Advanced Topics on Astrophysics: Lectures on dark matter

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Lecture notes will be available at
http://stavrogin.uwaterloo.ca/~jzavala/teaching.html

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Lecture 1 (Part I)

Gravitational evidence for DM and structure formation

Outline:

- Evidence for dark matter

  i) historical overview

  ii) modern evidence

- Structure formation in brief

  i) standard cosmological model

  ii) growth of density fluctuations in the linear regime

  iii) non-linear regime and N-body simulations

Literature: (i) Galaxy formation, M. S. Longair, Springer-Verlag, 1998 (ii) Galaxy formation and evolution, Mo, van den Bosch and White, Cambridge University Press, 2010 (iii) Modern Cosmology, S. Dodelson, Academic Press, 2003

Evidence for dark matter: historical overview

Fritz Zwicky 1937, dynamics of Coma (supported by “random” motions):

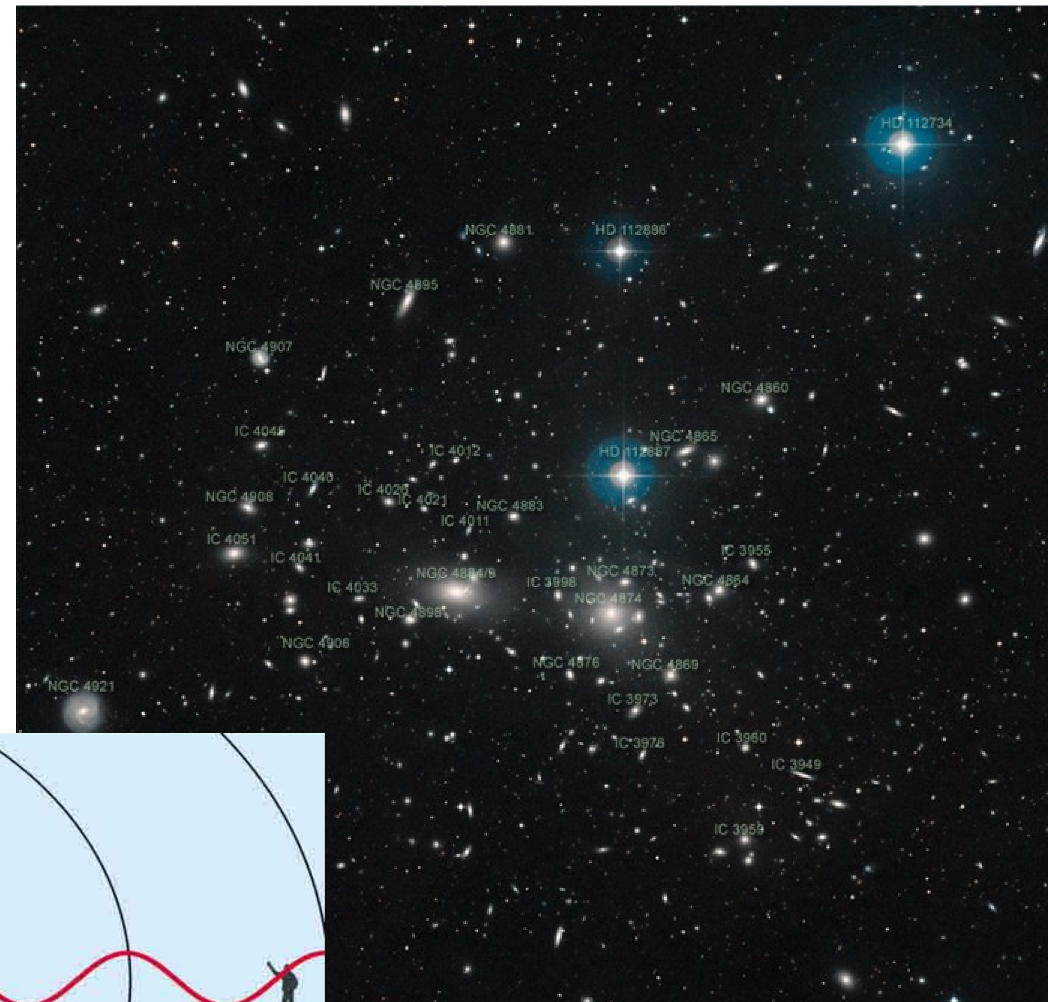
- Virial Theorem (equilibrium): 2K = -W
  - Measure angular positions and average distance from Earth (redshift)

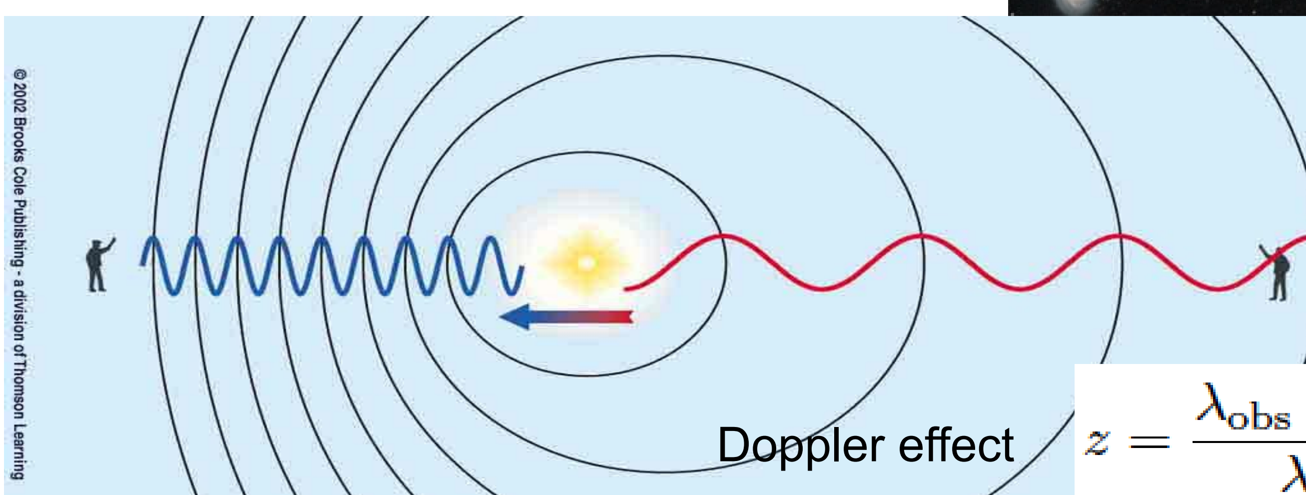
    ➔ $\langle R_c \rangle \sim 2\mathrm{Mpc}$

  - Measure radial velocities (spectra of individual galaxies)

    ➔ $\langle \sigma_c \rangle \sim 1000\mathrm{km/s}$

Coma cluster, fig. From STSI





Doppler effect

$$z = \frac{\lambda_{\mathrm{obs}} - \lambda_{\mathrm{emi}}}{\lambda_{\mathrm{emi}}}, \qquad E_{\mathrm{emi}} = (1+z)E_{\mathrm{obs}}$$

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→ $\langle R_c \rangle \sim 2\mathrm{Mpc}$

  - Measure radial velocities (spectra of individual galaxies)

→ $\langle \sigma_c \rangle \sim 1000\mathrm{km/s}$

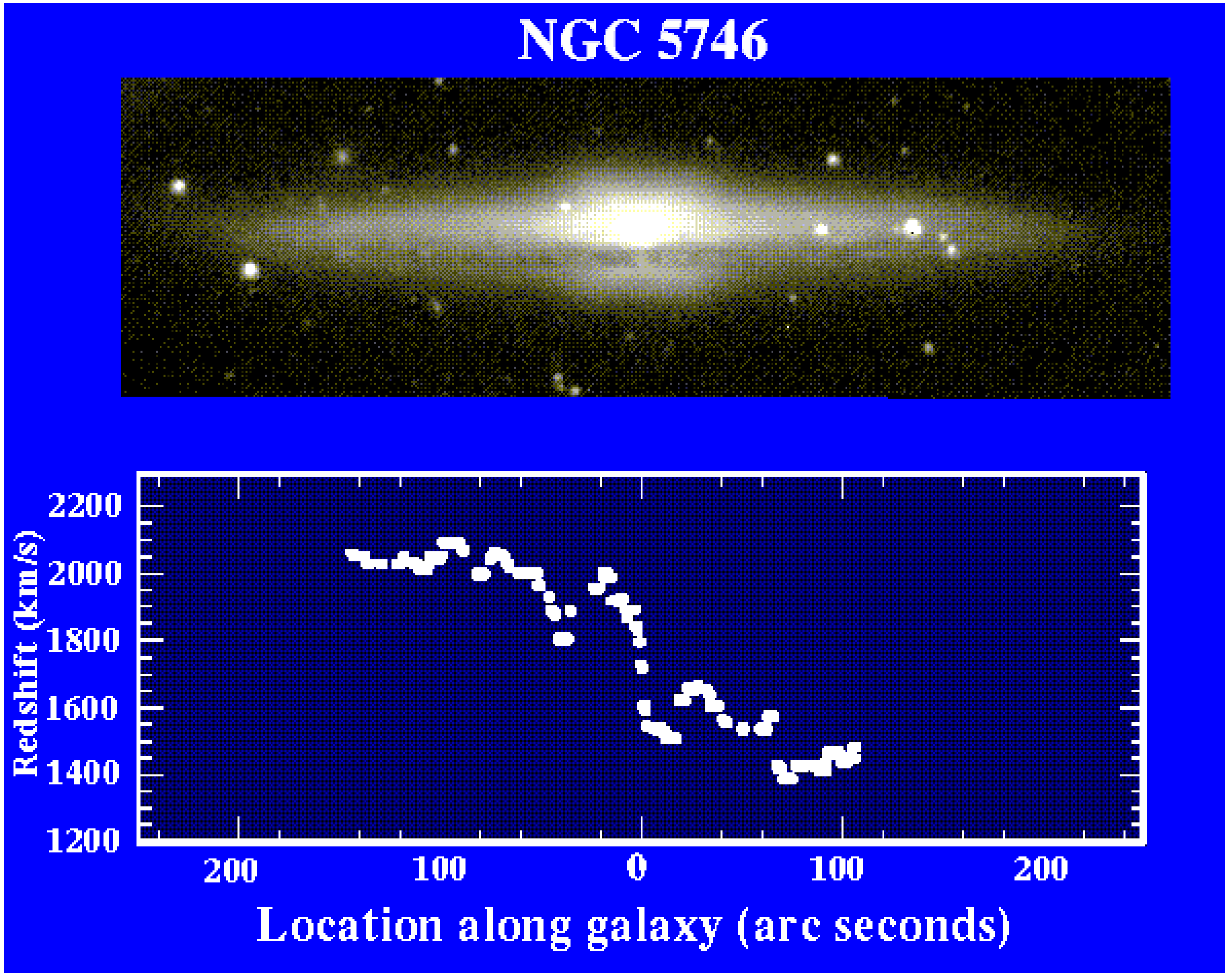
- Total mass: $\sim 2\langle \sigma_c \rangle \langle R_c \rangle / G \sim 5\mathrm{x}10^{14} M_{Sun}$
- Measure total luminosity in the cluster to get the mass to light ratio:
  M/L (blue band) ~ 250 (M_{Sun}/L_{Sun})

Coma cluster, fig. From STSI

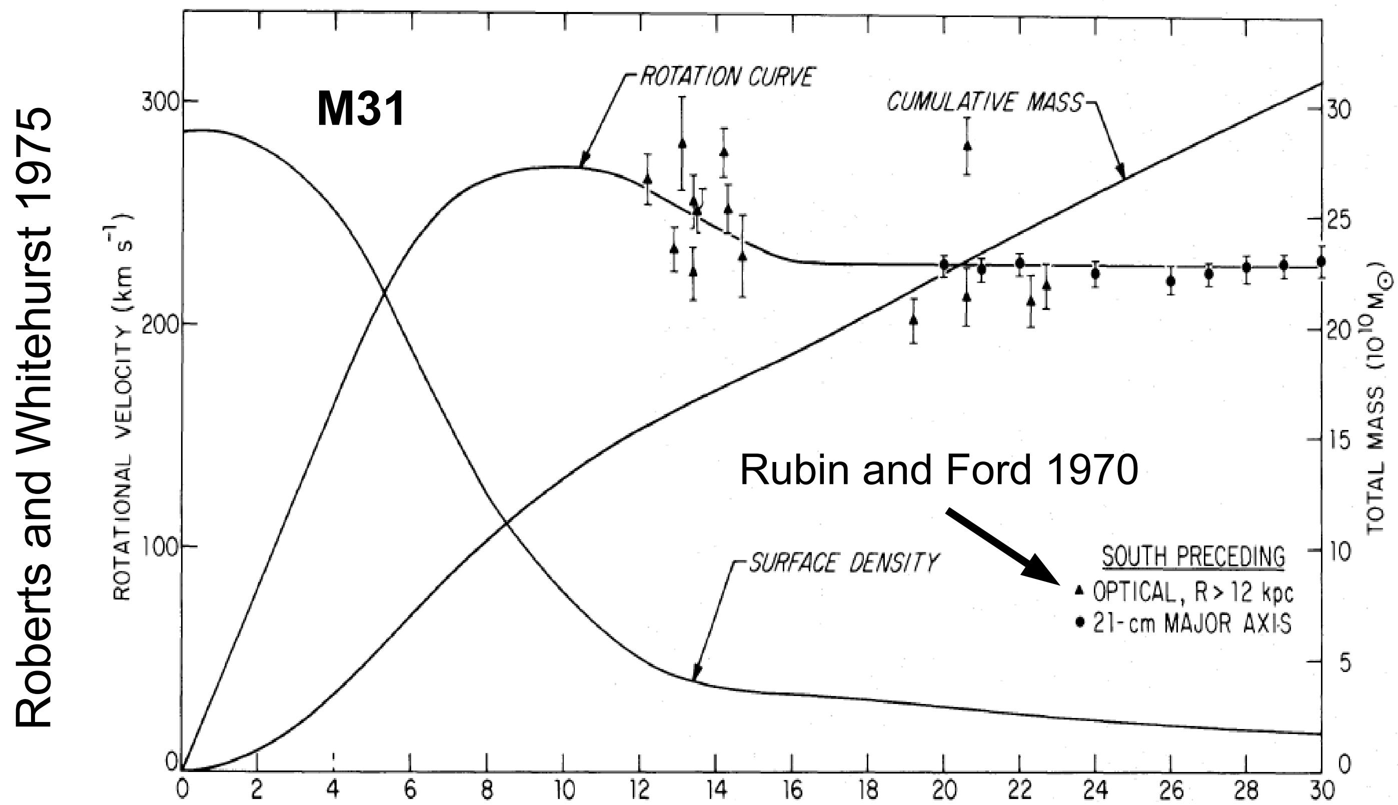
The cluster must contain a large a dominant type of matter not accounted by the light of stars!

Evidence for dark matter: historical overview

1970s and 1980s, dynamics of spiral galaxies (supported by rotational velocities):



Evidence for dark matter: historical overview



1970s and 1980s, dynamics of spiral galaxies (supported by rotational velocities):

- Surface density light profile (typically exponential for spirals): $\Sigma_d(r) = \Sigma_{d,0} e^{-r/h_d}$

$$\rightarrow \quad V_d^2 \approx \frac{GM_{d,light}}{8r}, \quad \text{for} \quad r \gg h_d$$

- Rotation "curve" measured (typically 21-cm line emission) is flat at large radii!, implies a mass component that doesn't emit light.

Evidence for dark matter: modern evidence

Gravitational lensing and X-ray emission in galaxy clusters

- Most of the mass in the visible matter is in the X-ray component (Helen's lectures):
  - ICM: hot “corona” (Abell 2390)
    $T \sim 10^8$K ~ 10keV
  - Hydrostatic equilibrium (sph. symm.):

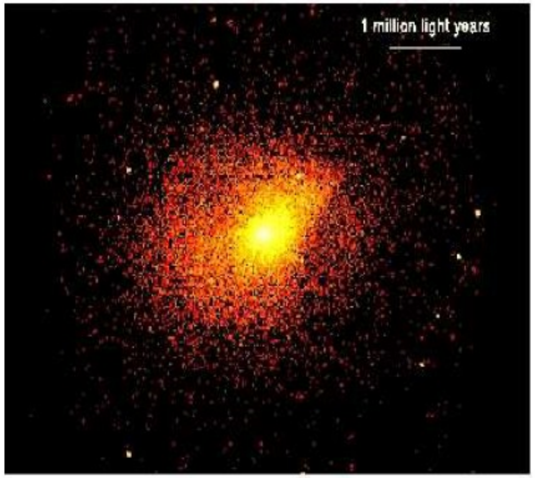
$$\frac{dP_{\rm gas}}{dr} = -\rho_{\rm gas}(r)\frac{GM_{\rm Tot}(<r)}{r^2}$$

  - Ideal gas equation of state

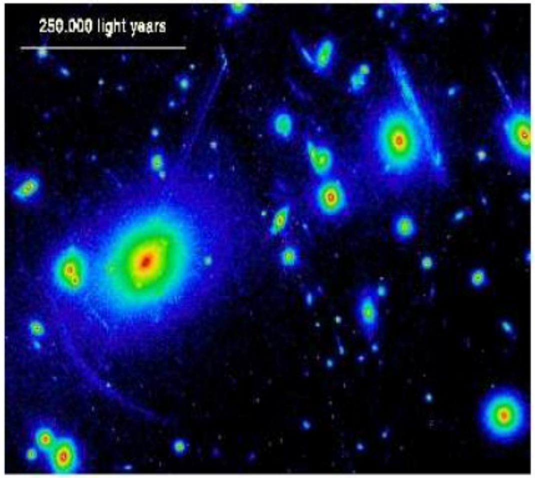
$$\longrightarrow \quad M_{\rm Tot}(<r) = -\frac{k_B T r^2}{G\mu m_p}\left[\frac{{\rm dln}n_{\rm gas}(r)}{{\rm d}r} + \frac{{\rm dln}T(r)}{{\rm d}r}\right]$$

- $M_{\rm Tot}$ can be compared with lensing studies
- $F_{\rm gas} = M_{\rm gas}/M_{\rm Tot} < 0.20$!

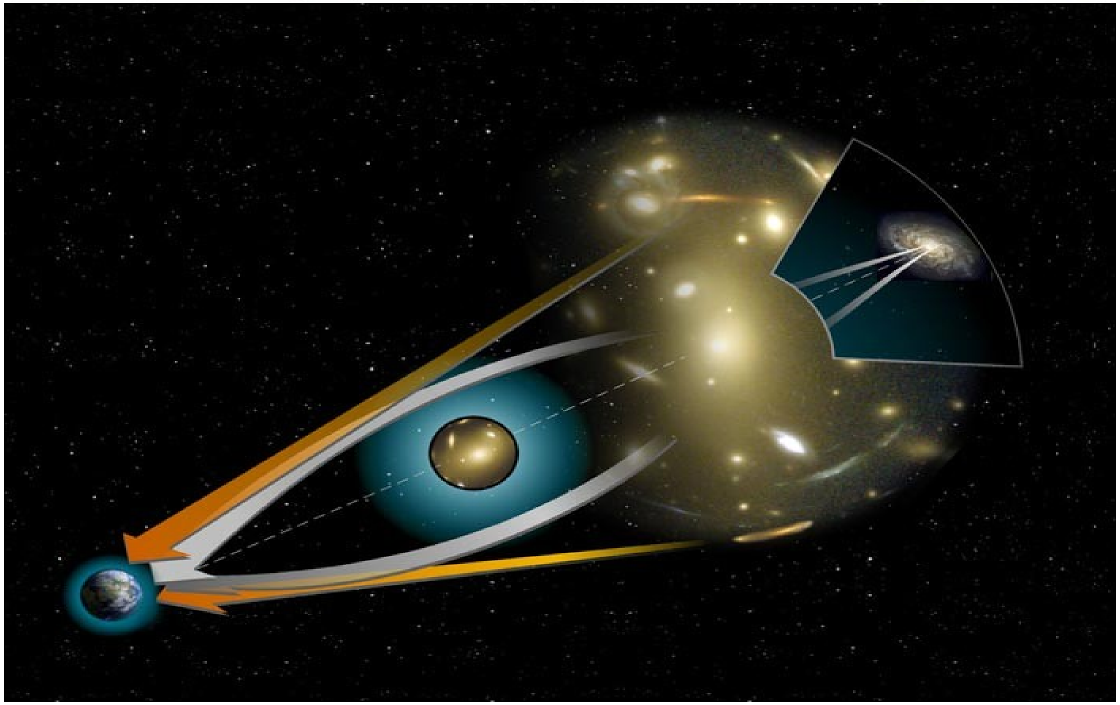
Fabian and Allen 2003



Abell 2390: Chandra (ACIS)



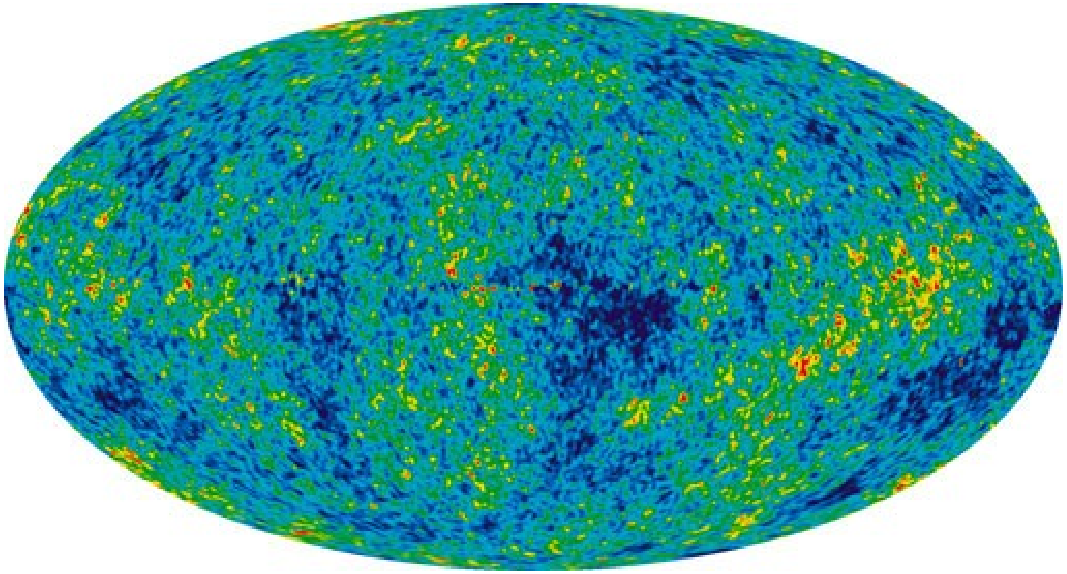
Abell 2390: HST (WFPC2)

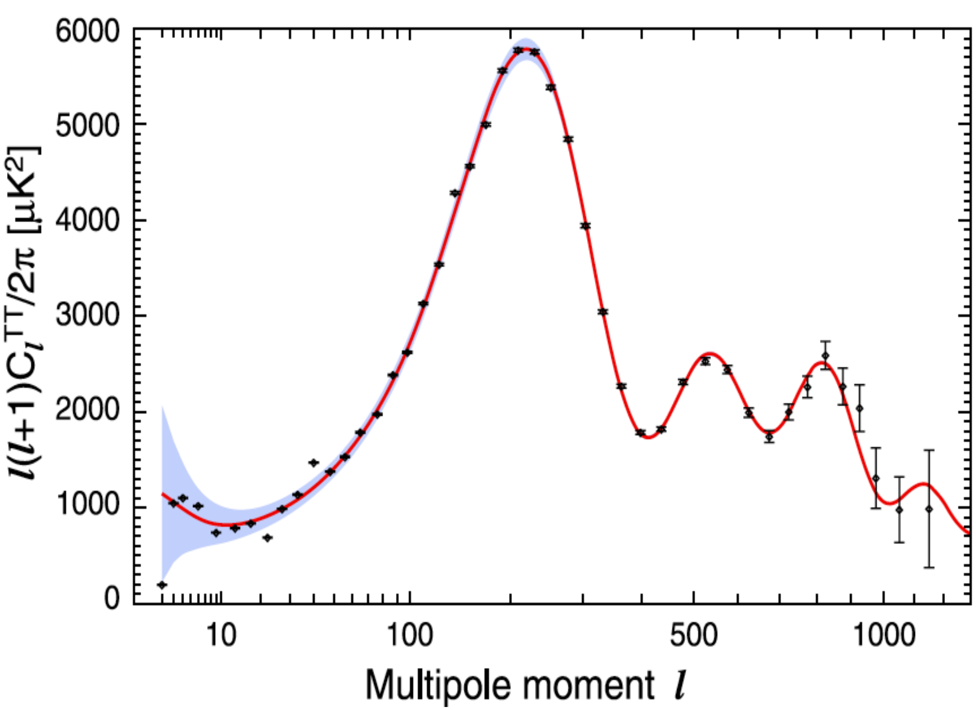


Evidence for dark matter: modern evidence

Cosmic Microwave Background (CMB)

NASA/WMAP-7yr Science Team





- Mean radiation has a black body energy spectrum with T ~2.73 K (0.23meV)

- Produced during "hydrogen recombination" t~380,000 yrs (z~1100)

- Primary anisotropies 1:100,000, relic of the primordial density perturbations

- Angular power spectrum measures the level of anisotropy at different angular scales.

- The third peak actually gives an important constraint on the global amount of DM:

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm b}} \approx 5$$

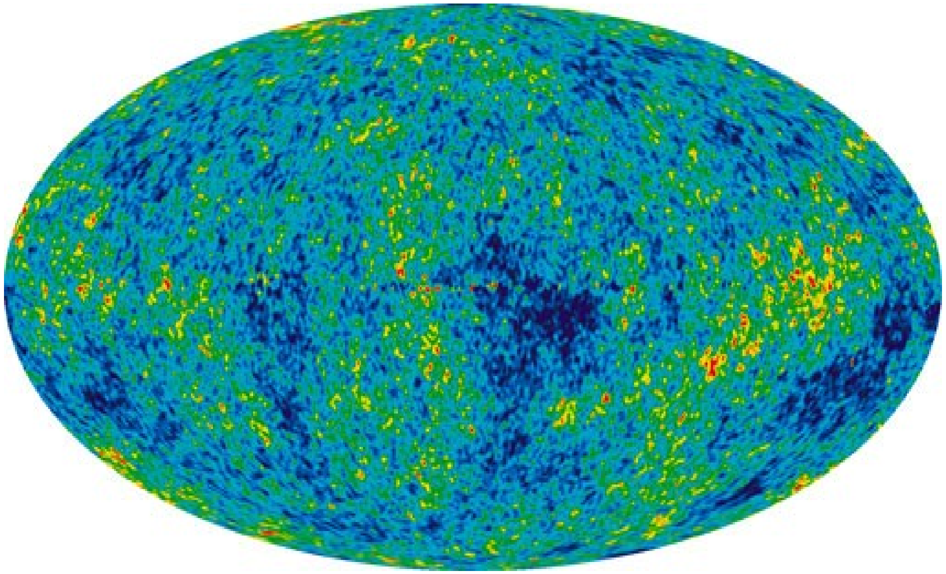
- Physics of the CMB very rich..., no details will be given here. For a nice explanation of the CMB power spectrum see:

http://background.uchicago.edu/~whu/

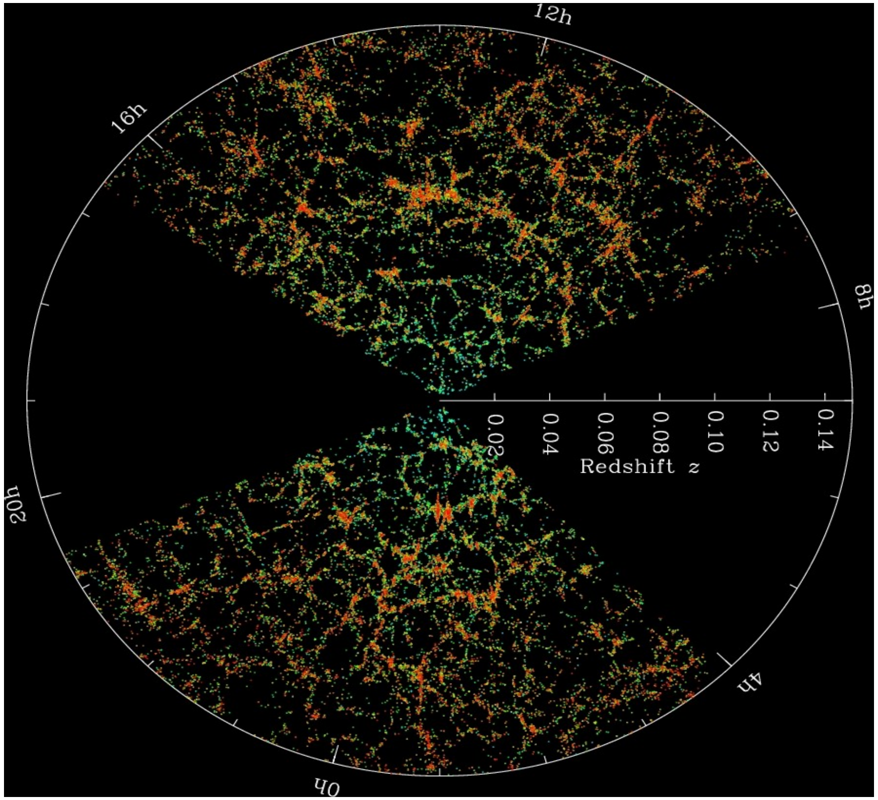
Structure formation in brief: the standard cosmological model

• Cosmological principle: At large scales (~1Gpc) the Universe is homogenous and isotropic, defines the background (average) evolution

Universe at t ~ 0.4 Myrs



Universe today (t ~ 13.8 Gyrs)



SDSS galaxy “map”, scale ~ 600 Mpc

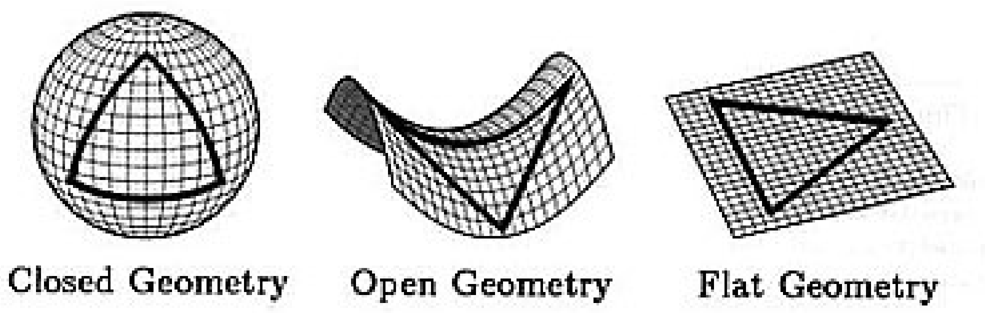
Background evolution (1st Friedmann eq.): BLACKBOARD!

Structure formation in brief: the standard cosmological model

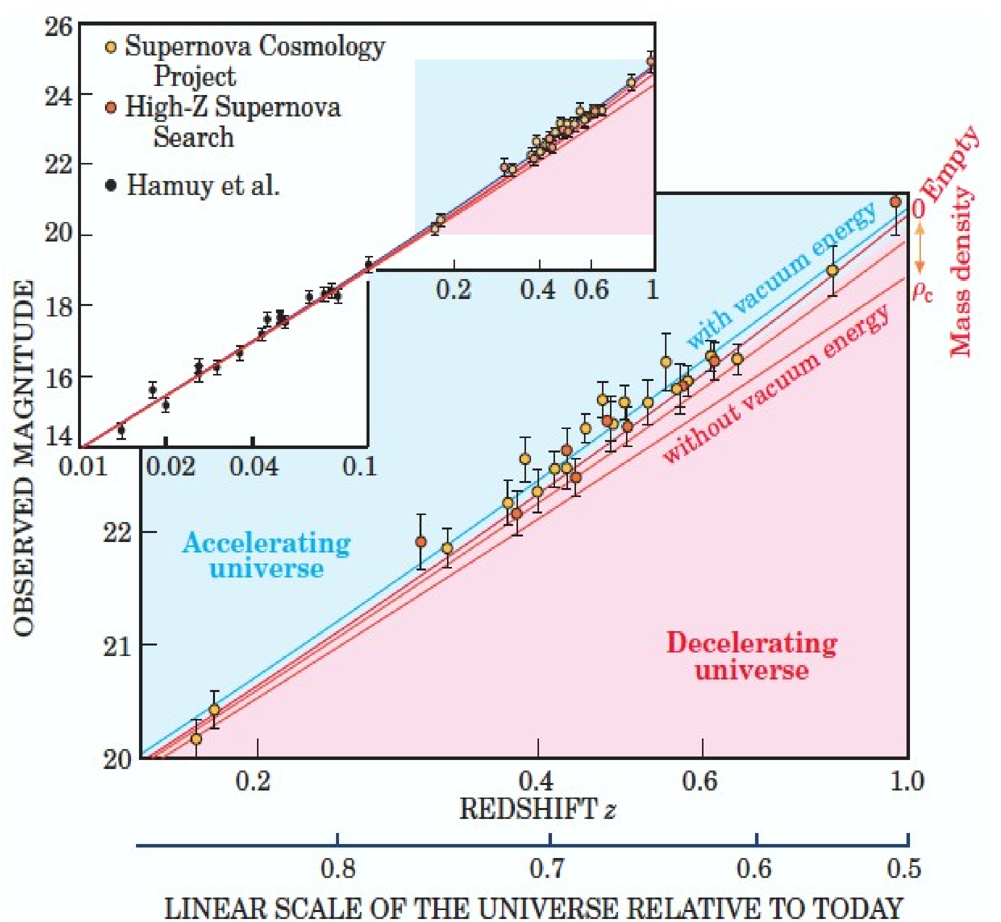
- Cosmological principle: defines the background evolution (1st. Friedmann equation):

$$H^2(t) - \frac{8\pi G\bar{\rho}(t)}{3} = -\frac{Kc^2}{a(t)^2} \qquad K = 0 \quad \Rightarrow \quad \bar{\rho}(t) \equiv \rho_{\rm crit}(t) = \frac{3H^2(t)}{8\pi G}$$

- "K" related to the spatial curvature (geometry) of the Universe:



- The universe is expanding at an accelerated rate



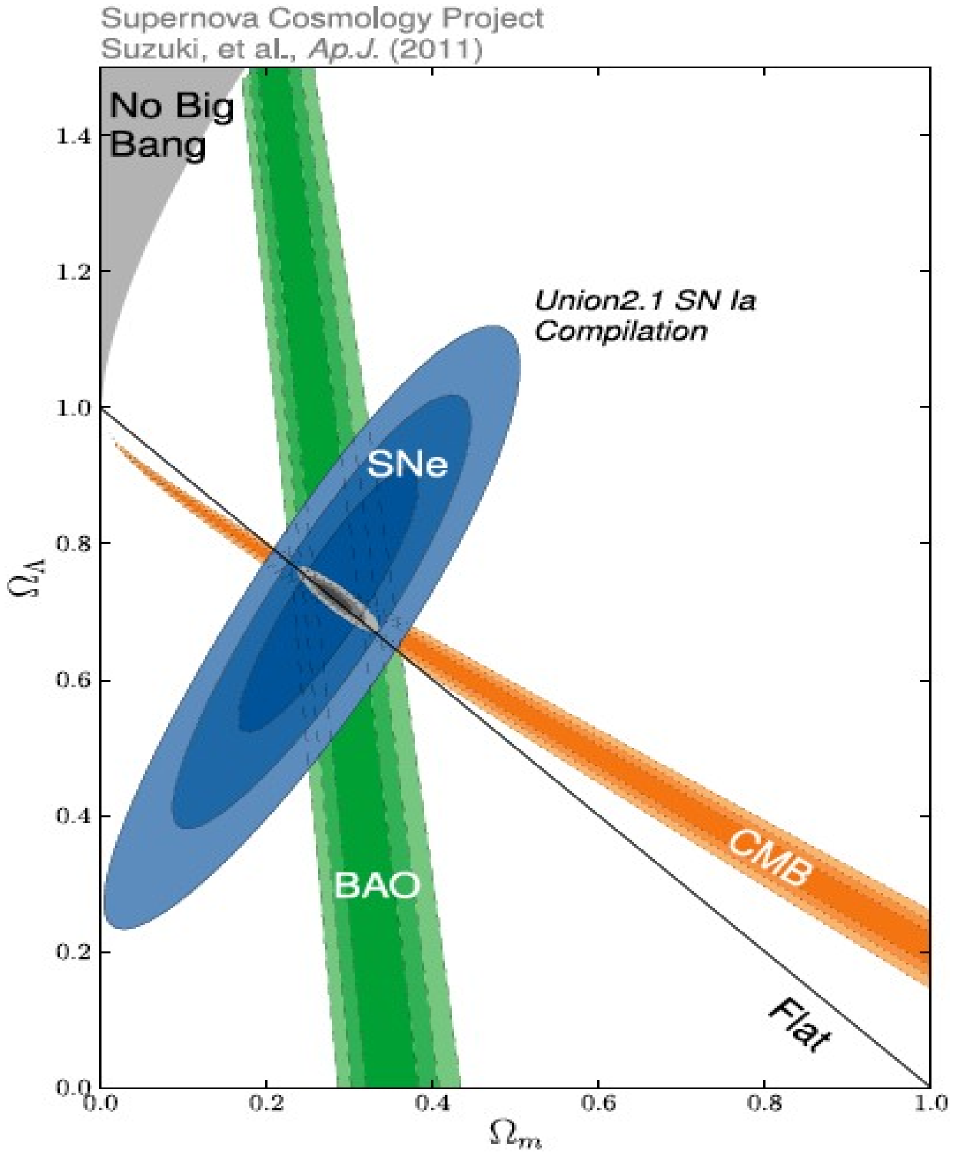
Structure formation in brief: the standard cosmological model

- Cosmological principle: background evolution
- The Universe is expanding at an accelerated rate
- Components (in terms of the critical density):

$$\Omega = \Omega_{\rm dm} + \Omega_{\rm b} + \Omega_{\rm rad} + \Omega_{\Lambda}$$

- The Universe has a flat geometry (CMB + SN)

$$\Omega \approx 1$$



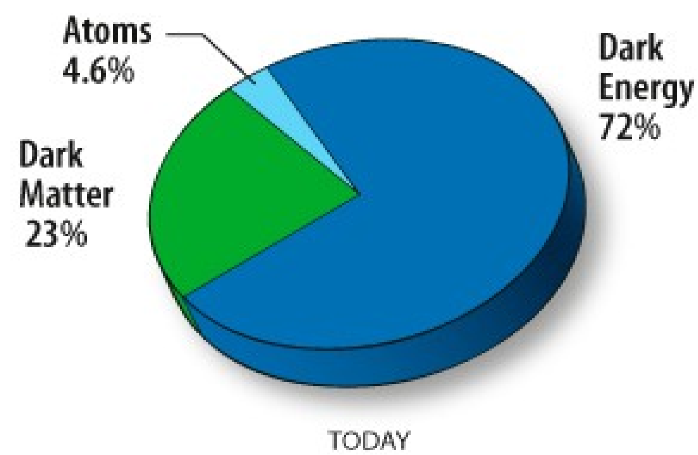
Structure formation in brief: the standard cosmological model

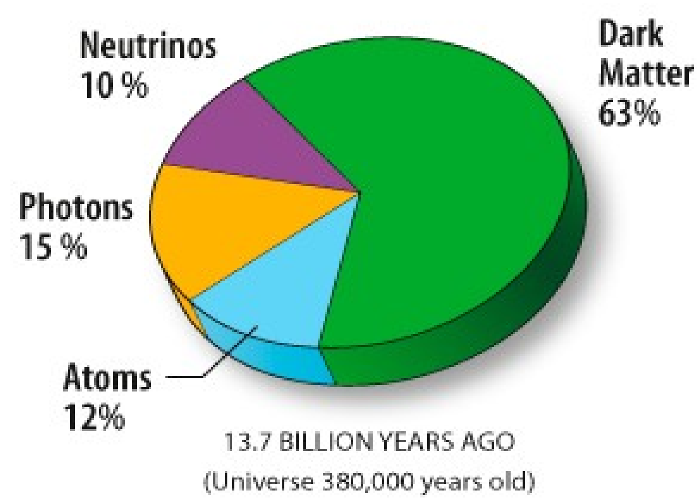
- Cosmological principle: background evolution
- The Universe is expanding at an accelerated rate
- Components (in terms of the critical density):

$$\Omega = \Omega_{\rm dm} + \Omega_{\rm b} + \Omega_{\rm rad} + \Omega_\Lambda$$

- The Universe has a flat geometry (CMB + SN)
- Mass-energy budget (time dependent)
  (2nd Friedmann eq.) BLACKBOARD!

$$\rho_m = \rho_{0,m} a^{-3} \qquad \text{(Mat.)}$$
$$\rho_r = \rho_{0,r} a^{-4} \qquad \text{(Rad.)}$$
$$\rho_r = \rho_{0,\Lambda} = \text{cte} \qquad (\Lambda)$$

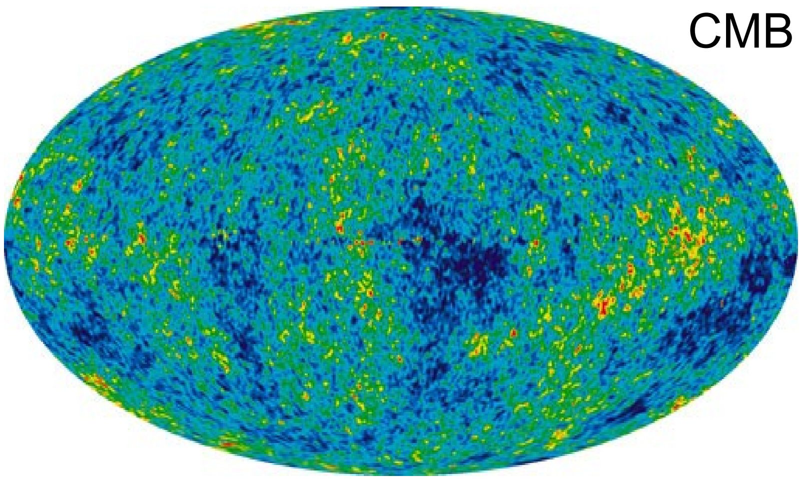




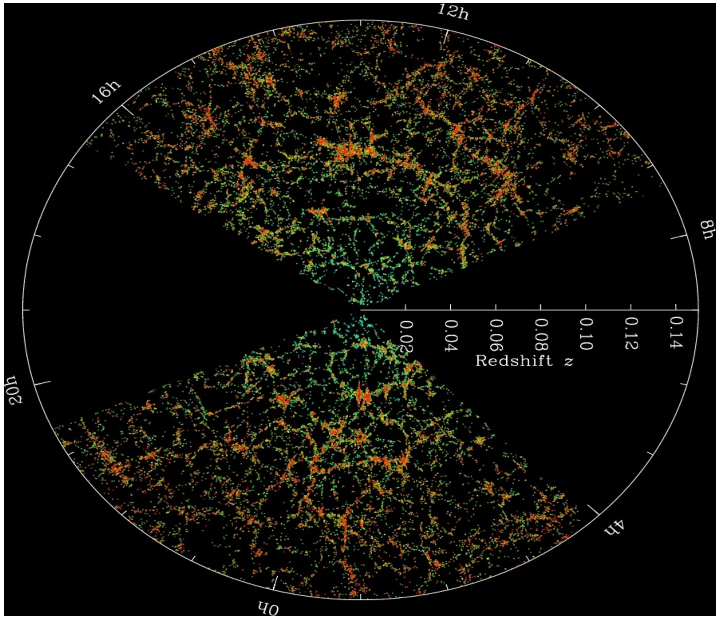
NASA/WMAP-7yr Science Team

Structure formation in brief: growth of density perturbations

- The standard cosmological model describes the isotropic and homogeneous Universe
- Theory of structure formation aims to connect the CMB anisotropies with the structures we see today



CMB $\frac{\delta\rho_m}{\rho_m} \sim 10^{-5}$



SDSS Map $\frac{\delta\rho_m}{\rho_m} \gtrsim 1$

M31

$\frac{\delta\rho_m}{\rho_m} \gg 1$

Structure formation in brief: growth of density perturbations

The linear regime and why do we need DM
BLACKBOARD!

Structure formation in brief: linear growth of density perturbations (summary)

- Small matter density perturbations (Δ=dρ/ρ<<1) of a given scale "k_c" grow independently from other scales according to:

$$\frac{d^2\Delta_{k_c}}{dt^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{d\Delta_{k_c}}{dt} = \Delta_{k_c}(4\pi G\rho_0 - k^2 c_s^2)$$

- Gravity and pressure support (driven by radiation) compete and generate "acoustic oscillations" in the evolution of the perturbations of ordinary matter (baryons and photons)

- When pressure can no longer support gravity, perturbations grow linearly with the scale factor (in an EdS Universe). They leave the oscillatory phase depending on their scale relative to the Jeans length:

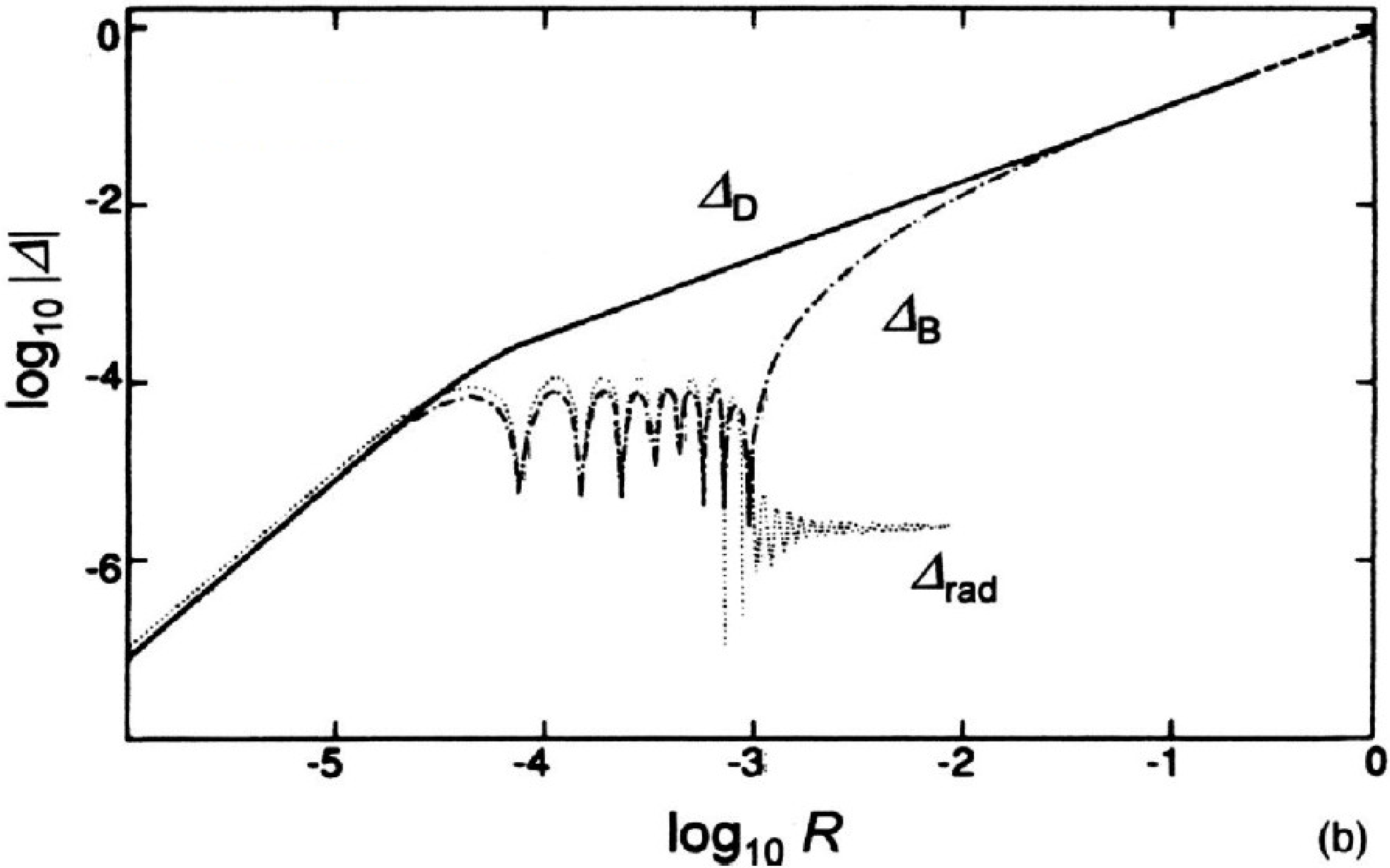
$$\Delta_{k_c} \propto t^{2/3} \propto a(t), \qquad k_c \ll k_c^J$$

- If there is no DM, the perturbations cannot grow enough from the epoch of last scattering to explain the overly dense structures we see today:

$$\Delta_\rho(z=0) \approx 10^{-2}, \quad \text{since}: \; \Delta_\rho(z_{\rm ls}) \sim 3\Delta_T(z_{\rm ls}) \approx 10^{-5}; \quad z_{\rm ls} \sim 1100$$

- The presence of DM allows the matter perturbations to be larger today by avoiding the period of oscillations before recombination and pulling the baryons into the DM potential wells afterwards (Summary plot!)

Structure formation in brief: linear growth of density perturbations (summary)



Galaxy Formation, Malcolm S. Longair, Springer-Verlag 1998

Structure formation in brief: N-body simulations

- Perturbation theory is no longer valid once $\Delta \sim 1$, non-linear evolution couples structures of different scales.

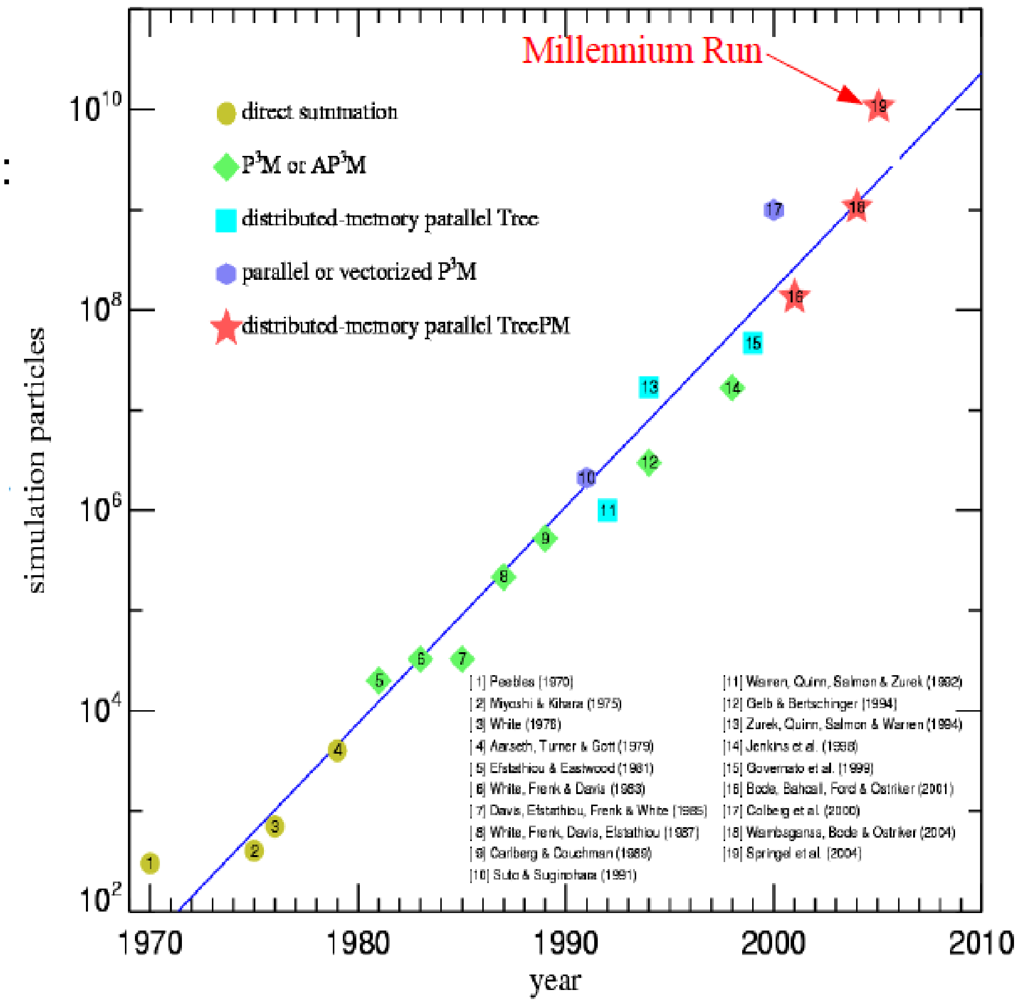
- Analytic treatment of the non-linear regime is difficult, although insight can be gained from simplified assumptions (e.g. Spherical collapse model): perturbations grow “separating” from the expansion of the Universe and collapsing under their own gravity until achieving equilibrium (DM haloes).

- The most precise method to study this regime is N-body simulations: discrete representation of the density field with a set of N point particles:

  - ICs given by the linear regime: generate displacements for the positions and velocities over the homogeneous background to represent, statistically, the perturbed field.

  - Compute the gravitational force for each particle and use eqs. of motion (Newtonian in an expanding background) to follow evolution.

  - A naive force calculation needs N^2 op's; computer power and improved algorithms have made it possible for simulations to double their size every 16.5 months.



Structure formation in brief: N-body simulations

Links to some N-body movies of structure formation (DM-only):

Miscellaneous:

http://www.mpa-garching.mpg.de/galform/data_vis/index.shtml

Millennium run:

http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Aquarius run:

http://www.mpa-garching.mpg.de/aquarius/