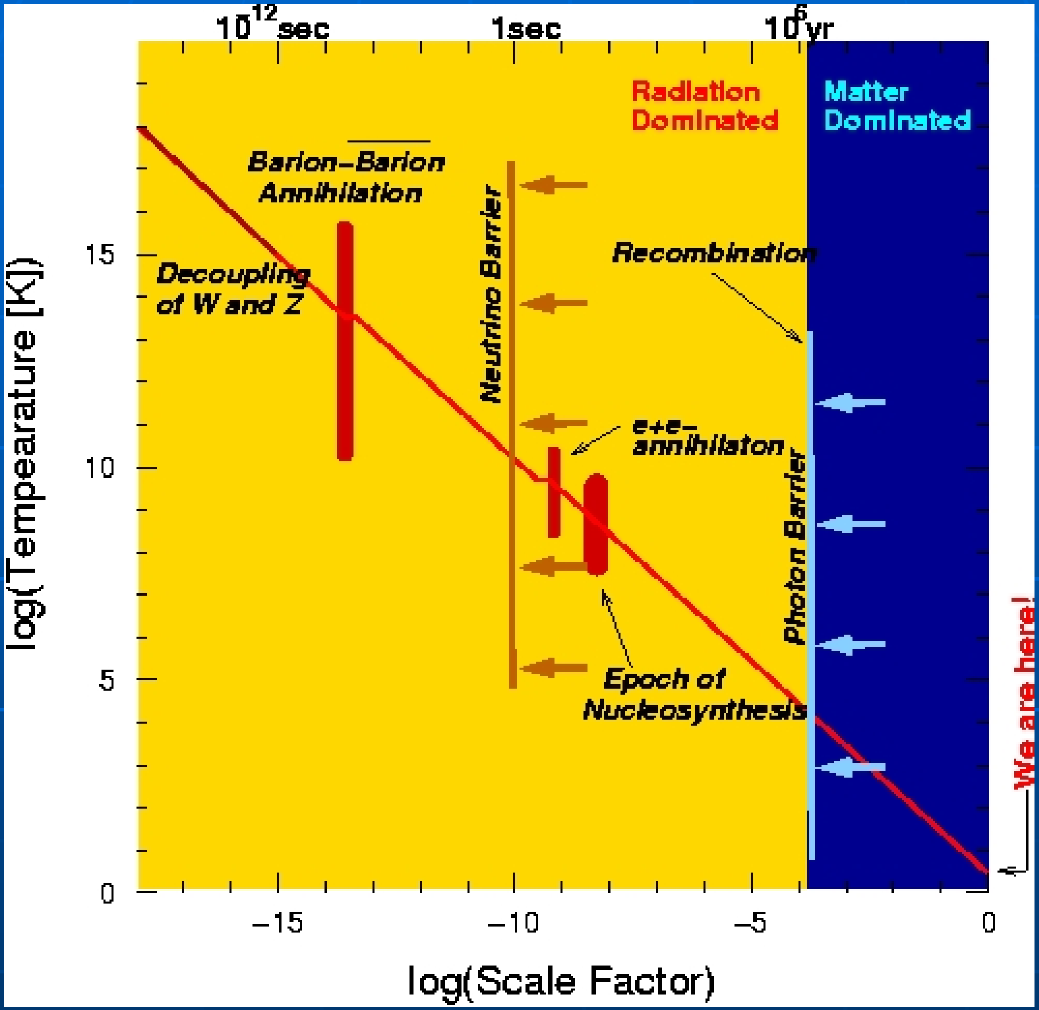
Thermal History of the Universe



Thermal History of the Universe

Planck Scale

QM: de Broglie wavelength $L_P = h/m_P c$

GR: event horizon $R_{EH} = 2Gm_P/c^2$

Limit of current physics when $L_P = R_{EH}$

Planck mass $m_P \sim 10^{-8}$ kg $\sim 10^{19}$ GeV/c^2
Planck length $L_P \sim 10^{-35}$ m
Planck time $t_P = L_P/c \sim 10^{-43}$ s

High-energy Era

$t < 10^{-8}$ s, $T > 10^{13}$ K

Universe consists of photons, quarks, leptons, ... in thermal equilibrium.

Particle–antiparticle pair production, e.g.

$$\gamma + \gamma \rightleftharpoons e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$$

$$\gamma + \gamma \rightleftharpoons q + \bar{q}$$

Particle Physics

At $t \sim 10^{-8}$ s, $T \sim 10^{13}$ K, baryons–antibaryons annihilate

$$b + \bar{b} \;\rightarrow\; \gamma + \gamma$$

Baryon asymmetry problem – for every 10^9 antibaryons, must be $10^9 + 1$ baryons

$\Rightarrow$ Baryon number not conserved; "CP violation" in QM

At $t \sim 0.1$ s, $T \sim 10^{10}$ K, universe is transparent to neutrinos

$\Rightarrow$ they "decouple" from the radiation

$\Rightarrow$ number of $\nu, \bar{\nu}$ stays constant ($\rho_{\nu 0} \sim 10^8$ m^{-3})

At $t \sim 1$ s, $T \sim 10^{10}$ K, electrons–positrons annihilate

$$e^- + e^+ \;\rightarrow\; \gamma + \gamma$$

Nucleosynthesis

$t \sim 1$–120 s, $T \sim 10^9$ K

Thermal energy, $kT \sim 0.1$ MeV

Nuclear binding energy, $E_B \sim 1$ MeV

$kT \ll E_B \quad \Rightarrow \quad$ nuclei form

← More detail on next transparencies

Epoch of Recombination

$t \sim 10^6$ yr, $T \sim 3000$ K, $z \sim 1100$

Previously, photons scattered by electrons $\Rightarrow$ universe was opaque.

Photon energy, $kT \sim 0.3$ eV

Hydrogen ionization energy, $E_I = 13.6$ eV

$kT \ll E_I \quad \Rightarrow \quad$ electrons "**recombine**" with protons/nuclei

$\Rightarrow$ universe becomes transparent

$\Rightarrow$ radiation no longer in thermal equilibrium with matter

$\Rightarrow$ origin of the CMB

Summary

Planck Scale: $t \sim 10^{-43}$ s, QM/GR limit

High-energy Era: $t < 10^{-8}$ s, particle "soup"

Inflation: $t \sim 10^{-35}$–10^{-32} s, rapid expansion of the universe

Particle Physics: $t \sim 10^{-8}$–1 s; baryon asymmetry problem

Nucleosynthesis:

$\Rightarrow$ $t \sim 1$–120 s, $T \sim 10^9$ K

$\Rightarrow$ right T & ρ for nuclear fusion to occur

$\Rightarrow$ main products: ^{4}He (23%), ^{2}H (0.002%), ^{3}He (0.001%), ^{3}H, ^{7}Be, ^{7}Li (all $<\sim 10^{-6}$)

$\Rightarrow$ density parameter in baryons $\Omega_b = \rho_b/\rho_0 = 0.045$

Recombination: $t \sim 10^6$ yr, $T \sim 3000$ K, $z \sim 1100$; electrons "recombine" with nuclei

Big Bang Nucleosynthesis

(much material courtesy M. Bartelman, ITA)

BBN and Expansion Rate

- as Universe expands, temperature drops through range which allows nuclear fusion
- since $T = T_0 a^{-1}$,
$$\dot{T} = \frac{T_0}{a}\frac{\dot{a}}{a} = TH \Rightarrow \Delta t \approx \frac{T}{\dot{T}} = H^{-1}$$
i.e. time for BBN determined by expansion rate: faster expansion leaves less time for BBN
- BBN, and thus abundance ratios of (light) elements, measure expansion rate in the early Universe
- *What fraction of (light) elements could form from protons and neutrons until the Universe was too cool?*

Historical Remarks

- Gamow (1942, 1946): can element abundances be explained with Big Bang Theory?
- Fermi & Turkevich: no significant production of nuclei more massive than ^{7}Li, thus ^{4}He expected to be most abundant element after H
- Alpher (1948): expansion dominated by radiation; Hayashi (1950): computed n/p ratio following Big Bang
- BBN physics in place by 1953 (Alpher, Follin & Herman)
- prediction of the CMB and its temperature
- abundance predictions by Peebles (1964), Hoyle & Tayler (1964), Wagoner, Fowler & Hoyle (1967); substantially unchanged, accuracy much improved

Baryogenesis

- *Why is there matter rather than antimatter?*
- What sets the baryon-to-photon ratio, η?

Sakharov conditions:

- CP violation (different interactions for matter and antimatter)
- interactions changing baryon number
- departure from thermodynamic equilibrium (e.g. during phase transitions)

Neutrons and Protons

- protons and neutrons form when $kT \sim 1\,\text{GeV}$
- afterwards, protons and neutrons interconvert through weak interactions, e.g.

$$n + \nu_e \leftrightarrow p + e^-$$

- remain in thermal equilibrium until...
- ... weak interactions freeze out at $kT \sim 800\,\text{keV}$

- at this point, neutron-to-proton number-density ratio was

$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = \exp\left(-\frac{\Delta mc^2}{kT}\right)$$

- mass difference is $\Delta mc^2 = 1.4\,\mathrm{MeV}$, thus

$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = \frac{1}{6}$$

when weak interaction freezes out

Fusion Steps

- need two-body processes because probability for others is too low
- first element to form is deuterium,

$$n + p \rightarrow {}^2\text{H} + \gamma$$

- next are helium isotopes, e.g.

$$^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + n$$
$$^3\text{He} + {}^2\text{H} \rightarrow {}^4\text{He} + p$$

- formation of ^{4}He is energetically favoured
- next element is ^{7}Li, e.g.

$$^4\text{He} + {}^3\text{H} \rightarrow {}^7\text{Li} + \gamma$$

- absence of stable nuclei with $A = 5$ and $A = 8$ and increasing Coulomb barriers make production of higher elements highly inefficient

Deuterium Production

- ^{2}H has binding energy of $2.2\,\mathrm{MeV}$, i.e. ^{2}H can form once $kT \lesssim 2\,\mathrm{MeV}$
- high photon density prevents ^{2}H formation via photo dissociation
- compare CMB recombination; see Saha's equation, see Saha's equation for the reaction

$$n + p \leftrightarrow {}^2\mathrm{H} + \gamma$$

- thus, ^{2}H formation delayed until $kT \sim 80\,\mathrm{keV}$, i.e. $\approx$ three minutes after the Big Bang
- well before matter-radiation equality, i.e. density, and thus expansion rate, is entirely determined by relativistic matter
- baryon-to-photon ratio $\eta = 10^{10}\eta_{10}$ is only relevant parameter,

$$\eta_{10} = 273\,\Omega_{\mathrm{B}} h^2$$

The Gamow Criterion

- ^{2}H production is first and crucial step for subsequent BBN
- if too much ^{2}H is formed, neutrons are locked up and no higher elements are formed
- if too little ^{2}H is formed, important agent for further fusion is missing
- production rate needs to be "just right":

$$n_{\rm B} \langle \sigma v \rangle t \approx 1$$

- velocity-averaged cross section $\langle \sigma v \rangle$ is known
- time t determined by expansion rate, thus by photon density, equivalently by photon temperature
- baryon density $n_{\rm B}$ can be constrained
- Gamow used this criterion to predict the CMB temperature from an estimate for the baryon density

Neutron Decay

- between neutron-proton conversion freeze-out at $kT \sim 800\,\mathrm{keV}$...
- ... and ^{2}H formation at $kT \sim 80\,\mathrm{keV}$,
- neutrons decay with half-life of

$$t_\mathrm{n} = 886.7 \pm 1.9\,\mathrm{s}$$

- equilibrium density ratio drops to

$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = \frac{1}{7}$$

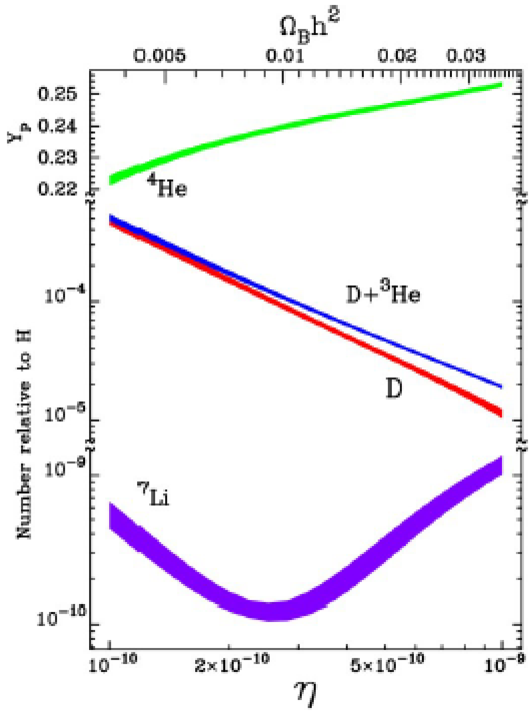
- once D exists, neutrons are very efficiently locked up in ^{4}He nuclei due to high binding energy
- expected primordial ^{4}He abundance (by mass):

$$Y_\mathrm{p} \simeq \frac{2n_\mathrm{n}}{n_\mathrm{p}+n_\mathrm{n}} = \frac{2(n_\mathrm{n}/n_\mathrm{p})}{1+n_\mathrm{n}/n_\mathrm{p}} = 0.25$$

- relatively insensitive to baryon density, and thus to η

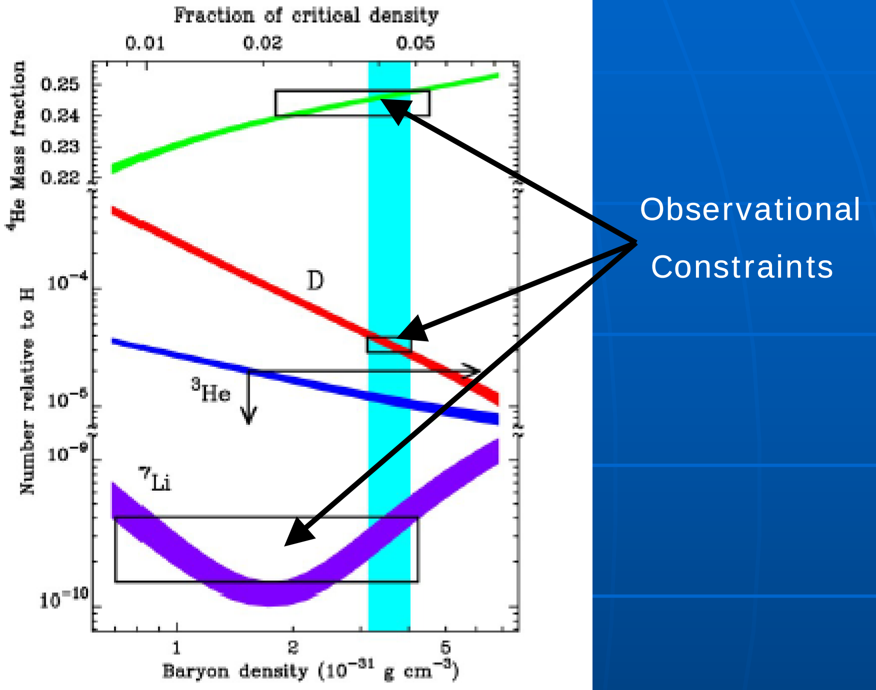
Expected Abundances vs. η

- gentle increase of Y_P with η as BBN starts earlier
- ^{2}H and ^{3}He are burnt away by fusion, thus their abundance decreases as η increases
- ^{7}Li is destroyed by protons for low η, with efficiency increasing with η
- precursor ^{7}Be is produced more efficiently as η increases
- competing effects create ^{7}Li "valley"



BBN Results

- BBN *alone* implies $\Omega_B h^2 = 0.019 \pm 0.0024$ at 95% significance
- mainly based on high-redshift ^{2}H abundance
- yields consistent set of light-element abundances



IV. Non-linear Density Perturbations and the Physics of Galaxy Formation

IV. I A simple Model for Collapsed Objects

Consider a sphere of homogeneous density; it acts exactly like a small universe (Birk-hoff's theorem):

- Its (proper) radius evolves as

  $r = \alpha\,(1-\cos\vartheta)$ $\qquad$ $t = \beta\,(\vartheta - \sin\vartheta)$

  where the constants are related through
  $\alpha^3 = GM\beta^2$ from dimensional analysis

  $$\left(\ddot{r} = -GM/r^2\right)$$

- At first the sphere expands as $r \sim t^{2/3}$ and its overdensities as

  $$\delta(t) \approx \frac{3}{20}\left(\frac{6t}{\beta}\right)^{2/3}$$

- Subsequent evolution
  - If the density is high enough (Ω < 1), "turn-around" occurs at $t = \pi\beta$ with a density enhancement of

$$\left[\left(\frac{\alpha}{2}\right)\left(\frac{6t}{\beta}\right)^{2/3}\right]^3 / r^3 = \frac{9\pi^2}{16} \approx 5.5$$

    Note: for this time linear theory $\delta_{lin} \sim t^{2/3}$ predicts $\delta_{lin} \approx 1$.
  - "Collapse": For a homogeneous sphere all parts fall back after maximal expansion to the center at the same instant at $\vartheta = 2\pi$; this occurs ath the same time as

$$\delta_{lin} = \frac{3}{20}(12\pi)^{2/3} \approx 1.69$$

  - $\Rightarrow$ The instant of collapse can be predicted from linear theory!
  - "Virialization": In practice, the collapse will not be to a singularity, and gravitational scattering will randomize the motions.

In the end the system will have to satisfy the virial theorem $E_{pot} \approx -2\ E_{kin}$, which corresponds to a virial radius of ~ 1/2 $r_{turn\ around}$.

⇒ The mean density of a collapsed and virialized system will be $2^3 \cdot 5.5$ higher than the mean density of the universe at the time of the turn-around.

⇒ The density of gravitationally formed objects reflects their formation epoch!

- Is there a natural final state for a collapsed system? ("Gravitational thermodynamics", Lynden-Bell, 1967)
  - For the gas analog, all particles in equilibrium should have velocities (energies?) drawn from a Maxwellian distribution, with a dispersion σ .
  - Even though individual DM particles do not interact, the overall potential fluctuation during collapse can randomize motions ("violent re-laxation").
  - The corresponding density is $\rho(r) = \frac{\sigma^2}{2\pi G} \cdot \frac{1}{r^2}$ ("isothermal sphere", I.S.).

Problems: I.S. has infite mass $\Rightarrow \rho \rightarrow r^{-\alpha}$, $\alpha > 3$ at large radii.
I.S. and all other self-gravitating systems have negative specific heat, i.e. $E_{tot}\downarrow$, T ($\cong \sigma$) $\uparrow$.

IV.2 The Abundance, Mass Scales and Interactions of Collapsed Objects

Qualitative picture:

If small-scale initial fluctuations are present (CDM), small objects will collapse first, forming successively larger objects („bottom-up“ or „hierarchical“ formation scenario)

IV.2.1. Press-Schechter Formalism

- Press and Schechter (1974) found a way to analyze the <u>statistics</u> of non-linear density fields, using linear theory.
  - Starting point: for collapse to occur, a certain threshold overdensity, δ_C, is necessary.
  - Filter (=convolve) the density field by a func-tion of length R_f , to localize fluctuations of size ~ R_f and mass $M \sim \bar{\rho} R_f^3$
  - If the density field was Gaußian (i.e. Gaußian amplitude distribution in amplitudes, random phases), one can predict the fraction of points with $\delta > \delta_C$:

$$p(\delta > \delta_c, R_f) = \frac{1}{2}\left(1 - erf\left(\nu / \sqrt{2}\right)\right)$$

  - where $\nu = \frac{\delta_c}{\sigma(R_f)}$ and $\sigma(R_f)$ is the rms fluctuation of the density field after filtering with R_f .

– Take $p(\delta > \delta_C)$ to be the probability that any point with $\delta > \delta_C$ is, or has been part of a collapsed object (= dark halo) with $R > R_f$.

$\Rightarrow$ fraction of total mass collapsed into objects $> M$ is

$$F(>M) = 1 - erf\left(\nu / \sqrt{2}\right)$$

– Note: $F(>M)$ has been multiplied by a factor of two, as half the material in a Gaußian field is underdense (no good justification).

– If we define $f(M)dM$ as the comoving number density of objects in $[M, M + dM]$, one gets

$$\frac{M^2 f(M)}{\bar{\rho}} = \frac{dF}{d\ln M} = \sqrt{\frac{2}{\pi}} \times \left| \frac{d \ln \sigma}{d \ln M} \right| \times \nu e^{-\nu^2/2}$$

– The spectrum of initial fluctuations enters through

$$\nu(M) = \left(\frac{M}{M_*}\right)^{(n+3)/6}$$ for $P(k) \sim k^n$.

– For $M \ll M_*$ we get $f(M) \sim M^{\frac{n-9}{6}}$ and for $n \approx -2$ one expects for the abundance of small dark halos $f(M) \sim M^{-2}$.
Note: For galaxies of luminosity L one observes $f(L) \sim L^{-1}$.

– Press-Schechter formalism shows good agreement with numerical N-body simulations.

- Application of the P.S. formalism:

– The abundance of objects at mass M is related to their density ($\rho_{virial} \rightarrow \rho_{turn\text{-}around} \rightarrow \delta$) relative to the rms density fluctuation at that mass scale,
$\sigma(M)$.

$\Rightarrow$ One can determine $\sigma(M)$ from the abundance of objects (this measures mass, not light fluctuations).

– Massive galaxy clusters are the largest collapsed objects $M \sim 10^{14.5} M_{sun} h^{-1}$ and

$$R_{Lagrange} \sim 6.5 \times \left(\Omega^{-1/3} h\right) Mpc$$

⇒ They probe density fluctuations on 5-10 Mpc scales.

⇒ $$\sigma(8\ Mpc) \approx 0.55 \pm 0.1$$

The P.-S. formalism treats the DM halos, that contain 90% of the total mass. However, we observe the compact concentrations of stars (galaxies) at the centers of halos.

What are the merger probabilities for galaxies?

- Mergers happen because orbital energy is transferred to internal kinetic energy ("dynamical friction").

Consider a mass moving through a uniform distribution of small particles *m* at velocity *v* (all *m*'s have negligible velocity).

During the passage of *M*, each small mass is deflected by

$$\alpha \approx \frac{\delta_{v_\perp}}{v} \approx \frac{2GM}{v^2 b}$$

for a minimum distance of *b*.

The resulting momentum change is $\Delta p_m = \frac{m}{2}\alpha^2 V$ at a cross-section $\Gamma(\Delta p) = 2\pi b n_m V db$.

$\Rightarrow$ $$F_{drag}(M,V) = \frac{4\pi G^2 M^2}{V^2}\rho \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$

with $\rho = n \cdot m$.

$\Rightarrow$ Orbital decay (drag) time scale

$$\mathrm{T}_D \approx \frac{p}{\dot{p}} = V^3 / \left(4\pi G^2 M \rho \Lambda\right)$$

with $\Lambda = \ln\left(\frac{b_{\max}}{b_{\min}}\right) \approx 5$

$\Rightarrow$ Dense environments with low relative velocities ($\sim V^3$!) are conducive to mergers.

$\Rightarrow$ Components of comparable mass merge fastest.

III.6 Numerical Simulations of Structure Formation

Most important method: Purely gravitational, dissipationless N-body simulations.

Advantages:

- No linear approximation.
- No simplifying geometry.
- Testing of analytic approximations

To achieve $t_{simulation} \approx t_{Hubble}$ we are limited to

$N_{particle} > 10^7$.

Simulations can be separated into four distinct steps:

(1) The equations of motion and their numerical solution.
(2) Boundary conditions (for an "infinite" universe).
(3) Initial conditions.
(4) Simulation analysis and interpretation.

(1) The already derived equations of motion

$$\frac{d^2\vec{x}}{d\tau^2} + \frac{\dot{a}}{a}\frac{d\,\vec{x}}{d\tau} = -\vec{\nabla}\phi$$

$$\text{with } \vec{\nabla}^2\phi = 4\pi G a^2\left\{\rho(\vec{x},\tau) - \bar{\rho}(\tau)\right\}$$

$$\text{and } d\tau = \frac{dt}{a}$$

The conformal time τ assures that the numerical time intervals remain more uniform than with *dt*.

Integration is carried out with a simple "leap frog":

a) $v'_{n+1} = v_n + F_n \cdot \Delta\tau$

$x'_{n+1} = x_n + v_n \cdot \Delta\tau$

b) $F_{n+1} = F\,(x'_{n+1}, v'_{n+1}, \tau + \Delta\tau)$

c)
$$v_{n+1} = v_n + \frac{\Delta\tau}{2}\left(F_n + F_{n+1}\right)$$
$$x_{n+1} = x_n + \frac{\Delta\tau}{2}\left(v_{n+1} + v_n\right)$$

- F_n is often determined from $\rho\,(x)$ applying the FFT method.
- In most cases, the same time intervals are used.
- Efficiency:
  - $\int \Delta\tau \approx t_{Hubble}$ must be possible
  - high mass resolution and spatial resolution

(2) Boundary conditions

- In order to reflect a representative volume of the universe, the simulation must be significantly larger than the correlation lenght.

- Periodic boundary conditions:
  - Most plausible boundary condition ("cosmological principle").
  - Yields correct $\bar{\rho}(\tau)$
  - But: all waves extending $k_{\min} = \frac{2\pi}{L_{sim}}$ are suppressed.

(3) Initial conditions

- Generally, this is simple:
  uniform density + small fluctuations

- How can particles be distributed uniformly?
  - Grid: Almost monochromatic Fourier spectrum.
  - Random distribution $\Rightarrow$ density fluctuation of a sphere with radius *R*:

$$\left\langle \left(\frac{\delta M}{M} \right)^2 \right\rangle \sim 1/\sqrt{N(<R)}$$

$\Rightarrow$ Fourier spectrum of the "unperturbed" universe:

$$\left|\delta_k\right|^2 \sim k^n \quad n = 0$$

Trick:

First, we use a random distribution of particles and develop it using "anti-gravitation".

$\Longrightarrow$ Equilibrium of vanishing forces.

In a second step, we include the perturbation.

(4) Results of simulations

Fig. 6

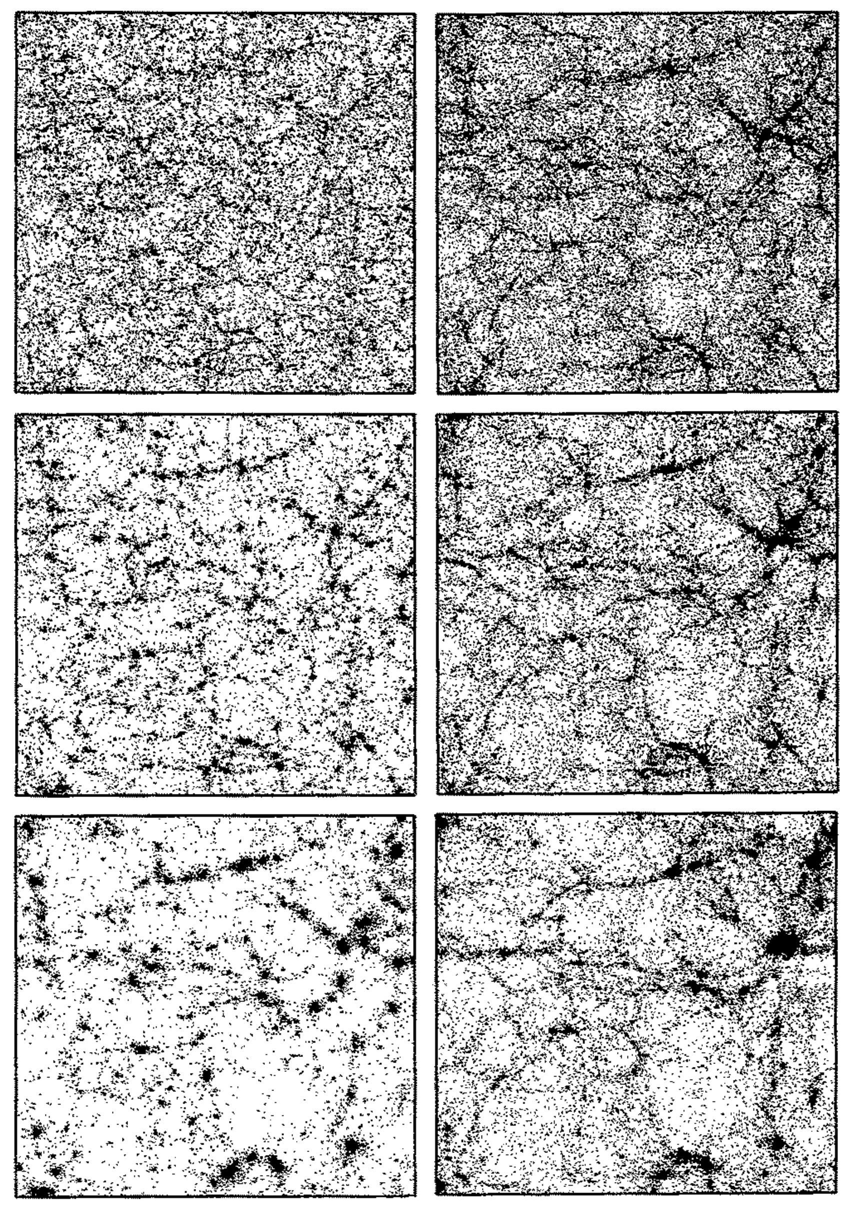


Fig. 7

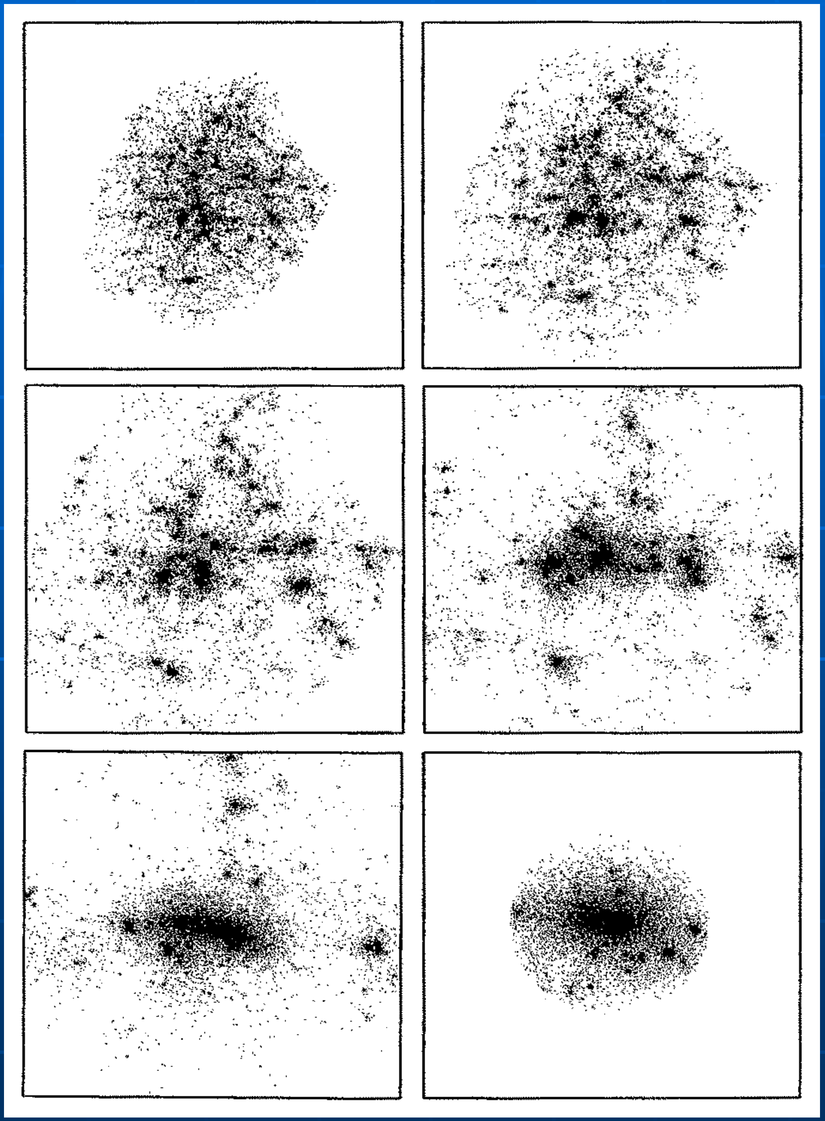
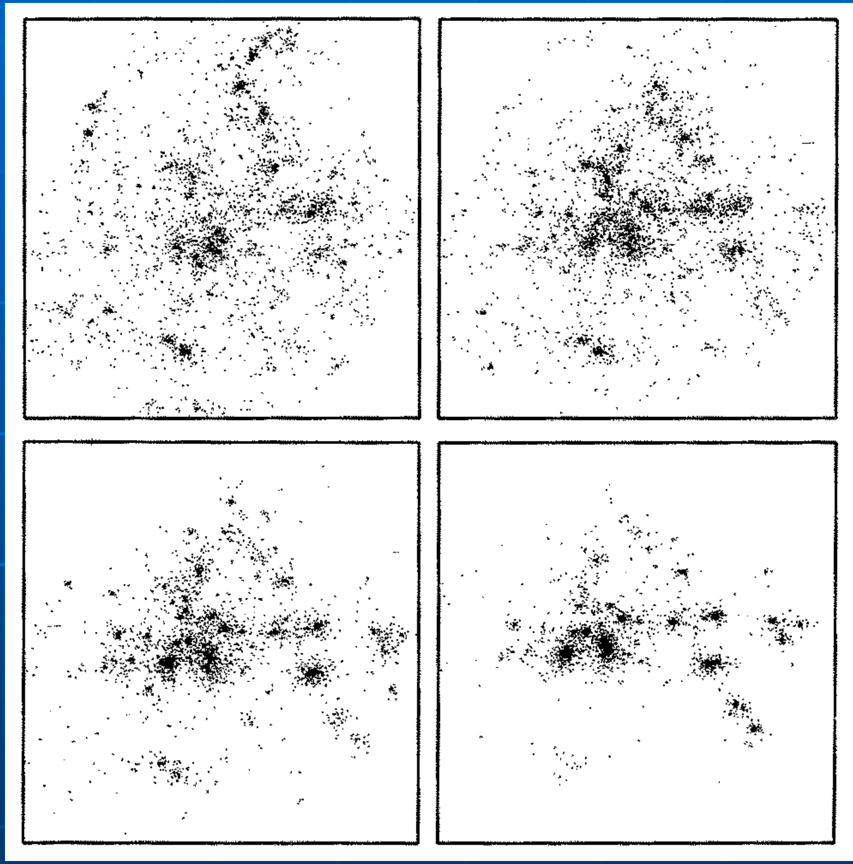


Fig. 8



IV.3. The Creation of Angular Momentum

- In disk galaxies the stellar body is centrifugally supported (stars move on near-circular orbits).

- This can be quantified by the "spin parameter", λ :

$$\lambda \equiv \frac{J}{G}\sqrt{\frac{E}{M^5}}$$

where *J* is the angular momentum and *E* is the binding energy of the system.

$\lambda_* \approx 0.5 - 1$ for disks.
$\lambda_* \approx 0.005$ for elliptical galaxies.

- Angular momentum arises from torques between protogalaxy fragments (Hoyle, 1949)

  - Linear evolution
    torque T ~ tidal acceleration · mass · lever arm

$$T \sim \frac{G\left[\delta(t)\cdot M\right]}{\left(a(t)R\right)^2}\times\frac{M}{2}\times\frac{a(t)R}{2}=\frac{\delta(t)}{4}\times\frac{GM^2}{\left(a(t)R\right)}$$

because $\delta(t) \sim a(t) \Rightarrow T \approx$ const. (in the linear regime!) and $J \sim t$, as long as $\Omega \approx 1$.

  - Non-linear collapse: at turn-around, we have:

$J \approx T \cdot t_{turn\text{-}around}$

$$E \approx -\frac{3}{5}\frac{GM}{r_{prop}}$$

$$\rho_{t.-a.} \approx \frac{9\pi^2}{16}\bar{\rho}(t_{t.-a.})$$

for an object with mass

$$M = \frac{4\pi}{3}\rho_0\left(\frac{R}{2}\right)^3$$

– These can be combined (after some calculation)

$$\lambda \approx \frac{1}{15}$$

We still need to explain why $\lambda_* \approx 1$ in disks.

10.IV.4. Dissipative Processes

Galaxies are baryon concentrations at the centers of the dark matter halos.

How did the stars and gas (=baryons) segregate from the dark matter?

Gas can dissipate, i.e. convert its internal energy into radiation, which is effectively removed from the system (for optically thin gas).

(a) Main Physical Processes:

Heating:

Shocks/Gravity

Photo-ionization

Cooling:

Radiation – continuum and line cooling

- Gas falls into DM halos $\Rightarrow$ shocks $\Rightarrow$

"virializes" , i. e. $kT_{gas} \approx \frac{1}{2} v_{circ}^2 \approx 10^6 K$

a) Radiative Cooling (Bremsstrahlung)

per unit volume $\frac{dE}{dt} \sim n_e n_H T^{1/2}$

Important at very high temperatures $T \geq 5 \cdot 10^6$ K because atoms are fully ionized.

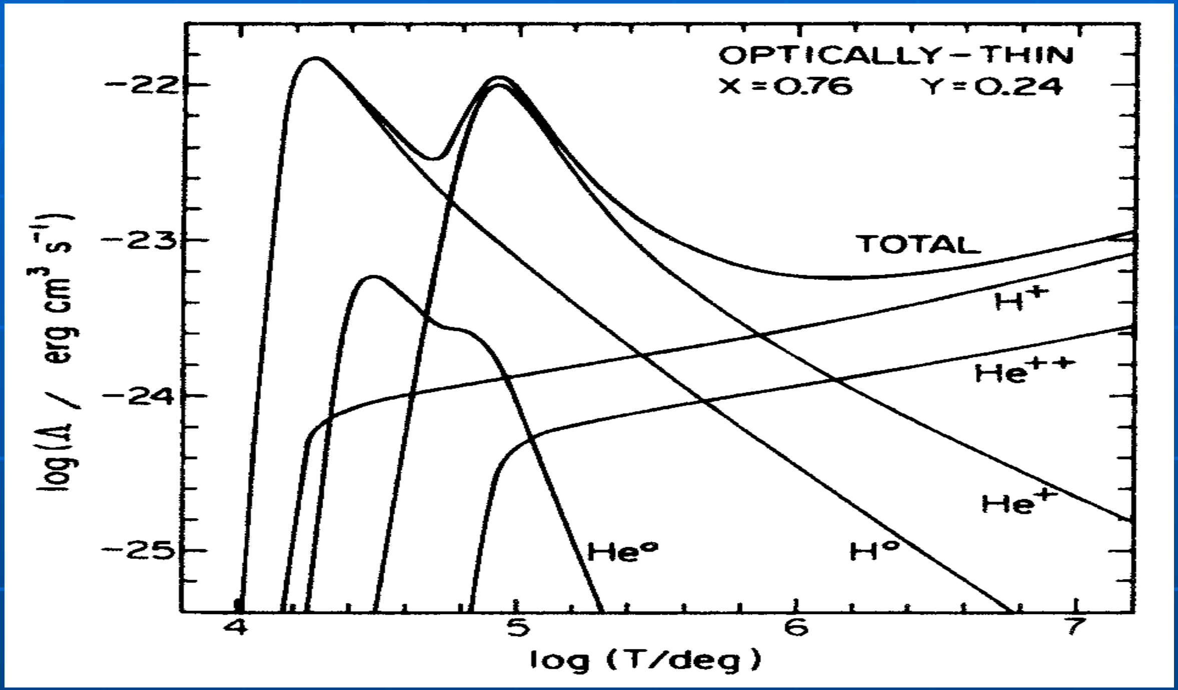
b) Collisional (Line) Cooling

- Recombination, collisional excitation.
- All processes can be described as

$$\frac{dE}{dt} \approx n_e n_H f(t) = n^2 \Lambda(T)$$

where $f(T)$ depends on the chemical composition of the gas.

Fig. 12 (p. 402, Les Houches)



Note: Below 10^4 K the gas is entirely neutral and can only cool via vibrational collisions in molecules.

Photo-ionization of the gas provides heating and can only cool via ionization changes.

(b) Gas Cooling and Galaxy Formation

Define the "cooling time" as

$$t_{cool} = \frac{E_{th}}{\dot{E}_{th}} = \frac{\frac{3}{2} nkT}{n^2 \Lambda(T)} \sim 7 \cdot 10^9 \, years \, \frac{T_6}{n_{-3} \Lambda_{-24}}$$

For $M_{gas} \approx 10^{11} M_{sun}$ at $z = 3$, we have
$t_{cool} \approx 2 \cdot 10^{9}$ *years*.

Compare this to the “free-fall” time of the parent halo:

$$t_{collapse} \approx \pi \sqrt{\frac{R^3}{G M}} = \sqrt{\frac{3\pi f}{4 G n \mu}} \approx 6 \cdot 10^9 \, years \cdot \sqrt{\frac{f}{n_{-3}}}$$

or $t_{collapse} \approx 10^{9}$ *years* in our case.

[f = fraction of total mass in gas; n_{-3}: number density [10^{-3} cm^{-3}]]

Binney (1977) suggested that in order to make galaxies (i.e. stars in collapsed objects) one needs $t_{cool} \leq t_{collapse}$ or

$$\frac{T_6}{\Lambda_{-24}} \leq \sqrt{f \cdot n_{-3}} \Rightarrow M_{gas} \leq 3 \cdot 10^{13} M_{sun} f^2 = M_{\lim} \cdot f$$

$\Rightarrow$ Maximal mass for (luminous) galaxies?

Agrees with observations if $f \equiv \frac{M_{gas}}{M_{tot}} \approx 0.05$

(c) "Cooling Catastrophe"

Assume gas in halos with $M < M_{lim}$ convert all their gas in stars (except halos with
$T_{virial} < 10^4$ K).

In the past, collapsed halos were smaller.

$\Rightarrow$ All gas was turned into smaller galaxies.

$\Rightarrow$ No gas left to make big galaxies.

We need feed-back in galaxy formation:

Stars start to form $\rightarrow$ massive stars become supernovae $\rightarrow$ explosion heats gas $\rightarrow$ quenches star formation.

IV.5 Disk Galaxy Formation

- Torques before the collapse induce spin $\lambda \sim 0.07$
- Fall and Efstathion (1980) showed that observed galaxy disks ($\lambda \sim 0.5$) can form only in DM halos through dissipation
  $\rightarrow$ central concentration $\rightarrow$ spin-up.

a) Presume there is no DM:

$$\lambda_{obs} \equiv \frac{J \cdot E^{1/2}}{GM^{5/2}} = \lambda_{init} \sqrt{\frac{R_{init}}{R}} \quad \Rightarrow \quad \frac{R_{init}}{R} \approx 50$$

We observe $M_{disk} \approx 10^{11}\ M_{sun}$, $R_{disk} \approx 5\ kpc \Rightarrow R_{init} \approx 300\ kpc$

$\Rightarrow R_{turn\text{-}around} \approx 2\ R_{init} \approx 600\ kpc$

$\Rightarrow t_{collapse} \sim 50 \cdot 10^9$ *years* for $M \sim 10^{11}\ M_{sun}$

b) If the gas is only a small fraction of the total mass:

$\Rightarrow v_c(r)$ remains unchanged

$\Rightarrow$ $R_{init} / R \sim \frac{\lambda_{obs}}{\lambda_{init}}$ $\Rightarrow R_{init} \sim 50\ kpc$

$\Rightarrow t_{dyn} \sim 10^9$ *years*

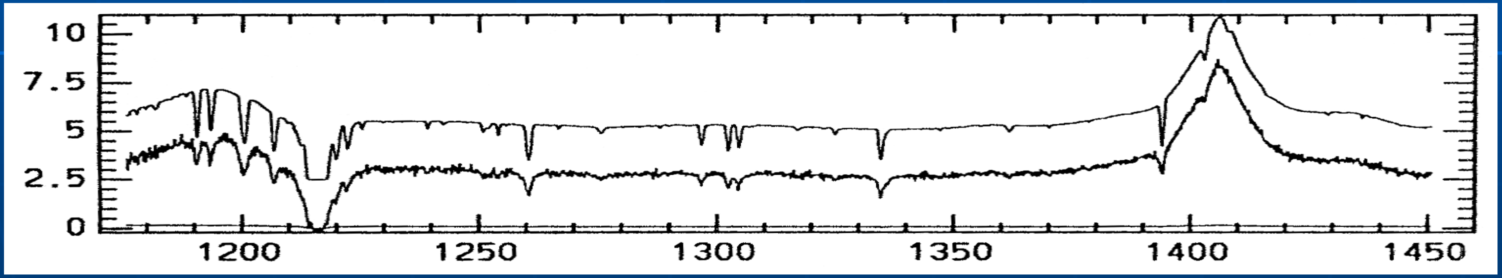
and there is enough time to form disks.

I.2 Structure of the Intergalactic Medium

- Galaxies only trace collapsed, highly overdense regions.
- The connection between the structure and clumping in the galaxy light and in the total mass is not clear.
- The majority of baryons resides as dilute (1 atom/m^3), highly ionized (neutral frac-tion ~ 10^{-4} - 10^{-7}), hot (10^4 K) plasma in the intergalactic space, forming the IGM.

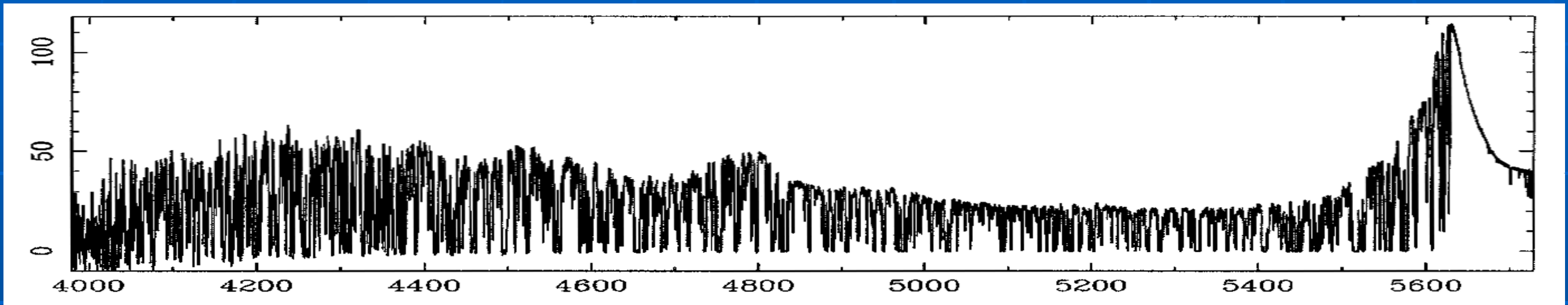
- The neutral fraction of this gas can be ob-served through the Ly-α absorption, if a suitable back-ground source of UV radiation is available.
  - Quasars provide such a source

Fig. 10. Absorption through intervening neutral hydrogen



- The „Ly-α Forest" is much more prominent at high redshift (when the universe was denser).

Fig. 11 High resolution spectrum of z_{em}



- The absorption $\left(\tau \approx \int n_{H^0} dz\right)$ is not uniform, where for $\tau(\lambda)$ the integral must include all gas with $z = \lambda / \lambda_{Ly-\alpha}$

  $\Rightarrow$ structure in the IGM!

  As the gas mass is a small fraction of the total mass, it passively reflects the overall mass fluctuations.

Issues:

- Redshift *z* reflects approximate distance, but not the exact distance.
  - There are peculiar motions.
  - These may lead to multiple locations with the same *z*.
- Absorption is a function of the neutral column density at a given *z*. This, in turn, is a complex function of the density, temperature and radiation.
- Are the regions of high optical depth bound „clouds“, or caustics in the weakly perturbed regime (= probes of the linear regime)?

Early attempts to quantify the structure in the Ly-α forest:

Step 1: Decompose the spectrum in *N* discrete components.

Step 2: Do correlation analysis of lines, $p(\lambda_i, \lambda_{i+1})$.

Recent shift in paradigm:

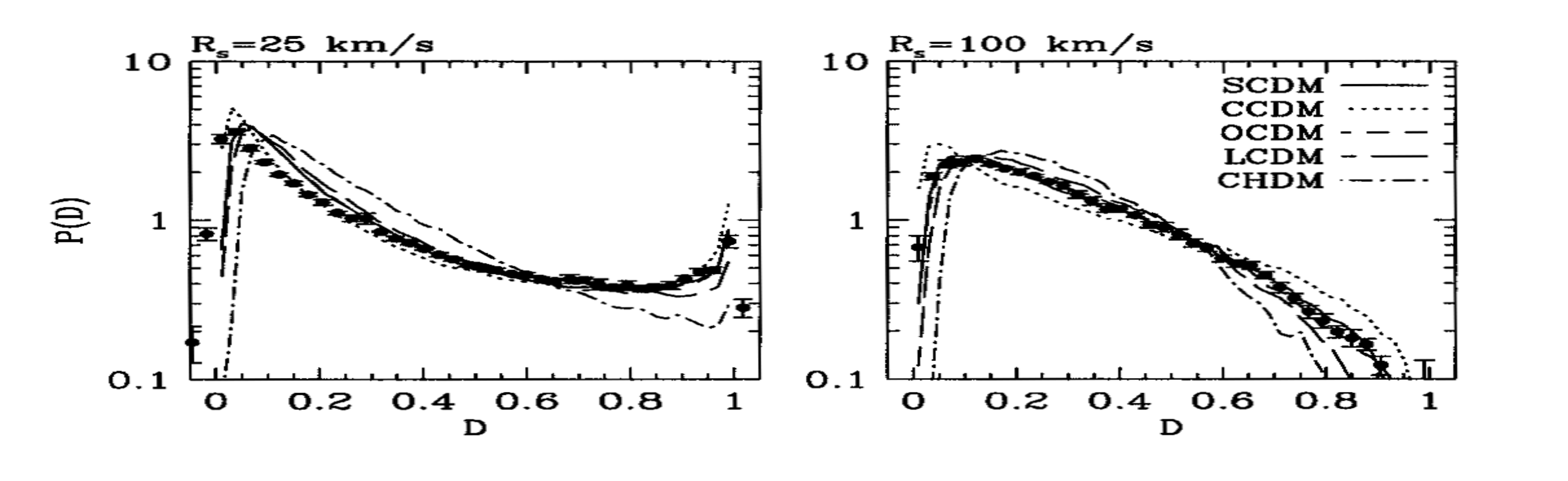
IGM does not contain discrete dense clouds on a smooth discrete background, but:

a) has mostly modest density fluctuations

$\delta\rho \leq 1$

b) material has peculiar velocities due to the underlying DM mass fluctuations

⇒ Investigate the statistical properties of the "absorptivity function" $D(\lambda) = 1 - e^{-\tau(\lambda)}$



Open Issues in Cosmology

- What is the Dark Energy?
- What is the Dark Matter?
- When and how did the first stars form?
- When and how did the first black holes form?