STRUCTURE FORMATION IN THE UNIVERSE

Origin of fluctuations

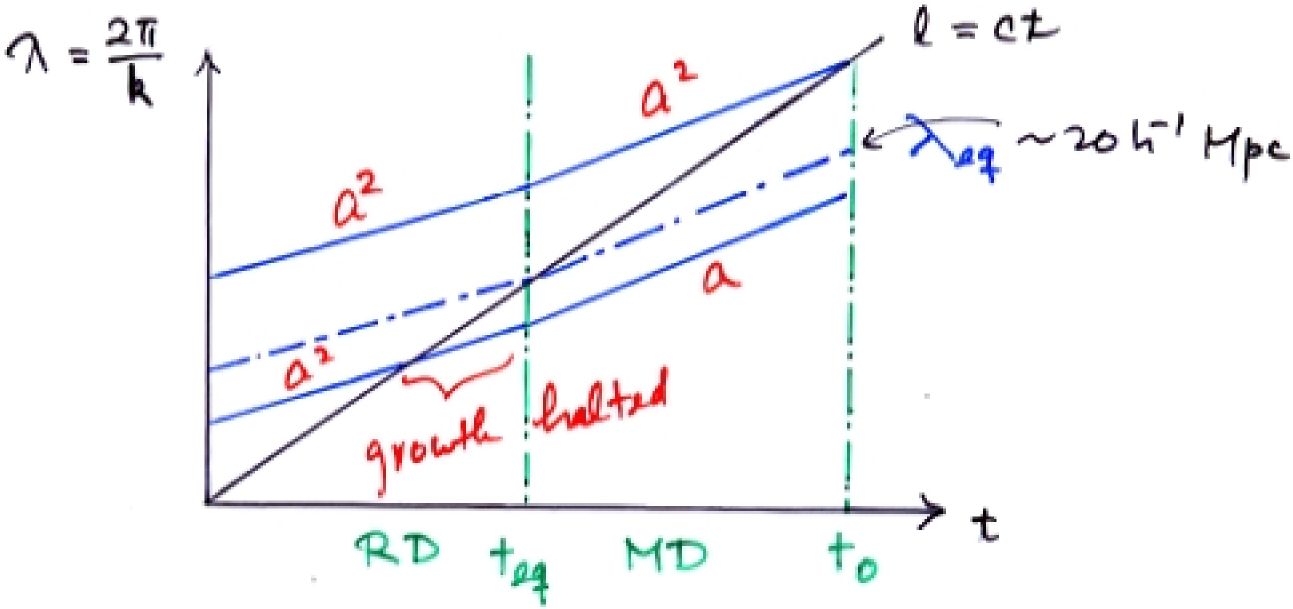
Quantum fluctuation in the de Sitter space

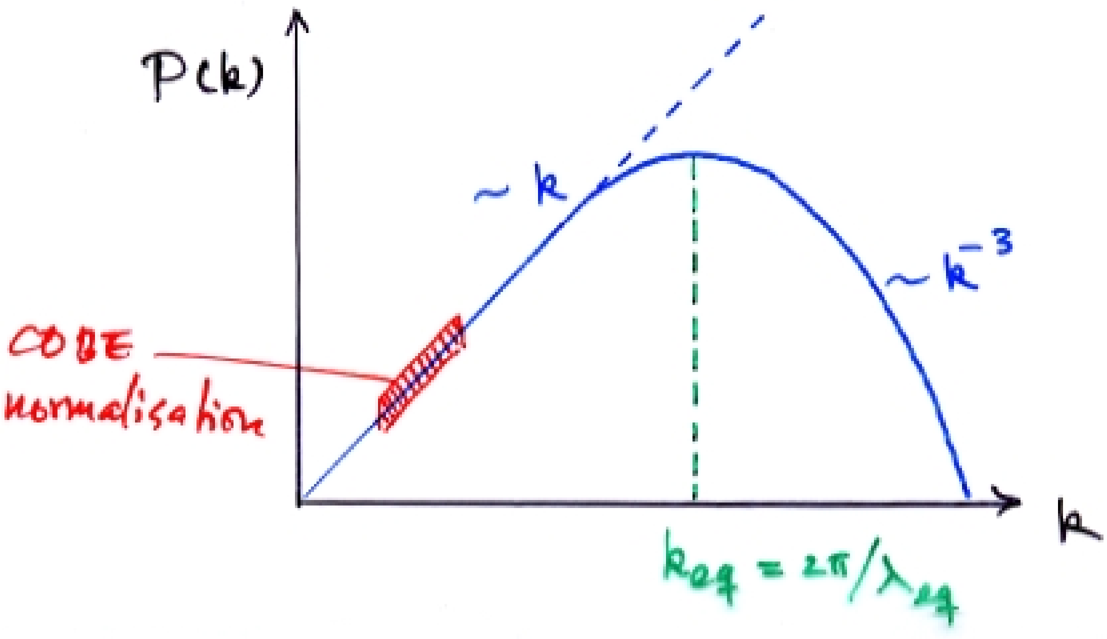
$$T = \frac{H}{2\pi}$$

$$P(k) \equiv |\delta_k|^2 = k^n \qquad n = 1 \pm \varepsilon$$

Amplification by self gravity (low-pass amp.)

$$P(k) = |\delta_k|^2 T(k) \qquad \text{T: transfer function}$$

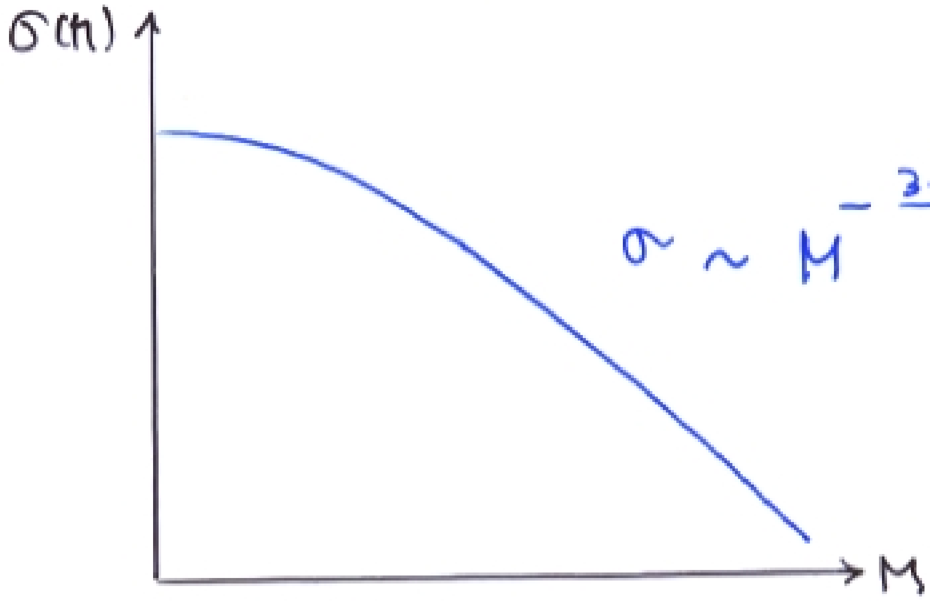




$$\sigma(M)^2 = \langle (\delta M/M)^2 \rangle$$

$$= \frac{V}{(2\pi)^3} \int d\ln k \overbrace{P(k)k^3}^{k^{3+n}} W(kR)$$

W has power for $kR < 1$ $\qquad k \sim \frac{1}{R}$



$\sigma \sim M^{-\frac{3+n}{6}} \cdot \frac{1}{1+z}$

$R = 8h^{-1}$ Mpc is often used to characterise the strength of fluctuations ($M \approx 6 \times 10^{14} M_\odot$): $\boxed{\sigma_8}$

Hierarchical clustering

small scale $\rightarrow$ large scale

i.e., galaxies $\rightarrow$ clusters $\rightarrow$ LSS

Measurement of the power spectrum

3D galaxy clustering:

$\xi_g(x) = \langle (n(x) - \bar{n})(n(0) - \bar{n}\rangle \bar{n}^{-2}$

$\xi(x) = \langle (\rho(x) - \bar{\rho})(\rho(0) - \bar{\rho}\rangle \bar{\rho}^{-2}$

$\xi_g(x) = \xi(x)$? (biasing problem)

$$\xi(x) = \frac{V}{(2\pi)^3} \int d\ln k \; 4\pi k^3 P(k) \frac{\sin kr}{kr}$$

2D galaxy clustering:

$w(\theta) \to P(k)$ w/ knowledge of $N(z)$

Number of clusters: no uncertainty of biasing

Amplitude at $\approx 8h^{-1}$ Mpc

At high z:

CMB temperature fields

$$C(\theta) = \langle \frac{\delta T}{T}(\theta) \frac{\delta T}{T}(0) \rangle = \sum C_\ell P_\ell(\cos\theta)$$

$$C_\ell = \frac{\Omega_0^{1.54}}{2\pi} H_0^4 \int_0^\infty \frac{P(k)}{k^2} j_\ell^2(kr_H) dk$$

Also we get $n = 1.0 \pm 0.07$, Gaussian nature

SDSS: Scranton et al.

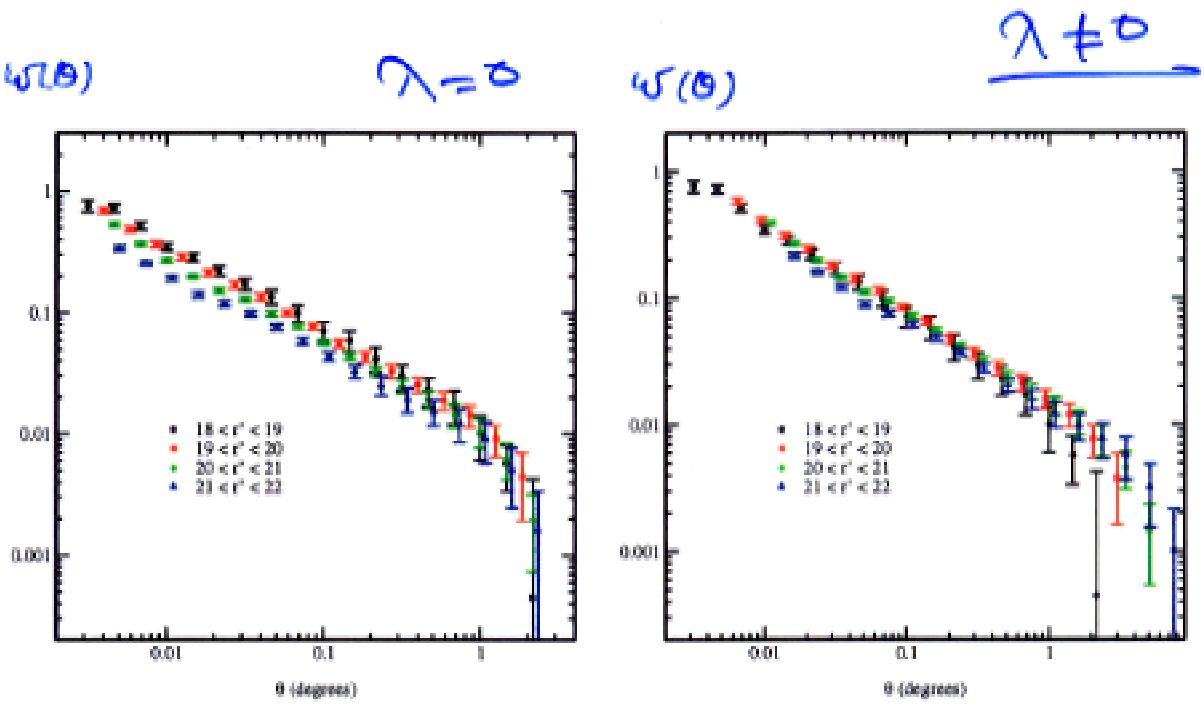
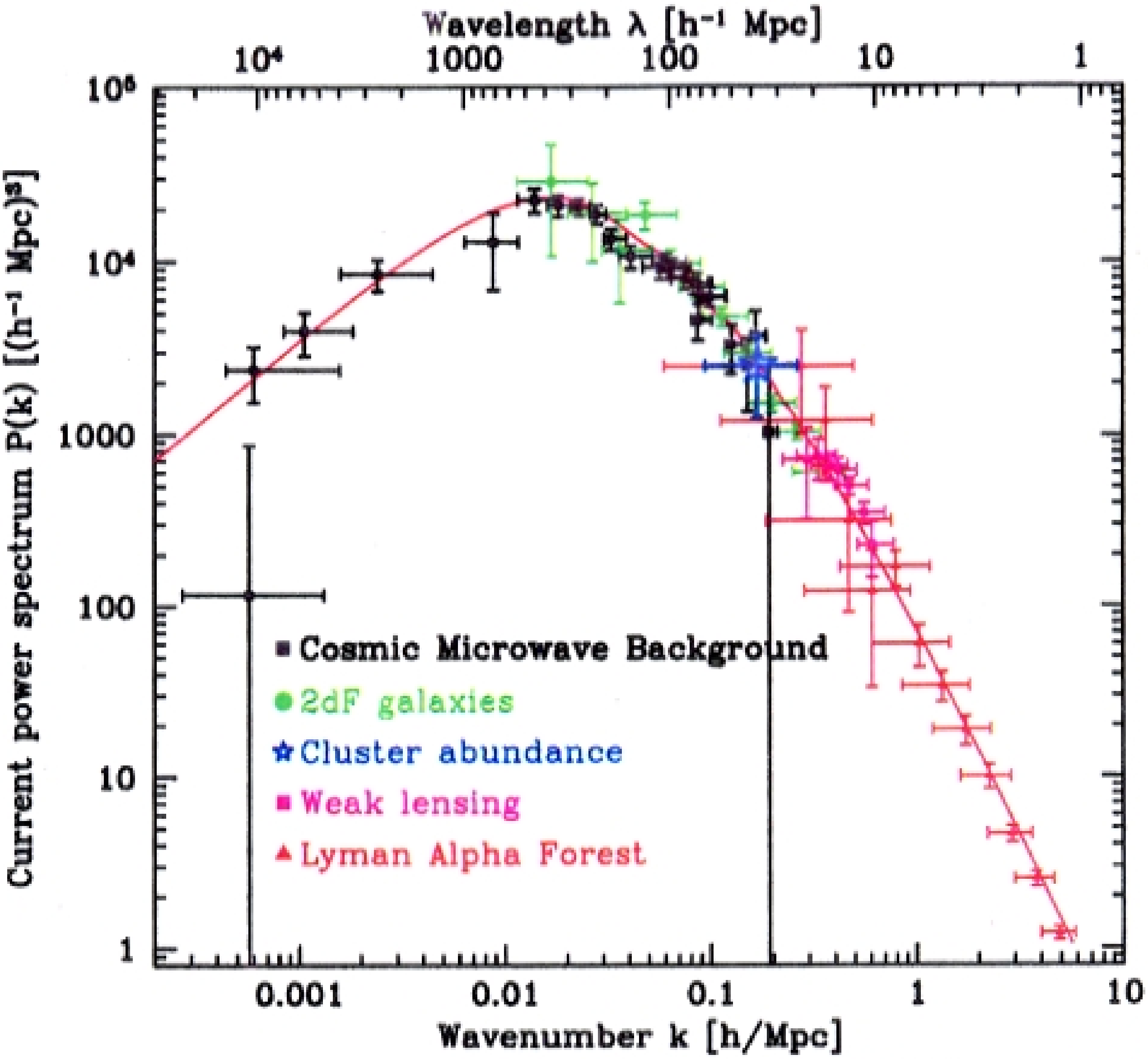


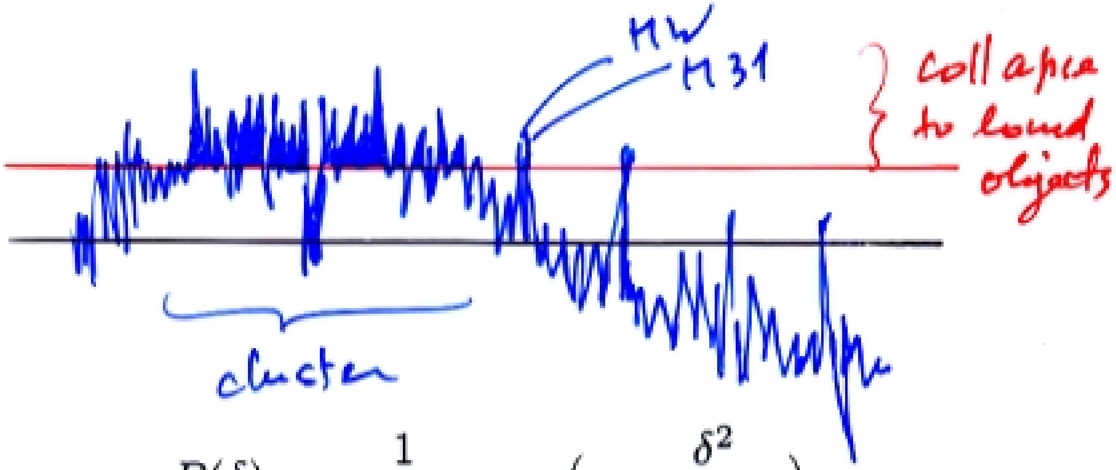
Fig. 26.— Limber scaling tests for the four magnitude bins assuming a flat, matter-dominated cosmology (left panel) and flat, Λ-dominated cosmology (right). In both cases, the measurements in the fainter bins have been scaled to the brightest magnitude bin.



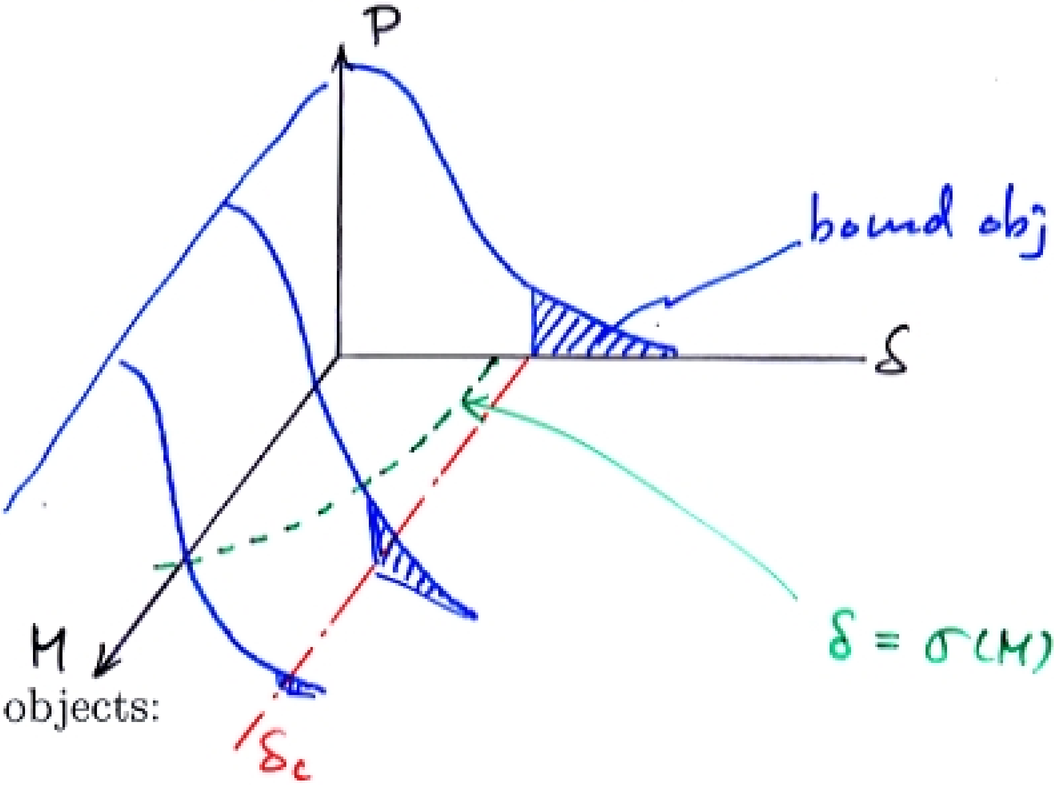
Tegmark + Zaldarriaga

Treatment of the Non-linear Growth

- N-body simulations
- Press-Schechter formalism (statistics of peaks)

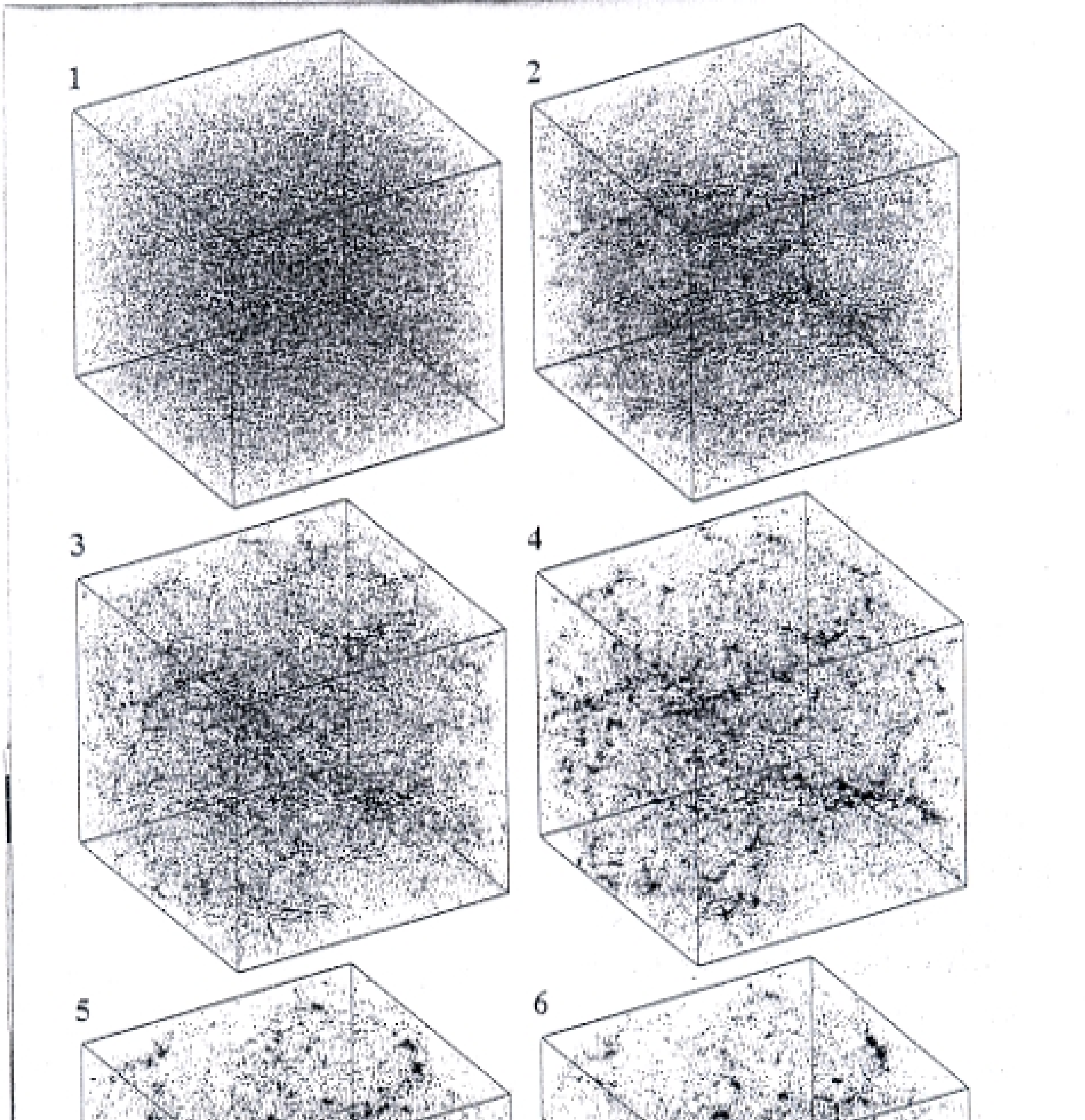


$$P(\delta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\big(- \frac{\delta^2}{\sigma^2(M)}\big)$$



bound objects:

$$P(\delta > \delta_c) = \int_{\delta_c}^{\infty} P(\delta) d\delta$$


1
2
3
4
5
6

Spectrum of the bound objects

$$\rho(M)dM = -\bar{\rho}\frac{\partial}{\partial M}P(\delta > \delta_c)dM$$

$$n(M)dM = \frac{1}{M}\rho(M)dM$$

$$\sim \frac{1}{M^2}\exp\big(-\frac{\delta_c^2}{2\sigma^2(M)}\big)$$

Clusters:

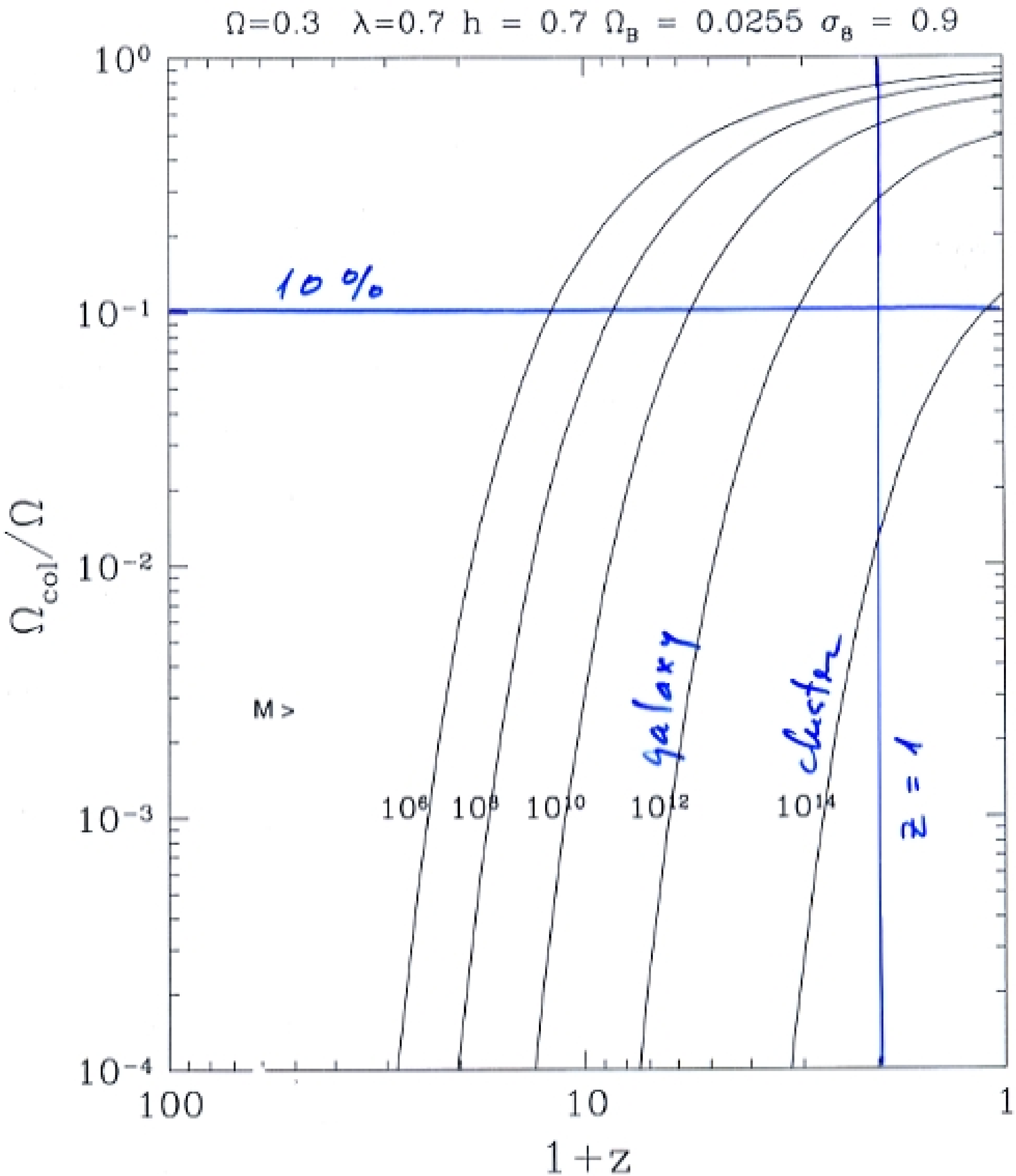
— Only gravity plays a role

— Only CDM plays a central role

Constraint on the neutrino mass

$\sum_i m_{\nu_i} < 2.5 - 4$ eV

MF, Liu, Sugiyama
Hu et al.



Collapsed matter fraction

SDSS

10

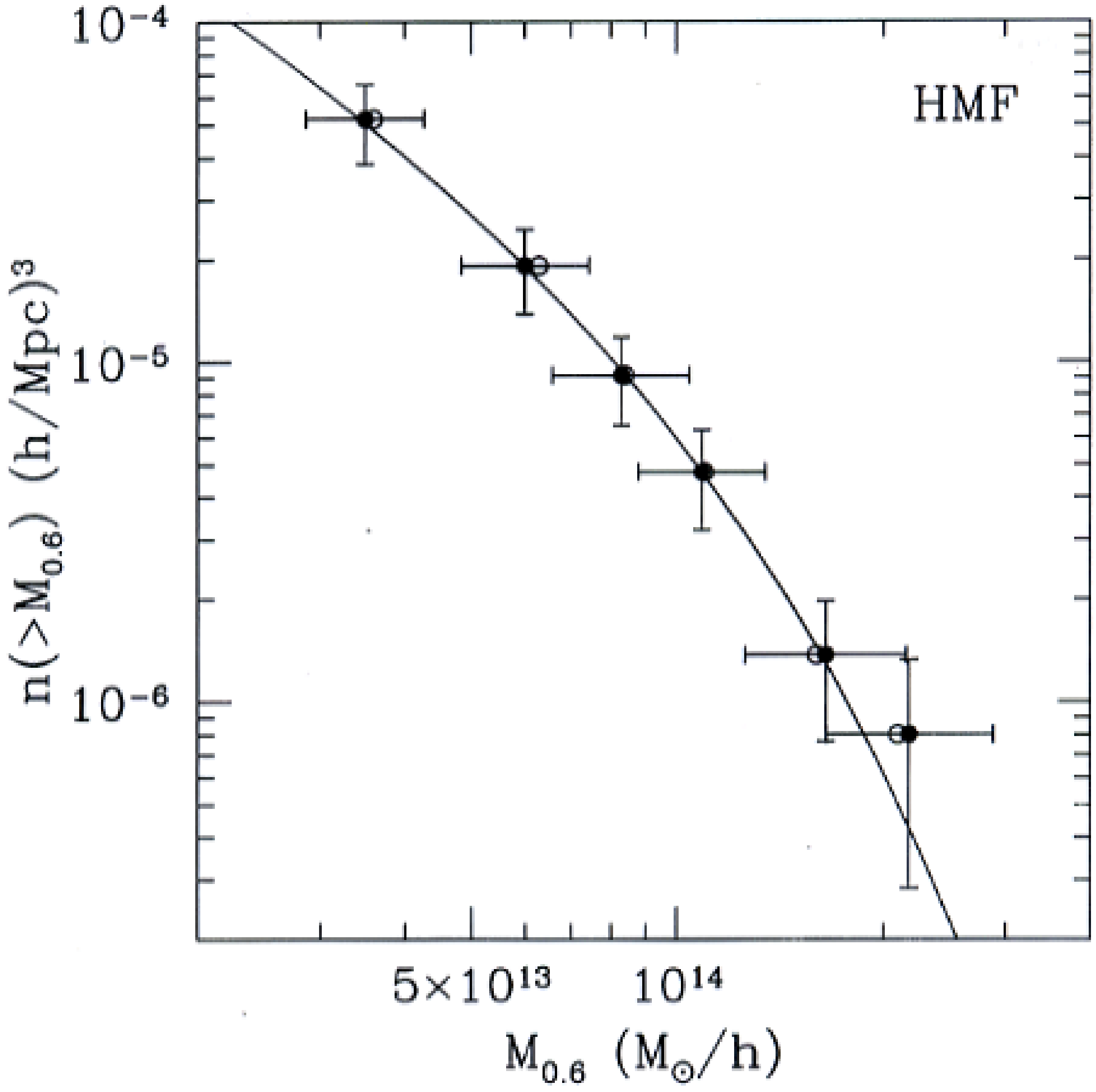
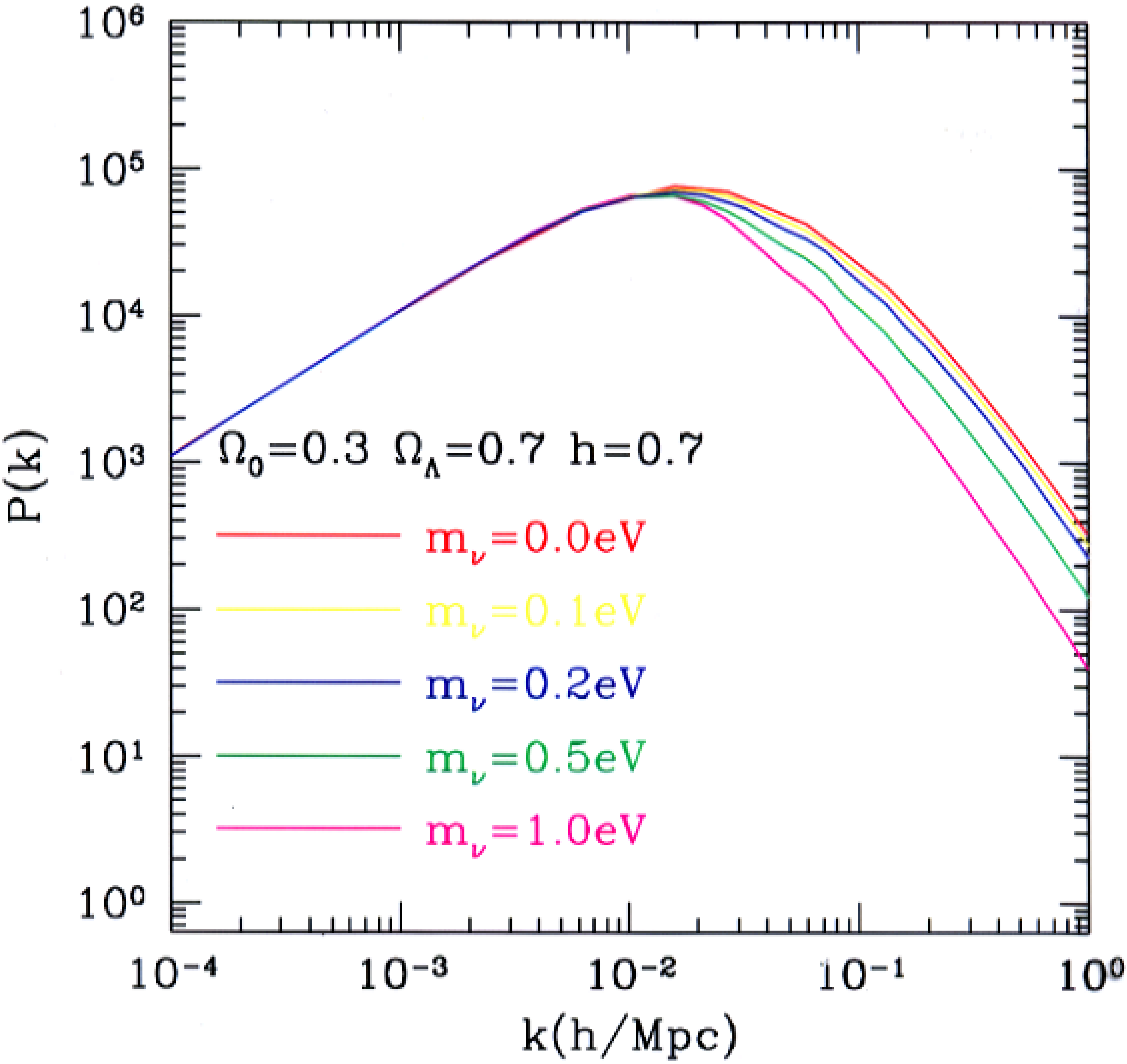


Fig. 2.— The HMF cluster mass function, showing masses (within 0.6 h^{-1} Mpc) determined from both the luminosity – mass calibration (filled circles) and the independent velocity dispersion – mass relation (open circles). (The observed cluster abundances assume a volume corresponding to a flat Ω_m= 0.2 cosmology.) The best-fit analytic model, with Ω_m= 0.19 and σ_8= 0.96, is shown by the solid line.



P(k)
k(h/Mpc)
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
Ω₀=0.3 Ω_Λ=0.7 h=0.7
m_ν=0.0eV
m_ν=0.1eV
m_ν=0.2eV
m_ν=0.5eV
m_ν=1.0eV

Condition for the galaxy formation

What makes differences between clusters and galaxies?

cooling

If

$$t_{\rm cool} = \frac{3nkT/2}{n^2\Lambda(T)} \quad < \quad t_{\rm dyn} = \frac{1}{\sqrt{G\rho}}$$

kinetic energies are removed → galaxies

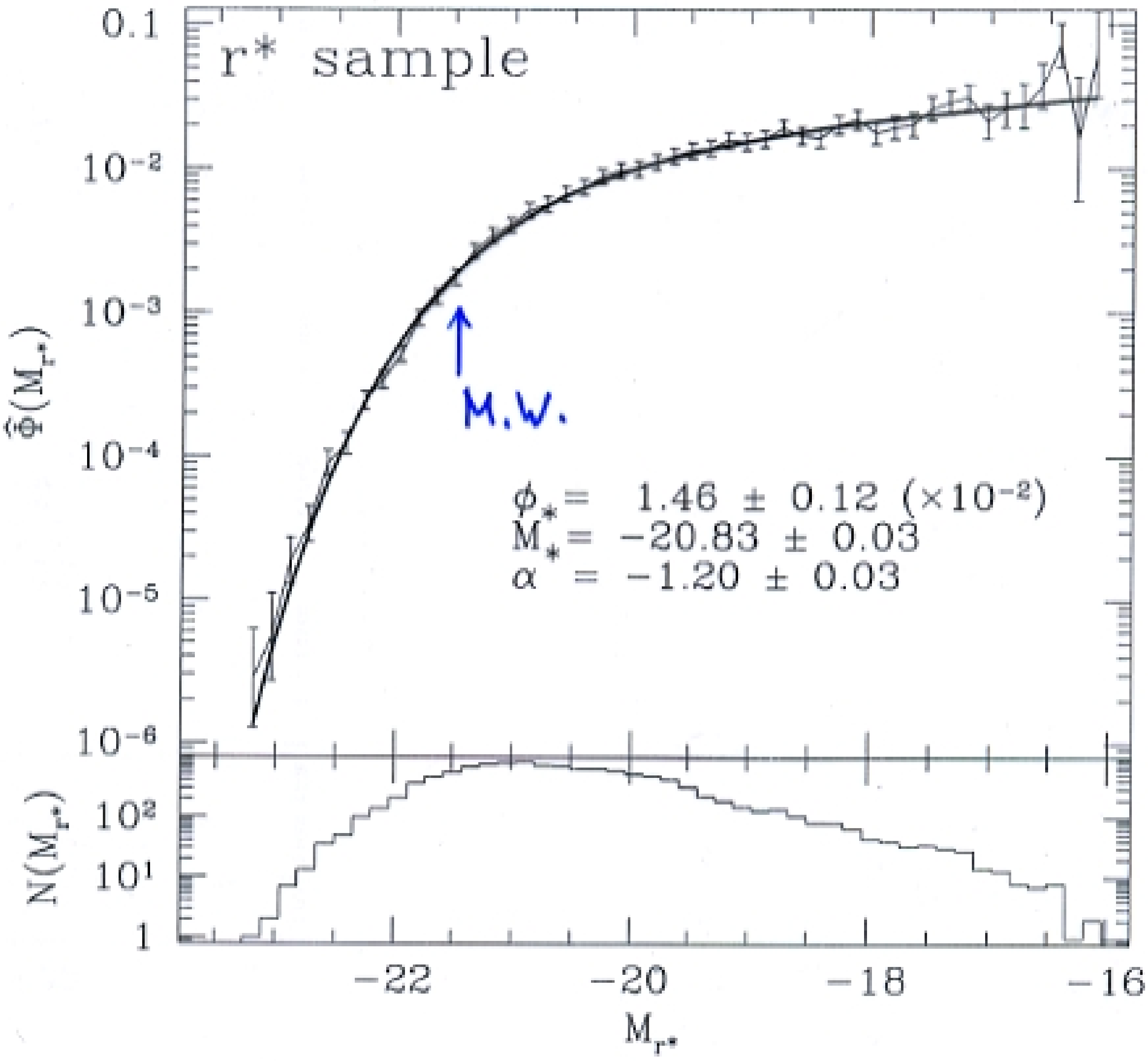
If $t_{\rm cool} > t_{\rm dyn}$,

kinetic energies remain → virialised cloud

This condition trasnlates to

$$M_{\rm crit} = 2 \times 10^{12} M_{\odot}$$

SDSS


r* sample
$\phi_* = 1.46 \pm 0.12\ (\times 10^{-2})$
$M_* = -20.83 \pm 0.03$
$\alpha = -1.20 \pm 0.03$
M.W.
$\hat{\Phi}(M_{r^*})$
$N(M_{r^*})$
M_{r^*}
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^1
1
−22
−20
−18
−16

Galaxy Formation and Evolution

Complications

CDM, baryon — both important

physical processes:

gravity

cooling – atomic/molecular

→ stars

OB stars → UV heat up

SNe → SN winds heat up

chemical enrichment

inhogeneity enhance cooling

Questions to answer

- Why ellipticals and spirals?
  What are irregulars?
- When and how elliptical galaxies formed?
- How bulge and disc formed in spirals?
- Luminosity function of galaxies

  $\phi(L, z=0) \sim L^{-1.2} \exp(-L/L^*)$

  instead of $\phi(L, z=0) \sim L^{-2} \exp(-L/L^*)$

  and how do they evolve?
- Global star formation history (Madau plot)
- Heavy element abundance
- Number count of galaxies $N(m)$
- Tully-Fisher relation (spirals) $L_B \sim v_c^{2.5}$
- Fundamental plane relation (ellipticals)

  $L \sim \sigma^\alpha \mu^\beta$

... and so on


NGC4030(4.0)


MCG0-29-36(4.0)


MCG0-32-15(4.0)


UGC8801(4.0)


CGCG13-94(4.0)

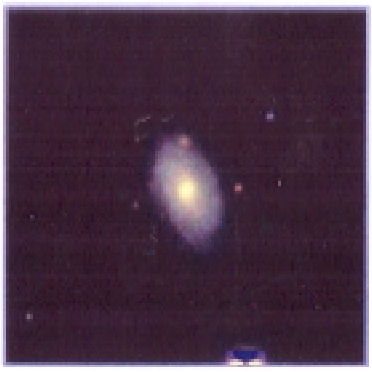

UGC6432(4.0)


UGC6340(4.0)

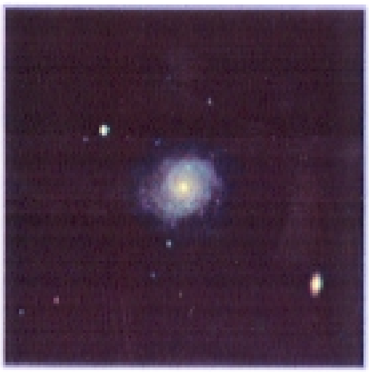

NGC4202(4.0)

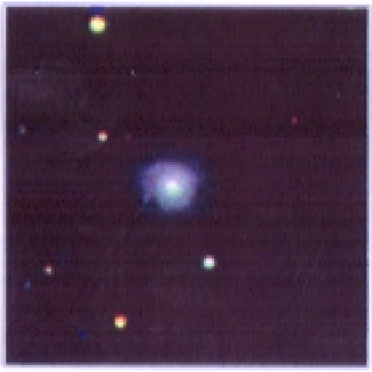

UGC5736(4.0)


UGC8994(4.0)


CGCG13-84(4.0)


NGC3340(4.0)


MCG0-32-5(4.0)


CGCG13-77(4.0)


UGC5715(4.0)


NGC3521(4.0)


CGCG12-29(-5.0)


NGC3325(-5.0)


CGCG13-83(-5.0)


CGCG12-54(-5.0)


UGC7813(-5.0)


CGCG11-49(-5.0)


CGCG10-55(-5.0)


CGCG14-4(-5.0)


UGC5515(-4.3)


CGCG13-95(-4.0)


NGC4493(-4.0)


CGCG11-27(-4.0)

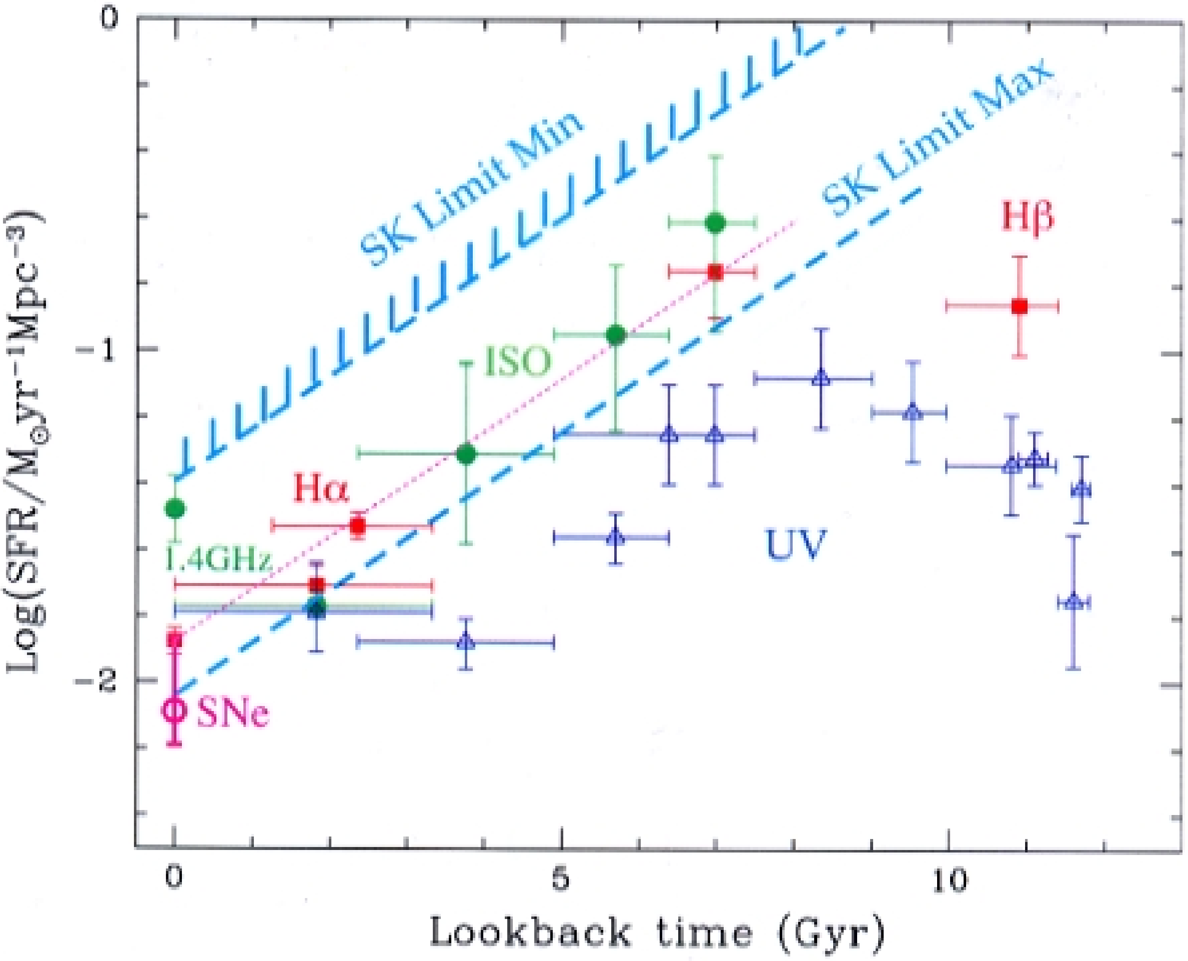

NGC4044(-3.8)


CGCG15-14(-3.0)

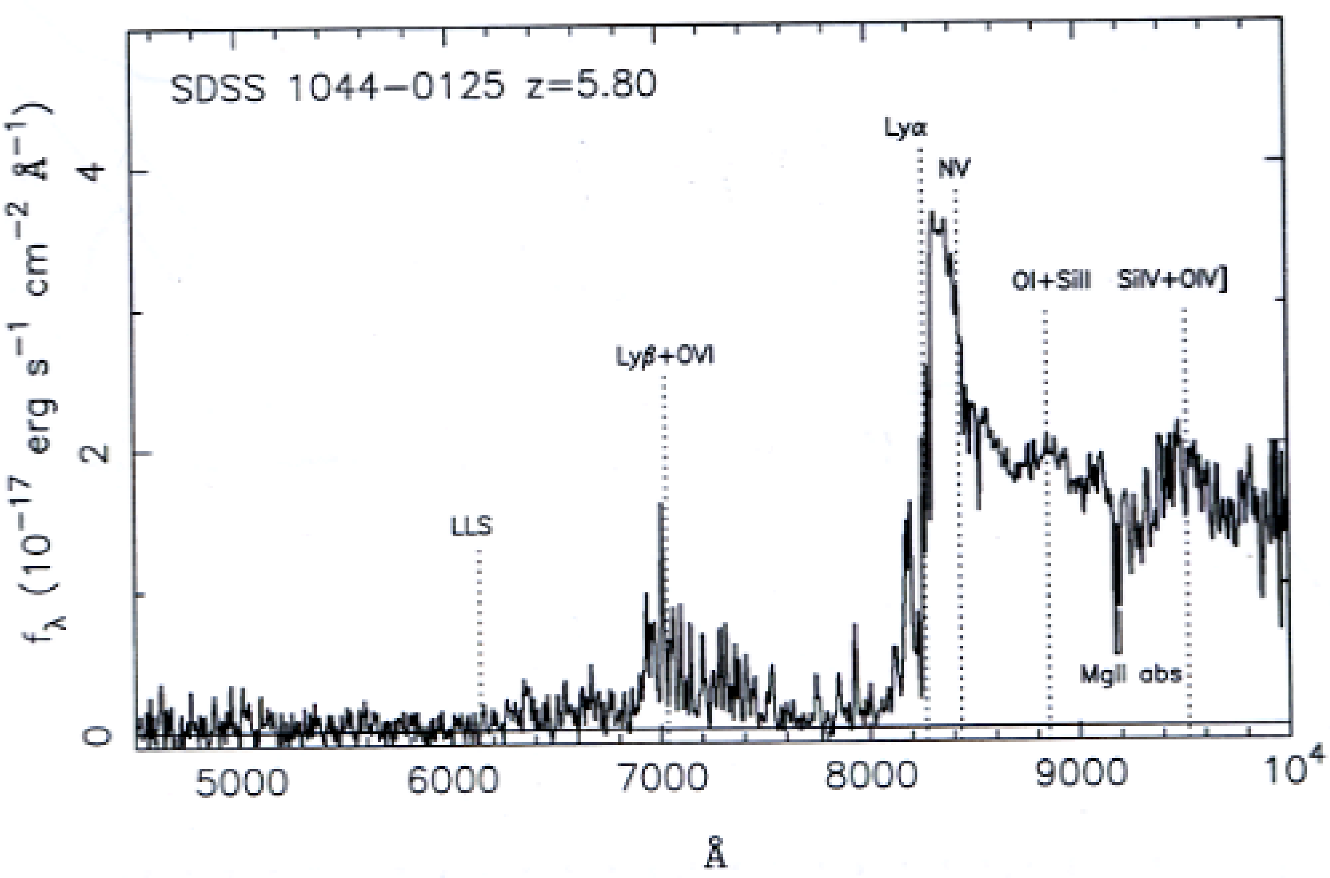

MCG0-28-13(-3.0)


CGCG11-112(-3.0)

MF Kawasaki



SK Limit Min
SK Limit Max
Hβ
ISO
Hα
1.4GHz
UV
SNe
Log(SFR/M⊙yr⁻¹Mpc⁻³)
0
-1
-2
0
5
10
Lookback time (Gyr)


SDSS 1044−0125 z=5.80
Lyα
NV
OI+SiII
SiIV+OIV]
Lyβ+OVI
LLS
MgII abs
0
2
4
5000
6000
7000
8000
9000
10⁴
Å
f_λ (10⁻¹⁷ erg s⁻¹ cm⁻² Å⁻¹)

Two approaches

- Semi-analytic approach

  Press-Schechter theory

  + virialised clouds

  + cooling + feedback

  in a parametrised form

- cosmological simulations

  include physical effects directly into simulations

  problems: coarse mesh; computational cost

  current best hydro: mesh = 30 kpc

Cosmological simulation of Cen & Ostriker (1992+)

Galaxies as overdense star forming regions
(Nagamine, MF, Cen & Ostriker, 2000+)

$\delta\rho/\rho > 5$

$\nabla \cdot v < 0$

$t_{\rm cool} < t_{\rm dyn}$

$m_{\rm gas} > m_J$

Parameters

$H_0 = 67, \quad \Omega_0 = 0.3, \quad \lambda_0 = 0.7$

$\Omega_b = 0.036, \quad \sigma_8 = 0.9,\ n = 1$

Box = $(25h^{-1})^3$, mesh=$33h^{-1}$ kpc

768^3 grid cells, 384^3 dark matter particles

mass of particles $\approx 10^7 h^{-1} M_\odot$

Feedback effect

Reionisation by UV from OB stars: $\Delta E_{\rm UV}$

Shock heating by SN winds: $\Delta_{\rm SN}$

Heavy element yield: 2% of star mass

Elementary tests

$\Omega_{rmstar} = 0.005$ obs: 0.002-0.05 (MF Hogan Peebles)

$Z = 10^{7.1} M_\odot\ ({\rm Mpc})^{-1}$ obs: $10^{7.4}$ (MF Peebles)

We undersdtand:

Dark matter haloes behave as $\phi(M) \sim M^{-2} \exp(-M/M_*)$

luminosity functions behave as $\phi(L) \sim L^{-1.2} \exp(-L/L^*)$

$\rightarrow$ numerous dark halos w/o stars

Luminosity and number of galaxies both evolve
in a way they tend to cancel
making LF evolution small

Luminosity density: right order of magnitudes

Heavy element abundance - luminosity correlation

High z galaxies may have solar heavy element anubdance

Global star formation history

We do not understand:

Small systems are always old and "dead"

$N(m)$: Not as numerous in the faint end as observed

Nagamine et al.

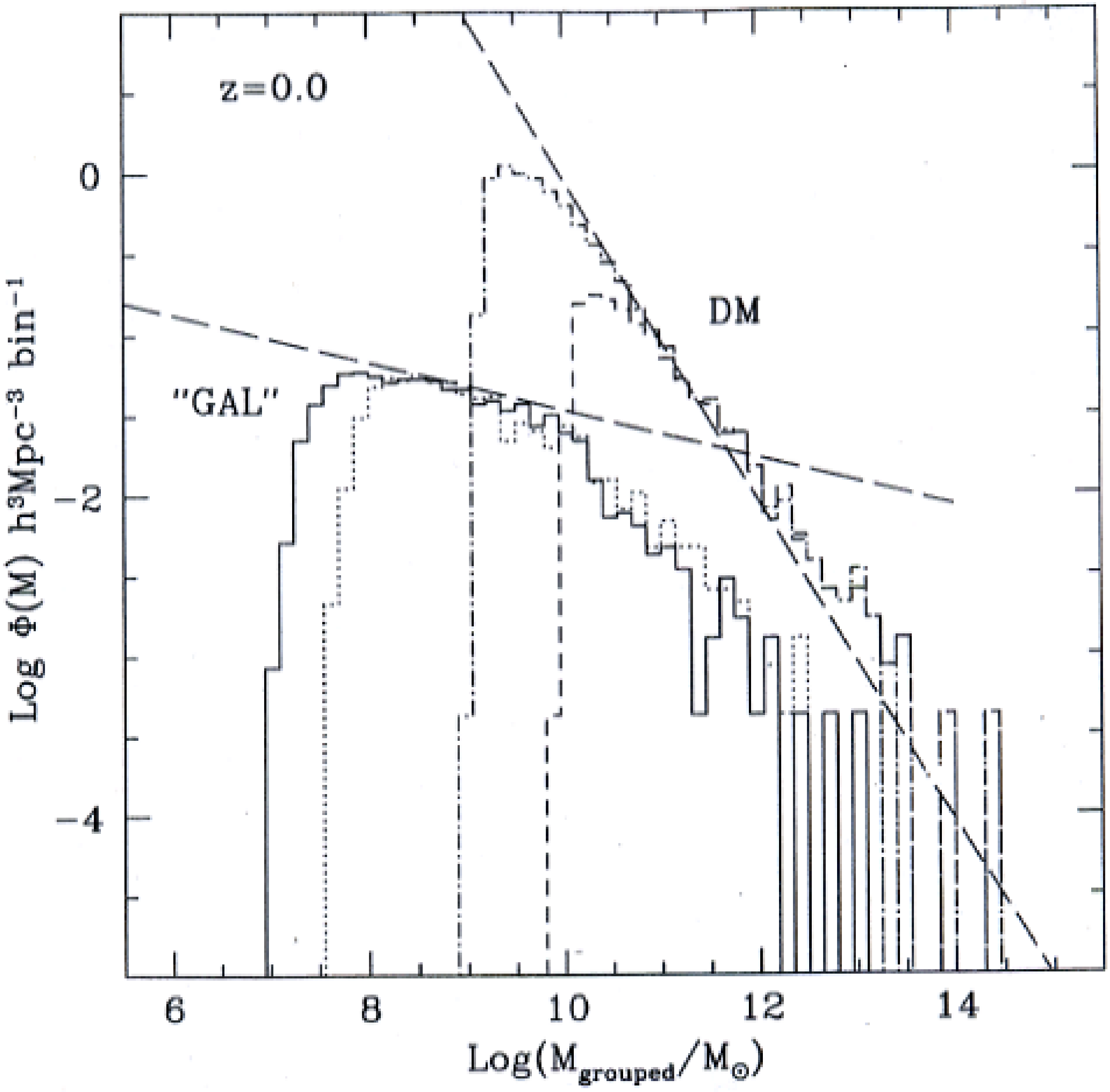
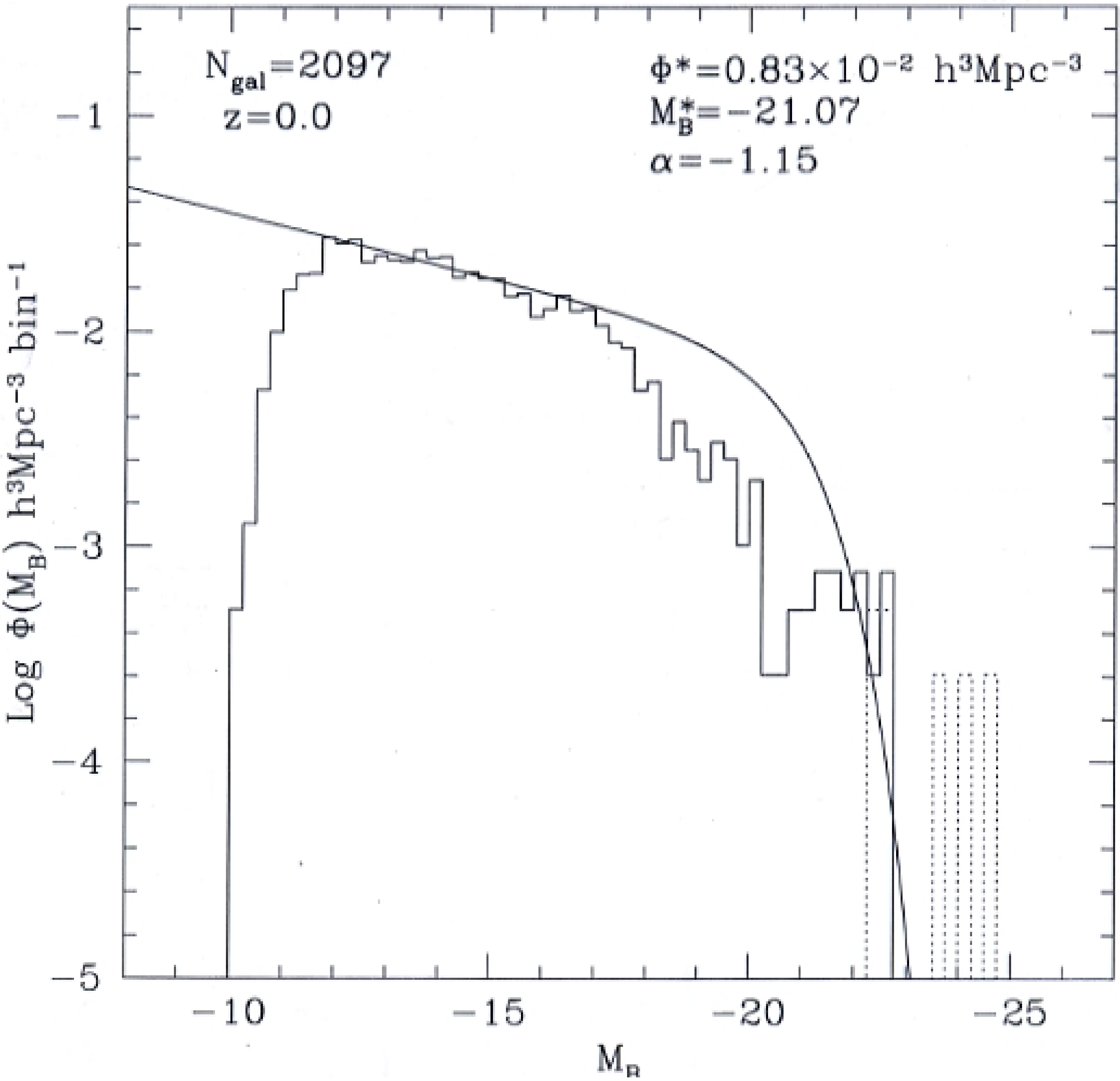
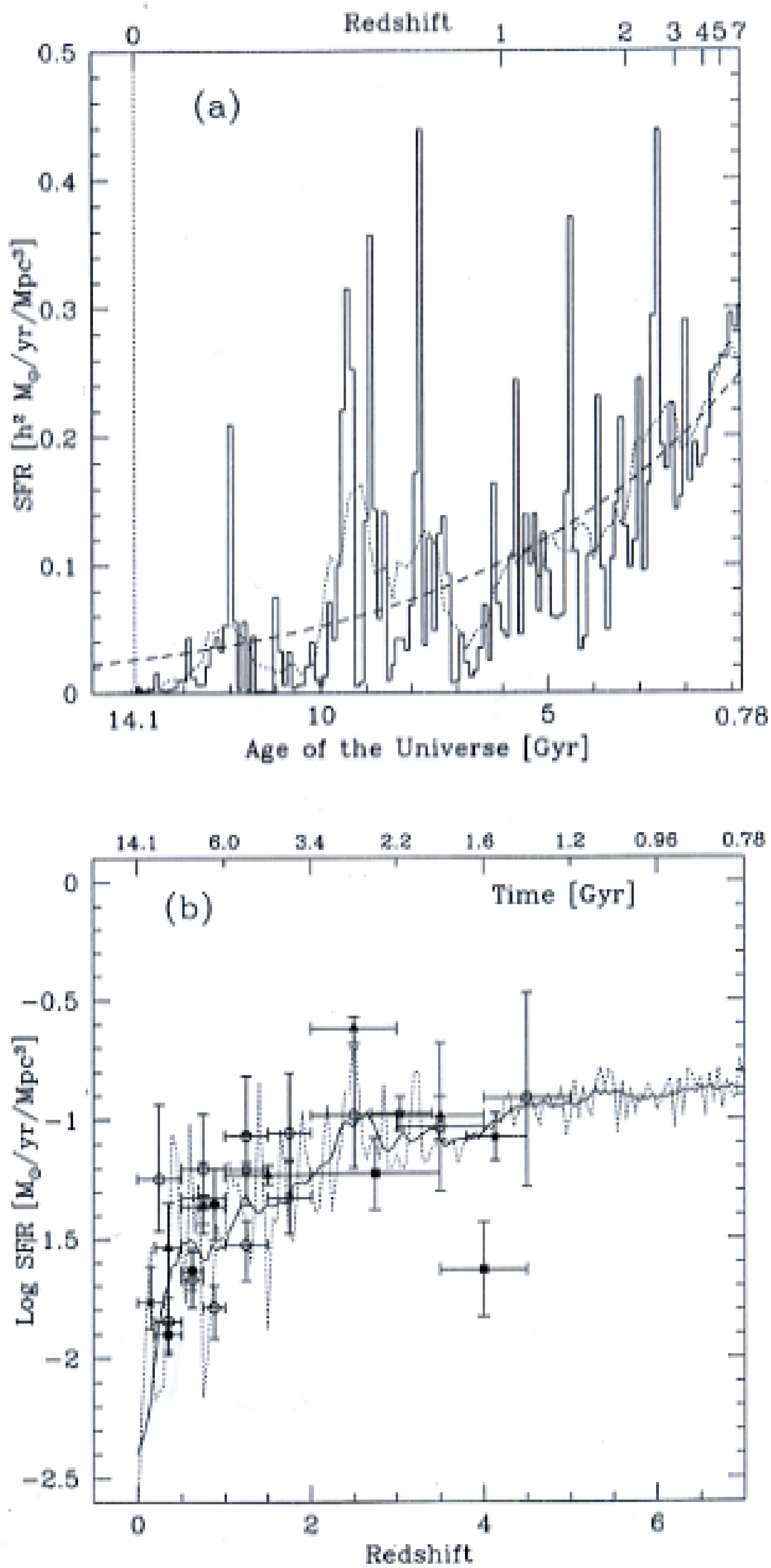


Figure 1. Mass function of dark matter haloes (dash-dotted N768 and short-dashed N384 histogram) and galaxy stellar mass (solid N768 and dotted N384 histogram). The two long-dashed lines show $\phi(M) \sim M^{-2}$ and $\phi_g(M) \sim M^{-1.15}$.

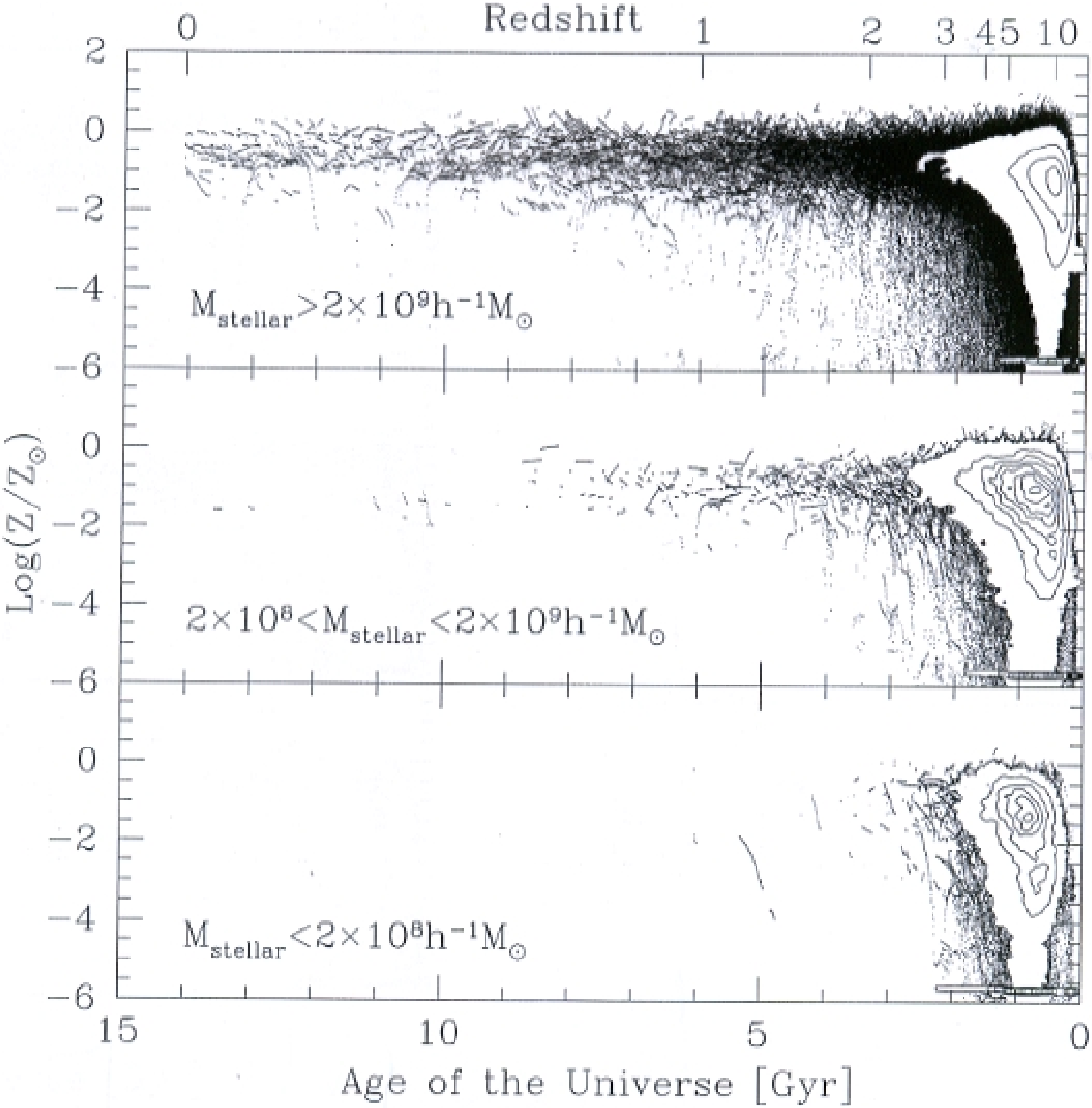
Nagamine Fukugita Cen Ostriker



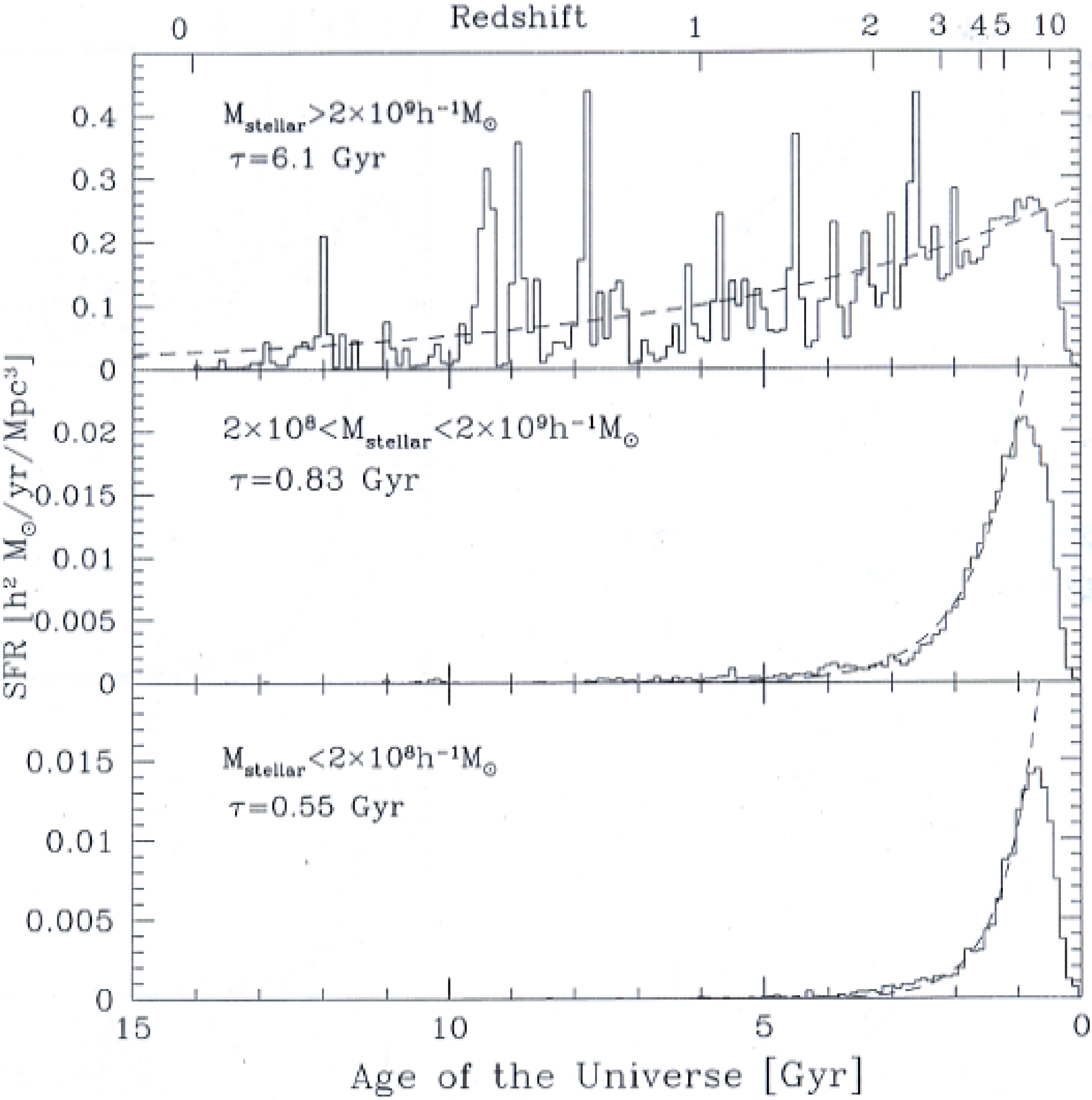

Redshift
0
1
2
3
4
5
7
(a)
SFR [h² M☉/yr/Mpc³]
0.5
0.4
0.3
0.2
0.1
0
14.1
10
5
0.78
Age of the Universe [Gyr]
14.1
6.0
3.4
2.2
1.6
1.2
0.96
0.78
(b)
Time [Gyr]
Log SFR [M☉/yr/Mpc³]
0
-0.5
-1
1.5
-2
-2.5
0
2
4
6
Redshift

26

NFCO


Redshift
0
1
2
3 45 10
2
0
−2
−4
−6
$M_{stellar}>2\times10^9h^{-1}M_\odot$
$Log(Z/Z_\odot)$
$2\times10^8<M_{stellar}<2\times10^9h^{-1}M_\odot$
$M_{stellar}<2\times10^8h^{-1}M_\odot$
15
10
5
0
Age of the Universe [Gyr]

Nagamine, Fukugita, Cen, Ostriker



CONCLUSIONS

- Large-Scale Strtucture ($\geq$ Clusters) is understood
- Full consistency of fluctuations in CMB and those

  from LSS
- Empirical power spectrum as predicted by the CDM model
- Galaxies: work in progress

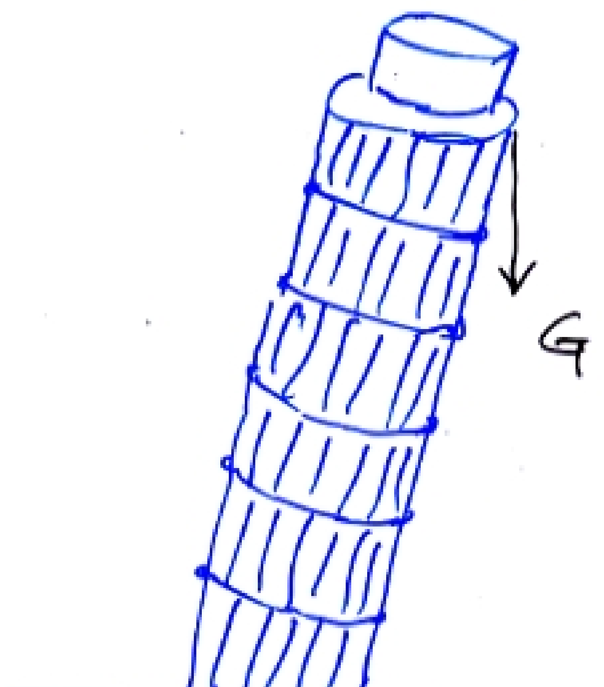
  Many aspects are explained with the CDM model, but some may not fit observations

  (Generally speaking, working well for big galaxies, but not quite so for small galaxies)
- We are looking for

  — What are *generic* predictions of the CDM model?

  — What are tests that falsify the CDM model predictions?
- We want to increase resolutions, at least to resolve bulges and discs

Salviati: *Ricordiamoci in grazia che il cercar la costituzione del mondo è de' maggiori e de' piú nobil problemi che sieno in natura,* …



GRAZIE MILLE!