Probing cosmic acceleration with galaxy clusters

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Outline

- Motivation
- Methodology
  - Known Problems (?)
  - Possible Solutions (?)
- Applications
  - Dark Energy Effects
  - Model Comparison
- Conclusions

Motivation

Why Cluster ?

: The largest virialized objects in the Univ

Formation solely depends on gravity irrelevant to gas dynamics, SF, feedback

Abundance and evolution $\Longleftrightarrow$ $P_{\rm lin}(k,a)$

Thus, abundance and distribution are determined by geometry of Univ and power spectrum

$$dn(M,z) = \frac{\rho_m^0}{M}\frac{d\ln\sigma(M,z)}{dM}\boxed{f(M)}dM$$

cosmology

simulation

$$\sigma_R^2(a) \equiv \left\langle \left| \frac{\delta M}{M(R,a)} \right|^2 \right\rangle = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k,a) \left|W(kR)\right|^2 dk,$$

$f(M)$: mass function

Methodology - I

- Problems (?)
  - Press-Schechter(PS) predicts too fe w high mass clusters and too many low mass ones
  - Too simple : not realistic ?
- Solutions (?) : traditional way
  - Find proper f(M) based on Si mulation
- Alternative
  - Check fundamental quantities σ , δ_c
- Evolutions outside and inside the overdensity region (R)

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_{\rm m} + \rho_{\rm de}) = \frac{8\pi G}{3}\rho_{\rm cr}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left[\rho_{\rm cluster} + (1 + 3\omega_{\rm de})\rho_{\rm dec}\right]$$

$$\dot{\rho}_{\rm dec} + 3(1 + \omega_{\rm de})\left(\frac{\dot{R}}{R}\right)\rho_{\rm dec} = \alpha\Gamma\,,$$

$$\text{where } \Gamma = 3(1 + \omega_{\rm de})\left(\frac{\dot{R}}{R} - \frac{\dot{a}}{a}\right)\rho_{\rm dec} \quad \text{with } 0 \le \alpha \le 1$$

- Find (semi)-analytic solutions for a ,R of spherical collapse model for general DE : compared to EdS model solution (cycloid) of Peebles

Methodology - II

- EdS cycloid nice but without DE solution

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2} = -\frac{4\pi G}{3}\langle\rho\rangle(1+\langle\delta\rangle)R$$

$$\frac{R}{R_m} = \frac{1}{2}(1-\cos\eta) \qquad \frac{t}{t_m} = \frac{1}{\pi}(\eta - \sin\eta)$$

- General solutions with DE (SL 10, SL & Ng 10)

$$x = \frac{a}{a_{\rm ta}}, \qquad y = \frac{R}{R_{\rm ta}}$$

$$d\tau \equiv H_{\rm ta}\sqrt{\Omega_{\rm m}(x_{\rm ta})}dt,\ \zeta \equiv \frac{\rho_{\rm cluster}}{\rho_{\rm m}}\Big|_{z_{\rm ta}},\ Q_{\rm ta} \equiv \frac{\rho_{\rm m}}{\rho_{\rm de}}\Big|_{z_{\rm ta}} = \frac{\Omega^0_{\rm m}}{\Omega^0_{\rm de}}(1+z_{\rm ta})^{-3\omega_{\rm de}}$$

$$\frac{2}{3}x^{\frac{3}{2}}F\left[\frac{1}{2}, -\frac{1}{2\omega_{\rm de}}, 1-\frac{1}{2\omega_{\rm de}}, -\frac{x^{-3\omega_{\rm de}}}{Q_{\rm ta}}\right] = \tau$$

$$\zeta_{13} = \left(\frac{\pi/2}{\frac{2}{3}F\left[\frac{1}{2},\frac{3}{2},\frac{5}{2},\frac{-1}{Q_{\rm ta13}}\right]}\right)^2 = \left(\frac{3\pi}{4}\right)^2\left(F\left[\frac{1}{2},\frac{3}{2},\frac{5}{2},-\frac{(1-\Omega^0_{\rm m})}{\Omega^0_{\rm m}}(1+z_{\rm ta})^{-1}\right]\right)^{-2}$$

- General solutions (continued)

$$\zeta_{\rm sk} = \left(\frac{3\pi}{4}\right)^2\Omega_{\rm mta}^{-0.724+0.157\Omega_{\rm mta}+\alpha(1+\omega_{\rm de})(1+3\omega_{\rm de})(0.064-0.368\Omega_{\rm mta})}$$

$$\begin{aligned}&\sqrt{y(1-y)} - \mathrm{ArcSin}[\sqrt{y}] + \frac{\pi}{2} + \left(-\frac{(1+3\omega_{\rm de})}{3}\Omega_{\rm mta}\right)^{2.7+0.1\Omega_{\rm mta}-3.4(1+\omega_{\rm de})-0.02\zeta_{\rm sk}+3(z_{\rm ta}-0.6)}\\ &= \sqrt{\zeta_{\rm sk}}(\tau-\tau_{\rm ta})\\ &= \frac{2}{3}\sqrt{\zeta_{\rm sk}}\left(x^{\frac{3}{2}}F\left[-\frac{1}{2\omega_{\rm de}},\frac{1}{2},1-\frac{1}{2\omega_{\rm de}},-\frac{x^{-3\omega_{\rm de}}}{Q_{\rm ta}}\right] - F\left[-\frac{1}{2\omega_{\rm de}},\frac{1}{2},1-\frac{1}{2\omega_{\rm de}},-\frac{1}{Q_{\rm ta}}\right]\right)\end{aligned}$$

- EdS virial solution instead of collaped one by using $z_{\rm vir} = ½\ z_{\rm ta}$

$$\frac{2}{3}x^{\frac{3}{2}} = \tau \qquad \zeta = \left(\frac{3\pi}{4}\right)^2 \qquad \frac{3}{20}(12\pi)^{\frac{2}{3}} \simeq \boxed{1.69}$$

$$\sqrt{y(1-y)} - \mathrm{ArcSin}[\sqrt{y}] + \frac{\pi}{2} = \sqrt{\zeta}\left(\tau - \frac{2}{3}\right) = \frac{\pi}{2}\left(x^{\frac{3}{2}} - 1\right)$$

$$\Delta_c^{\rm EdS} = \zeta\left(\frac{x_c}{y_{\rm vir}}\right)^3 = \left(\frac{3\pi}{4}\right)^2\left(\frac{2^{\frac{2}{3}}}{2^{-1}}\right)^3 = 18\pi^2 \simeq \boxed{178}$$

$$\Delta_{\rm vir}^{\rm EdS} = \zeta\left(\frac{x_{\rm vir}}{y_{\rm vir}}\right)^3 = \left(\frac{3\pi}{4}\right)^2\left(\frac{\left(\frac{1}{\pi}+\frac{3}{2}\right)^{\frac{2}{3}}}{2^{-1}}\right)^3 = 18\pi^2\left(\frac{1}{2\pi}+\frac{3}{4}\right)^2 \simeq 147$$

$$\delta_{\rm lin}(z_{\rm vir}) = \frac{3}{5}(\sqrt{\zeta})^{\frac{2}{3}}\left(\left(\frac{3}{4}+\frac{9\pi}{8}\right)\frac{1}{\sqrt{\zeta}}\right)^{\frac{2}{3}} = \frac{3}{20}(6+9\pi)^{\frac{2}{3}} \simeq 1.58$$

Application - I

- Do we need to care about small diff erence between 1.69 and 1.58 ?
  - PS mass function includes δ_c
  - PS used in dn(M,z) $f_{PS}(M,z) = \sqrt{\frac{2}{\pi}} \frac{\delta_c}{\sigma} \exp\left[-\frac{\delta_c}{2\sigma^2}\right]$
- Nonlinear overdensity in simulation use 200 in any case instead of 178, thus, is 147 important ?
- However, DE also alters $P_{\rm lin}$ and thus σ
  - DE is usually not clustered at small scale due to relativistic dispersion of its fluctuation and usually DE effects on σ_8 is ignored

- DE effects on $P_{\rm lin}$, σ (Ma etal 99, SL & Ng 10))

$$P(k,a) = A_Q k^{n_s} T_Q^2(k) \left(\frac{D(a)}{D(a_0)} \right)^2$$

$$A_Q = 2\pi^2 \delta_H^2 (c/H_0)^{n_s+3}$$

$$\begin{aligned}
\delta_H &= 2.05 \times 10^{-5} \alpha_0^{-1} (\Omega_m)^{c_1 + c_2 \ln \Omega_m} \exp[c_3(n_s - 1) + c_4(n_s - 1)^2], \text{with} \\
c_1 &= -0.789 |\omega_Q|^{0.0754 - 0.211 \ln|\omega_Q|}, c_2 = -0.118 - 0.0727\omega_Q, c_3 = -1.037, c_4 = -0.138 \\
\alpha &= (-\omega_Q)^s \text{ with } s = (0.012 - 0.036\omega_Q - 0.017\omega_Q^{-1})\big(1 - \Omega_m(a)\big) \\
&\quad + (0.098 + 0.029\omega_Q - 0.085\omega_Q^{-1}) \ln \Omega_m(a).
\end{aligned}$$

$$\sigma_R^2(a) \equiv \left\langle \left| \frac{\delta M}{M(R,a)} \right|^2 \right\rangle = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k,a) \left| W(kR) \right|^2 dk,$$

$$\sigma_8(\omega_Q) = (-\omega_Q)^{0.72 + 0.36\omega_Q} \sigma_8(\omega_Q = -1)$$

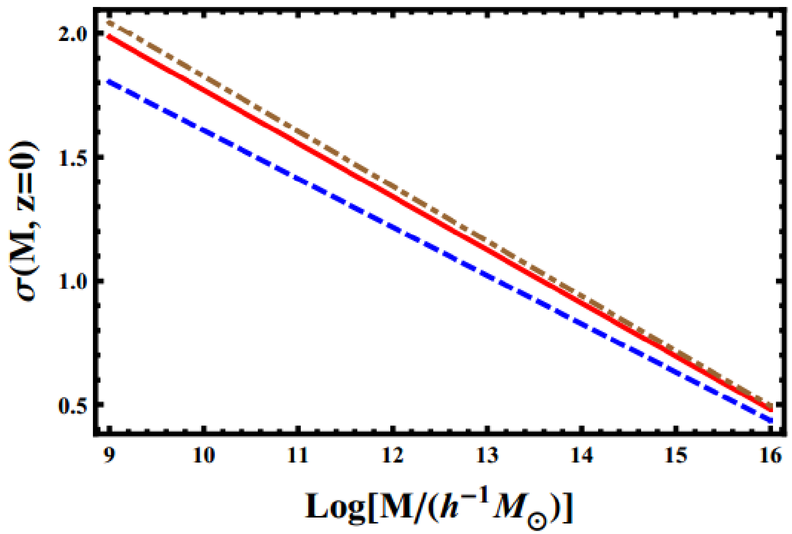
$$\sigma(M,z) \simeq (-\omega_Q)^{0.72+0.36\omega_Q} \left(3.90 - 0.215 \log\left[\frac{M}{h^{-1}M_\odot}\right]\right) \left(\frac{D_g(z)}{D_g(z_0)}\right)$$

$$R_8 = 8\ \mathrm{h^{-1}Mpc} \text{ as } M_8 = 5.95 \times 10^{14} \Omega_{\rm m}^0 h^{-1} \mathrm{M}_\odot$$

Application - II

- DE effects on Matter power spectrum and σ₈

More matter in the past for the smaller value of ω to give larger value of δ at present



−0.8
ırdt's

Figure 3: $\sigma(M, z=0)$ for different values of $\omega_Q = -1.1, -1.0$, and -0.8 (from top to bottom)

- DE effects on σ(M,z)

Application - III

- DE effects on Growth factor and Volume (SL & Ng 10)

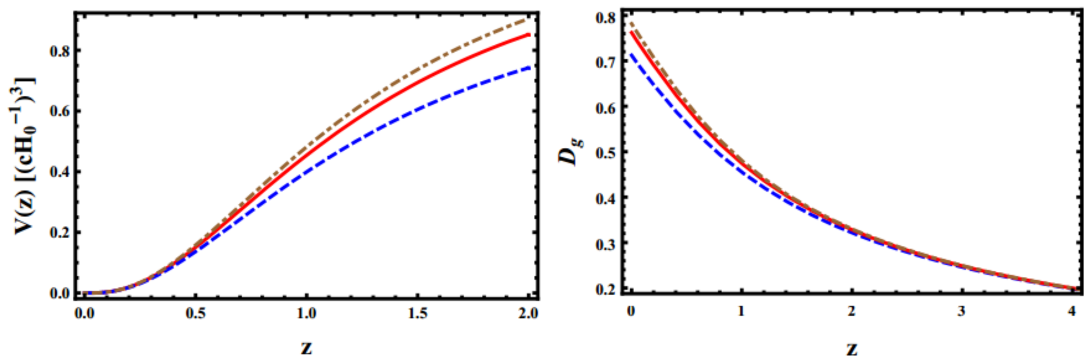


Figure 4: a) $V(z)$ for different values of $\omega_Q = -1.1, -1.0$, and -0.8 (from top to bottom). b) $D_g(z)$ for the same values of ω_Q as in the left panel.

- comoving number density of virialized objects

$$dn(M,z) = \sqrt{\frac{2}{\pi}}\frac{\rho_m^0}{M^2}\left|\frac{d\ln\sigma}{d\ln M}\right|\frac{\delta_c}{\sigma}\exp\left[-\frac{\delta_c^2}{2\sigma^2}\right]dM$$

$$f_{\rm ST}(\sigma) = A\sqrt{\frac{2b}{\pi}}\exp\left[-\frac{b\delta_c^2}{2\sigma^2}\right]\left[1+\left(\frac{\sigma^2}{b\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}$$

$$f_{\rm mod}(\sigma,z) = \tilde{A}\sqrt{\frac{2}{\pi}}\exp\left[-\frac{\tilde{b}\delta_c^2}{2\sigma^2}\right]\left[1+\left(\frac{\sigma^2}{\tilde{b}\delta_c^2}\right)^{\tilde{p}}\right]\left(\frac{\delta_c\sqrt{\tilde{b}}}{\sigma}\right)^{\tilde{q}}$$

Application - IV

- Results (data from Calberg et al 96)

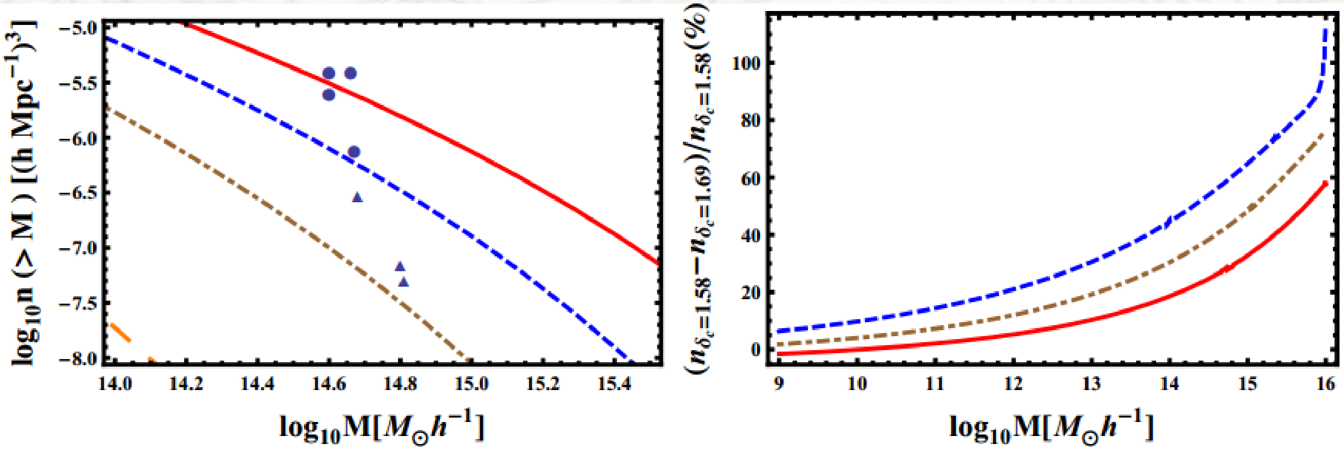


Figure 5: a) The comoving number density of clusters n of mass greater than M for different values of $z = 0$, 0.5, 1.0, and 2.0 (from top to bottom) when $\omega_Q = -1$ and $\delta_c = 1.58$. The circular ($z \simeq 0$) and triangular ($0.18 \leq z \leq 0.85$) dots represent the data from Ref. [33]. b) Errors of n when we use the correct threshold density contrast $\delta_c = 1.58$ instead of 1.69 for different values of $z = 0$, 0.5, and 1.0 (from bottom to top).

Conclusions

- We found the correct values of δ_c and Δ_{lin}
- Dark energy is known to be clustered only at large scale. However, it still affects on not only V and D but also P_{lin} and thus σ_8
- We apply correct values of δ_c and effects of DE on σ_8 to solve shortage problem of high mass clusters with PS formalism
- Low mass is still problem with PS. Not only gravity?