PRIMORDIAL CHEMISTRY AND THE FORMATION OF THE FIRST STARS

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Present-day gas

Heavy element mass fraction < 2%

C^+, O, CO, dust grains excellent radiators

Thermal eq. timescale « dynamical timescale

Typical cloud temperature ≈ 10 K

Primordial gas

No heavy elements

H, He poor radiators for $T < 10^4$ K

Cloud evolves almost adiabatically..

..unless H_2 molecules can form

MAIN COOLING PROCESSES IN PRIMORDIAL GAS

1. Radiative recombination

   Thermal energy loss of recombining proton and electron due to photon emitted in the process
   Recombinations to the lowest state lead to ionizing photons, hence net loss = 0
   Total rate obtained by summing over all rates for levels with n >1 (Case B recombination).

2. Collisional ionization

   Thermal energy of electrons converted in ionization energy

   $\sigma_{ion} = a\,(EB)^{-1} \ln (E/B)\ \{1 - b \exp[-c\,(E/B - 1)]\} \quad E \geq B = 13.6\ eV$

   Total rate by integrating cross section over Maxwellian distribution

3. Bound-bound transition of hydrogen atom

   Most important cooling process around 10,000 K; collisionally excited.
   Emitted radiation energy equal to energy difference between two levels
   Level population determined by excitation/de-excitation rates for each level

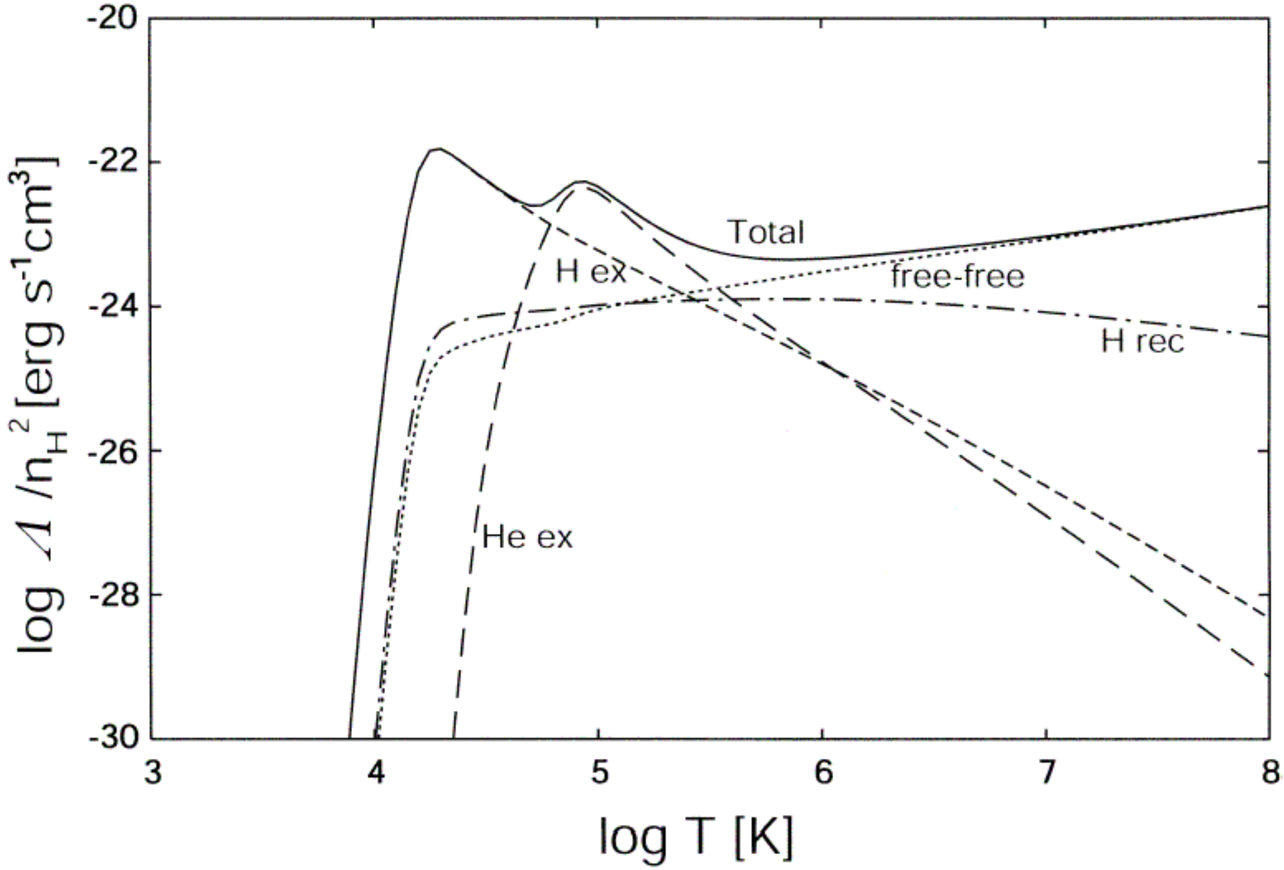
4. Thermal bremsstrahlung emission

   Radiation due to acceleration of a charge in a Coulomb field

   $dE/d\nu\, dV\, dt = (16\, \pi\, e^6 / 3\sqrt{3}\, c^3\, m_e^2\, v)\, n_e\, n_p\, g_{ff}$

   Total rate by integrating cross section over Maxwellian distribution

PRIMORDIAL COOLING FUNCTION



FUNDAMENTAL STAR FORMATION TIMESCALES

- Cooling time

$$t_{cool} = 3kT / 2n\Lambda(T)$$

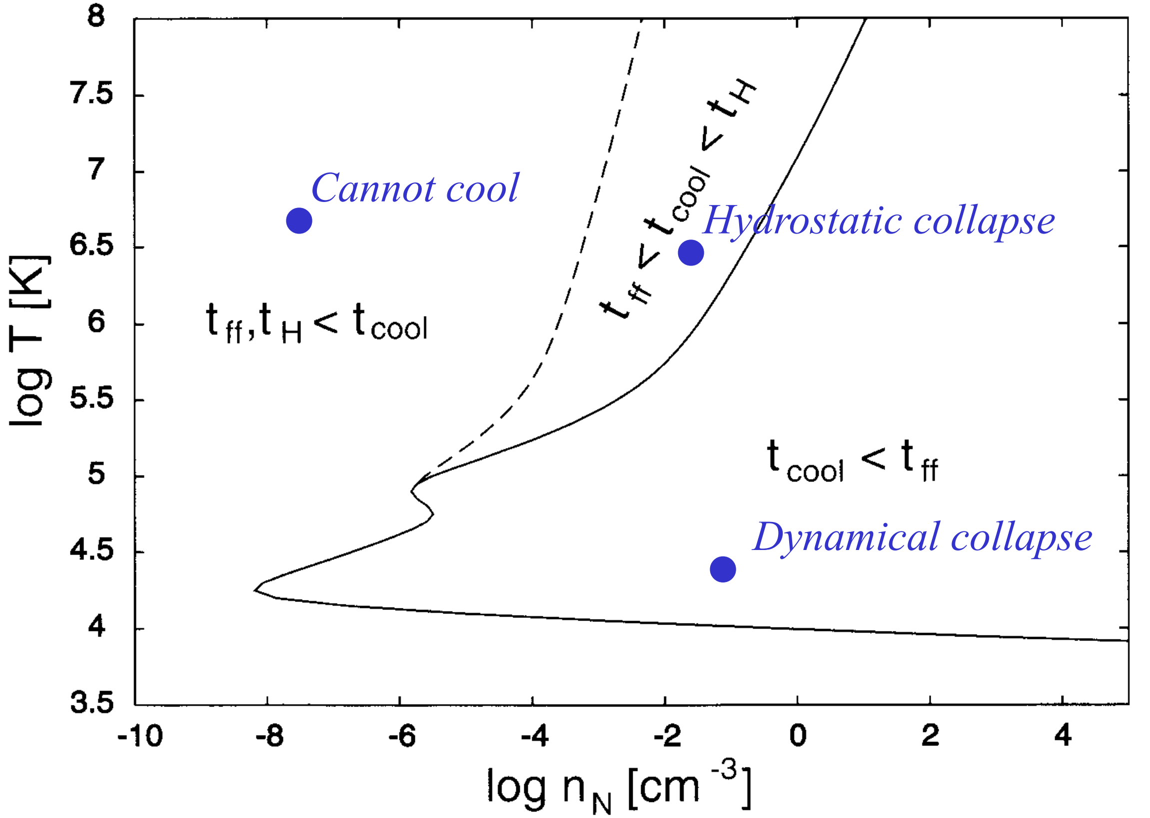
- Free-fall time

$$t_{ff} = (3\pi / 32\, G\rho)^{1/2}$$

- Hubble time

$$t_H = H^{-1}(z)$$

COOLING DIAGRAM



COOLING BY HYDROGEN MOLECULES

1. Radiative cooling

Hydrogen molecules have energy levels corresponding to vibrational (10^3 K < T < 10^4 K) and rotational (T < 10^3 K) transitions
Einstein's A-coefficient much smaller (no dipole moment) → Absorption coefficient very small

$$\Lambda_{H2} = n_{H2} [\, n_H L_{vr}^{H}(n,T) + n_{H2} L_{vr}^{H2}(n,T)]$$

H-H$_2$ | *H$_2$-H$_2$* *collisional excitations*

LEVEL POPULATION

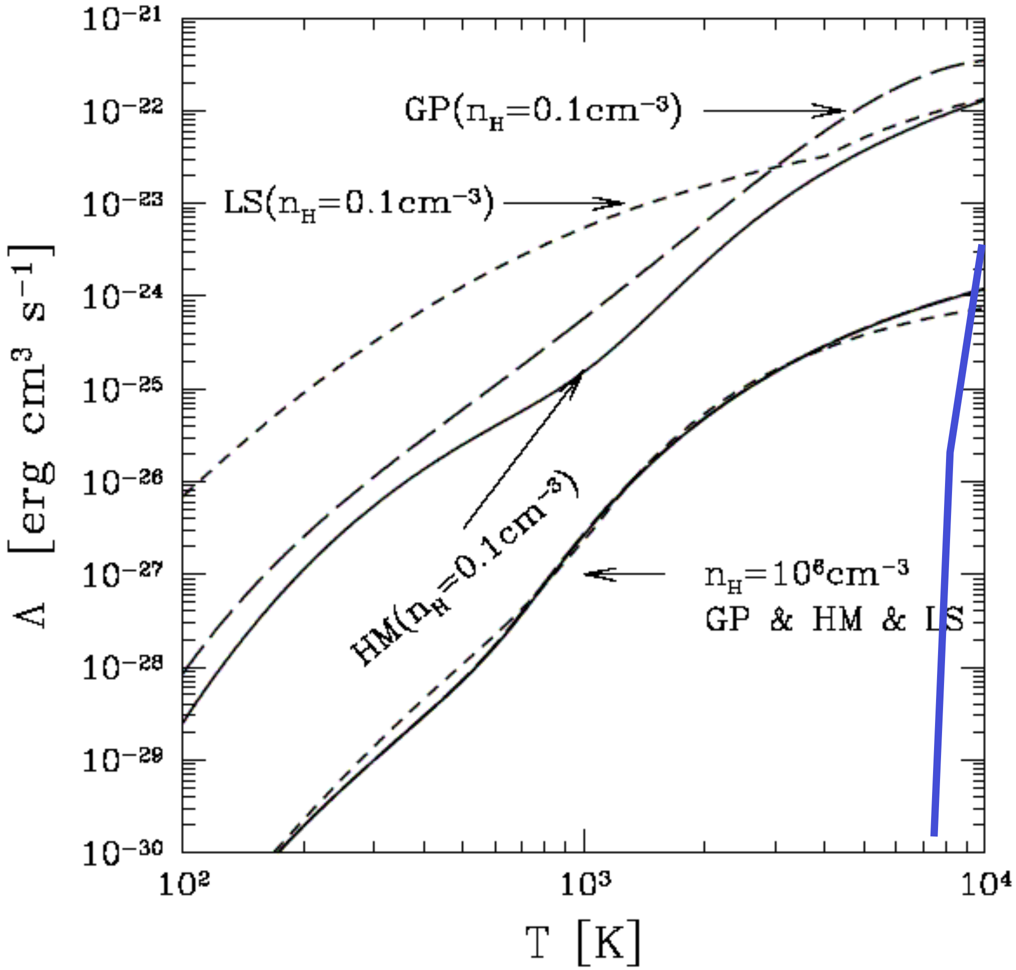
De-excitation rate = Excitation rate

collisional $\propto n^2$ — *collisional*
radiative decay $\propto n$

<u>*Critical density*</u> n_{crit} :: collisional exc. rate = radiative decay rate

$$\Lambda_{H2} \propto n^2 \quad \text{for } n < n_{crit}$$
$$\Lambda_{H2} \propto n \quad \text{for } n > n_{crit}$$

H_2 COOLING FUNCTION



COOLING BY HYDROGEN MOLECULES

2. Dissociation cooling/heating

Hydrogen molecules have lower potential energy than the state of two separated neutral H-atoms
H_2 molecules absorb the thermal energy of the colliding particle causing the dissociation

$$\Lambda_{diss} = 7.16 \times 10^{-12}\,(dn_{H2}/dt)_{-} \quad erg\ s^{-1}cm^{-3}$$

Dissociation of H_2 molecules can occur via three main channels:

- Collisions with H^+ ions — *high ionization level*
- Collisions with H atoms — *low ionization level*
- Collisions with H_2 molecules — *low ionization level*

Heating (reverse process) occurs when H_2 molecules form in an excited state
If collisional de-excitation dominates over radiative decay (high n), energy transported into gas thermal energy

$$\Gamma_{form} = 7.16 \times 10^{-12}\,(dn_{H2}/dt)_{+}\ (1+n_{cr}/n_H)^{-1} \quad erg\ s^{-1}cm^{-3} \longrightarrow 0\ \ for\ n \ll n_{cr}$$

FORMATION CHANNELS

1. H^- Channel

$$H + e \rightarrow H^- + \gamma$$
$$H^- + H \rightarrow H_2 + e$$

2. H_2^+ Channel

$$H + H^+ \rightarrow H_2^+ + \gamma$$
$$H_2^+ + H \rightarrow H_2 + H^+$$

- *Dipole moment necessary to form H_2 in two-body reactions*
- *Require electrons or protons: ionization degree important*

3. Three body reactions

$$3H \rightarrow H_2 + H$$
$$2H + H_2 \rightarrow 2H_2$$

- *Important at high $n > 10^8$ cm^{-3}, i.e. during prestellar collapse*

4. Direct collision between excited H atoms

$$H(n=1) + H(n=2) \rightarrow H_2 + \gamma$$

- *Important at $z > 10^3$ as CMB photons destroy H_2^+ and H^-*

DISSOCIATION CHANNELS

1. Impact with H / H_2

$$3H \leftarrow H_2 + H \ \text{or}$$
$$2H + H_2 \leftarrow 2H_2$$

• *T > 2000 K, lower T collisions not sufficiently energetic*

2. Impact with H^+

$$H_2^+ + H \leftarrow H_2 + H^+$$
$$2H \leftarrow H_2^+ + e$$

• *Important in hot (T>8000 K) and ionized gas*

3. Impact with electrons

$$2H + e \leftarrow H_2 + e$$

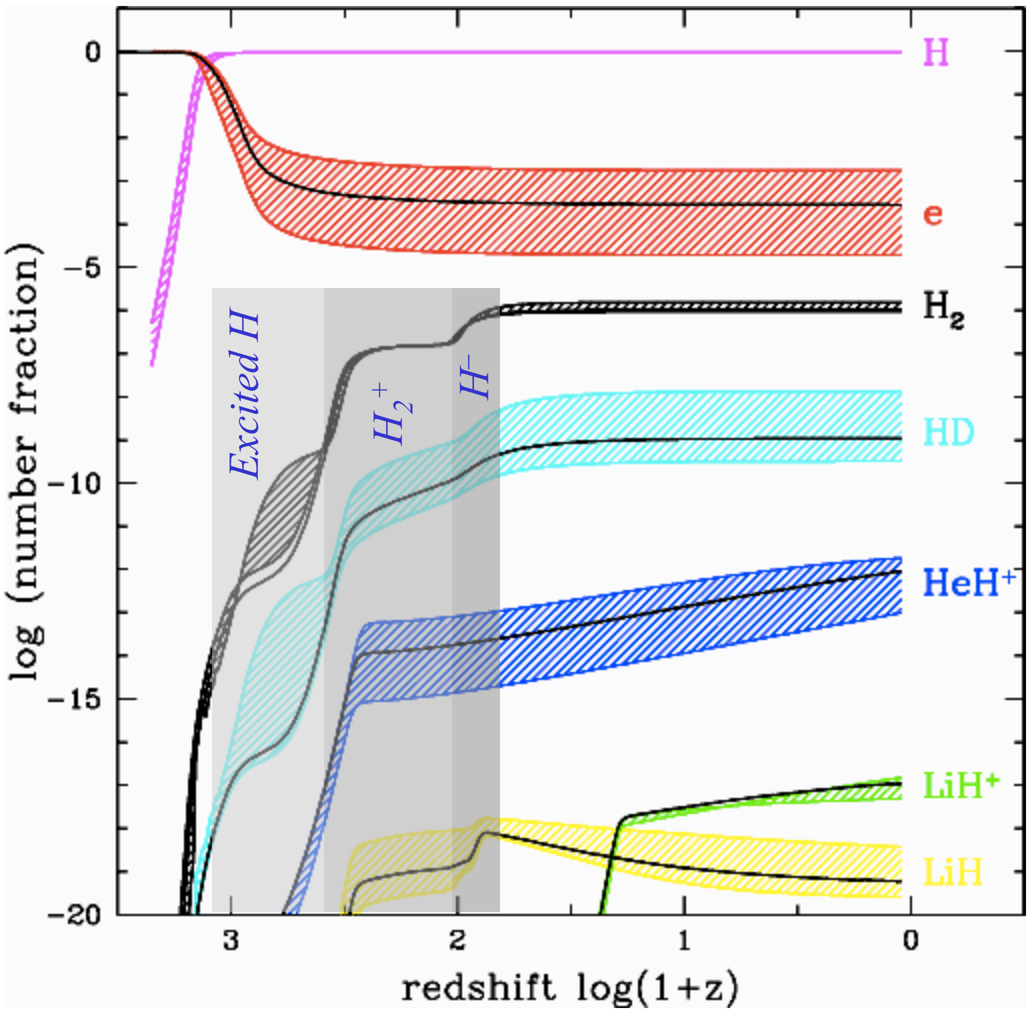
• *Always sub-dominant with respect to 2.*

4. Photodissociation

$$H_2^* \leftarrow H_2 + \gamma$$
$$2H + \gamma \leftarrow H_2^*$$

• *Two step Solomon process; very important.*

COSMIC FREEZE-OUT



Physical hint:

$t_{2body} \propto n^{-1} \propto (1+z)^{-3}$

$t_H \propto (1+z)^{-3/2}$

RELIC ELECTRONS

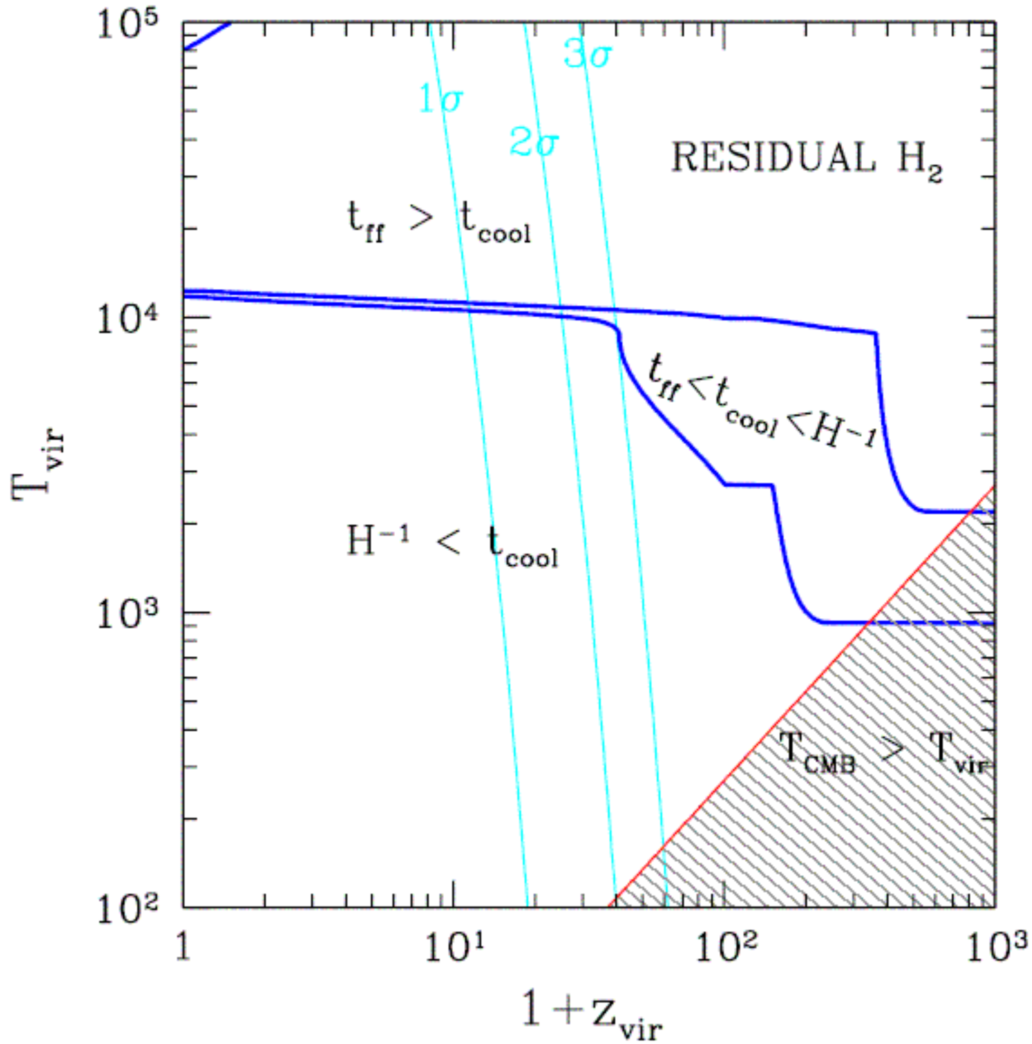
$x_e^{rel} \approx 3 \times 10^{-4}$

RELIC MOL. HYDROGEN

$y_{H2}^{rel} \approx 1.1 \times 10^{-6}, \quad z < 100$

$\approx 1.0 \times 10^{-7}, \quad 100 < z < 250$

$\approx 10^{-7} [(1+z)/250]^{-14}, \quad 250 < z$


10^5
10^4
10^3
10^2
T_{vir}
1
10^1
10^2
10^3
$1+z_{vir}$
1σ
2σ
3σ
RESIDUAL H_2
$t_{ff} > t_{cool}$
$t_{ff} < t_{cool} < H^{-1}$
$H^{-1} < t_{cool}$
$T_{CMB} > T_{vir}$

STRUGGLING FOR MORE H_2: SPHERICAL COLLAPSE

Dynamics

$$\frac{\rho}{\langle\rho\rangle} = \frac{9\,(\alpha - \sin\alpha)^2}{2\,(1-\cos\alpha)^3} \quad \textit{where} \quad \frac{1+z_{vir}}{1+z} = [(\alpha - \sin\alpha)/2\pi]^{2/3}$$

$$\textit{If} \quad \rho > \rho_{vir} = 18\pi^2 \langle\rho\rangle \quad \textit{then} \quad \rho = \rho_{vir}$$

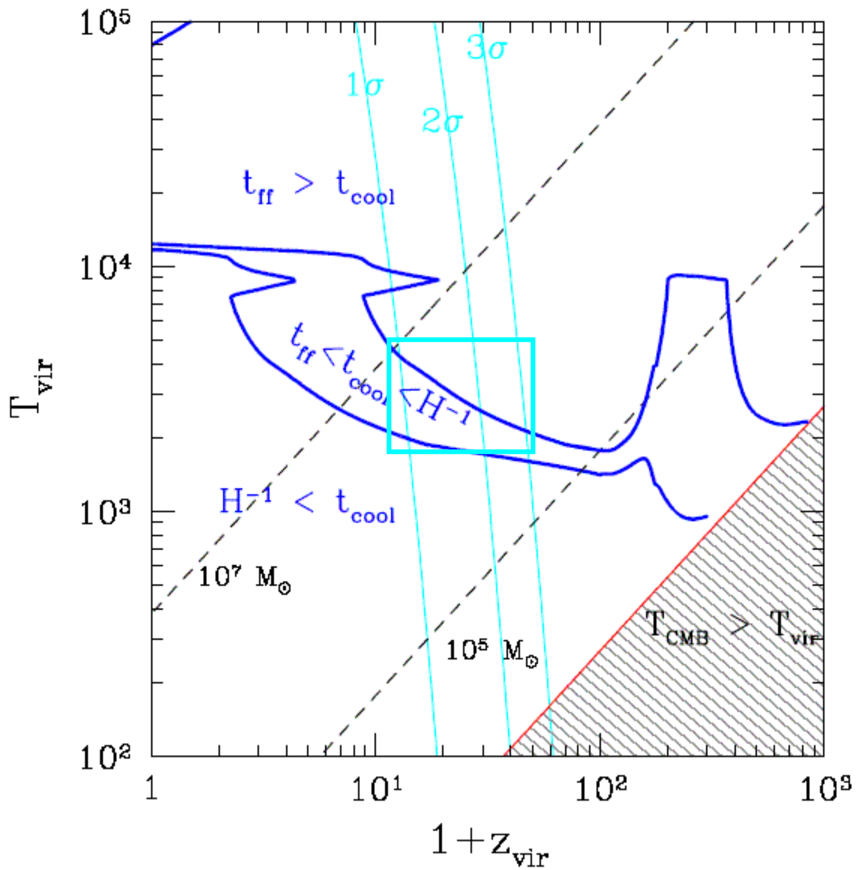
Thermo/chemical evolution

$$\frac{d}{dt}\frac{3\,k\,T}{2\mu\, m_p} = (p/\rho^2)\frac{d\rho}{dt} - \Lambda\,(T, y_i)$$

$$\frac{dy_i}{dt} = \sum k_j y_j + n_H \sum k_{kl} y_k\, y_l + n_H^2 \sum k_{mns}\, y_m y_n\, y_s$$

ENOUGH FOR COLLAPSE ?

$$t_{cool} = 3kT_{vir} / 2\mu\, n_{vir}\, \Lambda(y_{H2}, T_{vir}) = (3\pi / 32\, G\rho_{vir})^{1/2} = t_{ff}$$



- Barkana, R. & Loeb, A. 2001, *Phys. Rep.*, **349**, 125
- Bromm, V. & Larson, R. 2004, *ARA&A,* **42**, 79
- Ciardi, B. & Ferrara, A. 2006, *SSRv,* **116**, 625 (updated: Apr 2008)
- Ferrara, A. 2008, Saas-Fee School