Halo Model

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Outline

1. Introduction
2. Halo Model
   - Linear Theory
   - Press - Schechter Theory
   - Dark Matter
   - Galaxies
   - velocities
3. Program
   - Good Qualities
   - Bad Qualities
4. Thanks
Since 1998, type IA SN indicates that the universe started to accelerate at some point in the past.
Background evolution is determined by equation of state.
Knowing $\Omega_m$ (CMB or BAO), EOS is mainly obtained by SN assuming $w$ constant.
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.**

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} = \kappa^2 \left( T^{(m)}_{\mu\nu} + T_{\mu\nu}(\phi) \right) \tag{2}
\]
Scalar Field Dark Energy
aka quintessence

General features:

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

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

$\phi \sim 10^{28} \text{ eV} \sim M_{\text{Planck}}$

**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

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

\[ n = 2 \]
\[ \beta \rightarrow \infty \]
\[ f(R) = R - \alpha R_* \ln \left( 1 + \frac{R}{R_*} \right) \]

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

Hu & Sawicki’s model

Starobinsky’s model

\[ \alpha = \tilde{\alpha} / \beta \]
Can we differentiate the two approaches by measuring only the geometry?

NO!

We need the growth of structures

- Cluster Counts
- Lensing
\[
\frac{d^2N(z)}{dz d\Omega} = \frac{c}{H(z)} D_A^2 (1 + z)^2 \int_0^\infty f(O,z) dO \int_0^\infty g(O|M,z) \frac{dn(z)}{dM} dM
\]
"We have shown that any observation that purports to rule out $\Lambda$CDM 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 $\Lambda$CDM. 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"

\[ n = 1 - \frac{2\Phi(\vec{x}, \tau)}{c^2} \]  \hspace{1cm} (3)

Mean 3D Cluster Mass Profile from Statistical Lensing Johnston, et al

Virial mass

NFW fit

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

- Initial Conditions given by inflation.

\[
\Delta_R = A_s \left( \frac{k}{k_{\text{norm}}} \right)^{n_s-1}
\]  \hspace{1cm} (4)

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

\[
G(a) = \frac{\psi(k_{\text{norm}}, a)}{\psi(k_{\text{norm}}, a_{\text{init}})}
\]  \hspace{1cm} (5)
How to calculate the linear growth rate?

\[ \frac{\partial \delta}{\partial t} + 2H \frac{\partial \delta}{\partial t} - 4\pi G \bar{\rho} = 0 \]  \hspace{1cm} (6)

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

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

\[ + \frac{3}{2} \left[ 1 - w(a) \right] \Omega_{DE}(a) G = 0 \]  \hspace{1cm} (7)
- Transfer function that defines subhorizon evolution (Eisenstein and Hu)
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 field 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 $\delta_{sc}(z)$.
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- 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.

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

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

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

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

\[
t = \frac{R_m^{3/2}}{\sqrt{2GM}} (\eta - \sin(\eta)). \tag{11}
\]
**Spherical Collapse**

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Overdensity:

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

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

$$\delta(t) = \delta_L(t) = \frac{3}{20} \left( \frac{6 \pi t}{t_m} \right)^{2/3}.$$  \hspace{1cm} (13)

$$\delta_L(2t_m) = 1.686$$  \hspace{1cm} (14)

Virializarion

$$\frac{\rho(t_v)}{\bar{\rho}(t_v)} = 18 \pi^2$$  \hspace{1cm} (15)
Overdensity:

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Virialization:

\[ \frac{\rho(t_V)}{\bar{\rho}(t_V)} = 18\pi^2 \]  
(15)
Overdensity:

\[ 1 + \delta(t) = \frac{9 (\eta - \sin \eta)}{2 (1 - \cos \eta)^2}. \]  

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**Virialization**

\[ \frac{\rho(t_v)}{\bar{\rho}(t_v)} = 18\pi^2 \]  

(15)
**Comoving number density**

\[
dn = \frac{\bar{\rho}}{M} \nu f(\nu) \frac{d\nu}{\nu}
\]

\[
\nu = \left( \frac{\delta_{sc}(z)}{\sigma(m)} \right)^2
\]  \hspace{1cm} (16)

**Spherical Collapse**

\[
\nu f(\nu) = \frac{\sqrt{\nu}}{2\pi} \exp(-\nu/2)
\]  \hspace{1cm} (17)

**Ellipsoidal Collapse**

\[
\nu f(\nu) = A(p) \left( 1 + (q\nu)^{-p} \left( \frac{q\nu}{2\pi} \right)^{1/2} \exp -q\nu/2 \right)
\]  \hspace{1cm} (18)

\[
A(p) = \left[ 1 + 2^{-p} \Gamma(1/2 - p)/\sqrt{\pi} \right]^{-1}
\]  \hspace{1cm} (19)
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\[ n_{\ln M} \]

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Halo Model
bias

\[ \delta = \delta_b + \delta_p \] (20)

\[ \delta_{cp} = \delta_c - \delta_b \] (21)

\[ b(M) = 1 + \frac{q \nu - 1}{\delta_c} + \frac{2p}{\delta_c \left[ 1 + (q \nu)^p \right]} \] (22)
Fig. 4. Large scale bias relation between halos and mass (from [254]). Symbols show the bias factors at $z_{\text{obs}}$ for objects which were identified as virialized halos at $z_{\text{form}} = 4, 2, 1$ 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:

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

Normalization

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

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

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

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

For NFW profile:

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

\[ + \frac{4\pi \rho_s r_s^3}{m} \left[ \cos(kr_s) \left[ \text{Ci}((1+c)kr_s) - \text{Ci}(kr_s) \right] \right] \]
$z=0$

$F_{\text{NFW}} = M = 1 \times 10, 1 \times 12, 1 \times 14, 1 \times 16$
\[ P(k) = P^{1h}(k) + P^{2h}(k) \]  

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

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

\[ P_{\text{gal}}(k) = P_{\text{gal}}^{1h}(k) + P_{\text{gal}}^{2h}(k) \]  

\[ P_{\text{gal}}^{1h}(k) = \int d\ln M \frac{\langle N_{\text{gal}}(N_{\text{gal}} - 1) | M \rangle}{\bar{n}_{\text{gal}}^2} \frac{dn}{d\ln(M)} u^p(k, M) \]  

\[ P_{\text{gal}}^{2h}(k) = \left( \int d\ln M \frac{\langle N_{\text{gal}} | M \rangle}{\bar{n}_{\text{gal}}} \frac{dn}{d\ln(M)} b(M) u(k, M) \right)^2 P_l(k) \]
Galaxy Power Spectrum

- If $\langle N_{gal} | M \rangle < 1$, then $p = 1$. Else $p = 2$.
- Variance:
  \[
  \langle N_{gal}(N_{gal} - 1) | M \rangle = \alpha(m)\langle N_{gal} \rangle \text{ where } (34)
  \]
  \[
  \alpha = \log \left( \sqrt{\frac{M}{(10^{11} M_{\odot} h^{-1})}} \right)
  \]
- Mean:
  \[
  \langle N_{gal} | M \rangle = 0 \text{ if } M \leq 10^{11} M_{\odot} h^{-1} \quad (35)
  \]
  \[
  = 0.7 + \left( \frac{M}{(2.5 \times 10^{12})} \right)^{0.9} \text{ if } 10^{11} \leq M \leq 4 \times 10^{12} M_{\odot} h^{-1}
  \]
  \[
  = 0.7 \left( \frac{M}{(4 \times 10^{12})} \right)^{0.8} + \left( \frac{M}{(2.5 \times 10^{12})} \right)^{0.9}
  \]
  \[
  \text{if } 4 \times 10^{12} \leq M (M_{\odot} h^{-1})
  \]
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$z = 0$

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Halo Model

Power Spectra

Linear Power Spectra

1 Halo Term

2 Halo Term

$D_k^2$
\[ p(v|m)dv = \text{Probability of a particle in a halo of mass m, has velocity in the range } dv \text{ about } v. \]

\[
f(v) = \frac{\int dm n(m)p(v|m)}{\int dmmn(m)} \quad (36)
\]

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

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

\[ \sigma_{\text{virial}}^2 \propto \frac{GM}{r} \propto \frac{GMr^2}{r^3} \]

\[ \propto (\Delta_{\text{vir}}\rho_{\text{crit}}) \left( \frac{3m}{4\pi \Delta_{\text{vir}}\rho_{\text{crit}}} \right)^{2/3} \]

\[ \sigma_{\text{virial}}^2 = 102.5 \times 0.9 \times \left( \frac{H(z)}{H_0} \right)^{1/3} \left( \frac{m}{10^{13} M_{\odot}/h} \right) \text{km/s} \]
Halo Motions:

\[ \sigma_{\text{halo}} = \frac{d \log(a \mathcal{G})}{d \log(a)} \star \sigma_{-1} \sqrt{1 - \frac{\sigma_0^4}{\sigma_1^4 \sigma_{-1}^4}} \]  \hspace{1cm} (39)  

\[ \sigma_j^2(R) = \frac{1}{2\pi^2} \int dk k^{2 + 2j} P^{\text{lin}}(k) W^2[kR] \]  \hspace{1cm} (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.
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- 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:

\[ w_{de} = w_0 + w_1 z \]  
\[ w_{de} = w_0 + w_1 \frac{z}{1.0 + z}. \]  

- Allows you to choose between 3 different concentration parameters:

\[ c = 10 \]  
\[ c = \bar{c} \]  
\[ c \text{ given by } p(c). \]
# LIST OF KEYWORDS CAN BE FOUND AT INPUT.txt

# PHYSICAL INPUT
hubble_uncertainty 0.70
T_cmb 2.728
omega_matter 0.27
spectral_index 0.966
scale_factor 0.5
window_index 0
omega_DE 0.73
index_w_de 0
w_0 -1.0
w_1 0.0
ST_p 0.3
ST_a 0.75
c_marginalize 1

# TECHNICAL 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" IF TRUE THE PROGRAM WILL SELECT THE REMAINING PARAMETERS TO BE READ DEPENDING ON THE VALUE OF THESE VARIABLE.

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
<table>
<thead>
<tr>
<th>Physical Parameters</th>
<th>Technical Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble $h$ parameter:</td>
<td>Growth Function: initial redshift 0</td>
</tr>
<tr>
<td></td>
<td>Growth Function: final redshift 100</td>
</tr>
<tr>
<td>CMB Temperature:</td>
<td>Growth Function: FDO routine EPS 1e-06</td>
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<tr>
<td>Omega Matter - z=0</td>
<td>Growth Function: delta scale factor 0.01</td>
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<td>Spectral Indices:</td>
<td>Growth Function: number of points 5000</td>
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<td>Starting Scale Factor:</td>
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<td>Window Function Indice:</td>
<td>Interpolation Sigma: number of points 1300</td>
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<tr>
<td>Omega Dark Energy - z=0</td>
<td>Interpolation Sigma: delta R 0.01</td>
</tr>
<tr>
<td>DE Eo3 Function Indice:</td>
<td>Interpolation Sigma: Initial R 0.001</td>
</tr>
<tr>
<td>DE Eo3 Constant Parameter:</td>
<td>Plot Dark Matter PS? true</td>
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<tr>
<td>DE Eo3 Slope Parameter:</td>
<td>Plot Galaxy PS? false</td>
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<tr>
<td>Sheth Tormen &quot;p&quot; Parameter:</td>
<td>Plot Velocity Distribution? false</td>
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<tr>
<td>Sheth Tormen &quot;a&quot; Parameter:</td>
<td>I1 and I2 EPS Integral Parameter 0.0001</td>
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<tr>
<td>Concentration Function Indice</td>
<td>One-Two Halo min number steps 4</td>
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</tbody>
</table>

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**Halo Model**
# Last Wave Number (PS evaluation) | 800

<table>
<thead>
<tr>
<th>k</th>
<th>(k^3/2π^2)</th>
<th>I_1</th>
<th>I_2</th>
<th>linear_delta</th>
<th>P_NL</th>
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<tbody>
<tr>
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<td>419.707</td>
<td>0.313802</td>
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<td>421.928</td>
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<td>34.5152</td>
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INTRODUCTION

Halo Model program

Thanks

[Image]

Vinicius Miranda

Halo Model
run: make -f Makefile.mak final_project

- Growth Function: EBO 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): 0.23
- 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 $k \gg 1 \text{Mpc}/h^{-1}$,
- 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."

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