Halo Model

Vinicius Miranda

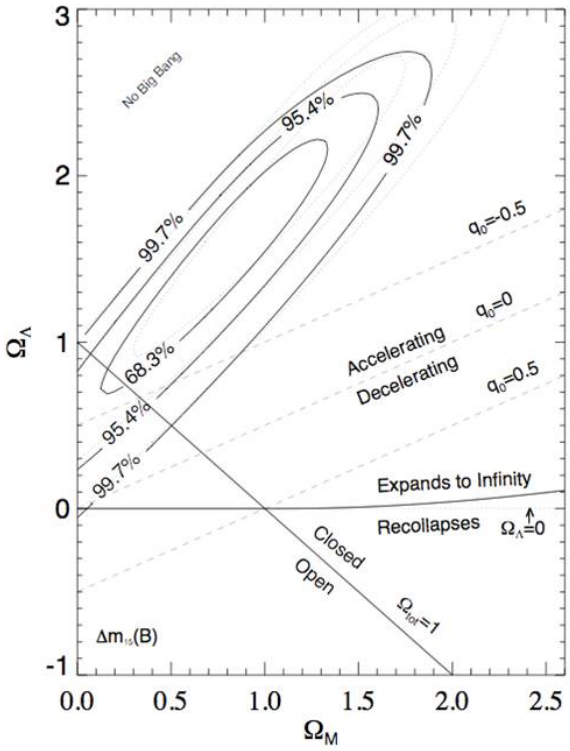
Department of Astronomy and Astrophysics
University of Chicago

Cosmology Course - Astro 321, 2011

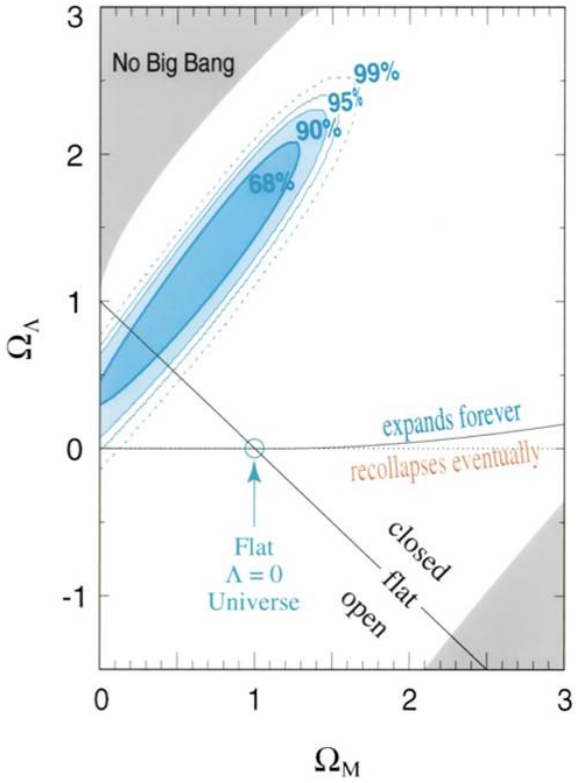
Outline

Since 1998, type IA SN indicates that the universe started to accelerate at some point in the past.

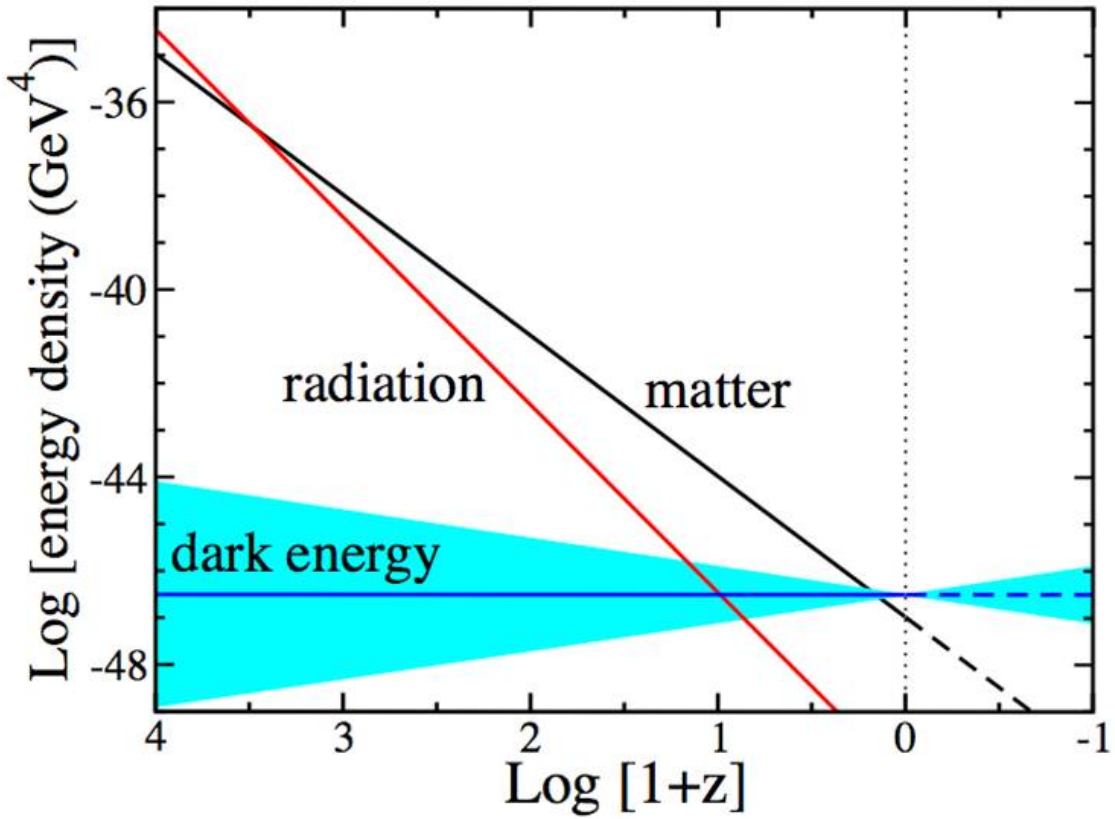
Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)

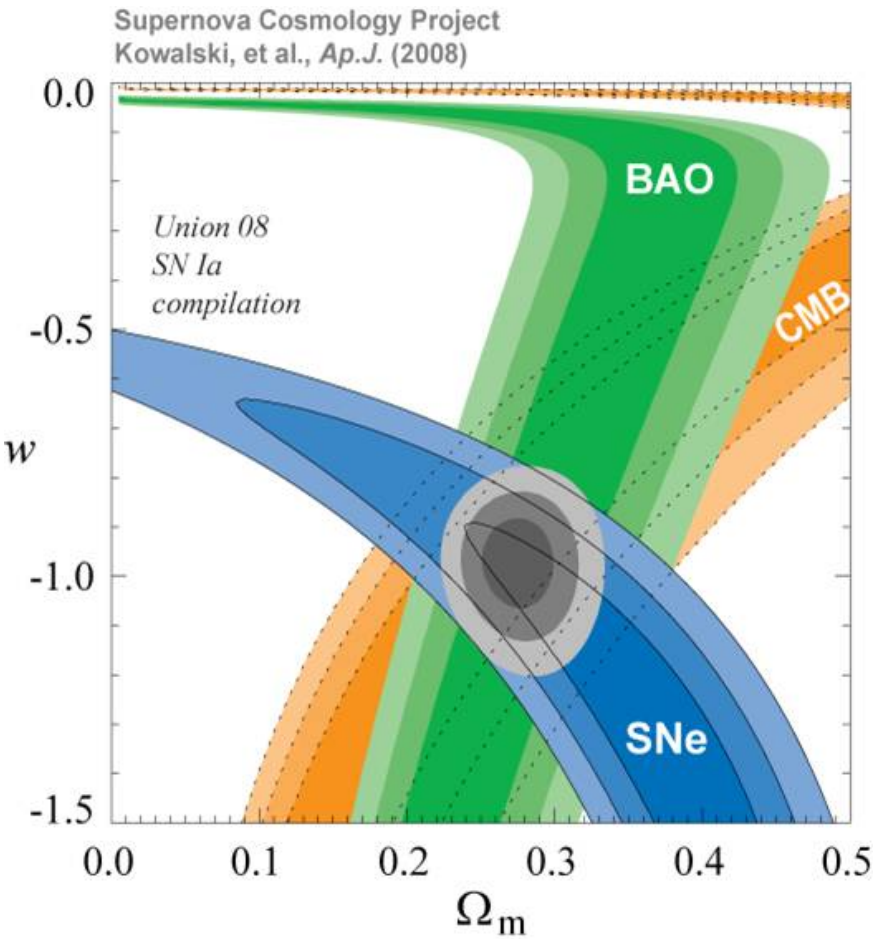


Background evolution is determined by equation of state.



Knowing Ω_m (CMB or BAO), EOS is mainly obtained by SN

assuming w constant



Limitations of Kinematic Tests

Theoretical alternatives: Assuming the dynamics of Dark Energy is given by a scalar field, Two very distinct possibilities are subject of intense research.

Modified gravity.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} + L_{\mu\nu}(g_{\mu\nu}) = \kappa^2 T^{(m)}_{\mu\nu} \tag{1}$$

New non-gravitational field.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} = \kappa^2 \left(T^{(m)}_{\mu\nu} + T_{\mu\nu}(\phi) \right) \tag{2}$$

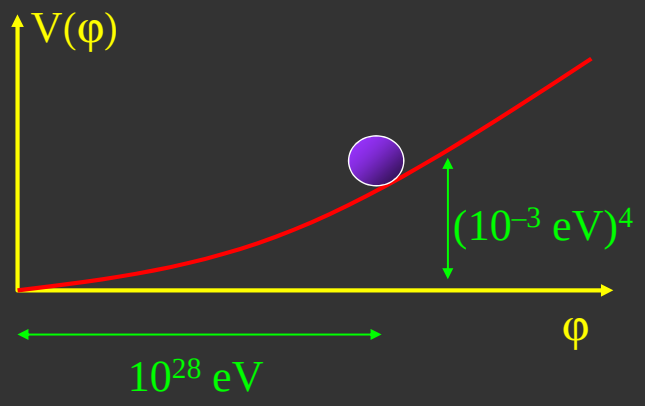
Example of the former approach (JF slide)

Scalar Field Dark Energy

aka quintessence

General features:

$m_{eff} < 3H_0 \sim 10^{-33}$ eV $(w < 0)$
(Potential > Kinetic Energy)



$V \sim m^2\varphi^2 \sim \rho_{crit} \sim 10^{-10}$ eV^4

$\varphi \sim 10^{28}$ eV $\sim M_{Planck}$

Ultra-light particle: Dark Energy hardly clusters, nearly smooth
Equation of state: usually, $w > -1$ and evolves in time
Hierarchy problem: Why $m/\phi \sim 10^{-61}$?
Weak coupling: Quartic self-coupling $\lambda_\phi < 10^{-122}$

Example of the second approach

Our Work

(V. Miranda, S. Jorás, I. Waga and M. Quartin – PRL v102, p 221101,2009)

In our work we tried to figure out if it is possible to build a viable f(R) model, without high curvature corrections, that is compatible with the existence of relativistic star and which does not suffer from Frolov's singularity.

We started from the following generalization of the HSS models

$$f(R) = R - \alpha R_* \beta \left\{ 1 - \left[1 + \left(\frac{R}{R_*} \right)^n \right]^{-\frac{1}{\beta}} \right\}$$

$$\beta \to \infty$$

$$f(R) = R - \alpha R_* \ln\left(1 + \frac{R}{R_*} \right)$$

$$\beta = 1 \qquad f(R) = R - \alpha R_* \left\{ 1 - \frac{1}{1 + \left(\frac{R}{R_*} \right)^n} \right\}$$

Hu & Sawicki's model

$$n = 2$$
$$\beta = m \qquad f(R) = R - \tilde{\alpha} R_* \left\{ 1 - \frac{1}{\left[1 + \left(\frac{R}{R_*} \right)^2 \right]^m} \right\}$$
$$\alpha = \tilde{\alpha} / \beta$$

Starobinsky's model

Dinamical Tests

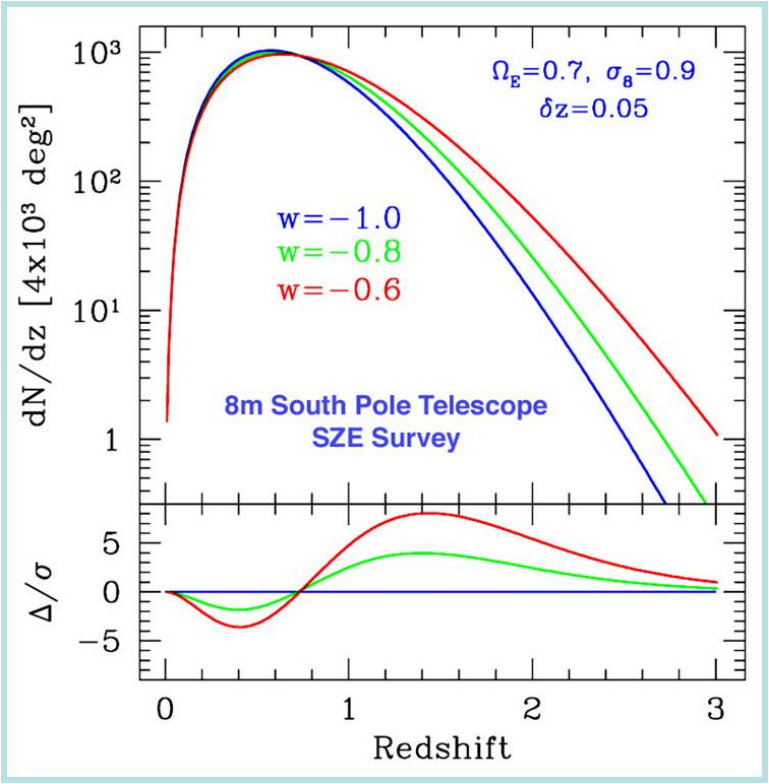
Can we differentiate the two approaches by measuring only the geometry?

NO!

We need the growth of structures

- Cluster Counts
- Lensing

$$\frac{d^2N(z)}{dzd\Omega} = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_{O_{min}}^{\infty} f(O,z)dO \int_0^{\infty} g(O|M,z)\frac{dn(z)}{dM}dM$$



(Mortonson, Hu,Huterer)

"We have shown that any observation that purports to rule out ΛCDM from the existence of massive clusters at any redshift also rules out quintessence, since quintessence models can suppress but not enhance the abundance of rare clusters compared to ΛCDM. This conclusion still holds if dark energy is a non-negligible fraction of the total density at high redshift. Once normalized to the CMB, quintessence models can only reduce the number of clusters"

Gravitational Lensing: "Light Propagate as if in a medium with spatially varying index of refraction"

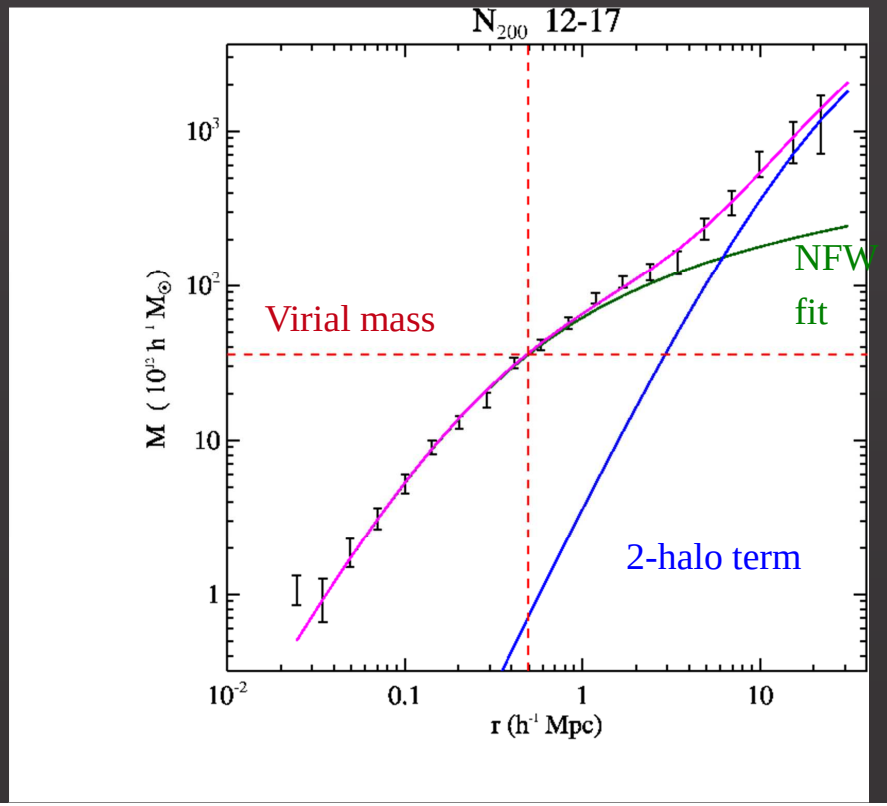
$$n = 1 - \frac{2\Phi(\vec{x}, \tau)}{c^2} \tag{3}$$

JF slide

Mean 3D Cluster Mass Profile

from Statistical Lensing

Johnston, etal



Linear Power Spectrum

In linear theory, it is possible to analyze the Dark Matter Power Spectrum with the following pieces:

- Initial Conditions given by inflation.

$$\Delta_{\mathfrak{R}} = A_s \left(\frac{k}{k_{\text{norm}}} \right)^{n_s - 1} \tag{4}$$

- The linear growth rate of the gravitational potential as a function of time.

$$G(a) = \frac{\Psi(k_{\text{norm}}, a)}{\Psi(k_{\text{norm}}, a_{\text{init}})} \tag{5}$$

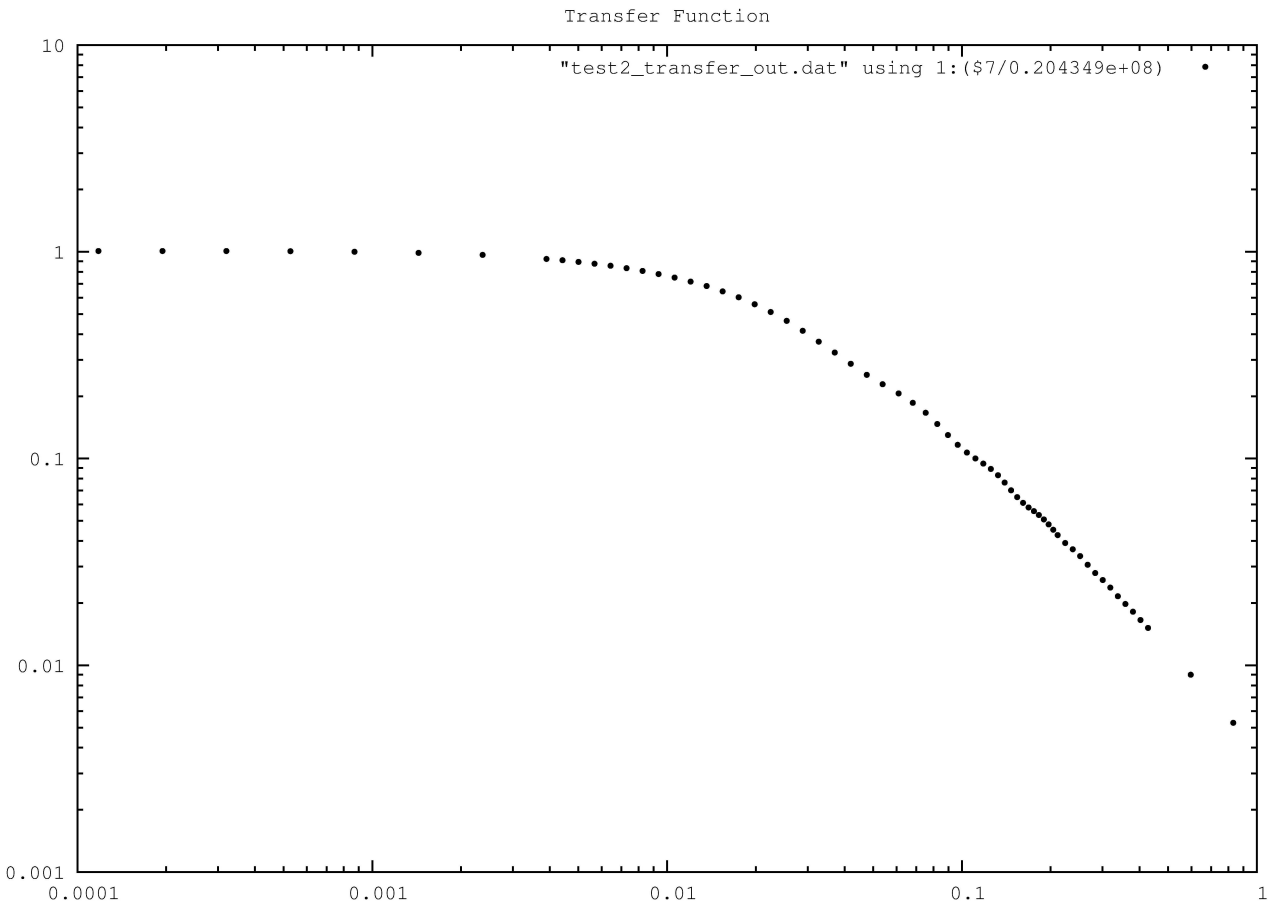
How to calculate the linear growth rate ?

$$\frac{\partial \delta}{\partial t} + 2H\frac{\partial \delta}{\partial t} - 4piG\bar{\rho} = 0 \tag{6}$$

where $\delta(k, a) = G(a)a\delta(k, 0)$.

$$\frac{d^2 G}{d(\ln a)^2} + \left[\frac{5}{2} - \frac{3}{2}w(a)\Omega_{DE}(a)\right]\frac{dG}{d\ln a} + \frac{3}{2}\left[1 - w(a)\right]\Omega_{DE}(a)G = 0 \tag{7}$$

- Transfer function that defines subhorizon evolution (Eisenstein and Hu)



Press - Schechter Theory

Can we estimate qualitatively the non linear power spectrum without doing a N Body simulation?

ANSATZ: Choose some particle in the initial density Field. Smooth the density filed around this particle with a top hat filter of scale R. Assume the collapse of dark matter particle is spherical.

- For R of the other if Hubble volume, the overdensity of this smoothed field should be very small.
- As R decreases, the overdensity value will vary, sometimes up, sometimes down.
- Eventually the ovedensity will cross some threshold value $\delta_{sc}(z)$.

Press - Schechter Theory

Can we estimate qualitatively the non linear power spectrum without doing a N Body simulation?

ANSATZ: Choose some particle in the initial density Field. Smooth the density filed around this particle with a top hat filter of scale R. Assume the collapse of dark matter particle is spherical.

- For R of the other if Hubble volume, the overdensity of this smoothed field should be very small.
- As R decreases, the overdensity value will vary, sometimes up, sometimes down.
- Eventually the ovedensity will cross some threshold value $\delta_{sc}(z)$.

Press - Schechter Theory

Can we estimate qualitatively the non linear power spectrum without doing a N Body simulation?

ANSATZ: Choose some particle in the initial density Field. Smooth the density filed around this particle with a top hat filter of scale R. Assume the collapse of dark matter particle is spherical.

- For R of the other if Hubble volume, the overdensity of this smoothed field should be very small.
- As R decreases, the overdensity value will vary, sometimes up, sometimes down.
- Eventually the ovedensity will cross some threshold value $\delta_{sc}(z)$.

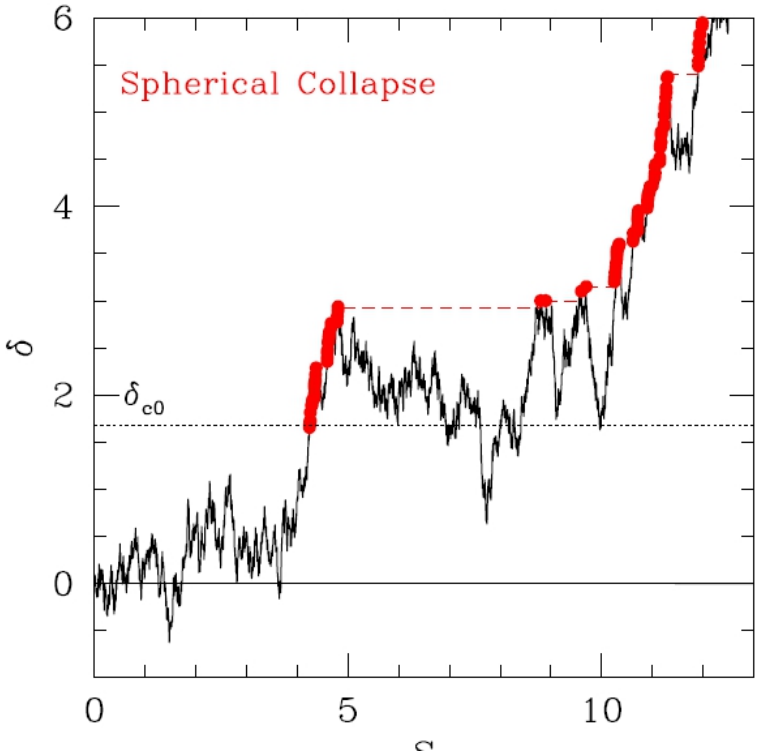
Press - Schechter Theory

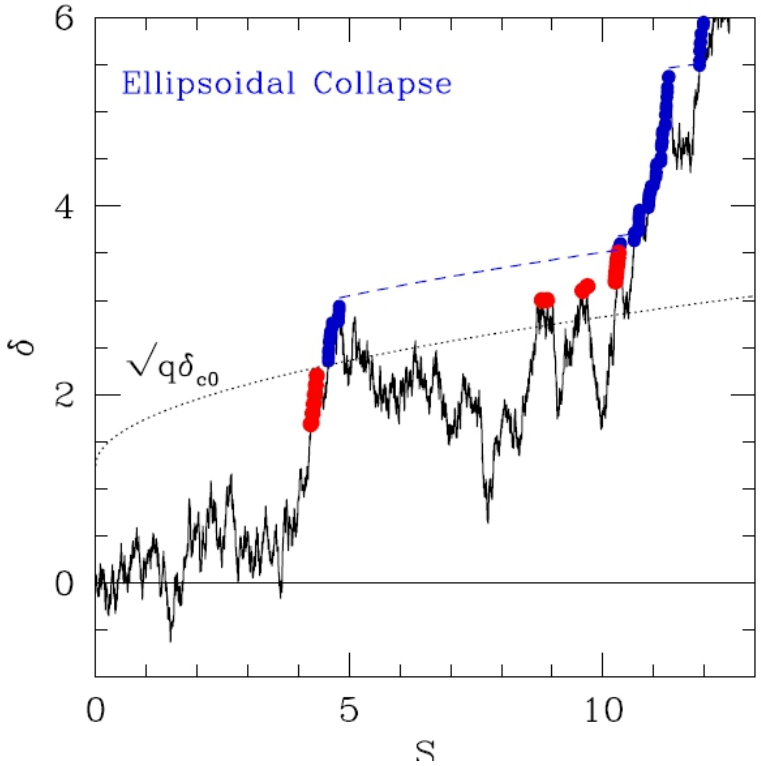
Can we estimate qualitatively the non linear power spectrum without doing a N Body simulation?

ANSATZ: Choose some particle in the initial density Field. Smooth the density filed around this particle with a top hat filter of scale R. Assume the collapse of dark matter particle is spherical.

- For R of the other if Hubble volume, the overdensity of this smoothed field should be very small.
- As R decreases, the overdensity value will vary, sometimes up, sometimes down.
- Eventually the ovedensity will cross some threshold value $\delta_{sc}(z)$.

- First crossing of this value indicates the scale where the field is dense enough to form a virialized halo at redshift z.





Spherical Collapse

Equation of motion.

$$\frac{d^2R}{dt^2} = -\frac{GM(R)}{R^2} + \frac{\Lambda R}{3}, \tag{8}$$

$$\left(\frac{dR}{dt}\right)^2 = \frac{2GM}{R} + \frac{\Lambda R^2}{3} - E_i. \tag{9}$$

Assume $\Lambda = 0$. Make a rescale in time: $d\eta = \sqrt{2GM/R_m}dt/R$.

$$R = \frac{R_m}{2}\left(1 - \cos(\eta)\right), \tag{10}$$

$$t = \frac{R_m^{3/2}}{\sqrt{2GM}}\left(\eta - \sin(\eta)\right). \tag{11}$$

Spherical Collapse

Equation of motion.

$$\frac{d^2R}{dt^2} = -\frac{GM(R)}{R^2} + \frac{\Lambda R}{3}, \tag{8}$$

$$\left(\frac{dR}{dt}\right)^2 = \frac{2GM}{R} + \frac{\Lambda R^2}{3} - E_i. \tag{9}$$

Assume $\Lambda = 0$. Make a rescale in time: $d\eta = \sqrt{2GM/R_m}dt/R$.

$$R = \frac{R_m}{2}\left(1 - \cos(\eta)\right), \tag{10}$$

$$t = \frac{R_m^{3/2}}{\sqrt{2GM}}\left(\eta - \sin(\eta)\right). \tag{11}$$

Spherical Collapse

Equation of motion.

$$\frac{d^2R}{dt^2} = -\frac{GM(R)}{R^2} + \frac{\Lambda R}{3}, \tag{8}$$

$$\left(\frac{dR}{dt}\right)^2 = \frac{2GM}{R} + \frac{\Lambda R^2}{3} - E_i. \tag{9}$$

Assume $\Lambda = 0$. Make a rescale in time: $d\eta = \sqrt{2GM/R_m}dt/R$.

$$R = \frac{R_m}{2}\left(1 - \cos(\eta)\right), \tag{10}$$

$$t = \frac{R_m^{3/2}}{\sqrt{2GM}}\left(\eta - \sin(\eta)\right). \tag{11}$$

Overdensity:

$$1 + \delta(t) = \frac{9}{2}\frac{(\eta - \sin\eta)}{(1 - \cos\eta)^2}. \tag{12}$$

For $\delta << 1$ and $\eta << 1$:

$$\delta(t) = \delta_L(t) = \frac{3}{20}\left(\frac{6\pi t}{t_m}\right)^{2/3}. \tag{13}$$

$$\delta_L(2t_m) = 1.686 \tag{14}$$

Virializarion

$$\frac{\rho(t_v)}{\bar{\rho}(t_v)} = 18\pi^2 \tag{15}$$

Overdensity:

$$1 + \delta(t) = \frac{9}{2}\frac{(\eta - \sin\eta)}{(1 - \cos\eta)^2}. \tag{12}$$

For $\delta << 1$ and $\eta << 1$:

$$\delta(t) = \delta_L(t) = \frac{3}{20}\left(\frac{6\pi t}{t_m}\right)^{2/3}. \tag{13}$$

$$\delta_L(2t_m) = 1.686 \tag{14}$$

Virializarion

$$\frac{\rho(t_v)}{\bar{\rho}(t_v)} = 18\pi^2 \tag{15}$$

Overdensity:

$$1 + \delta(t) = \frac{9}{2}\frac{(\eta - \sin\eta)}{(1 - \cos\eta)^2}. \tag{12}$$

For $\delta << 1$ and $\eta << 1$:

$$\delta(t) = \delta_L(t) = \frac{3}{20}\left(\frac{6\pi t}{t_m}\right)^{2/3}. \tag{13}$$

$$\delta_L(2t_m) = 1.686 \tag{14}$$

Virializarion

$$\frac{\rho(t_v)}{\bar{\rho}(t_v)} = 18\pi^2 \tag{15}$$

Comoving number density

$$dn = \frac{\bar{\rho}}{M}\nu f(\nu)\frac{d\nu}{\nu} \qquad \nu = \left(\frac{\delta_{sc}(z)}{\sigma(m)}\right)^2 \tag{16}$$

Spherical Collapse

$$\nu f(\nu) = \frac{\sqrt{\nu}}{2\pi}\exp(-\nu/2) \tag{17}$$

Ellipsoidal Collapse

$$\nu f(\nu) = A(p)\left(1 + (q\nu)^{-p}\left(\frac{q\nu}{2\pi}\right)^{1/2}\exp -q\nu/2\right) \tag{18}$$

$$A(p) = \left[1 + 2^{-p}\Gamma(1/2 - p)/\sqrt{\pi}\right]^{-1} \tag{19}$$

Comoving number density

$$dn = \frac{\bar{\rho}}{M}\nu f(\nu)\frac{d\nu}{\nu} \qquad \nu = \left(\frac{\delta_{sc}(z)}{\sigma(m)}\right)^2 \tag{16}$$

Spherical Collapse

$$\nu f(\nu) = \frac{\sqrt{\nu}}{2\pi}\exp(-\nu/2) \tag{17}$$

Ellipsoidal Collapse

$$\nu f(\nu) = A(p)\left(1 + (q\nu)^{-p}\left(\frac{q\nu}{2\pi}\right)^{1/2}\exp -q\nu/2\right) \tag{18}$$

$$A(p) = \left[1 + 2^{-p}\Gamma(1/2 - p)/\sqrt{\pi}\right]^{-1} \tag{19}$$

Comoving number density

$$dn = \frac{\bar{\rho}}{M}\nu f(\nu)\frac{d\nu}{\nu} \qquad \nu = \left(\frac{\delta_{sc}(z)}{\sigma(m)}\right)^2 \tag{16}$$

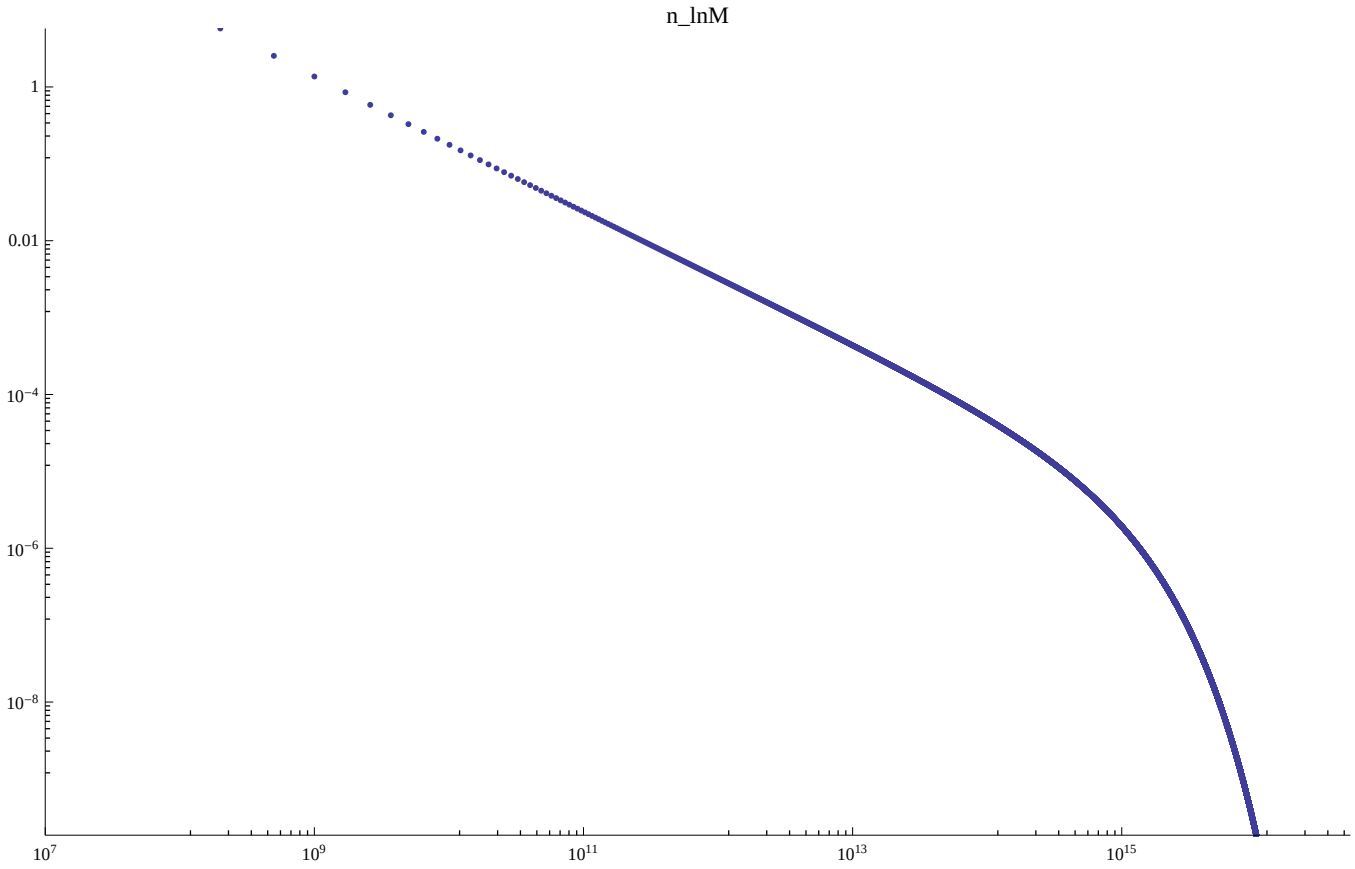
Spherical Collapse

$$\nu f(\nu) = \frac{\sqrt{\nu}}{2\pi}\exp(-\nu/2) \tag{17}$$

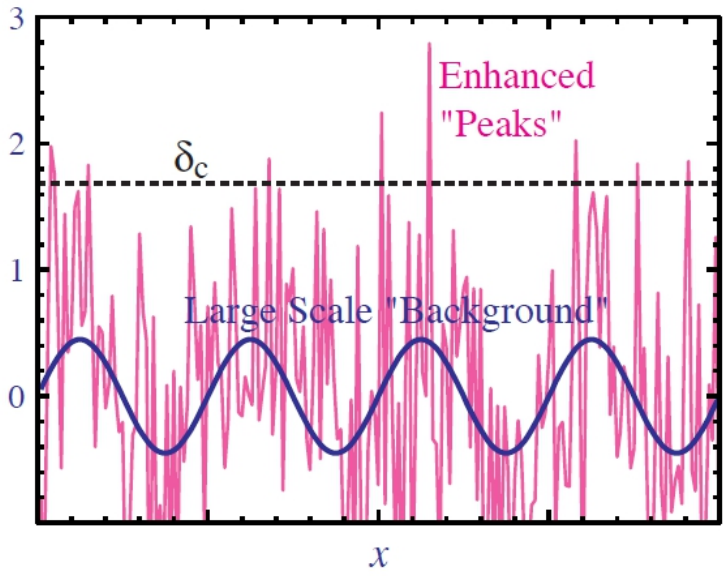
Ellipsoidal Collapse

$$\nu f(\nu) = A(p)\left(1 + (q\nu)^{-p}\left(\frac{q\nu}{2\pi}\right)^{1/2}\exp -q\nu/2\right) \tag{18}$$

$$A(p) = \left[1 + 2^{-p}\Gamma(1/2 - p)/\sqrt{\pi}\right]^{-1} \tag{19}$$


n_lnM
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}

bias



$$\delta = \delta_b + \delta_p \tag{20}$$

$$\delta_{cp} = \delta_c - \delta_b \tag{21}$$

$$b(M) = 1 + \frac{q\nu - 1}{\delta_c} + \frac{2p}{\delta_c\left[1 + (q\nu)^p\right]} \tag{22}$$

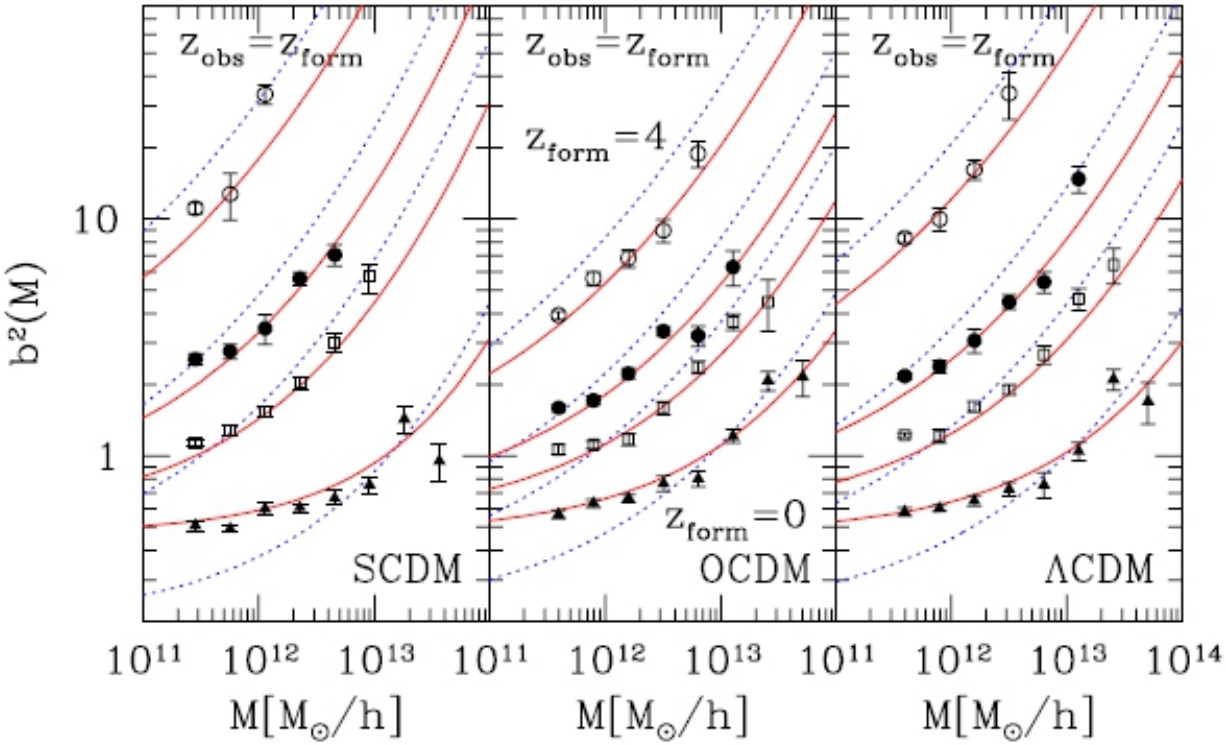
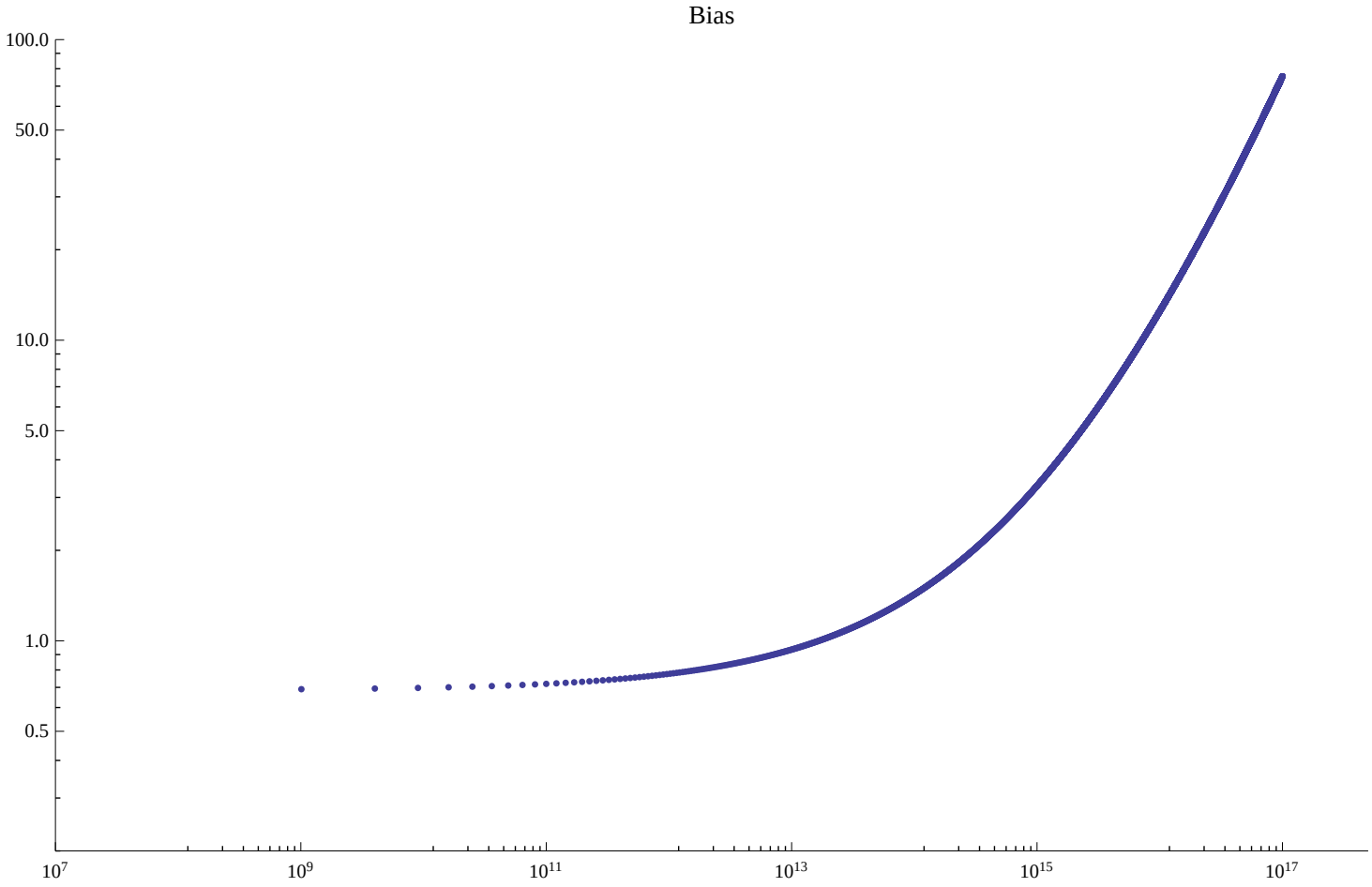


Fig. 4. Large scale bias relation between halos and mass (from [254]). Symbols show the bias factors at z_{obs} for objects which were identified as virialized halos at z_{form} = 4,2,1 and 0 (top to bottom in each panel). Dotted and solid lines show predictions based on the Press-Schechter and Sheth-Tormen mass functions.

z=0



NFR Profile

Definition:

$$\rho(r|m) = \frac{\rho_s}{(r/r_s)\,(1 + r/r_s)^2}. \tag{23}$$

Normalization

$$m = 4\pi\rho_s r_s^3 \left[\ln(1+c) - \frac{c}{1+c}\right] \tag{24}$$

$$p(c|m,z)dc = \frac{d(\ln c)}{\sqrt{2\pi\sigma^2_{\ln c}}} \exp\left(\frac{-\ln^2[c/\bar{c}(m,z)]}{2\sigma^2_{\ln c}}\right) \tag{25}$$

$\bar{c} = \frac{9}{1+z}\left[\frac{m}{\widetilde{m}}\right]^{-0.20}$, $\sigma_{\ln c} \approx 0.25$ and $\widetilde{m} \sim 2 \times 10^{13} M_\odot$

NFR Profile

Definition:

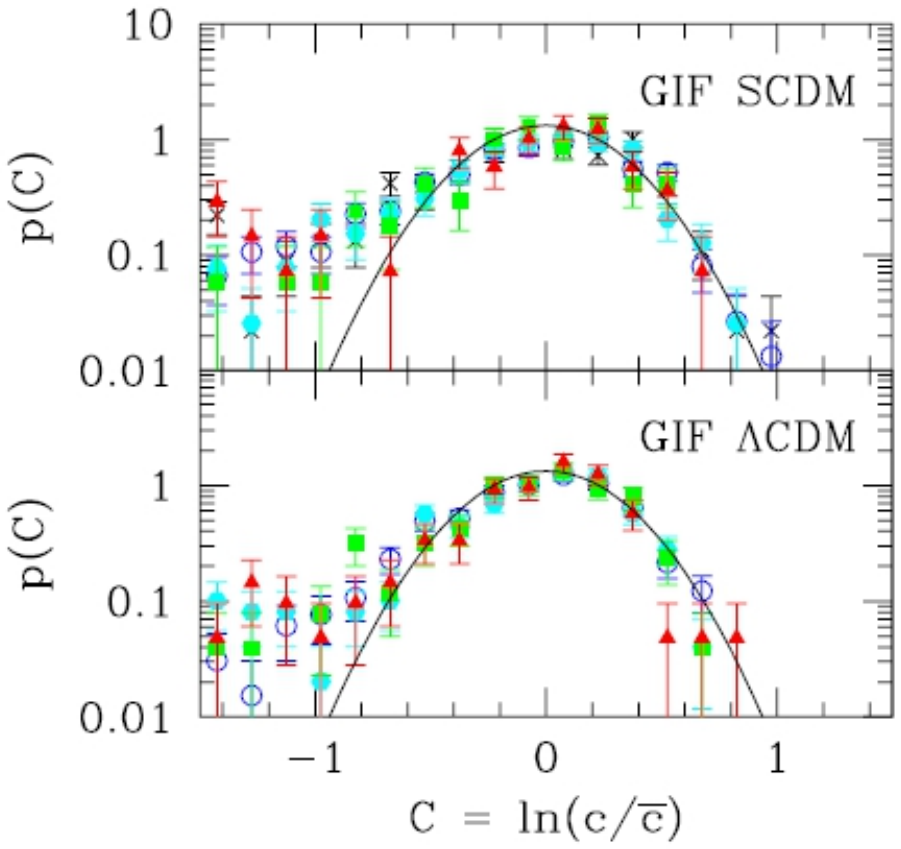
$$\rho(r|m) = \frac{\rho_s}{(r/r_s)\,(1 + r/r_s)^2}. \tag{23}$$

Normalization

$$m = 4\pi\rho_s r_s^3 \left[\ln(1+c) - \frac{c}{1+c}\right] \tag{24}$$

$$p(c|m,z)dc = \frac{d(\ln c)}{\sqrt{2\pi\sigma^2_{\ln c}}} \exp\left(\frac{-\ln^2[c/\bar{c}(m,z)]}{2\sigma^2_{\ln c}}\right) \tag{25}$$

$\bar{c} = \frac{9}{1+z}\left[\frac{m}{\widetilde{m}}\right]^{-0.20}$, $\sigma_{\ln c} \approx 0.25$ and $\widetilde{m} \sim 2 \times 10^{13} M_\odot$


GIF SCDM
GIF ΛCDM
p(C)
p(C)
10
1
0.1
0.01
1
0.1
0.01
−1
0
1
C = ln(c/c̄)

NFR Profile

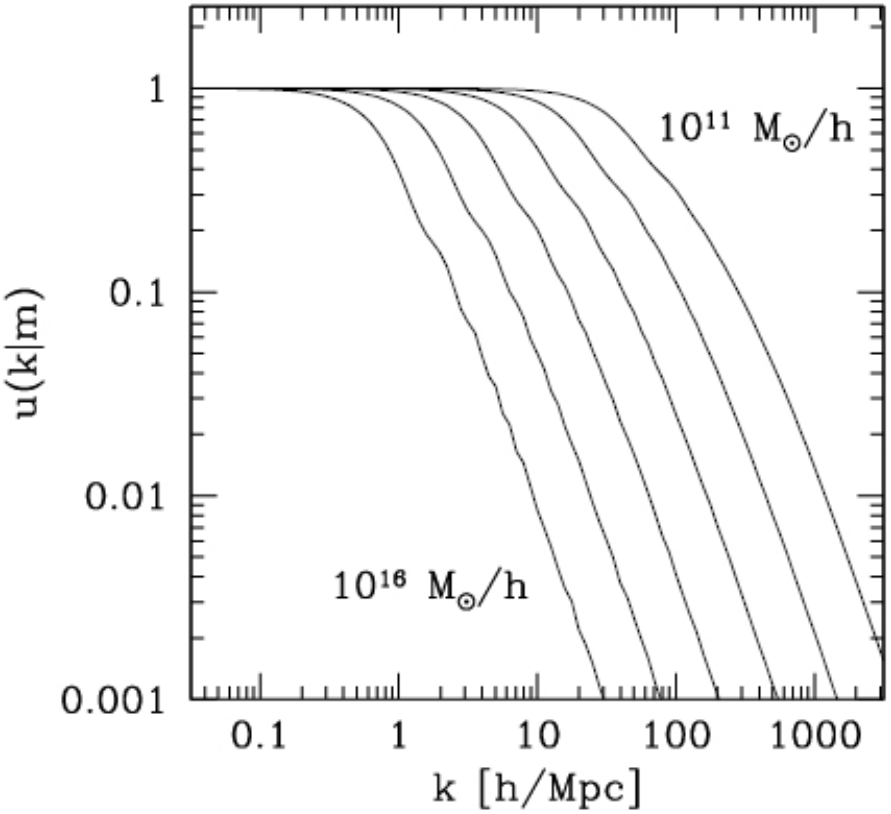
Normalize Fourier Transform:

$$u(k|m) = \frac{\int d^3\vec{x}\rho(\vec{x}|m)e^{-i\vec{k}\cdot\vec{x}}}{\int d^3\vec{x}\rho(\vec{x}|m)} \tag{26}$$

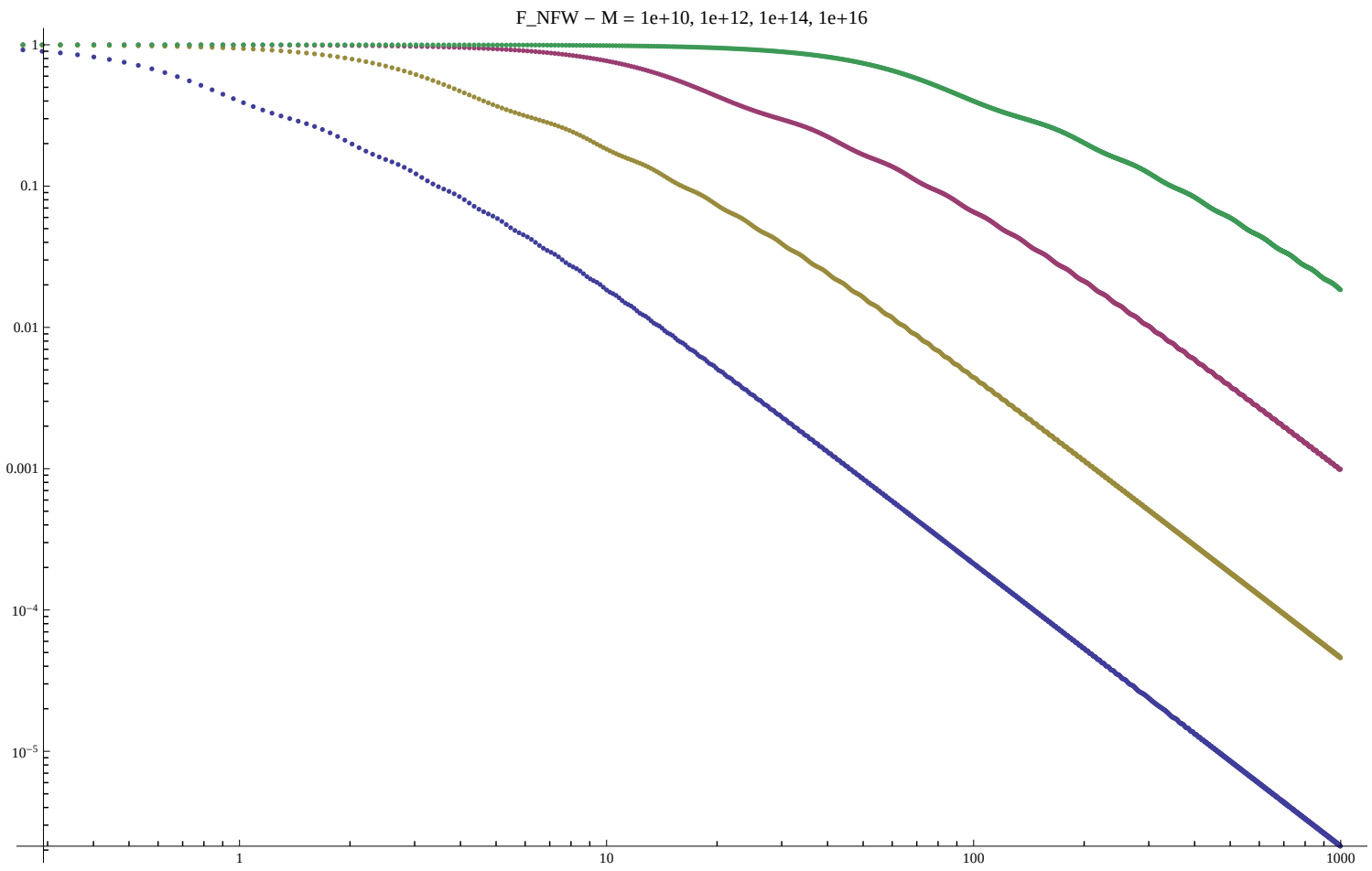
For NFW profile:

$$u(k|m) = \frac{4\pi\rho_s r_s^3}{m}\left[\sin(kr_s)\left[\mathrm{Si}([1+c]kr_s) - \mathrm{Si}(kr_s)\right] - \frac{\sin(ckr_s)}{(1+c)kr_s}\right] \tag{27}$$

$$+ \frac{4\pi\rho_s r_s^3}{m}\left[cos(kr_s)\left[\mathrm{Ci}([1+c]kr_s) - \mathrm{Ci}(kr_s)\right]\right]$$


1
0.1
0.01
0.001
u(k|m)
0.1
1
10
100
1000
k [h/Mpc]
10^{11} $M_\odot/h$
10^{16} $M_\odot/h$

z=0



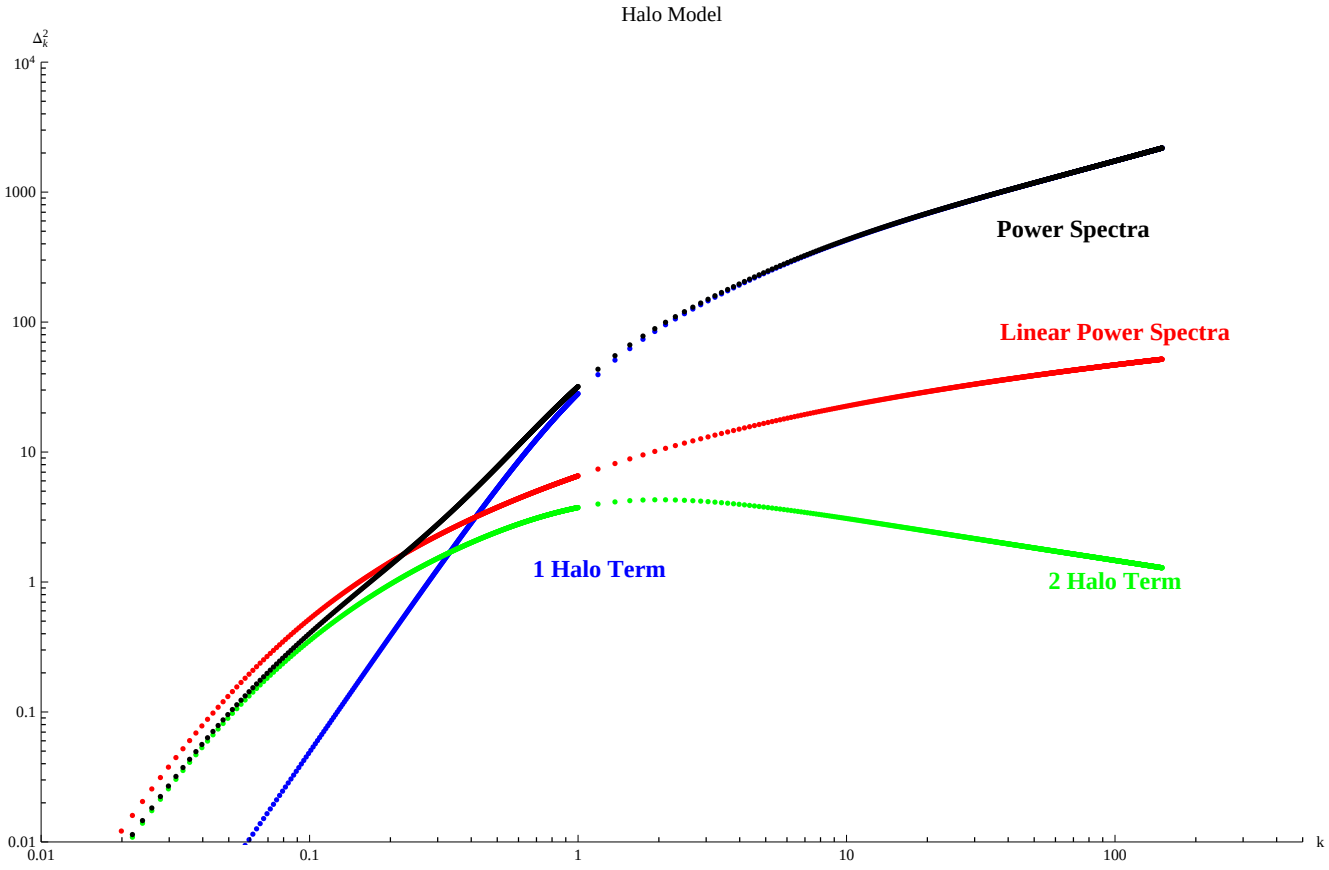
Dark Matter Power Spectrum

$$P(k) = P^{1h}(k) + P^{2h}(k) \tag{28}$$

$$P^{1h}(k) = \int d\ln M \left(\frac{M}{\bar{\rho}_m(z=0)}\right)^2 \frac{dn}{d\ln(M)} u^2(k, M) \tag{29}$$

$$P^{2h}(k) = \left(\int d\ln M \left(\frac{M}{\bar{\rho}_m(z=0)}\right) \frac{dn}{d\ln(M)} b(M) u(k, M)\right)^2 P_l(k) \tag{30}$$

z = 0


Halo Model
Δ_k^2
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
k
Power Spectra
Linear Power Spectra
1 Halo Term
2 Halo Term

Galaxy Power Spectrum

$$P_{gal}(k) = P^{1h}_{gal}(k) + P^{2h}_{gal}(k) \tag{31}$$

$$P^{1h}(k) = \int d\ln M \frac{\langle N_{gal}(N_{gal}-1)|M\rangle}{\bar{n}^2_{gal}} \frac{dn}{d\ln(M)} u^p(k,M) \tag{32}$$

$$P^{2h}(k) = \left(\int d\ln M \frac{\langle N_{gal}|M\rangle}{\bar{n}_{gal}} \frac{dn}{d\ln(M)} b(M) u(k,M)\right)^2 P_l(k) \tag{33}$$

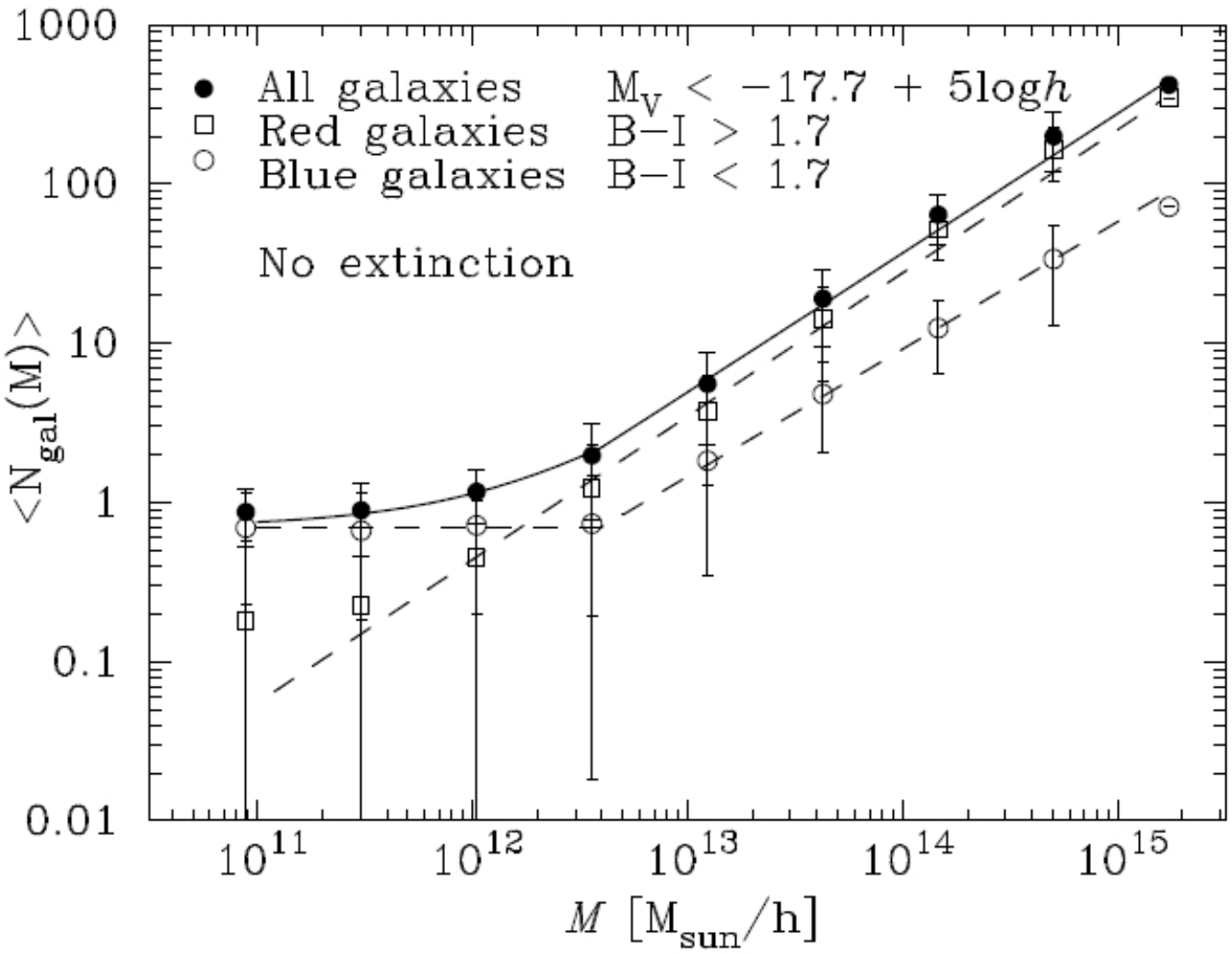
Galaxy Power Spectrum

- If $\langle N_{gal}|M\rangle < 1$, then $p = 1$. Else $p = 2$.
- Variance:

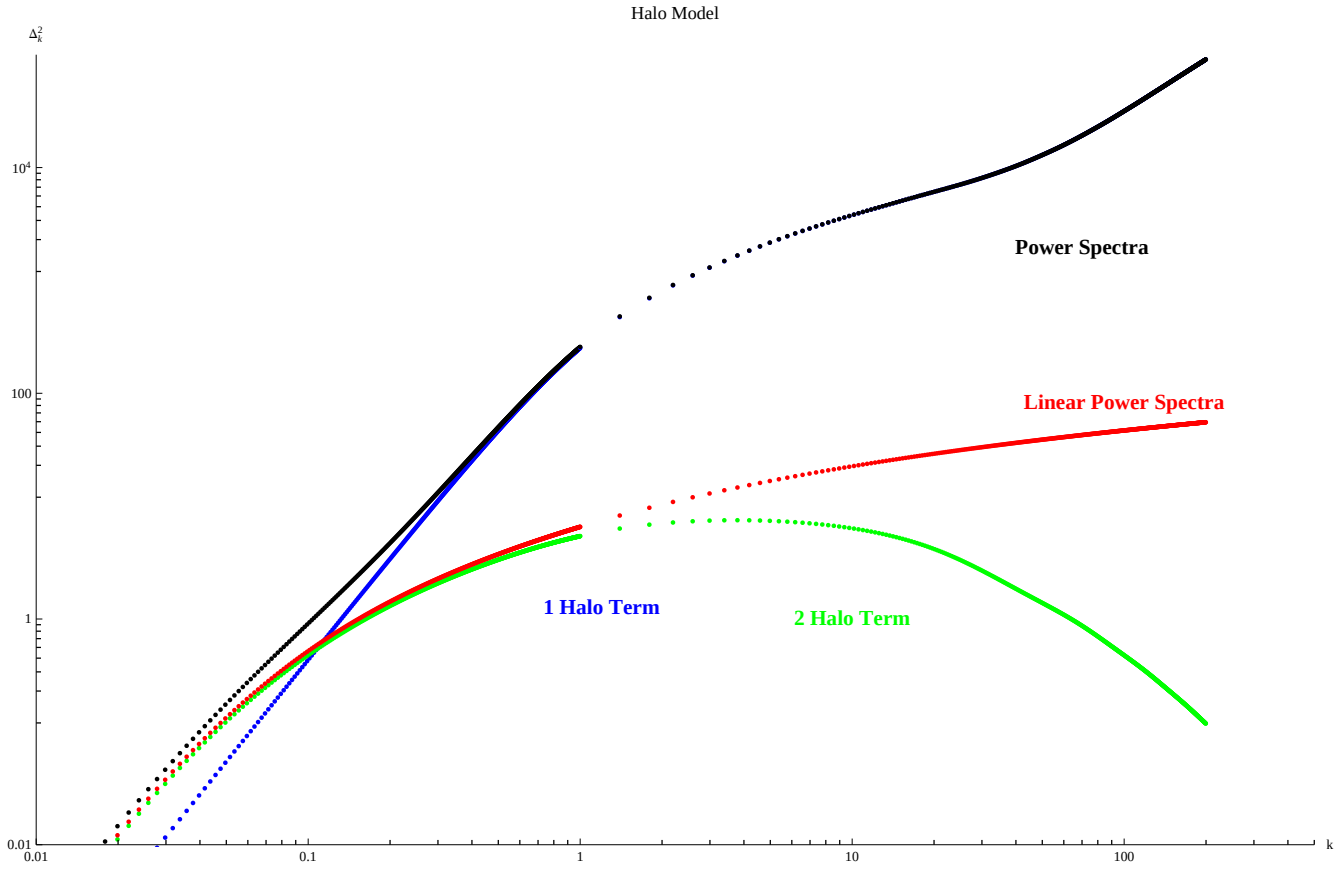
$$\langle N_{gal}(N_{gal}-1)|M\rangle = \alpha(m)\langle N_{gal}\rangle \text{ where} \tag{34}$$
$$\alpha = \log\left(\sqrt{M/(10^{11}M_{\odot}h^{-1})}\right)$$

- Mean:

$$\langle N_{gal}|M\rangle = 0 \text{ if } M \leq 10^{11}M_{\odot}h^{-1} \tag{35}$$
$$= 0.7 + \left(M/(2.5\times 10^{12})\right)^{0.9} \text{ if } 10^{11} \leq M \leq 4\times 10^{12}M_{\odot}h^{-1}$$
$$= 0.7\left(M/(4\times 10^{12})\right)^{0.8} + \left(M/(2.5\times 10^{12})\right)^{0.9}$$
$$\text{if } 4\times 10^{12} \leq M\ (M_{\odot}h^{-1})$$


All galaxies $M_V < -17.7 + 5\log h$
Red galaxies B−I > 1.7
Blue galaxies B−I < 1.7
No extinction
$\langle N_{gal}(M) \rangle$
M [M_{sun}/h]
1000
100
10
1
0.1
0.01
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}

z = 0


Halo Model
Δ_k^2
10^4
100
1
0.01
0.01
0.1
1
10
100
k
Power Spectra
Linear Power Spectra
1 Halo Term
2 Halo Term

velocities

$p(v|m)dv =$ Probability of a particle in a halo of mass m, has velocity in the range dv about v.

$$f(v) = \frac{\int dmn(m)p(v|m)}{\int dmmn(m)} \tag{36}$$

Shape of $p(v|m)$: 2 components.

- Virial Motions: Maxwell Boltzmann Distribution.
- Gaussian Field: Halo motions also obey Maxwell Boltzmann

Virial Motions:

$$\sigma^2_{virial} \propto \frac{GM}{r} \propto \frac{GMr^2}{r^3}$$
$$\propto (\Delta_{\rm vir}\rho_{\rm crit}) \left(\frac{3m}{4\pi\Delta_{\rm vir}\rho_{\rm crit}}\right)^{2/3} \quad (37)$$

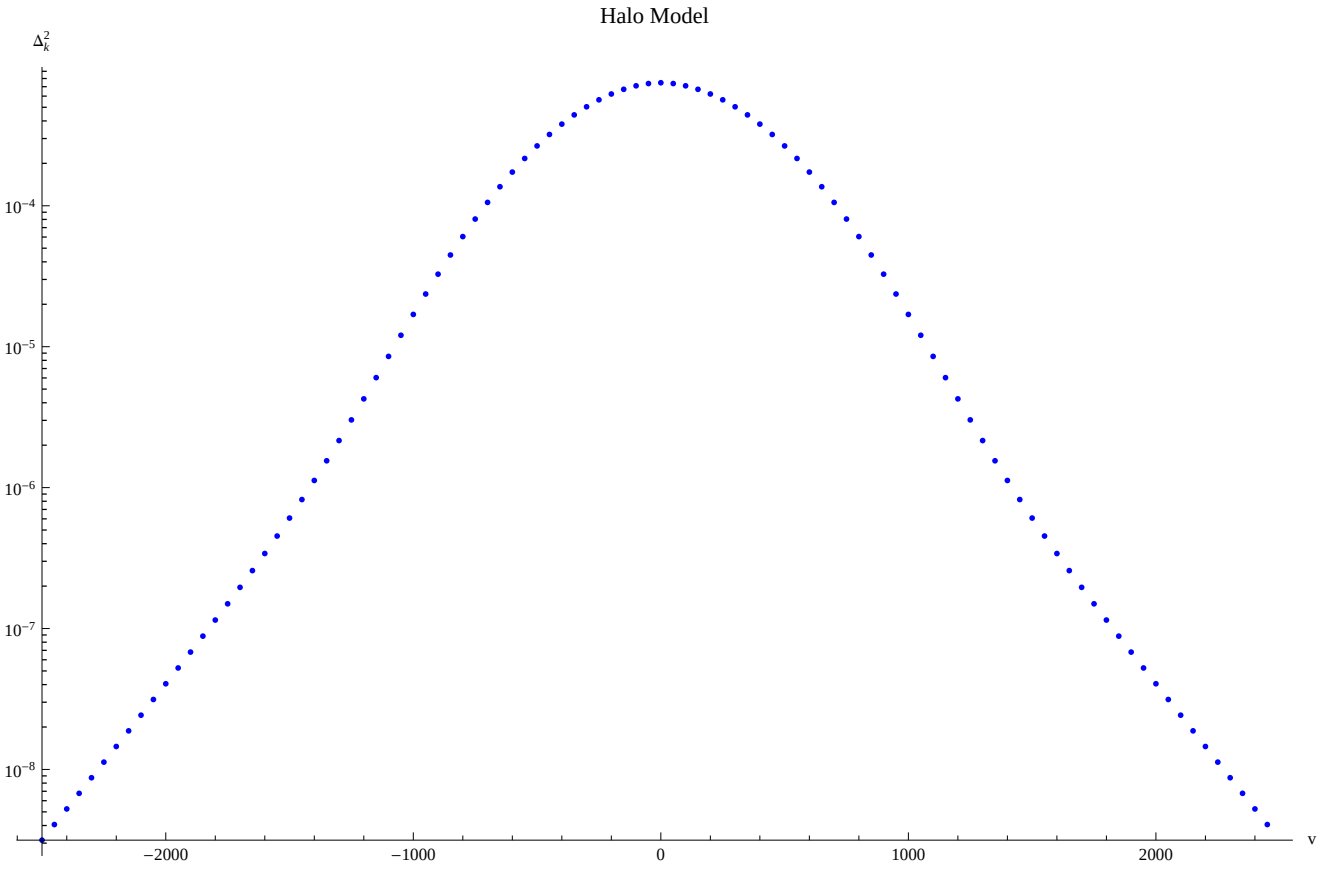
$$\sigma^2_{virial} = 102.5 * 0.9 * \left(\frac{H(z)}{H_0}\right)^{1/3} \left(\frac{m}{10^{13}M_\odot/h}\right) \text{km/s} \quad (38)$$

Halo Motions:

$$\sigma_{\text{halo}} = \frac{d\log(aG)}{d\log(a)} * \sigma_{-1}\sqrt{1 - \sigma_0^4/\sigma_1^4\sigma_{-1}^4} \tag{39}$$

$$\sigma_j^2(R) = \frac{1}{2\pi^2}\int dk k^{2+2j} P^{\text{lin}}(k) W^2\left[kR\right] \tag{40}$$

z = 0



Good Qualities

- It is organized. (readable)
- Calculates matter power spectrum, galaxy power spectrum, and peculiar velocity distribution.
- Input file allows you to change many physical and optimization parameters.

Good Qualities

- It is organized. (readable)
- Calculates matter power spectrum, galaxy power spectrum, and peculiar velocity distribution.
- Input file allows you to change many physical and optimization parameters.

Good Qualities

- It is organized. (readable)
- Calculates matter power spectrum, galaxy power spectrum, and peculiar velocity distribution.
- Input file allows you to change many physical and optimization parameters.

- Allows you to choose between 2 different dark energy parameterizations:

$$w_{de} = w_0 + w_1 z \tag{41}$$
$$w_{de} = w_0 + w_1 \frac{z}{1.0 + z}.$$

- Allows you to choose between 3 different concentration parameters:

$$c = 10 \tag{42}$$
$$c = \bar{c}$$
$$c \text{ given by p(c).}$$

Input.txt

```
# LIST OF KEYWORDS CAN BE FOUND AT INPU

# PHYSICAL INPUT
hubble_uncertainty 0.70
T_cmb 2.728
omega_matter 0.27
spectral_indice 0.966
scale_factor 0.5
window_indice 0
omega_DE 0.73
indice_w_de 0
w_0 -1.0
w_1 0.0
ST_p 0.3
ST_a 0.75
c_marginalize 1
```

```
# TECHINICAL INPUT

# GROWTH FUNCTION CALCULATION
gr_z_max  100.0
gr_z_min  0.0
gr_eps    1e-6
gr_dx_intermediate  0.01
gr_max_intermediate 5000

# SIGMA CALCULATION
SIGMA_EPS   0.001
sigma_R_initial 0.001
sigma_dr 0.01
boost 5

# OUTPUT FILE NAME
file_name dark_matter_3
```

```
# THE FIRST PARAMETERS OF BELOW NEEDS TO BE THE "HALO_PLOT", "GALAXY_PLOT" AND "VELOCITY_PLOT"
# PROGRAM WILL SELECT THE REMAINING PARAMETERS TO EB READ DEPENDING ON THE VALUE OF THESE VARIA

halo_plot 1
galaxy_plot 0
velocity_plot 0

# PROGRAM WILL ALWAYS READ BECAUSE ALL CASES NEEDS THEM
halo_j_min 4
I_1_I_2_EPS 0.001

# IF HALO_PLOT OR GALAXY_PLOT IS TRUE, PROGRAM WILL READ
number_points_non_linear_plot 150
first_point_non_linear_plot 0.01
last_point_non_linear_plot 10

# IF GALAXY_PLOT IS TRUE PROGRAM WILL READ
galaxy_min_step 4
galaxy_eps 0.001

# IF VELOCITY PLOT IS TRUE PROGRAM WILL READ
number_points_velocity_plot  100
first_point_velocity  -2500
last_point_velocity  2500
```

Ouput.txt

```
#-----------------------------------------------------
#                Physical Parameters
#-----------------------------------------------------
# Hubble h parameter:                0.7
#-----------------------------------------------
# CMB Temperature:                   2.728
#-----------------------------------------------
# Omega Matter - z=0                 0.27
#-----------------------------------------------
# Spectral Indice:                   0.966
#-----------------------------------------------
# Starting Scale Factor:             1
#-----------------------------------------------
# Window Function Indice:            0
#-----------------------------------------------
# Omega Dark Energy - z=0            0.73
#-----------------------------------------------
# DE EoS Function Indice             0
#-----------------------------------------------
# DE EoS Constant Parameter          -1
#-----------------------------------------------
# DE EoS Slope Parameter:            0
#-----------------------------------------------
# Sheth Tormen "p" Parameter:       0.3
#-----------------------------------------------
# Sheth Tormen "a" Parameter:       0.75
#-----------------------------------------------
# Concentration Function Indice      1
#-----------------------------------------------
```

```
#                Technical Parameters
# Growth Function: initial redshift     0
#-----------------------------------------------
# Growth Function: final redshift       100
#-----------------------------------------------
# Growth Function: EDO routine EPS      1e-06
#-----------------------------------------------
# Growth Function: delta scale factor   0.01
#-----------------------------------------------
# Growth Function: number of points     5000
#-----------------------------------------------
# Sigma Function EPS Integral Parameter 0.001
#-----------------------------------------------
# Interpolation Sigma: number of points 1300
#-----------------------------------------------
# Interpolation Sigma: delta R          0.01
#-----------------------------------------------
# Interpolation Sigma: Initial R        0.001
#-----------------------------------------------
# Plot Dark Matter PS?                  true
#-----------------------------------------------
# Plot Galaxy PS?                       false
#-----------------------------------------------
# Plot Velocity Distribution?           false
#-----------------------------------------------
# I_1 and I_2 EPS Integral Parameter    0.0001
#-----------------------------------------------
 One-Two Halo min number steps         4
-----------------------------------------------
# Number of Points (PS evaluation)      100
#-----------------------------------------------
```

```
#-------------------------------------------------
# Last Wave Number(PS evaluation)        800
#  k    (k^3/2pi^2)I_1     I_2    linear_delta     P_NL
10      419.707      0.313802      22.5566      421.928
17.9      633.794      0.246964      28.0264      635.504
25.8      798.128      0.212687      31.7097      799.563
33.7      936.067      0.190837      34.5152      937.324
41.6      1057.55      0.175275      36.7924      1058.68
49.5      1167.67      0.163418      38.7144      1168.7
57.4      1269.38      0.153962      40.3805      1270.33
65.3      1364.57      0.146171      41.8527      1365.46
73.2      1454.54      0.139593      43.1729      1455.38
81.1      1540.22      0.133932      44.3705      1541.02
89      1622.3      0.128984      45.4671      1623.05
96.9      1701.26      0.124606      46.4788      1701.99
104.8      1777.55      0.120691      47.4183      1778.24
112.7      1851.47      0.11716      48.2955      1852.13
120.6      1923.29      0.11395      49.1185      1923.92
128.5      1993.23      0.111013      49.8936      1993.84
136.4      2061.48      0.108311      50.6264      2062.07
```

```
/* TECHNICAL PARAMETERS*/
/* GROWTH FUNCTION CALCULATION FOR INTERPOLATION */
extern double gr_z_max;                         /* redshift used to start the evolution */
extern double gr_z_min;                         /* redshift in which the evolution will stop */
extern double gr_eps;                           /* Growth ODE Solver Fractional Accuracy */
extern double gr_dx_intermediate;               /* STEP THAT IS KEPT TO DO INTERPOLATION */
extern int gr_max_intermediate;             /* MAX NUMBER OF POINTS THAT WILL BE CALCULATED */

/* SIGMA AND dSIGMA/dR CALCULATION FOR INTERPOLATION */
extern double sigma_R_initial;                  /* INITIAL R CALCULATED */
extern double sigma_dr;                         /* R STEP THAT IS KEPT TO DO INTERPOLATION */
extern double SIGMA_EPS;                        /* SIGMA INTEGRAL FRACTIONAL ACCURACY*/
extern int boost;               /* MAX NUMBER OF POINTS THAT WILL BE CALCULATED */

/* MEAN GALAXY NUMBER CALCULATION */
extern int galaxy_min_step;                     /* Mean Galaxy Integral min number of steps (3^min steps) */
extern double galaxy_eps;                       /* Mean Galaxy Integral fractional Accuracy */

/* OUTPUT TABLE */
extern bool halo_plot;                          /* PLOT Halo non Linear Power Spectra ? */
extern bool galaxy_plot;                        /* PLOT Galaxy non Linear Power Spectra ? */
extern bool velocity_plot;                      /* PLOT velocity distribution ? */
                                                /* Important: Only one of these 3 can be true!*/
extern int halo_j_min;                          /* I_1 and I_2 Integrals min number of steps (3^min steps) */
extern double I_1_I_2_EPS;                      /* I_1 and I_2 Integrals fractional Accuracy */

extern double number_points_non_linear_plot;    /* Number of Points that will be calculated (Non Linear or Galaxy Power Spe
extern double first_point_non_linear_plot;      /* First  Point that will be calculated (Non Linear or Galaxy Power Spectru
extern double last_point_non_linear_plot;       /* Last  Point that will be calculated (Non Linear or Galaxy Power Spectrum

extern int number_points_velocity_plot;         /* Number of Points that will be calculated (velocity distribution)*/
extern double first_point_velocity;             /* First  Point that will be calculated (velocity distribution)*/
extern double last_point_velocity;              /* Last  Point that will be calculated (velocity distribution)*/
```

run: make -fMakefile.mak final_project

```
viniciusvmb@elara:~/cursos/wayne/projeto_final_march
-----------------------------------------------
Growth Function: EDO routine EPS      1e-06
-----------------------------------------------
Growth Function: delta scale factor   0.01
-----------------------------------------------
Growth Function: number of points     5000
-----------------------------------------------
Sigma Function EPS Integral Parameter 0.001
-----------------------------------------------
Interpolation Sigma: boost delta R     5
-----------------------------------------------
Interpolation Sigma: delta R          0.01
-----------------------------------------------
Interpolation Sigma: Initial R        0.001
-----------------------------------------------
Plot Dark Matter PS?                  true
-----------------------------------------------
Plot Galaxy PS?                       false
-----------------------------------------------
Plot Velocity Distribution?            false
-----------------------------------------------
One-Two Halo EPS Integral Parameter   0.001
-----------------------------------------------
One-Two Halo min number steps         4
-----------------------------------------------
Number of Points (PS evaluation)      150
-----------------------------------------------
First Wave Number(PS evaluation)      0.01
-----------------------------------------------
Last Wave Number(PS evaluation)       10

-----------------------------------------------------
 Solving linear growth rate differential equation.
-----------------------------------------------------

-----------------------------------------------------
 Calculating SIGMA for Interpolation
-----------------------------------------------------
-------------------------------------------------------------------
Calculating the Halo model Dark matter non linear power spectrum
-------------------------------------------------------------------
- Time to Calculate one Point (sec):     0.29
- Time to Calculate All The Plot Points (min): 0.725
```

Optimization

- It is $\sim$ optimized.

  Run: 0.2 - 1.5 seconds/point. For a entire plot: 2 - 10 minutes (30 - 45 seconds to calculate and fit sigma + 1s/point).

  Can be better?

  Use of inline functions - Integral code that double (not triple) the number of points on each call...

Bad Qualities

- Normalization bug (someone really should make an independent check).
- Not written in a C++ class style.
- NR copyrighted $$$ code.

However, integrands are written in gsl function style. Thus, it should be simple to use GSL integration code.

Bad Qualities

- Normalization bug (someone really should make an independent check).
- Not written in a C++ class style.
- NR copyrighted $$$ code.

However, integrands are written in gsl function style. Thus, it should be simple to use GSL integration code.

Needs to incorporate more physics:

- subhalos structure for $k >> 1\mathrm{Mpc}/h^{-1}$) ,
- weak lensing,
- momentum power spectra,
- dark matter - galaxy cross power spectrum.

Thanks and sorry about the thousands of questions (some "out of phase" with the lecture subject!)

Funny thing about my "impatience". First Time I attended a class on Halo Model was during the 2008 BSCG.

Ravi Sheth BSCG proceedings:

" I thank (..) V. Miranda for raising so many interesting questions, M. Calvao for keeping him under control.."

Thanks for Keeping me under control! :)

Thanks and sorry about the thousands of questions (some "out of phase" with the lecture subject!)

Funny thing about my "impatience". First Time I attended a class on Halo Model was during the 2008 BSCG.

Ravi Sheth BSCG proceedings:

" I thank (..) V. Miranda for raising so many interesting questions, M. Calvao for keeping him under control.."

Thanks for Keeping me under control! :)

Thanks and sorry about the thousands of questions (some "out of phase" with the lecture subject!)

Funny thing about my "impatience". First Time I attended a class on Halo Model was during the 2008 BSCG.

Ravi Sheth BSCG proceedings:

" I thank (..) V. Miranda for raising so many interesting questions, M. Calvao for keeping him under control.."

Thanks for Keeping me under control! :)