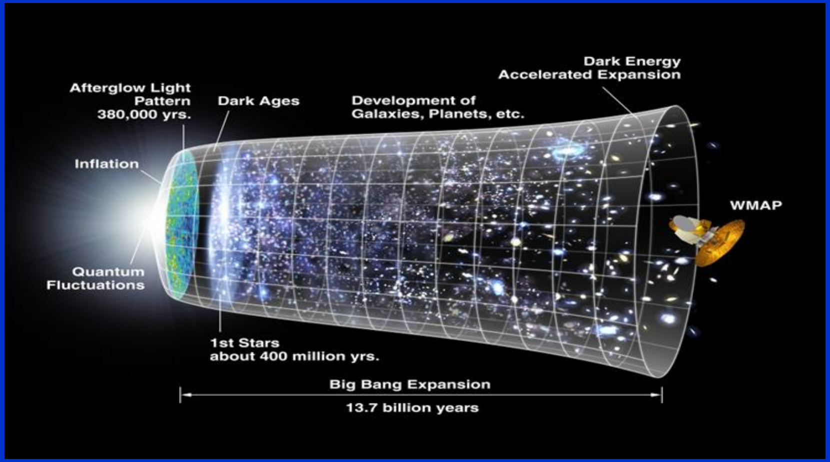
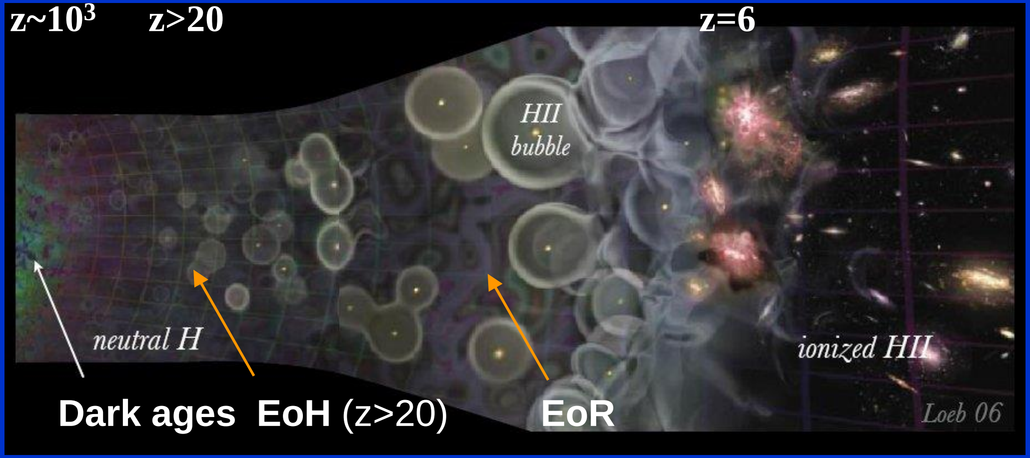
STELLAR BLACK HOLES AT COSMIC DAWN

I.F. Mirabel (DAP-CEA & IAFE-Argentina) & Ph. Laurent (DAP-CEA)

« SWISS CHEESE » MODEL ⇒ PATCHY STRUCTURE





Cosmic Dawn: when first stars and BHs of Pop III are formed in **<2x10^7yrs (EoH)**

Mirabel, Diskra, Laurent, Loeb and Pritchard (A&A 2011)

Propose that BH-HMXBs are prolifically formed in the EoH and EoR

⇒ Hard X-Rays from BH-HMXBs pre-heat the IGM before EoR is finish

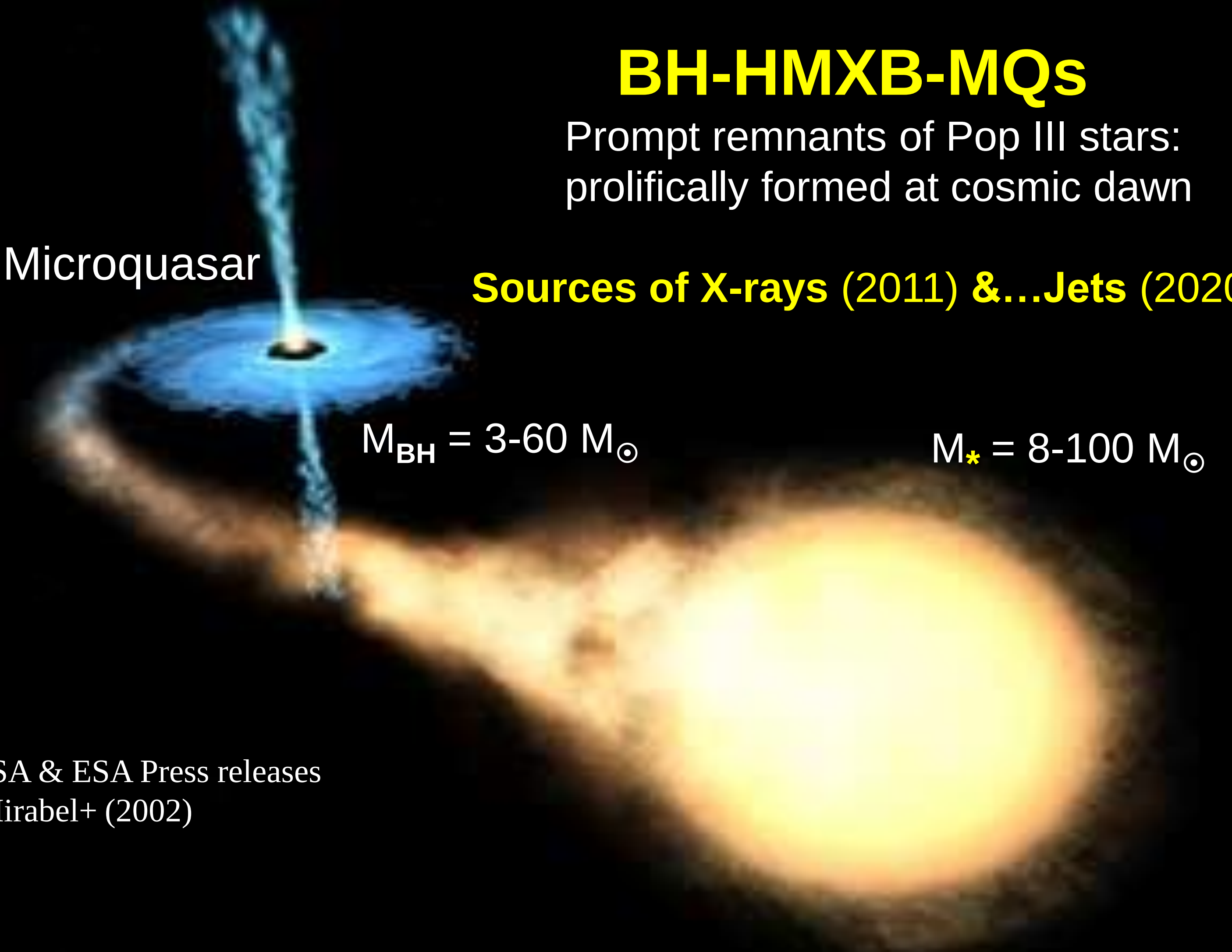
⇒ A smoother end of reionization News & Views in Nature by Haiman (2011)

STELLAR BLACK HOLES IN HMXBs

BH-HMXB-MQs

Prompt remnants of Pop III stars:
prolifically formed at cosmic dawn

Sources of X-rays (2011) **&…Jets** (2020)



$M_{BH} = 3\text{-}60\ M_{\odot}$

$M_{*} = 8\text{-}100\ M_{\odot}$

Credit: NASA & ESA Press releases
Mirabel+ (2002)

If M_{*} >18 $M_{\odot}$ BH-HMXBs are a transition phase in the formation of BBHs

ASTROPHYSICAL GROUNDS FOR A PROLIFIC FORMATION OF BH-HMXBs AT COSMIC DAWN

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 BY DIRECT COLLAPSE**
  Fryer,1999;Heger+2003;Georgy+2009;Woosley+2008;Nomoto+2010;Linden,Kalogera+2011

OBSERVATIONAL GROUNDS

- **BHs FORM WITH NO ENERGETIC SNe⇒BHs & DONORS REMAIN BOUND**
  Mirabel & Rodrigues, Science 2003; Mirabel+ Nature 2008

- **MOST ULXs & LGRBs ARE HOSTED IN LOW Z-HIGH-SSFR GALAXIES**
  Feng & Soria,2011;LeFloc'h,Duc,Mirabel;2003;Fruchter+ Nature, 2006; Perley+ 2014

- **IN LOW Z GALAXIES Lx/SFR IS LARGER THAN IN MAIN-S GALAXIES**
  Thuan+ 2004; Kaaret+ 2014; Brobry+ 2018; Douna, Pellizza & Mirabel (2015, 2018)

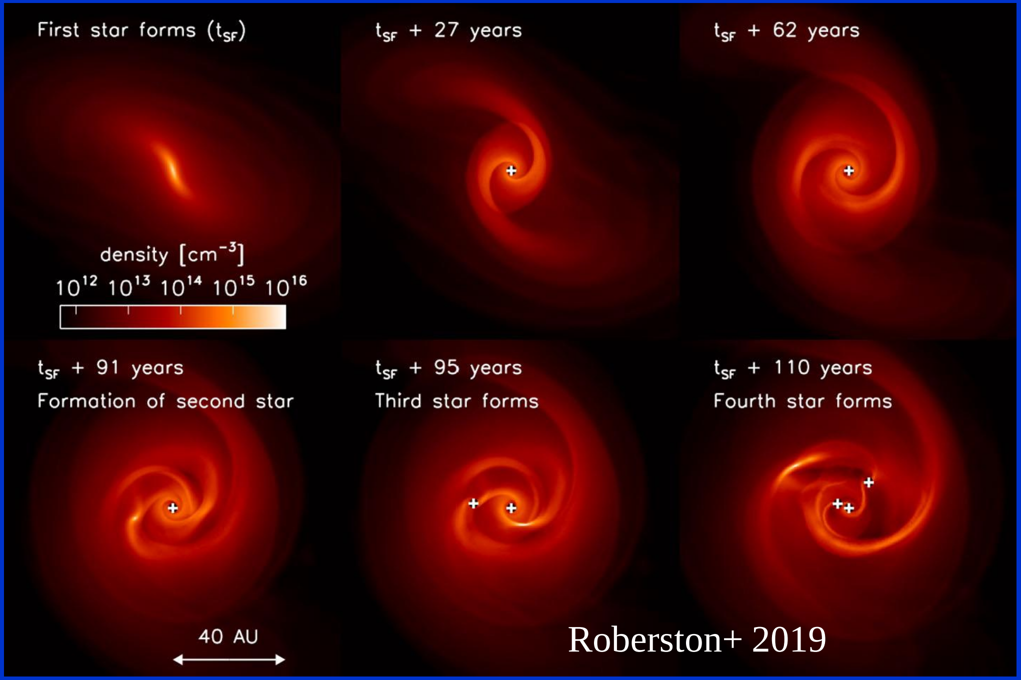
- **Lx/SFR EVOLUTION WITH z IS DRIVEN BY Z EVOLUTION IN BH-HMXBs**
  Fragos+2012; Basu-Zych+2012; Lehmer, Basu-Zych, Mineo+ (2016); Fornasini+ (2019)…
  up to z~2.5 $L_{2\text{-}10\ \mathrm{keV}}$ (HMXB)/SFR α $(1 + z)$

&

- **HIGH MASSES AND HIGH MERGER RATE OF BBHs** (LIGO-Virgo)
  up to 50 $M_\odot$ BBH merger rate R = 53.2 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Reviews by Mirabel (2017 & 2019)

1) MASSIVE STARS ARE FORMED IN BINARIES & MULTIPLE SYSTEMS



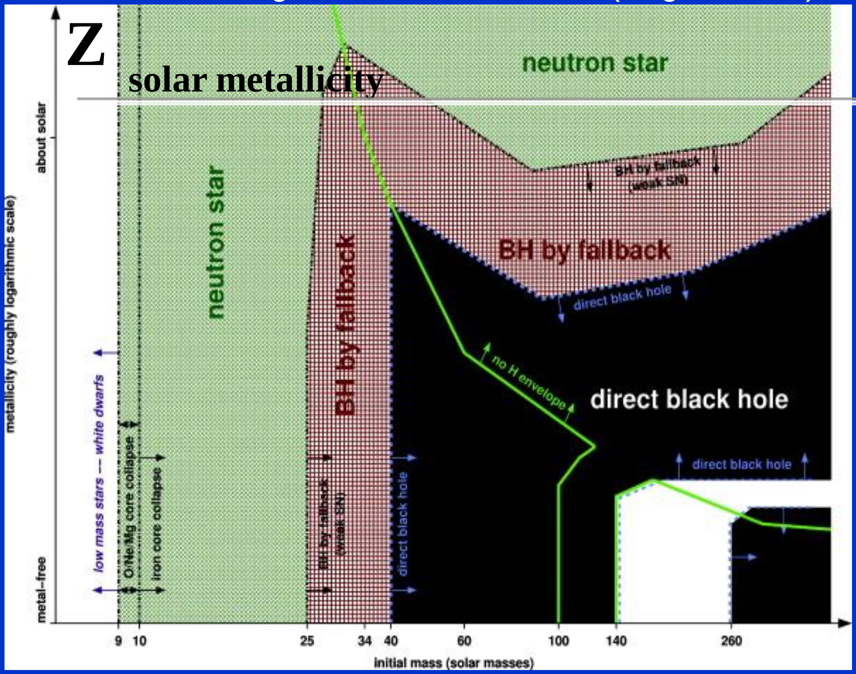
Roberston+ 2019

Observations: >90% are in binaries and multiple systems. In the MW Sana+ (2017) and in the LMC ~63% pre-interacting systems, ~17% as semi-detached systems, and ~20% as systems in close contact phase (Mahy+ 2020)

Models: N-body simulations of stellar clusters at $Z=0.0002\ Z_\odot$ show that the IMF is top-heavy, with most of the mass locked up in stars of a few tens up to ~70 $M_\odot$ (Sugimura+ (2020). When coupled with binary population synthesis it is found that **BHs are formed with masses up to ~60 $M_\odot$** and <0.1% with intermediate masses of up to ~140 $M_\odot$ from merged stars (Di Carlo+ 2020)

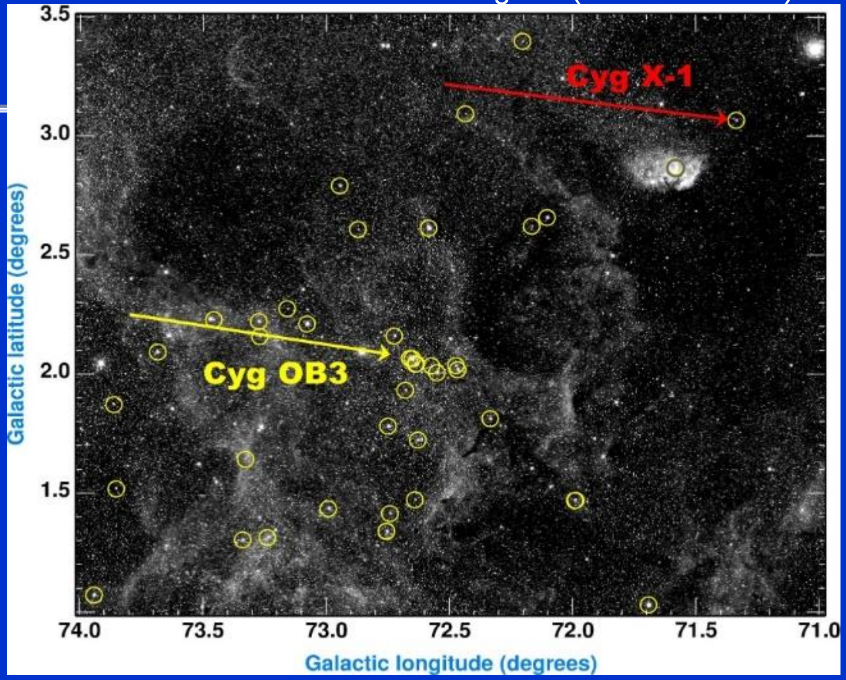
2) STELLAR BHs FORMED BY IMPOSION OF MASSIVE STARS

MODEL: for single star with no rotation (Heger+ 2003)



Mass of progenitor star

OBSERVATION: Mirabel & Rodrigues (Science 2003)



Generally observed in BHs of >10 $M_\odot$ (Mirabel 2017)

The BH of ~15 $M_\odot$ in the BH-HMXB Cygnus X-1 was formed by failed SN/direct collapse of a star of ~40 $M_\odot$

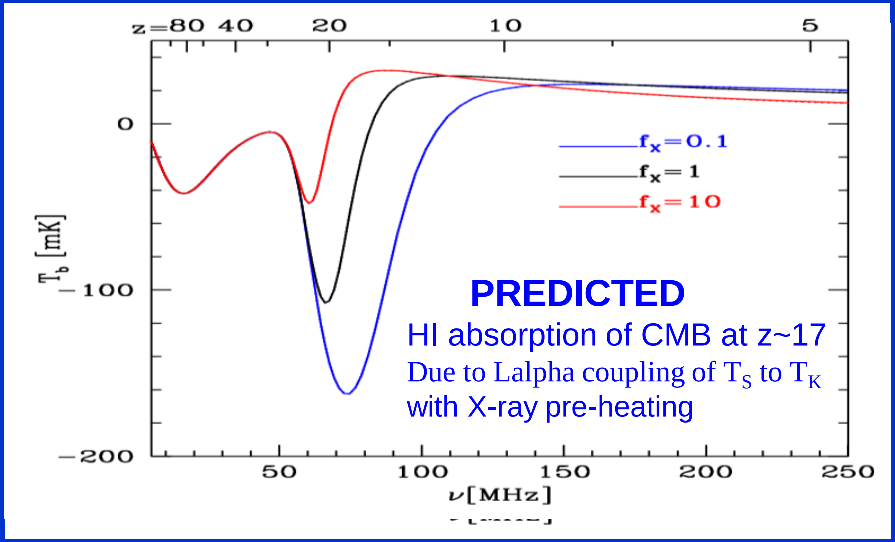
D =1.86 ± 0.1 kpc; M_{BH} =14.8±1.0 $M_\odot$; Donor=O9.7 lab of 19.2±1.9 $M_\odot$; P=5.6 days; e =0.018±0.003; Progenitor mass ~40 ±5 $M_\odot$

If >90% of massive stars at cosmic dawn are formed in binaries and end as BHs remaining in situ, BH-HMXBs must have been prolifically formed in the EoH

THE INPRINT OF STARS & BHs OF POP III IN HI λ21cm LINE

Global signatures with single dipoles (e.g. EDGES) and Tomography with interferometers (e.g. SKA)

Pritchard & Loeb (2010); Mirabel+ (2011)…

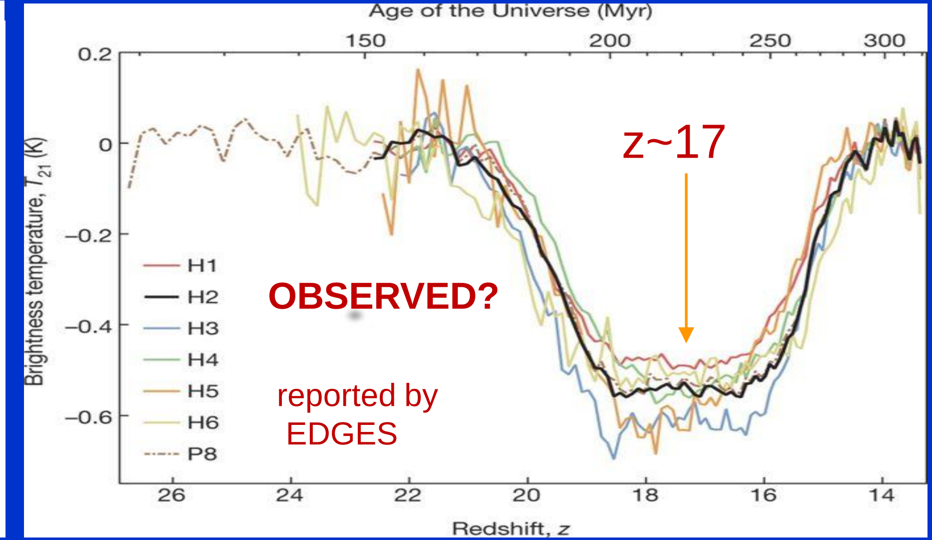


PREDICTED

HI absorption of CMB at z~17

Due to Lalpha coupling of T_S to T_K with X-ray pre-heating

Bowman+ (Nature 2018a)



OBSERVED?

reported by EDGES

The absorption reported by EDGES needs confirmation. If confirmed:

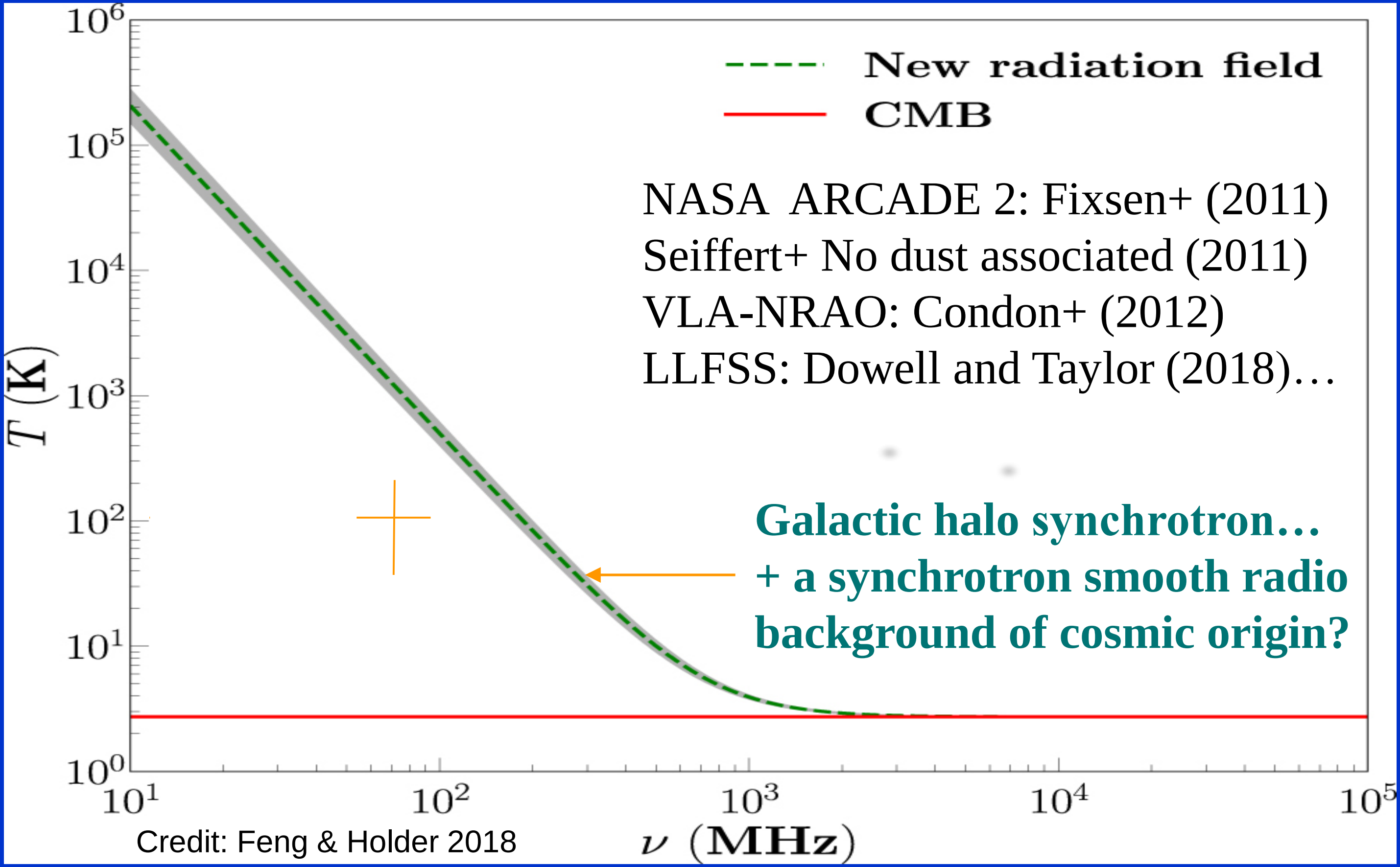
- Absorption at z~18 with $f_X < 0.1 \Rightarrow N_H \sim 5 \times 10^{23}$ cm^{-2} and $T_s \sim 10$ K
- However it is of 2-3 times of larger amplitude & bottom-flat instead Gaussian

- **New physics:** $\delta T_b \propto \{1 - (T_{CMB} / T_s)\}$; $T_s \longrightarrow 0$ by interaction with DM (Barkana 2018…)

- **Astrophysics:** $\delta T_b \propto \{1 - (T_{CMB} + T_{CRB})/T_s)\}$ (Feng & Holder 2018; Ewall-Wice+ 2018)

Is there a Cosmic Radio Background (CRB)? …If so what are the sources?

A low frequency synchrotron background radiation of possible cosmic origin reported by the NASA ARCADE 2 experiment



NASA ARCADE 2: Fixsen+ (2011)
Seiffert+ No dust associated (2011)
VLA-NRAO: Condon+ (2012)
LLFSS: Dowell and Taylor (2018)…

Galactic halo synchrotron…
+ a synchrotron smooth radio background of cosmic origin?

Credit: Feng & Holder 2018

- This CRB is substantially larger than expected from observed radio counts and unresolved emission from the known radio point source population (Condon+ 2012) & is not associated with far-infrared thermal emission from dust (Ysard & Lagache 2012)

- Confirmed by Dowell and Taylor (2018), but >10 larger at 78 MHz than the T_{CRB} from the EoH

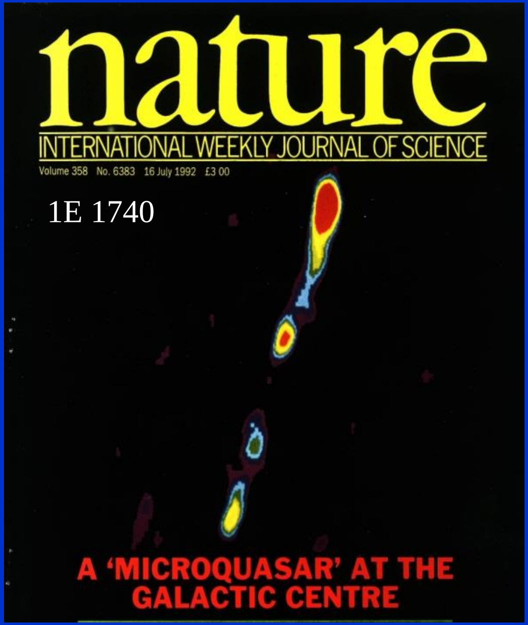
BH-HMXRB-MQs OF POP-III ARE SOURCES OF A CRB

VLA λ3.6 cm

STEADY

JETS

Mirabel, Rodríguez+1992



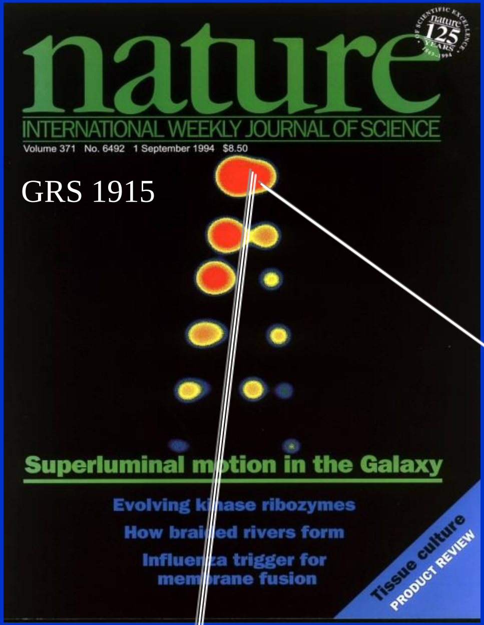
nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 358 No. 6383 16 July 1992 £3 00

A 'MICROQUASAR' AT THE GALACTIC CENTRE

Mirabel & Rodríguez 1994



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INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 371 No. 6492 1 September 1994 $8.50

Superluminal motion in the Galaxy

Evolving kinase ribozymes

How braided rivers form

Influenza trigger for membrane fusion

Tissue culture PRODUCT REVIEW

Luis F. Rodríguez

TRANSIENT

JETS

SYNCHROTRON COMPACT JETS

with VLBA at λ3.6cm sub-marc-sec

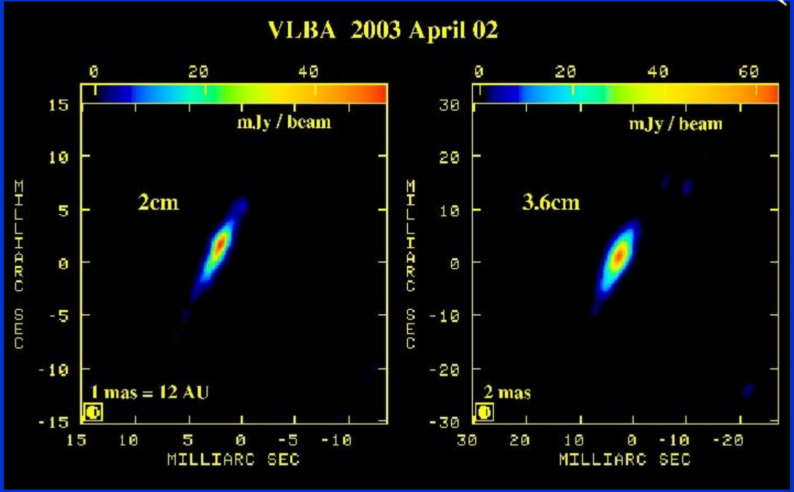
In X-ray low hard state: lengths = $10\lambda_{cm}$AU

LF_{Syn}~730 $(B/10^{-3}G)^{-1/2}$ at 1.42 GHz (Sharma 2018)

for LF_{Syn}~2.6 in Cyg X-1 (Tetarenko+2019)$\Rightarrow$ **B~10^2 G**

Cygnus X-1 is the best studied BH-HMXB-MQ

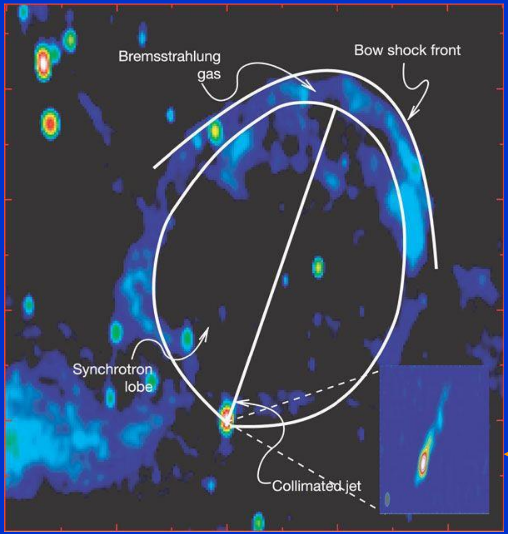
Dhawan, Mirabel, Rodríguez (2000)



VLBA 2003 April 02

BH-HMXB-MQs ARE POWERFUL SOURCES OF SYNCHROTRON RELATIVISTIC COMPACT JETS

Gallo+ (Nature 2005)

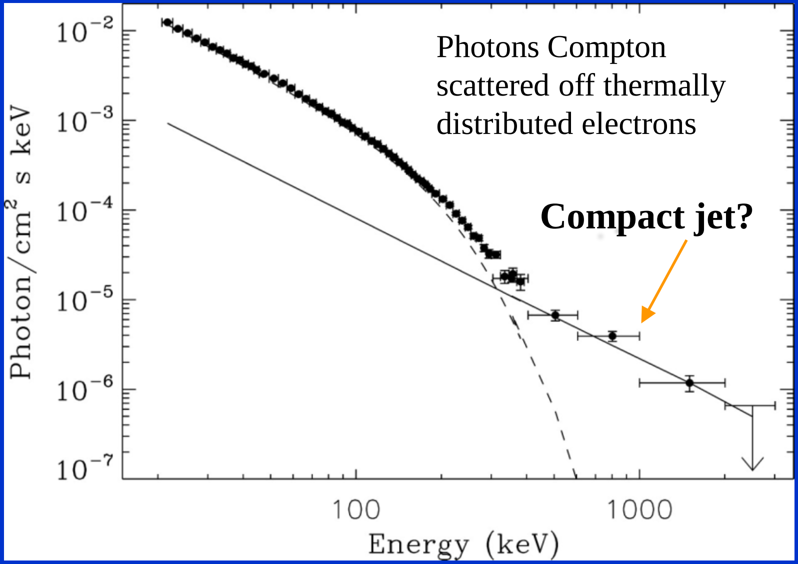


Cygnus X-1

5pc

Compact Jet

Laurent+ with INTEGRAL (Science 2011)



Quasi-steady jet injection of a power
10^36< Pjet <10^37 erg s-1 in 0.02–0.32 Myr
and a total injected energy of ~10^49 erg

B ~10^2 G

Polarization between 0.4 and 2 MeV
75%±32% with IBIS) & 76%±15% with SPI

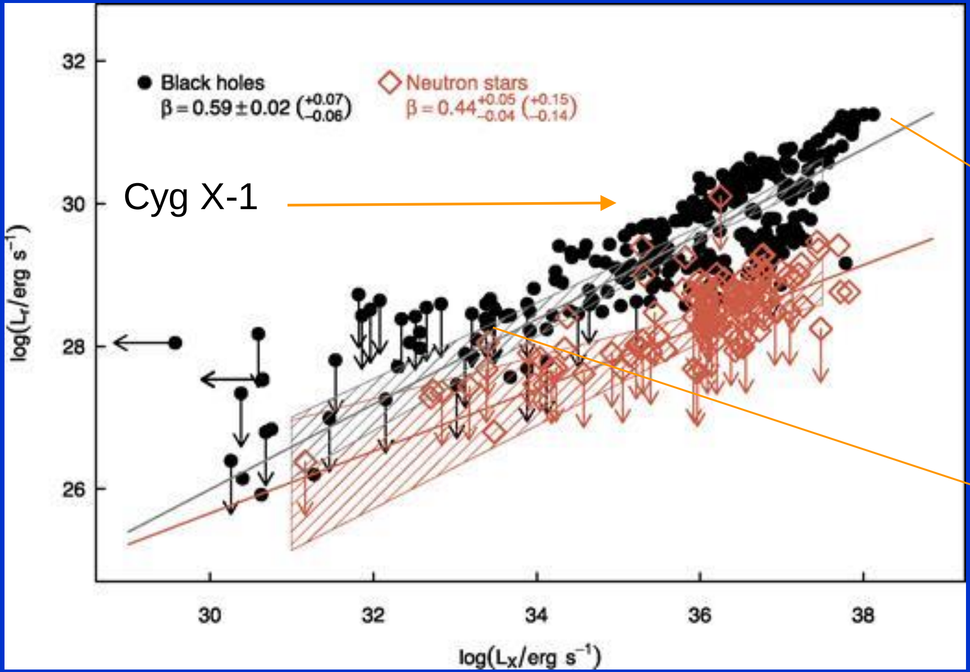
B ~10^4 G close to the BH

$T_{syn}\sim 0.05$ Myr $[(B/10^{-3}\,G)]^{-3/2} = 1.7 \times 10^{-3}$ yr $<< T_{IC} \sim 0.046$ Myr $(B/10^{-3})^{1/2}\,[(1+z)/20]^{-4}$ at $z\sim20$

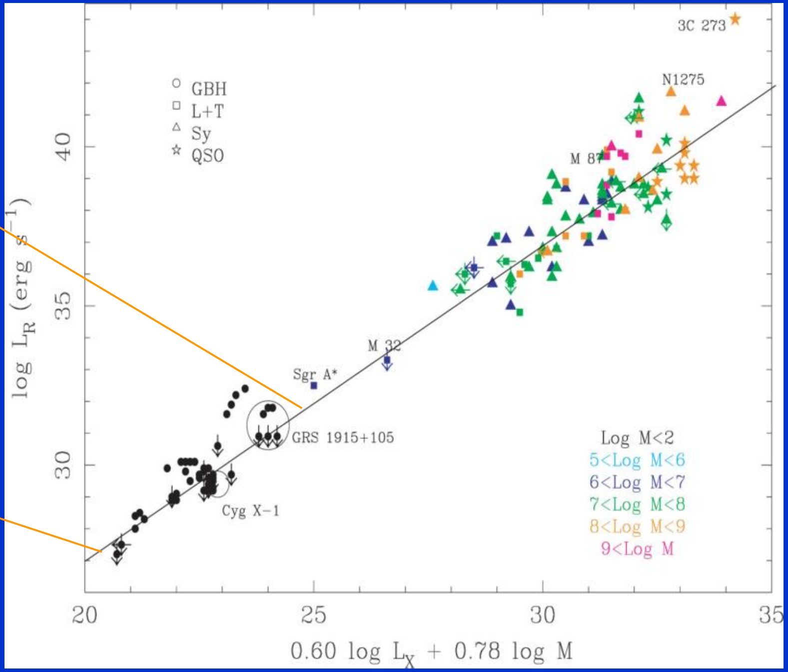
Synchrotron cooling of the BH compact jets dominates over IC cooling by several orders of magnitude, even at the CMB densities at z~20

RADIO/X-RAY CORRELLATION IN BLACK HOLES

Stellar BHs & NSs (Gallo+ 2018)



Merloni+ (2003)….Falcke+ (2004)



BH-XRB-MQs: Log (L_R/erg s^{-1}) ~ 30±1

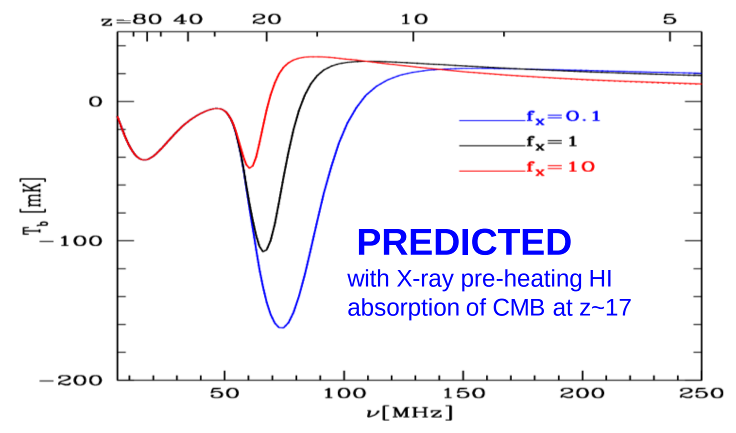
$L_R = 0.60 \log L_X + 0.78 \log M + 7.33$

Cygnus X-1 is a good representative of BH-HMXRB-MQs

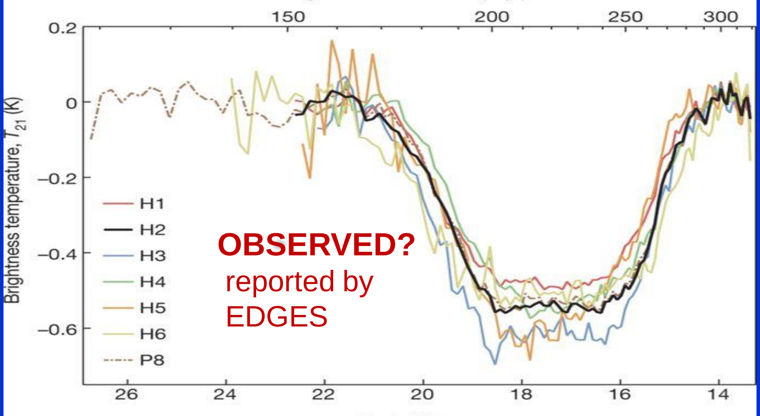
$P_{MS} = 10^{10}(M_{\odot}/M_{*})^{2.5}\,\mathrm{yr}$

NUMBER OF BH-HMXBs FOR THE T_{CRB} REQUIRED BY EDGES

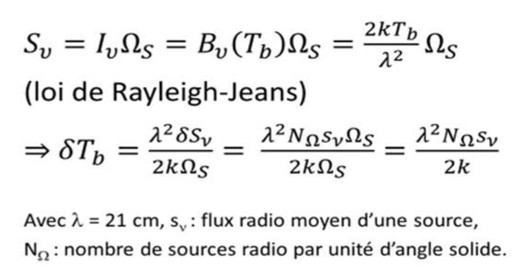
- N



PREDICTED
with X-ray pre-heating HI absorption of CMB at z~17



OBSERVED?
reported by EDGES



$$S_\nu = I_\nu \Omega_S = B_\nu(T_b)\Omega_S = \frac{2kT_b}{\lambda^2}\Omega_S$$

(loi de Rayleigh-Jeans)

$$\Rightarrow \delta T_b = \frac{\lambda^2 \delta S_\nu}{2k\Omega_S} = \frac{\lambda^2 N_\Omega s_\nu \Omega_S}{2k\Omega_S} = \frac{\lambda^2 N_\Omega s_\nu}{2k}$$

Avec λ = 21 cm, s_ν : flux radio moyen d'une source,
N_Ω : nombre de sources radio par unité d'angle solide.

Assuming BH-HMXB-MQs of Pop III are at z=20.5: T_{CMB}=2.7 x (1+z)=58 K. Comparing amplitudes T_{boost}= 3.4

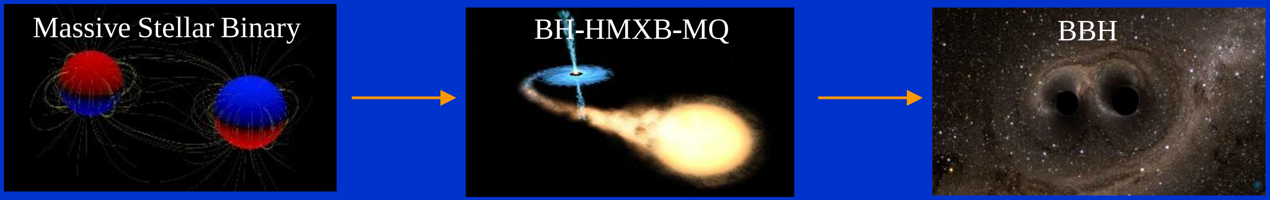
From $\delta T_b \propto \{1 - (T_{CMB} + T_{CRB})/T_S)\}$,
$T_{boost} = 1 + T_{CRB}/T_{CMB} = 3.4 \Rightarrow$ **T_{CRB} ~140 K**

Number of BH-HMXB-MQs as Cyg X-1 formed 10^5 years before z~20 to produce a T_{CRB} =140 K

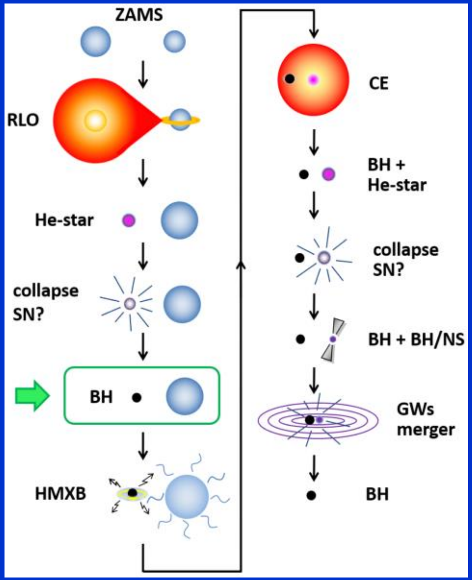
Source	Mean flux 1.4 GHz	N_Ω (n/str)	N_Ω (n/deg^2)	%hard	N_{tot}
Cygnus X-1	14.62 mJy	6,0 10^8	190000	67	**1.1 10^{10}**

FROM THE NUMBER OF BH-HMXB-MQs TO THE NUMBER OF MASSIVE STARS OF Pop III

Mirabel (2019)



Langer+40 (2020)



POP-III BH-HMXB-MQs similar to Cyg X-1 = $1.1x10^{10} \pm 10^{9}$

&

Following the relations by Langer+40 (2020)

~100 BH-HMBs per BH-HMXB-MQ ⇒ **< N1 of BH-HMBs**

~3% of OB stars have a BH⇒ **< N2 of OB stars in the EoH**

These numbers will be upper limits because:

IMF at z>20 is top heavy and BHs more massive than in MW and LMC
(Sugimura+ 2020; Di Carlo+ 2020)

CONCLUSIONS

(in progress)

1) A fraction of Pop III promptly end as BH-HMXB-MQs, the sources of a CRB at $z>20$

2) Synchrotron cooling of the jets largely dominate over inverse Compton cooling at $z\sim20$

3) A large absorption amplitude of HI at 1.42 GHz is expected due to the CRB from MQs

4) The EDGES absorption at $z\sim17$ with $f_X < 0.1 \Rightarrow N_H \sim 5 \times 10^{23}$ cm^{-2} and $T_S \sim 10$ K

5) The EDGES absorption onset at $z=20\text{-}18 \Rightarrow$ SF enhanced 10^2 in $\sim10^6\ M_\odot$ DM haloes at $z>20$

6) BH-HMXB-MQs of Pop III are formed before the appearance of SNe, NSs and dust…

7) For an EDGES CRB=140 K would be needed < N1 BH-HMXB-MQs like Cyg X-1

8) Langer+40 (2020)$\Rightarrow$ < N2 of OB stars of Pop III formed in $\sim1.4\times10^7$yr

(Life-time of a 14 $M_\odot$ star in the Main Sequence: $P_{MS}=10^{10}(M_\odot/M_*)^{2.5}$yr)

Jets from stellar black holes are the smoking guns from Pop-III stars in the absorption trough of the redshifted 21cm line of HI