Probing the dark Universe with weak lensing effects

Zuhui Fan
Dept. of Astronomy, Peking University

XK. Liu, CZ. Pan, S. Yuan, DZ.Liu
R.Li, Q.Wang, W.Du, HY Shan, LP. Fu, J-P Kneib and CS82 team
GB. Zhao, BJ.Li, W. Fang, MC. Chiu
J.Zhang, GL. Li

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Outline

- Introduction
- Cosmological studies with weak lensing peak statistics
  -- Model WL peak abundances
  -- Cosmological constraints from WL peak analyses
- Discussions
Introduction

Gravitational light deflections by large-scale structures induce small changes in shape (and magnitude) of background sources → Weak lensing effects

Exist almost everywhere in the Universe

- sensitive to – formation and evolution of large-scale structures
  -- cosmological distances

- clean physics
- excellent cosmological probe, particularly for understanding
  the nature of the two dark components and probing the law of gravity
  (stage II- CFHTLenS, CS82; III-DES, HSC, KiDS; IV – LSST, Euclid, WFIRST)

Wittman et al. 2000
Weak lensing shear signals are weak (at least a few times smaller than the intrinsic ellipticity of galaxies)

Observationally extremely challenging

-- measure accurately the shapes of millions to billions faint galaxies
-- redshift information of individual galaxies

Outstanding issues theoretically

-- How to extract cosmological information from WL data as much as possible?
  - statistical analyses are necessary
  - fully explore different statistical quantities

-- How to obtain the cosmological information accurately?
  - observational applicability of different statistics
  - thorough understanding about potential systematics, both theoretical and observational
Weak lensing analyses

-- 2-pt shear correlations are the most commonly applied analyses
  Cannot reveal non-Gaussian features

-- higher order correlations are natural extensions -- analyses are rather complicated

Kilbinger et al. 2013, CFHTLenS

Fu et al. 2014, CFHTLenS
Weak-lensing peak analyses provide another important means

Massive structures, such as clusters of galaxies, are expected to generate high lensing signals and appear as peaks in weak-lensing convergence maps.

→ related to the mass function of dark matter halos and lensing efficiency factor → cosmology sensitive
Comparing to conventional cluster studies: WL effect is gravitational in origin

X-ray, SZ, optical: baryonic observables

Observable – mass relations are needed in cosmological studies using the dark halo mass function

Major systematics in using clusters as cosmological probes E.g., X-ray

\[ L_{500}(0.1–2.4 \text{ keV}) = 0.1175 \left[ M_{200}^{\text{gsi}} h^{-2} \right] E(z)^{\alpha_{\text{sli}}} \]

Boehringer, H. et al. 2014
Complications: "false peaks" $\leftrightarrow$ shape noise (chance alignment) + LSS projection effects

The key is to predict accurately the cosmology dependence of peak statistics

Two approaches – Build a numerical library by running massive simulations
  - labor intensive – many cosmological parameters
    - different gravity theories, astrophysical effects
  - combination of different effects
    -- Build theoretical models – clean physics
      approximations are inevitable

The combination of the two provides the best solution
  -- theoretical model tested and calibrated by simulations

*Advanced rapidly very recently – CFHTLenS, CS82, DES, KiDS, …*
Cosmological studies with WL peak statistics

Model building
-- predicting peak abundances given a cosmological model

Halo model for high peaks taking into account the shape noise effect
– crucial for cosmological studies with WL peaks

Large sets of ray-tracing simulation

Set up fast computation code for cosmological analyses

Observational analyses with CFHTLS CFHT Stripe 82, and CFHTLenS WL data

Simulation studies

Observational analyses
Theoretical model for high WL peak abundances

- True high WL peaks are contributed dominantly by massive halos along lines of sight
- Chance alignments of intrinsic ellipticities of source galaxies contribute false peaks
- Intrinsic ellipticities result in a Gaussian random noise field added to the true lensing convergence signals
  \[ K_N(\theta) = K(\theta) + N(\theta) = \int d\mathbf{k} \exp(-i\mathbf{k} \cdot \theta) c_\alpha(k) \Sigma^{(o)}(k) \]
- Large-scale structures also contribute -- ignored at the current version of model
  for \( n_g \sim 10 \text{ arcmin}^{-2}, z_s \sim 1 \)

\[ \sigma_{\text{shape noise}} \sim 0.025, \sigma_{\text{lss}} \sim 0.009 \]
Theoretical model for high WL peak abundances
(Fan et al. 2010)

Halo region \((M > \sim 10^{13.9} h^{-1} M_{\text{sun}})\) cut off at virial radius

** Halo peak is affected by noise
** Number of noise peaks is enhanced by halo mass distribution

\[ K_N = K_{NFW}(M, z) + N \]

Gaussian random field modulated by the halo density profile

Field region outside halos:

** false peaks from shape noise field
Theoretical model for high WL peak abundances
(Fan et al. 2010)

WL Peak number density

\[ n_{\text{peak}}(\nu) d\nu = n_{\text{peak}}^c(\nu) d\nu + n_{\text{peak}}^n(\nu) d\nu \]

\[ n_{\text{peak}}^c(\nu) = \int d\nu \frac{dV(z)}{d\nu d\Omega} \int dM n(M, z) f(\nu, M, z) \]

\[ f(\nu, M, z) = \int_0^{R_{\text{vir}}} dR (2\pi R) n_{\text{peak}}(\nu, M, z) \]

\[ n_{\text{peak}}(\nu_0) = \exp \left[ -\frac{(K_1^2 + K_2^2)^2}{\sigma_1^2} \right] \left\{ 1 + \frac{1}{2\pi \theta^2_{\text{vir}} (2\pi)^{3/2}} \right\} \]

\[ \times \exp \left[ -\frac{1}{2} \left( \frac{\nu_0 - K}{\sigma_0} \right)^2 \right] \int_{2\pi \left(1 - \gamma_N^2\right)}^{\frac{dx_N}{2\pi \left(1 - \gamma_N^2\right)^{1/2}}} d\nu \]

\[ \times \exp \left\{ -\frac{\left[ x_N + (K_1^1 + K_2^2)/\sigma_2 - \gamma_N(\nu_0 - K/\sigma_0) \right]^2}{2(1 - \gamma_N^2) \left(2\pi \right)^{3/2}} \right\} \times F(x_N) \]

Cosmological information:
- DM halo mass function
- DM halo internal profile
- Cosmological volume
- and lensing efficiency factor

Total peak counts without the need to differentiate true and false peaks
Simulation tests (Fan et al. 2010, Liu et al. 2014, 2015, 2016)
Observational comparisons (Shan et al. 2012, 2014)

CFHTLS

Develop a fast code for peak model calculations

-- important for deriving cosmological constraints from WL peak abundances
CS82 WL peak studies

CFHT Stripe 82
weak lensing survey

CFHT MegaCam observations
-- 173 tiles $1\text{deg}^2$ each
-- seeing $0.4''-0.8''$
-- four $\sim410s$ exposures each pointing
-- $i_{AB}\sim24$ (5$\sigma$)

Shear measurements
-- Lensfit
-- 5,475,318 galaxies with weight$>0$
-- $ng\sim11.8\ \text{arcmin}^{-2}$
-- median redshift $z\sim0.83$
shear measurements

\[ \epsilon(\theta, z) = \begin{cases} 
\frac{\epsilon_s(\theta, z) + g(\theta, z)}{1 + \epsilon_s^*(\theta, z) \epsilon_s(\theta, z)} & \text{for } |g(\theta, z)| \leq 1 \\
\frac{1 + g(\theta, z) \epsilon_s^*(\theta, z)}{\epsilon_s^*(\theta, z) + g^*(\theta, z)} & \text{for } |g(\theta, z)| > 1 
\end{cases} \]

iterative convergence reconstruction

\[
\langle \epsilon \rangle (\theta) = \frac{\sum_j W_{\theta_0}(\theta_j - \theta) w(\theta_j) \epsilon^c(\theta_j)}{\sum_j W_{\theta_0}(\theta_j - \theta) w((\theta_j)(1 + m_j))}
\]

\[
\hat{\gamma}(k) = \pi^{-1} \hat{D}(k) \hat{k}(k)
\]

\[
\hat{D}(k) = \pi \frac{k_1^2 - k_2^2 + 2ik_1k_2}{k_1^2 + k_2^2}
\]
peak analyses

MCMC module

cosmological constraints – comparable, consistent, and complementary
Further explored the potential to constrain halo profiles and cosmological parameters simultaneously (note we only used flat and loose priors here).
Constraints on f(R) gravity theory (Liu et al. 2016, PRL)

What drives the accelerating expansion of the Universe?

- GR – add the dark energy component
- Modified gravity theories --
  - e.g., f(R) gravity theory with chameleon effect
    - give rise to the late-time cosmic accelerating expansion
    - satisfy the solar system gravity test

However, the formation and evolution of LSS are different

LSS observations are crucial in understanding the underlying mechanism driving the evolution of the Universe
In our theoretical model, the physics behind the WL high peaks is clear and the cosmologically-dependent quantities are known explicitly. Therefore we can extend our analyses beyond GR.

CFHTLenS: 154 deg$^2$, u*g'r'i'z', photo-z distribution for each galaxy.
HS f(R) theory – $f_{R0}$ parameter with $f_{R0}=0$ for GR

Mock simulation tests show that WL high peaks depend on $f_{R0}$ sensitively.

With priors from WMAP9 or Planck15, $f_{R0}$ can be constrained tightly
CFHTLenS observations

Strong constraints
-- comparably tighter than other studies on cosmological scales

No evidence of deviations from GR
Summary and discussion

We have carried out series studies about WL peak statistics
model building – simulations – computational tool – observations

-- Demonstrate well the great potential of WL peak analyses in cosmological studies

Ongoing efforts – model improvement for future precision WL studies
  -- future large surveys can reduce the statistical errors dramatically
  -- more accurate modeling is needed

LSS contributions (Yuan et al. 2016)
Ongoing efforts

-- Build a computational platform to include WL 2pt+3pt+peaks
-- tomographic analyses
-- detailed systematic studies

Fully realize the power of WL analyses in future precision era

Thank you