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

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; But are caveats!
- **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)

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

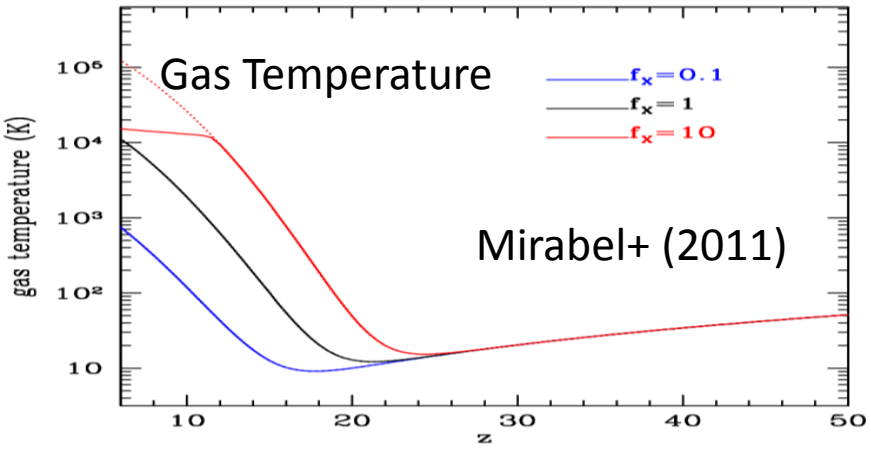
- But in a fully neutral medium **N_{sec*} = 25 (E_γ /1 keV),** where E_γ is the photon energy

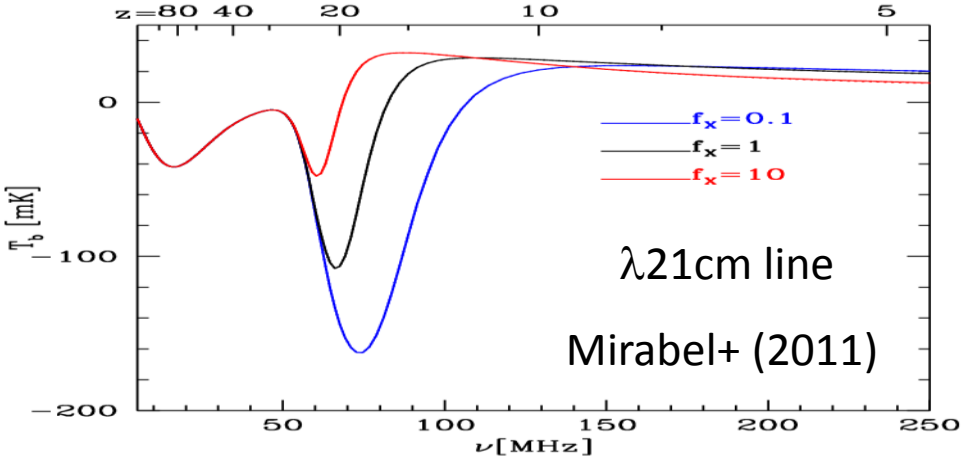
However, not all stars will be massive and lead to the formation of BH-HMXBs…

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 $Z < 10^{-5}\ Z_\odot$

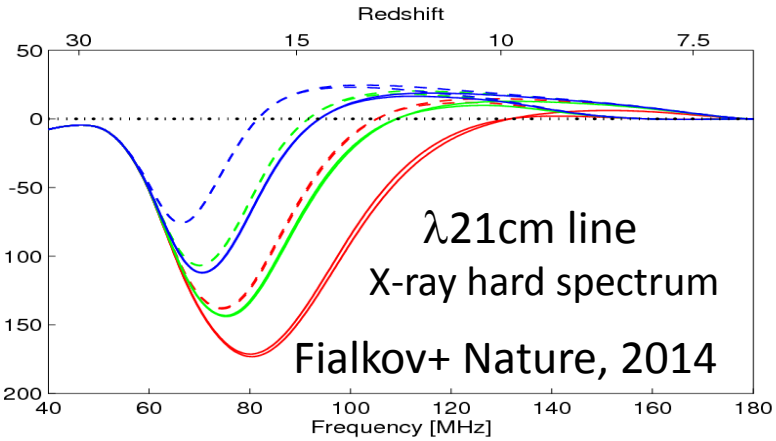




BH-HMXBs HEATED THE IGM TO ~10^4 K OVER LARGE VOLUMES

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.



X-RAY IMPACT ON THE 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**

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 is a population of naked dark matter haloes with M <10^9 $M_\odot$**