Constraints on Dark Energy from Future Weak Lensing Surveys

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The expansion of the universe is accelerating
- discovered by looking at distant Supernovae in 1998
- confirmed recently by studying the CMB, clusters.

Three different explanations
1. vacuum has finite (nonzero) energy density
2. “dark energy”: a new uniform component of the universe with large negative pressure
3. general relativity fails on cosmological scales

Commonly regarded “most important problem in physics”
- accounts for ~70 percent of total energy in the universe
Dark Energy

- Characterizing dark energy
  - equation of state $p = w \rho$
  - vacuum: $w=-1$ vs dark energy or non-GR: $w=w(t) \neq -1$

- Universe is “flat”: no spatial curvature (CMB)
  - fixes energy density $\rho$. Need to measure $w$
  - $w$ affects: (i) evolution of expansion rate
    (ii) growth of structure

- Solution will come from astronomers: no small-scale effect
A tool: Weak Gravitational Lensing
Simulated Map of Weak Lensing

$3 \times 3 \text{ deg}^2$; $1 \text{ amin}^2 \text{ pixels}$
Extracting information from WL maps

- Traditional statistic:
  - (tomographic) two-point correlation function $C_i$
  - depends on $w$, linear regime analytically predictable

- **Question:** is there significant information in the non-linear regime beyond “usual” LSS statistics?

  1. Statistical power of $dN/dz$ (cluster counts)
  2. Complementarity of $dN/dz$ and $C_i$
Several large ($\geq 1,000$ sq. deg) WL surveys forthcoming:
(e.g. Pan-STARRS, KIDS, DES, LSST)

Shear power spectrum and related large-scale statistics

E.g. $\sigma(w_0)=0.06$; $\sigma(w_a)=0.1$ from 11-paramater fit to
tomographic shear power spectrum (LSST) + Planck

Comparable statistical errors from cluster number counts
(e.g. Wang et al. 2004, 2005; Fang & Haiman 2007; Takada & Bridle 2007; Marian & Bernstein 2006, 2008)

E.g. $\sigma(w_0)=0.04$; $\sigma(w_a)=0.09$ from 7-paramater fit to
$\sim 200,000$ shear-selected cluster counts (LSST) + Planck
Adding Non-Linear Info

- Cluster counts and shear power spectrum can be considered independent observables – high synergy. Covariance changes parameter-estimates by < few % (Fang & Haiman 2007; Takada & Bridle 2007)

- However, selection effects are (probably) a showstopper in a WL survey alone, due to projection effects. Filter-dependent trade-off between completeness and purity: “best compromise” values are ~70% for both (e.g. White et al. 2002; Hamana et al. 2005; Hennawi & Spergel 2005)

- Why not define observable immune to projection effects? historical reason: cosmology-dependence of halo mass function calculable from Press-Schechter
A simple statistic: one-point function of convergence i.e. fraction of sky above a fixed threshold $\kappa > \kappa_T = \nu \sigma_N$

“analytically” calculable, analogous to mass function:

$$\nu \sigma_N$$

Simulations by M.White (2005)

$F = \int_{\nu \sigma} P(\kappa) d\kappa$

$z_s = 0.6$

Cosmology dependence only through $\langle \kappa^2 \rangle$ and $\kappa_{\text{min}}$
Peak counts

- Another simple statistic: # of shear peaks, regardless of whether or not they correspond to true bound objects as a function of height, redshift and angular size
  Kratochvil, Haiman, Hui & May (2009)

- Fundamental questions about “false” (non-cluster) peaks:
  1. How does N(peak) depend on cosmology ?
  2. What is the field-to-field variance $\Delta N(\text{peak})$ ?

- Requires simulations
N-body Simulation Details

- pure DM (no baryons, neutrinos, or radiation)
- public code GADGET-2, modified to handle \( w_0 \neq -1 \)
- fiducial \( \Lambda \)CDM cosmology from WMAP5:
  \[(w_0, \Omega_\Lambda, \Omega_m, H_0, \sigma_8, n) = (-1.0, 0.74, 0.26, 0.72, 0.79, 1.0)\]
- fix primordial amplitude \( \Delta^2_R = 2.41 \times 10^{-9} \) at \( k = 0.002 \) Mpc\(^{-1}\)
  \( (\sigma_8=0.79 \text{ vs. } 0.75) \)
- two alternative cosmologies, differ only in \( w_0 = -0.8 \) or \(-1.2\)
- \( 512^3 \) box, size \( 200h^{-1} \) Mpc, \( z_{in}=60, M_{DM}=4.3 \times 10^9 M_\odot \)
- gravitational softening length \( \varepsilon_{Pl} = 7.5h^{-1} \) kpc
- output particle positions every \( 70h^{-1} \) comoving Mpc
- runs performed at NSF TeraGrid and at Brookhaven
Simulating Weak Lensing Maps

✿ Ray-tracing
- compute 2D potential (2048×2048) in each lens plane
- implement algorithm to follow rays (Hamana & Mellier 2001)
- compute shear (γ), convergence (κ) and reduced shear (μ)

✿ Mock “observational” parameters
- gaussian 1-component shear noise from intrinsic ellipticity:
  \[ \sigma_\gamma = 0.15 + 0.035z \] (Song & Knox 2004)
- \( n_{\text{gal}} = 30 \) arcmin\(^{-2} \) background galaxies, at \( z_s = 1, 1.5, \) and 2
- smooth κ-map with 2D finite Gaussian 0.25 - 30 arcmin
- use 3×3 deg\(^2\) smoothed convergence maps

✿ Identifying peaks
- find all local maxima, record their height
Example

raw convergence map (3×3 deg²; 2048×2048 pixels)

w=-1

w=-0.8
Example
convergence map with *noise* and 1-arcmin *smoothing*

\[ w = -1 \quad \text{and} \quad w = -0.8 \]
Basic Results

- 3×3 deg² field, smoothing with 1-arcmin, galaxies at $z_s = 2$

- Expectations based on clusters with $\kappa_G \geq 4.5\sigma_k$
  
  (Fang & Haiman 2007)

  $N(\text{clusters}) = 150 \pm 25$ for $w=-1$

  $N(\text{clusters}) = 103 \pm 21$ for $w=-0.8$

  $\Rightarrow S/N \approx 2\sigma$ mostly coming from change in $\sigma_8$

- Total peak counts above same threshold [w/no noise]

  $N(\text{peaks}) = 576 \pm 86$ [$230 \pm 42$] for $w=-1$

  $N(\text{peaks}) = 547 \pm 85$ [$186 \pm 37$] for $w=-0.8$

  $\Rightarrow S/N \approx 0.3\sigma$: (i) smaller difference, (ii) larger variance

- Total peak counts (all peaks):

  $N(\text{peaks}) = 11,622 \pm 62$ for $w=-1$

  $N(\text{peaks}) = 11,562 \pm 62$ for $w=-0.8$
Covariance matrix for number of binned, tomographic peaks:

\[ C_{i,j}^m = \frac{1}{R-1} \sum_{r=1}^{R} \left[ N_i^m(r) - \bar{N}_i^m \right] \left[ N_j^m(r) - \bar{N}_j^m \right] \]

- R=500 realizations in cosmology \( m \) (rotate/shift/slice box)
- \( i = 15 \) (height) x 3 (source redshift) = 45 bins

Compute \( \chi^2 \) between test (\( m \)) and fiducial (\( n \)) cosmology:

\[ \chi^2_{2;m,n}(r) = \sum_{i,j=1}^{45} \left[ N_i^m(r) - \bar{N}_i^n \right] \left[ C_{i,j}^n \right]^{-1} \left[ N_j^m(r) - \bar{N}_j^n \right] \]

Compute likelihood at which cosmology \( m \) can be distinguished from cosmology \( n \):

- given by overlap between two distributions \( \chi^2_{2;m,n} \) and \( \chi^2_{2;n,n} \)
Chi Square Distributions

3 redshift bins, 15 peak height bins, 0.5 arcmin smoothing

\[ \chi^2 \]

w = -1 versus w = -1
\[ \langle \chi^2 \rangle = 44.89 \]

w = -0.8 versus w = -1
\[ \langle \chi^2 \rangle = 55.51 \]

\[ \rightarrow \Delta \langle \chi^2 \rangle \approx 10 \]
or 85% confidence
Which peaks dominate constraints?

- smoothing with 0.5 arcmin, galaxies at $z_s=2$
- $w=-1$ more peaks at high+low ends (DE dominates later)
- $w=-0.8$ peaks are more sharply peaked
- medium height ($\kappa \approx 0.04$, or $2\sigma$) peaks dominate the total $\chi^2$
Conclusions

- Number of shear peaks in 9 deg$^2$ has statistically significant ($\sim 1.5\sigma$) difference between $w=-0.8$ and $w=-1.0$

- Encouraging, since # of peaks is a robust observable

- Similar to cluster $dN/dz$, but most of the information comes from lower (non-cluster) peaks

- Just a first step: we need suite of simulations to address degeneracies when other parameters are included
We do not know a-priori how changes in $w$ affect map

Peak counts may not capture most of the information

Can we use some ‘artificial neural network’ approach?

- simulate maps in different cosmologies “training sets”
- algorithm itself should come up with a discriminator
- problem(?): small training sets (100 realizations/model)
The End
Fractional Area of “Hot Spots”

- Forecast $\rho$ constraint (S/N) from Fisher matrix - need:
  cosmology-dependence (S): $\frac{d \langle F \rangle}{dp}$ ✓
  variance (N): $\langle F^2 \rangle$ ?

- Full covariance matrix from log-normal model vs simulations

\[ C_{ij} = \langle F(\kappa_i, z_i) F(\kappa_j, z_j) \rangle \]

Simulations by M. White (2005)
Constraints from “Hot Spots”

- Fiducial 7-parameter flat $\Lambda$CDM cosmology ($\sim$WMAP):
  \[ (\Omega_{DE}, \Omega_m h^2, \Omega_b h^2, w_0, w_a, \sigma_8, n_s) = (0.72, 0.14, 0.024, -1, 0, 0.9, 1) \]

- Assume LSST-like survey parameters:
  * $\Delta \Omega = 20,000 \text{ deg}^2$; $n_g = 40 \text{ gal/deg}^2$; $\sigma_\epsilon = 0.3$
  * 1-arcmin smoothing
  * three redshift bins: $z_g = 0.6, 1.1, 1.9$
  * seven convergence bins: $\nu = 2, 2.5, 3, 3.5, 4, 4.5, 5$ ($\kappa = \nu \sigma_G$)

- Six Nuisance parameters:
  * $\sigma_G$ = free parameter in each $z$-bin with 0.01-1% priors
  * $\kappa_{bias}$ = free parameter in each $z$-bin with 0.05-1% priors

- Planck Priors ($\Omega_m h^2, \Omega_b h^2, n_s$)

- Ref: noise from intrinsic ellipticity ($\sigma_G = 0.023$) vs. smoothed convergence field at $z = (0.6, 1.1, 1.9)$: $\sigma = 0.01, 0.017, 0.025$
Constraints approaching those expected from cluster dN/dz

DETF figure of merit:
\[(\Delta w_0 \Delta w_a)^{-1} = 180 \text{ (pessimistic)} \text{ vs } 760 \text{ (optimistic)}\]

Nonlinear info - complementary to shear power spectrum
Results: statistical significance

- $w = -0.8$ distinguishable at 85% confidence from $w = -1.0$
  - 70% chance for 68% CL
  - 26% chance for 95% CL

- covariance has small effect overall (cuts high-$\chi^2$ tail)

- co-adding several smoothing scales gives only modest ($\sim 10\%$) improvement over single best scale ($\sim 0.5$ arcmin – smaller than best cluster case)

- scaling from $3 \times 3 = 9$ deg$^2$ to 20,000 deg$^2$:
  - rough guess:
    - significance $\sqrt{20,000/9}$=50 times better
    - $1.5\sigma$ constraint on $w_0$ is $\Delta w_0 = 0.2/50 = 0.004$