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An exploration of the effects of HD cooling on primordial star formation

Primordial gas cooling - halo mass

Halo must virialize:

low mass, low T_{vir} halos virialize early

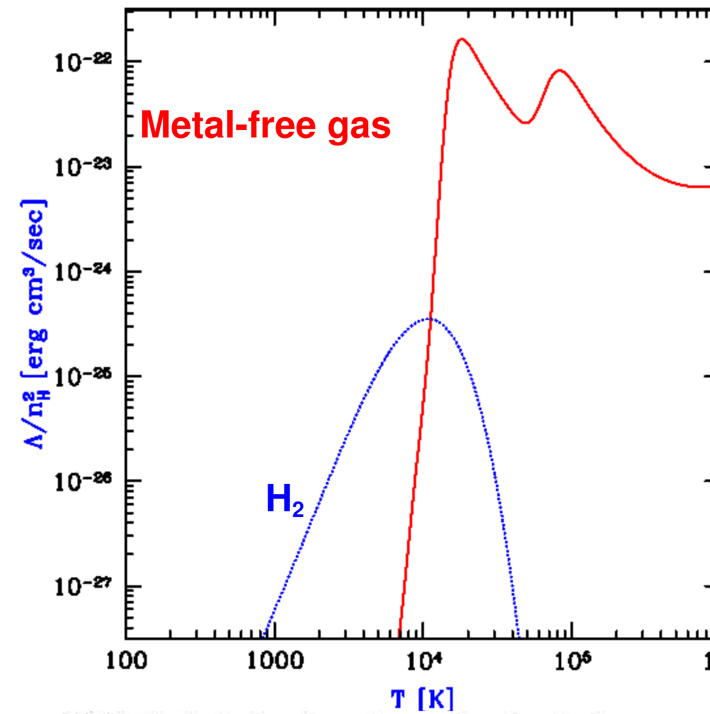
Gravity must overcome pressure:

$M_{gas} > M_{jeans} \sim 10^4\ M_{sun}\ [(1+z)/30]^{3/2}$

Gas must be able to cool:

in halos with $T_{vir} < 10^4$ K

molecular cooling must be efficient



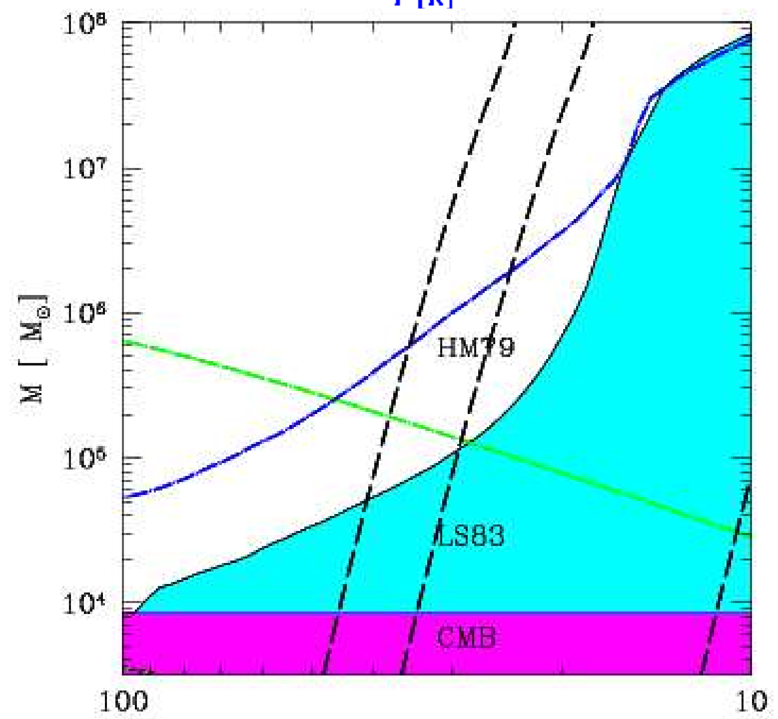
$M_{halo} \sim 10^{5\text{-}6}\ M_{sun}$

$T_{vir} \sim 10^3$ K

$z_{vir} \sim 20\text{-}30$

$f_{H2} > 5\times10^{-4}$

(Tegmark et al. 1997, Abel et al. 1998)



H2 cooling - IMF

H_2 cooling determines the properties of primordial star formation:

Halo mass ($\sim 10^6$ M_{sun})

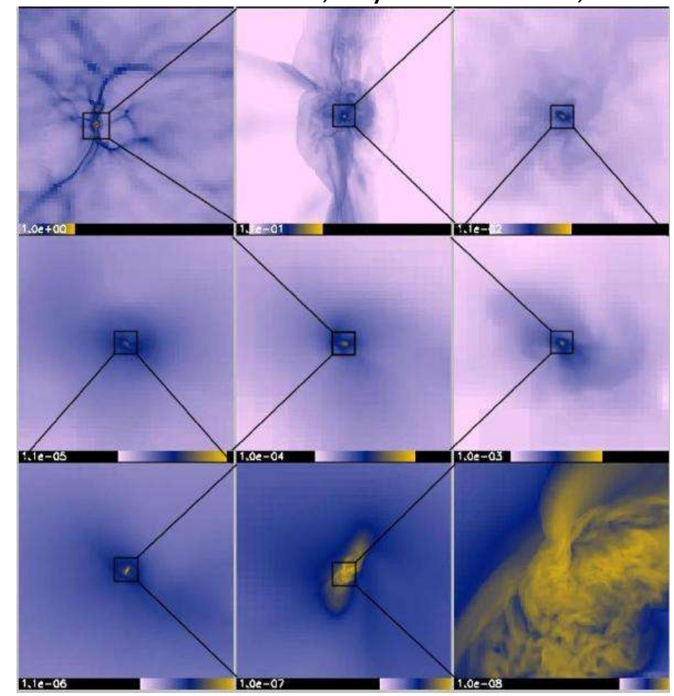
Fragment mass: non-LTE->LTE transition ($n \sim 10^4$ cm^{-3}, $M \sim 100\text{-}1000$ M_{sun})

Transition to optically thick regime

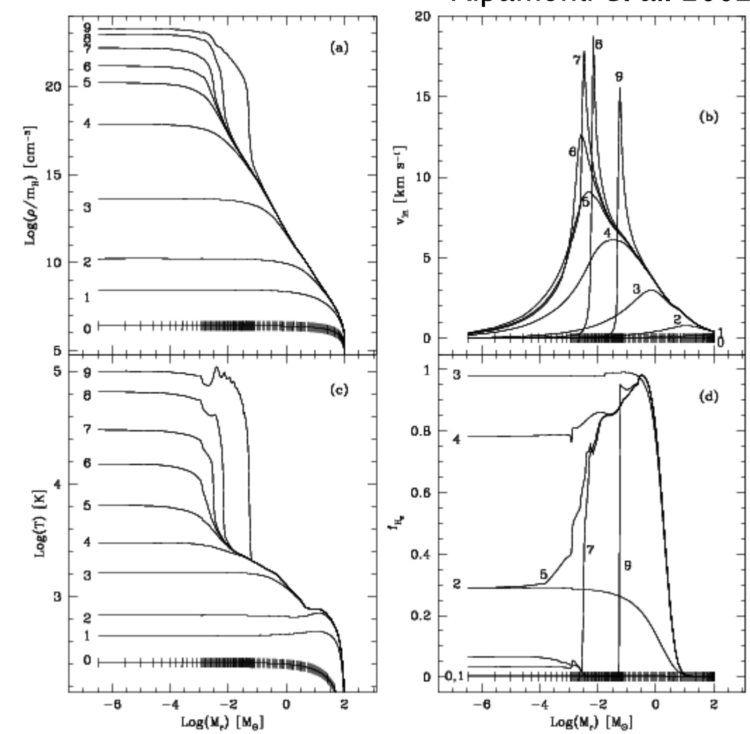
Accretion rate: c_s^3/G is high because of H_2 cooling inefficiency below ~ 200 K

H_2 cooling probably results in a top-heavy Initial Mass Function

Abel, Bryan & Norman, 2002



Ripamonti et al. 2002



The HD molecule – a missing ingredient?

n(D)<<n(H) (~2-4 10^{-5}), so n(HD)<<n(H_2)

But

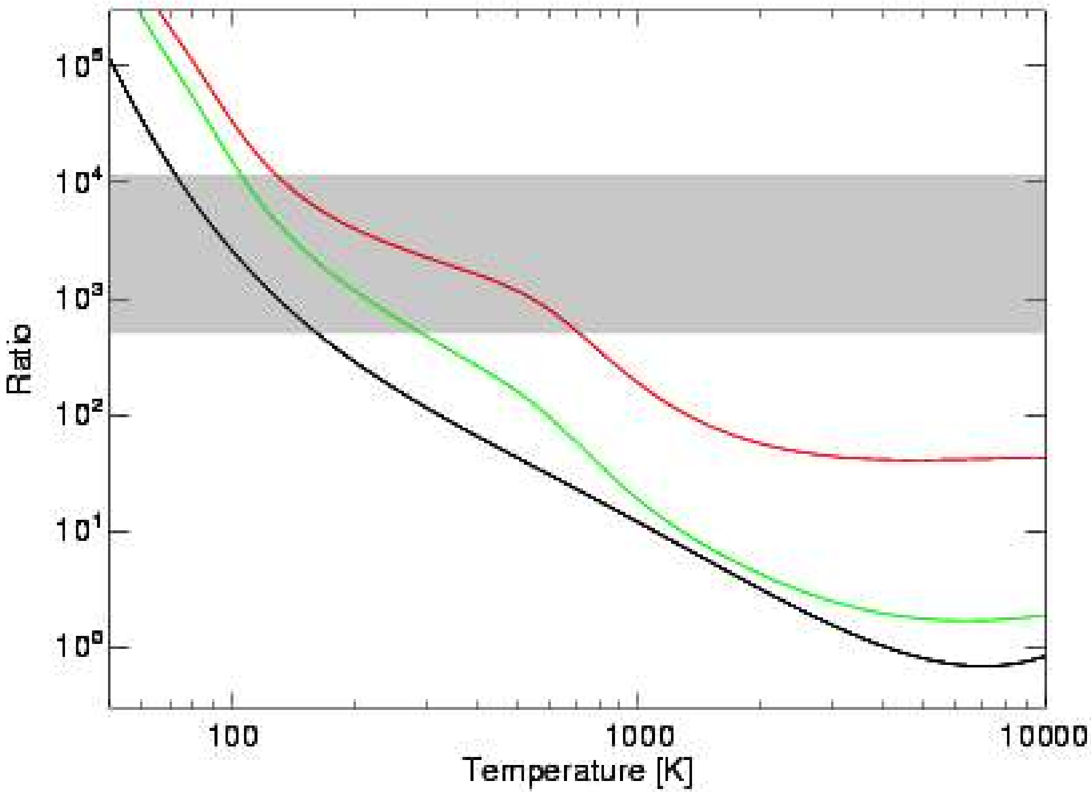
- n(HD)/n(H_2) ~ 2 [n(D)/n(H)] exp(465/kT)

  because HD binding energy is ~ 4.52 eV and H_2 binding energy is ~ 4.48 eV

- HD is a much better coolant than H2

  because HD dipole moment is non-zero (and the minimum transition energy is excited at ~ 128 K rather than ~ 512 K)

Depending on thermal and chemical evolution, HD can become the main cooling agent



The HD molecule – proposed effects

Galli & Palla 1998, 2002, Flower 2000, Flower & Pineau des Forets 2001:
HD can affect the thermal balance of primordial objects

Kamaya & Silk 2002: Observable HD line?

Nakamura & Umemura 2002: HD can lower the typical stellar mass to ~ 10 M_{sun}

Lipovka et al. 2005: HD cooling important up to T~3000 K
(see poster by R. Nunez Lopez)

Nagakura & Omukai 2005: changes of fragmentation in "fossil" HII regions

Uehara & Inutsuka 2000, Johnson & Bromm 2005, Shchekinov & Vasiliev 2005:
effects of HD behind shock waves (due e.g. to mergers or SNe)

On the other hand

Bromm Coppi & Larson 2002: little or no effects

Models

We explore a large range of parameters, focusing on the minimum (critical) halo mass and on the fragmentation properties:

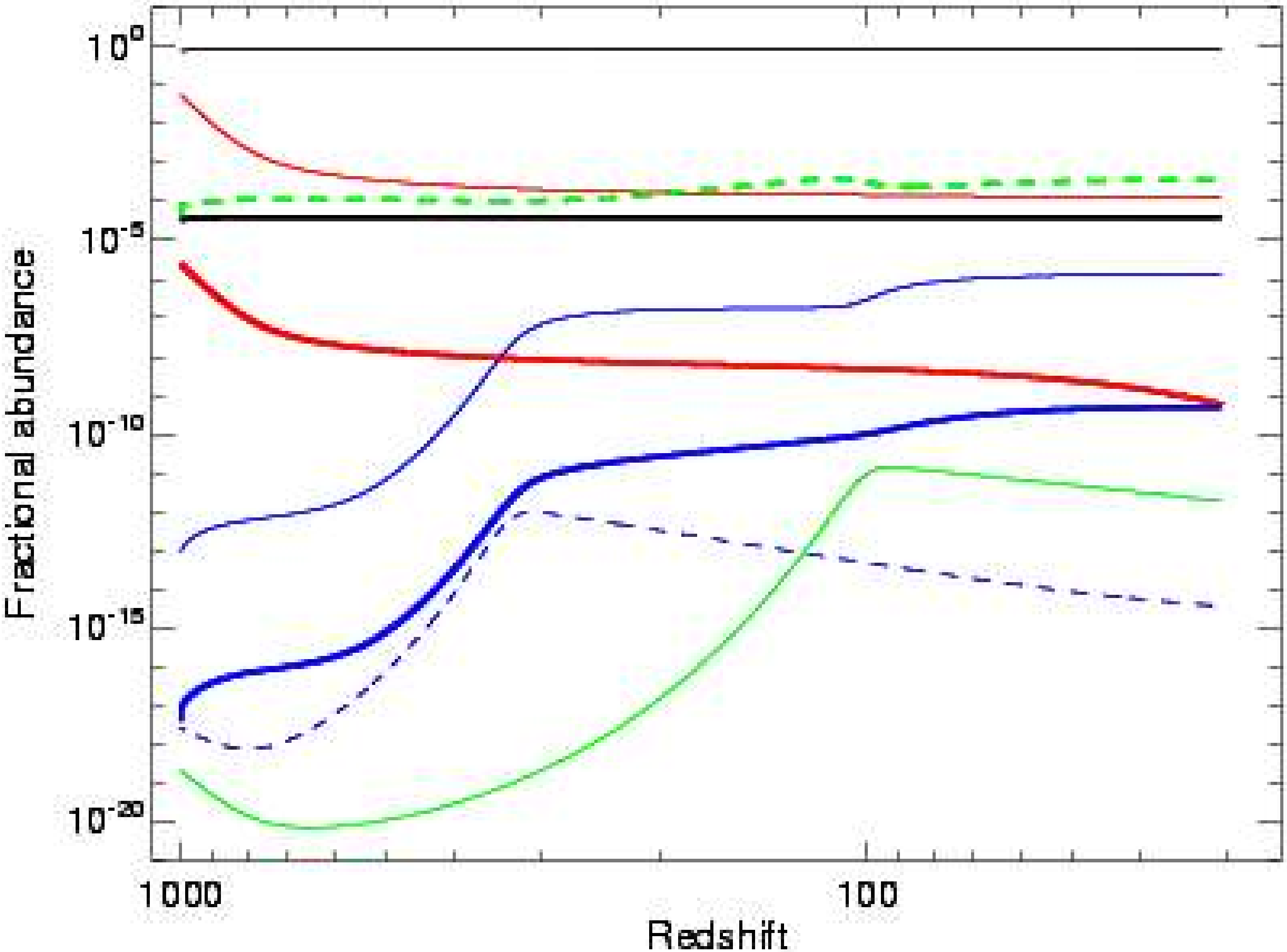
Collapse of halos with $100 \leq z_{vir} \leq 20$,
$10^4\ M_{sun} \leq M_{halo} \leq 3x10^6\ M_{sun}$ from turn-around to z=10

Adapted a Lagrangian 1-D code to include:
- treatment of deuterium chemistry and HD cooling
(plus Compton and H lines cooling, coupling to CMB)
- approximate collapse of DM at virialization

Two set of models
(with/without HD cooling)

Pre-collapse evolution

Initial conditions through single zone evolution from z=1000 to turn-around of an overdense region virializing at z_{vir}



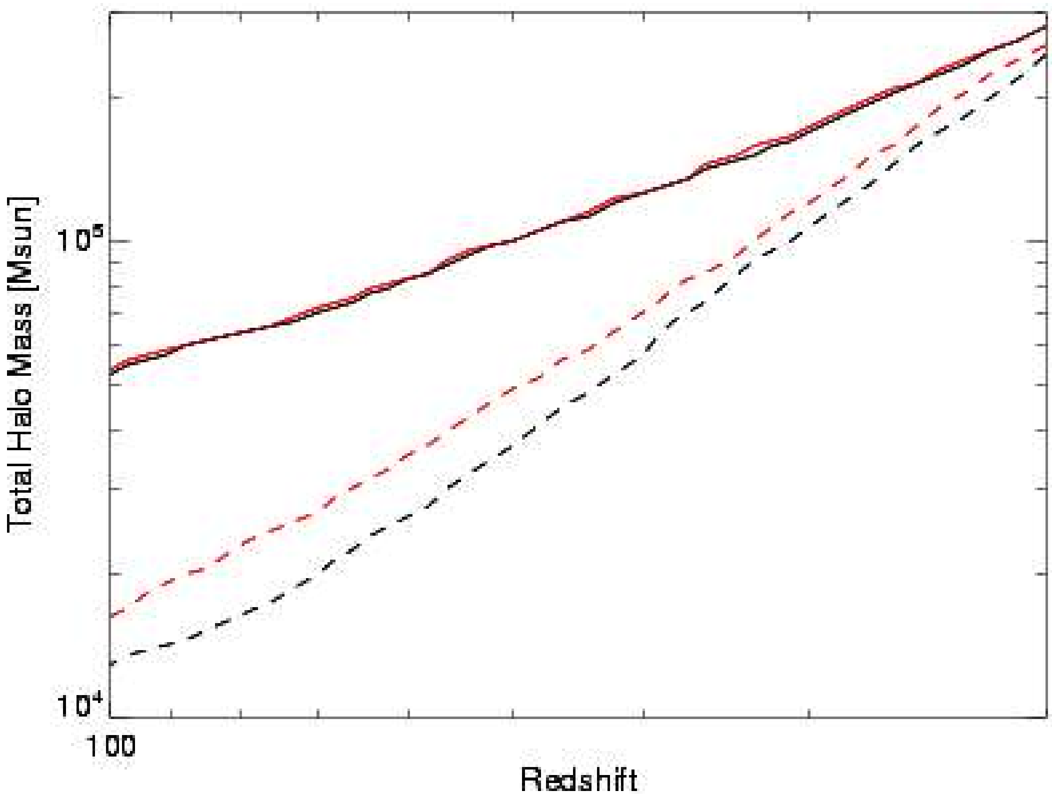
The minimum halo mass

Halos were classified into 3 groups:

- efficiently collapsing halos (reach threshold density in less than an Hubble time)
- inefficiently collapsing halos (reach density threshold before z=10)
- non-collapsing (failed) halos

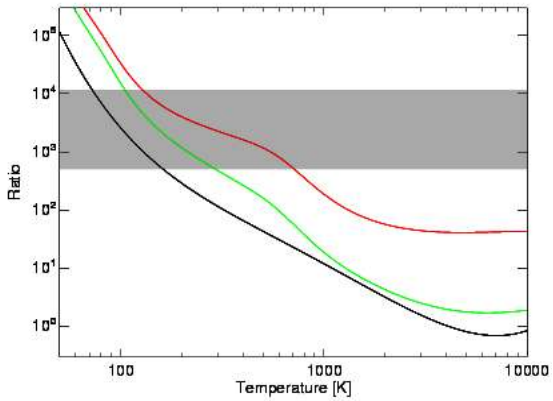
HD makes no difference in M_{crit}

M_{fail} decreases only slightly

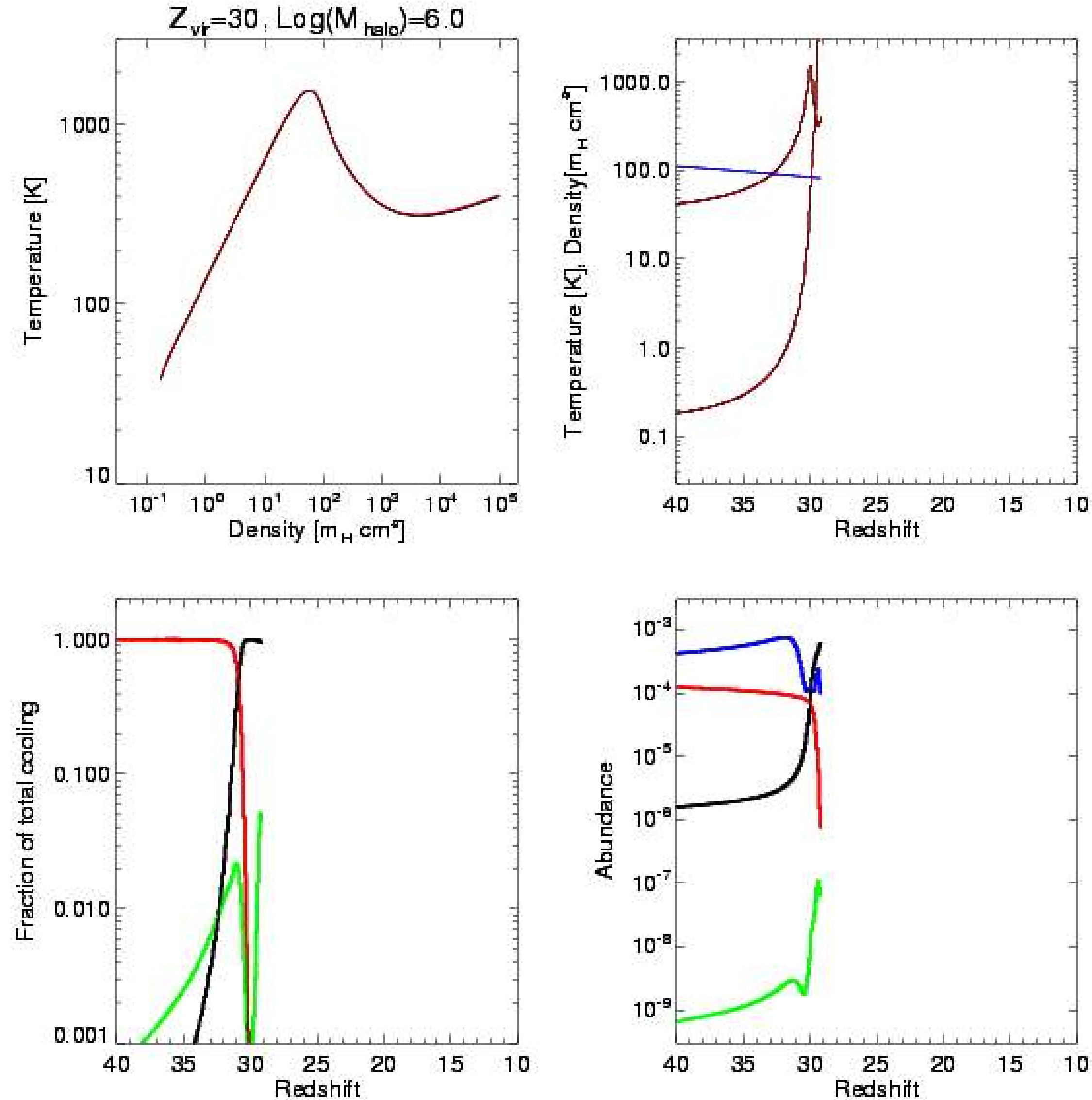


HD and the IMF: no effect "high mass" halos

T_{vir} is high enough (~1000 K) to make HD cooling initially irrelevant in all halos



In relatively large halos, T never reaches the range below ~ 200 K, where HD is important



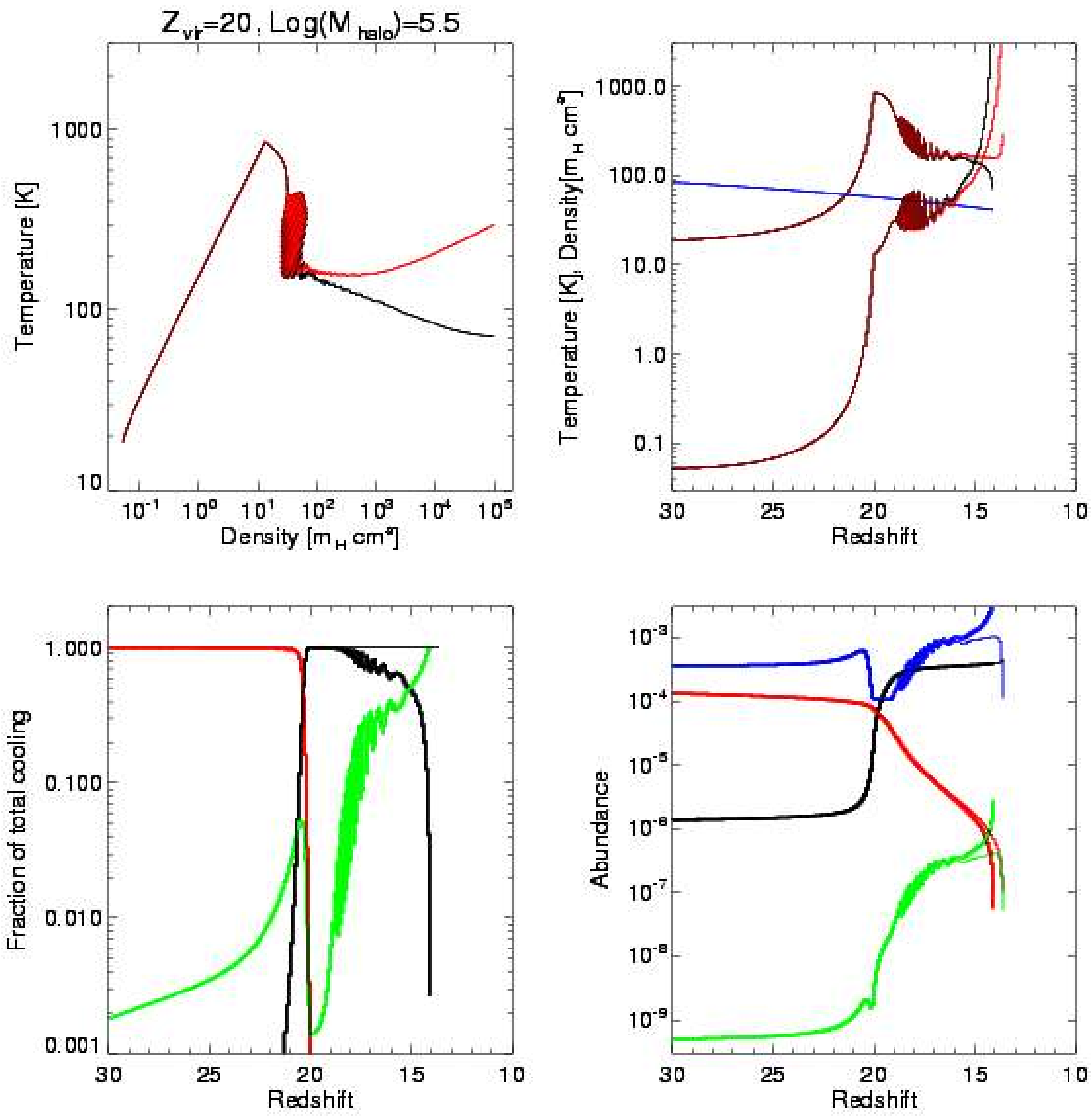
HD and the IMF in “low mass” halos

In smaller halos, T can decrease to ~ 200 K, leading to strong HD cooling

If this happens, T is significantly lowered, and so is the Jeans mass

in such objects the collapse takes longer than where HD can be neglected; however, they are more abundant

Caveat: all objects where HD becomes important go through an oscillatory phase



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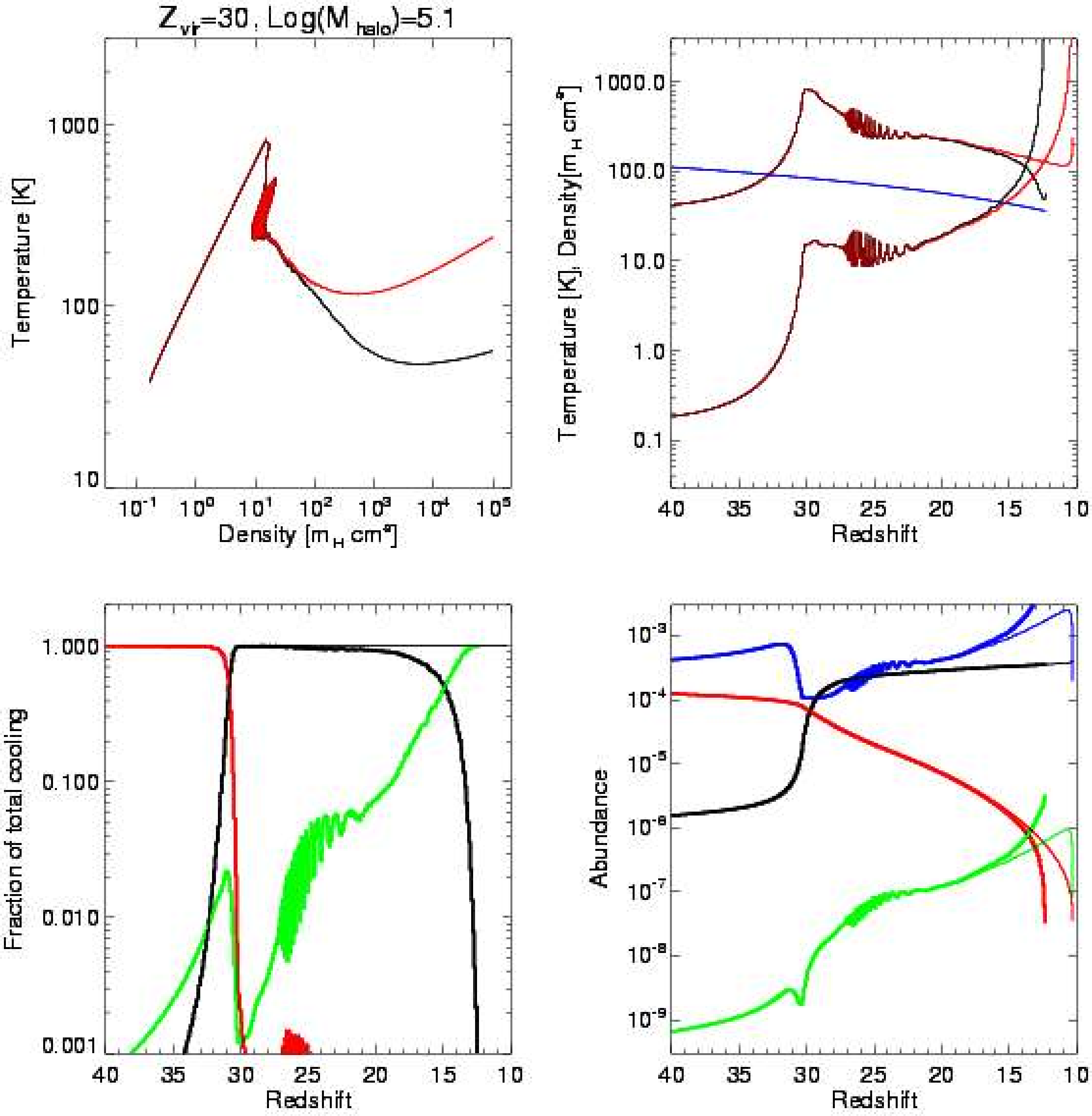
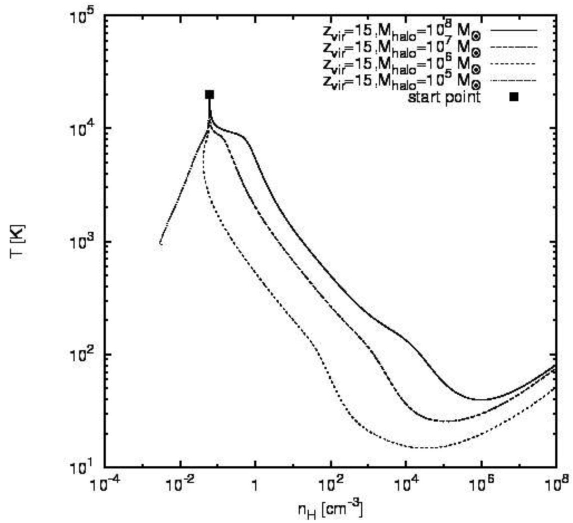
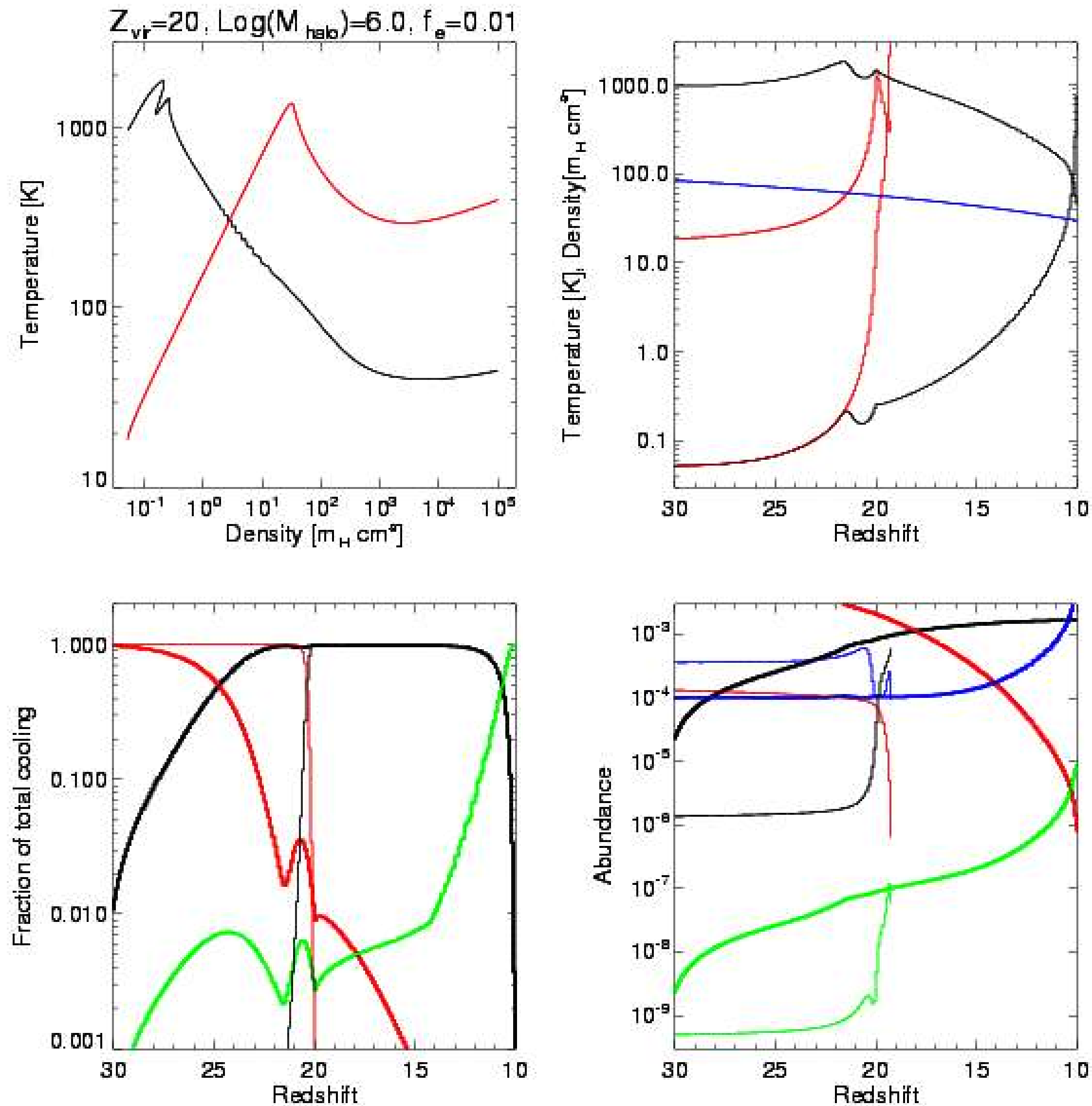


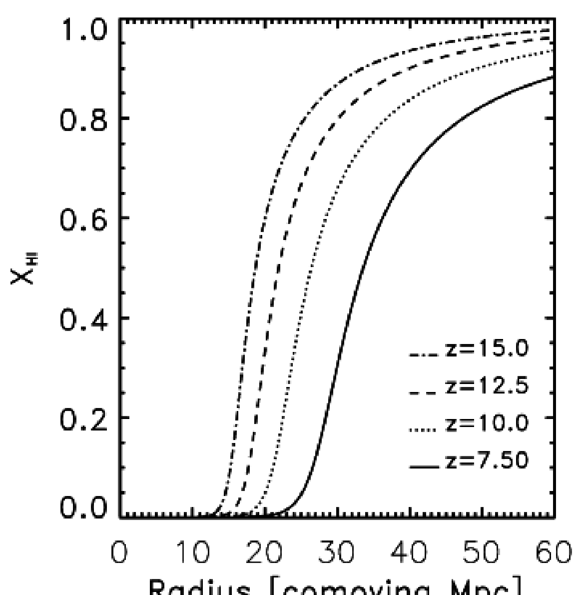
Further possibilities: (partially) ionized regions

Nagakura & Omukai, astro-ph/0505599





Zaroubi & Silk 2005



Need to include photodissociation and heating from ionizing radiation

Conclusions:

HD cooling does not affect the mass range of efficiently cooling halos and only marginally extends that of inefficiently cooling halos

However, HD cooling can lower the gas temperature and alter the star formation process in halos with $M \sim M_{crit}$
Preliminary estimates based on the EPS formalism indicate that this is likely a minor effect except at very high z (~50) though it could be significant in extreme scenarios

HD could have an important role in the formation of the second generation of stars, especially in regions where some kind of feedback (shock fronts, ionization) has taken place