Growth of Cosmic Structure: the Next Frontier

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 $w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$

Current evidence for dark energy is impressively strong

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Big questions

1. Is the cosmic acceleration due to something other than vacuum energy?

2. Does GR self-consistently describe the acceleration?

Wish List

Goals:

 $w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$ $\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$

Measure $\Omega_{\rm DE}, w$ Measure $\rho_{\rm DE}(z)$ or w(z)Measure any clustering of DE

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DE theory target accuracy, in e.g. w(z), not known *a priori*

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1. Neutrino masses: $(\Delta m^2)_{sol} \approx 8 \times 10^{-5} \text{ eV}^2$ $(\Delta m^2)_{atm} \approx 3 \times 10^{-3} \text{ eV}^2$ $\sum_{i=0.10 \text{ eV}^* \text{ (inverted)}}^* (\text{assuming } m_3=0)$

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$$\sum_{i=0.10 \text{ eV}^* \text{ (inverted)}} \sum_{i=0.10 \text{ eV}^* \text{ (inverted)}}$$

2. Higgs Boson mass (before LHC 2012): m_H ≤ O(200) GeV (assuming Standard Model Higgs)

Current constraints on w(z): largely from geometrical measures



Planck XIV, "Dark Energy and Modified Gravity", arXiv:1502.01590

Dark Energy suppresses the growth of density fluctuations

(a=1/4 or z=3) 1/4 size of today (a=1/2 or z=1) 1/2 size of today

(a=1 or z=0) Today



with DE

without DE

Huterer et al, Snowmass report, 1309.5385

The Virgo Consortium (1996)

Using growth to separate GR from MG:

For example:



Modified gravity

GR + dark energy

Growth of density fluctuations can decide: $\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M \delta = 0$ (assuming GR) LSS tracers and their statistical probes

Clusters of galaxies

1-point function - cluster counts (dn/dlnM), sens to DE
2-pt function - sensitive to primordial NG

Galaxies: LRG, ELG, also quasars

2-point function: pretty well understood, easily measured
anisotropic 2-pt function - Redshift Space Distortions (RSD)
3-pt function: powerful, but issues in predicting b_G(k, a, env)
also galaxy-CMB cross-correlation

•Weak Lensing Shear:

2-point function: measurements systematics dominated
3-pt function: future; systematics a huge challenge
also gal-gal (γ-g), shear peaks,

Counting galaxy clusters



Allen, Evrard & Mantz review, 2011

cluster number (measure)



(simulations)

$$(z) \ \frac{r(z)^2}{H(z)}$$

 \mathbf{v}



distance factors (theory)

Vikhlinin et al, 2009

10¹⁵



Hardest part of this: simulating/calculating the covariance matrix (that is: clustering in nonlinear regime)



Giannantonio et al. 2013

Weak Gravitational Lensing



WL systematics are very challenging:

$$\gamma^{\rm obs} = \gamma^{\rm true} (1 + m) + \gamma^{\rm add} + \gamma^{\rm noise}$$

Measured 2-pt correlation func from CFHTLens



Next Frontier: Growth (+geom) from LSS

	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{\rm max}^2$	∝k _{max} ³
can slice in	λonly	λ, M, bias
temporal evol.	no	yes
systematics?	relatively clean	relatively messy
theory modeling	easy	can be hard

Systematic Errors, top two:

Photometric Redshift errors
 (photometric) Calibration errors

Poster child for the systematics: photometric redshift errors

Zphot-Zspec from "training set"





Ma, Hu & Huterer 2006

(Photometric) calibration errors

Detector sensitivity: sensitivity of the pixels on the camera vary along focal plane.
 Observing conditions: spatial and temporal variations.

Bright objects: The light from foreground bright stars and galaxies.

Dust extinction: Dust in the MW absorbs light from the distant galaxies.

Star-galaxy separation: Faint stars erroneously included in the galaxy sample.
 Deblending: Galaxy images can overlap.

Huterer, Cunha & Fang 2013 Shafer & Huterer 2015



Leistedt et al 2013

Explicitly separating information from growth and geometry using current data

Ruiz & Huterer, PRD 2015, arXiv:1410.5832

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3}/r_s(z_d)$	
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2} D_A(z_*)$	
Cluster counts	$rac{dV}{dz}$	$rac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)}W_i(z)W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Idea: compare geometry and growth

e.g. Wang, Hui, May & Haiman 2007

Our approach:

Double the standard DE parameter space $(\Omega_{M}=1-\Omega_{DE} \text{ and } w):$ $\Rightarrow \Omega_{M}^{\text{geom}}, w^{\text{geom}} \Omega_{M}^{\text{grow}}, w^{\text{grow}}$ [In addition to other:

standard parameters: $\Omega_{M}h^{2} \Omega_{B}h^{2}$, n_s, A) nuisance parameters: probe-dependent]

Ruiz & Huterer, 2015

(Current) Data used



CMB (Planck peak location) Weak Lensing (CFHTLens) BAO (6dF, SDSS LRG, BOSS CMASS)



Standard parameter space



EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s , A) SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

Omega matter: geometry vs. growth



* SN not the recalibrated JLA compilation - need to update; will move Ω_M^{grow} up

w (eq of state of DE): geometry vs. growth



Therefore: growth probes point to even less growth than LCDM with ~Planck parameters (i.e. $w^{grow} > -1$)

(but the evidence is still not very strong...)

Probably equivalent to these recent findings:

 $\bullet \ \sigma_8 \ from \ clusters \ is \ lower \ than \ that \ from \ CMB \ (eg. \ Hou \ et \ al, Bocquet \ et \ al, Costanzi \ et \ al)$

- $\bullet~\sigma_8~from~WL~is~lower~than~that~from~CMB$ (eg. MacCrann et al)
- evidence for neutrino mass (eg. Beutler et al, Dvorkin et al)
- evidence for interactions in the dark energy sector (eg. Salvatelli et al)

RSD prefer $w^{grow} > -1$ (slower growth than in LCDM)



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"Are there cracks in the Cosmic Egg?"

Michael Turner, Aspen, summer 2014

Dark Energy Survey Instrument (DESI)





- Huge spectroscopic survey on Mayall telescope (Arizona)
 ~5000 fibres, ~15,000 sqdeg, ~30 million spectra
- LRG in 0 < z < 1, ELG in 0 < z < 1.5, QSO 2.2 < z < 3.5
- Great for dark energy (RSD, BAO)
- Great for primordial non-Gaussianity P(k, z), bispectrum...
- Start ~2018, funding DOE + institutions

Conclusions

- **Growth of structure** gives an extremely powerful set of measurements to complement geometrical measures
- Systematics are challenging but entirely possible to overcome: require sophisticated statistical techniques.
 Principal challenge: photometric calibration errors.
- Separating growth from geometry is a good way to get a) constraints b) insights into DE constraints; it now indicates a 3-sigma growth ≠ geometry discrepancy

EXTRA SLIDES

Redshift Space Distortion data



(Pretty high) neutrino mass can relieve the tension



Ruiz & Huterer, arXiv:1410.5832