STELLAR BLACK HOLES AT THE DAWN OF THE UNIVERSE

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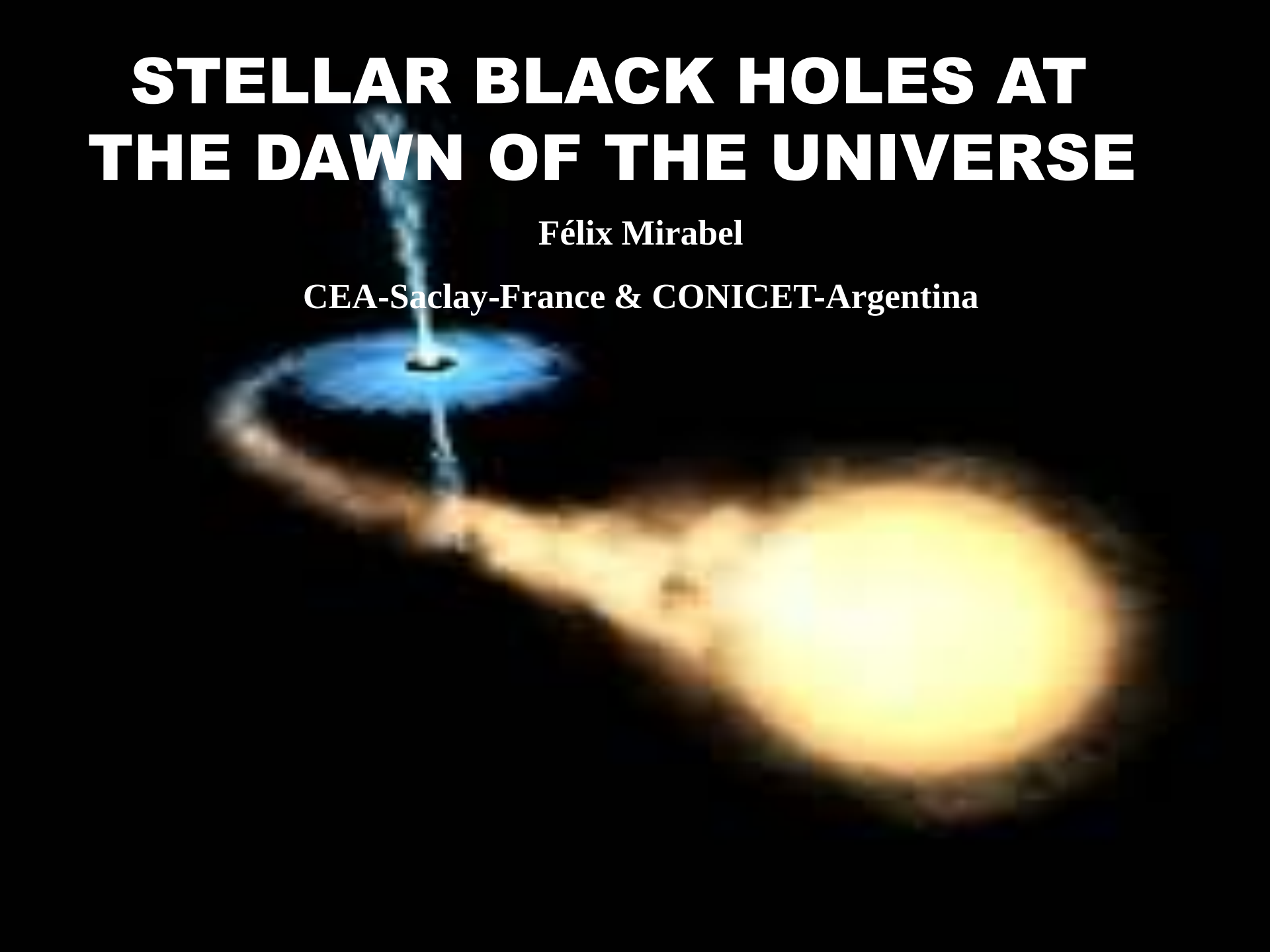
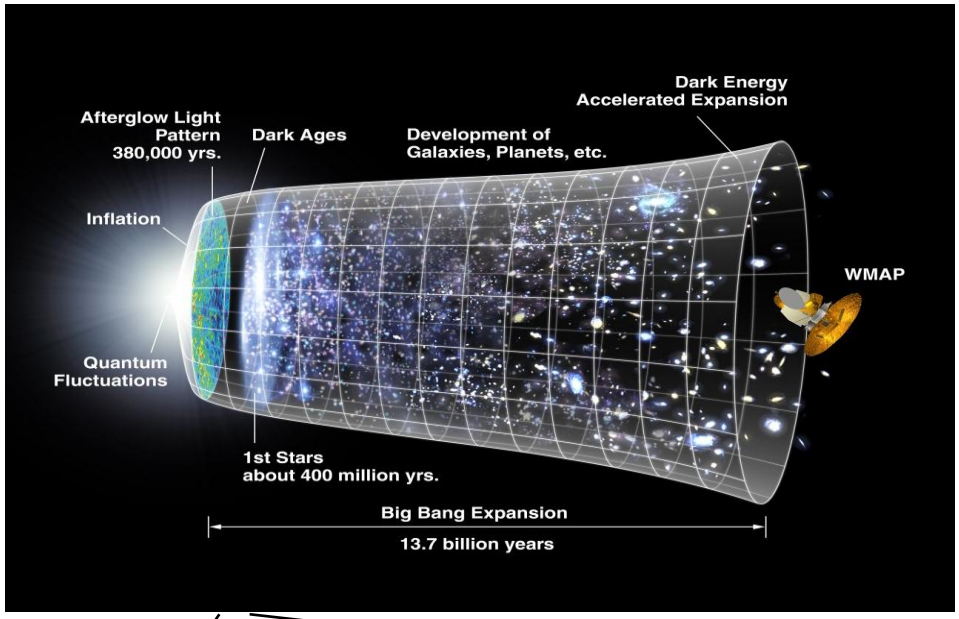
CEA-Saclay-France & CONICET-Argentina



THE « DARK AGES »: A MAJOR FRONTIER IN COSMOLOGY



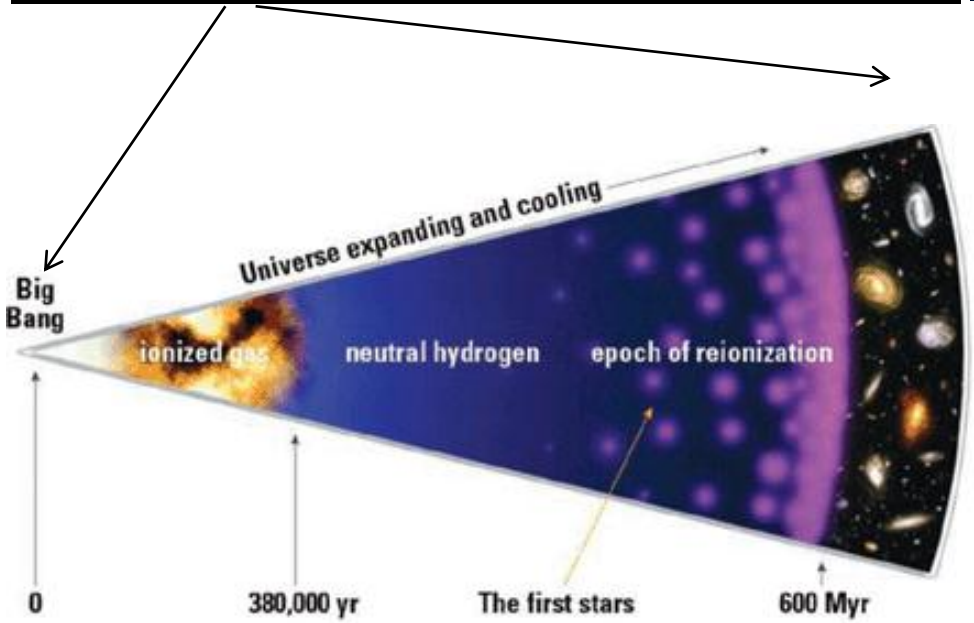
THE « SWISS CHEESE » MODEL

for the re-ionization of the IGM:

- The IGM was fully ionized by the UV from the first stars (Pop III & II) producing expanding Stromgrën spheres

A question of topical interest:

- What is the topology of the redshifted HI?



However, several observations suggest the possible existence of heating sources of the IGM at redshift z > 9

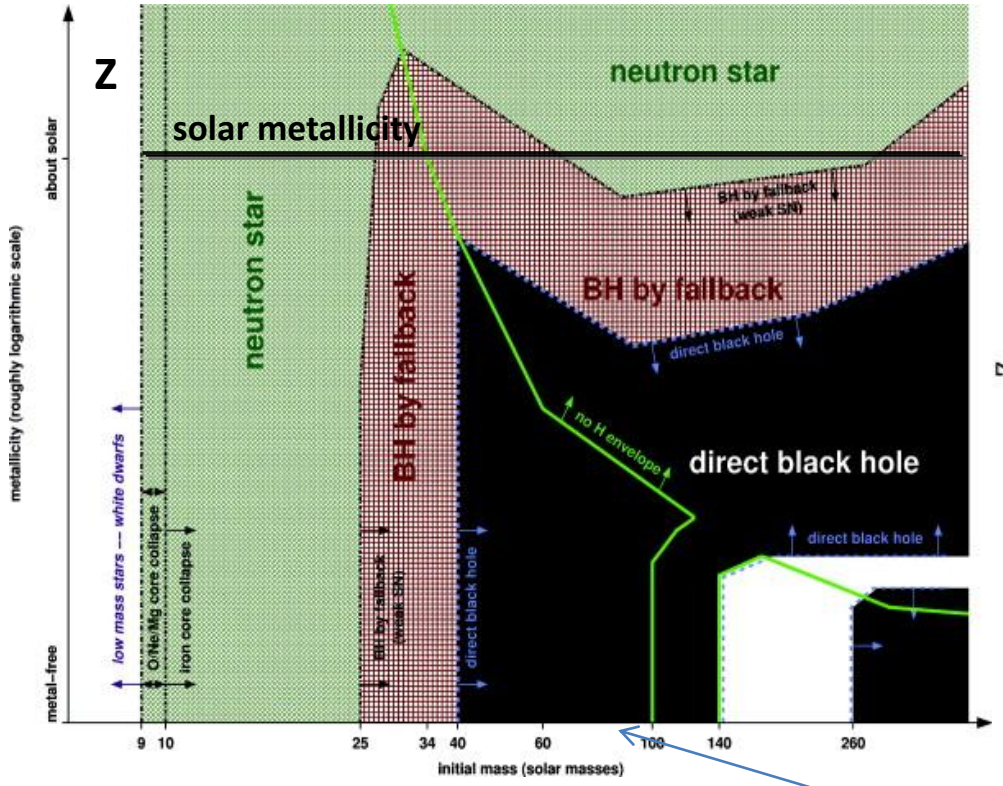
From recent results in Stellar Evolution, Galaxy Evolution, & High Energy Astrophysics and Cosmology

I propose that at z > 8 there has been a large population of Black Hole High Mass X-Ray Binaries (BH-HMXBs), which played an important role (different to “miniquasars” of Madau+).

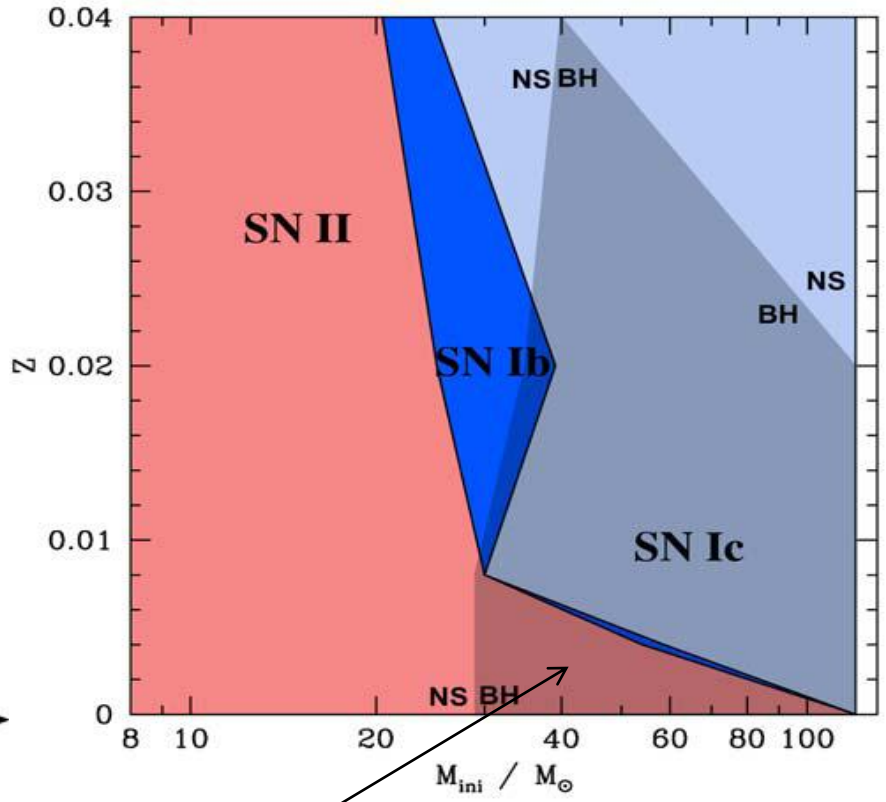
This hypothesis is based on models & observations:

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

with no rotation (Heger+ 2003)



with rotation (Georgy+ 2009)

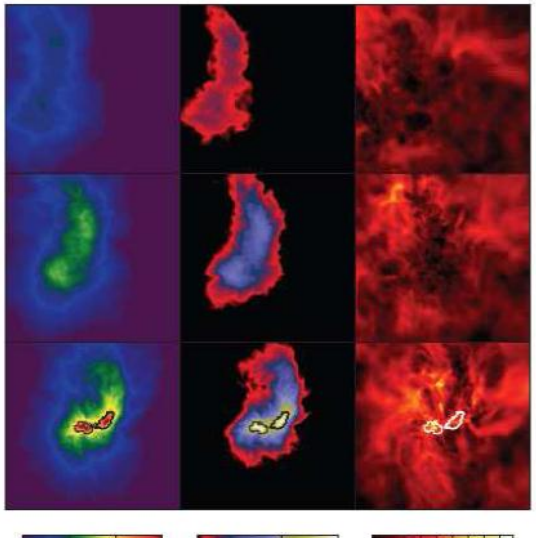


Mass of progenitor star

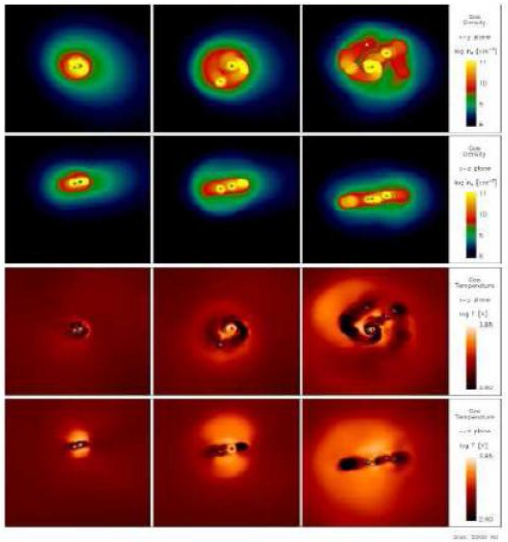
Low metal progenitors form BHs by IMPLOSION (Fryer, 1999)

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

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)

1) **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)

2) **Observations in MW ⇒ >70% of OB type stars are binaries** (e.g. Chini+, 2011)

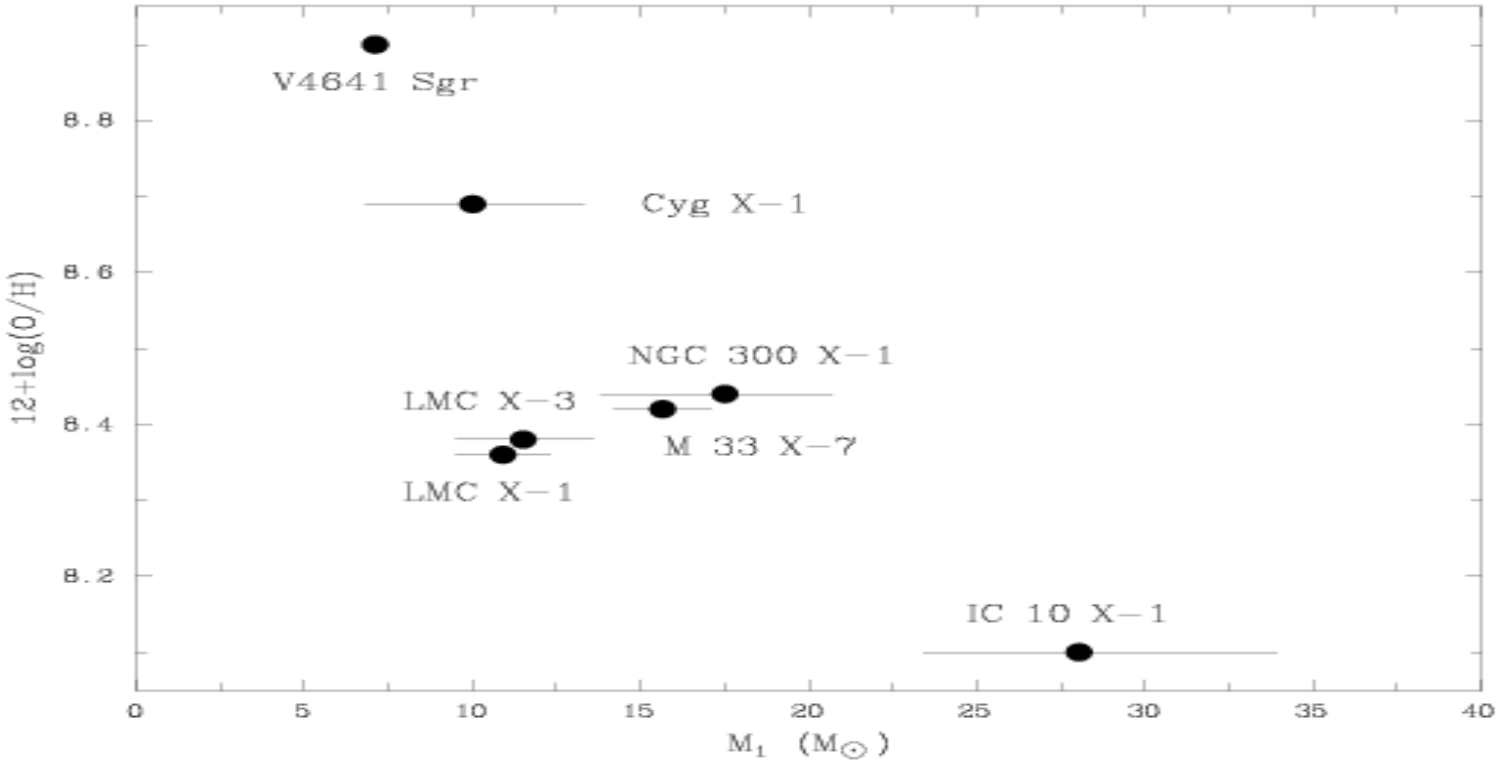
3) **Protostellar Feedback limited the mass of Pop IIIs to < 43 $M_\odot$** (Hosokawa+ 2011)

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

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

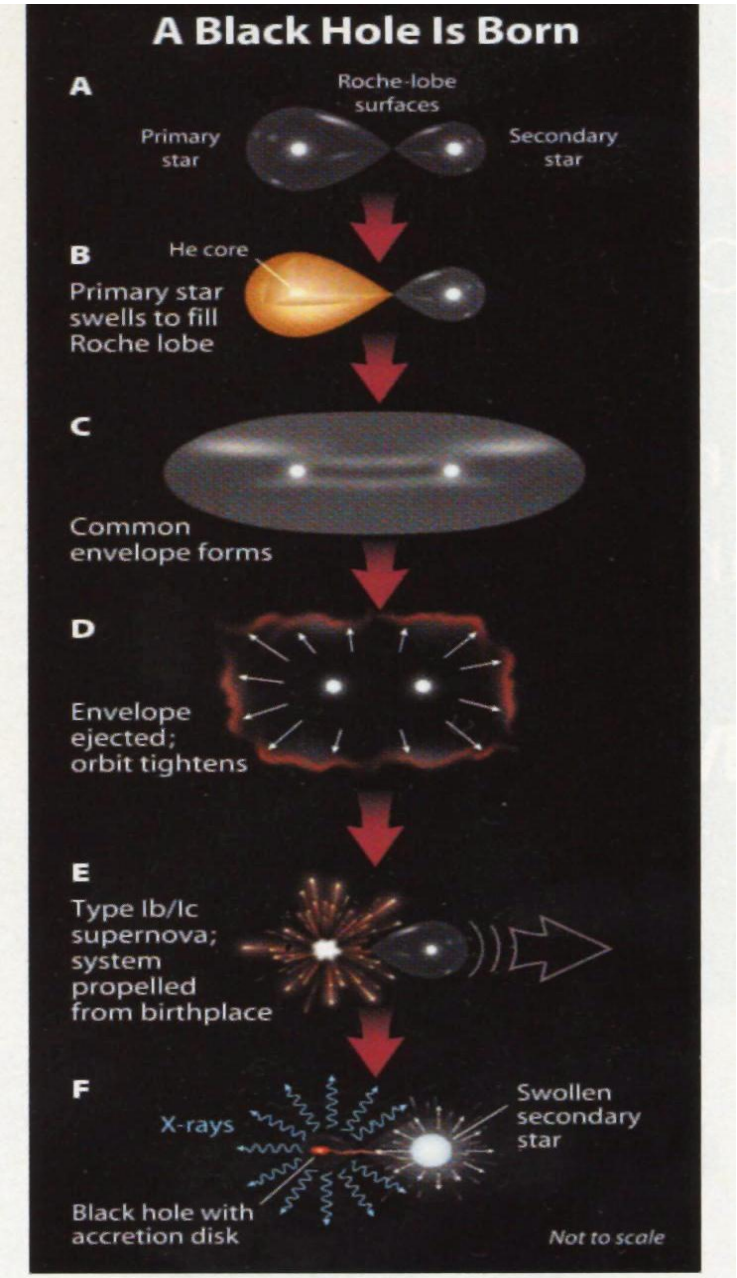
THE MASS OF BHs IN HMXBs SEEMS TO BE A DECREASING FUNCTION OF METALLICITY

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 $M_{BH}<15\ M_{\odot}$

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

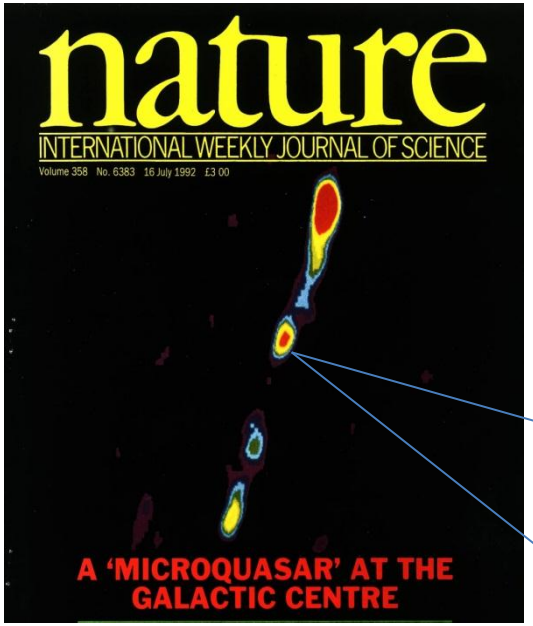
Mirabel & Irapuan Rodrigues (2001-2009)

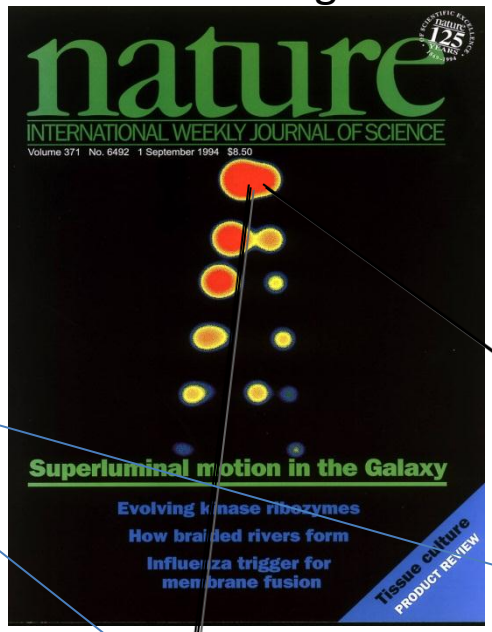
JETS IN MICROQUASARS

Mirabel, Rodriguez+ 1992

Mirabel & Rodríguez 1994

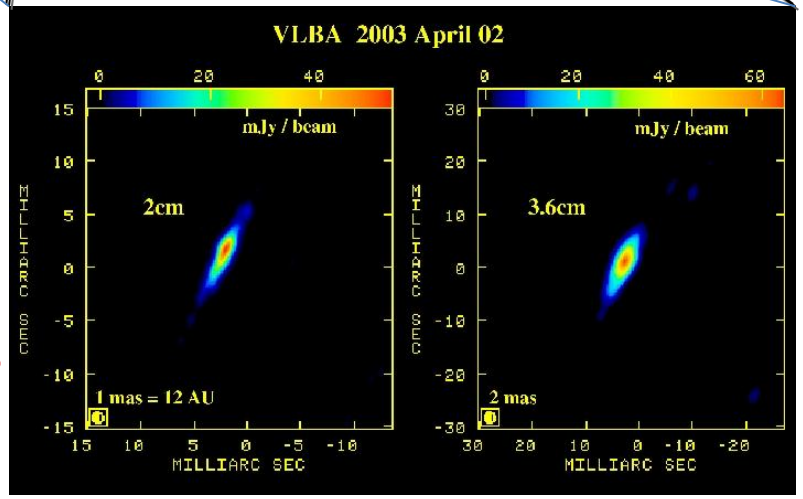
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

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

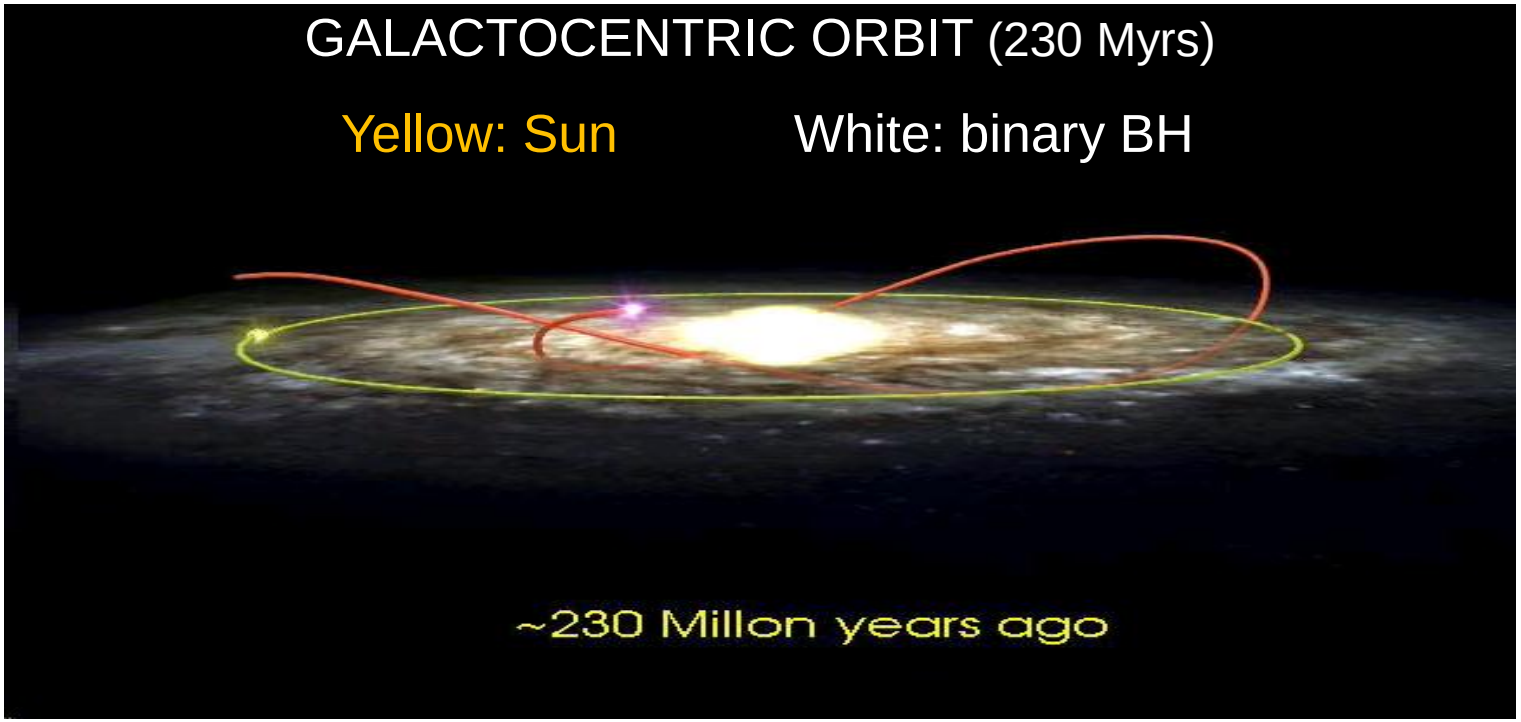
USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

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)

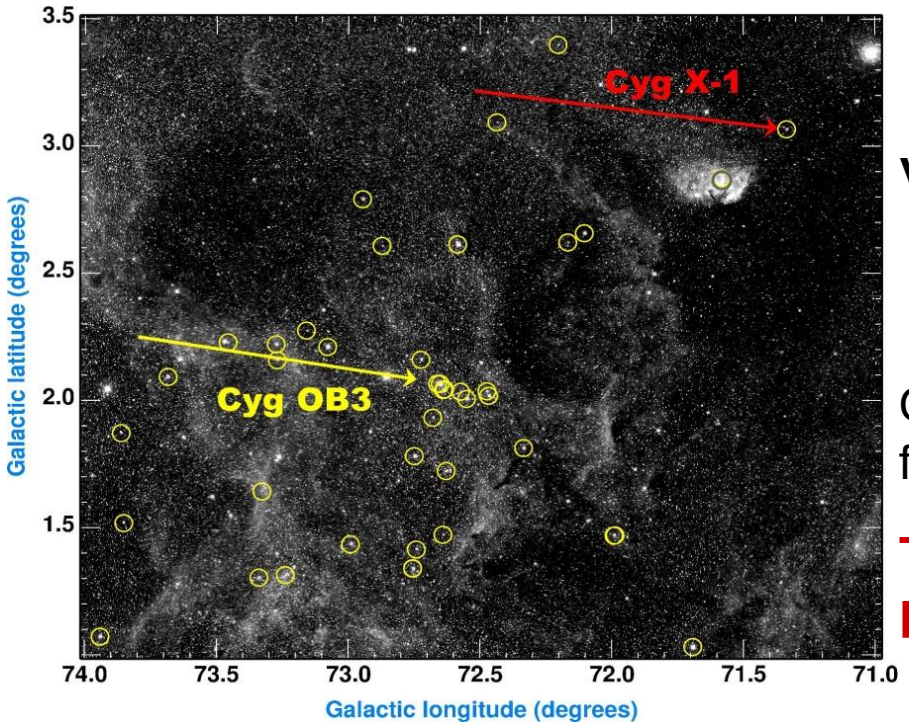
M_{BH}~5-7 $M_\odot$ M_*~2 $M_\odot$;D=1-3 kpc; **V_p=112+/-18 km/s** (Mirabel et al. 2002)

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

⇒ **BHs OF LOW MASS FORM THROGH A SNe PHASE**

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

Mirabel & Rodrigues (Science, 2003)



Cygnus X-1

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

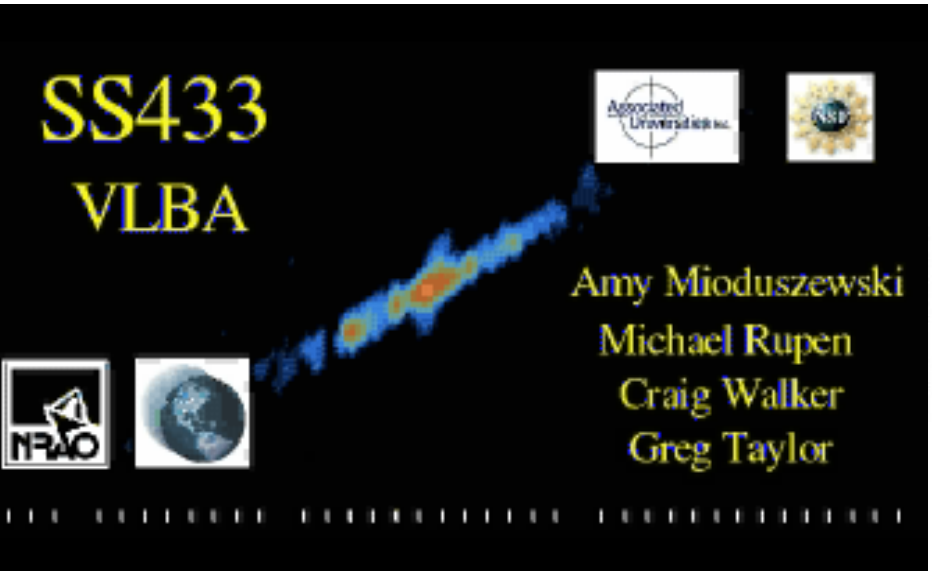
Otherwise it would have been shot out from the parent stellar association

THE ~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 2001)
V404 Cyg: **Vp= 45-100 km/s & W = 0.2+/-3 km/s** (Miller-Jones et al. 2009)

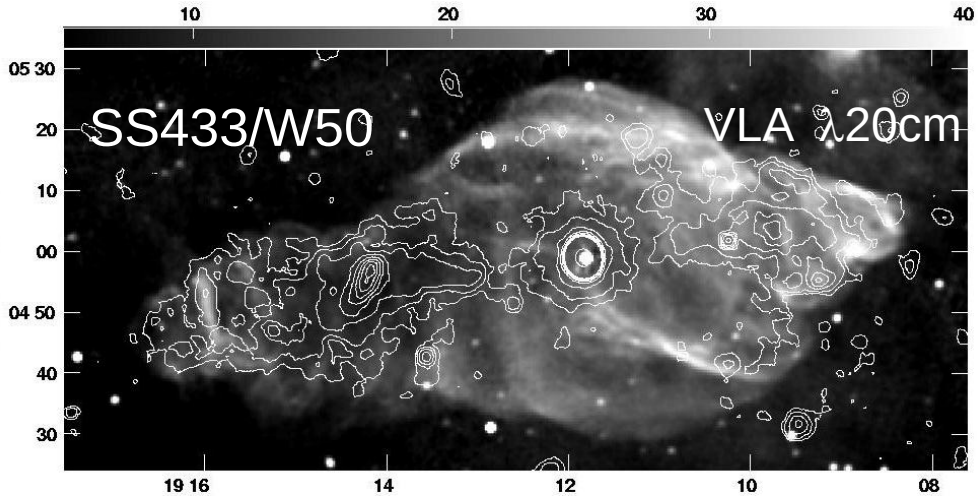
MOST OF THE MASSIVE STELLAR BINARIES END AS BH-HMXBs

POWERFUL JETS FROM BH-HMXBs (μQSOs)



1arcsec

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



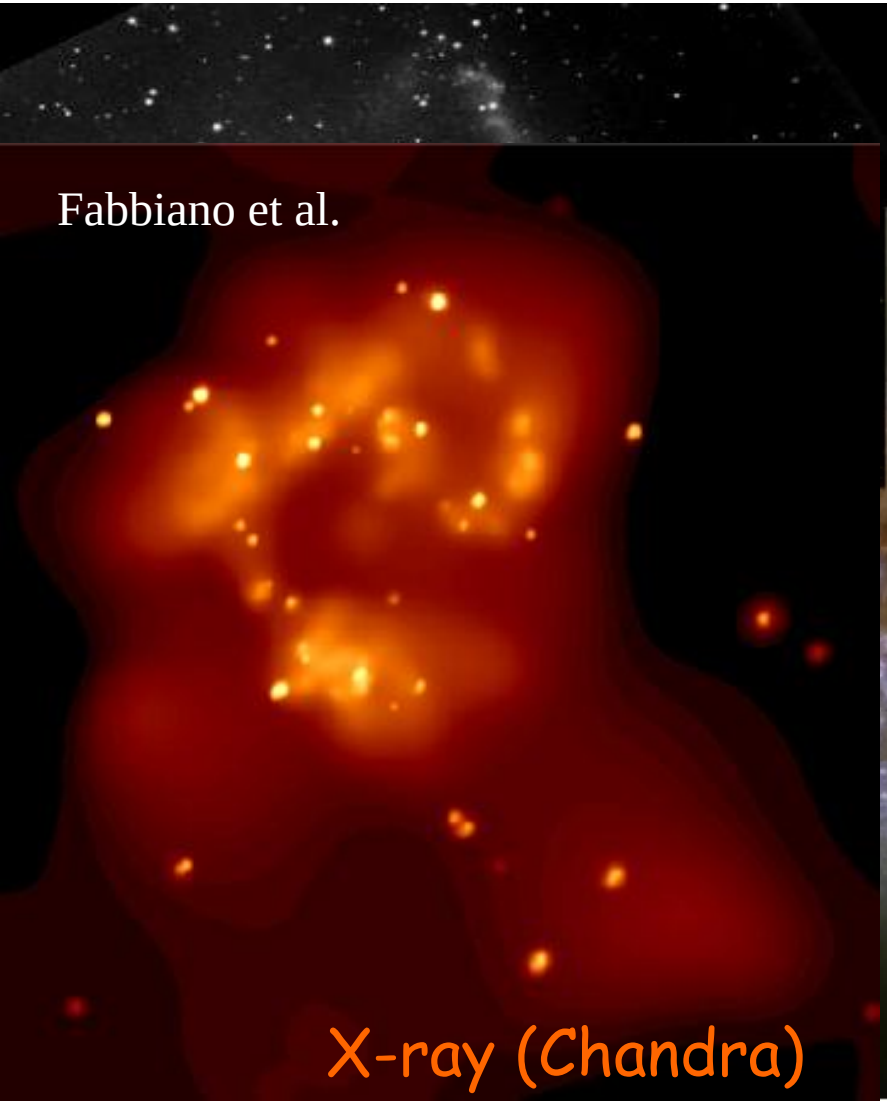
1^{o} = 60 pc

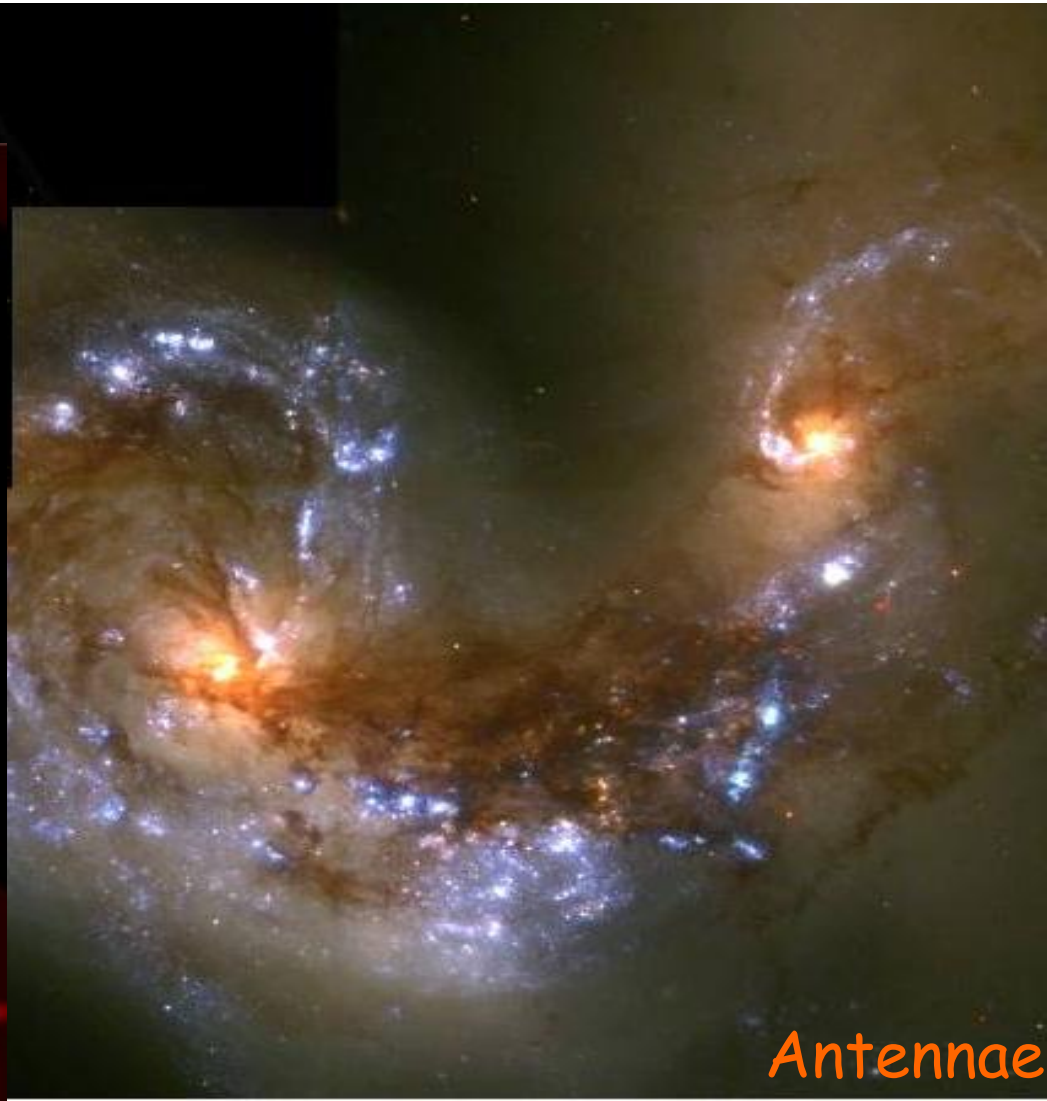
- **ATOMIC NUCLEI MOVING AT 0.26c ⇒**
- **MECHANICAL LUMINOSITY > 10^{39} erg/sec**
- **NON RADIATIVE JETS = "DARK" JETS**
- **>50% OF THE ENERGY IS NOT RADIATED**

ULTRALUMINOUS X-RAY SOURCES (ULXs)

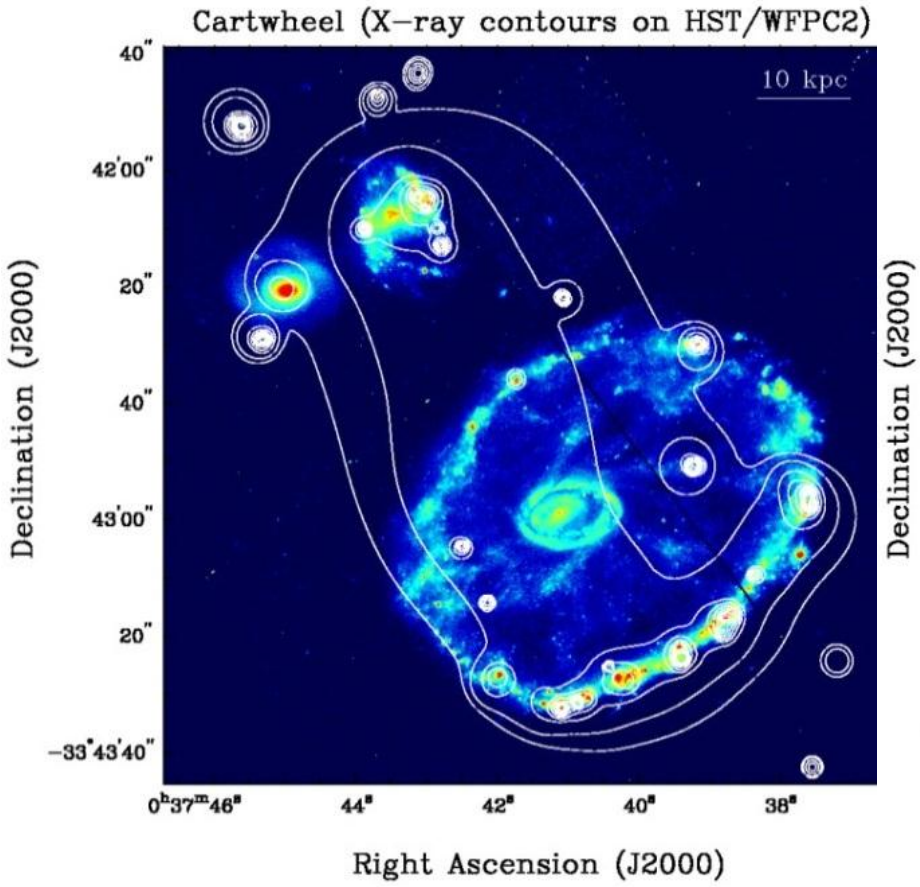
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS IS AN INCREASING FUNCTION OF THE SFR AND A DECREASING FUNCTION OF THE METALLICITY

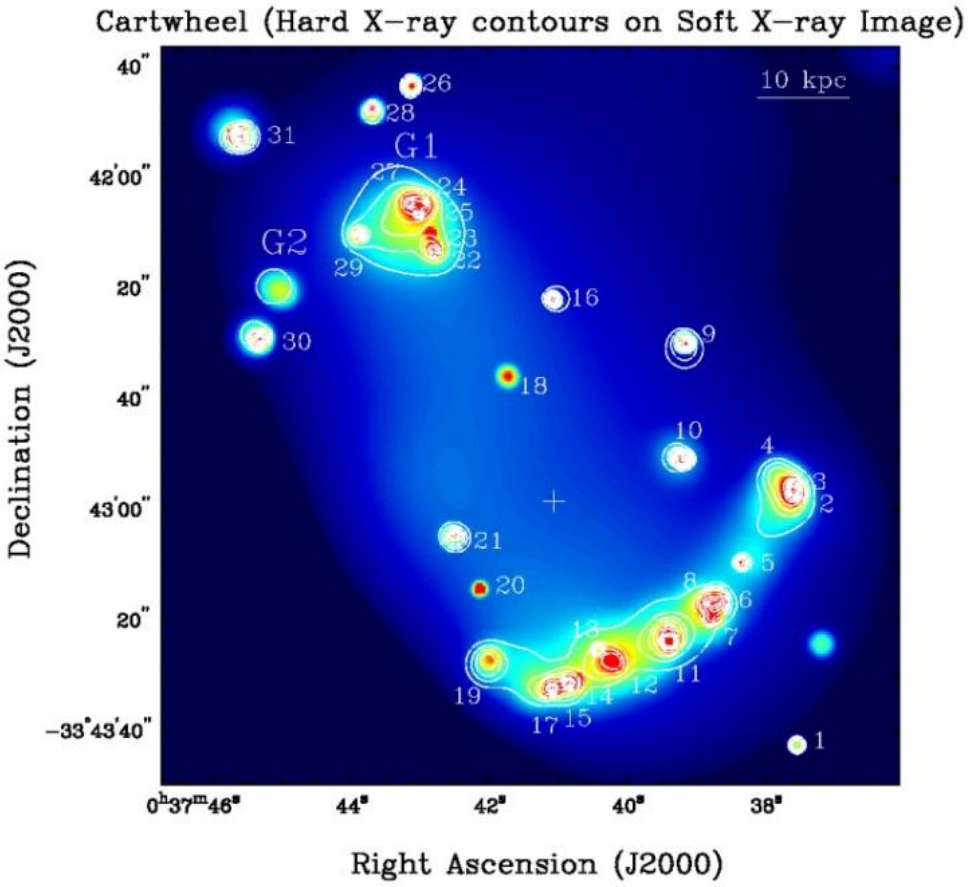
e.g. Zampieri & Roberts (2009)





ULXs IN TEMPLATES OF HIGH z GALAXIES



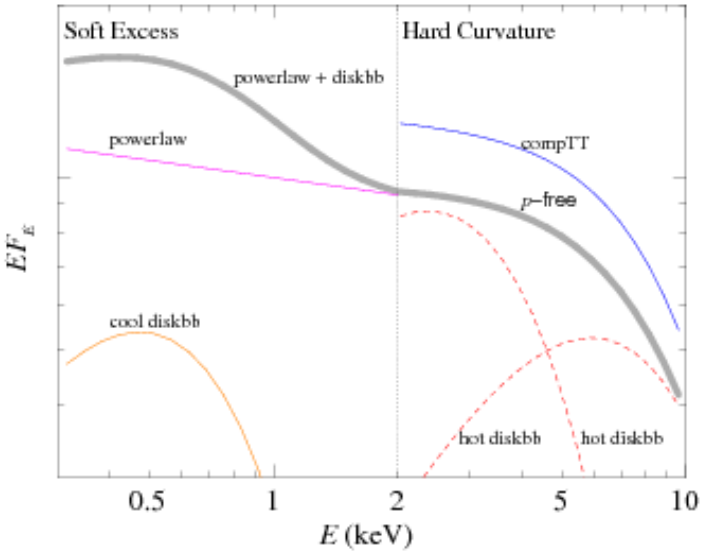


The ULXs luminosity of ~10^{42} erg s^{-1} in the Cartwheel rivals that of AGN

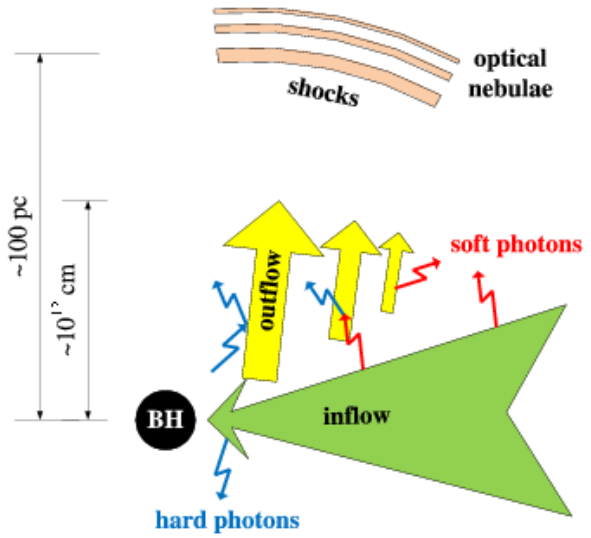
(Gao+ 2003)

BH-HMXBs IN STAR-FORMING GALAXIES OF LOW METALLICITY

The spectra are soft

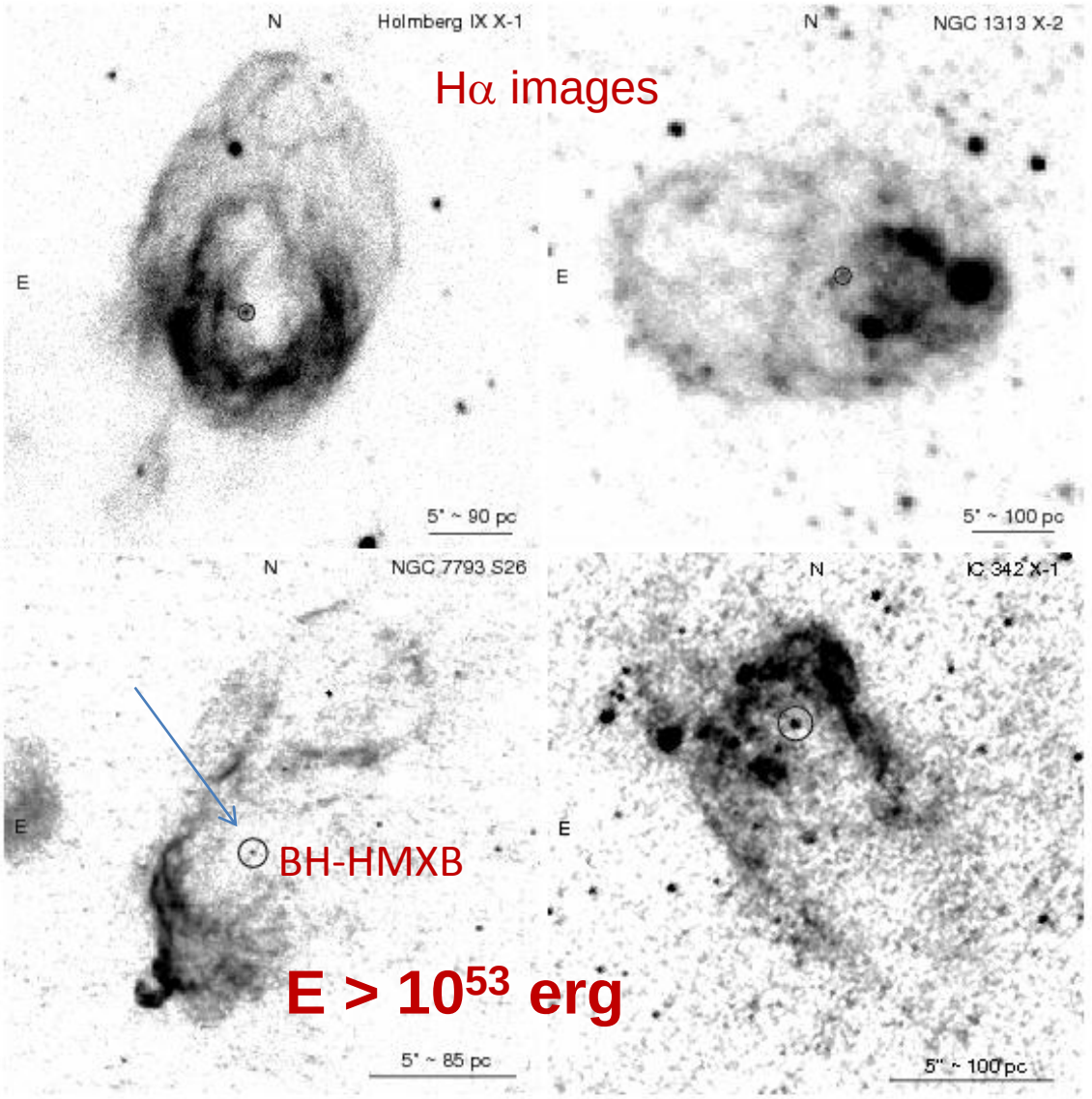


Massive outflows



From Feng & Soria (2011)

shock & photonionized bubbles of > 100 pc size

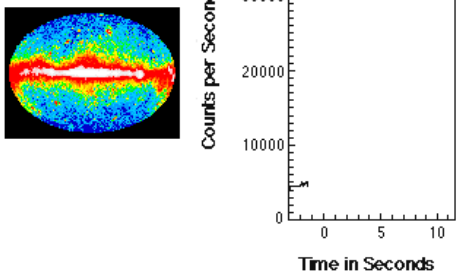


E > 10^{53} erg

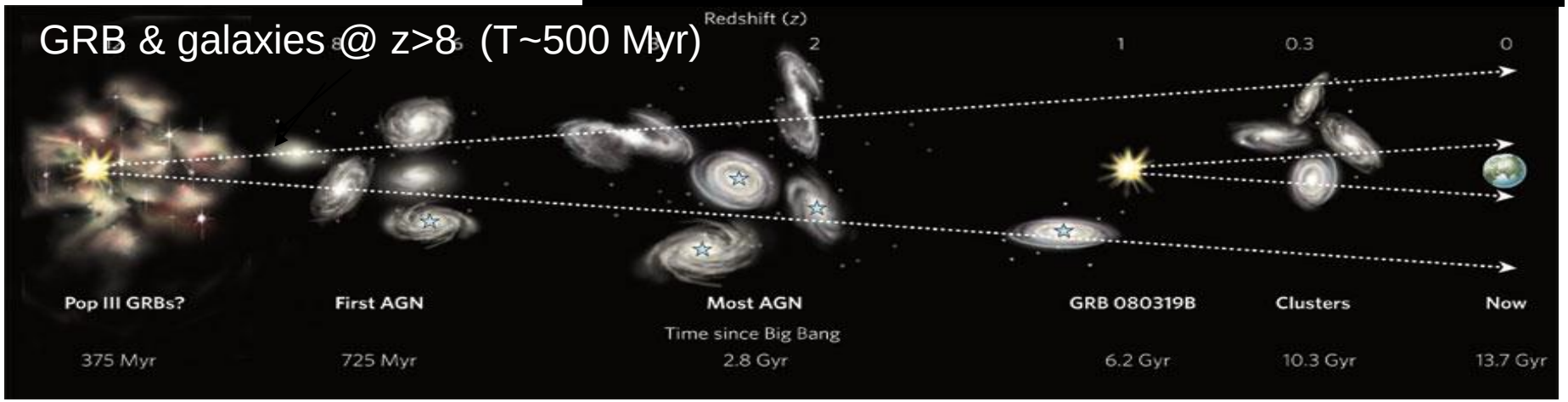
GAMMA-RAY BURST = FORMATION OF STELLAR BLACK HOLES

THE MOST ENERGETIC EXPLOSIONS AFTER THE "BIG BANG"

Stellar collapse & super-relativistic jets Associated to Hiper-novae (SNe Ic)



or by implosion (Mirabel & Rodrigues, Science)

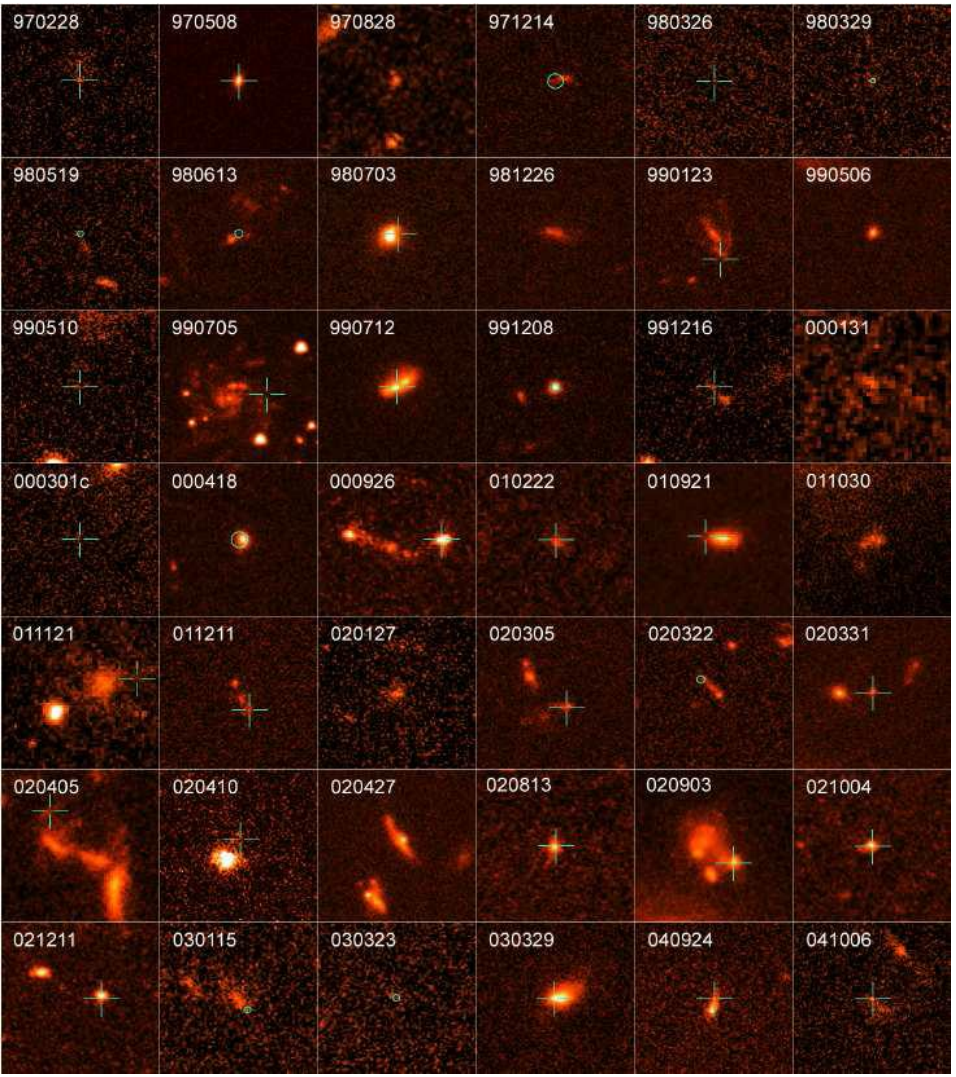


Universal time line since the formation of the first stars

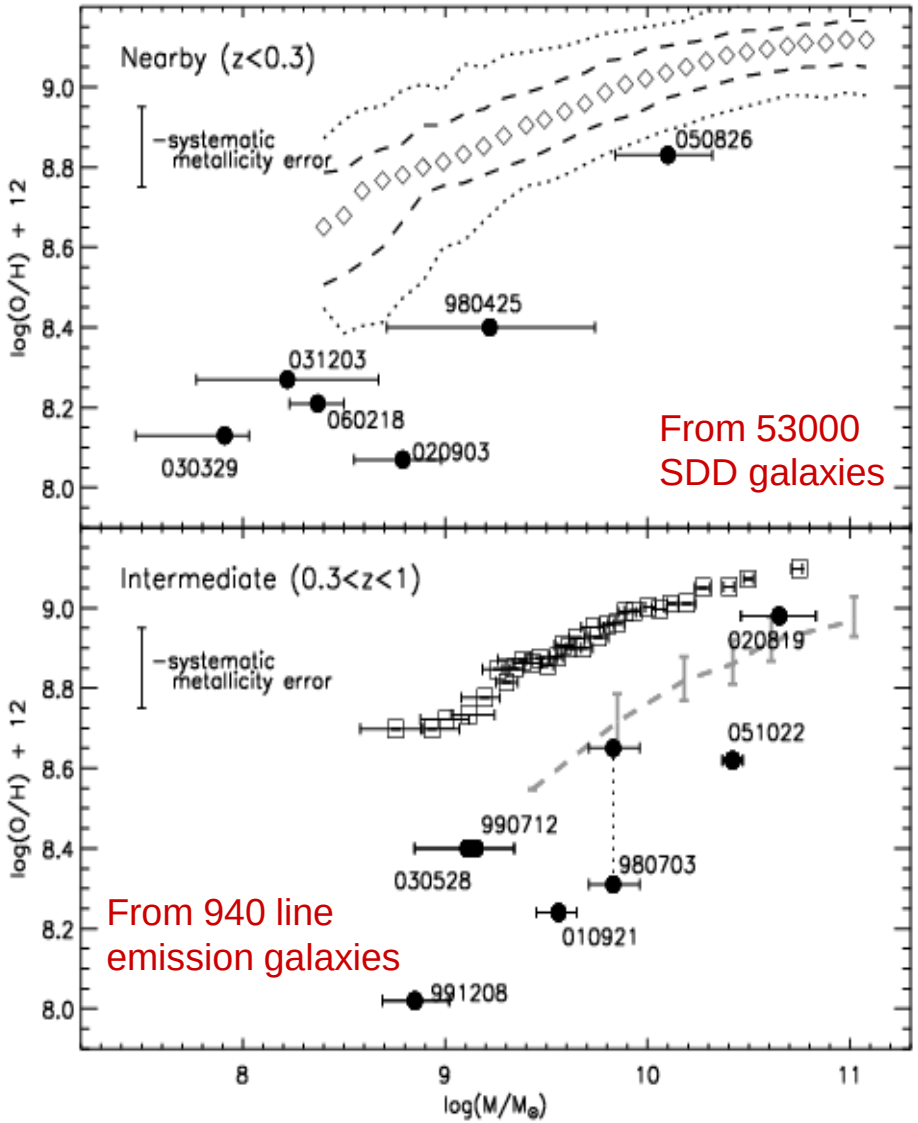
HOSTS OF LGRBs ARE SMALL IRR. GALAXIES WITH HIGH SSFR & RELATIVE LOW METALLICITY

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

Fruchter + with HST (Nature, 2006)



Levesque et al. (2010)



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

SHOULD INCREASE WITH REDSHIFT

Beyond the theoretical uncertainties (e.g. mixing due to rotation in Pop III stars), the observation of ULXs in the Local Universe support this hypothesis

WHAT ARE THE COSMOLOGICAL IMPLICATIONS OF LARGE POPULATIONS OF BH-HMXRBs DURING THE DARK AGES THAT LASTED FROM 4×10^4 up to 10^9 yr?

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

$\langle E\rangle_\gamma$ = 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

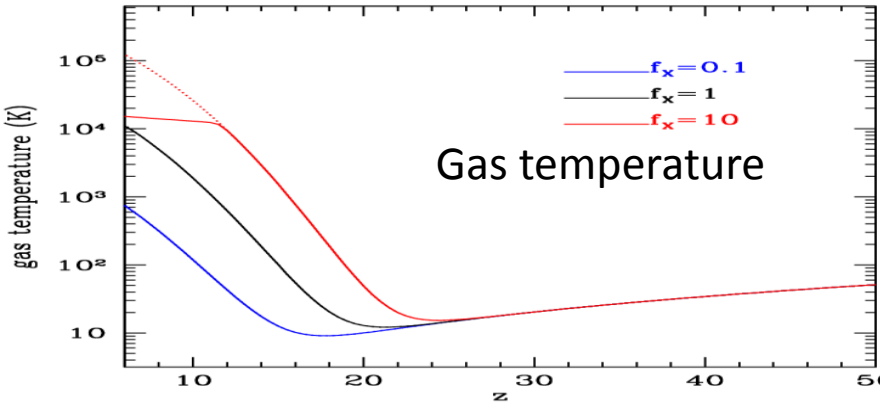
$$L_{2-10} = f_X \times 3.5 \times 10^{40} SFR \quad erg/s$$

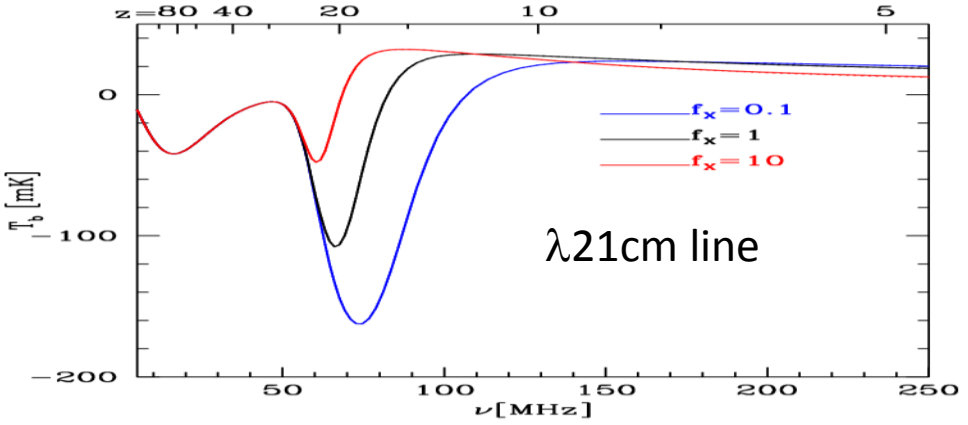
f_x does not seem to change up to z=4

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 may increase at z > 6





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

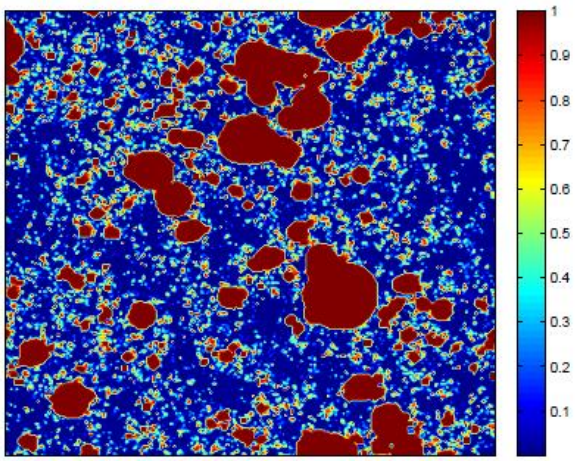
GMRT λ21cm @ z~9 ⇒Was the IGM heated before being fully ionized? (Paciga+ 2011)

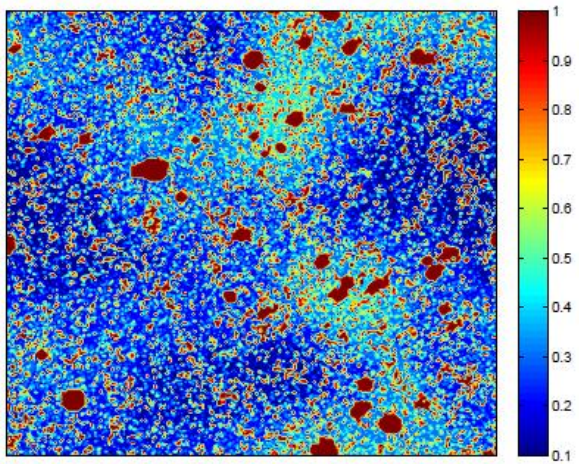
HI TOPOLOGY

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 × 170 × 0.66 Mpc^3 (Visbal & Loeb, 2011)

X-rays = 0





X-rays = 50%

BH-HMXBs LIMITED THE MASS OF DWARF GALAXIES

From Loeb (2010): $T_{vir} = 1.04 \times 10^4 (\mu/0.6) (M/10^8 M_\odot)^{2/3} [(1+z)/10]$ 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 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 STELLAR BLACK HOLES HAD AN IMPACT ON THE PROPERTIES OF THE FAINTEST GALAXIES AT HIGH z AND THE SMALLEST GALAXIES IN THE LOCAL UNIVERSE. BESIDES THE SN MECHANISM, FEEDBACK FROM STELLAR BLACK HOLES COULD ALSO BE CLAIMED TO REDUCE THE NUMBER OF DWARFS PREDICED BY THE λCDM**

SOME CONCLUSIONS

I) Could the BH-HMXBs with non-thermal emission up to 2 MeV, as in Cyg X-1, that formed at z > 7, be cosmic sources of the unresolved hard X-ray background ? (Diskra et al. 2012)

II) Could BH-BH stellar binaries be the more likely sources of gravitational waves to be detected ? (Belczynski et al. 2011)

III) ARE THERE LARGE NUMBERS OF NAKED HALOS WITH MASSES < 10^{8-9} $M_{\odot}$ IN THE IGM ?

IV) FEEDBACK FROM SUPERMASSIVE BHs MAY STOP THE UNLIMITED GROWTH OF MASSIVE GALAXIES IN CLUSTERS.
FEEDBACK FROM STELLAR BHs DURING REIONIZATION MAY HAVE LIMITED THE MASS OF DWARF GALAXIES.

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)
- News & Views by Haiman in Nature of 7 April, 2011

OTHER PUBLICATIONS IN 2012 RELATED TO THIS WORK

- Justham & Schawinski:: Feedback from HMXBs more important than that from SNe
- Marks, Kroupa, et. al.: Show evidence for top-heavy IMFs with decreasing metallicity
- Dopcke et al.: Flat and top heavy IMF at $Z < 10^{-5}\ Z_{\odot}$ which implies that a change in f_x should significantly take place at very high redshifts (z>6), which is consistent with
- Dijkstra, Gilvanov, Loeb, Sunyaev (2012) and Cowie, Barger Hasinger (2012).