STELLAR BLACK HOLES WITH SKA-LOFAR

I.F. Mirabel (CEA-Saclay)

I) HOW ARE FORM STELLAR BLACK HOLES?
II) FEEDBACK FROM StBHs DURING THE EoR?
III) SOLITARY BHs DETECTED WITH SKA?

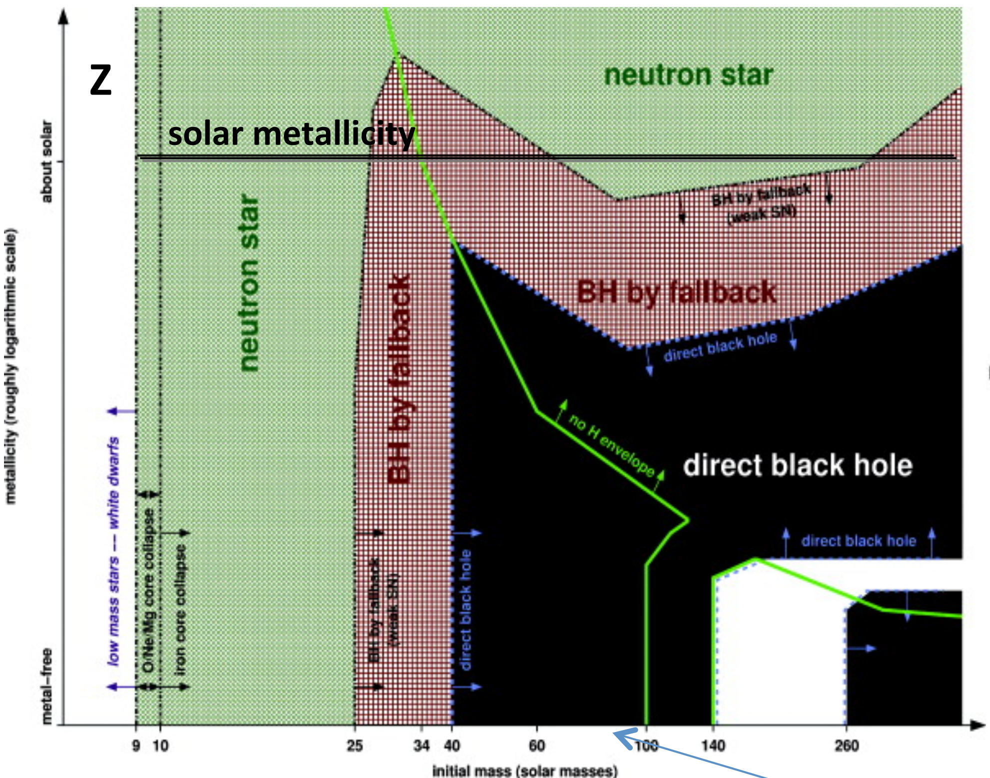
I. **Formation mechanisms of stellar black holes:** long term proper motion of compact binaries using SKA in VLBI networks (10-30 GHz) will complement GAIA in the observational constraints of the formation mechanisms of stellar black holes.

II. **Feedback from stellar black holes** will impact in the LOFAR & SKA tomography of HI during the Epoch of Reionization (EoR).

III. **Solitary Stellar black holes** could be detected with SKA as faint high proper motion radio sources (Fender, Maccarone, Heywood, 2013)

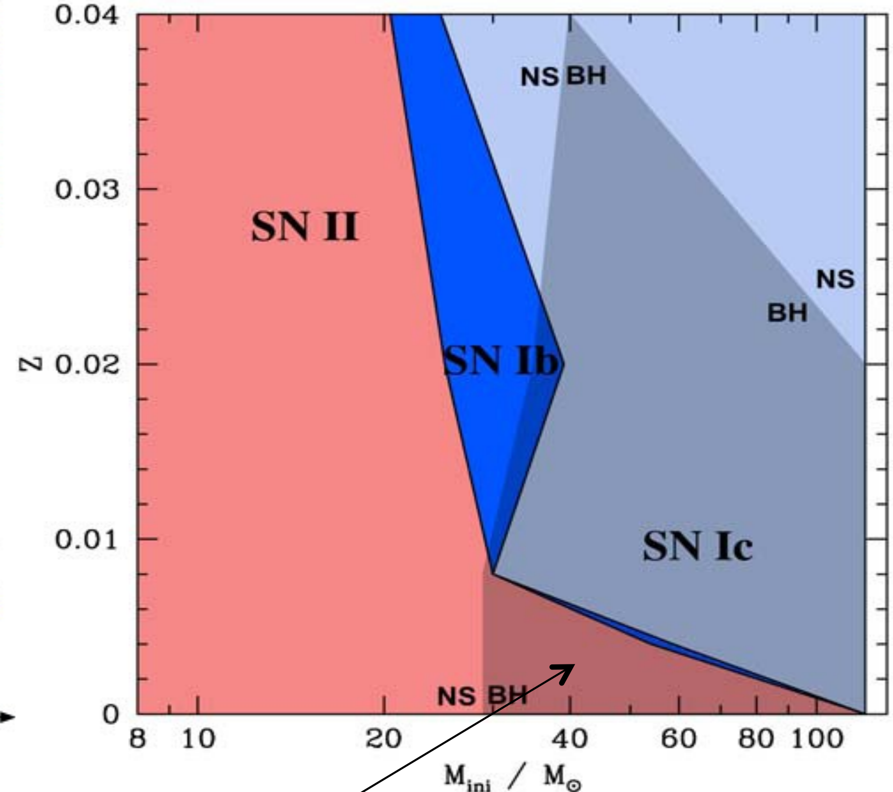
I) FORMATION OF BLACK HOLES BY THE COLLAPSE OF MASSIVE STARS

with no rotation (Heger+ 2003)



Mass of progenitor star

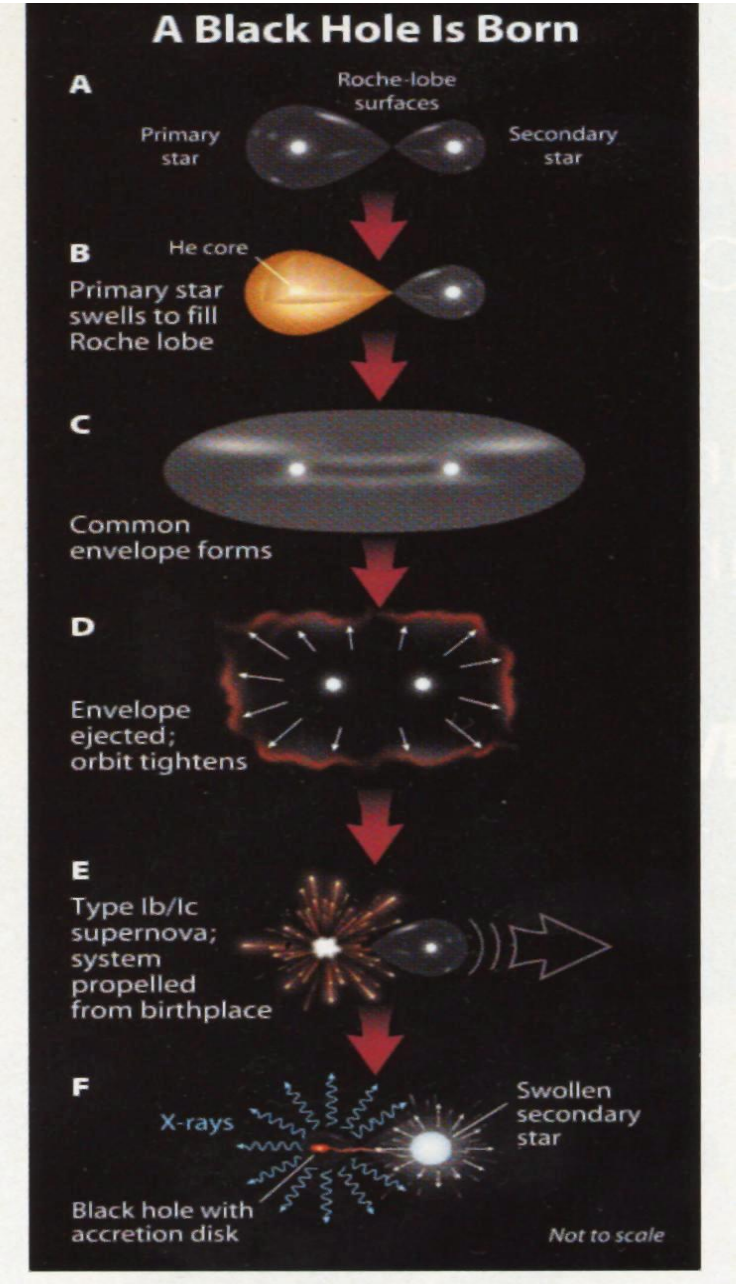
with rotation (Georgy+ 2009)



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

Presently, there are no observational constraints to the current model

STELLAR BLACK HOLES ARE OBSERVED IN BINARIES



CORE COLLAPSE MODELS:

Massive stellar black holes ($M>10\ M_{\odot}$) should form with no energetic kicks (Fryer & Kalogera; Woosley & Heger; Nomoto et al.)

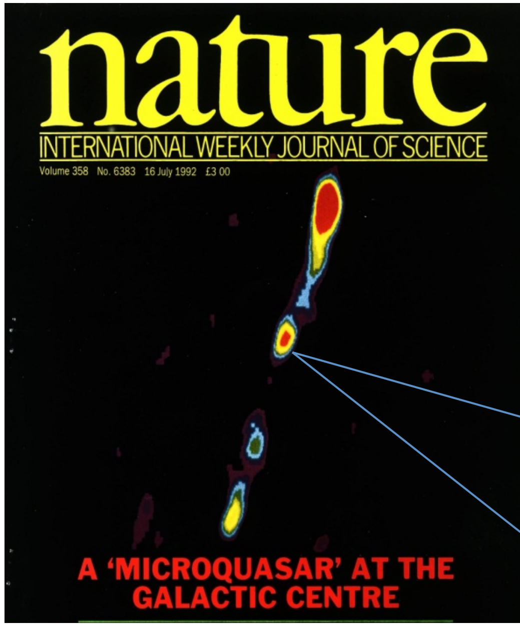
- **IS THERE ANY EVIDENCE OF StBH FORMATION BY DIRECT COLLAPSE?**
- **IS THERE A RELATION BETWEEN KICK VELOCITIES AND BH MASS?**

THE CORE COLLAPSE MODELS CAN BE TESTED USING THE KINEMATICS OF μQSOs

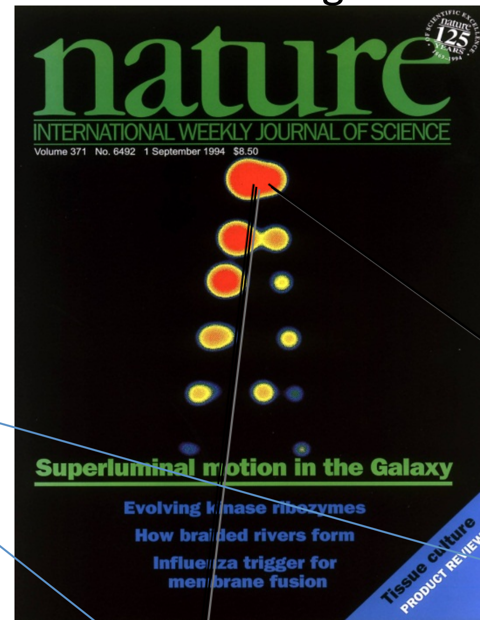
Mirabel et al. (2001-2009)

PROPER MOTIONS USING COMPACT JETS

Mirabel, Rodriguez+ 1992



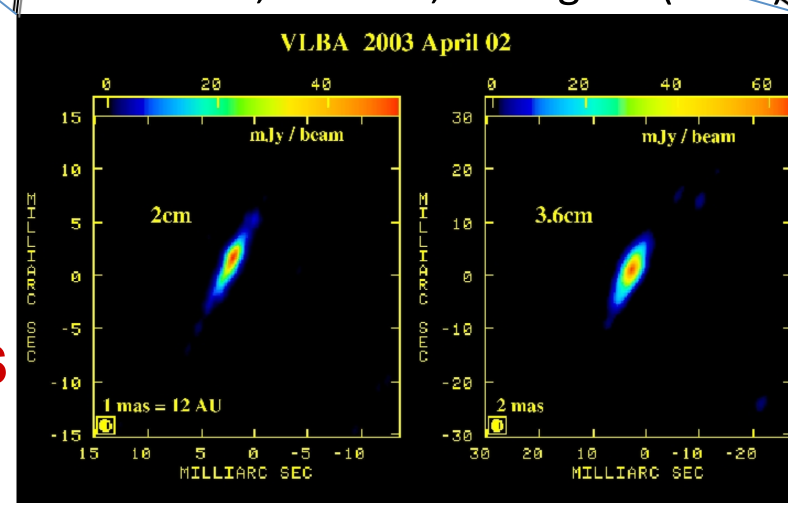
Mirabel & Rodríguez 1994



STEADY JETS

TRANSIENT JETS

Dhawan, Mirabel, Rodríguez (2007)



COMPACT JETS

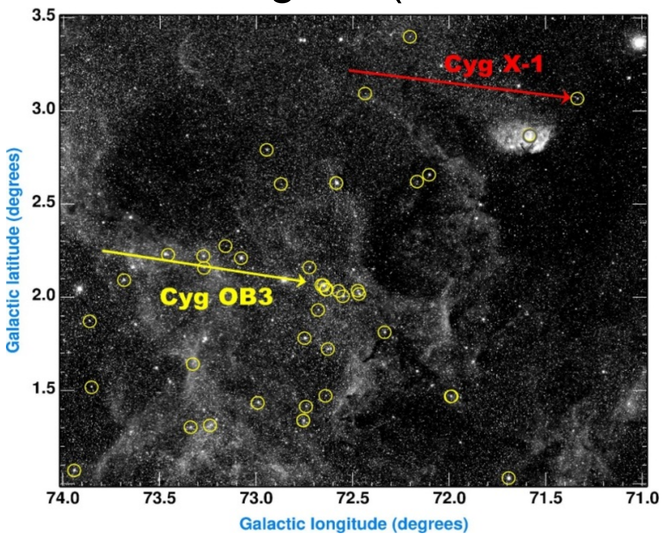
In low hard state. Size ~ 100 AU. Same PA

USED TO DETERMINE PROPER MOTIONS

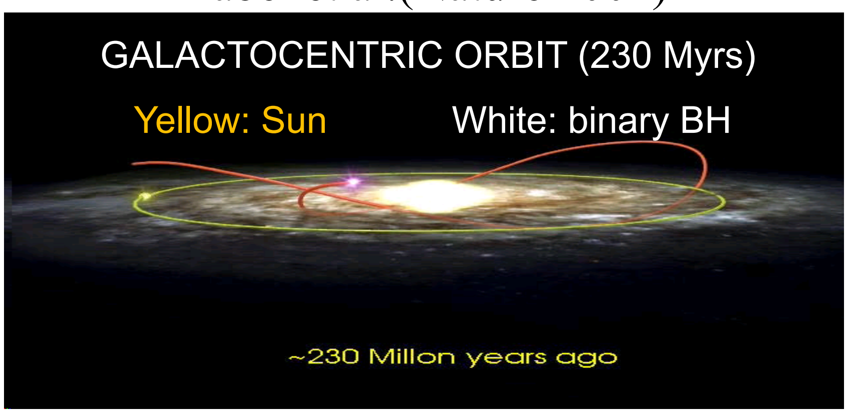
(with VLBI to get sub-miliarc sec precision)

RESULTS FROM FIVE BH-XRBs

Mirabel & Rodrigues (Science, 2003)



Mirabel et al.(Nature 2001)



Cygnus X-1

V_p< 9+/-2 km/s ⇒ < 1 $M_\odot$ ejected in a SN

together with

GRS 1915+105 & V404 Cyg

suggest that

BHs WITH >9 $M_\odot$ MAY FORM IN THE DARK

XTE J1118+480; GRO J1655-40

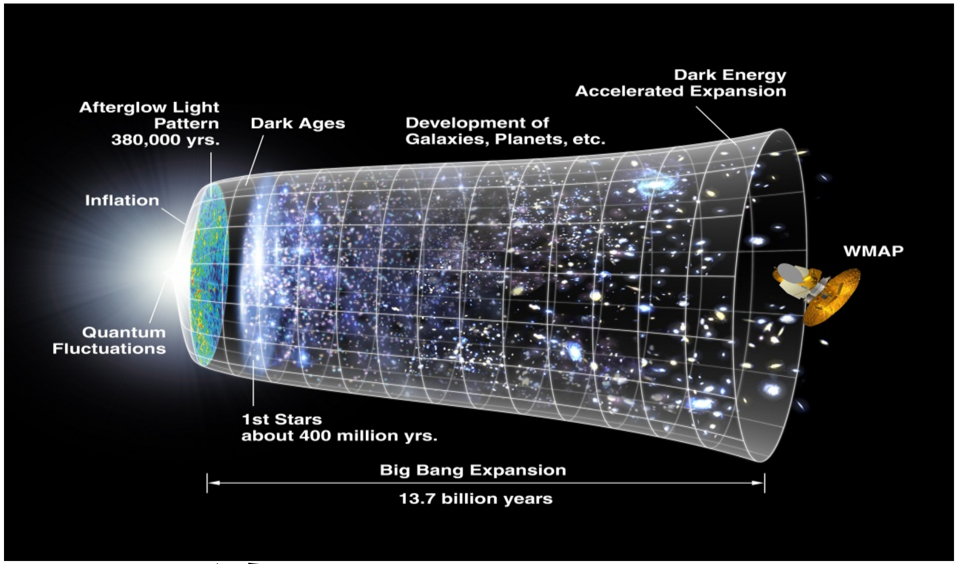
WITH BHs OF < 9 $M_\odot$

are

RUNAWAY BLACK HOLES

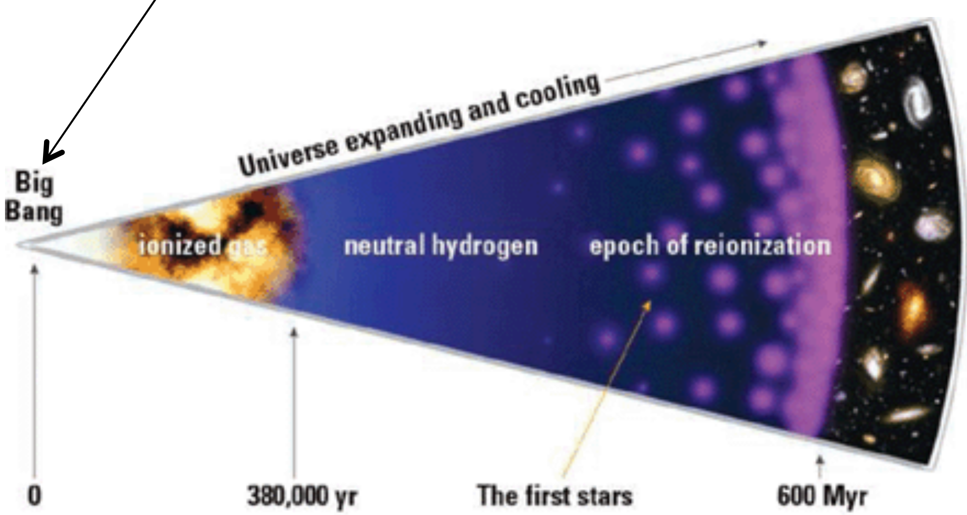
THE STATISTICS WILL BE IMPROVED WITH GAIA (V<20 mag) & SKA IN VLBI NETWORKS

2) FEEDBACK FROM HMXBs IN THE EoR



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.



Because the evolution of massive stars is metallicity driven I proposed that

In the first galaxies (z > 10) a large fraction of Pop III-II stars ended as High Mass X-Ray Binaries (HMXBs). The X-rays overtake the HII regions heating and partially ionizing the IGM over large volumes of space.

FROM STUDIES OF HMXBs IT IS CONCLUDED

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

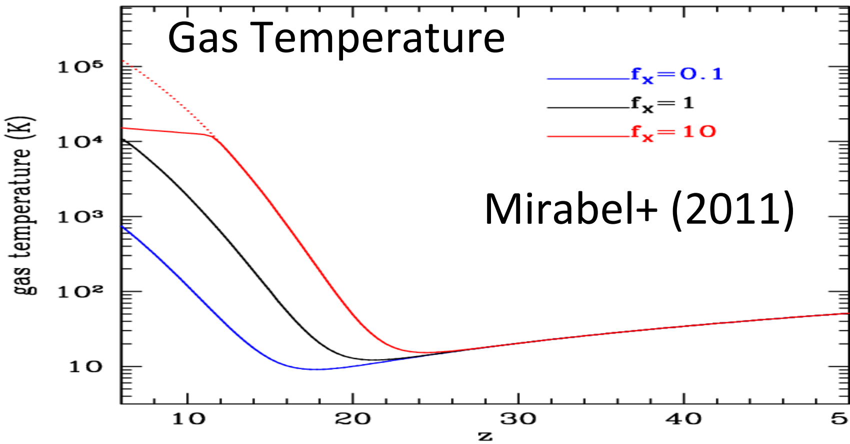
Mirabel. Invited Review. Proceedings of IAU Symp. 275 (2011)
(arXiV:1012.4944v1 [astro-ph.CO] 22 Dec 2010)

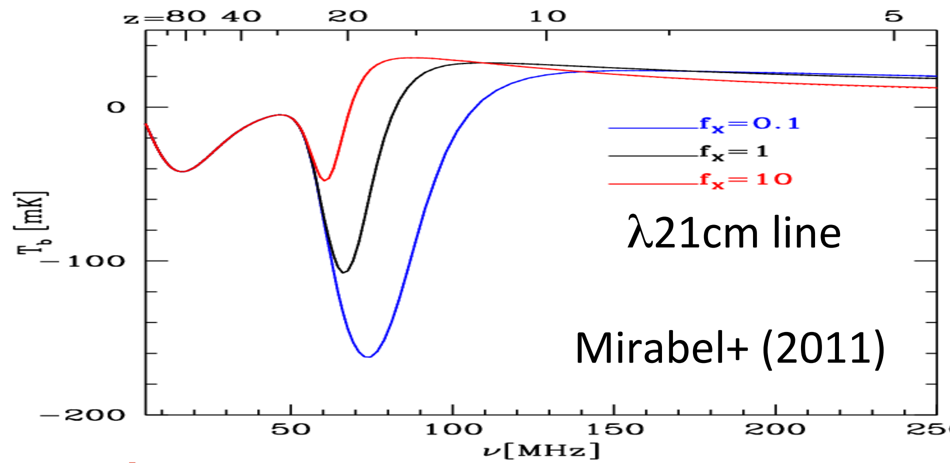
HMXBs & HI TOMOGRAPHY DURING THE EoR

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

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

For $Z < 10^{-5} Z_\odot$ the IMF is top heavy and flat ⇒ f_x must increase at z > 6



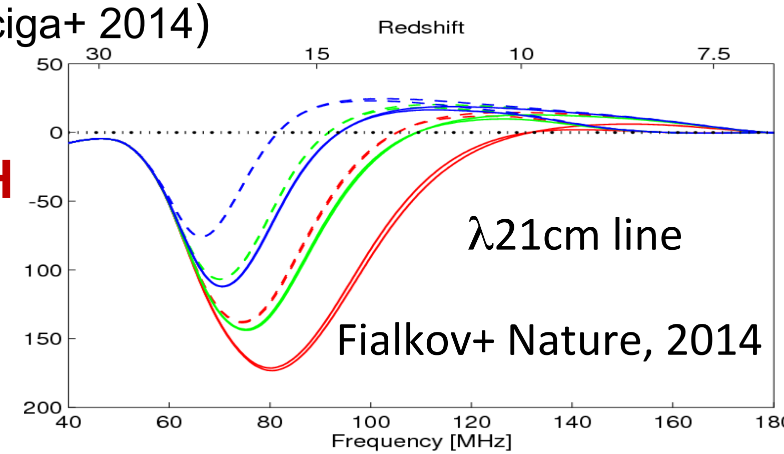


BH-HMXBs HEATED THE IGM TO ~10^4 K OVER LARGE VOLUMES

At z=8.9 the IGM was already heated and ionized (Paciga+ 2014)

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.



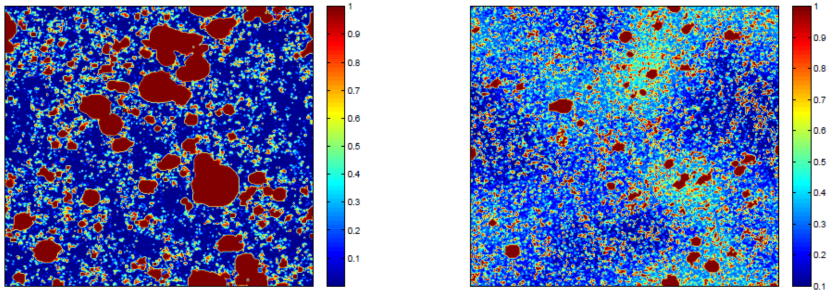
OPEN QUESTIONS

I) Will the λ21cm signals from HI at high z (to be measured with LOWFAR, SKA, and single dipole experiments as EDGES), have lower amplitudes and be more uniform, rather than HII region dominated with 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

λ21cm tomography (Visbal & Loeb, 2011)

X-rays=0 ⇒ large fluctuations



X-rays=50% ⇒ lower fluctuations due to more uniform heating

II) Could the BH-HMXBs with emission up to 2 MeV -as in Cyg X-1-, that formed at z>7, contribute significantly to the 10-20% unresolved hard X-ray background?

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

IV) Did the heating the IGM to ~10^4 K reduced the number of dwarf galaxies predicted by the λCDM?

V) Are there naked haloes with $M < 10^{8-9} M_\odot$

Ionizing power of μQSOs versus ionizing power of massive stars

Counting photons Mirabel (IAFE), Laurent (Saclay), Loeb, Diskra, Pritchard (Harvard)

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

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…

BH-HMXBs LIMITED THE MASS OF DWARF GALAXIES

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

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

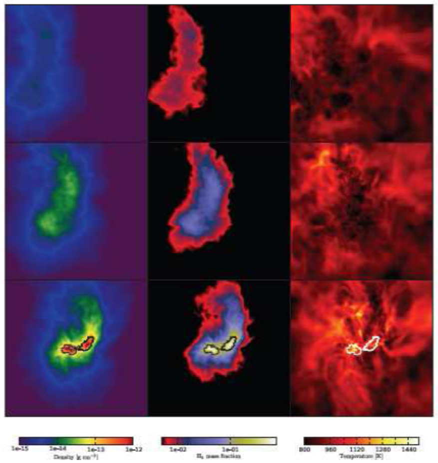
ρ_c = critical mass density for a flat universe, r = mass density in the galaxy

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

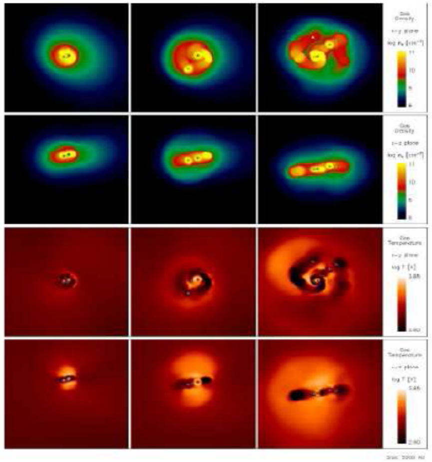
X-ray heating of the diffuse IGM during reionization resulted in an additional increase of the minimum galaxy mass. Once the IGM was heated to ~10^4 K by the X-rays from the first generations of BH-HMXBs, dark matter haloes with masses below a certain mass (10^x $M_\odot$) could not accrete gas from 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, REDUCING THE NUMBER OF DWARF GALAXIES PREDICED BY THE λCDM**

MASSIVE STARS OF 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 $M_\odot$**
- **This is consistent with no signatures of PISNe in the halo** (Becker+2011; Frebel,2011)

OBSERVATIONS

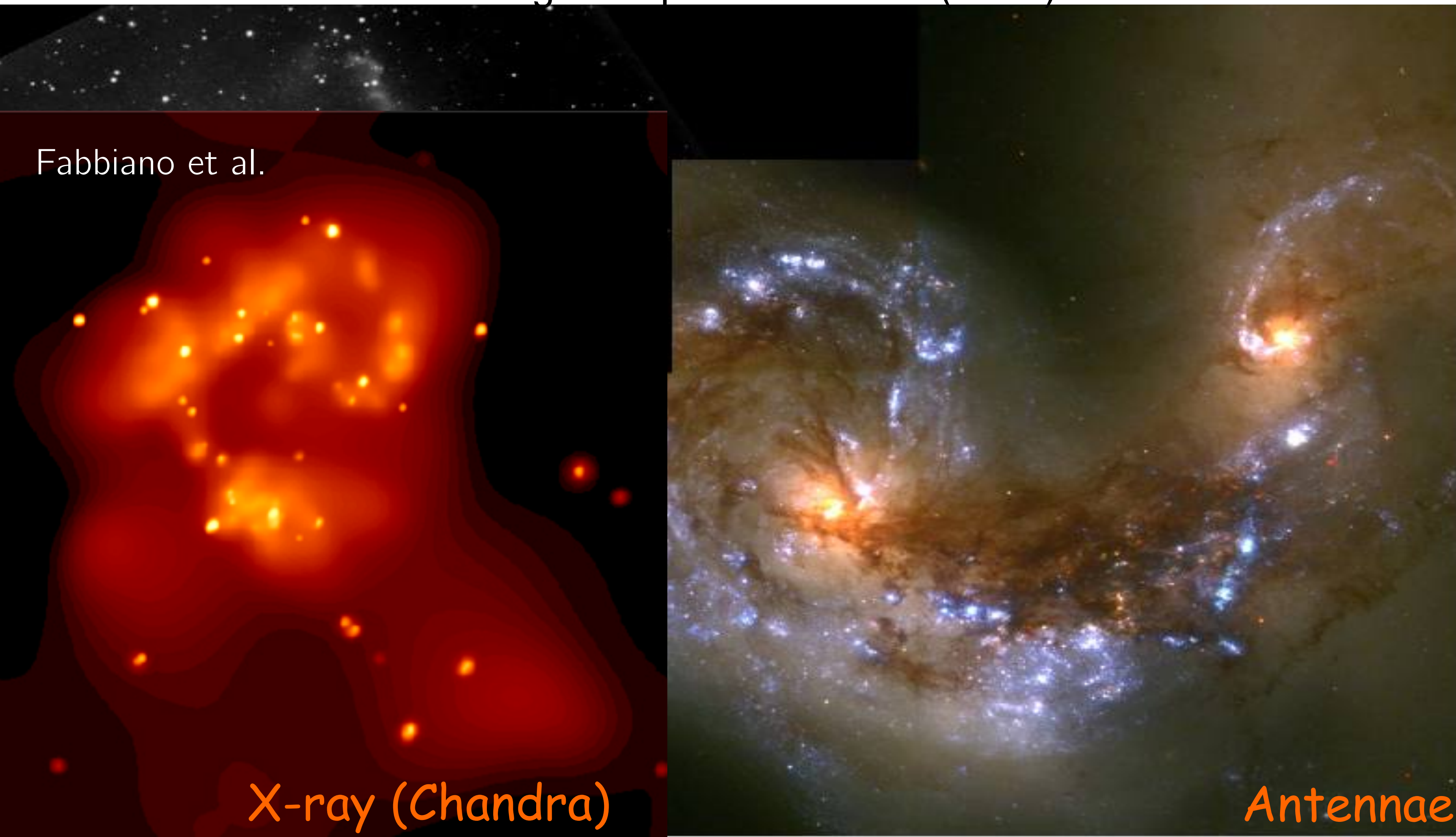
- **In the MW >70% of OB type stars are binaries** (Chini+ 2011; Sana+ Science 2012)

DID A LARGE FRACTION OF Pop III & II STARS END AS BHs ?

ULTRALUMINOUS X-RAY SOURCES (ULXs)

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

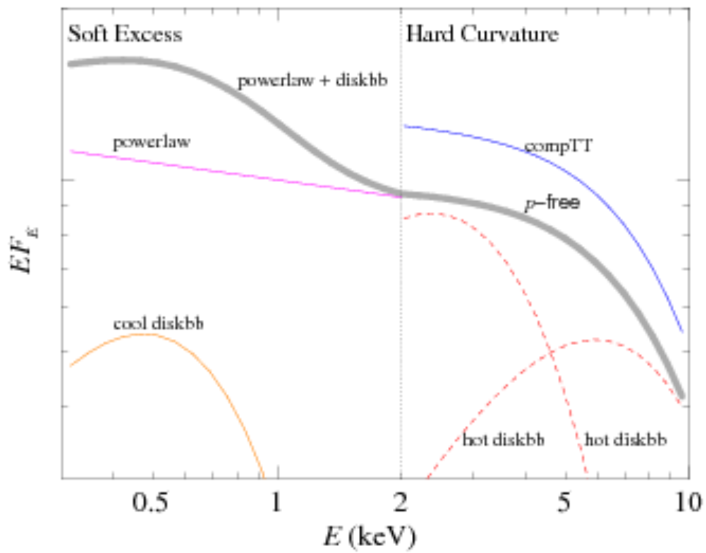
e.g. Zampieri & Roberts (2009)



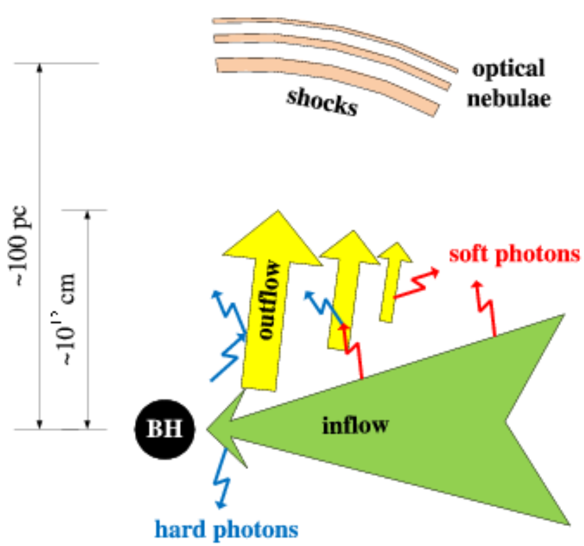
BH-HMXBs IN STAR-FORMING GALAXIES OF LOW METALLICITY

e.g. the local templates of primeval galaxies

From Feng & Soria (2011)



Massive outflows



shock & photonionized bubbles of > 100 pc size