Cold dark energy and cosmological parameter estimation

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Texas Symposium 2015, Geneva, December 15
What cold dark energy & why

• k-essence with negligible speed of sound

$$c_s^2 = \frac{\delta p_Q}{\delta \rho_Q} = \frac{\rho_Q + \bar{p}_Q}{\rho_Q + \bar{p}_Q + 4M^4}$$

• comoving with CDM -> FLRW solution

• $c_s = 0$ vs. $c_s = 1$: ‘most extreme’ cases viable for $w < -1$

• DE pert. impact structure formation:
linear & non-linear regime, sign for dynamical DE
-> test scale dependence
Cold dark energy - CMB power spectrum

But e.g. Planck 2015 XIV results:

no change on w-limits when sound speed added as parameter

-> other probes, go non-linear
Cold dark energy - some observables

CMB lensing

Hojjati & Linder '15

Majerotto, Sapone, Schäfer '15

galaxy clustering + CMB, Takada '06

Planck + galaxy + cluster, Basse et al. '14

<table>
<thead>
<tr>
<th>CMF</th>
<th>$w_0$</th>
<th>$w_m$ (fixed)</th>
<th>$c_s^2$</th>
<th>$\log c_s^2$</th>
<th>$\log c_s^2$ 68% (95%) C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>equation (3.1)</td>
<td>-0.83</td>
<td>0.00</td>
<td>$10^{-6}$</td>
<td>-6</td>
<td>$&lt;-5.9(-3.5)$</td>
</tr>
<tr>
<td>equation (7.3)</td>
<td>-0.83</td>
<td>0.00</td>
<td>$10^{-6}$</td>
<td>-6</td>
<td>$&lt;-1.4(1.4)$</td>
</tr>
<tr>
<td>$P_{\text{lin}}(k,z)$ only</td>
<td>-0.83</td>
<td>0.00</td>
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<td>-6</td>
<td>$&lt;-2.5(0.12)$</td>
</tr>
</tbody>
</table>
Parameter estimation - Cluster Cosmology

- Information on: expansion - background structure growth - linear / non-linear
- sensitive to scale dependence

- extended BCS (Ebeling et al ’98, 2000), REFLEX (Böhringer et al ’04), MACS (Ebeling et al ’01, ’07, ’10)
- X-ray follow-up 94 clusters (Mantz et al ‘14b)
- WtG: WL calibration 50 clusters (Subaru/CFHT, vd Linden et al ‘14)

Allen, Evrard, Mantz ’11, credits: X-ray - Mantz, Optical - v. d. Linden, SZ - Marrone
Cluster number counts

Tinker-HMF: \( \frac{d n_T}{d M} (M, z) = f(\sigma) \ \frac{\bar{\rho}_m}{M} \ \frac{d \log \sigma^{-1}}{d M} \) (Tinker et al '08)

Sheth-Tormen: \( \frac{d n_{ST}}{d M} (M, z) = \nu f(\nu) \ \frac{\bar{\rho}_m}{M^2} \ \frac{d \log \nu}{d \log M} \) (Sheth & Tormen '09)

\( \nu f(\nu) = A \sqrt{\frac{\alpha \nu}{2\pi}} \left[ 1 + (\alpha \nu)^{-p} \right] \exp \left[ -\alpha \nu \right] \)

with peak height \( \nu = \left( \frac{\delta_c}{\sigma_M} \right)^2 \)

via Spherical Collapse: \( \delta_c(z) \)
Spherical Collapse formalism

- spherical homogeneous top-hat overdensity ≈ closed FLRW universe with scale factor $R$

- SC approximation valid for $c_s = 0$ and $c_s = 1$

Pseudo-Newtonian approach:

$$\dot{\delta}_i + 3H \left( c_{s,i}^2 - w_i \right) \delta_i + \frac{\theta_i}{a} \left[ (1 + w_i) + (1 + c_{s,i}^2) \delta_i \right] = 0$$

$$\dot{\theta}_i + 2H \theta_i + \frac{\theta_i^2}{3a} = \nabla^2 \phi$$

$$\nabla^2 \phi = -4\pi G \sum_i \left( 1 + 3c_{s,i}^2 \right) a^2 \tilde{\rho}_i \delta_i$$

see e.g. Pace et al.’14, Creminelli et al. ‘08
Linear density threshold of collapse $\delta_c (z)$

dependence on cosmological parameters
Virial threshold

\[ \Delta_{\text{vir}} = (\delta_{NL,\text{vir}} + 1) = (\delta_i + 1) \left( \frac{a_{\text{vir}}}{a_i} \right)^3 \left( \frac{R_i}{R_{\text{vir}}} \right)^3 \]

(with time of virialization depending on turn-around)

dependence on cosmological parameters
Virial threshold

\[ \Delta_{vir} = (\delta_{NL, vir} + 1) = (\delta_i + 1) \left( \frac{a_{vir}}{a_i} \right)^3 \left( \frac{R_i}{R_{vir}} \right)^3 \]

(with time of virialization depending on turn-around)

\[ \Delta_{vir} (z) = - \left[ 18\pi^2 + a (1 - \Omega_m (z)) + b (1 - \Omega_m (z))^2 \right] / \Omega_m (z) \]
include: DE mass

\[ M_{e,v} = \frac{4\pi}{3} R_v^3 \bar{\rho}_{e,v} \delta_{e,v} \]

\[ M_{m,v} = \frac{4\pi}{3} R_v^3 \bar{\rho}_{m,v} (\delta_{m,v} + 1) \]

\[ \epsilon(z) = \frac{M_{e,v}}{M_{m,v}} \]

[Creminelli et al '08]

\[ M \rightarrow M (1 + \epsilon) : \quad \frac{dn}{d \log M}(M, z) \rightarrow \frac{dn}{d \log M}(M (1 - \epsilon), z) \]
Calibrated HMF: $\delta_c \Delta_{\text{vir}} \epsilon$

$$\frac{dn_{cal}}{dM} (M, z) = \frac{dn_{ST}/dM (M, z; c_s = 0)}{dn_{ST}/dM (M, z; c_s = 1)} \ast \frac{dn_T}{dM} (M, z)$$

- Account for non-linear effects via ratio ST-HMFs
- Shape of Tinker-HMF
  - solely based on linear order
  - accurate N-body fit
  - widely used in parameter estimation (cluster)
Calibrated HMF:

\[
\frac{dn_{\text{cal}}}{dM}(M, z) = \frac{dn_{ST}/dM(M, z; c_s = 0)}{dn_{ST}/dM(M, z; c_s = 1)} \times \frac{dn_T}{dM}(M, z)
\]

\[-\rightarrow\text{ scale dependence, high-mass end}\]
Calibrated HMF:

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\]

\[
\rightarrow \text{scale dependence, high-mass end}
\]
+ Cluster sample

+ Account for errors & covariances in HMF

+ Spherical Collapse: $\delta_c, \Delta_{vir}, \epsilon$

+ Calibrated HMF: \[ \frac{dn_{cal}}{dM} (M, z) \propto \frac{(dn_{ST}/dM)_{c_s=0}}{(dn_{ST}/dM)_{c_s=1}} \]

MCMC (CAMB & CosmoMC)
calibrated, preliminary

\[ \Omega_m = 0.263 \pm 0.015 \]

\[ w = -1.11 \pm 0.06 \]

\[ \sigma_8 = 0.813 \pm 0.032 \]

* CH (+Rapetti, Cataneo, Mantz, Allen, vd Linden, Applegate) to be submitted
• feasible to include non-linear model characteristics

• possible bias, needed for precision cosmology

• test for dynamical DE, scale dependence! different for modified gravity, neutrino mass

Improvements

• use lensing, other combinations

• bigger effect for early DE

• let the sound speed vary

Mantz et al. ‘15a
backup
Cluster sample

Select bright, relaxed, redshift complete clusters: set of 224, $L > 2.55 \times 10^{44} h_{70}^{-2} \text{erg/s}$

- extended BCS
  (Ebeling et al ’98, 2000)
- REFLEX
  (Böhringer et al ’04)
- MACS
  (Ebeling et al ’01, ’07, ’10)
+ X-ray follow-up of 94 clusters (Mantz et al ’14b)
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Scaling relations: observable-mass

X-ray follow-up of 94 clusters

mean relation + intrinsic scatter, <10% scatter in L-M-relation

simultaneous analysis of (flux-lim.) survey and follow-up data

+ ‘Weighing the Giants’ (WtG):
  Weak lensing mass calibration of 50 clusters (Subaru/CFHT)

Mantz et al ‘14b
Gas mass fraction $f_{gas}$

$$f_{gas}^{\Lambda CDM}(z; \theta_{2500}^{\Lambda CDM}) = f_{gas}^{true}(z; \theta_{2500}^{\Lambda CDM}) \left( \frac{d_A^{\Lambda CDM}}{d_A^{true}} \right)^{3/2}$$

with

$$f_{true}^{gas}(z; \theta_{2500}^{\Lambda CDM}) \propto \left( \frac{\Omega_b}{\Omega_m} \right)$$

luminous & dyn. relaxed clusters
- 40 clusters within $0.07 < z < 1.1$

Mantz et al '14a
Tracking the radius evolution example

\[ w = -0.7 \]

\[ \delta_c \]

\[ R/R_\odot \]

\[ \lambda = 1.6868 \]