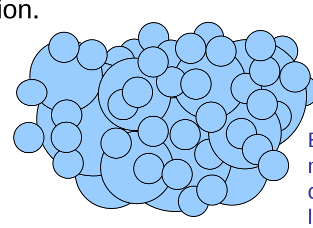
Hot & Cold Dark Matter

- Dark Matter = matter not coupled to electromagnetic field
  - unable to condense by dissipation.
  - growth of structure depends on properties of Dark Matter.



Early U. contained more small condensations than large ones.

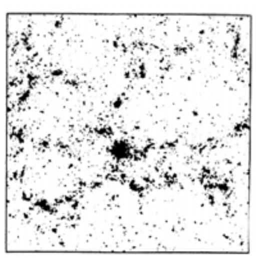
- Hot Dark Matter (HDM)
  - relativistic for $T \sim 10^5$ K
  - can "free-stream" out of galaxy-sized matter concentrations.
  - erases small-scale structures early in life of universe.
    ➔ top-down structure formation, starting from structures $>10^{13}\ M_{sun}$.

- Cold Dark Matter (CDM)
  - slow moving (non-relativistic)
  - does not erase small concentrations.
  - preponderance of low-mass structures predicted by inflation survive.
    ➔ lower mass concentrations form first (bottom up structure formation).

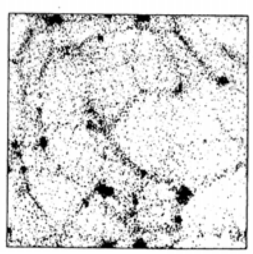
N-body simulations ➔ CDM

Standard CDM = SDCM, replaced by ΛCDM model

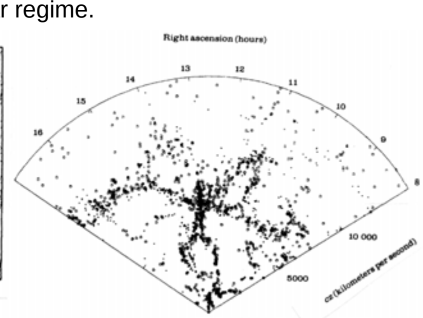
- Start with perturbation spectrum at time of decoupling
- Follow perturbations into highly non-linear regime.



CDM



HDM



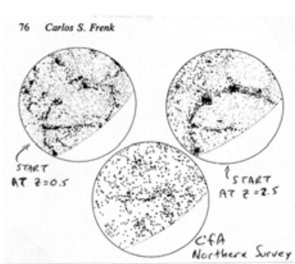


Fig. 4. Equal area projections of the galaxy distributions on the northern sky and in artificial catalogues made from *N*-body simulations. The top two diagrams correspond to neutrino dominated universes in which galaxy formation began at a redshift 0.5 (top left) and 2.5 (top right). In both cases $\Omega = 1$, but $h = 0.8$ for the model at the left, and $h = 0.5$ for the model at the right. The circles represent the "galaxies" while the dots represent the neutrino distribution. The bottom diagram is the CfA northern survey. The outer circle represents galactic latitude +40, and the empty regions lie at declinations below 0°. Even the model with a completely unrealistic epoch of galaxy formation is more strongly clustered than the data. This disagreement persists for any combination of model parameters.

Cold Dark Matter (CDM)

- slow moving
- mass power spectrum only slightly modified by free-streaming
- less massive concentrations form first (bottom up).

CDM
Menu of the Day
Axions
Axinos
Gravatinos
Neutralinos
Wimpzillas
⋮

CDM candidates

- Axions
  - zero momentum
  - very light ==> huge number density needed to make up W_M
  - should be detectable within a few years if present.
- WIMPs
  - Weakly Interacting Massive Particles
  - 50x proton mass
    - set by the weak interaction cross-section
- Leftovers from GUT era
  - Expansion, cooling of U
    ➔ frozen out of equilibrium reactions
  - Lots of theories ➔ lots of candidates

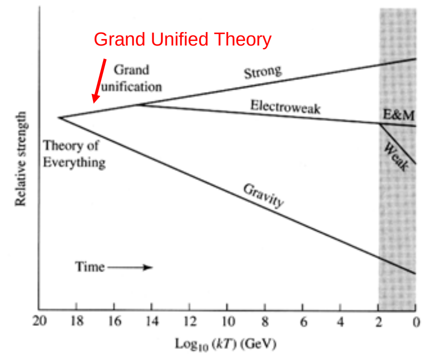


Fig. 30.2

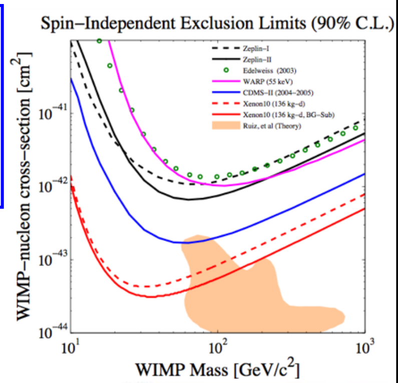
Cold Dark Matter in the Lab

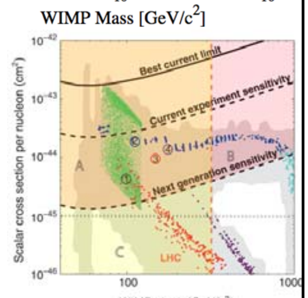
CDM candidates

- Axions
  - zero momentum
  - very light ==> huge number density needed to make up Ω_M
- WIMPs
  - Weakly Interacting Massive Particles
  - 50x proton mass
    - set by the weak interaction cross-section
  - χ neutralino is best candidate

CDM
Menu of the Day
Axions
Axinos
Gravatinos
Neutralinos
Wimpzillas
⋮

- Can be detected through elastic scattering off various target nuclei
  - measure recoil energy imparted to target
  - look for seasonal variation due to Earth's orbital motion
  - these WIMPS are the MW halo
  - Massive neutrinos (m ~ 100-1000 m_p) already ruled out.
- Hope is to identify CDM, then manufacture it in Large Hadron Collider



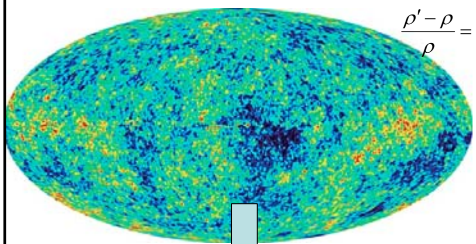


The Growth of Structure

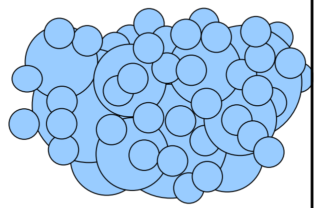
Read [CO 30.2]

WMAP

Density fluctuations at t = 379,000 yr



$$\rho = 1.0000$$
$$\rho' = 1.0001$$
$$\frac{\rho' - \rho}{\rho} = \frac{\delta\rho}{\rho} = 0.0001 = 10^{-4}$$

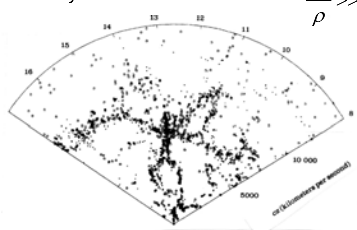


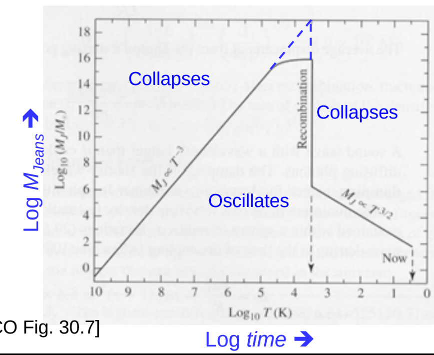
Early U. contained condensations of many different sizes.

Current large-scale structure

$t = t_0$ = 13.7 Gyr

$$\frac{\delta\rho}{\rho} >> 1$$





[CO Fig. 30.7]

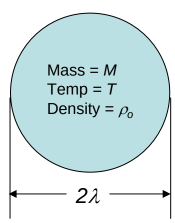
The Simplest Picture of Galaxy Formation and Why It Fails

(chapter title from Longair, "Galaxy Formation")

Will a condensation collapse?

The Jeans criterion:

(see [CO Sect. 12.2 and pg. 1250]



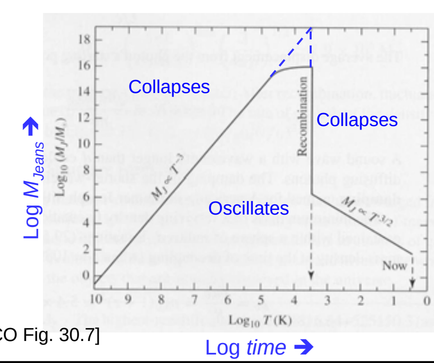
Unstable to collapse if

$$2K < -U$$

Pressure < Gravity

$$\frac{3MkT}{\mu m_H} < \frac{3}{5}\frac{GM^2}{\lambda}$$

$$M = \frac{4}{3}\pi\lambda^3\rho_o > \underbrace{\left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_o}\right)^{1/2}}_{\text{Jeans mass } M_J}$$



[CO Fig. 30.7]

How fast will it collapse?

In a static medium (e.g. star formation):

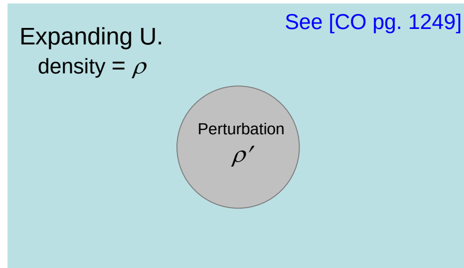
Perturbation analysis shows

$M < M_J$

$\delta\rho/\rho \propto exp(-ir/\lambda - i\omega t)$ ➔ Oscillations

$M > M_J$

$\delta\rho/\rho \propto exp(-ir/\lambda + Kt)$ ➔ Exponential growth

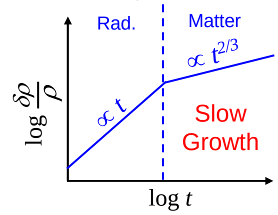


In an expanding medium (e.g. the universe):

Outside the perturbation (flat universe): $H^2R^2 - \frac{8}{3}\pi G\rho R^2 = 0$ (Friedman Eqn)

Inside the perturbation (closed mini-universe): $H^2R^2 - \frac{8}{3}\pi G\rho' R^2 = -kc^2$

$$\frac{\delta\rho}{\rho} = \frac{\rho' - \rho}{\rho} = \frac{3kc^2}{8\pi G\rho R^2}$$



Radiation era: $\rho = \rho_0 R(t)^{-4}$ $\quad R(t) \propto t^{1/2}$ ➔ $\frac{\delta\rho}{\rho} = \left(\frac{\delta\rho}{\rho}\right)_i \left(\frac{t}{t_i}\right)$

Matter era: $\rho = \rho_0 R(t)^{-3}$ $\quad R(t) \propto t^{2/3}$ ➔ $\frac{\delta\rho}{\rho} = \left(\frac{\delta\rho}{\rho}\right)_i \left(\frac{t}{t_i}\right)^{2/3}$

The Simplest Picture of Galaxy Formation and Why It Fails

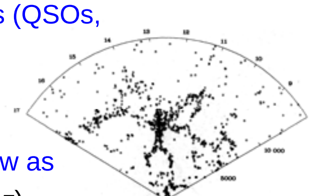
- Cosmic Microwave Background is smooth to a few parts in 10^5

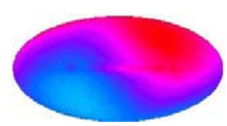
  $\delta\rho/\rho \sim 10^{-4}$

Blue = 0°K
Red = 4°K

- Yet high contrast structures (QSOs, galaxies) by $z \sim 6$.

  $\delta\rho/\rho >> 1$





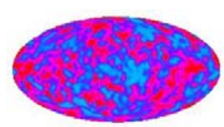
Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
~ 1 part in 300

- Adiabatic perturbations grow as

  $\delta\rho/\rho \propto t^{2/3} \propto R(t) \propto 1/(1+z)$

- Expect only

$$\left(\frac{\delta\rho}{\rho}\right)_{QSO} = \frac{(1+z)_{CMB}}{(1+z)_{QSO}}\left(\frac{\delta\rho}{\rho}\right)_{CMB} = \frac{1100}{7}\times 10^{-4} = 0.01$$



After removing dipole
Red – blue = 0.0002°K
~ 1 part in 10^5

So where did galaxies and clusters come from?

In an expanding universe, will a cloud collapse?

The Jeans criterion Version 2:

$2K < -U$

Pressure support < gravity

Collapse if $2K < -U$

$$2\left(\frac{1}{2} M_T v_s^2\right) < \frac{3}{5}\frac{GM_T^2}{\lambda}$$

$$v_s^2 < \frac{3}{5}\frac{GM_T}{\lambda} = \frac{3G}{5}\frac{(4/3)\pi\lambda^3\rho_T}{\lambda} = \frac{4}{5}\pi G\lambda^2\rho_T$$

$$\left(\frac{3M_b}{4\pi\rho_b}\right)^{2/3} = \lambda^2 > \frac{5v_s^2}{4\pi G\rho_T}$$

$$M_{J,b} > const. \times \frac{\rho_b v_s^3}{(G\rho_T)^{3/2}}$$ = [CO eq. 30.27]

Radiation era

$$v_s = \frac{c}{\sqrt{3}}$$

$$\rho_b \propto R(t)^{-3} \propto T^3$$

$$\rho_T \propto R(t)^{-4} \propto T^4$$

$$M_{J,b} \propto T^{-3}$$

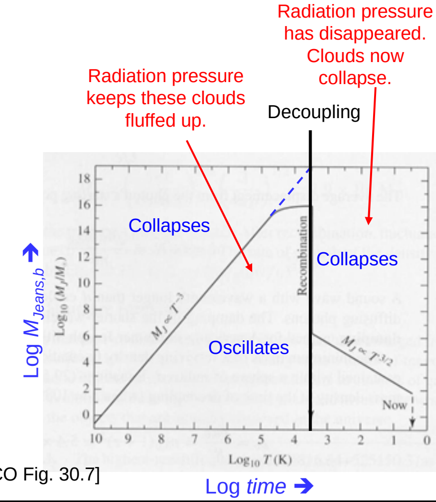
After decoupling

$$v_s = \sqrt{\frac{5kT}{3\mu m_H}}$$

$$\rho_b \propto T^0$$

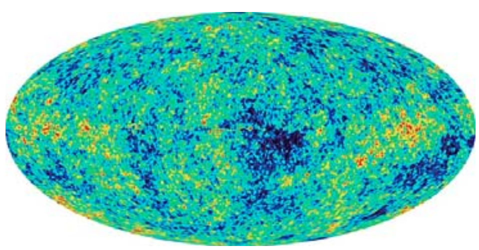
$$\rho_T \approx \rho_b \propto T^0$$

$$M_{J,b} \propto T^{3/2}$$



[CO Fig. 30.7]

In an expanding universe, will a cloud collapse?

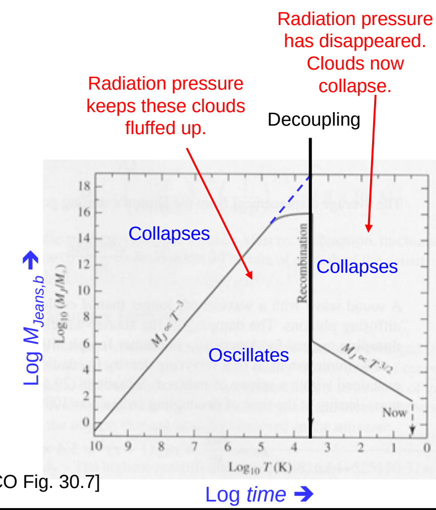


WMAP image

- Snapshot of oscillating condensations on all size scales.
- Taken at the moment of decoupling.
- Brightness $\propto \rho \propto (\delta\rho/\rho)$

$2K < -U$

Pressure support < gravity



[CO Fig. 30.7]