Emanuele Ripamonti
Kapteyn Astronomical Institute,
University of Groningen

The role of HD cooling in the formation of primordial stars

Open Questions in Cosmology, Garching, August 23 2005

Primordial gas cooling - halo mass

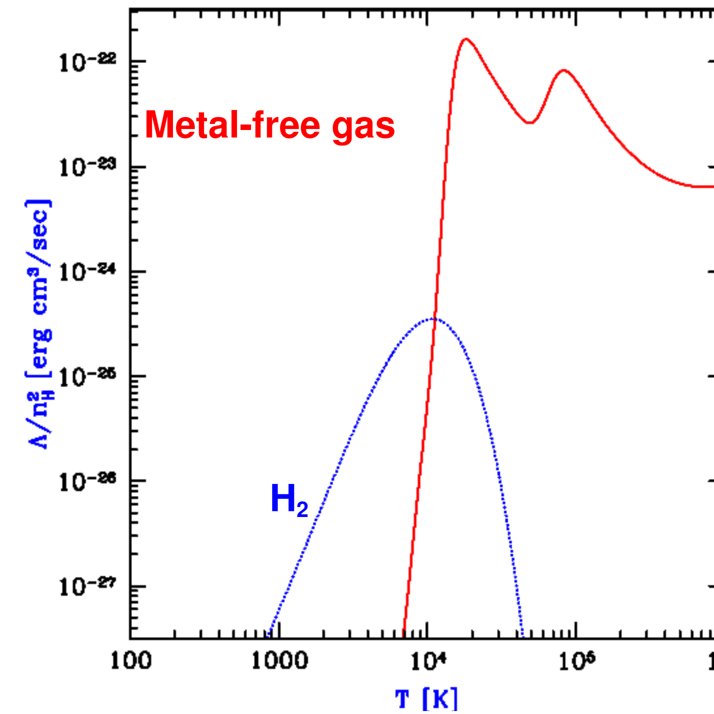
Halo must virialize:
low mass, low T_{vir} halos virialize early

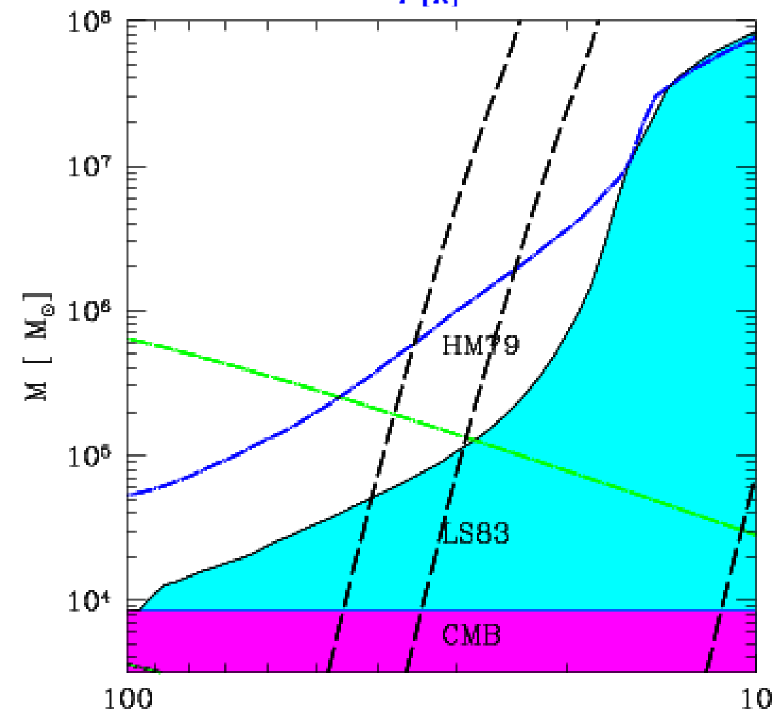
Gravity must overcome pressure:
$M_{gas} > M_{jeans} \sim 10^4\ M_{sun}\ [(1+z)/30]^{3/2}$

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)

Barkana & Loeb 2001





H2 cooling - IMF

H_2 cooling determines the properties of primordial star formation:

Halo mass (~10^6 M_{sun})

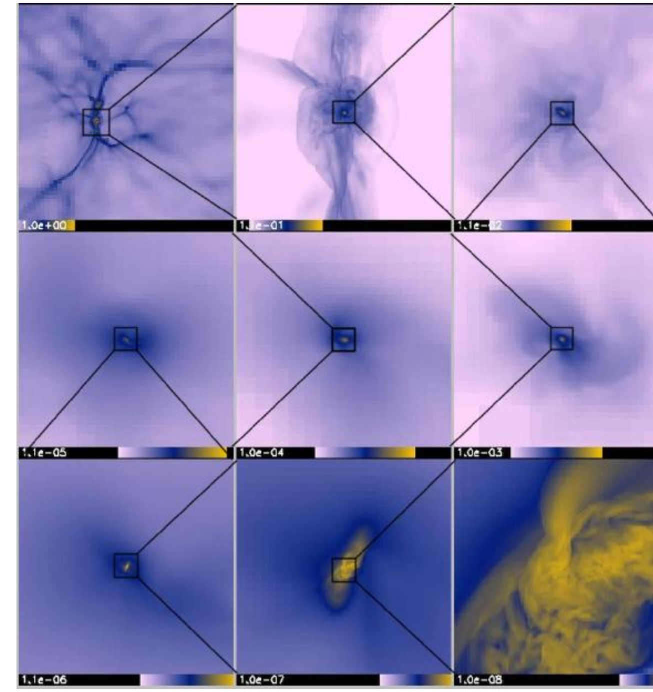
Fragment mass: non-LTE->LTE transition ($n \sim 10^4$ cm^{-3}, $M \sim 100$-1000 M_{sun})

Transition to optically thick regime ($n \sim 10^{9-10}$ cm^{-3})

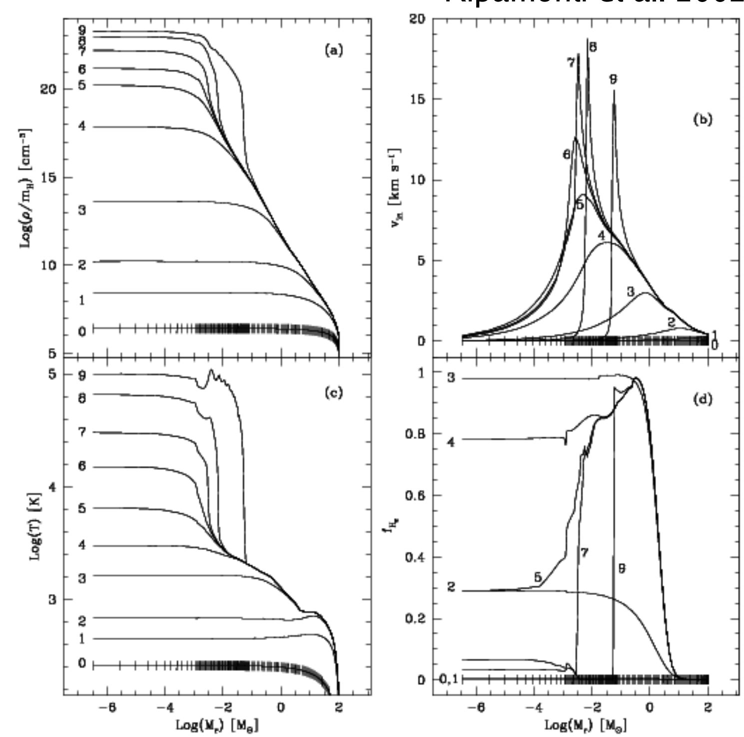
Accretion rate: c_s^3/G is high because of H_2 cooling inefficiency below ~ 200 K

H_2 driven SF probably results in a top-heavy Initial Mass Function

Abel, Bryan & Norman, 2002



Ripamonti et al. 2002



The HD molecule – a missing ingredient?

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

But

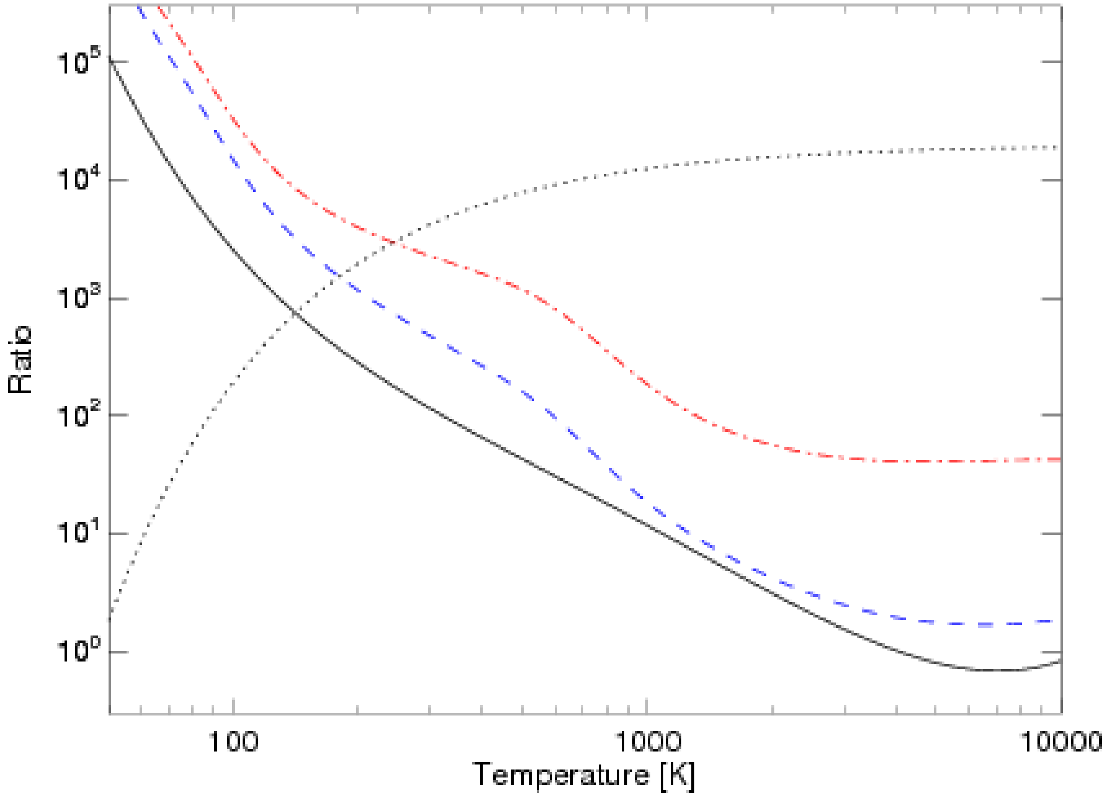
- $n(HD)/n(H_2) \sim 2\,[n(D)/n(H)]\,\exp(465/kT)$

  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

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 $100 \leq z_{vir} \leq 15$,
$10^3\ M_{sun} \leq M_{halo} \leq M(T_{vir}=10^4\ K)$
from turn-around to z=10

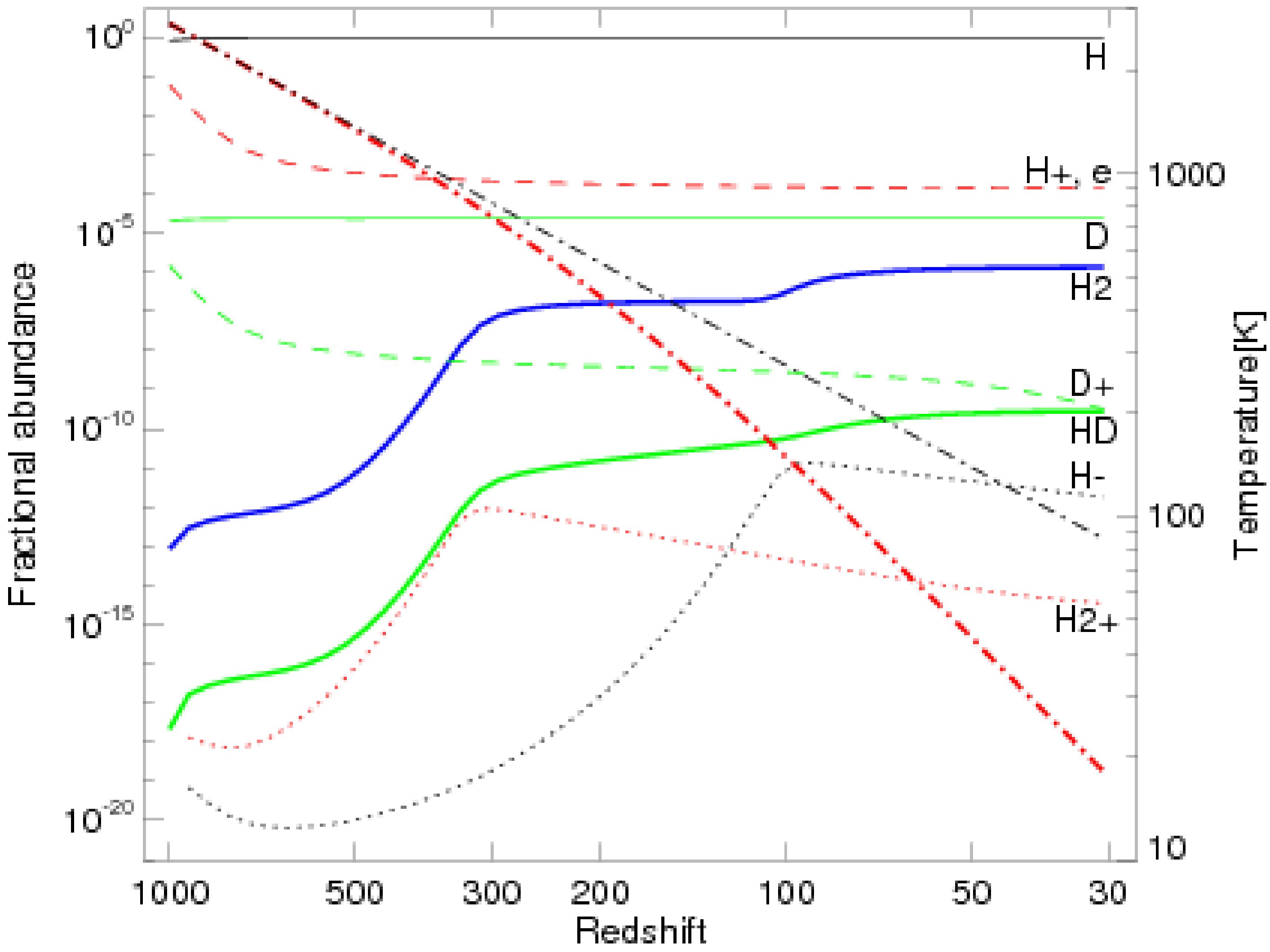
Adapted a Lagrangian 1-D code to include:

- treatment of deuterium chemistry and HD cooling (plus Compton and H lines cooling, coupling to CMB)
- approximate collapse of DM at virialization (2 different assumptions about the final profile)

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}



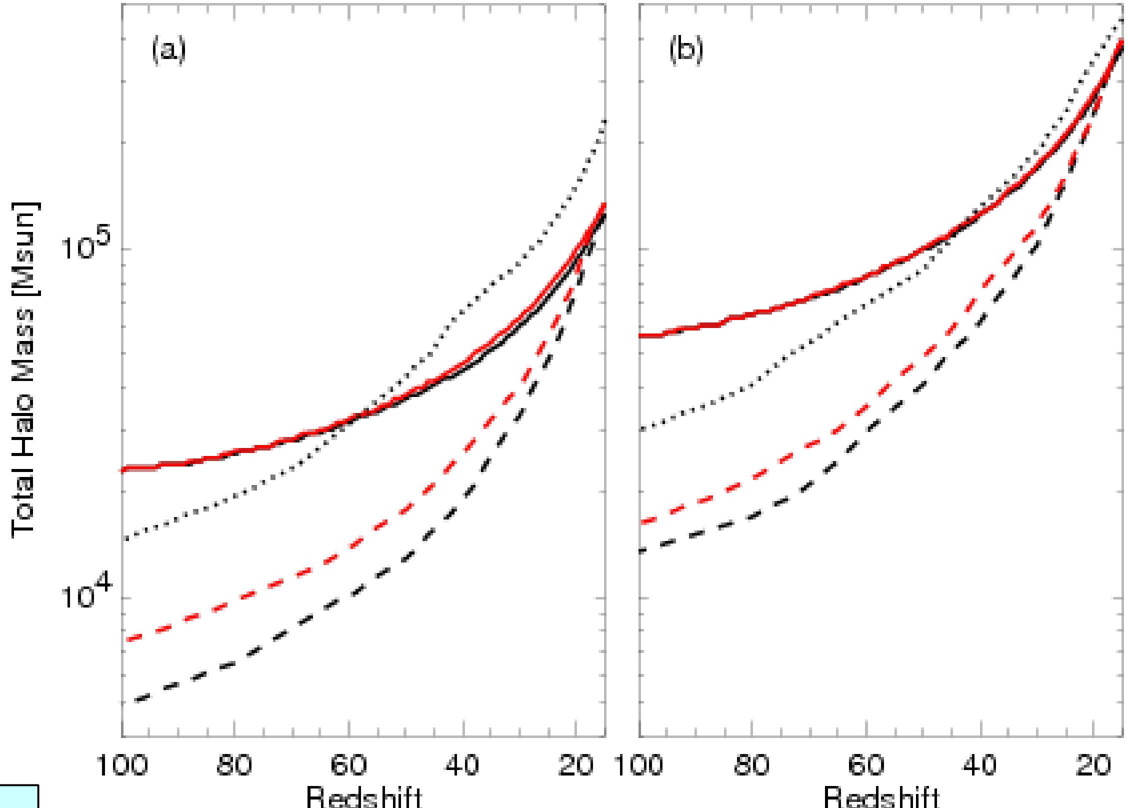
The minimum halo mass

Halos were classified into 3 groups:

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

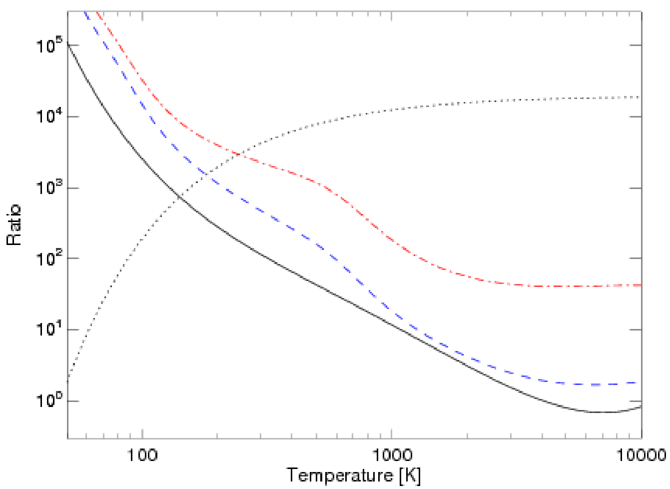
HD makes no difference in M_{crit}

M_{nc} decreases only slightly

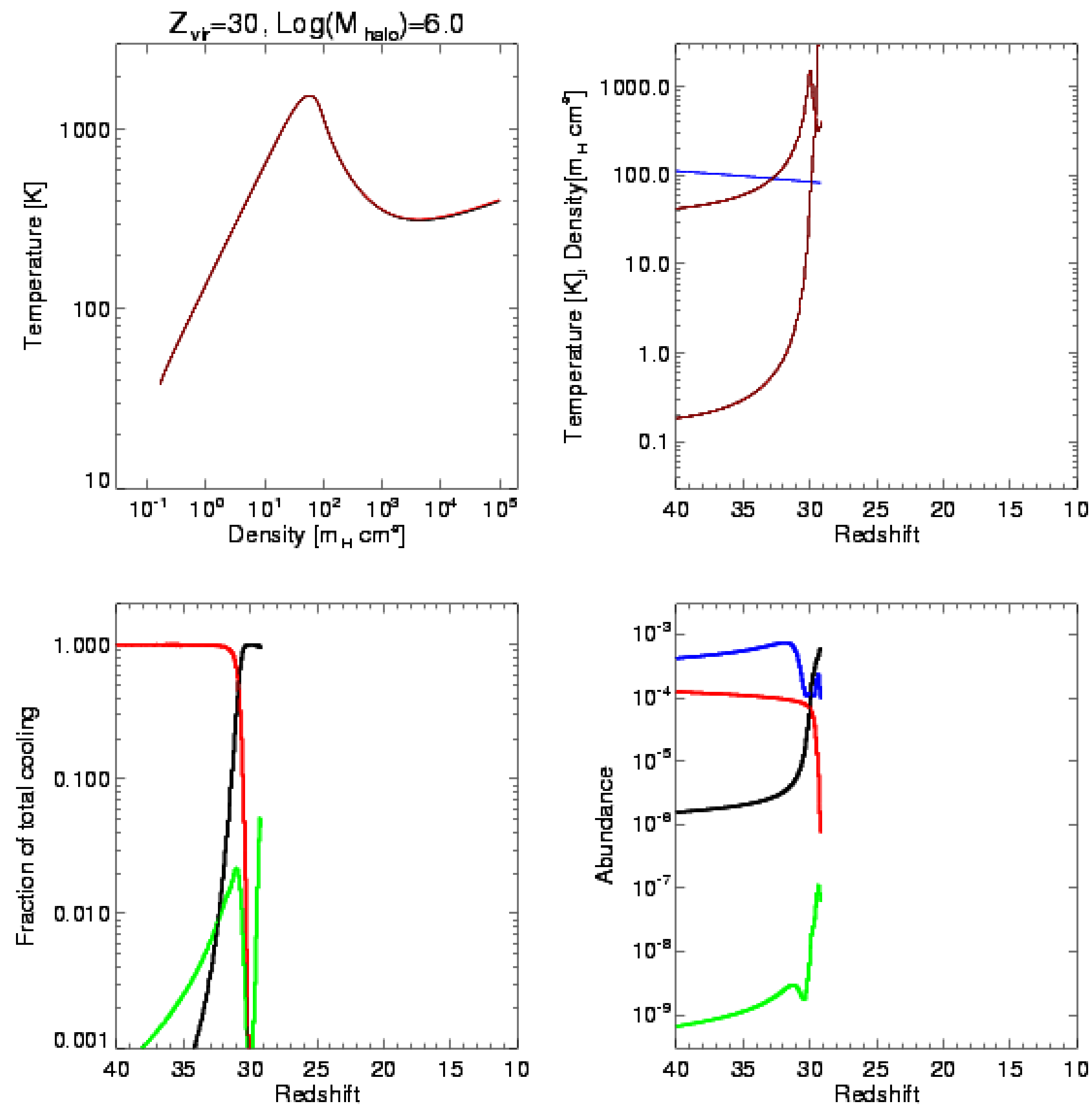


effects of HD on fragmentation: massive halos

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



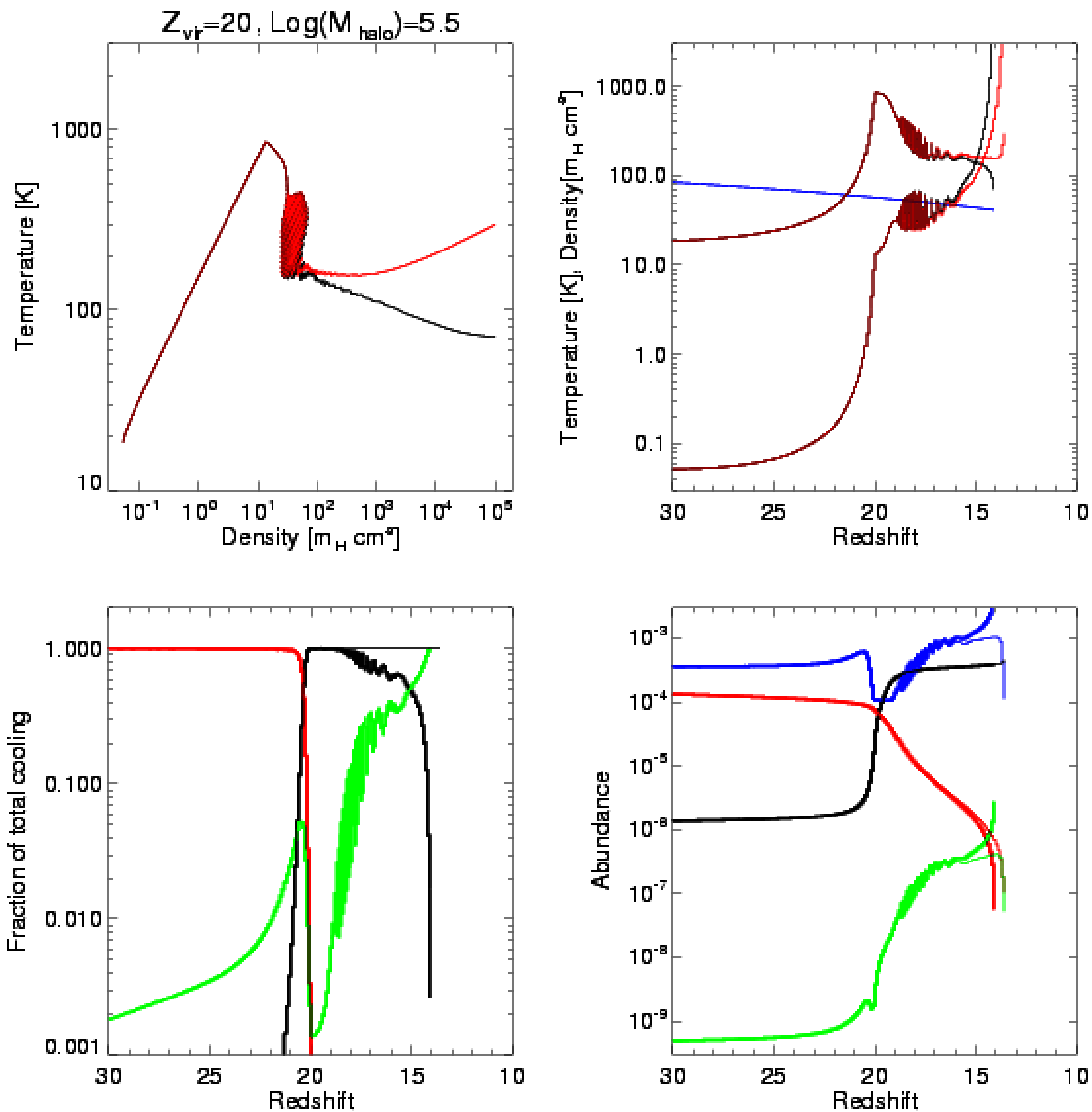
effects of HD on fragmentation: small halos

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

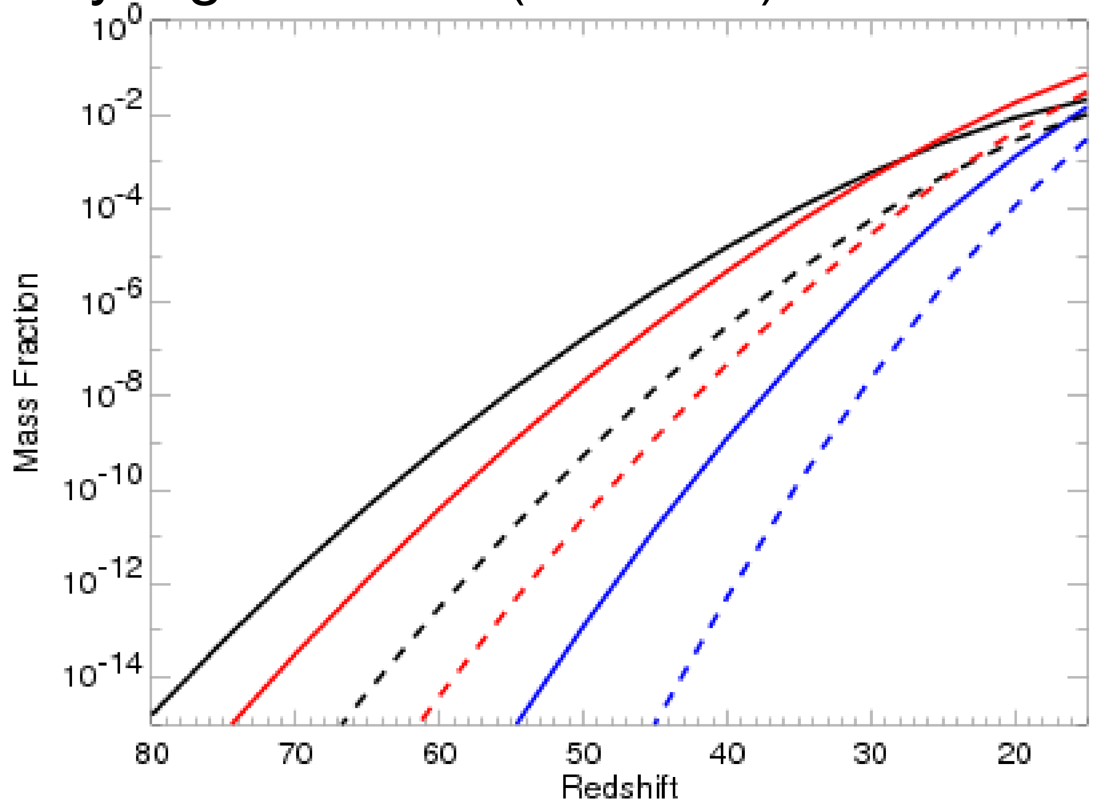
Caveat: all objects where HD becomes important go through an oscillatory phase



How many halos form stars in the HD regime?

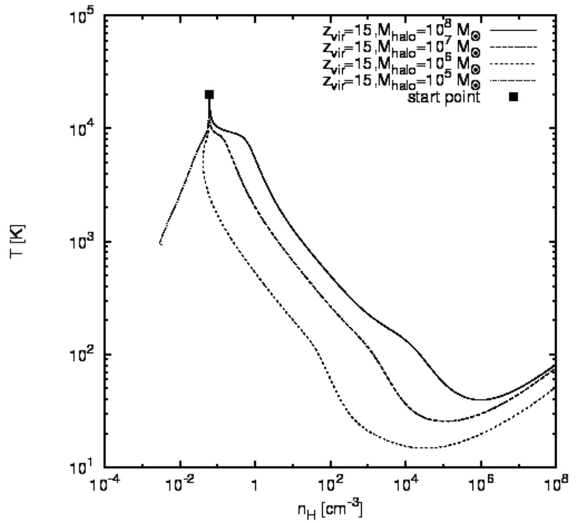
We used the EPS formalism (Sheth & Tormen 1999) in order to estimate the relative importance of the various modes of star formation.

HD-driven SF is marginal, but dominates in low mass halos which form stars at very high redshift (z>30-40)

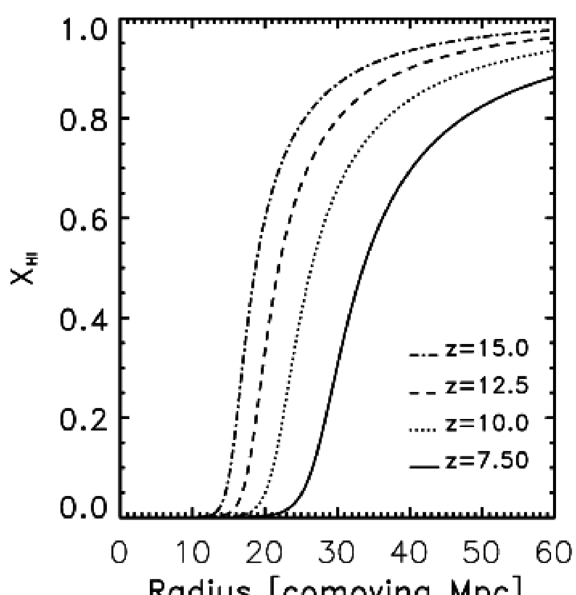


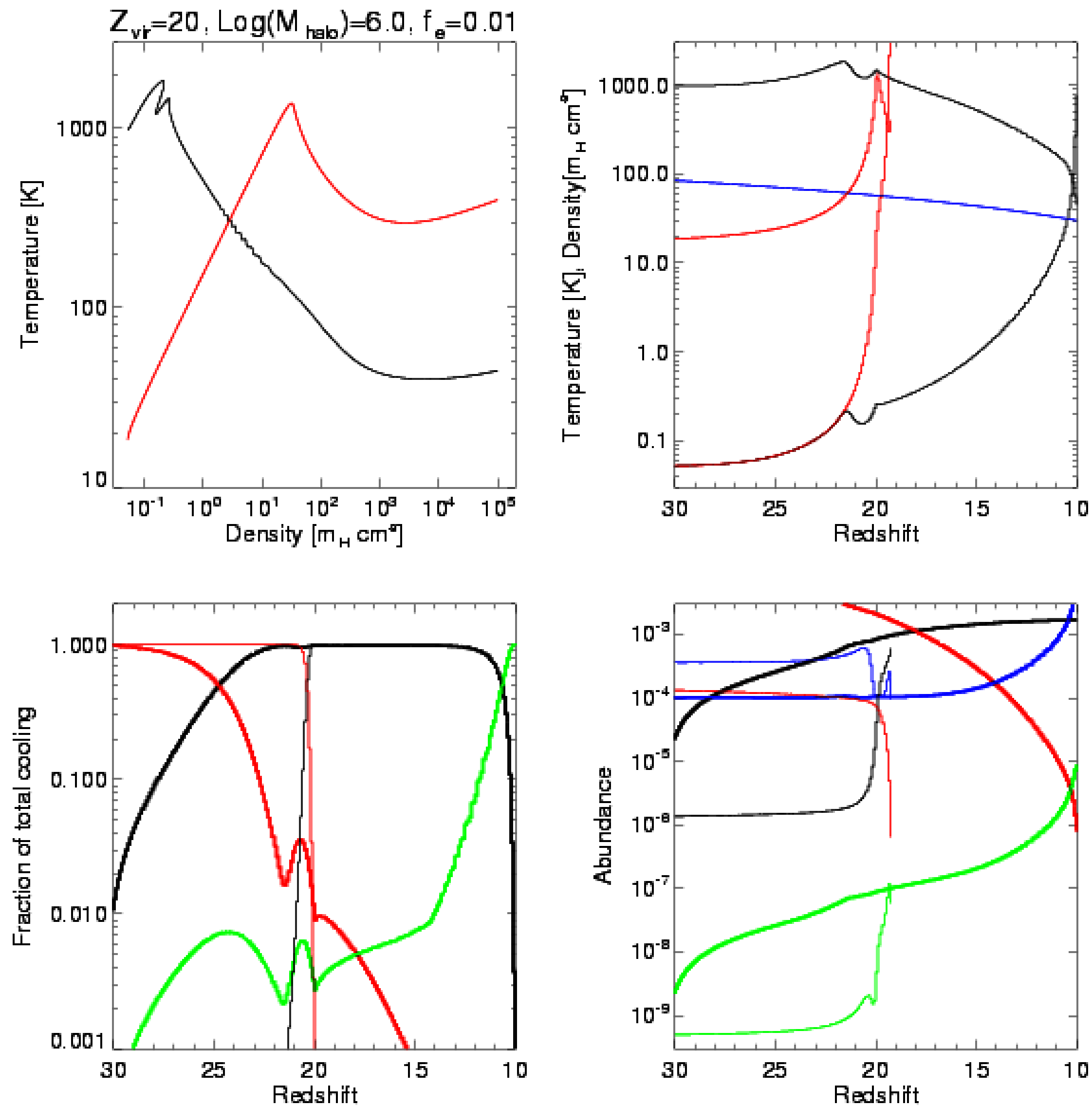
Further possibilities: slightly ionized regions

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

- HD cooling can alter the star formation process in halos with $M<M_{HD}\sim M_{crit}$
  estimates based on the EPS formalism indicate this can be important at very high z (>30-40); however, the mass of stars formed in this regime is likely small

- HD cooling does not affect the proto-stellar collapse of fragments

- 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