Testing Cosmology with Extreme Galaxy Clusters

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Harrison & Coles (2011) MNRAS 418, L20, arXiv:1108.1358

Harrison & Coles (2012) MNRAS 421, L19, arXiv:1111.1184

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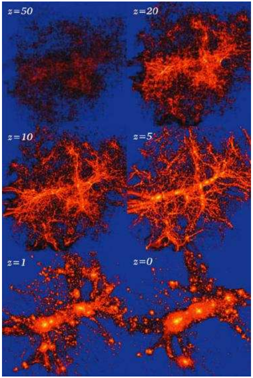
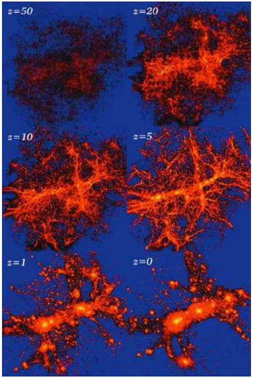
- Makes definite predictions for structure formation
- Many of the plausible extensions to ΛCDM are capable of enhancing (or depleting) structure formation



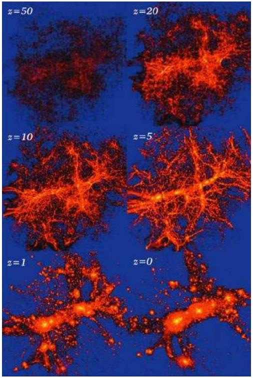
Structure Formation

- Standard Model Cosmology in 2012
- Makes definite predictions for structure formation
  - 'bottom up' or hierarchical
  - Haloes, filaments, voids
  - Quantitatively: HMF, linear growth function
- Many of the plausible extensions to ΛCDM are capable of enhancing (or depleting) structure formation



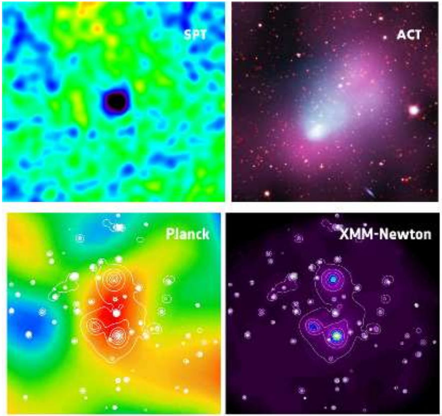
Structure Formation

- Standard Model Cosmology in 2012
- Makes definite predictions for structure formation
- Many of the plausible extensions to ΛCDM are capable of enhancing (or depleting) structure formation
  - Priomordial non-Gaussianity
  - Scalar fields
  - Modified gravity, *etc*



High m, z Clusters – Concerns for ΛCDM?

- Have recently begun to probe the largest structures at higher and higher redshifts (XMM-Newton, SPT, ACT, Planck)



High m, z Clusters – Concerns for ΛCDM?

- Have been claims that some of the galaxy clusters observed are too massive, too early to have been produced by the ΛCDM model

(Jimenez & Verde, Hoyle et al, Cayon et al, Holz & Perlmutter, Jee et al, Enqvist et al)

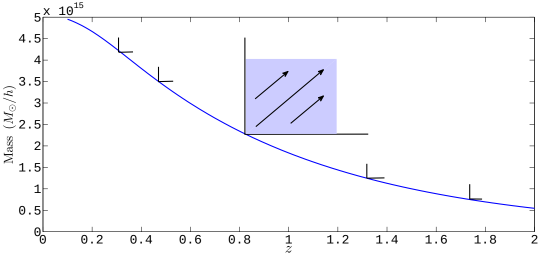
  - Calculate abundance of clusters $\langle N(> m_{cl}, > z_{cl})\rangle$ in a survey from the HMF
  - Find fraction of realisations of ΛCDM with such a cluster to be very low $\rightarrow$ tension with ΛCDM
  - Point out tension can be eased with large f_{NL} ($\sim 300 - 500!$)

High m, z Clusters – Concerns for ΛCDM?

- Unfortunately, these analyses shown to be biased as count the wrong number of 'equally rare' events

  Fergus Simpson on CosmoCoffee, Hotchkiss (2011)

- Overestimate the tension with ΛCDM
- Take bias into account: tension goes away



Hotchkiss (2011)

High m, z Clusters – Concerns for ΛCDM?

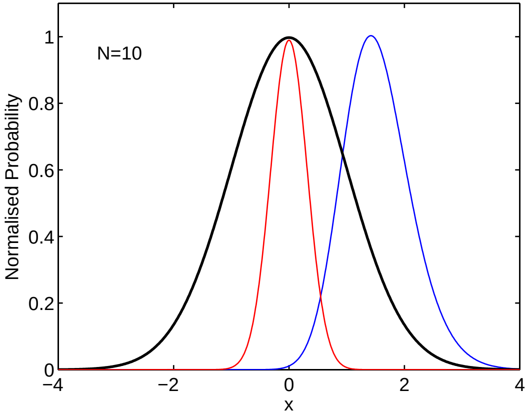
- But high-m, high-z clusters are still interesting
  - Have only surveyed fraction of the sky with enough sensitivity for these objects
  - A ΛCDM-killer could still be out there

'Rareness' based estimates can clearly be slippery,
is there a cleaner option?

Can ask: what do we expect the most massive cluster in the Universe to be?
Answer lies in Extreme Value Statistics

Predicting Extremes

- Usual question: "What is the distribution of sample means?"
- EVS question: "What is the distribution of sample extrema?"



Extreme Value Statistics

- Have a long history in environmental sciences, finance *etc*...
- Exact distribution for maximum M_{max} of N i.i.d. random variates from underlying pdf $f(m)$, cdf $F(m)$

$$\begin{aligned} \Phi(M_{\rm max} \leq m; N) &= F^N(m) \\ \phi(M_{\rm max} = m; N) &= Nf(m)\left[F(m)\right]^{N-1} \end{aligned}$$

- Just as CLT, is an asymptotic distribution as $N \to \infty$

$$P_{GEV}(m; \alpha_N, \beta_N, \gamma) = \exp\left\{ -\left[1 + \gamma\left(\frac{m - \alpha_N}{\beta_N}\right)\right]^{-1/\gamma} \right\}$$

- Where γ depends on the underlying distribution

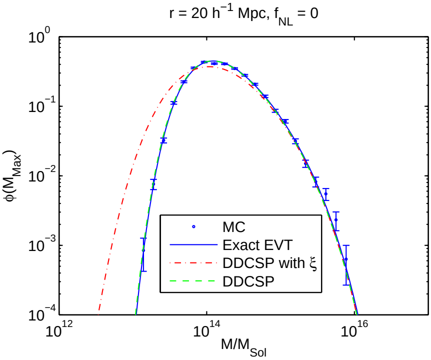
EVS of HMFs - Exact Distribution

- For CDM haloes, we know $f(m)$: the Halo Mass Function
- Can construct PDF:

$$
\begin{aligned}
f(m) &= \frac{1}{n_{\text{tot}}} \frac{dn(m)}{dm}, \\
F(m) &= \frac{1}{n_{\text{tot}}} \left[\int_{-\infty}^{M} dM \, \frac{dn(M)}{dM} \right].
\end{aligned}
$$

- ...and feed this into $\phi(M_{\max} = m; N)$ with $N = n_{tot} V$
- Can predict the PDF of highest mass object on a spatial hypersurface

EVS of HMFs - Results



IH & Coles (2011)

- Well matches other results (& N-body simulations)

Davis *et al* 2011 (DDCSP)

$$\Phi^{\mathrm{void}}(M_{\max} = m) = \frac{dP_0(m)}{dm}$$

$$P_0(m) = \exp(-n(> m)V)$$

Comparing with Observations

Can do EVS for simulations, what about observations?

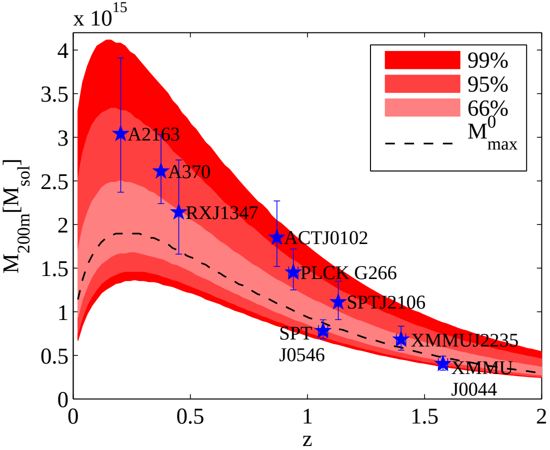
- EVS in a survey, not just a spatial hypersurface
  - $n(m) \to n(m,z)$
  - $V \to dV/dz$

$$\begin{aligned} f(m) &= \frac{1}{N_{tot}} \left[f_{sky} \int_{z_{min}}^{z_{max}} dz \, \frac{dV}{dz} \frac{dn(m,z)}{dM} \right], \\ N_{tot} &= \left[f_{sky} \int_{z_{min}}^{z_{max}} \int_{-\infty}^{\infty} dz \, dM \, \frac{dV}{dz} \frac{dn(m,z)}{dM} \right]. \end{aligned}$$

- Specify cosmology
  - WMAP7 parameters
  - Tinker HMF
  - Use cluster M_{200m}^{Edd} masses

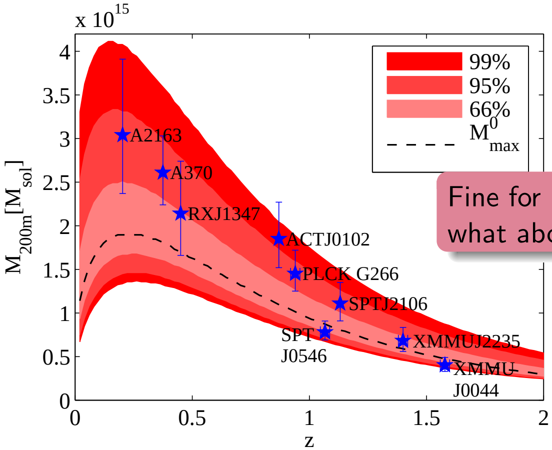
Result – ΛCDM Survives

- Compute confidence regions in bins $\Delta z = 0.02$, with $f_{sky} = 1$ and plot clusters



IH & Coles (2012)

Result – ΛCDM Survives



Fine for ruling out ΛCDM, what about alternative models?

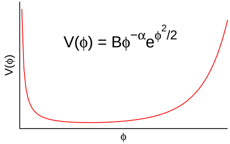
IH & Coles (2012)

Two Toy Models

1. Primordial non-Gaussianity
   - Generated by non-vanilla inflaton Lagrangians
   - $f_{NL} \sim 300 - 500$ suggested as explanation for high-m, high-z clusters
   - Include via non-Gaussian correction factor $\mathcal{R}(f_{\mathrm{NL}})$ to a ΛCDM mass function:

$$\begin{aligned} \mathcal{R}(f_{NL}) &= n^{th}_{nG}(f_{NL})/n^{th}_{G}, \\ n^{sim}_{nG}(f_{NL}) &= \mathcal{R}(f_{NL})n^{sim}_{G} \end{aligned}$$

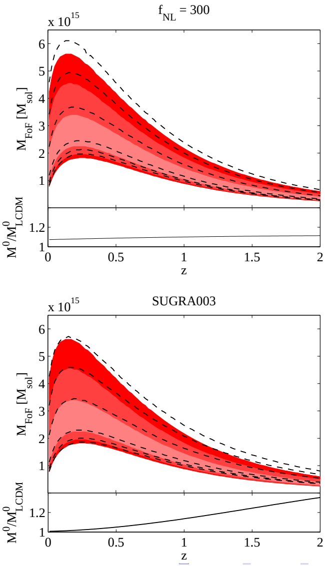
2. Coupled scalar field Dark Energy 'SUGRA003'
   - SUGRA motivated quintessence model with 'bounce' (Brax & Martin 1999)



   - Structure formation enhanced (depleted) before (after) the bounce

Two Toy Results

- Make use of ΛCDM and SUGRA003 CoDECS simulations (Baldi 2011)
    - $h(z)$
    - $D(z)$
    - Halo mass function
- Large clusters at high and/or low redshifts can disfavour different models of enhanced structure formation



Beyond a Null Test

- Can test one cluster at a time, what about information from multiple clusters to do proper parameter estimation?
- To get constraints on a parameter, need to guarantee are not missing any more extreme clusters in our survey
- SZ surveys are 'nearly mass-limited to arbitrarily high redshift'

Consider an idealised survey:
complete above some mass threshold $m_{thresh} \sim 5 \times 10^{14} M_\odot$

f_{NL} from 'idealised' SPT

- Take the 26 highest SZ S/N clusters from SPT Williamson et al (2011), treat as complete above the mass of the lowest of these 26 (i.e. $m_{thresh} = \min\{m_1 \ldots m_{26}\}$)
- Define redshift bins
  - Occupied bins: Treat this as most massive cluster
  - Unoccupied bins: Most massive cluster is not more massive than m_{thresh}
- Take sharp priors on everything else (σ_8, hmf parameters...)
- Calculate probabilities for both types of bins and form likelihood for $f_{\rm NL}$

$$\mathcal{L}(f_{\rm NL}) = \prod_{Occ.} \phi(m_{obs}; f_{\rm NL}, \Delta z_i) \prod_{Unocc.} \left[\int_{-\infty}^{m_{thresh}} \phi(m; f_{\rm NL}, \Delta z_j)\, dm\right]$$

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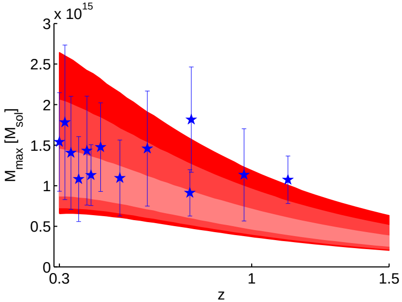
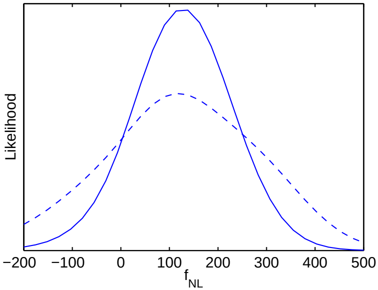
Likelihood for $f_{\rm NL}$





- Have 13 filled bins

- $f_{\rm NL} = 128^{+75}_{-119}$, $\sigma_8 = 0.801$
- $f_{\rm NL} = 101^{+111}_{-197}$, $\sigma_8 = 0.801 \pm 0.030$

Preliminary!

Summary and Prospects

- Extreme Value Statistics can predict PDF for the most massive cluster M_{max} in a given cosmology
- Observation of even a single cluster significantly larger than M_{max} is good evidence against that cosmology
  - ΛCDM survives current observations
  - Other models easily tested
- In order to do parameter estimation, require survey with mass limit less than expected region for M_{max}

Open Questions

- EVS for cluster *observables* (rather than masses)?
- Are we throwing too much information away?
- Extension to other objects (e.g. lenses, voids, quasars, superstructures...)
- How much can we trust the halo mass function?

End

Thanks