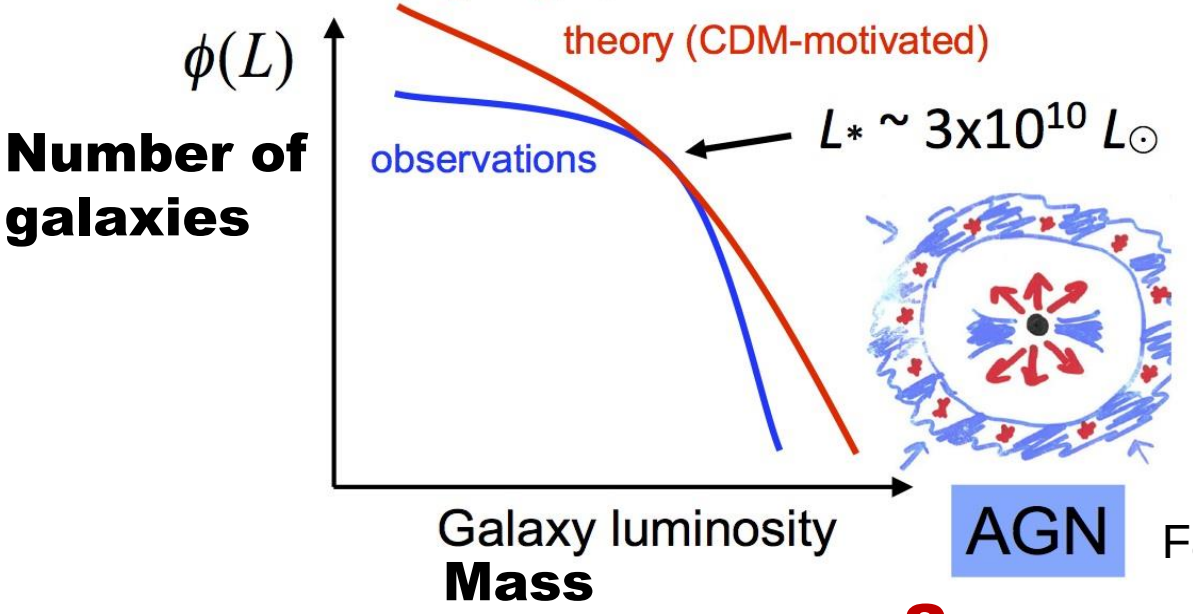
Stellar Black Holes

HMXBs

SN



Silk & Mamon, (2012)



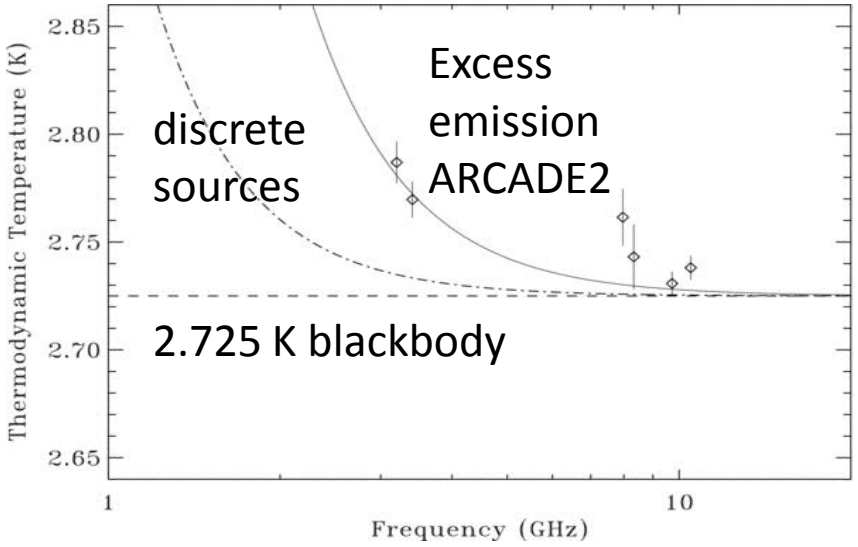
AGN

Fabian+ (2010)

Supermassive Black holes

OBSERVATIONS RELATED TO HMXBs?

- **COSMIC RADIO BACKGROUND WITH ARCADE 2**



(Fixsen+; Seiffer+ 2011)

VLA follow up by Condon+ (2012): The ARCADE 2 excess is smooth ⇒ **A new unexpected discrete-source population too numerous to be associated with bright galaxies**

- **He II IONIZATION AT z > 3.5** (Worseck+; Compostella+ 2014)

Absorption spectroscopy of the He II Lα line λ_{rest}=303.78°A ⇒ A radiation field with photons hν> 54.4 eV that **can not be provided by luminous QSQs**

ARE THE RADIO BACKGROUND & PHOTONS WITH hν>54.4 eV FROM A POPULATION OF HMXBs AT z>6 OR FROM SUPERMASSIVE BHs? (Biermann+2014)

IMPLICATIONS OF THE BH-HMXB HYPOTHESIS

- **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) Stellar mass BH-BH binaries may be the more likely detected sources of gravitational waves** (e.g. Belczynski+2011;Ziosi+2014)
- **IV) Feedback from AGN at the centre of clusters stop the unlimited growth of galaxies** (Fabian+); **feedback from stellar BHs reduce the λCDM predicted number of dwarf galaxies**
- **VI) There should be a population of naked dark matter haloes with M $<10^9$ $M_\odot$**