Testing Cosmology with Extreme Galaxy Clusters

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In the context of. . .

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Overview

Standard Concordance Model

Λ cold dark matter (ΛCDM) approach

- hierarchical bottom-up structure formation
- small perturbations in initial distribution of CDM
- large fluctuations are very rare!

Decoupling matter from radiation

Decoupling of baryonic matter from radiation happens after decoupling of dark matter

Observations of the early universe at 380.000 years

Three driving mechanism

- Sachs-Wolfe effect
  - explains the change of energy of photons due to early gravitation potentials
  - indicator for dark matter and dark energy
- Silk diffusion damping
  - obstruct the development of baryonic matter density fluctuations due to radiation
  - dark matter must have decoupled before barionic matter
- barionic acoustic oscillations of the plasma
  - caused by the interaction between gravitation and radiation in the early universe
  - observable in the CMB

Adaptations to ΛCDM

Possible extensions

- non-Gaussian primordial density distribution
- modified theory of gravity
- scalar field scenarios (e.g. dark energy)
- models allowing an enhanced rate of structure formation

Overview

1. Structure Formation
2. Extreme Value Statistics (EVS)
3. Mass distribution in clusters
4. Test results with large clusters

Bayes statistics

Conditional probabilities

$$P(A \cap B) = P(A|B) \cdot P(B) = P(B|A) \cdot P(A)$$

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)}$$

Conditional distributions (Bayes theorem)

$$P(\theta = \theta_0 | x) = \frac{f(x|\theta_0) \cdot P(\theta = \theta_0)}{\sum_{\theta' \in \Theta} f(x|\theta') \cdot P(\theta = \theta')}$$

Bayes statistics

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Bayes statistics

Bayes approach

$$P(\theta = \theta_0|x) \propto f(x|\theta_0) \cdot P(\theta = \theta_0) \rightarrow \max$$
$$\theta_0 = \underset{\theta \in \Theta}{\operatorname{argmax}} f(x|\theta) \cdot P(\theta)$$

- observations: $x = (x_1, \ldots, x_n)$
- likelihood: $f(x|\theta) = \prod_{i=1}^{n} f(x_i|\theta) = \mathcal{L}(\theta|x)$
- a-priori distribution: $P(\theta)$
- a-posterior distribution: $P(\theta|x)$

Likelihood

Likelihood estimation

- observations: $x = (x_1, \ldots, x_n)$
- no a-priori distribution: $P(\theta) \equiv 1$
- maximize likelihood: $\mathcal{L}(\theta|x) \rightarrow \max$
- equivalent to maximize log-likelihood: $\log \mathcal{L}(\theta|x) \rightarrow \max$

Gaussian likelihood

Example - Gaussian probability density function f

- observations: $x = (x_1, \ldots, x_n)$
- Gaussian probability density function:
  $f(x|\mu, \sigma) = \frac{1}{2\pi\sigma^2} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- maximize log-likelihood: $\log \mathcal{L}(m_n, s_n | x_1, \ldots, x_n) =$
  $$= -\frac{n}{2}\log(2\pi s_n^2) - \frac{1}{2s_n^2}\sum_{i=1}^{n}(x_i - m_n)^2 \rightarrow \max$$
- results in: $m_n = \bar{x}, s_n^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$
- NB: not "erwartungstreu", since $E(s_n^2) = \frac{n-1}{n}\sigma^2$

Modeling of mass distribution of clusters

Mass distribution of clusters

- N observations with $M_{\max} = \sup\{M_1, \dots M_N\}$
- cum. distr.: $P(M_{\max} \leq m) = \prod_{i=1}^{N} F_i(M_i \leq m) = F^N(m)$
- prob. dens. func: $p(M_{\max} = m) = N f(m) F(m)^{N-1}$
- $f(m) \propto \frac{dn(m)}{dm}$ is the initial mass function

Ultimate goal

Use maximum likelihood approach to estimate (parameters of) $f(m)$ and $F(m)$ resp. $p(m)$ and $P(m)$ with given observations $\{M_i\}$ of galaxy clusters. Are the most extreme clusters within certain boundaries?

Involve variable red-shifts

Involving variable red-shifts

$$f(m) = \frac{1}{N}\int_{z_{\min}}^{z_{\max}} \frac{dn(m,z)}{dm}\frac{dV}{dz}dz$$

$$F(m) = \frac{1}{N}\int_{z_{\min}}^{z_{\max}} \int_{0}^{m} \frac{dn(M,z)}{dM}\frac{dV}{dz}dM\,dz$$

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Modeling the initial mass function

Yes, it is possible, but it is tricky and outruns the frame of this talk. In short it takes:

- lots of observations
- auto-correlation function
- a linear matter power spectrum
- top hat window to smooth
- a linear growth function (redshift)
- variance of matter field
- mass corrections
- lots of previously estimated parameters

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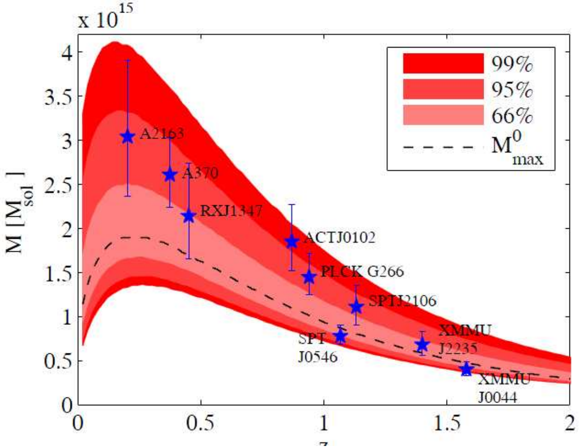
List of extreme clusters

Cluster	z	$M_{200m}^{Edd}/M_\odot$
A2163[1]	0.203	$3.04^{+0.87}_{-0.67} \times 10^{15}$
A370[1]	0.375	$2.62^{+0.87}_{-0.67} \times 10^{15}$
RXJ1347[1]	0.451	$2.14^{+0.60}_{-0.48} \times 10^{15}$
ACT-CL J0102[2]	0.87	$1.85^{+0.42}_{-0.33} \times 10^{15}$
PLCK G266[3]	0.94	$1.45^{+0.27}_{-0.20} \times 10^{15}$
SPT-CL J2106[4]	1.132	$1.11^{+0.24}_{-0.20} \times 10^{15}$
SPT-CL J0546[5]	1.067	$7.80^{+1.27}_{-0.90} \times 10^{14}$
XXMU J2235[6]	1.4	$6.82^{+1.52}_{-1.23} \times 10^{14}$
XXMU J0044[7]	1.579	$4.02^{+0.88}_{-0.73} \times 10^{14}$

Expected size of extreme clusters



Conclusion

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All extreme galaxy cluster masses are within a 99% percentile of expectation. There is no urge to make adaptations to the standard "concordance" ΛCDM model.