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Effects of early black holes upon 21-cm radiation

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Motivation

Observation: Super Massive Black Holes with $M \sim 10^8\text{-}10^9\ M_{sun}$ are already in place at $z \sim 6$

Theory: (massive) BHs form inside the first galaxies and keep accreting/merging (e.g. Volonteri Haardt Madau 2003)

Observational implications: X-ray background, luminosity functions

At $z > \sim 6$ direct observations of particular objects are difficult

Can we hope to detect the "collective" feedback effects from BHs at very high z in 21 cm radiation?

Are these effects important for cosmology (e.g. for reionization)?

SMBH formation & emission – getting to 10^9 Msun in 1 Gyr

Mass of the Sloan quasars at z~6: 10^8-10^9 M_{sun}

Age of the Universe at z~6: ~ 10^9 yr

Eddington accretion:

$M(t) \sim M_{BHseed}\ 2\text{\^{}}(t/t_{Edd})$ [t_{Edd} ~ 50 Myr]

at z~6, t<10^9 yr (~20 doubling times) => $M(z\sim6) < 10^6\ M_{BHseed}$

Super-Eddington accretion and/or BH mergers might help
but simulations can't get non-stop BH accretion at z<10

Then

- **$M_{BHseed} > 100\ M_{sun}$**
- **BHs might (should?) be very luminous at high z**

Background radiation & the IGM – mean free path

Mean distance between active BHs

$d(z) \sim [\rho_{BH}(z)\ y\ /\ \hat{C}\ \langle M_{BH}\rangle(z)]^{-1/3}$

typical values at z~10-20 are ~ 5-20 comoving Mpc

Mean free path within an uniform neutral IGM

$\lambda(E,z) = 1\ /\ [n(z)\ \sigma(E)]$ $\qquad$ $n(z) \propto (1+z)^3$

$\sigma(E) \propto E^{-2.65}$ (for E<250 eV)

$\sigma(E) \propto E^{-3.3}$ (for E>250 eV)

for instance, $\lambda(E=0.5keV,z=20)=9$ Mpc(comoving)

$\lambda(E=1keV,z=20)=90$ Mpc(comoving)

Energetic photons (E>~0.5 keV at z~20) can travel from one active BH to the next

A roughly uniform background can be established

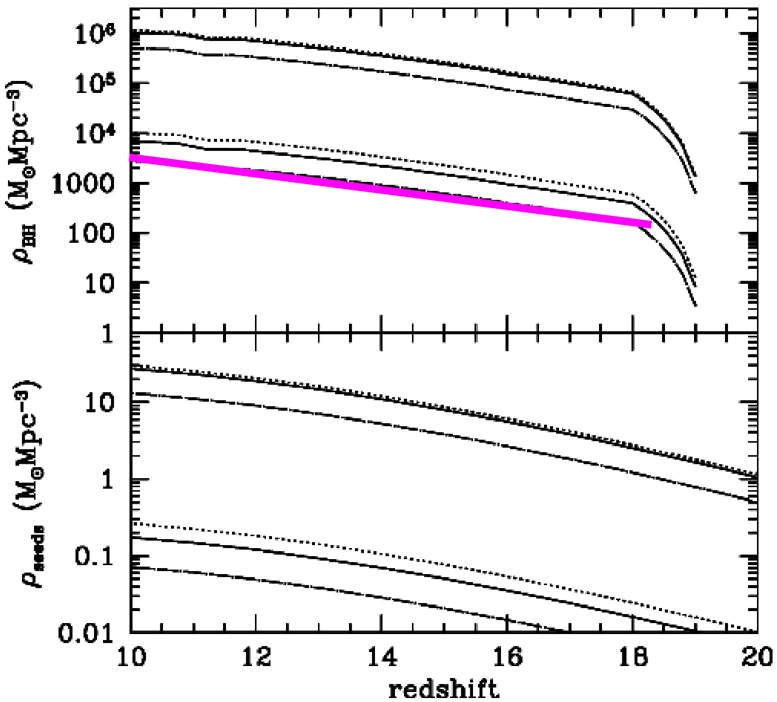
SMBH formation & emission – ρ_{BH} evolution

SMBH scenarios

large “seeds” form directly in the collapse of halos with low angular momentum and $M \sim 10^8\ M_{sun}$

(Begelman, Volonteri &Rees 2006)

$M_{BHseed} \sim 10^4 - 10^6\ M_{sun}$

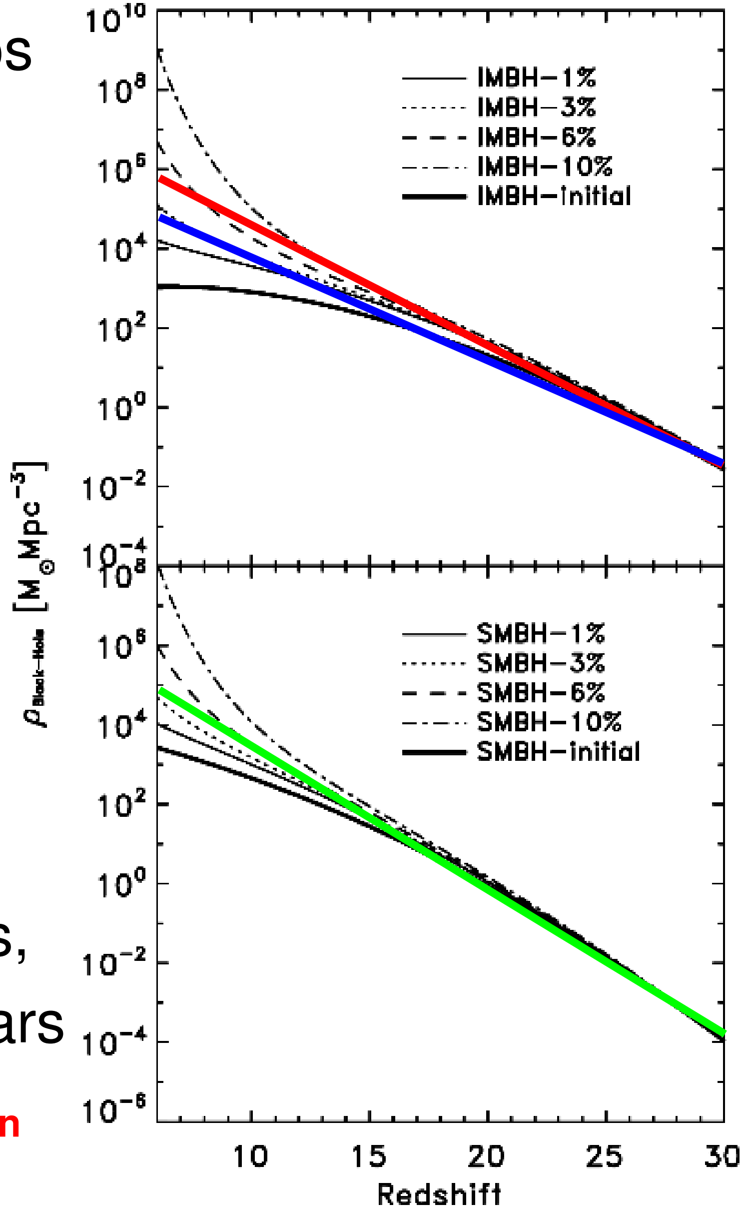


IMBH scenarios

(e.g. Zaroubi et al. 2007)

stellar “seed” BHs form in $\sim 10^6\ M_{sun}$ halos, possibly from popIII stars

$M_{BHseed} \sim 100 - 1000\ M_{sun}$



SMBH formation & emission – luminosity and spectral templates

Accretion emissivity

Hypothesis:

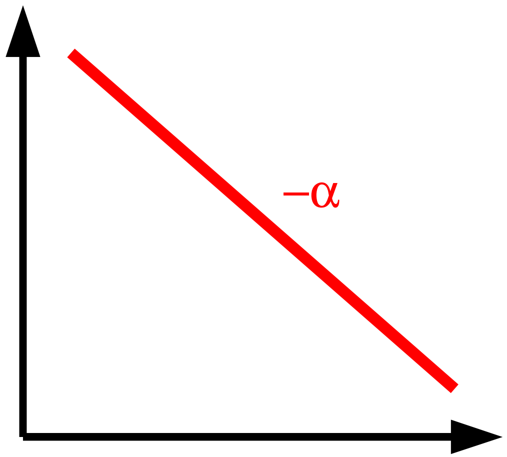
- any BH is “active” for a fraction y (duty-cycle) of time
- during active phases, BH emit a fraction η of $L_{Eddington}$

$$j(E,z) = \mathscr{L}_{Eddington}\, F(E)\, \rho_{BH}(z)\, \eta\, y\, (1+z)^3$$

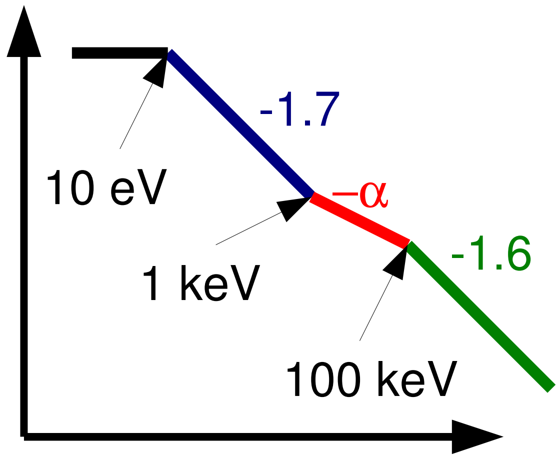
Spectral energy distribution

Various possibilities:

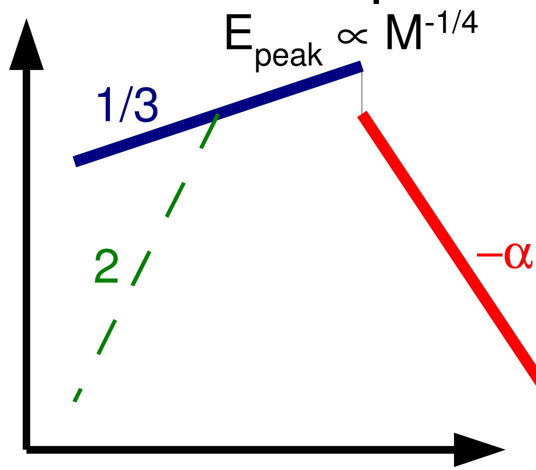
power-law



Sazonov et al. 2004



multi-component

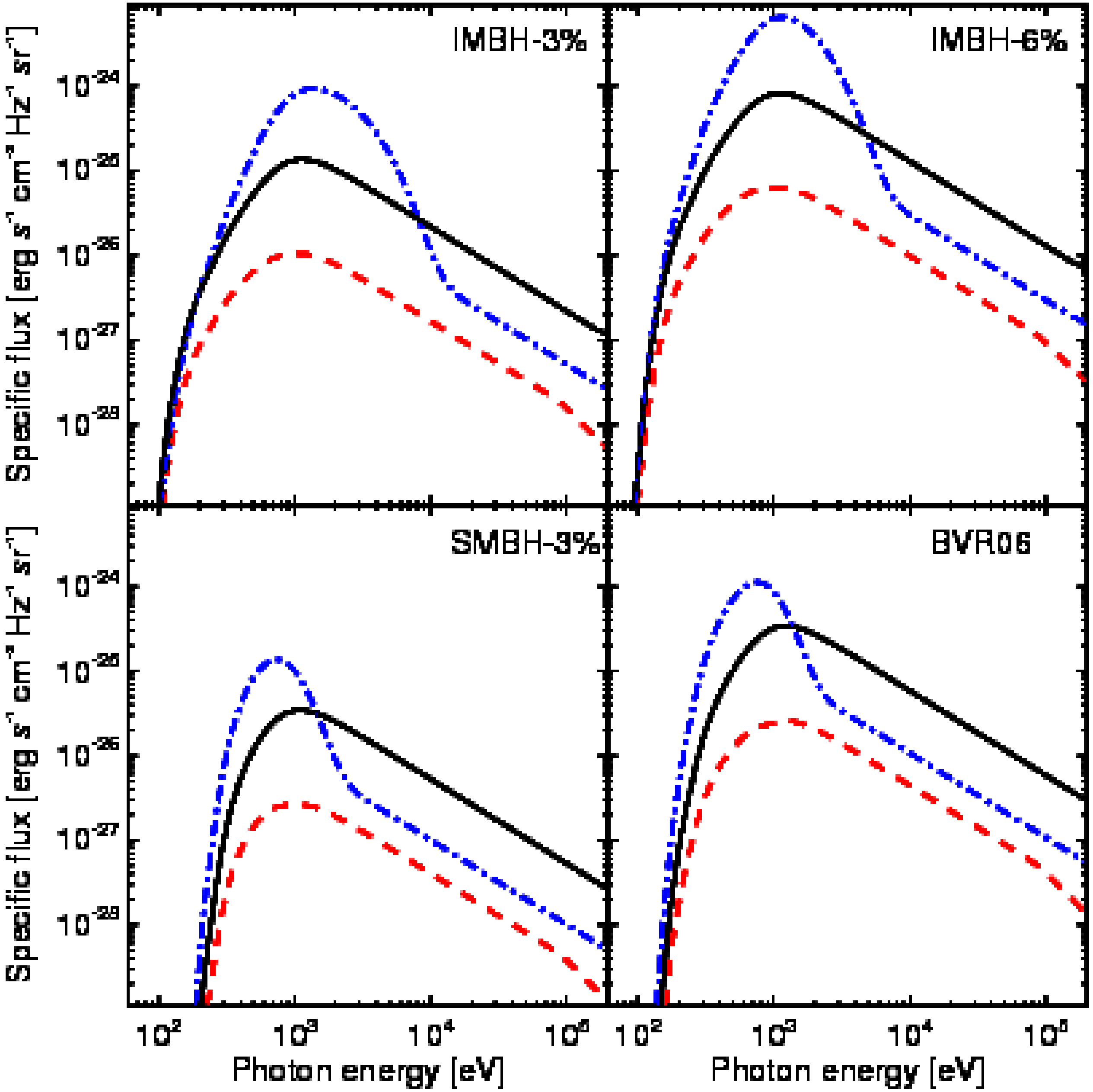


Background radiation & the IGM – radiation field (different SED)

Radiation field spectrum

at z=10

with different possible SEDs:
- PL1 SED
- Sazonov, α=1
- Multi-component, α=1 Φ=0.1



Background radiation & the IGM – constraints from the X-ray bkg

Are our models consistent with X-ray background observations?

Not completely. But details are important: dropping the duty cycle to 0.001 at z_{drop}=7 (rather than 5) reconciles everything

> bkg

> 0.5 bkg

reconciled

Model		z_{drop}	0.5-2 keV[a]	2-8 keV[b]	1-2 keV[c]	2-5 keV[d]	0.65-1 keV[e]
IMBH-3%+PL1		5	0.32(0.21)	0.19(0.10)	0.37(0.26)	0.42(0.13)	0.078(0.065)
IMBH-3%+SOS1		5	0.024(0.016)	0.014(0.008)	0.028(0.020)	0.031(0.010)	0.006(0.005)
IMBH-3%+MC01	NO	5	0.67(0.44)	0.043(0.023)	0.24(0.17)	0.096(0.030)	0.21(0.18)
IMBH-3%+MC01	OK	6	0.18(0.11)	0.014(0.008)	0.057(0.041)	0.031(0.010)	0.054(0.045)
IMBH-3%+MC01	OK	7	0.046(0.033)	0.005(0.003)	0.016(0.011)	0.011(0.003)	0.015(0.012)
IMBH-6%+PL1	NO	5	2.5(1.7)	1.5(0.82)	2.9(2.1)	3.3(1.0)	0.63(0.52)
IMBH-6%+PL1	NO	6	0.79(0.51)	0.47(0.25)	0.92(0.65)	1.0(0.32)	0.19(0.16)
IMBH-6%+PL1	OK	7	0.26(0.17)	0.16(0.084)	0.30(0.21)	0.34(0.10)	0.064(0.053)
IMBH-6%+SOS1		5	0.19(0.13)	0.12(0.062)	0.22(0.16)	0.25(0.076)	0.046(0.040)
IMBH-6%+MC01	NO	5	1.1(0.71)	0.33(0.16)	0.65(0.46)	0.72(0.22)	0.24(0.20)
IMBH-6%+MC01	OK	6	0.29(0.19)	0.10(0.056)	0.20(0.14)	0.23(0.069)	0.063(0.052)
IMBH-6%+MC01	OK	7	0.086(0.056)	0.034(0.018)	0.087(0.062)	0.075(0.023)	0.018(0.015)
SMBH-3%+PL1		5	0.26(0.17)	0.16(0.085)	0.30(0.22)	0.34(0.11)	0.065(0.054)
SMBH-3%+SOS1		5	0.020(0.13)	0.012(0.006)	0.023(0.016)	0.026(0.008)	0.005(0.004)
SMBH-3%+MC01		5	0.048(0.031)	0.029(0.016)	0.055(0.039)	0.063(0.019)	0.012(0.010)
BVR06+PL1		5	0.30(0.19)	0.18(0.097)	0.35(0.25)	0.39(0.12)	0.074(0.061)
BVR06+SOS1		5	0.023(0.015)	0.014(0.007)	0.027(0.019)	0.030(0.009)	0.005(0.004)
BVR06+MC01		5	0.054(0.035)	0.032(0.018)	0.063(0.044)	0.071(0.022)	0.013(0.011)

Background radiation & the IGM – energy input

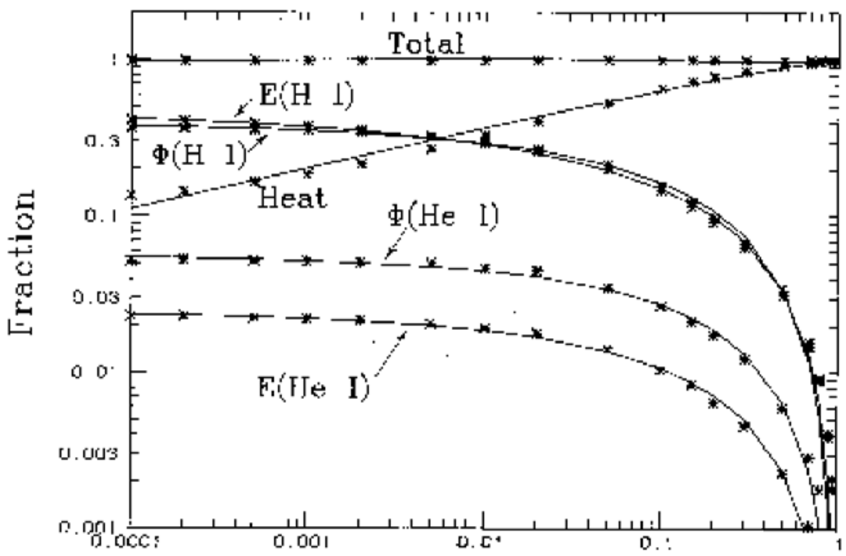
Energy input

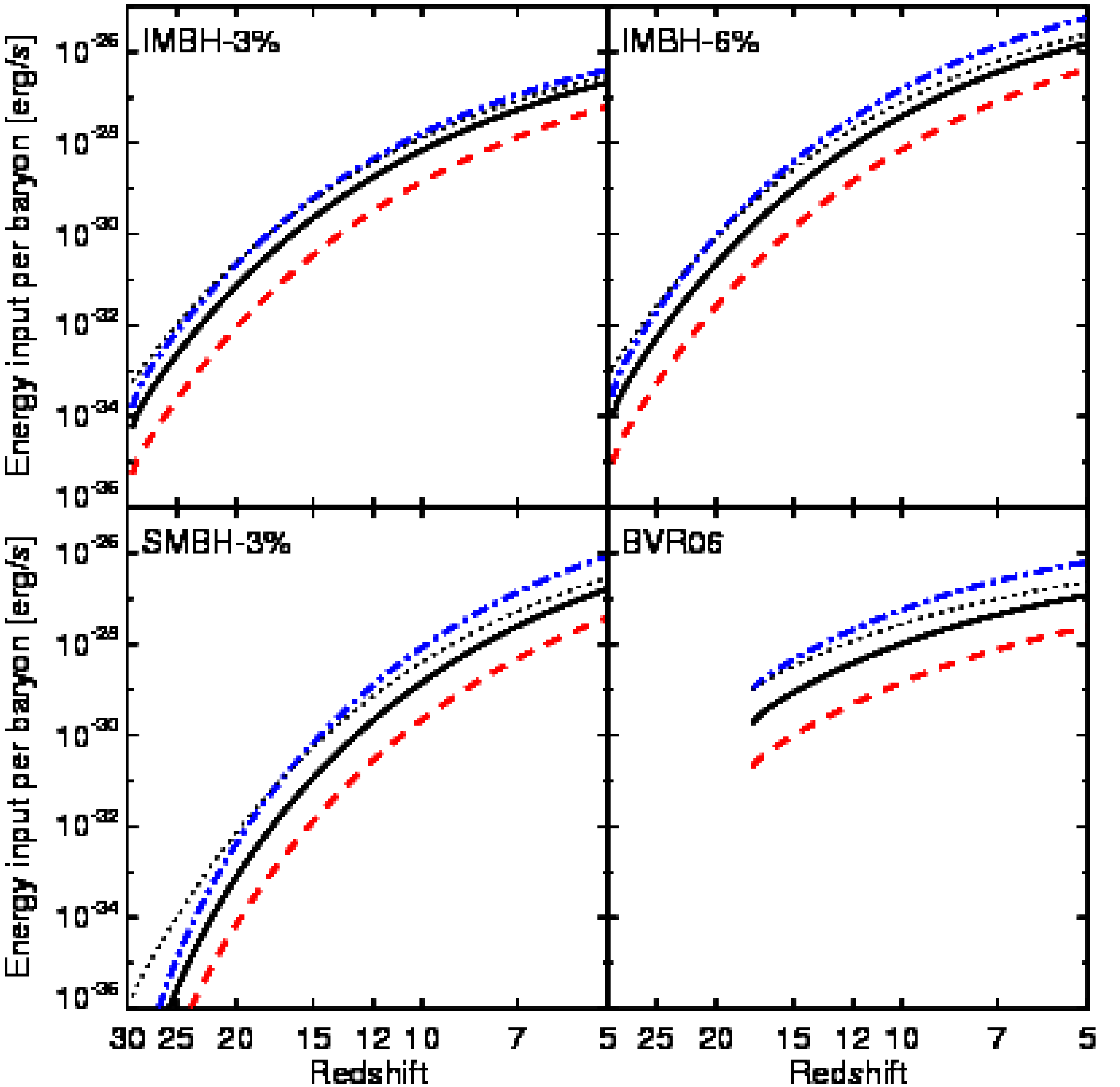
$\epsilon_{heat} = f_{heat} \int dE \{4\pi\, J(E,z)\, \sigma(e)\}$

$\epsilon_{ion} = f_{ion} \int dE \{4\pi\, J(E,z)\, \sigma(e)\}$

$\epsilon_{exc} = f_{exc} \int dE \{4\pi\, J(E,z)\, \sigma(e)\}$

f_{heat}, f_{ion}, f_{exc} from
Shull & Van Stenberg (1985)





Background radiation & the IGM – IGM redshift evolution

Evolution of the neutral IGM

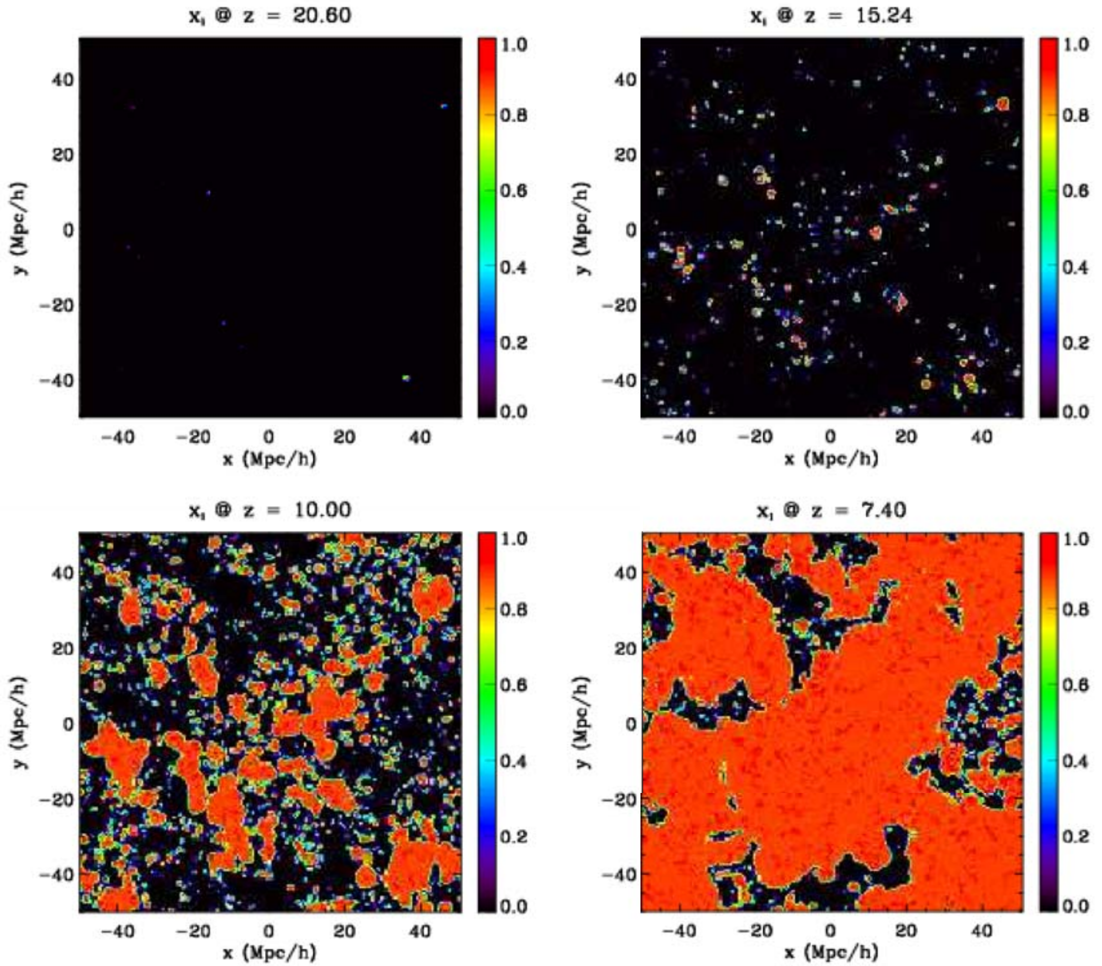
Physical conditions evolved with code based on Ripamonti et al. 2002

We look **only at NEUTRAL regions** (black in figure)

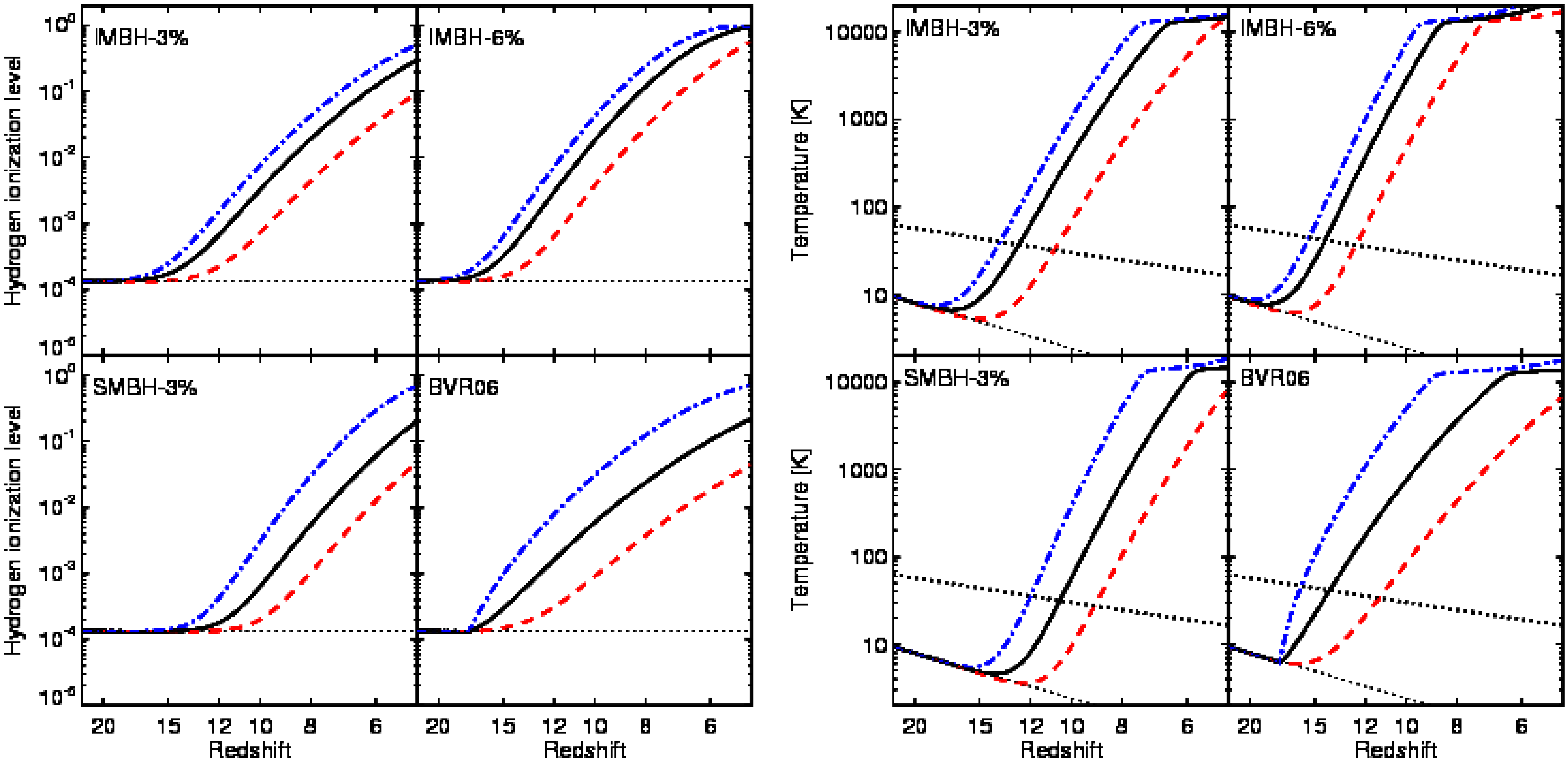
Figures from Santos et al. 2007

heating: from BH radiation
cooling: adiabatic,
- Compton coupling with CMB,
- HD and H_2 molecules,
- H, He, He^+ cooling

chemistry: Galli & Palla (1998)
- minimal network for
- H, H^+, H^-, He, He^+, He^{++}, H_2,
- H_2^+, D, D^+, HD, e^-
- plus other reactions (e.g. ionizations by BH radiation)



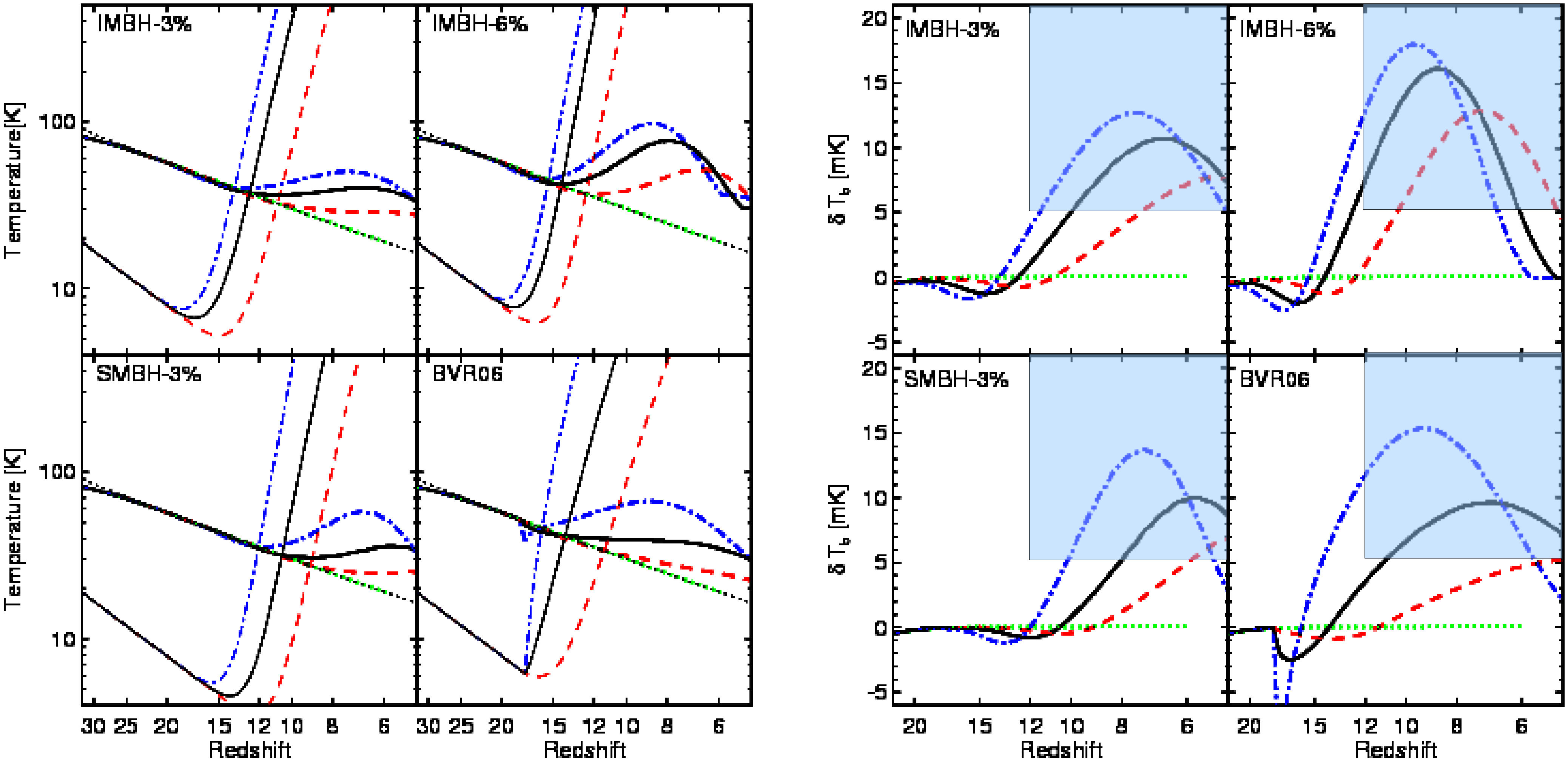
Background radiation & the IGM – ionization & temperature



Complete ionization only in most extreme models and at low z

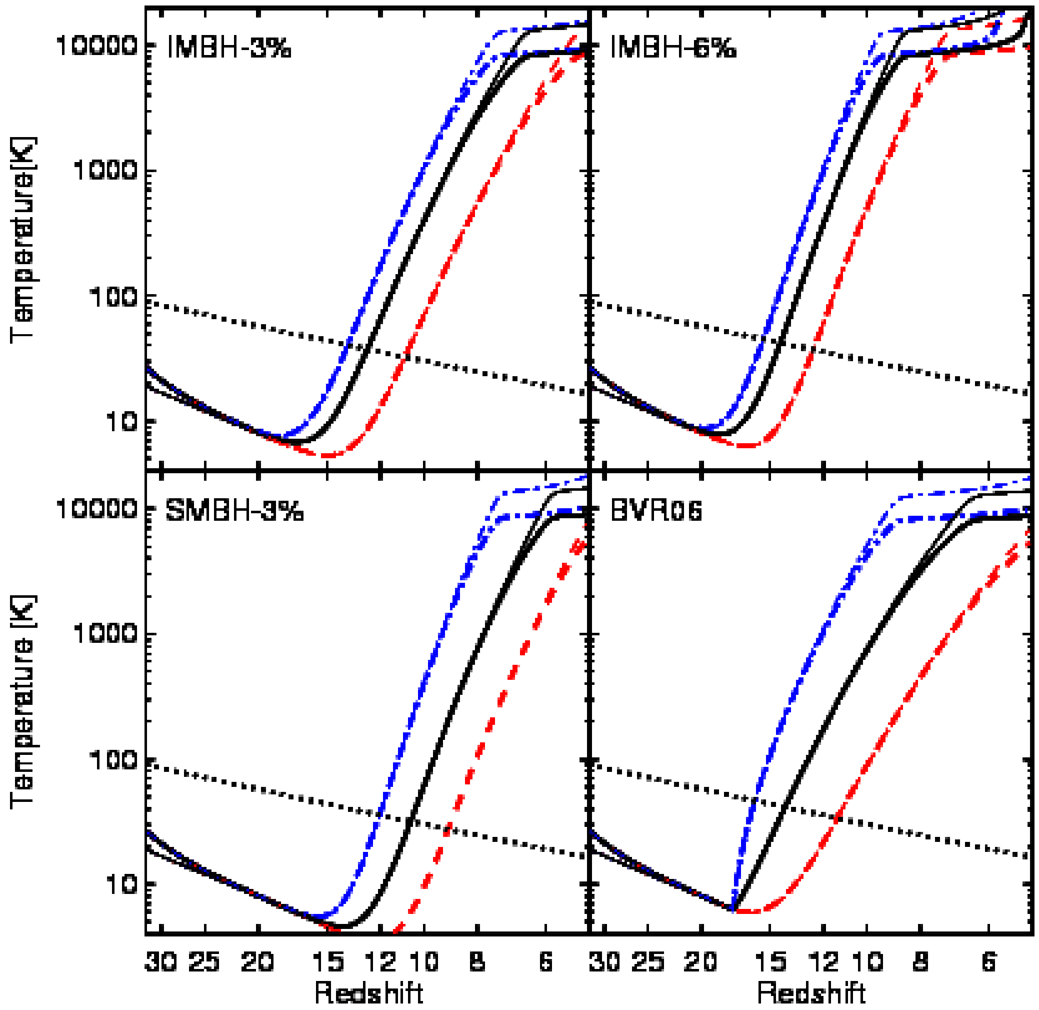
Remarkable change in T in all models for z<12

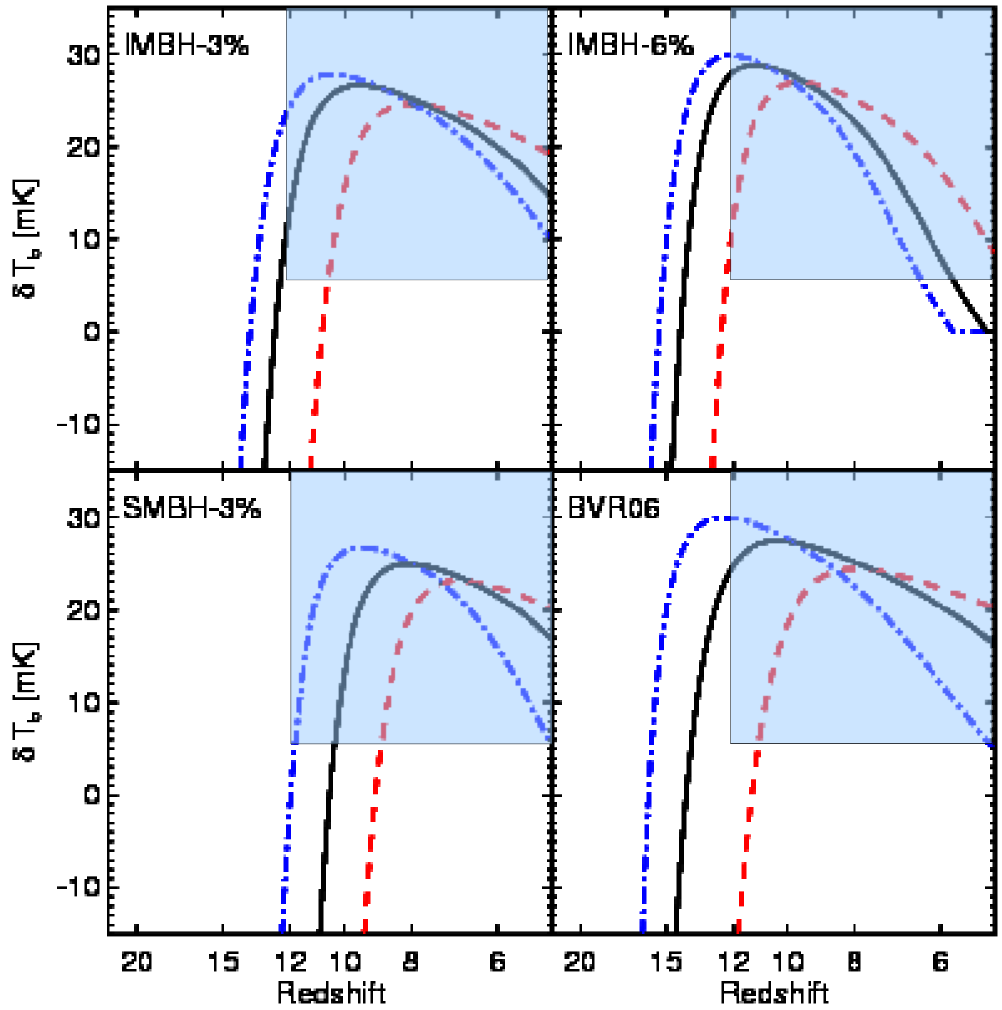
Effects on 21-cm radiation (NO stellar coupling)



Here we consider only the coupling due to the radiation emitted by BHs

Effects on 21-cm radiation (WITH stellar coupling)





Here we consider also the coupling due to the radiation emitted by stars (see Ciardi & Salvaterra 2007), which SHOULD be there

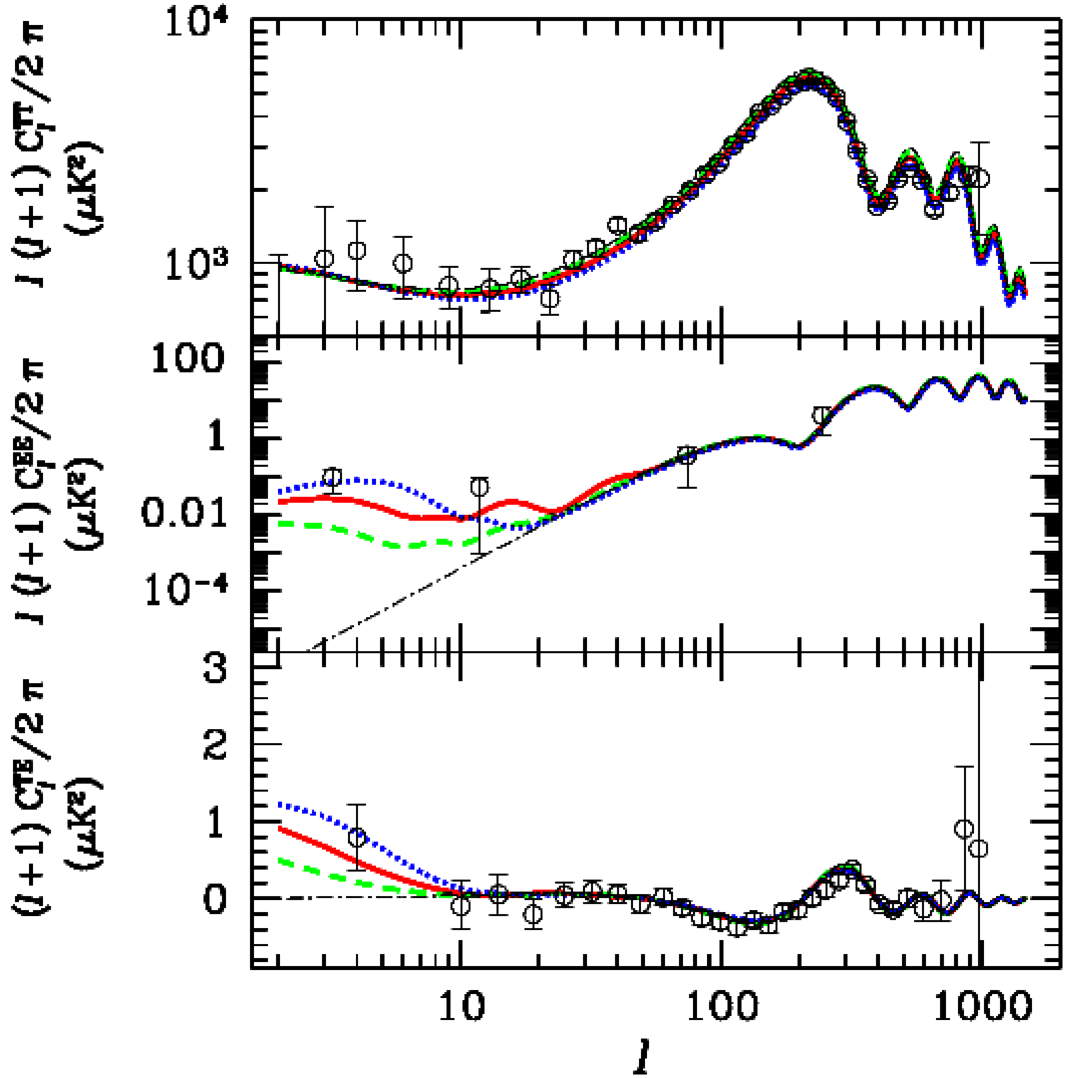
Effects on CMB angular spectrum

Negligible effects on CMB temperature-temperature spectra and at high multipoles (expected)

polarization spectra are affected at large scales (low multipoles)

But it is indistinguishable from a model with sudden reionization at z=11

τ_{es} **< 0.07**



Effects on structure formation – critical mass

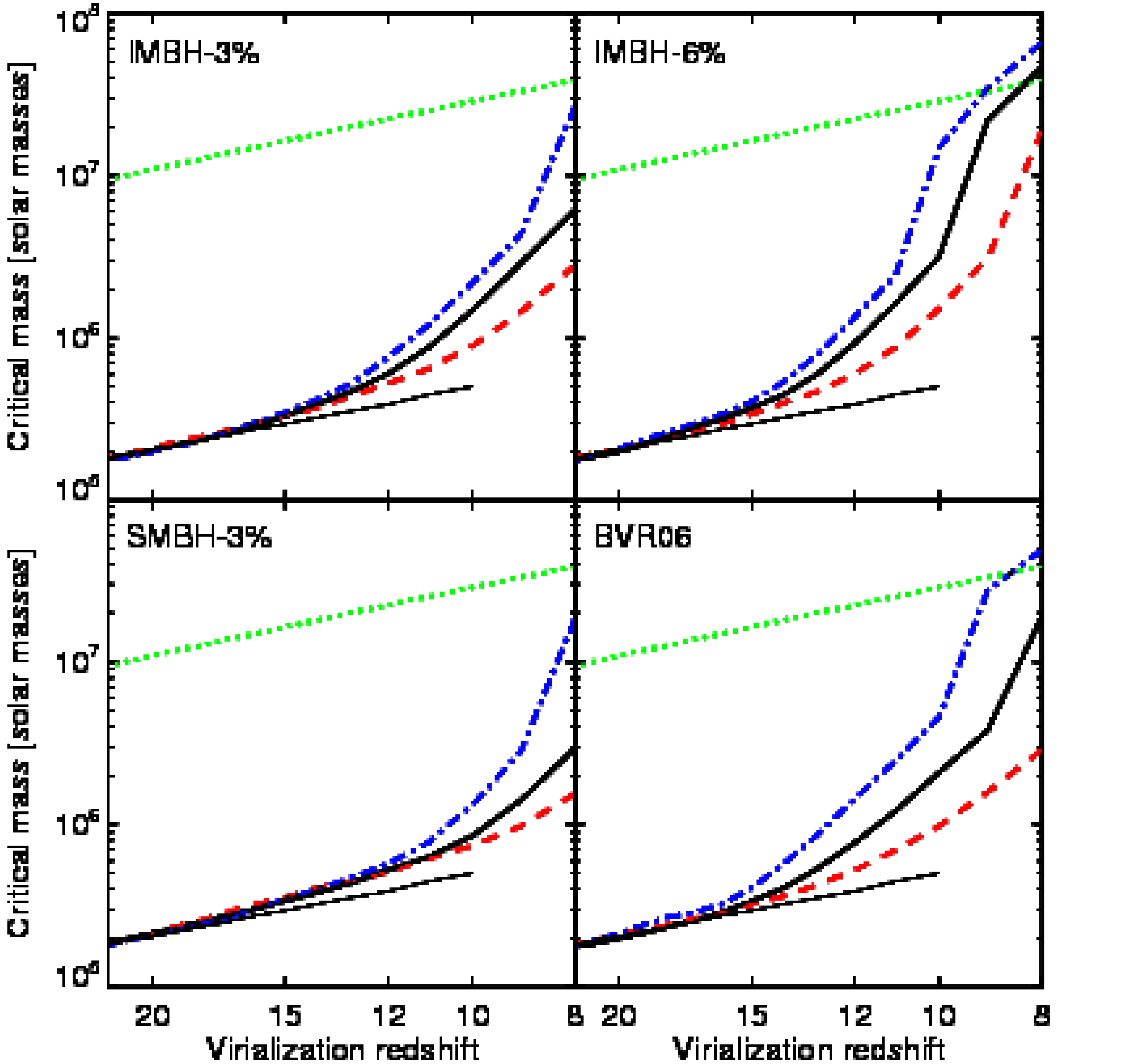
Evolution of halos

Ripamonti et al. 2002 code is used to look at the evolution of halos

spherically symmetric calculation
DM component is included by using analytical approximations

at each virialization redshift, we look for the minimum halo where a central density $n > 10^5$ cm^{-3} is reached within a (local) Hubble time from virialization

The energy injection due to BHs leads to a large increase in the critical mass al low z



Effects on structure formation – gas retention

Properties of halos

How much gas ends up inside the halo?

naïve expectation:

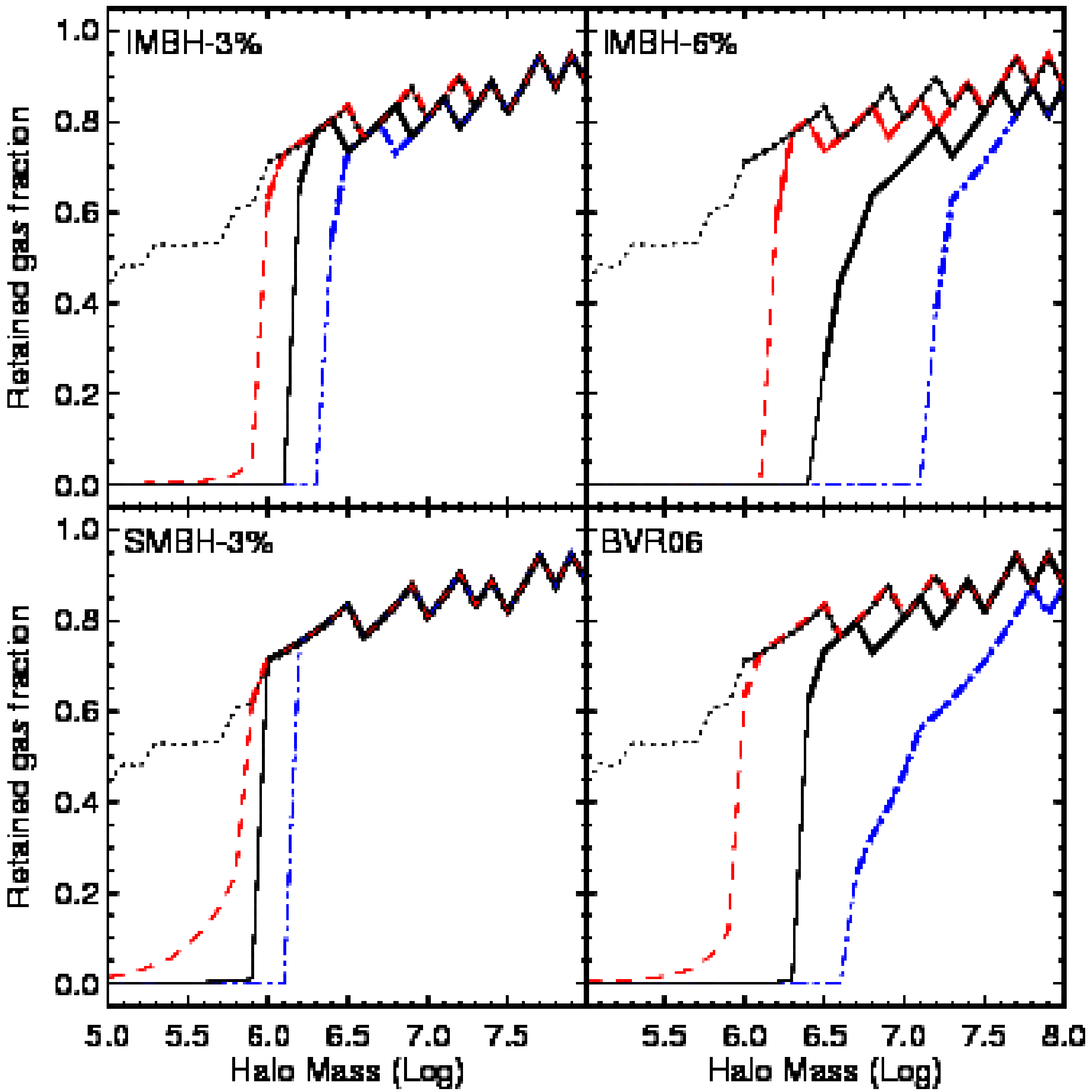
$M_{exp} \sim M_{halo}\, \Omega_b/\Omega_M \sim 0.2\, M_{halo}$

In large halos, $M_{gas} \sim M_{exp}$

in small halos, $M_{gas} << M_{exp}$

in some models,
$M_{gas} <\sim 0.5 M_{exp}$
even if $M_{halo} > M_{crit}$

$z_{vir} = 10$



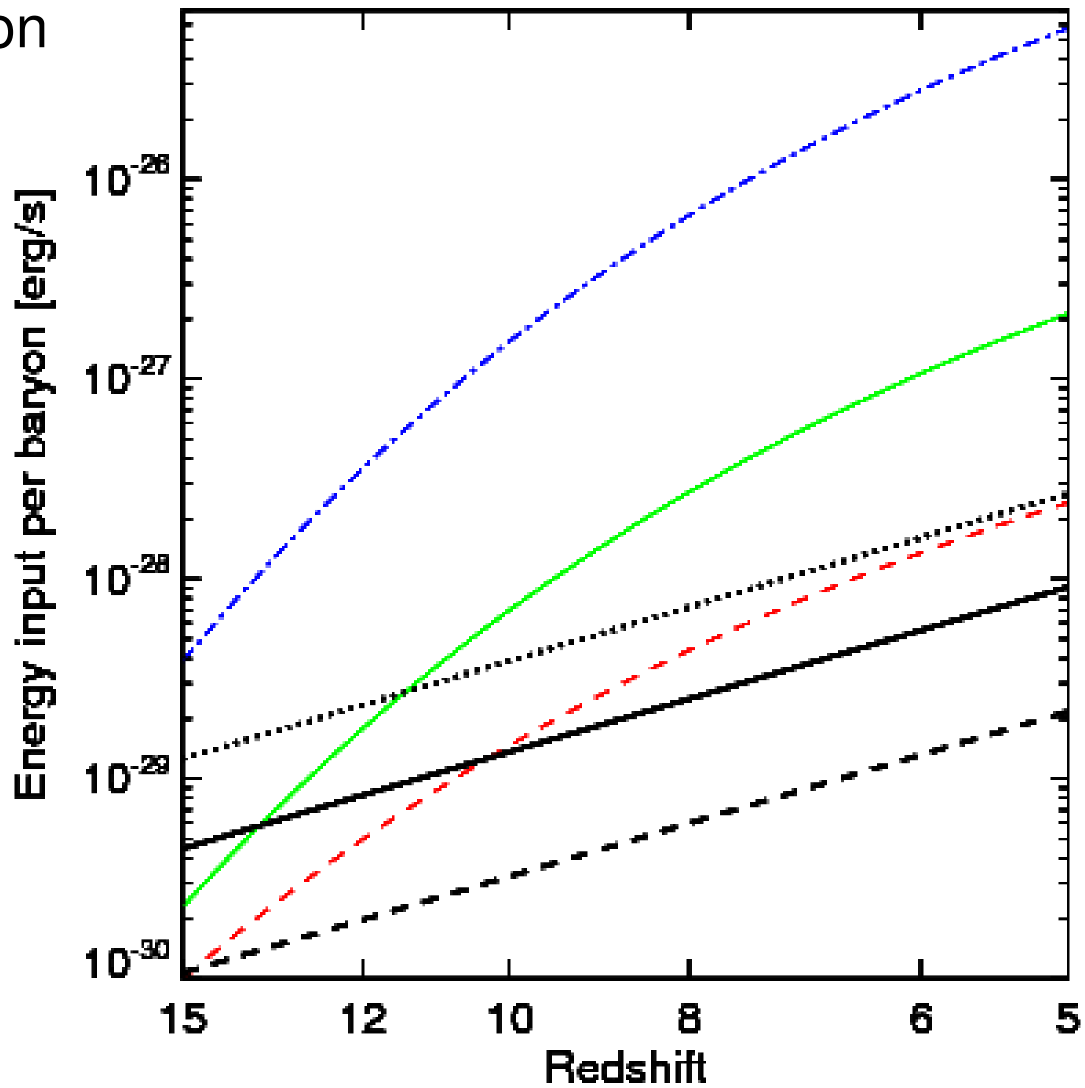
Alternative scenarios – comparison with XRB emission

Are the effects on 21 cm unique signatures of BHs?

At z~0, star formation is associated with HMXB formation and X-ray emission (Grimm et al. 2003)
$L_X \sim 6 \times 10^{38}$ [SFR/(M_{sun}/yr)]

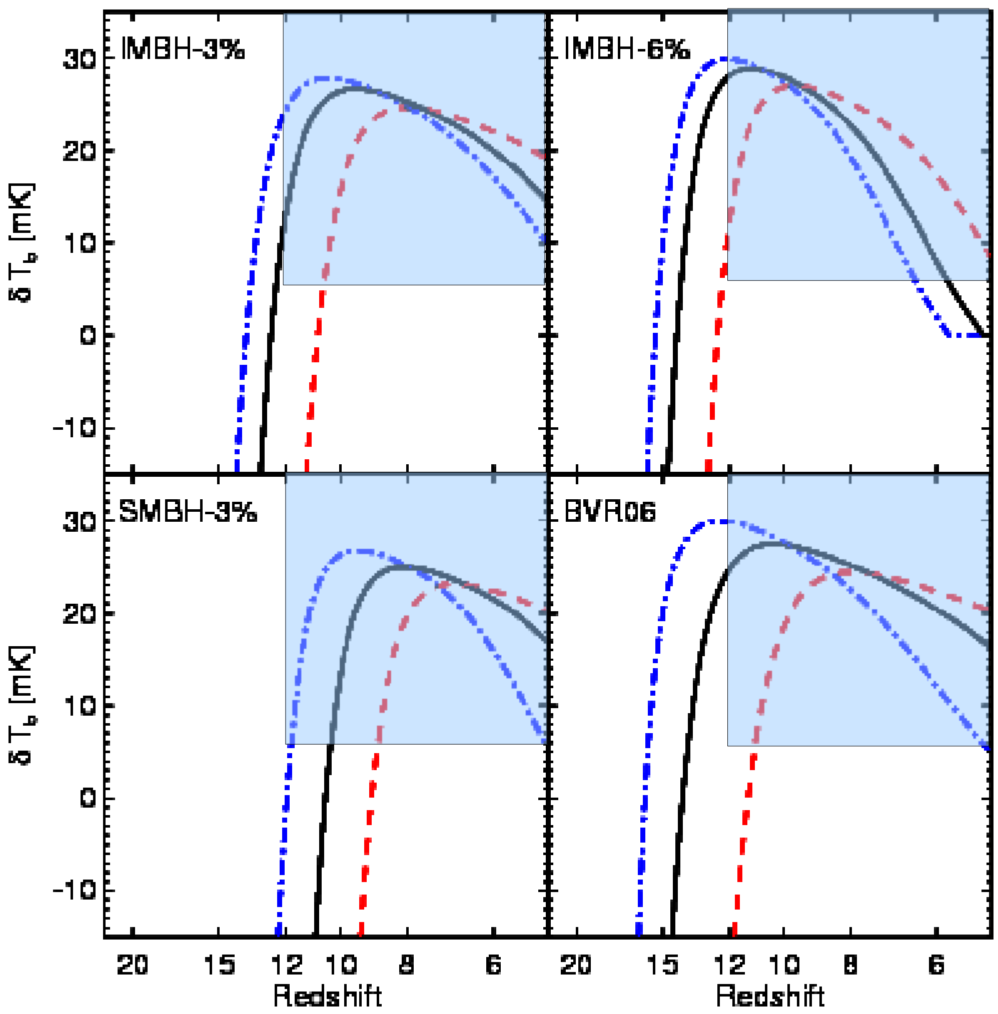
The emissivity inferred from theoretical high-z SF histories leads to $\epsilon_{XRB} << \epsilon_{BH}$

UNLESS
high-z SF is (much) more favourable for X-ray emission than the present one



Conclusions - developments

Early BH feedback should induce detectable changes in the properties of high-z 21-cm radiation



Open issues

Can we distinguish the effects of BHs from those of XRBs?

Can we distinguish different BH growth scenarios?

The expected 21-cm power spectrum radiation might help discriminate

Reference: Ripamonti, Mapelli & Zaroubi, 2008, MNRAS 387, 158