Galaxy Formation and non Linear collapse
Part II

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Cosmology Lectures
This part follows to a large extent Padmanabhan

Cooling and Mass limits - Is any mass allowed?

- Assume I have the baryonic part in thermal equilibrium, the hot gas will radiate and the balance must be rearranged as a function of time.
- The following relations exist between the Temperature, cooling time and dynamical (or free-fall) time:
- Here n is the particle density per cm^3 (n in units cm^{-3}), $\Lambda(T)$ the cooling rate of the gas at temperature T.

$$T = \frac{\mu m_p v^2}{3k} = \frac{\mu m_p}{3k}\left(\frac{3G\mathfrak{M}}{5r_{vir}}\right) = \frac{\mu m_p}{5k}\frac{G\mathfrak{M}}{R}$$

$$t_{free-fall} = \frac{1}{\sqrt{2}} t_{dyn} = \frac{1}{\sqrt{2}}\left(\frac{3\pi}{16G\rho}\right)^{\frac{1}{2}} = 5\,10^7 \frac{1}{\sqrt{n}} yr$$

$$t_{cool} = \frac{E}{\dot{E}} = \frac{3kT\rho}{2\mu m_p \Lambda(T)}$$

Mechanisms

- No cooling: $t_{cool} > H^{-1}$
- Slow cooling via ~ static collapse: $H^{-1} > t_{cool} > t_{free\text{-}fall}$
- Efficient cooling: $t_{cool} < t_{free\text{-}fall}$
- (In the last case the cloud goes toward collapse and could also fragment – instability - and form smaller objects, stars etc.).
- Cooling via:

Brehmsstrahlung

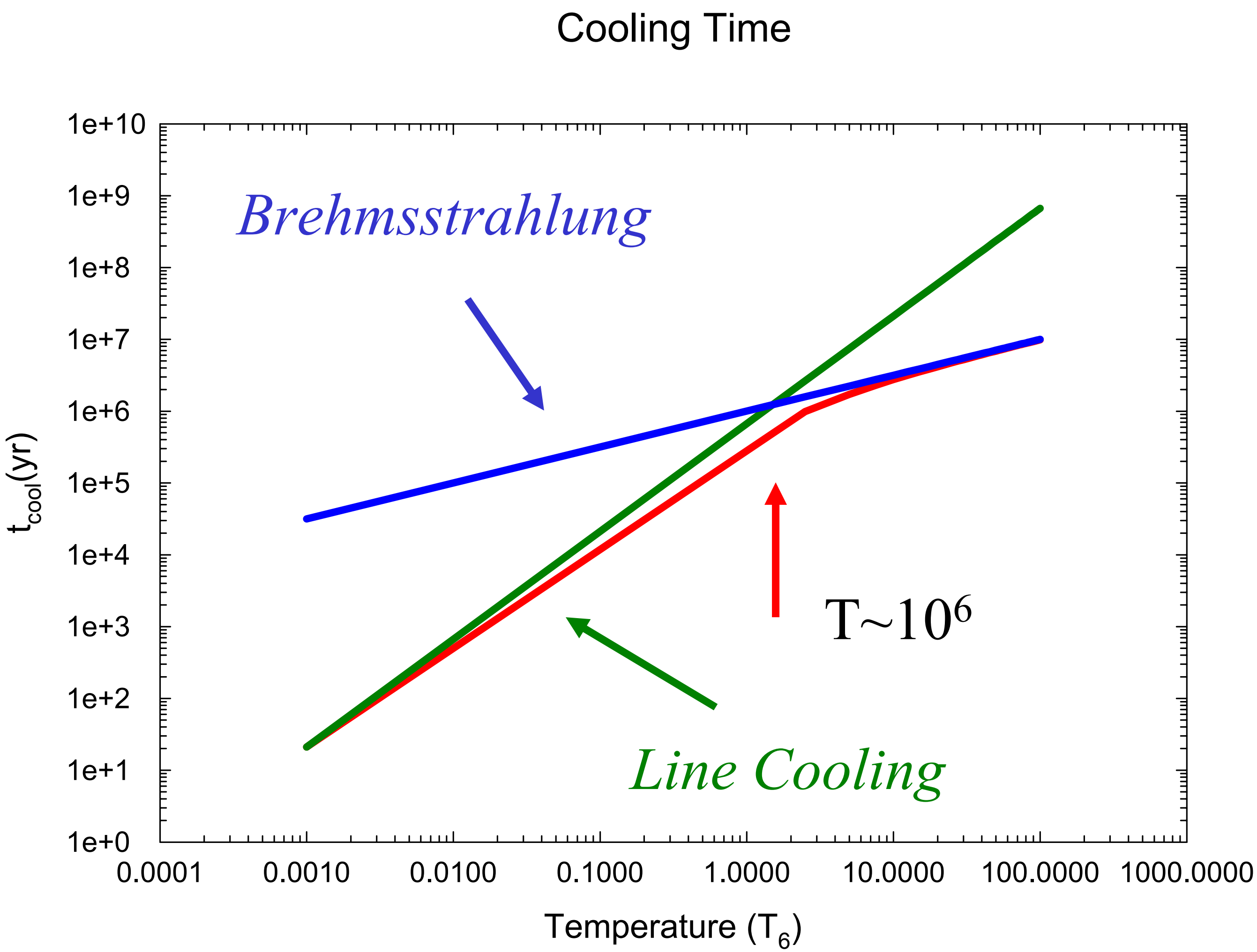
Recombination, lines and continuum cooling

Inverse Compton

[the latter important only for z > 7 as we will see]

$$t_{cool} = 8\ 10^6\ (n_{\ cm\text{-}3})^{-1}\ [T_6^{-1/2} + 1.5\ f_m\ T_6^{-3/2}]^{-1}$$

In the following I use f_m=1 (no Metal) for solar f_m=30



Derivation t_{cool}

$T<10^6$

$$\tau = t_{cool}/t_{dyn}\,; \quad t_{cool} \propto T^{3/2}/\rho\,; \quad t_{dyn} \propto \rho^{-1/2}\,; \quad \tau \propto T^{3/2}\rho^{-1/2}$$

$$\tau \propto T^{3/2}\rho^{-1/2} \propto \frac{\left(v^2\right)^{\frac{3}{2}} \Rightarrow \left(\mathfrak{M}/R\right)^{3/2}}{\left(\mathfrak{M}/R^3\right)^{1/2}} = \mathfrak{M}$$

$$\mathfrak{for}\ \mathfrak{M} = const\,; \quad T \propto \rho^{1/2\,2/3}; T \propto \rho^{1/3}$$

$$\mathfrak{M} = \frac{\left(\mathfrak{M}/R\right)^{3/2}}{\left(\mathfrak{M}/R^3\right)^{1/2}} = \frac{\left(5k/G\mu m_p\right)^{3/2} T^{3/2}}{\left(4\pi\,\mu m_p/3\right)^{1/2} n^{1/2}} = 5.7\,10^{44}\,T_6^{3/2} n^{-1/2} = 2.8\,10^{11}\,T_6^{3/2} n^{-1/2}\mathfrak{M}_{\odot}$$

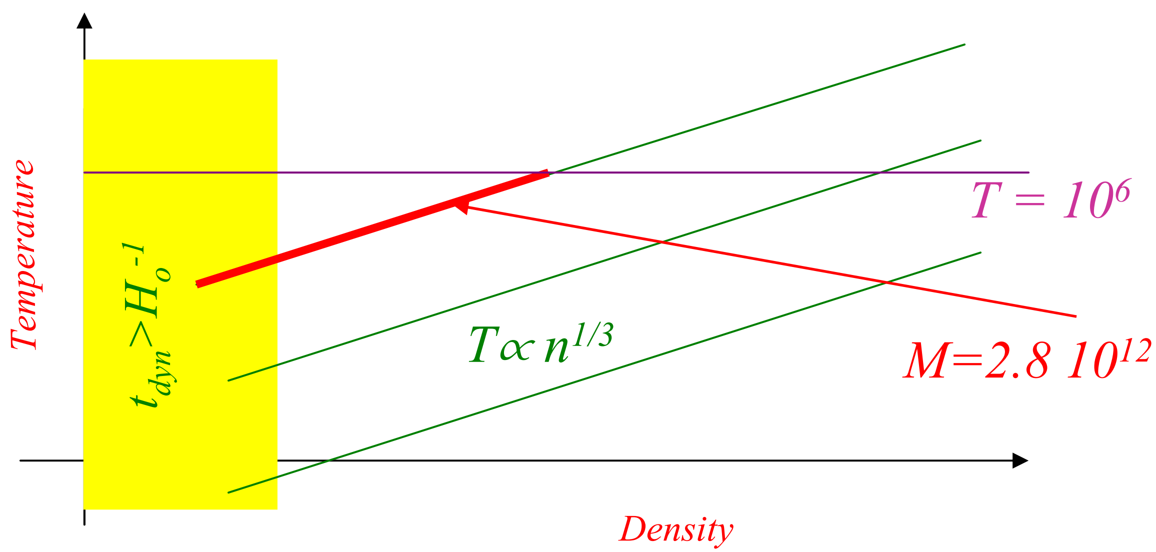
$T<10^6$ - Continue

$$1=\tau=\{Slide\ 40\}\frac{8\,10^6 n^{-1}(1.5)^{-1}T_6^{3/2}}{5\,10^7 n^{-1/2}} \Rightarrow \quad 9.37=n^{-\frac{1}{2}}T_6^{3/2}$$

$$n^{-\frac{1}{2}}T_6^{3/2}\bullet 2.8\,10^{11}\bullet\mathfrak{M}_\odot \gtreqless 9.37\bullet 2.8\bullet 10^{11}\mathfrak{M}_\odot$$

If $M=2.8\ 10^{11}\ n^{-1/2}\ T^{3/2} > 2.8\ 10^{11}\ \ 9.37 = =2.8\ 10^{12}$

Then $\tau>1$ Cooling not very Efficient. Vice-versa if $\tau<1$.



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$T > 10^6$

$$\tau = t_{cool} / t_{dyn}\,; \quad t_{cool} \propto T^{1/2} / \rho\,; \quad t_{dyn} \propto \rho^{-1/2}\,; \quad \tau \propto T^{1/2} \rho^{-1/2}$$

$$\tau \propto T^{1/2} \rho^{-1/2} \propto \frac{\left(\mathfrak{M}/R\right)^{1/2}}{\left(\mathfrak{M}/R^3\right)^{1/2}} = R$$

$$\mathit{for}\ R = const\,; \quad T \propto \rho$$

$T > 10^6$ - Continue

$$1 = \tau = \frac{8\,10^6\, n^{-1}\, T_6^{1/2}}{5\,10^7\, n^{-1/2}} \Rightarrow \quad 6.25 = n^{-1/2} T_6^{1/2}$$

$$R = \frac{\left(\mathfrak{M}/R\right)^{1/2}}{\left(\mathfrak{M}/R^3\right)^{1/2}} = \left(\frac{\frac{5k}{G\,\mu\, m_p} T}{\frac{4}{3}\pi\, n\, \mu\, m_p} \right)^{\frac{1}{2}} = \left(\frac{5 \bullet 3 \bullet k}{4 \bullet \pi \bullet G} \right)^{1/2} \frac{1}{\mu m_p} n^{-1/2} T_6^{1/2} \left(10^6\right)^{1/2} =$$

$$5.22\,10^{22}\, n^{-1/2} T_6^{1/2}\ cm = 16.9\, n^{-1/2} T_6^{1/2}\ kpc$$

$$If \quad R = 16.9\, n^{-1/2} T_6^{1/2} > 16.9 \bullet 6.25 = 105.6 \quad \tau > 1$$

If the radius is too large the cooling is not very efficient and chances are I am not forming galaxies. In other words in order to form galaxies and have an efficient cooling the radius of the cloud must shrink below an effective radius which is of the order of 105 kpc.

For fun compare with the estimated halos of the galaxies along the line of sight of a distant quasar. More or less we estimate the same size. Or we could also follow the reasoning that very large clouds would almost be consistent with a diffuse medium. Try to follow these reasoning to derive ideas on the distribution of matter in the Universe.

$T > 10^6$ - Continue

Or an other way to look at it is (see notes Page 46):

$$R = 16.9\, kpc\, T^{1/2} n^{-1/2} = 16.9\, kpc\, \frac{\tau}{0.16}$$

For $\tau > 1$ ➡ $R > 105$ kpc ➡ $t_{cool} > t_{dyn}$

Vice versa for $\tau < 1$; in this case cooling is efficient
The cloud must shrink for efficient cooling

Summary

For a given Mass of the primordial cloud and $T < 10^6$ we have the following relation:

$$T \propto \rho^{1/3}$$

The Mass of the forming object is smaller than a critical mass. $M < 2.6\ 10^{12}$ solar masses.

For a given Radius of the primordial cloud and $T > 10^6$ we have the following relation:

$$T \propto \rho$$

The Radius of the primordial cloud must be smaller than a critical Radius in order to have efficient cooling and form galaxies. $R < 105$ kpc.

Continue

The dashed light blue line next slide

$$T < 10^6$$

$$t_{cool} = n^{-1} T^{3/2} = H_o^{-1} = const \Rightarrow \quad T \propto n^{2/3}$$

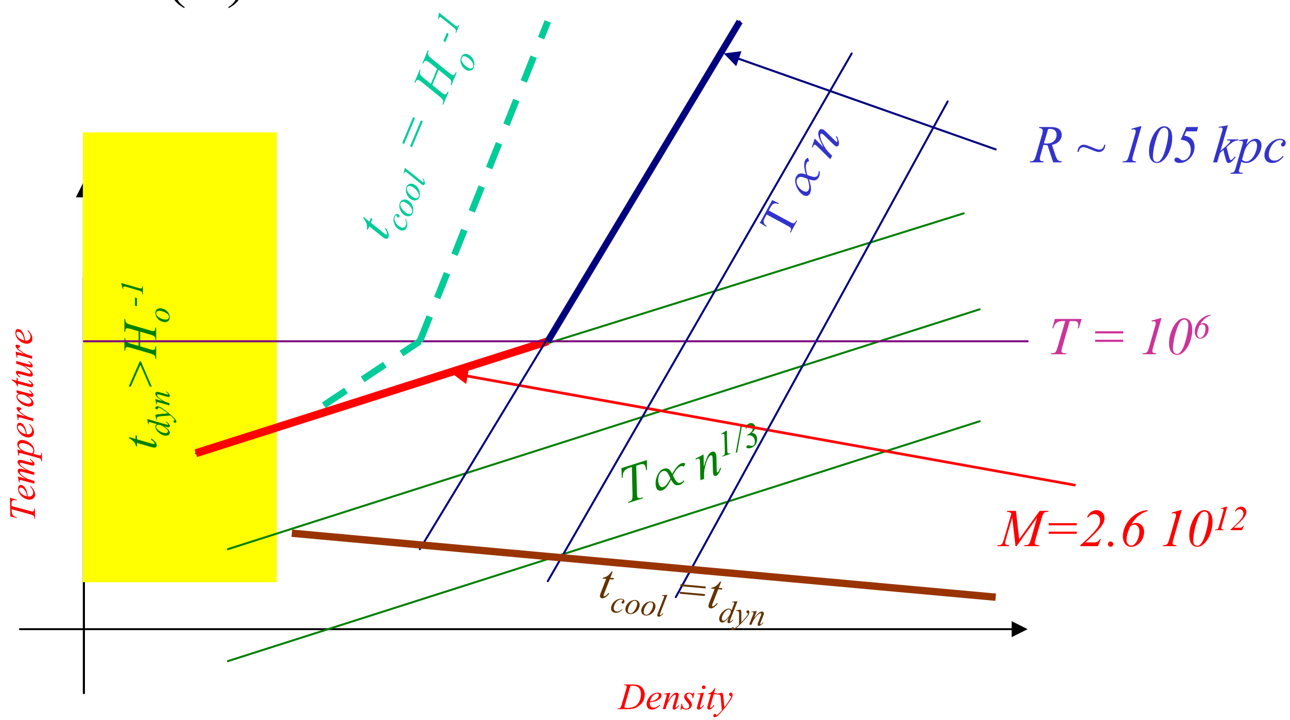
$$T > 10^6$$

$$t_{cool} = n^{-1} T^{1/2} = H_o^{-1} = const \Rightarrow \quad T \propto n^2$$

$T>10^6$

$$Spitzer \quad page\,140 \;\; for \quad \Lambda(T) \;\; for \; 4000 < T < 12000$$

$$t_{cool} = \frac{3/2\, nkT}{\Lambda(T)} \quad ; \quad \Lambda(T) = 7.3\,10^{19}\, n_e n(HI) Exp(-\frac{118400}{T})$$



DM & Baryons together

Cooling: Only the baryonic matter is at work – The gas initially is not at virial Temperature.

Dynamics: Dark Matter dominates.

Shocks and Heating.
$t_{cool} > t_{dyn}$
gas may be
heated to Virial Temp
equilibrium

$t_{cool} < t_{dyn}$
May never reach
Equilibrium may sink in
the potential well, sink
Fragment etc.

.

Assumption & Definition

- We assume a gas fraction F of the total Mass.
- Assume Line cooling dominates.
- The gas is distributed over a radius $r_m/2 = r_{vir}$.
- We also assume $t_{dyn} \sim \frac{1}{2} t_{coll}$ so that we have:

$$t_{dyn} = \frac{1}{2} t_{coll} \sim \frac{\pi}{2} \left(\frac{2G\mathfrak{M}}{R^3} \right)^{1/2} \sim 1.5\,10^9\, \mathfrak{M}_{12} \left(r_m / 200\ kpc \right) yr$$

$$T_{vir} \sim \mu m_p\, v^2 / 3k \quad ; \quad v^2 \sim \frac{6G\mathfrak{M}}{5r_m}$$

$$t_{cool} \propto \frac{T^{-3/2}}{\rho} \propto \frac{\left(\mathfrak{M}/R \right)^{3/2}}{\left(\mathfrak{M}/R^3 \right)} \propto \mathfrak{M}^{1/2} R^{3/2}$$

Continue

- *So that assuming spherical collapse and again using the reasoning with τ, we have [for f_m metal abundance see slide 42]:*

$$t_{cool} = 2.4\,10^9 f_m^{-1} \left(F/0.1 \right)^{-1} (\mathfrak{M}_{12})^{1/2} \left(r_m / 200\ kpc \right)^{3/2} yr$$

$$\tau = \left(\frac{t_{cool}}{t_{dyn}} \right) \sim 1.6 f_m^{-1} \left(F/0.1 \right)^{-1} (\mathfrak{M}_{12})^{1/2}$$

$$\tau < 1 \quad if$$

$$\mathfrak{M} < \mathfrak{M}_{crit} \sim 6.4\,10^{11} \mathfrak{M}_{\odot} f_m \left(F/0.1 \right)$$

Again masses of the order $10^{11} - 10^{12}$ are picked up preferentially

And for the Compton Cooling

- N_e Electron density.
- T Gas temperature.
- ρ_r Density of the radiation, MWB.
- T_r Radiation Temperature.
- ❑ Λ_{comp} Cooling Rate – and assume $T >> T_r$.

$$\Lambda_{compton} = \frac{4\sigma_T N_e \rho_r \left(T - T_r\right)}{m_e}$$

$$t_{comp} = \frac{3\rho kT}{2\mu\,\Lambda_{comp}} = \frac{3m_p N_e kT m_e}{2\mu 4\sigma_T N_e \rho_r \left(T - T_r\right)} = \frac{3m_p m_e kT}{8\,\mu\,\sigma_T \rho_r T}$$

& The relevant equations are

See notes for details:

$$\rho_r = \rho_c \Omega_r (1+z)^4$$

$$t_{comp} = \frac{3 m_p m_e k}{8\, \mu\, \sigma_T \rho_c \Omega_r (1+z)^4} \sim 2.1\,10^{12} \left(1+z\right)^{-4} yr$$

$$t_{dyn} = {}^1\!/_2\, t_{coll} = {}^1\!/_2\, t_0 (1+z)^{-3/2} \quad ; \quad \Omega_0 = 1$$

$$t_0 = 0.65\,10^{10}\, h^{-1} yr$$

And t_{dyn} at $t_{collapse}$

$$t_{dyn} = {}^1\!/_2\, 0.65\,10^{10}\, (1+z_{coll})^{-3/2} h^{-1}$$

Combining

$$\tau = \frac{t_{compton}}{t_{collapse}} = \frac{2.1\,10^{12}\left(1+z_{coll}\right)^{-4} h}{\frac{1}{2}\,0.65\,10^{10}\,\left(1+z_{coll}\right)^{-3/2}} = 1.6\,10^{2}\left(1+z_{coll}\right)^{-5/2}$$

That is $\tau < 1$ only for $z_{coll} > 7.6$ independent of mass. That is Compton Cooling is important for those objects collapsing at $z > 7.6$

An uinteresting game could be to consider what happened of these clouds just before re-ionozation and indeed find out how efficient these hot clouds could be in reionizing the intergalactic medium.
Develop a chapter on the ionization of the Intergalactic Medium.

An other example

- *Assume that after maximum expansion we have a contraction of a factor f_c and assume that after virialization the density does not change, then:*

$$\rho_{obs} \simeq f_c^3 \, {}^{9\pi^2}\!/_{16} \, \rho_b(t_m) \simeq \rho_{b0}\left(1+z_m\right)^3 f_c^3 \, 5.6 \simeq \rho_{c0}\Omega_0(1+z_m)^3 f_c^3 \, 5.6$$

- *For a galaxy with a mass of about $10^{11}\ M_\odot$ within a radius of 10 kpc we have $\rho_{obs}/\rho_{c,0} \sim 10^5$ so that:*

$$\left(\rho_{obs}/\rho_{c,0}\right)^{1/3}\left(1/5.6\,\Omega_0\right)^{1/3} 1/f_c = 1+z_m \quad => \quad z_m \simeq 30/f_c\Omega^{1/3}$$

- *So that (note however that since the time of collapse is rather long we should account for the variation of ρ_b as a function of time) the redshift of formation is too close:*

Angular Momentum

- Mass: M
- Energy (At max. expansion) $E \sim - GM^2/R$
- Angular Momentum: $L = Mv \wedge R = M\,\omega R^2$
- Angular velocity: $\omega = L/MR^2$
- Equilibrium condition: $\omega^2_{(support)} R = GM/R^2$
- $\lambda = \omega$ *(the rotational Energy available)* / ω_{sup}*(needed to counterbalance the gravitational field.*

Angular Velocity

$$\lambda = \frac{\omega}{\omega_{\text{sup}}} = \frac{L}{\mathfrak{M}R^2} \frac{R^{3/2}}{G^{1/2}\mathfrak{M}^{1/2}} = \frac{L}{G^{1/2}\mathfrak{M}^{3/2}R^{1/2}} = \frac{L|E|^{1/2}}{G\mathfrak{M}^{5/2}}$$

ω Support

The facts

The Observations show that we have $\lambda \sim 0.05$ for Elliptical galaxies and $\lambda \sim 0.4 - 0.5$ for disk galaxies.

The gas is about 10 % of the Halo mass and during collapse the gas will dissipate and during his evolution to a disk could cool rapidly, fragment and form stars.

N body simulations show that due to the irregular distribution of matter an object will acquire via tidal torques a λ value in the range of 0.1 – 0.01 with a mean value of about 0.05. That is of the same order for Ellipticals but much to low for disk galaxies.

Comments to the facts

- *That is the gas in forming a disk galaxy should collapse (during collapse we conserve the Mass) of a factor* $fc = R_{initial}/R_{disk} = (\lambda_{disk}/\lambda_{in})^2 = (0.5/0.05)^2 = 100$ *in order to satisfy the observations. (See slide **)*
- *That is in order to form a galaxy of* $10^{11}\,M_\odot$, $R = 10$ *kpc I have to beginn with a cloud of about 1 Mpc.*
- *However to such a cloud it will take to collapse:*

$$t_{coll} = (\pi/2)\,(R^3/2GM)^{1/2} \sim 5.3\ 10^{10}\ yr$$

- *Much too long and the same would be for the 3 kpc core which should start from a 300 kpc radius region.*

Let's look into some details

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- *Note that both the gas and the DM are virialized, and however at the beginning the disk did not collapse yet.*

$$\lambda_{initial} = \frac{L|E|}{G\mathfrak{M}^{5/2}} \quad ; \quad \lambda_{disk} = \frac{L_{disk}|E_{disk}|}{G\mathfrak{M}_{disk}^{5/2}}$$

After collapse The Disk is selfgravitating

Refer to the Halo, DM + gas Even if gas gives a minor contribution

$$\frac{\lambda_d}{\lambda_i} = \frac{L_d}{L}\left(\frac{|E_d|}{|E|}\right)^{1/2}\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)^{-5/2}$$

DM $\quad |E| = k_1\left(G\mathfrak{M}^2 / R_c\right) \quad ; \quad |E_d| = k_2\left(G\mathfrak{M}_d^{\,2} / r_c\right)$ *Disk*

- R_c *,* r_c *(disk after collapse),* k_1*,* k_2*, are characteristic radii and parameters accounting for the geometry and mass distribution.*

Continue

- *Note that the Angular momentum per Unit mass acquired by the gas is the same as that gained by the DM since at the beginning all the matter of the perturbation is subject to the same tidal torques.*
- *The gas, during collapse from R_c to r_c, conserve angular momentum. $L_d/M_d = L/M$.*

$$\frac{\lambda_i}{\lambda_d} = \frac{L_d}{L}\left(\frac{|E_d|}{|E|}\right)^{1/2}\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)^{-5/2} = \left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)\left(\frac{k_2}{k_1}\right)^{1/2}\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)\left(\frac{R_c}{r_c}\right)^{1/2}\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)^{-5/2}$$

$$\frac{\lambda_i}{\lambda_d} = \left(\frac{k_2}{k_1}\right)^{1/2}\left(\frac{R_c}{r_c}\right)^{1/2}\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)^{1/2} \quad \textit{that is:}$$

$$\left(\frac{R_c}{r_c}\right) = \left(\frac{k_1}{k_2}\right)\left(\frac{\mathfrak{M}_d}{\mathfrak{M}}\right)\left(\frac{\lambda_d}{\lambda}\right)^2$$

Conclusion

- *The Collapse factor has been reduced by about a factor of 10 due to the fact that the mass of the disk is about 10% of the mass of the halo DM.*

More about when – Primeval Galaxies

- *The MWB tell us that at $z \sim 1000$ the perturbations were in the linear regime since otherwise we would have detected them. It is therefore very clear that galaxy formation occur after decoupling.*
- *We also determined that at the turn around time – top hat model -the spherical over dense region has a density which is $9\,\pi^2/16$ times higher than the background density, ρ_b.*
- *If the material contracts by a factor f_c then the over-density increases by a factor $f_c^{\,3}$.*
- *We consider a galaxy with $M=10^{11}\,M_{\odot}$, $r \sim 10$ kpc so that $\rho_{obs}/\,\rho_c \sim 10^5$.*

$z_{collapse}$

- *So that:*

$$\rho_{obs} \simeq f_c^3 \frac{9\pi^2}{16} \rho_b(t_m) \simeq 5.6\,\Omega\,\rho_c\,(1+z_{turn\ around})^3 f_c^3$$

$$z_{turn\ around} = \frac{1}{f_c}\left(\frac{\rho_{obs}}{5.6\,\Omega\,\rho_c}\right)^{1/3} \simeq \frac{30}{f_c \Omega^{1/3}}$$

- *Note also that we should integrate to account for the change of ρ_b during the collapse.*
- *The factor $2^{2/3}$ since: t collapse ~ 2 t_m ; $\rho_b \propto a^{-3} \propto t^{-2}$; so that the density contrast increases by a factor 2^2 and $z_{collapse}$ factor $2^{2/3}$.*
- *For dissipation_less collapse $f_c \sim 2$.*
- *For a disk $f_c \sim 10$ or more.*

Program - Go to L_S_S

- Before doing the Gaussian Fluctuations and the evolution of the Power Spectrum it is wise to discuss the Large Scale Structure as done in the Power Point Lecture (to be improved).
- Develop Further this part since it seems to be very interesting and useful to the students,

Typical mass in hierarchical models

- *See eventually details on the Power Spectrum, what it is. Lecture LSS to be completed.*
- *Fluctuations of M within a sphere of Radius R described by the variance $\sigma(M)$, Gaussian distribution of density inhomogeneities.*

$$\text{Contrast } \delta_o = \nu\, \sigma(M)\ ,\ M \propto \lambda^3 \propto k^{-3}$$

$$\&$$

$$\sigma(M)^2 = \langle(\delta M/M)^2\rangle = C\, M^{-(3+n)/3}$$

$$\sigma(M) = (M/M_o)^{-(3+n)/6}$$

With the constant M_o to be determined.

Normalization

- *Counting galaxies we see that*

$$\delta N/N \sim 0.9 \text{ at } 10\ h^{-1}\ Mpc$$

- *and we measure*

$$M_{(R=10\ h^{-1}\ Mpc)} \sim 1.15\ 10\text{^}15\ (h^{-1}\ \Omega)\ M_{\odot}$$

- *We finally assume:*

$$\frac{\delta N}{N} = b\left(\frac{\delta M}{M}\right) = b\,\sigma(M) = b\left(\frac{M}{M_o}\right)^{-\frac{3+n}{6}} \quad ; \quad b \equiv Bias \quad factor$$

Normalization and derivation of the redshift at which a given mass collapse

$$\delta N / N = 0.9 = b\left(\frac{1.15\,10^{15}\left(\Omega h^{-1}\right)\mathfrak{M}_{\odot}}{\mathfrak{M}_o}\right)^{\frac{-(3+n)}{6}};$$

$$\mathfrak{M}_o = \left(\frac{0.9}{b}\right)^{\frac{6}{3+n}} 1.15\,10^{15}\left(\Omega h^{-1}\right)\mathfrak{M}_{\odot}$$

$$\sigma\left(\mathfrak{M}\right) = \frac{0.9}{b}\left(\frac{\mathfrak{M}}{1.15\,10^{15}\left(\Omega h^{-1}\right)\mathfrak{M}_{\odot}}\right)^{-\frac{(3+n)}{6}};$$

$$\delta_o\left(\mathfrak{M}\right) = \nu\,\sigma\left(\mathfrak{M}\right);\ \&\ for\ \Omega = 1;\ \left(1+z_{coll}\right) = \frac{\delta_o\left(\mathfrak{M}\right)}{1.686}$$

Finally and However

$$\mathfrak{M}(z) = 1.15\,10^{15}\ h^{-1}\mathfrak{M}_{\odot}\left[(1+z_{coll})\,1.686\ {}^{b}\!\!\diagup_{0.9\,\nu}\right]^{-\frac{6}{n+3}}$$

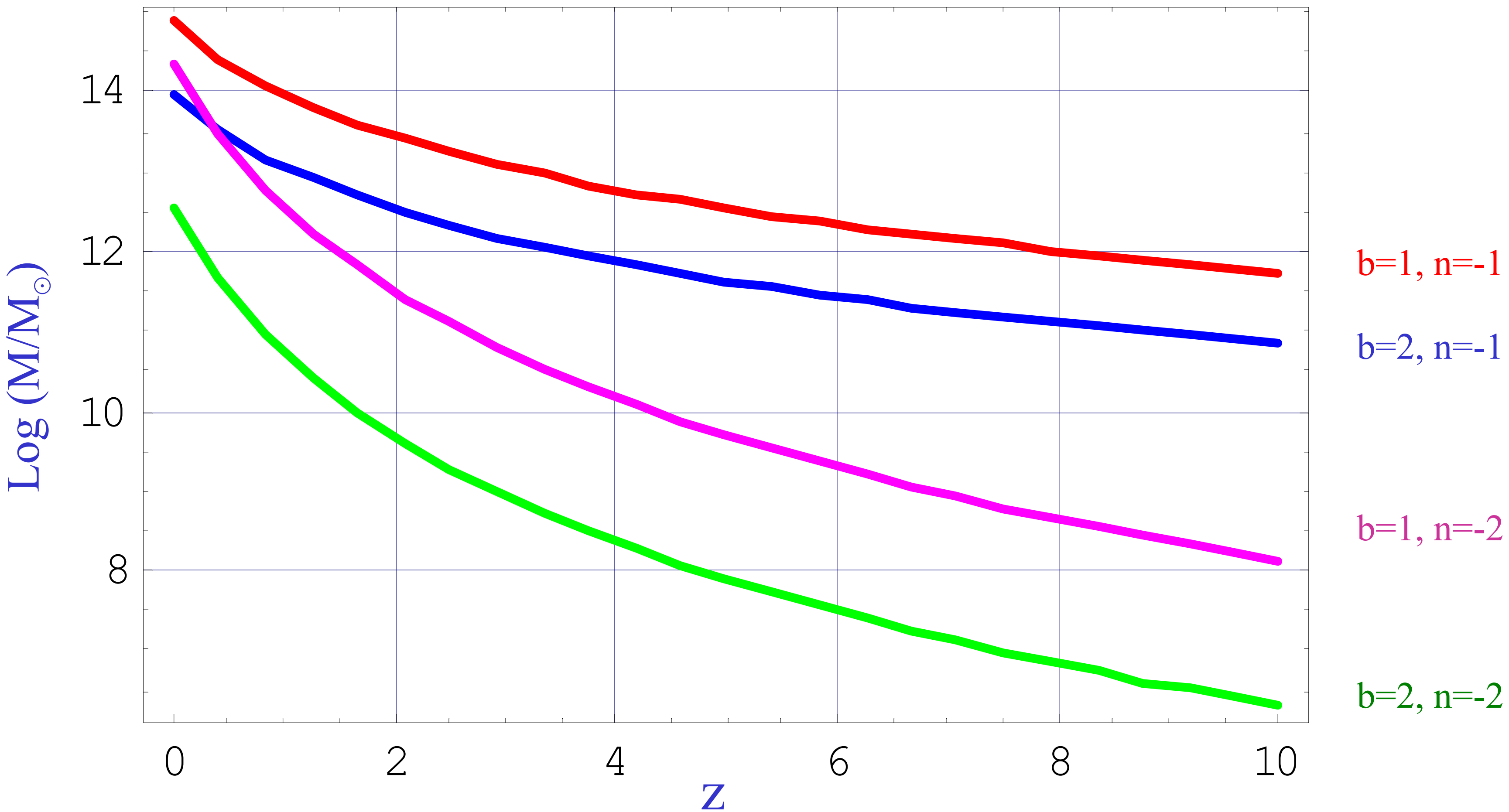
- *The reasoning was not completely correct since for $\delta N/N \sim 1$ at some mass scale M_o we are already in the non linear regime. We did more or less:*
- *By definition $\delta M/M = 1/b\ \delta N/N$ and we would like to set, in agreement with the above, $\sigma(M_o) = 1/b$. If the theory says that $\sigma(M) = 1/b\ (M/M_c)^{-n}$ then we will take $M_c = M_o$.*
- *Suppose we now observe $\delta_o = 1$ as evolved considering non linear effects. It would be $\delta_o = 0.57$ using linear theory and coming from a fluctuation δ_i at t_i.*

Or saying differently

- *In our spherical model we had $\delta = (\rho / \rho_b - 1)$ is unity at $\theta = 2\pi / 3$. Using this value of θ the density excess extrapolated at the present epoch is 0.57. That is the normalization of the spectrum should be $\sigma(M_o) = 0.57/b$ rather than $\sigma(M_o) = 1/b$. Applying this correction we find:*

$$\mathfrak{M}(z) = 1.15\,10^{15}\; h^{-1}\mathfrak{M}_{\odot}\left[(1+z_{coll})\,1.686\; {}^{b}\!\big/_{0.57\,\nu}\right]^{-\frac{6}{n+3}}$$

Typical Mass which collapse and becomes non linear at various redshifts. Ω=1,h=0.5 and density contrast $\delta_o(M) = \nu\,\sigma(M)$ with ν=2.



Timetable for Formation

Gravitational potential fluctuations	$Z \gtrsim 10^3$
Spheroids of Galaxies	$Z \sim 20$
The first Engines for active galactic nuclei	$Z \gtrsim 10$
The intergalactic medium	$Z \sim 10$
Dark Matter	$Z \gtrsim 5$
Dark halos of galaxies	$Z \sim 5$
Angular momentum of rotation of galaxies	$Z \sim 5$
The first 10% of the heavy elements	$Z \gtrsim 3$
Cosmic magnetic fields	$Z \gtrsim 3$
Rich clusters of galaxies	$Z \sim 2$
Thin disks of spiral galaxies	$Z \sim 1$
Superclusters, walls and voids	$Z \sim 1$

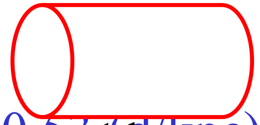
Intergalactic (& ISM) Medium

- Observational evidence exists that the column density of Hydrogen is related to the color excess (HI & Dust). The empirical relation:

$$N_{Htot} = 5.8\,10^{25}\,E(B-V)\;m^{-2}mag^{-1}$$

$$E(B-V) = \frac{N_{Htot}}{5.8\,10^{25}}\,m^{-2}$$

- Near the Sun we have: $n_H = 10^6\ m^{-3}$ so that for a distance d through the disk we have:



- $N_H = 3.09\ 10^{25}$ (d/kpc) m^{-2}; $E_{(B-V)} = 0.53$ (d/kpc) and $A_V = 1.6$ (d/kpc)

Toward the GC

- $A_M \sim 0.6$; $A_B = 34.5$
- The Probability for a B photon to reach us is:
- $10^{-0.4\,(34.5)} = 10^{-13.8} = 1.6\ 10^{-14}$

Standard ISM Extinction

Band X	λ_{eff}/nm	$M_\odot$	(E_{X-V}/E_{B-V})	(A_X/A_V)
U	365	5.61	1.64	1.531
B	445	5.48	1.	1.324
V	551	4.83	0	1.
R	658	4.42	-0.78	.748
I	806	4.08	-1.60	.482
J	1220	3.64	-2.22	.282
H	1630	3.32	-2.55	.175
K	2190	3.28	-2.74	.112
L	3450	3.25	-2.91	.058
M	4750		-3.02	.023
N			-2.93	.052