# Stellar Black Holes at the Dawn of the Universe

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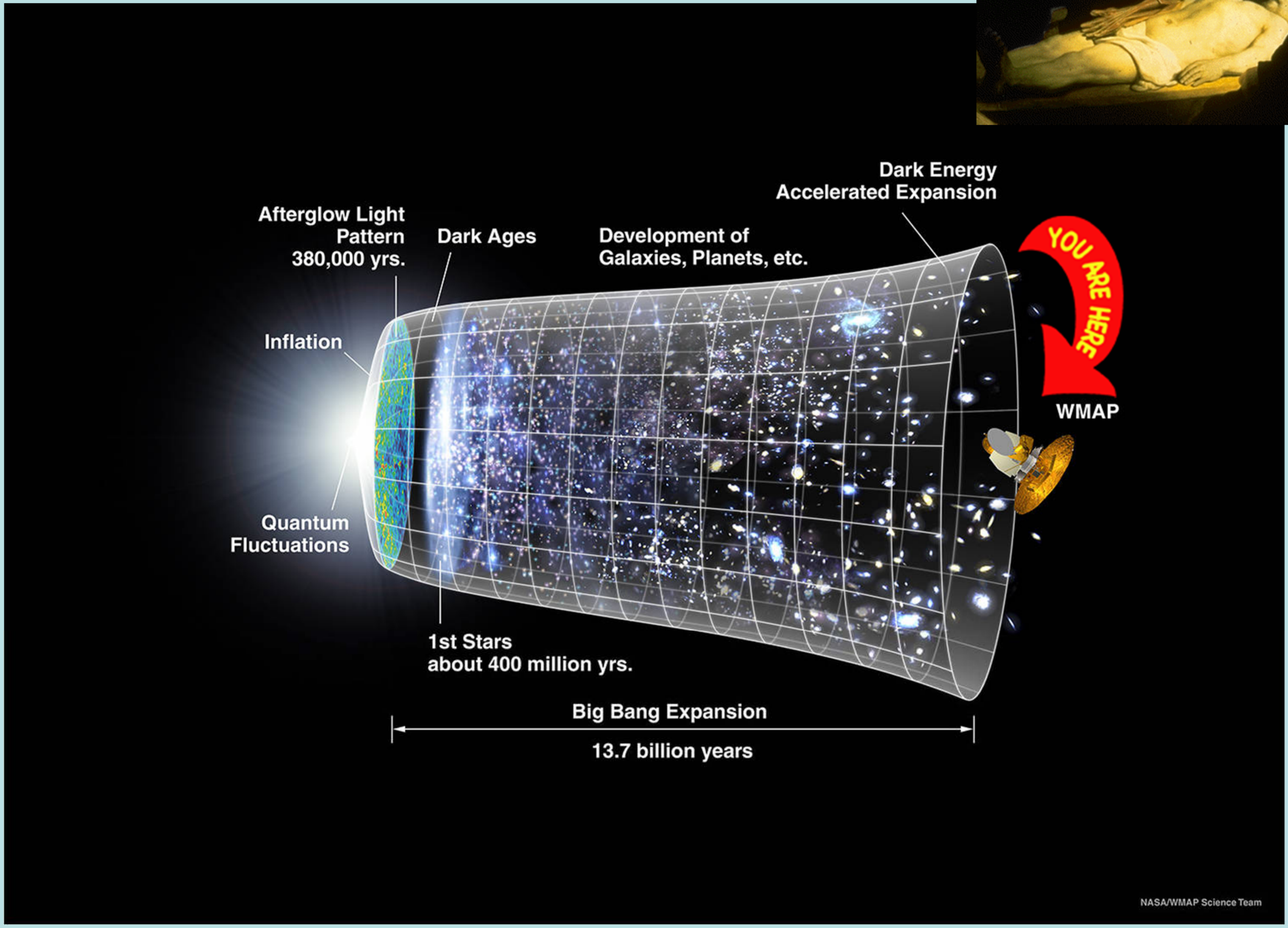
# Cosmic Renaissance



# Candidate z~10 galaxies

- Rapid galaxy evolution
- These galaxies cannot reionize the universe alone
- JWST observations to extend range to z~10-15, indirect 21 cm measurements

# What caused Reionization?

- UV photons from young stars
  - Insufficient
- Feedback from accreting black holes
  - Black holes in high-mass X-ray binaries (BH-HMXBs)
- Supporting Evidence
  - Sims & obs indicate abundance of BH-HMXBs
  - Greater ionizing potential than progenitor star

# Dark Ages

- Early universe composed of neutral H
  - Reionization occurs btwn 380k - 1B years
- Primitive galaxies trap UV photons
  - HST finds UV shortage over large volumes
- Faint galaxies (below detection limit) one possible source of additional UV photons

# BH Feedback

- X-rays have longer MFP
  - Why?
- Number of X-rays photons is comparable to # of UV photons from progenitor star
- Each X-ray photon capable of multiple secondary ionizations
  - Also a source of heating and excitation

# Mini-quasars

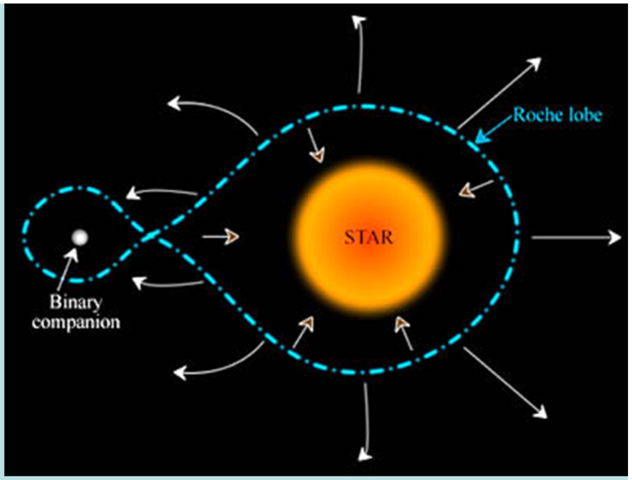
- Intermediate mass (z > 10)
  - Solitary BHs
  - Bondi-Hoyle accretion
    - Feedback suppresses further accretion, and therefore ionization

$$\dot{M} = \pi R^2 \rho v$$

$$R = \frac{2GM}{c_s^2}$$

$$\Rightarrow \dot{M} = \frac{4\pi G^2 M^2}{c_s^3}$$

# Micro-quasars

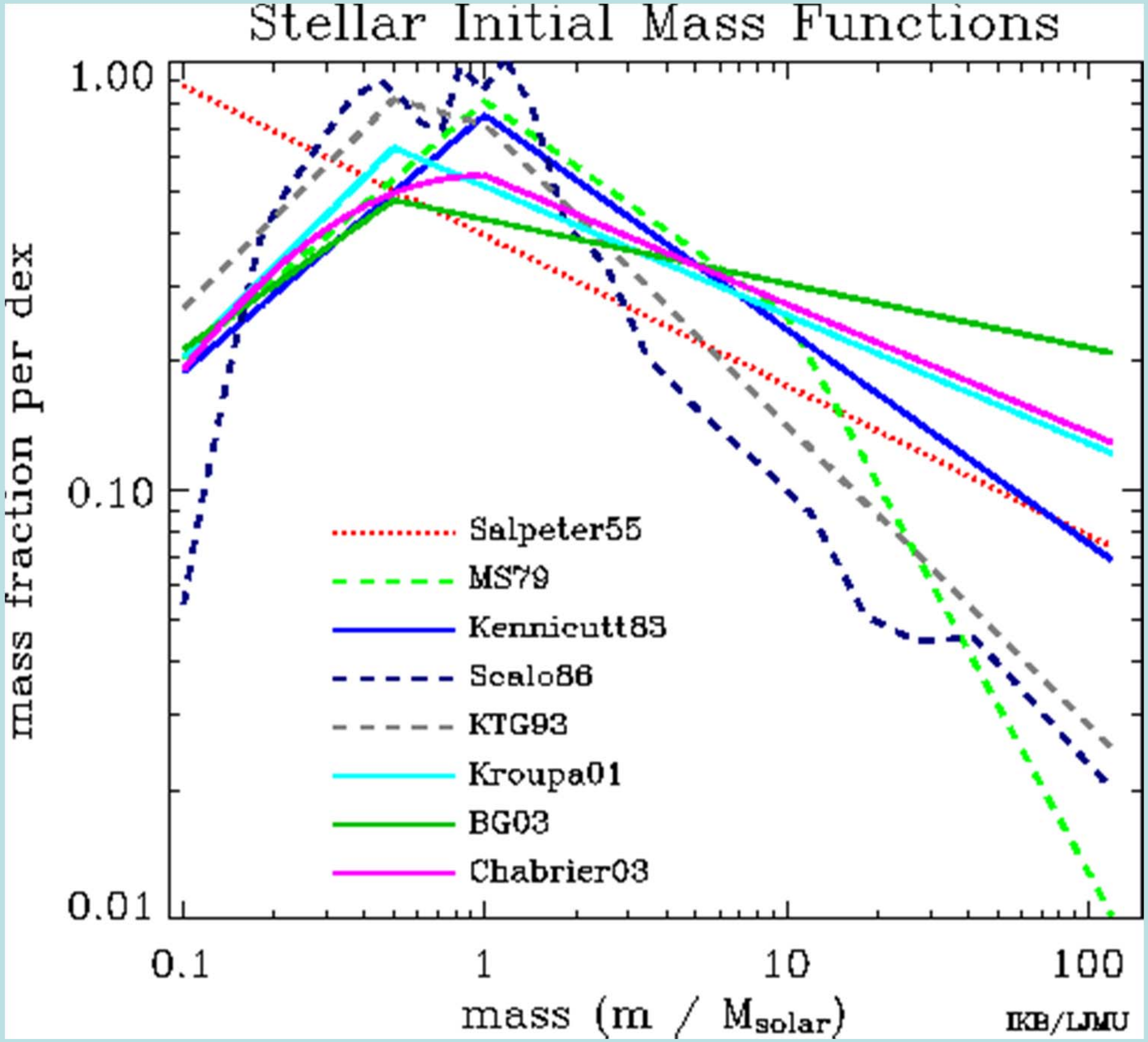



- Stellar mass (z > 6)
  - Stellar remnants as BH-HMXBs
  - Roche-lobe accretion from companion
  - Complementary, possibly greater ionization potential than progenitors
  - # Ionizing photons:

$$\frac{N_{BH}}{N_{star}} = 0.6\left(\frac{M_{BH}}{M_{star}}\right)\left(\frac{f_{ED}}{0.1}\right)\left(\frac{t_{acc}}{20Myr}\right)\left(\frac{f_{esc,BH}}{1.0}\right)\left(\frac{N_{phot}}{64{,}000}\right)^{-1}\left(\frac{\langle E_{photon}\rangle}{keV}\right)^{-1}\left(\frac{f_{esc,star}}{0.1}\right)^{-1}$$

# Early Stars

- More commonly formed in binary systems
- Typical mass ~ 10x Solar (many Bhs)
  - Why higher?
- Collapse to BH without kicking companion
- More binaries & BHs → More BH-HMXBs
  - How can we detect these?



Stellar Initial Mass Functions
1.00
0.10
0.01
mass fraction per dex
0.1
1
10
100
mass (m / Msolar)
IKB/LJMU
Salpeter55
MS79
Kennicutt83
Scalo86
KTG93
Kroupa01
BG03
Chabrier03

# Observations & Metallicity

- More BH-HMXBs at low Z (high z)
- 16-30 Solar Mass Bhs observed in three nearby low-Z galaxies
  - Selection effect?
  - High-Z stars preferentially form NS
  - Strip large fraction of primary envelope

$$L_{2-10} = f_{2-10} f_{BH} t_{acc} f_{bin} f_{Edd} \cdot SFR \cdot 1.5 \cdot 10^{38} erg s^{-1} M_{O}^{-1}$$

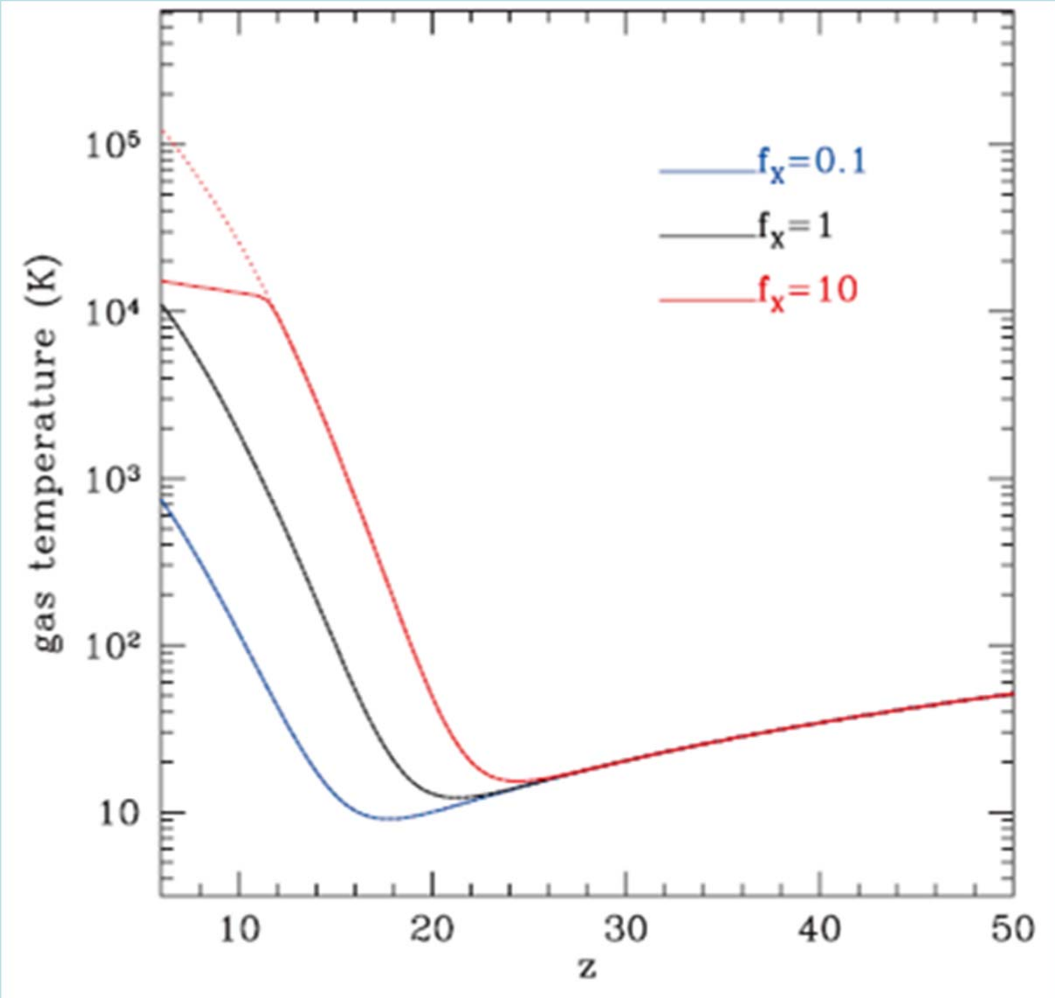
# X-ray luminosity in early Universe

- Coefficient on X-ray luminosity at least an order of magnitude higher than local
  - Microquasars have harder spectra
  - Early Universe had top-heavy IMF
  - BH fraction higher in low Z environments
  - More ionizing radiation!

# X-ray luminosity in early Universe

IGM heating scales with X-ray luminosity coefficient

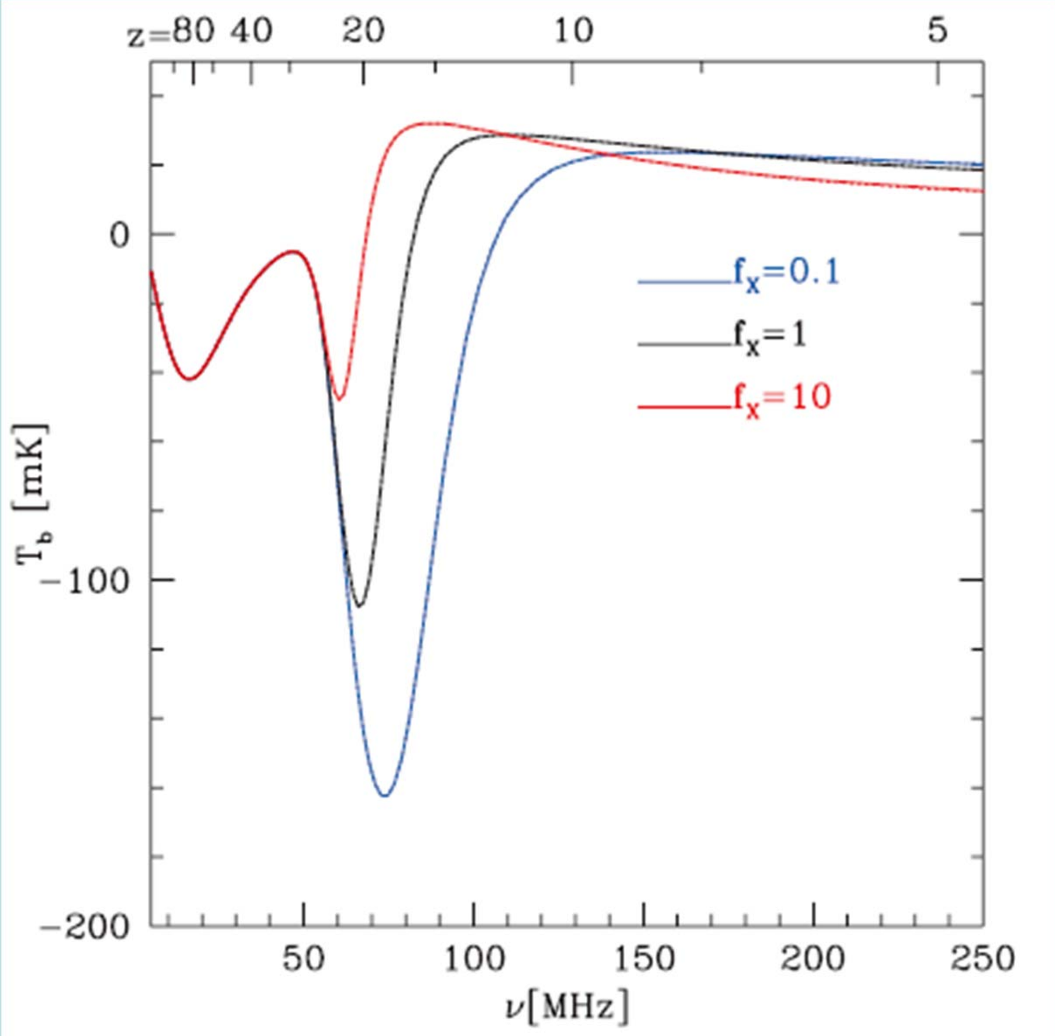
Formation of low-mass galaxies suppressed at z = 10-20 for $f_x > 0.5$



# 21 cm

- Spin temperature *also* scales with luminosity coefficient → 21 cm emission visible earlier

- Fluctuations in 21 cm background contain valuable cosmological information



# Black Holes and ΛCDM

- Early SMBHs quench growth of massive galaxies
- Early BH-HMXBs increase minimum galaxy mass at high redshift
- Sets relative abundance of dwarf galaxies

# Conclusions

- BH and binary fractions increase with z
- BH-HMXB feedback ~$10^{54}$ ergs (lifetime)
- Ionizing photons comparable to progenitor star, w/ each capable of 10's of ionizations
- Important source of heating in early universe

# Conclusions (cont.)

- IGM temperature ~$10^4$ K limits formation of faint galaxies at high redshift
  - Sets minimum mass ~$10^9$ $M_O$
  - Explains "missing" dwarf galaxies
- Abundant BH-HMXBs are potential sources of gravitational waves
  - Detectable?