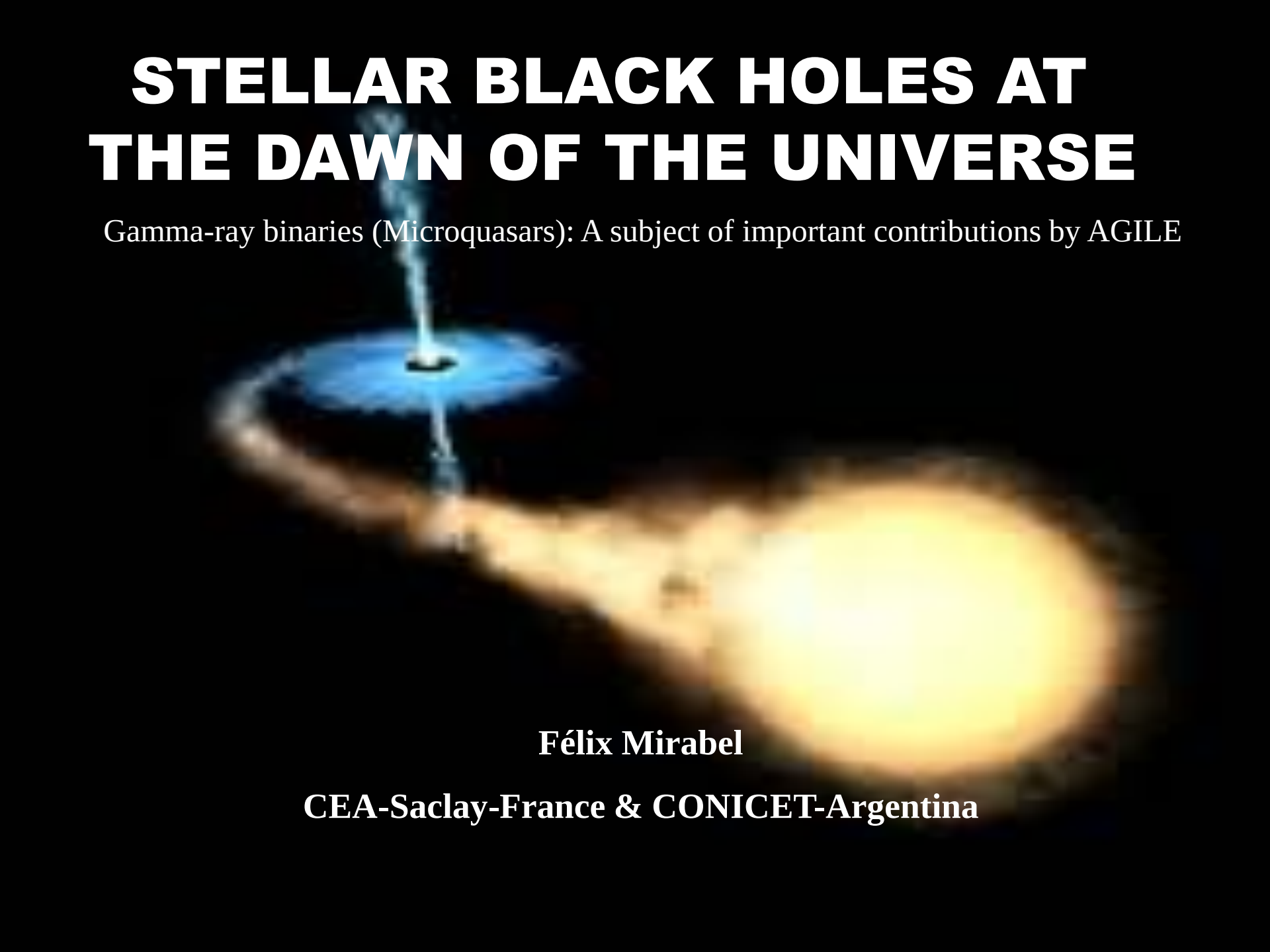
STELLAR BLACK HOLES AT THE DAWN OF THE UNIVERSE

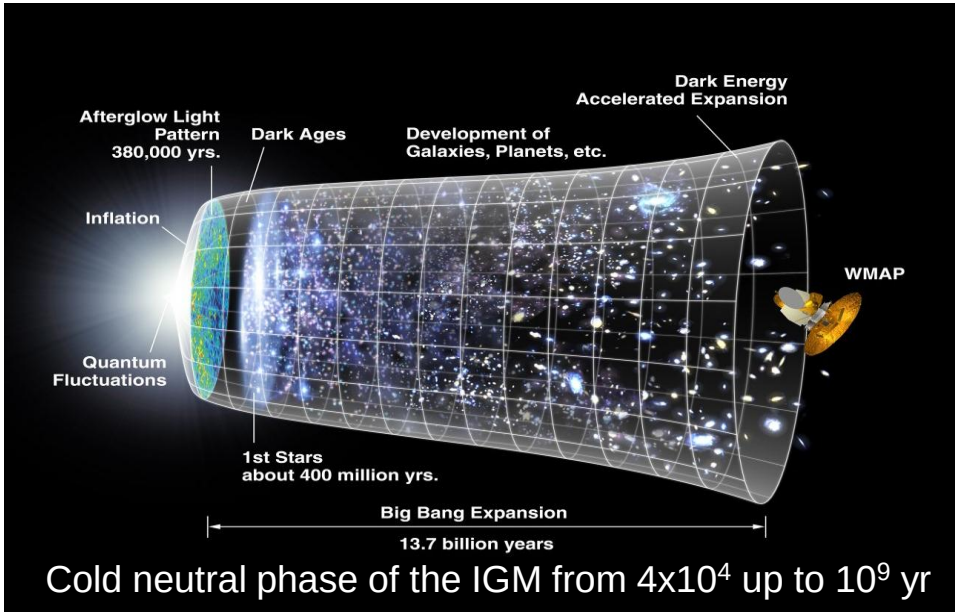
Gamma-ray binaries (Microquasars): A subject of important contributions by AGILE



Félix Mirabel

CEA-Saclay-France & CONICET-Argentina

COSMIC RE-IONIZATION: A MAJOR FRONTIER IN COSMOLOGY



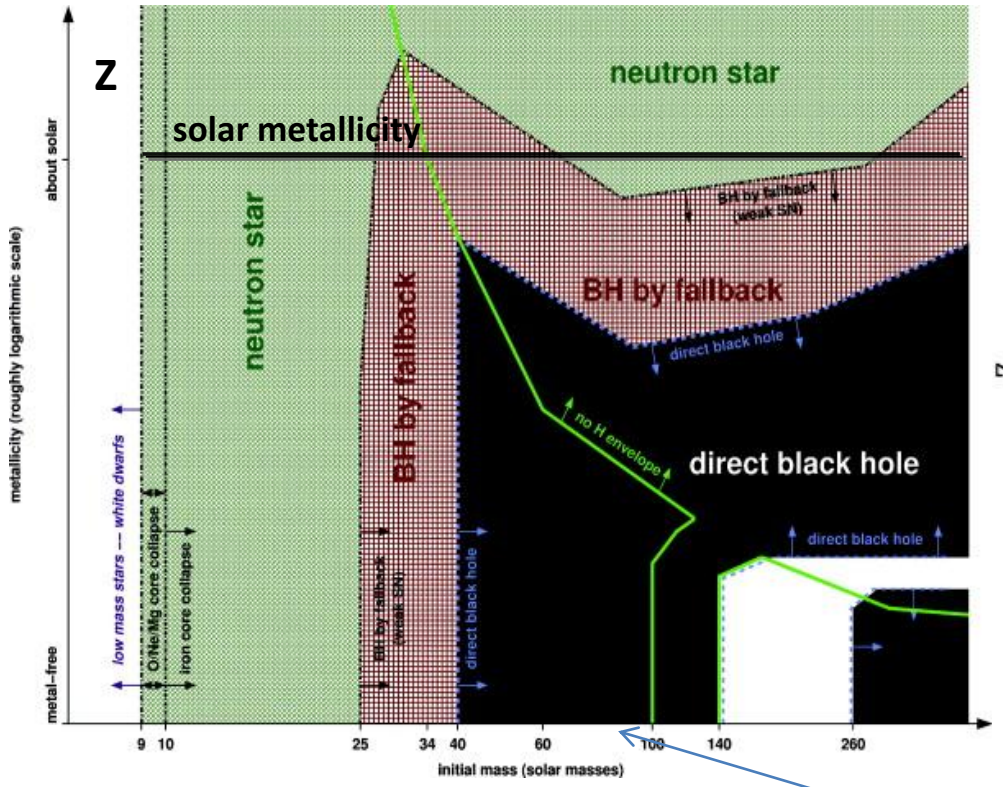
Cold neutral phase of the IGM from 4×10^4 up to 10^9 yr

Localized in individual Stromgren spheres

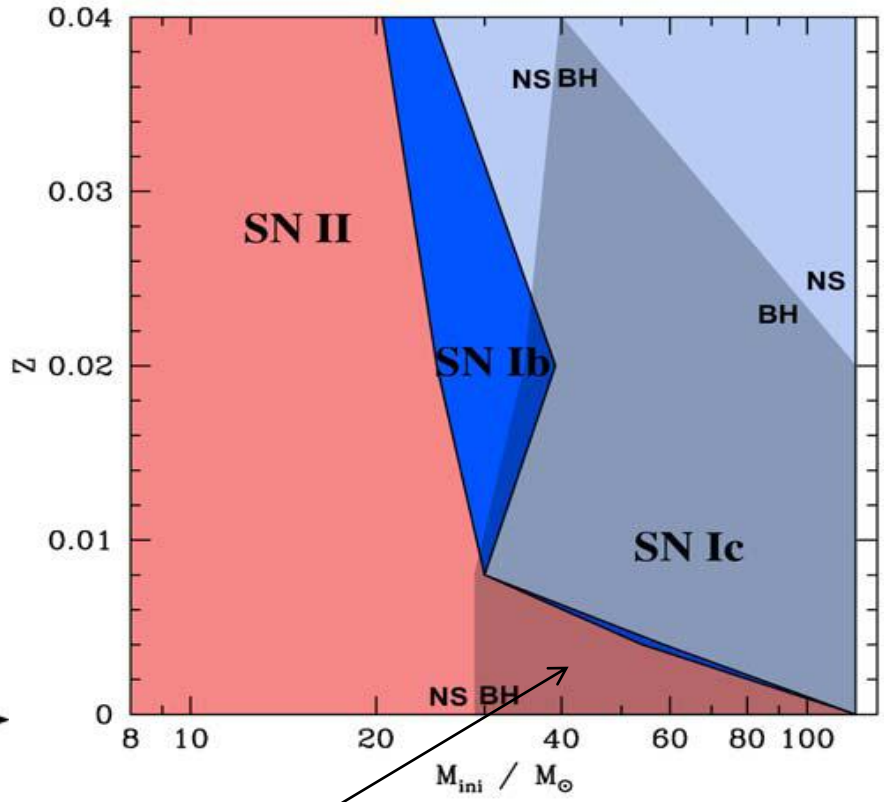
- **Up to now the cosmology community assumed that the IGM was fully ionized by the UV from the first stars (Pop III & II)**
- **From recent results in Stellar Evolution, Galaxy Evolution, High Energy Astrophysics and Cosmology**
- **I propose that at z > 8 there has been a large population of Black Hole High Mass X-Ray Binaries (BH-HMXBs),which played an important role, that so far has been overlooked**
- This hypothesis is based on the following theoretical models & observations:

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

with no rotation (Heger+ 2003)



with rotation (Georgy+ 2009)

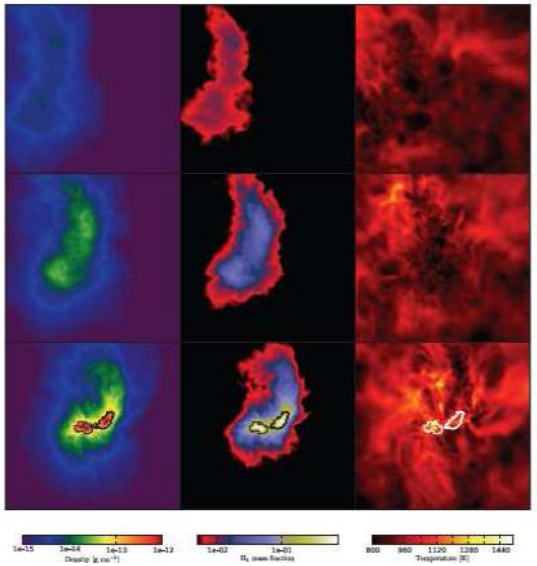


Mass of progenitor star

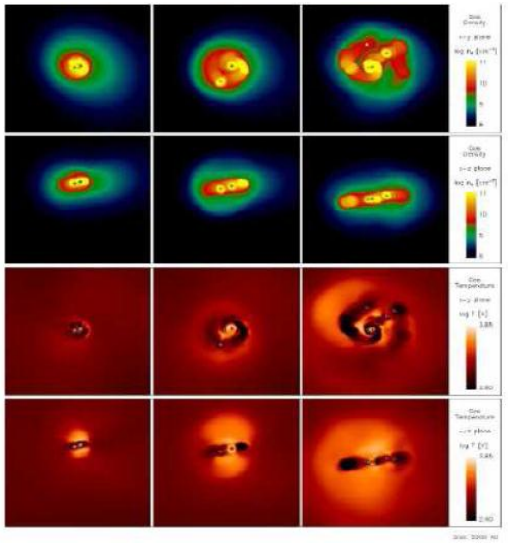
Low metal progenitors form BHs by IMPLOSION (Fryer, 1999)

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 $\Rightarrow$ >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)

FROM CURRENT MODELS OF MASSIVE STAR FORMATION AND EVOLUTION

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

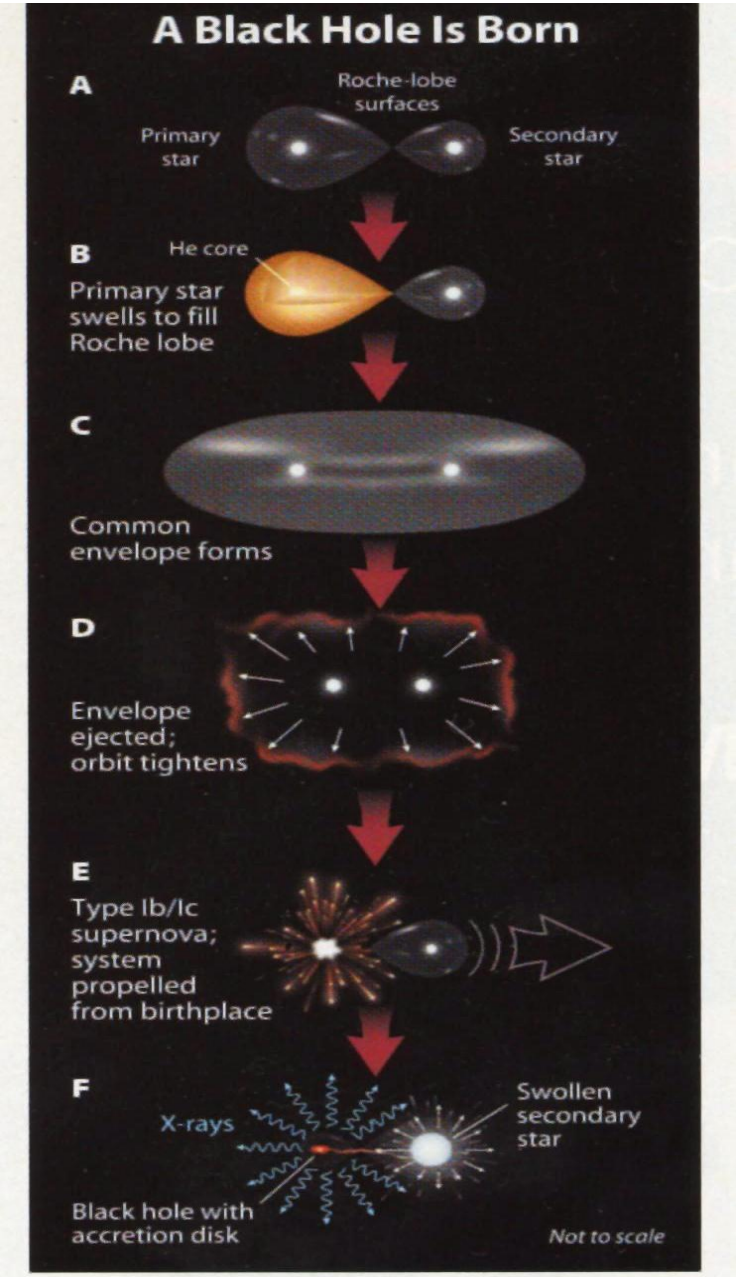
SHOULD INCREASE WITH DECREASING METALLICITY OF THE PROGENITORS

Because at low Z's BHs form directly (with no energetic SNe), the fraction of binary systems that remain gravitationally bound increases, and therefore, from a theoretical point of view one expects that

THE FRACTION OF BH-HMXBs INCREASES WITH DECREASING METALLICITY

WHAT OBSERVATIONS CAN TEST THESE THEORETICAL PREDICTIONS?

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

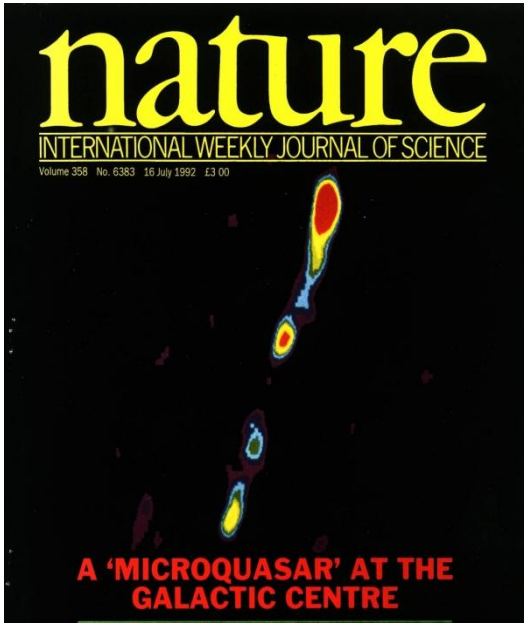
Mirabel & Irapuan Rodrigues (2001-2009)

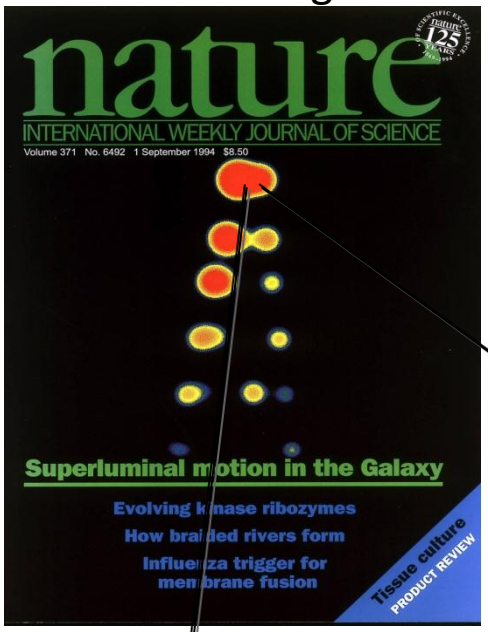
JETS IN MICROQUASARS

Mirabel, Rodriguez+ 1992

Mirabel & Rodríguez 1994

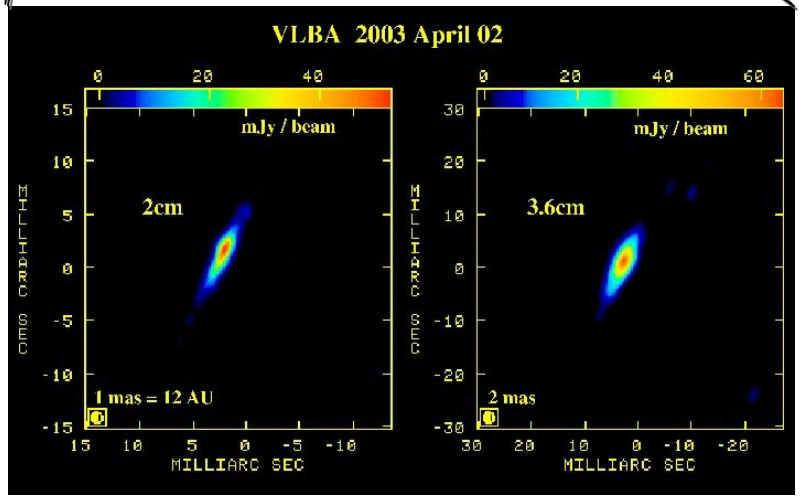
STEADY JETS





TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

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

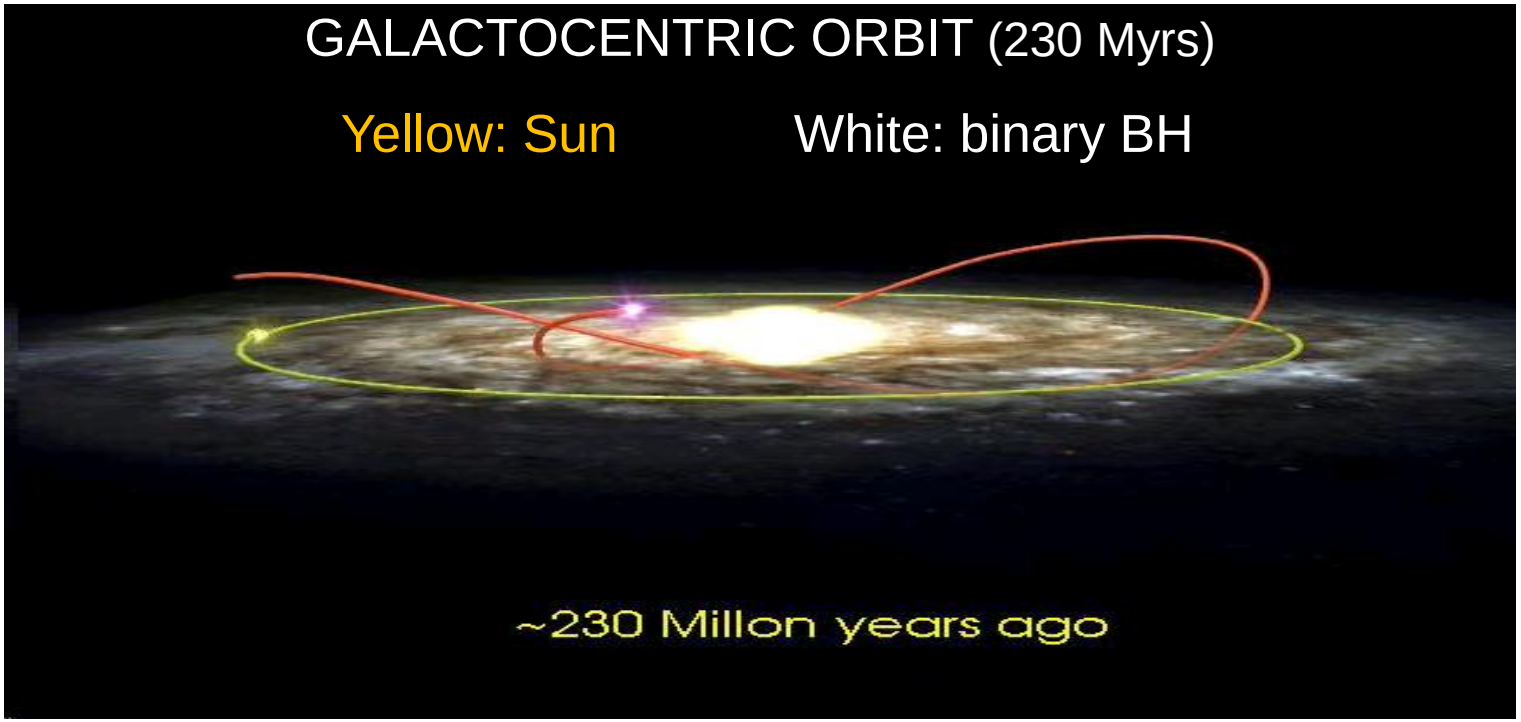
USED TO DETERMINE PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

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)

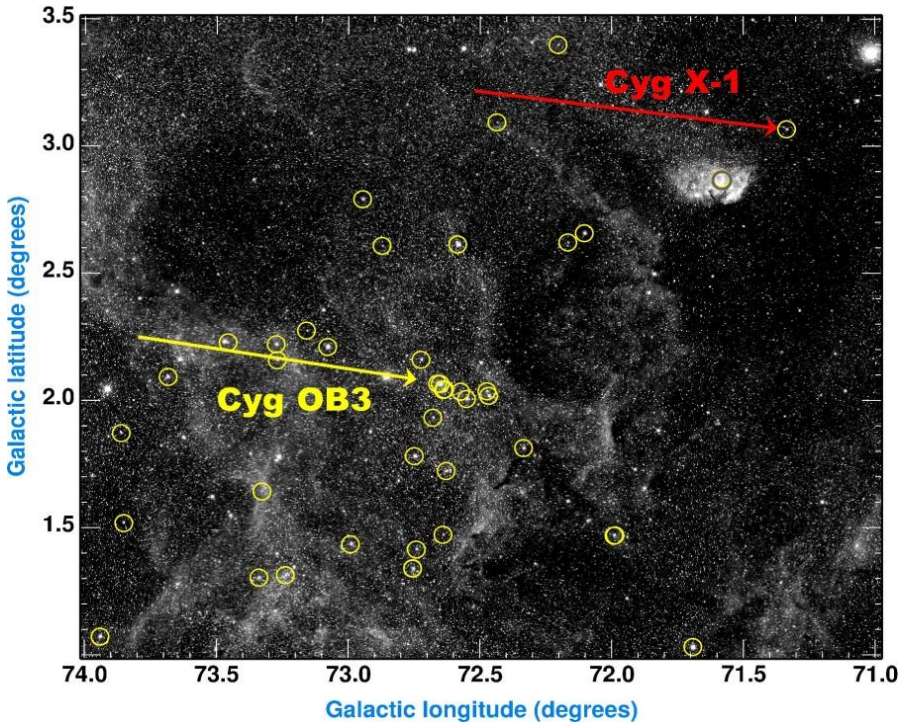
M_{BH}~5-7 $M_\odot$ M_*~2 $M_\odot$;D=1-3 kpc; V_p=112+/-18 km/s (Mirabel et al. 2002)

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

THREE BLACK HOLES OF >10 $M_\odot$ FORMED BY DIRECT COLLAPSE

Mirabel & Rodrigues (Science, 2003)

Proper motion by Lestrade et al. (1999)



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)

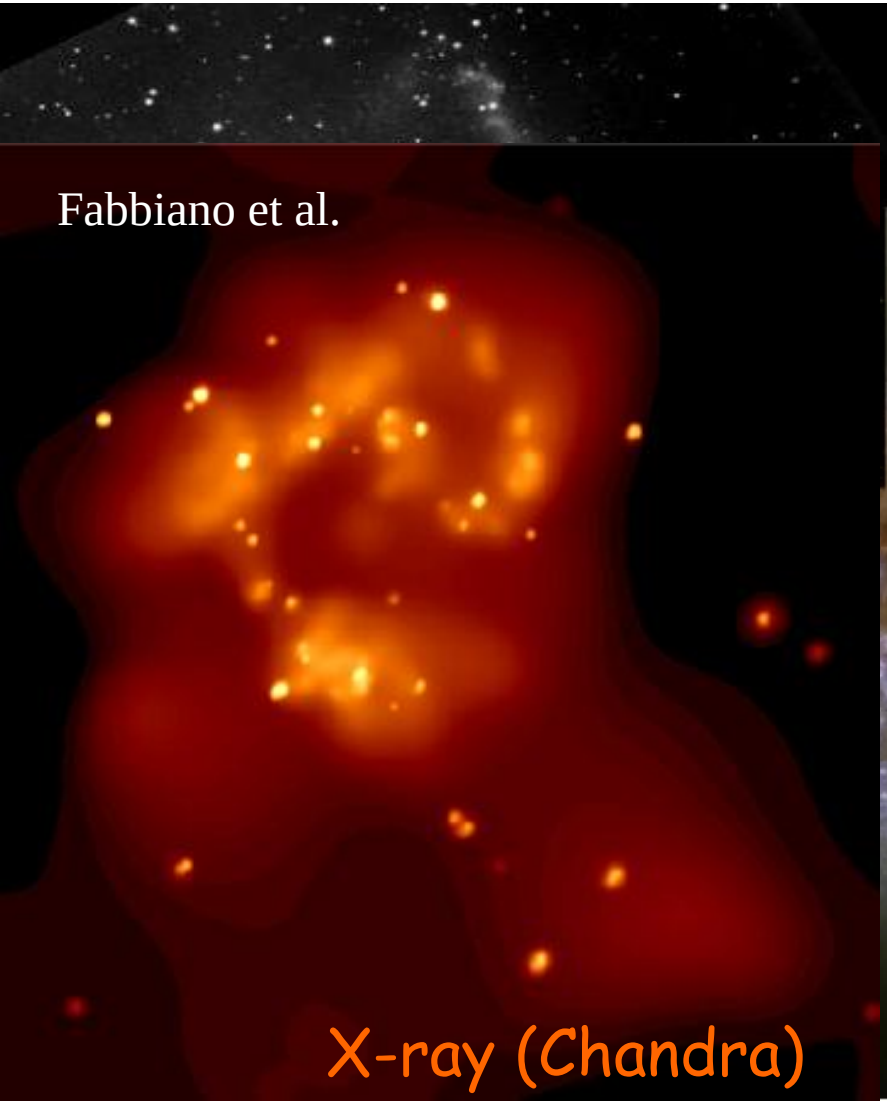
V404 Cyg: **Vp= 45-100 km/s & W = 0.2+/-3 km/s** (Miller-Jones et al. 2009)

BHs with > 10 $M_\odot$ form by implosion

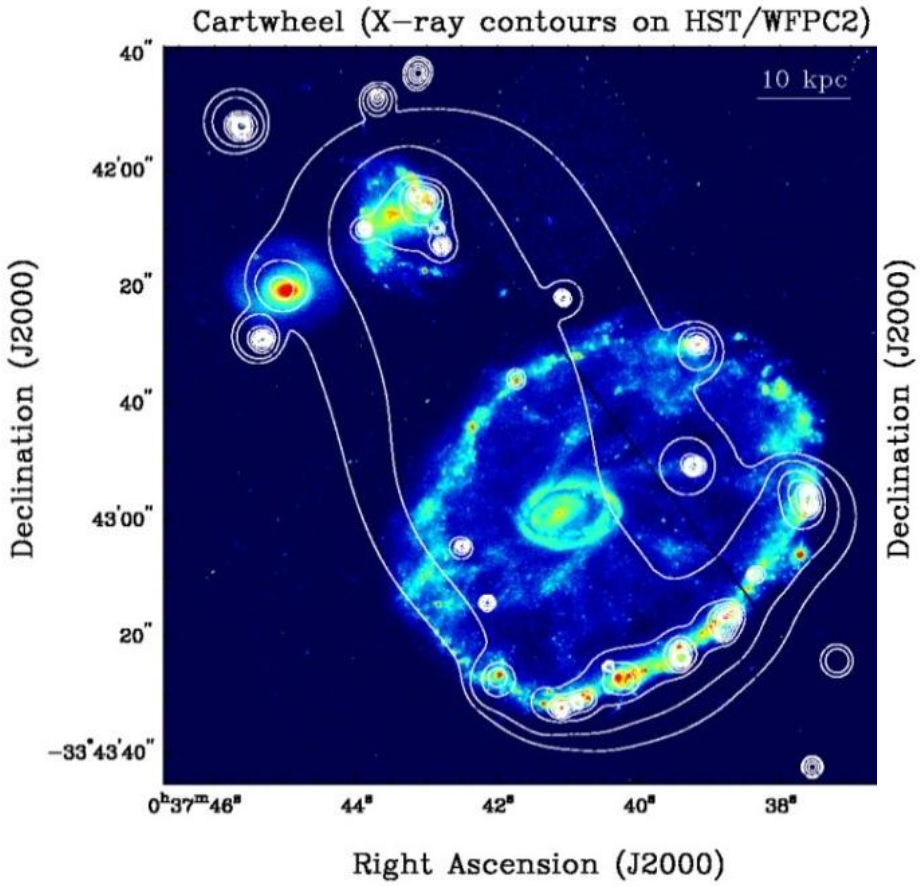
This line of research will be enhanced with GAIA

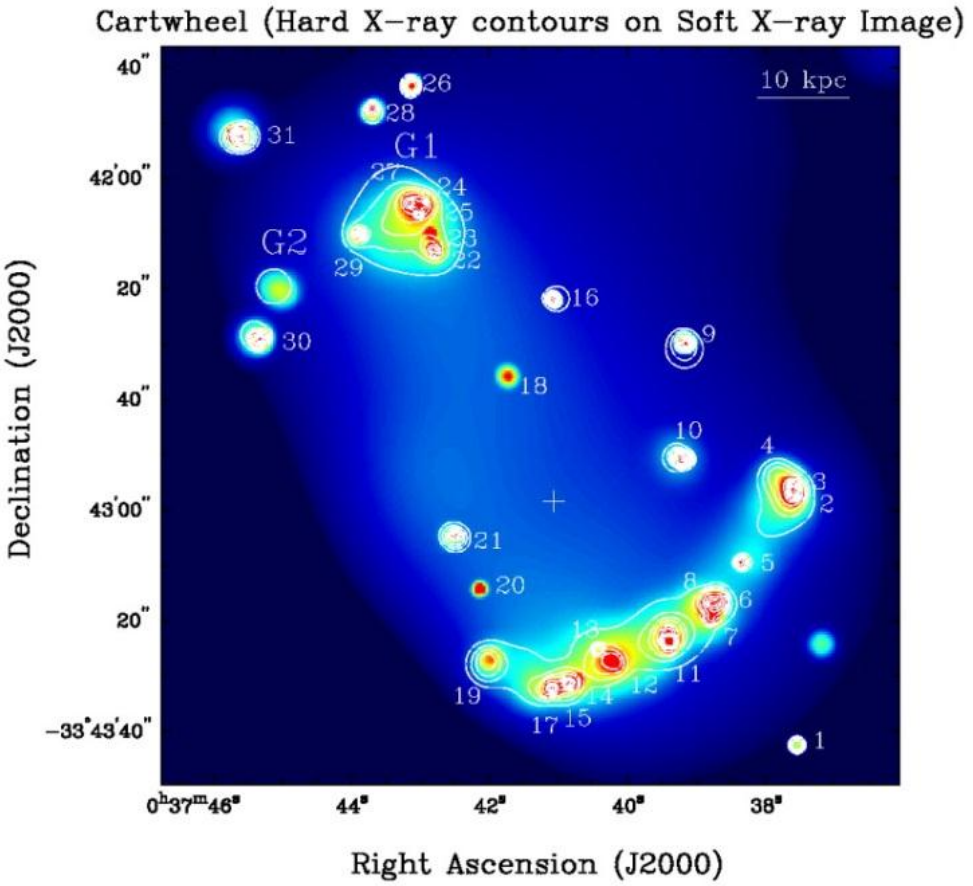
THE OCCURRENCE RATE OF ULXs PER UNIT GALAXY MASS IS AN INCREASING FUNCTION OF THE SSFR AND A DECREASING FUNCTION OF THE METALLICITY OF THE HOST GALAXY

e.g. Zampieri & Roberts (2009)



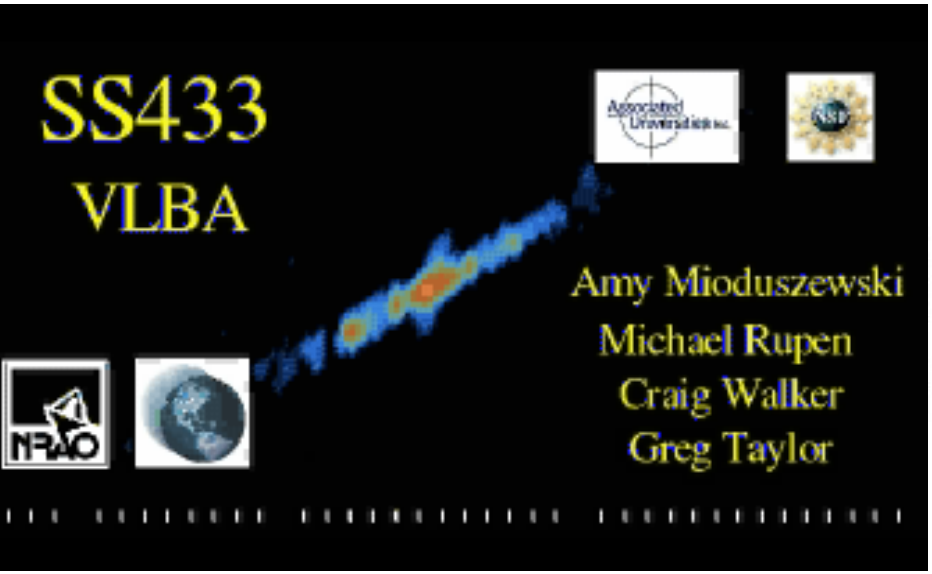
ULXs IN TEMPLATES OF HIGH z GALAXIES





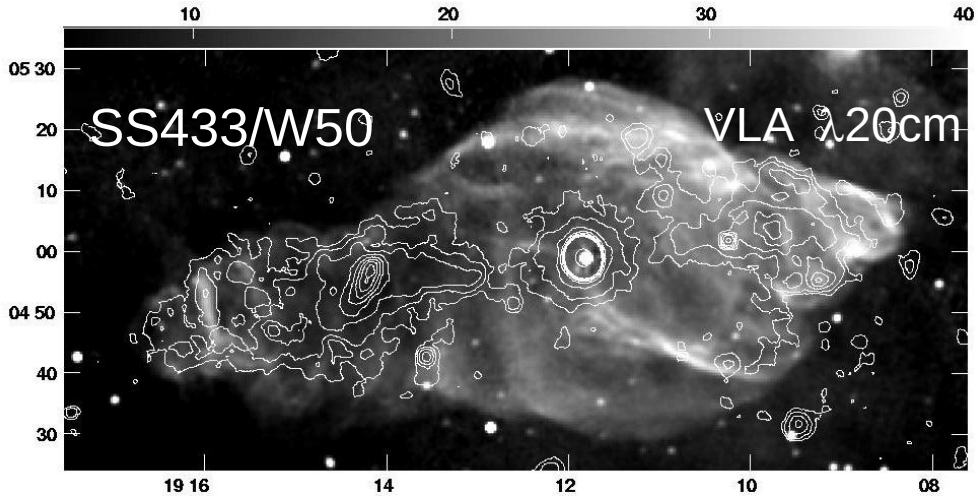
The ULXs luminosity of ~10^{42} erg s^{-1} in the Cartwheel rivals that of AGN

(Gao+ 2003)



1arcsec

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



1^o = 60 pc

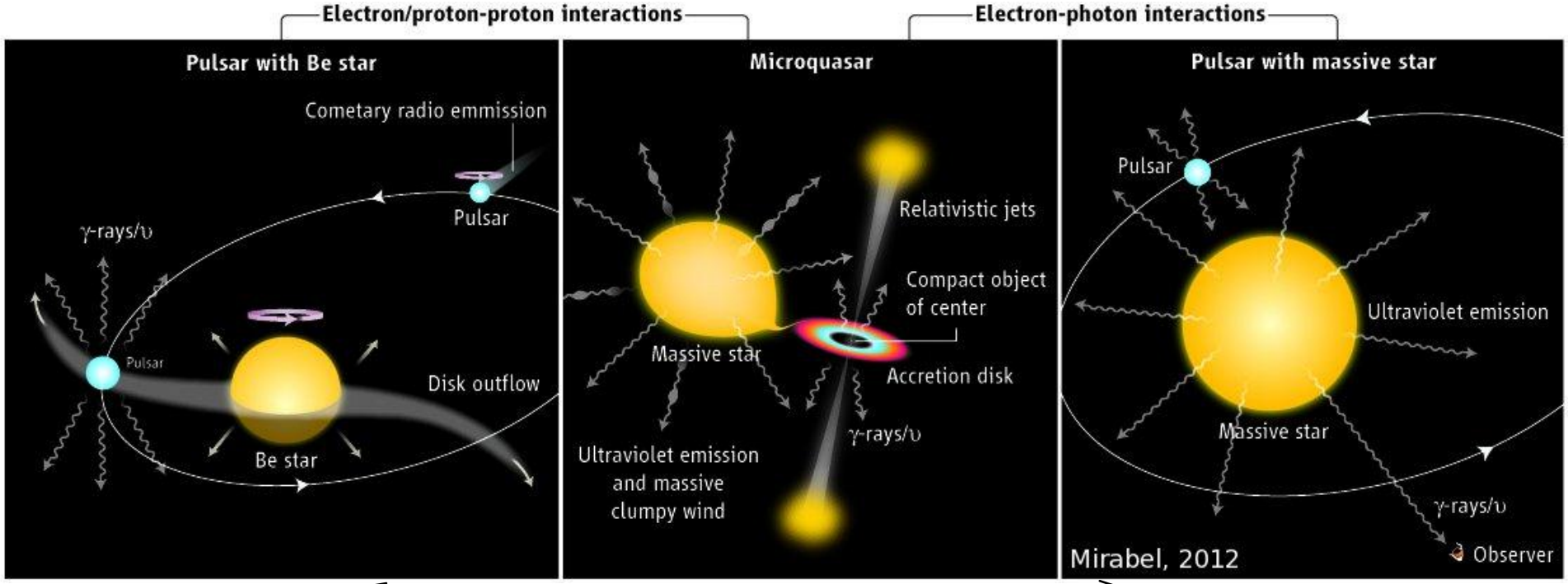
- **ATOMIC NUCLEI MOVING AT 0.26c ⇒**
- **MECHANICAL LUMINOSITY > 10^{39} erg/sec**
- **NON RADIATIVE JETS = "DARK" JETS**
- **>50% OF THE ENERGY IS NOT RADIATED**

POWERFUL JETS FROM BH-HMXBs (μQSOs)

GeV & TeV PHOTONS FROM HMXBs

(Targets for AGILE, Fermi & CTA)

Mirabel (Perspectives in Science 2006 & 2012)

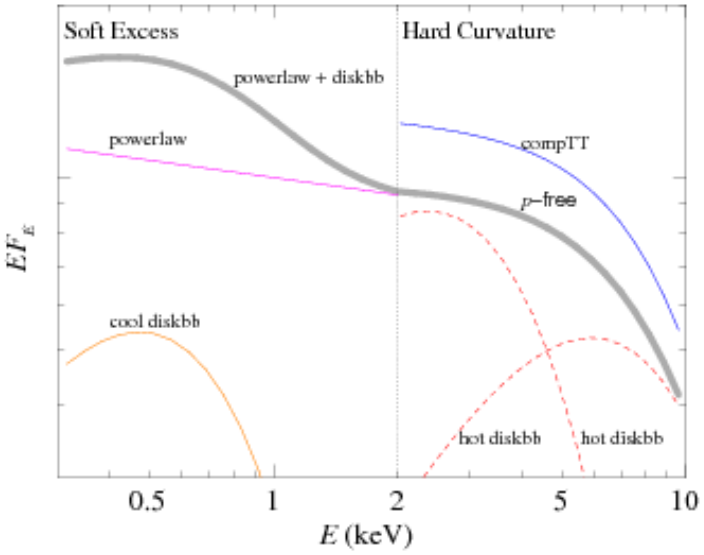


Detected by AGILE (Tavani et al. 2010-2012)

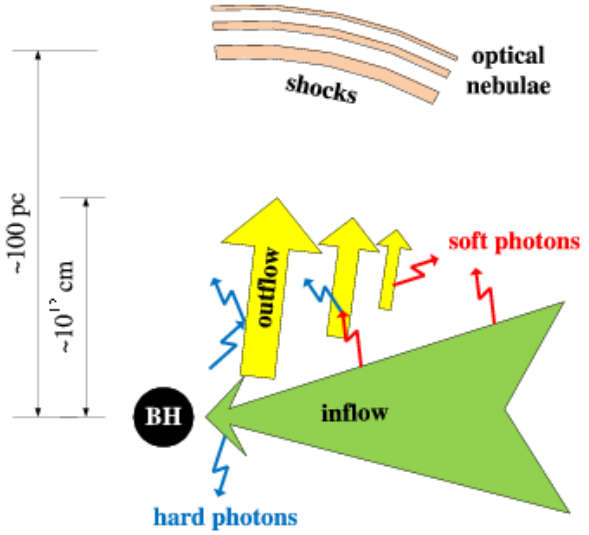
MAY ALSO BE SOURCES OF HIGH ENERGY NEUTRINOS

BH-HMXBs IN STAR-FORMING GALAXIES OF LOW METALLICITY

Spectra

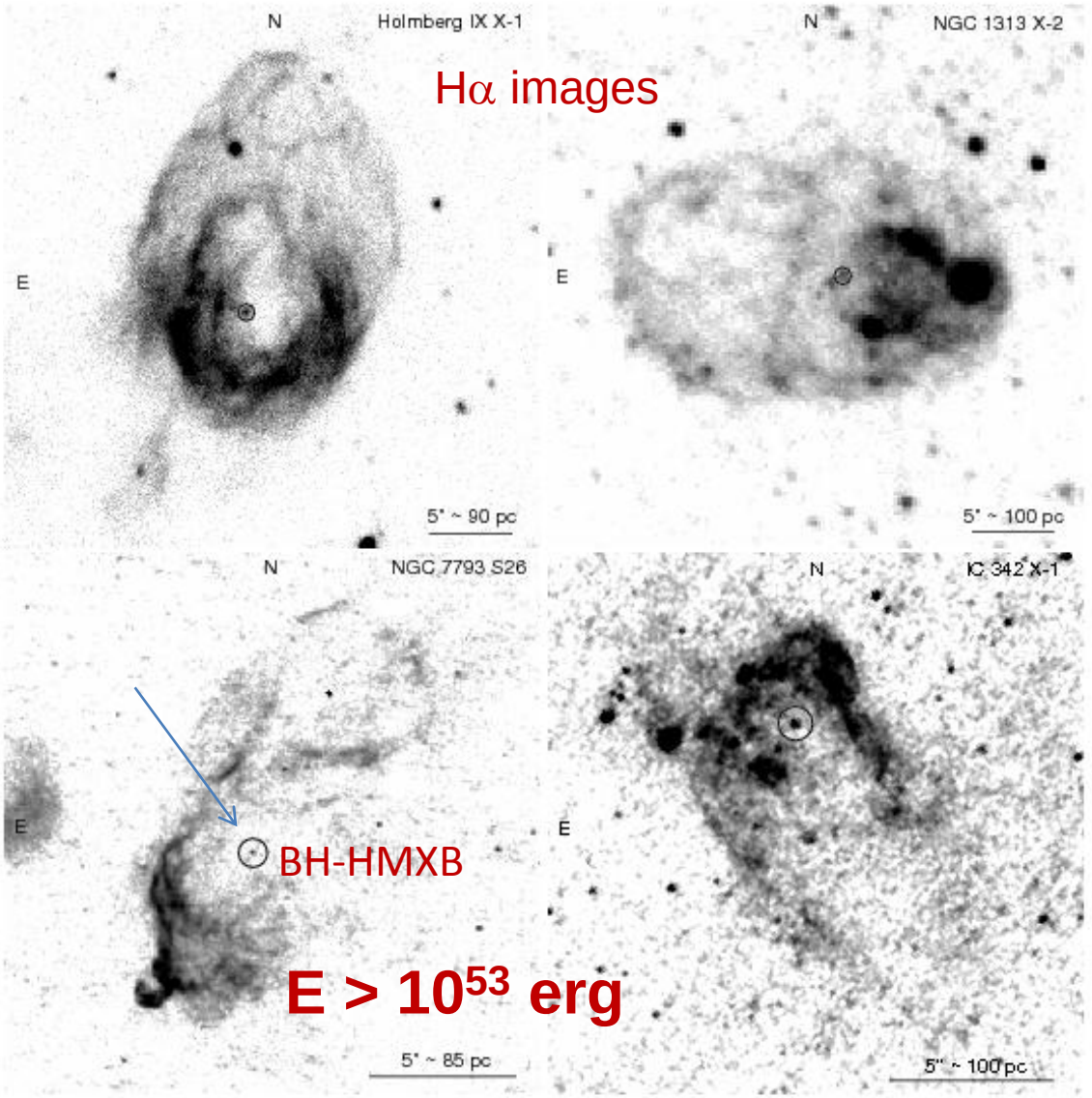


Massive outflows



From Feng & Soria (2011)

shock & photonionized bubbles of > 100 pc size



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

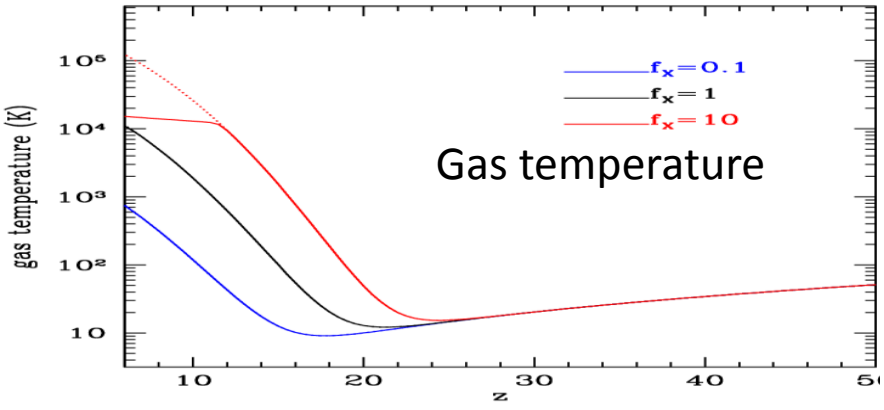
$$L_{2-10} = f_X \times 3.5 \times 10^{40} SFR \quad erg/s$$

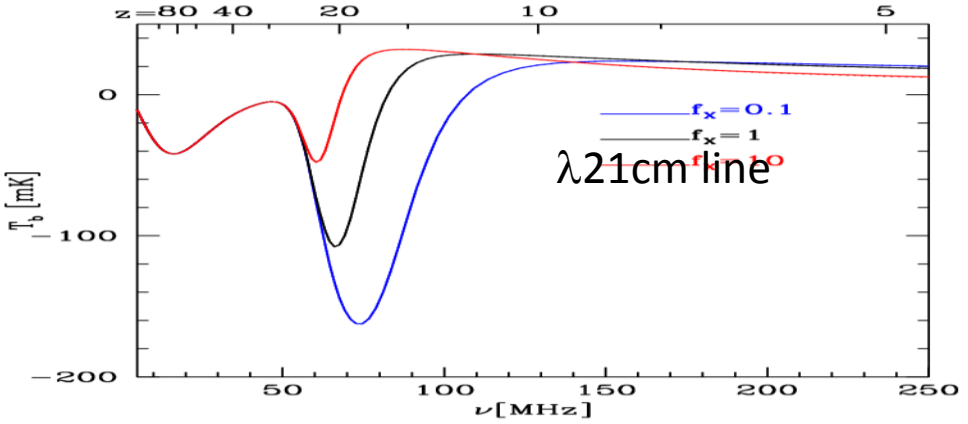
f_x does not seem to change up to z=4

Correlation between X-ray luminosity and SFR. f_x = 0.2 at z=0 (Grim, Gilfanov, Sunyaev, 2003), 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 should increase at z > 6





•DID BH-HMXBs HEATED THE IGM ABOVE 10^4 K OVER LARGE VOLUMES?

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

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

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

ρ_c = critical mass density for a flat universe, r = mass density in the galaxy
m = 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 a certain mass ($10^x M_\odot$) could not accrete gas from IGM.

- **NAKED HALOES OF < $10^8 M_\odot$ HOULD EXIST IN THE 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 SOLVING INCONSISTENCIES OF THE λCDM**

GENERAL CONCLUSION

STELLAR EVOLUTION, MICROQUASARS IN NEARBY GALAXIES, AND HIGH ENERGY ASTROPHYSICS OF COMPACT OBJECTS SHOULD BE INCORPORATED IN THE MODELS OF COSMIC EVOLUTION, TO KNOW HOW THE DARK AGES CAME TO AN END

REFERENCES RELATED OF 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

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 only significantly take place at very high redshifts (z>6), which is consistent with Dijkstra, Gilvanov, Loeb, Sunyaev (2012) and Cowie, Barger Hasinger (2012).