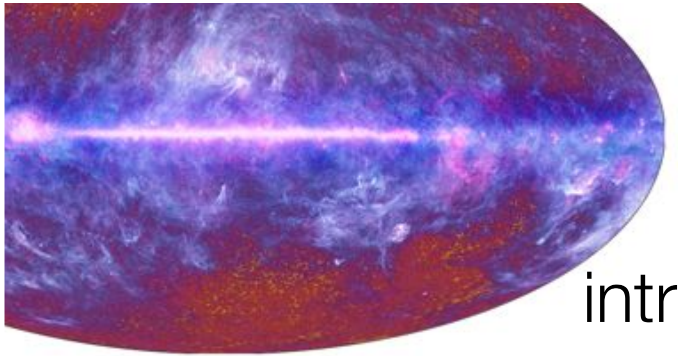


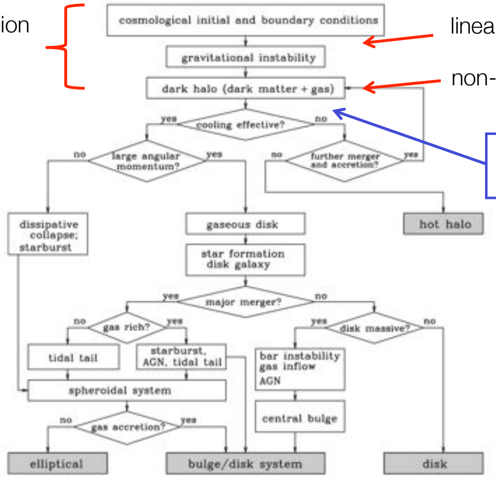
lecture 4
introduction
to galaxy formation

Hervé Dole

Institut d'Astrophysique Spatiale, Orsay
Université Paris-Sud 11 et CNRS
Institut Universitaire de France
http://www.ias.u-psud.fr/dole/m2.php

---

structure and galaxy formation



structure formation

galaxy formation

linear regime

non-linear regime

today: dark halo, and cooling

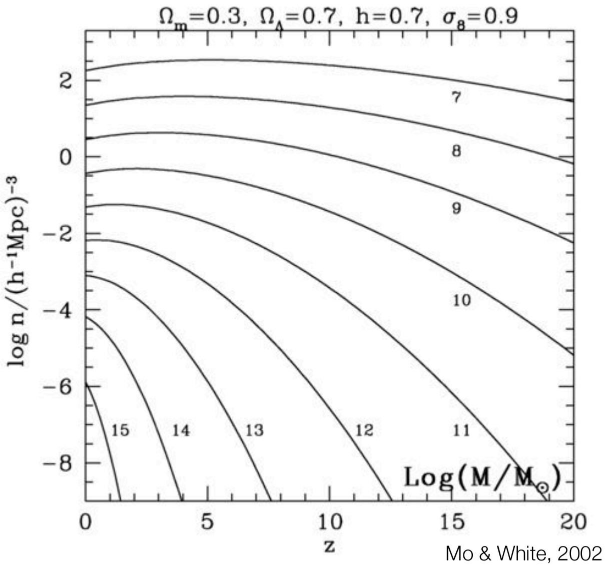
Fig. 1.1. A logic flow chart for galaxy formation. In the standard scenario, the initial and boundary conditions for galaxy formation are set by the cosmological framework. The paths leading to the formation of various galaxies are shown along with the relevant physical processes. Note, however, that processes do not separate as neatly as this figure suggests. For example, cold gas may not have the time to settle into a gaseous disk before a major merger takes place.

Mo, van den Bosch, White fig 1.1

---

1. collapsing haloes

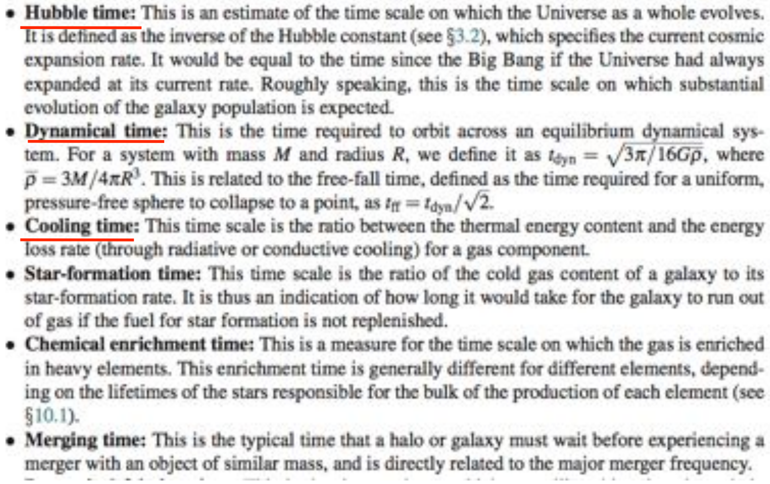
variation with redshift of the comoving number density of DM haloes with masses exceeding the specific value M



Mo & White, 2002

---

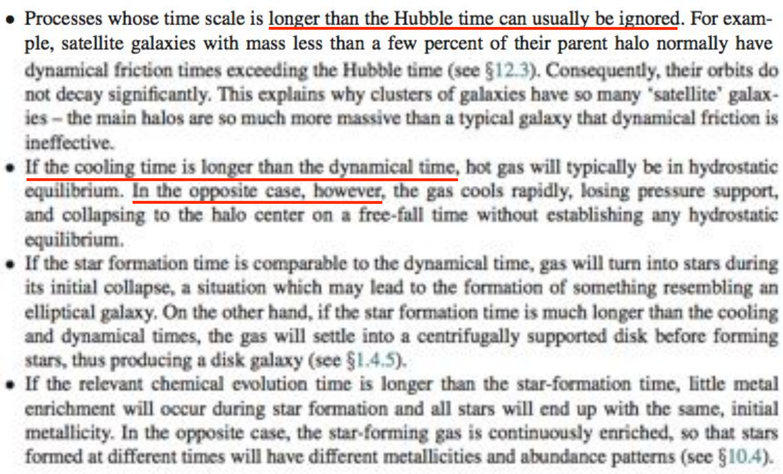
2. cooling of structures - some timescales



- **Hubble time:** This is an estimate of the time scale on which the Universe as a whole evolves. It is defined as the inverse of the Hubble constant (see §3.2), which specifies the current cosmic expansion rate. It would be equal to the time since the Big Bang if the Universe had always expanded at its current rate. Roughly speaking, this is the time scale on which substantial evolution of the galaxy population is expected.
- **Dynamical time:** This is the time required to orbit across an equilibrium dynamical system. For a system with mass M and radius R, we define it as $t_{\rm dyn} = \sqrt{3\pi/16G\bar{\rho}}$, where $\bar{\rho} = 3M/4\pi R^3$. This is related to the free-fall time, defined as the time required for a uniform, pressure-free sphere to collapse to a point, as $t_{\rm ff} = t_{\rm dyn}/\sqrt{2}$.
- **Cooling time:** This time scale is the ratio between the thermal energy content and the energy loss rate (through radiative or conductive cooling) for a gas component.
- **Star-formation time:** This time scale is the ratio of the cold gas content of a galaxy to its star-formation rate. It is thus an indication of how long it would take for the galaxy to run out of gas if the fuel for star formation is not replenished.
- **Chemical enrichment time:** This is a measure for the time scale on which the gas is enriched in heavy elements. This enrichment time is generally different for different elements, depending on the lifetimes of the stars responsible for the bulk of the production of each element (see §10.1).
- **Merging time:** This is the typical time that a halo or galaxy must wait before experiencing a merger with an object of similar mass, and is directly related to the major merger frequency.

Mo, van den Bosch, White sect 1.3

some timescales



- Processes whose time scale is longer than the Hubble time can usually be ignored. For example, satellite galaxies with mass less than a few percent of their parent halo normally have dynamical friction times exceeding the Hubble time (see §12.3). Consequently, their orbits do not decay significantly. This explains why clusters of galaxies have so many 'satellite' galaxies – the main halos are so much more massive than a typical galaxy that dynamical friction is ineffective.
- If the cooling time is longer than the dynamical time, hot gas will typically be in hydrostatic equilibrium. In the opposite case, however, the gas cools rapidly, losing pressure support, and collapsing to the halo center on a free-fall time without establishing any hydrostatic equilibrium.
- If the star formation time is comparable to the dynamical time, gas will turn into stars during its initial collapse, a situation which may lead to the formation of something resembling an elliptical galaxy. On the other hand, if the star formation time is much longer than the cooling and dynamical times, the gas will settle into a centrifugally supported disk before forming stars, thus producing a disk galaxy (see §1.4.5).
- If the relevant chemical evolution time is longer than the star-formation time, little metal enrichment will occur during star formation and all stars will end up with the same, initial metallicity. In the opposite case, the star-forming gas is continuously enriched, so that stars formed at different times will have different metallicities and abundance patterns (see §10.4).

Mo, van den Bosch, White sect 1.3

2.b.ii. cooling functions in a plasma

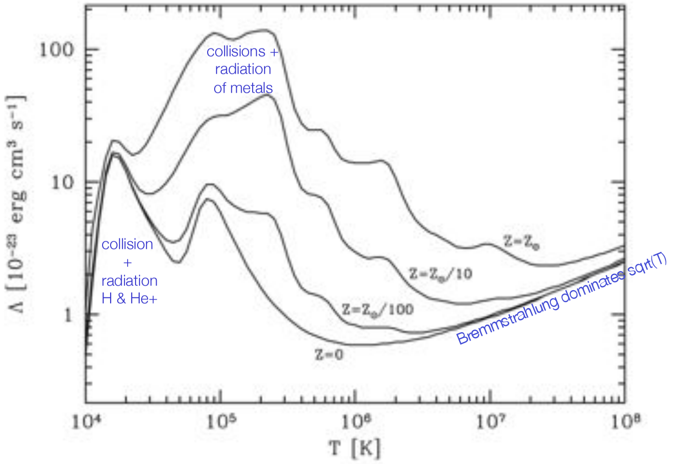
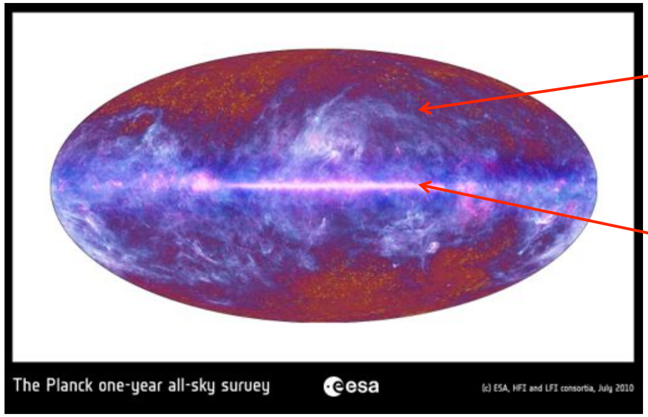


Fig. 8.1. Cooling functions for primordial ($Z = 0$) gas (assuming $n_{He}/n_H = 1/12$), and for gases with metallicities $Z/Z_\odot = 0.01$, 0.1 and 1.0, as indicated. [Based on data published in Sutherland & Dopita (1993)]

Mo, van den Bosch, White fig 8.1

3. conditions for collapse

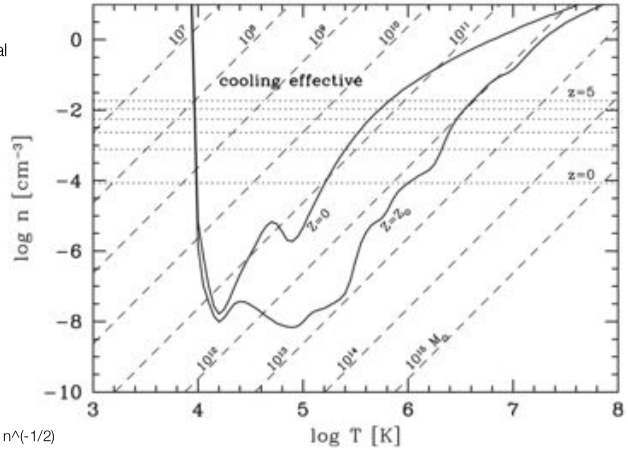


diffuse HI clouds

dense cores

4. cooling vs free-fall

simplifications here:
- uniform & spherical distribution
- virialized
- no merger



δ~200 at various z

Mgas ~ T^3/2 fgas^3/2 n^(-1/2)

Fig. 8.6. Cooling diagram showing the locus of $t_{\rm cool} = t_{\rm ff}$ in the n–T plane. The upper and lower curves correspond to gas with zero and solar metallicity, respectively. The tilted dashed lines are lines of constant gas mass (in M$_\odot$), while the horizontal dotted lines show the gas densities expected for virialized halos ($\delta = 200$) at different redshifts. All calculations assume $f_{\rm gas} = 0.15\ \Omega_{m,0} = 0.3$, and $h = 0.7$. Cooling is effective for clouds with n and T above the locus.

Mo, van den Bosch, White fig 8.6

4. cooling vs free-fall

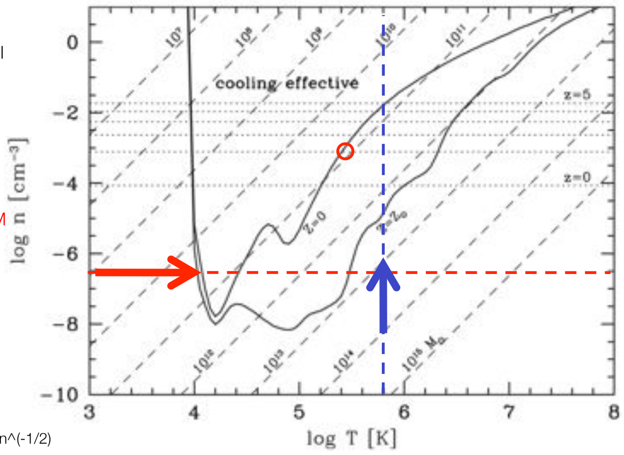
simplifications here:
- uniform & spherical distribution
- virialized
- no merger

in red: dependence M vs T (at n=cst)

in blue: M vs n (at T=cst)

red circle; 10^11 galaxy at z=1

Mgas ~ T^3/2 fgas^3/2 n^(-1/2)



δ~200 at various z

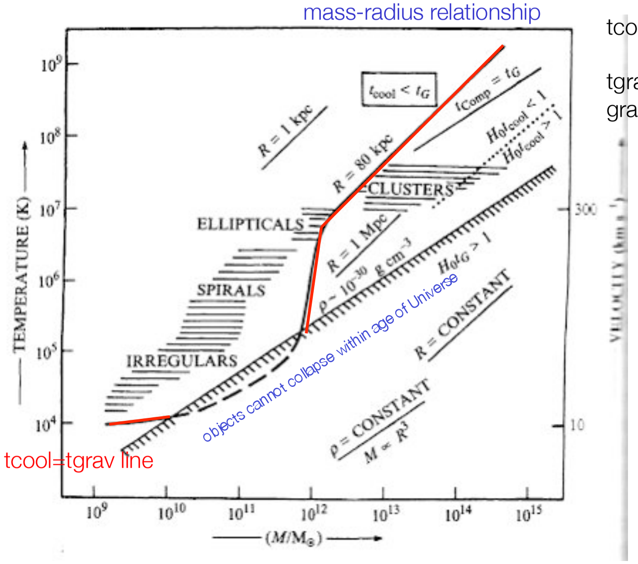
Fig. 8.6. Cooling diagram showing the locus of $t_{\rm cool} = t_{\rm ff}$ in the n–T plane. The upper and lower curves correspond to gas with zero and solar metallicity, respectively. The tilted dashed lines are lines of constant gas mass (in $M_\odot$), while the horizontal dotted lines show the gas densities expected for virialized halos ($\delta = 200$) at different redshifts. All calculations assume $f_{\rm gas} = 0.15$ $\Omega_{m,0} = 0.3$, and $h = 0.7$. Cooling is effective for clouds with n and T above the locus.

Mo, van den Bosch, White fig 8.6

---

mass-radius relationship

GMmp/R: potential well



tcool=tgrav line

tcool = cooling time

tgrav = timescale for gravitational collapse

Padmanabhan, 1993, fig8.3

---

5. overcooling pb in hierarchical formation

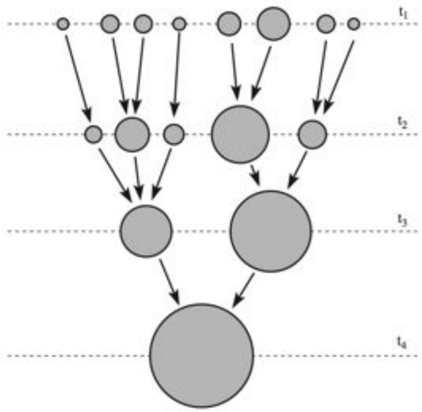


Fig. 1.3. A schematic merger tree, illustrating the merger history of a dark matter halo. It shows, at three different epochs, the progenitor halos that at time t_4 have merged to form a single halo. The size of each circle represents the mass of the halo. Merger histories of dark matter halos play an important role in hierarchical theories of galaxy formation.

Mo, van den Bosch, White fig 1.3

---

cooling functions

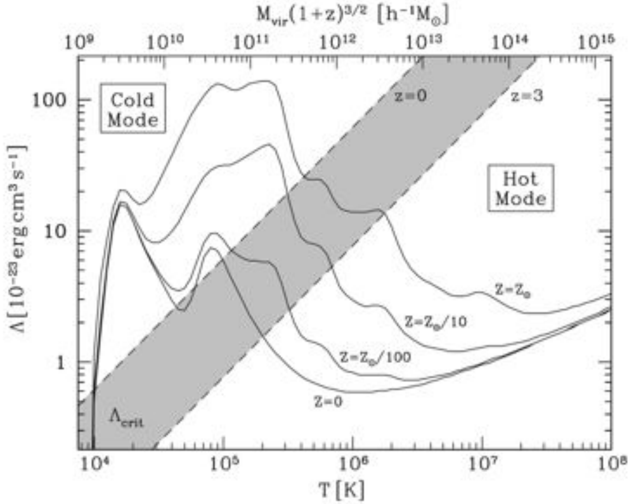
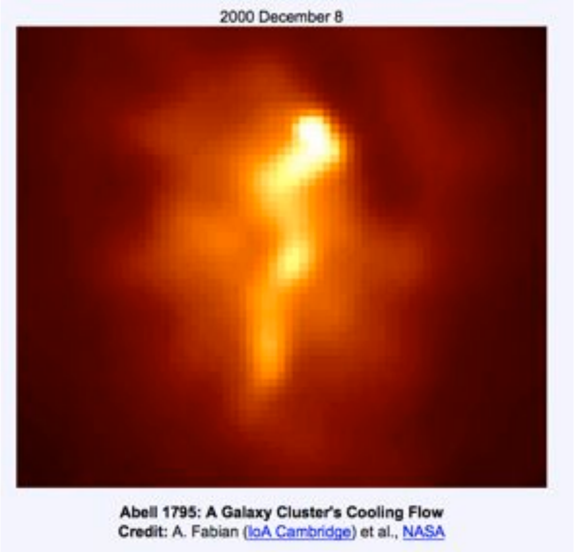


Fig. 8.7. Same as Fig. 8.1, except that now we also indicate $\Lambda_{\rm crit}$ for halos in the redshift range $0 \leq z \leq 3$ (shaded area). Halos with $\Lambda > \Lambda_{\rm crit}$ accrete their gas in the cold mode, while those with $\Lambda < \Lambda_{\rm crit}$ experience hot mode accretion.

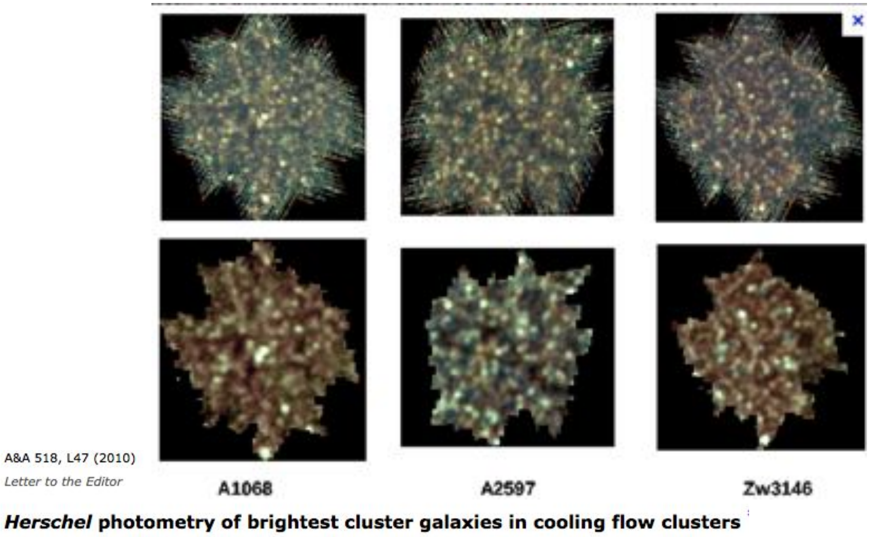
Mo, van den Bosch, White fig 8.7

Galaxy cluster cooling flows



Abell 1795: A Galaxy Cluster's Cooling Flow
Credit: A. Fabian (IoA Cambridge) et al., NASA

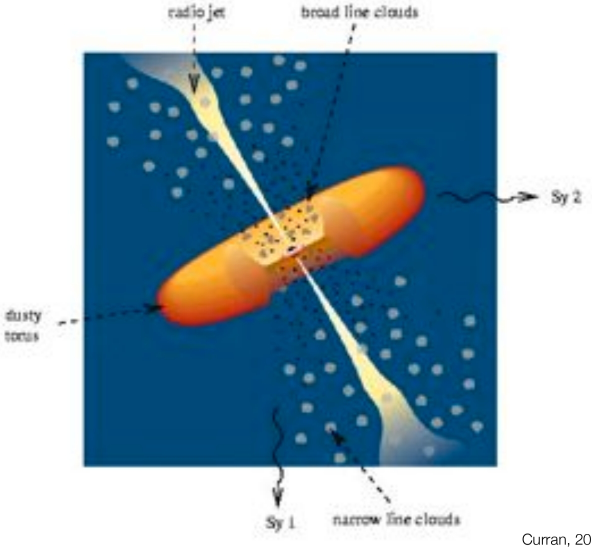
Galaxy cluster cooling flows



A&A 518, L47 (2010)
Letter to the Editor

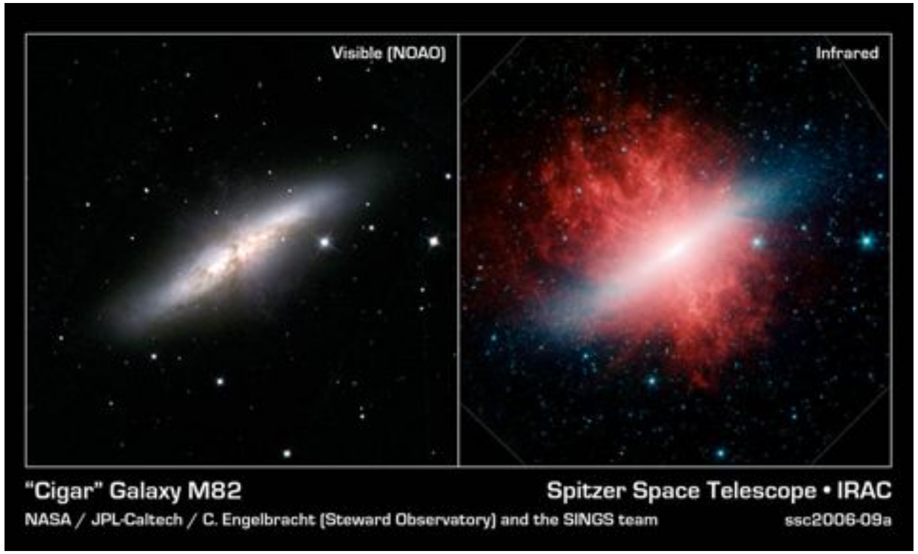
Herschel **photometry of brightest cluster galaxies in cooling flow clusters**

AGN unified scheme

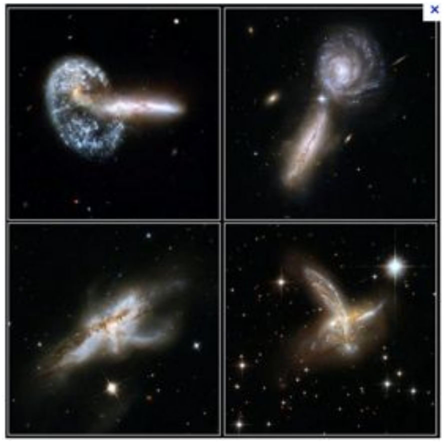


Curran, 2000

Galactic fountains: SNs



mergers



---

mergers

---

6. How H2 helps cooling

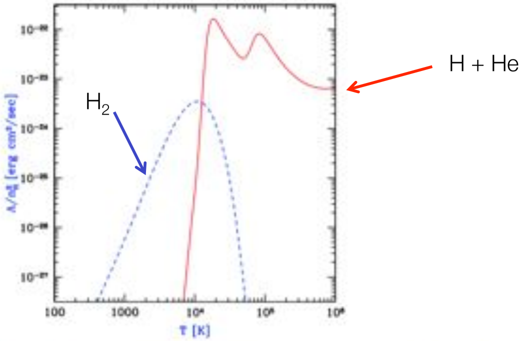
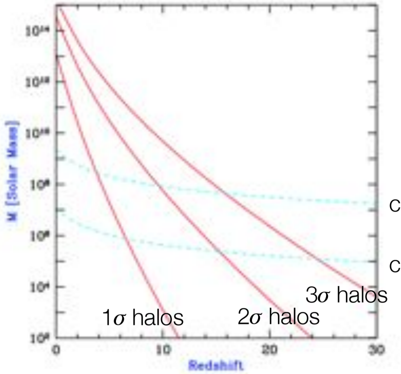


Fig. 20. Cooling rates as a function of temperature for a primordial gas composed of atomic hydrogen and helium, as well as molecular hydrogen, in the absence of any external radiation. We assume a hydrogen number density $n_H = 0.045\ \mathrm{cm}^{-3}$, corresponding to the mean density of virialized halos at $z = 10$. The plotted quantity Λ/n_H^2 is roughly independent of density (unless $n_H > 10\ \mathrm{cm}^{-3}$), where Λ is the volume cooling rate (in erg/sec/cm^3). The solid line shows the cooling curve for an atomic gas, with the characteristic peaks due to collisional excitation of H1 and He2. The dashed line shows the additional contribution of molecular cooling, assuming a molecular abundance equal to 1% of n_H.

A. Loeb., 2006

---

collapsing halos and H2 cooling (1)



added cooling by H2 makes possible the collapse of more haloes.
e.g. z=15 ony 3σ halos (i.e. rare) collapse possible; w/ H2, 2σ is possible (i.e. more sources of reionization)

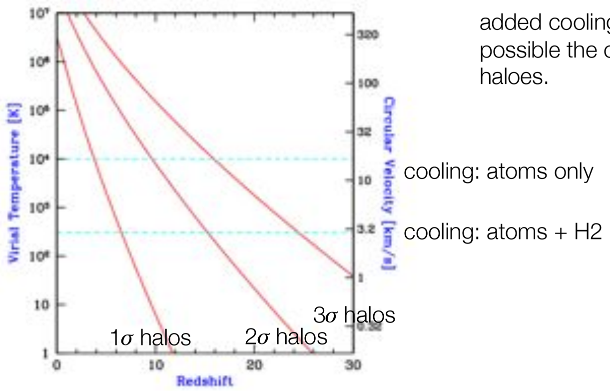
cooling: atoms only

cooling: atoms + H2

Fig. 15. Characteristic properties of collapsing halos: Halo mass. The solid curves show the mass of collapsing halos which correspond to $1-\sigma$, $2-\sigma$, and $3-\sigma$ fluctuations (in order from bottom to top). The dotted curves show the mass corresponding to the minimum temperature required for efficient cooling with primordial atomic species only (upper curve) or with the addition of molecular hydrogen (lower curve).

A. Loeb., 2006

collapsing halos and H2 cooling (2)



added cooling by H2 makes possible the collapse of more haloes.

Fig. 17. Characteristic properties of collapsing halos: Halo virial temperature and circular velocity. The solid curves show the virial temperature (or, equivalently, the circular velocity) of collapsing halos which correspond to $1-\sigma$, $2-\sigma$, and $3-\sigma$ fluctuations (in order from bottom to top). The dotted curves show the minimum temperature required for efficient cooling with primordial atomic species only (upper curve) or with the addition of molecular hydrogen (lower curve).

A. Loeb., 2006