Constraining modified gravity from weak-lensing peak statistics

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Outline

- Introduction
- Weak-lensing peak statistics
- Constraints on f(R) theory using CFHTLenS peaks
- Discussion

Introduction

The accelerating expansion of the universe has posed great challenges to our understanding about the fundamental laws of nature

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

modified gravity Or adding new component – dark energy

Different modified theories have been proposed, and among them, f(R) theory is a representative one

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R + f(R)}{2\kappa^2} + \mathcal{L}_\mathrm{m}\right]$$

Equivalent as introducing an additional field $f_R \equiv \frac{\mathrm{d}f(R)}{\mathrm{d}R}$

$$3\Box f_R - R + f_R R - 2f = -\kappa^2\rho \qquad \Box f_R = \frac{\partial V_\mathrm{eff}}{\partial f_R} \qquad \frac{\partial V_\mathrm{eff}}{\partial f_R} = \frac{1}{3}(R - f_R R + 2f - \kappa^2\rho)$$

$$m_{f_R}^2 = \frac{\partial^2 V_\mathrm{eff}}{\partial f_R^2} = \frac{1}{3}\left(\frac{1 + f_R}{f_{RR}} - R\right) \qquad \boxed{\lambda_{f_R} \equiv m_{f_R}^{-1}} \qquad f(R) = -m^2\frac{c_1(R/m^2)^n}{c_2(R/m^2)^n + 1}$$

By design → the global expansion history ~ ΛCDM.
Also with the Chameleon mechanism, it satisfies the Solar System gravity test
However, on cosmological scales → leave imprints on structure formation
Thus observations of large-scale structures are essential to discriminate the two theories.

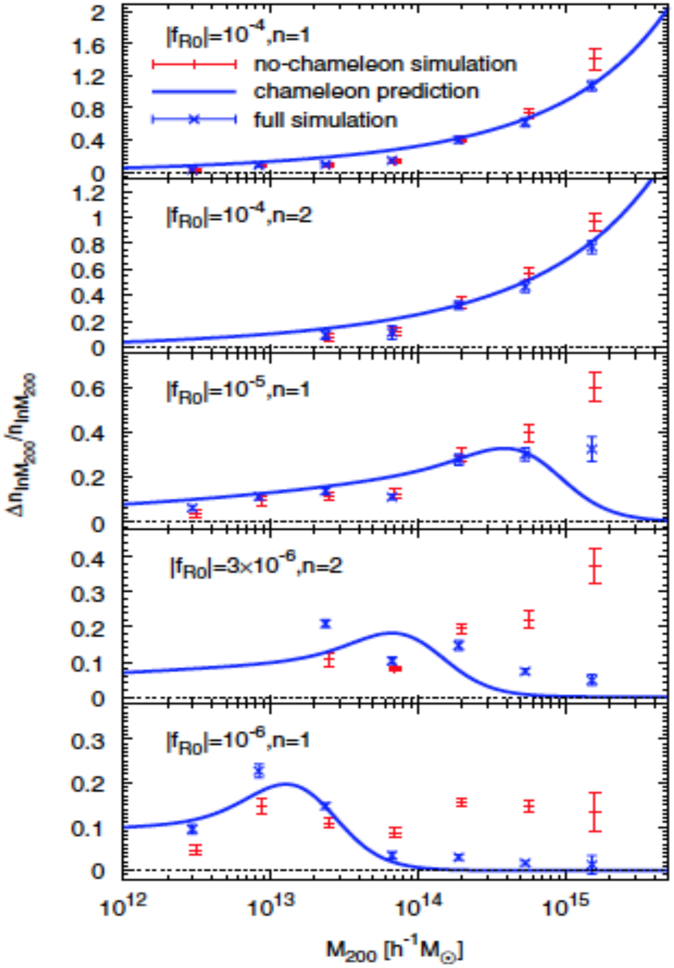
We focus on nonlinear halo structures

At clusters/groups scales, the deviations from GR can be significant

→ Abundance analyses from observations can put strong constraints on f(R) theory

Cluster abundance analyses have been done

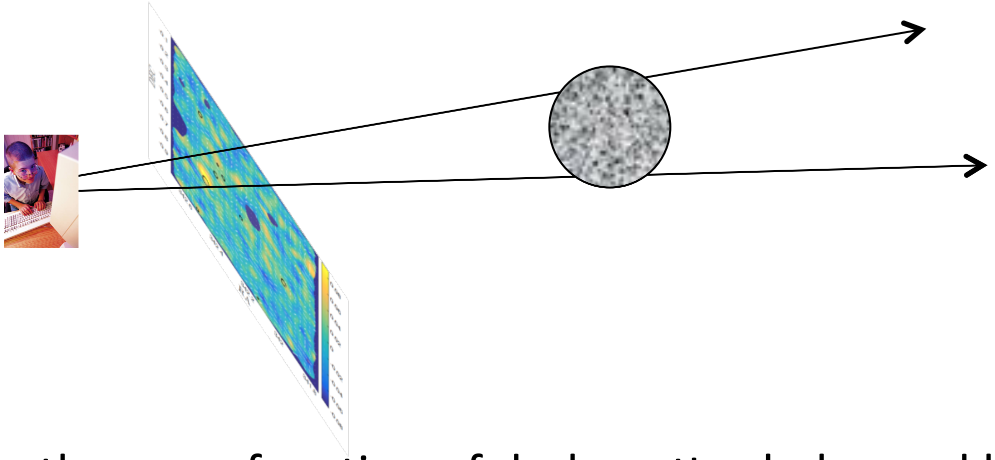
We apply **weak-lensing peak abundance analyses to CFHTLenS** to derive stringent constraints on f_{R0} parameter



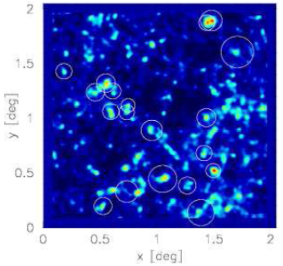
Li & Hu 2011

Weak-lensing peak statistics

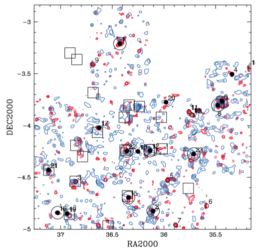
Massive structures, such as clusters of galaxies, are expected to generate high lensing signals and appear as peaks in weak-lensing convergence maps.



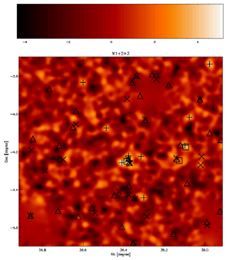
→ related to the mass function of dark matter halos and lensing efficiency factor → cosmology sensitive



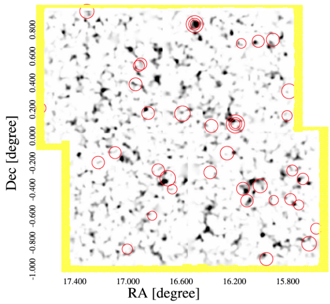
Hamana et al. 2004



Miyazaki et al. 2007

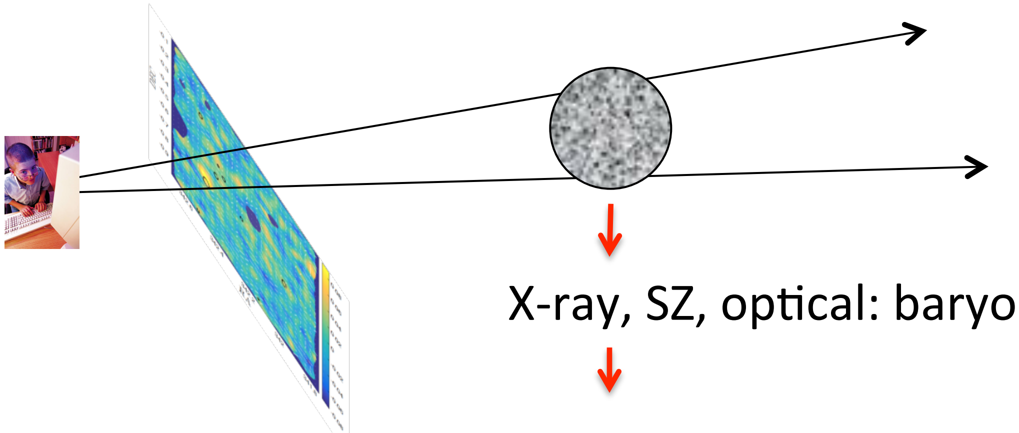


Shan et al. 2012, CFHTLS



Shan et al. 2014, CS82

Comparing to conventional cluster studies: WL effect is gravitational in origin



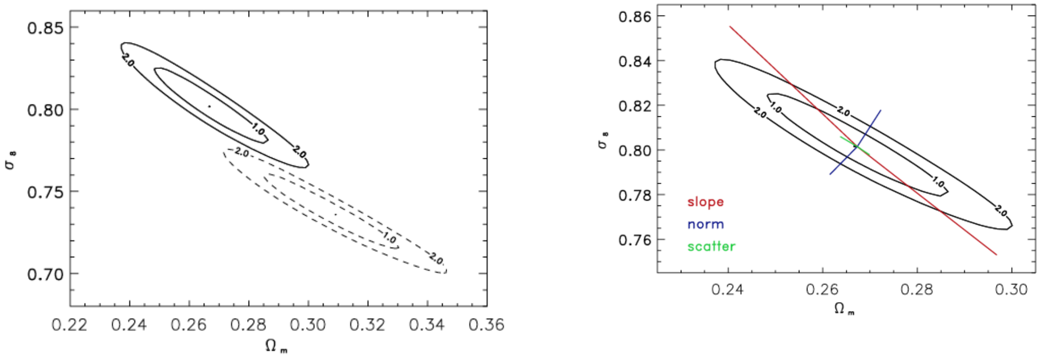
X-ray, SZ, optical: baryonic observables

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

Major systematics in using clusters as cosmological probes

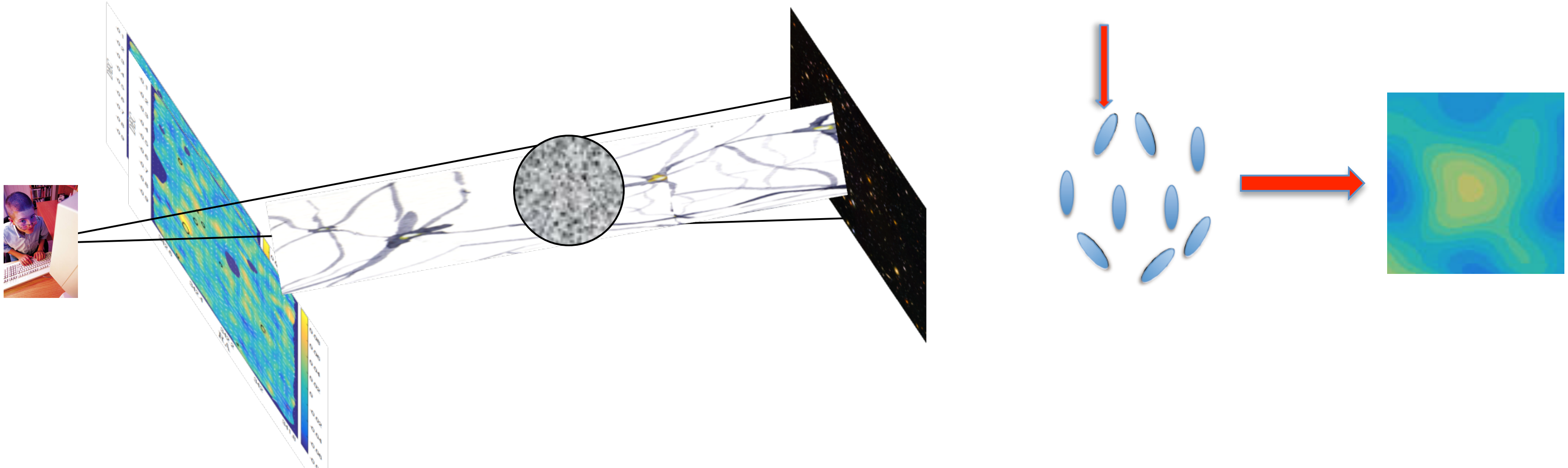
E.g., X-ray

$$L_{500}(0.1\text{–}2.4\,\mathrm{keV}) = 0.1175\, M_{200}^{\alpha_{\rm sl}}\, h^{\alpha_{\rm sl}-2}\quad E(z)^{\alpha_{\rm sl}}$$



Boehringer, H. et al. 2014

Complications: “false peaks” ← 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 – physics is clear
approximations are inevitable

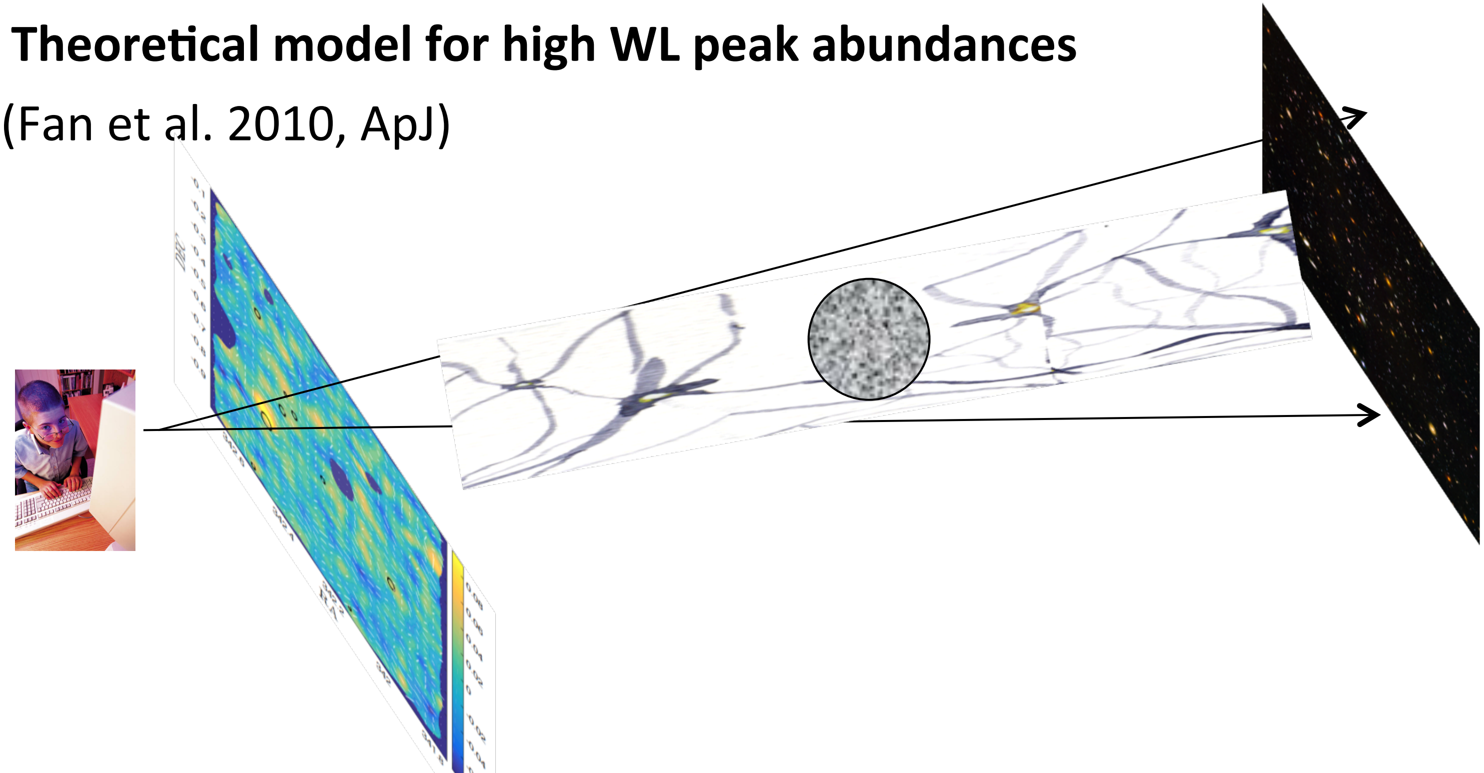
The combination of the two provides the best solution

-- theoretical model tested and calibrated by simulations

Advanced rapidly very recently – CFHTLenS, CS82, DES, KiDS, …

Theoretical model for high WL peak abundances

(Fan et al. 2010, ApJ)



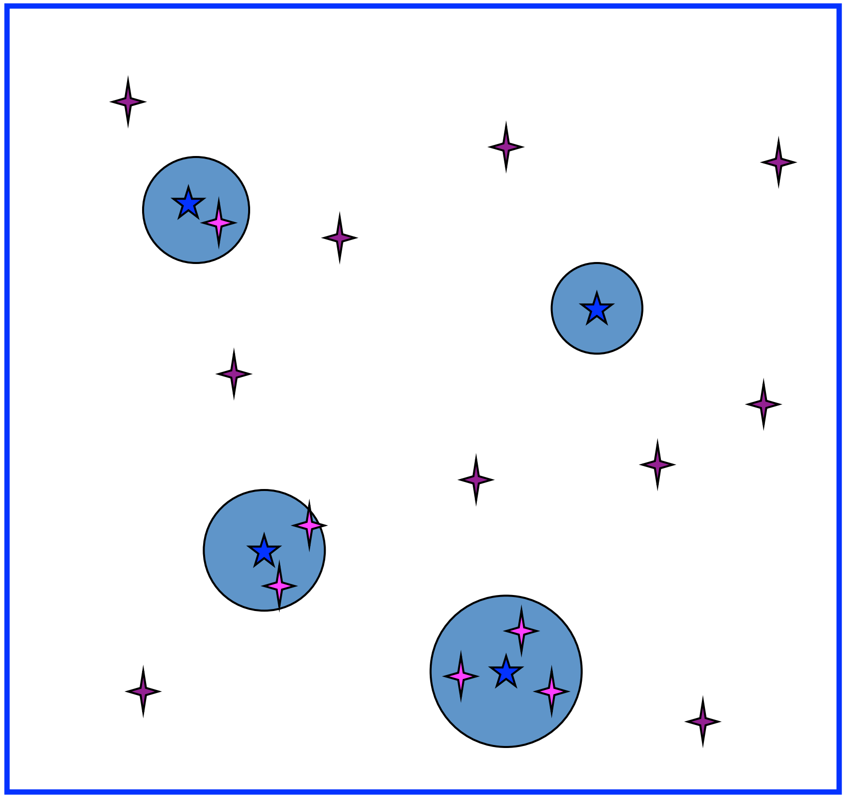
- True high WL peaks are contributed dominantly by massive halos along LOS
- Chance alignments of intrinsic ellipticities of galaxies contribute false peaks
- Intrinsic ellipticities result in a Gaussian random noise field added to the true lensing convergence signals

$$\mathrm{K}_N(\boldsymbol{\theta}) = K(\boldsymbol{\theta}) + N(\boldsymbol{\theta}) = \int d\mathbf{k}\, \exp(-i\mathbf{k}\bullet\boldsymbol{\theta})c_\alpha(\mathbf{k})\Sigma_\alpha^{(o)}(\mathbf{k})$$

- Large-scale structures also contribute – important for high z for current surveys with z~0.7, n_g~10 arcmin^{-2}

$$\sigma_{shapenoise} \sim 0.025, \sigma_{lss} \sim 0.009$$

Halo model for high peaks



Halo region ($M>\sim10^{13.9}h^{-1}M_{sun}$
cut off at virial radius)

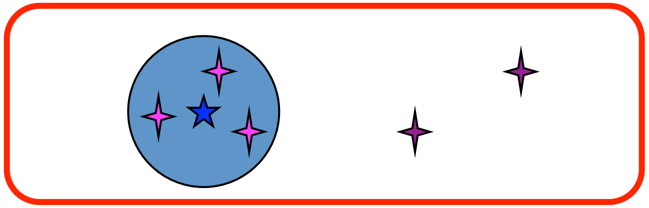
** Halo peak is affected by noise
** Number of noise peaks is
enhanced by halo mass distribution

$$K_N = K_{NFW}(M,z) + N$$

Gaussian random field modulated by the halo density profile

Field region outside halos:

** false peaks from shape noise field



WL Peak number density $n_{\mathrm{peak}}(\nu)d\nu = n^c_{\mathrm{peak}}(\nu)d\nu + n^n_{\mathrm{peak}}(\nu)d\nu$

$$n^c_{\mathrm{peak}}(\nu) = \int dz \frac{dV(z)}{dz d\Omega} \int dM\, n(M,z) f(\nu, M, z)$$

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

$$\begin{aligned} n_{\mathrm{peak}}(\nu_0) = {} & \exp\left[-\frac{(K^1)^2+(K^2)^2}{\sigma_1^2}\right]\left\{\frac{1}{2\pi\theta_*^2}\frac{1}{(2\pi)^{1/2}}\right\} \\ & \times \exp\left[-\frac{1}{2}\left(\nu_0 - \frac{K}{\sigma_0}\right)^2\right] \int \frac{dx_N}{\left[2\pi\left(1-\gamma_N^2\right)\right]^{1/2}} \\ & \times \exp\left\{-\frac{\left[x_N+(K^{11}+K^{22})/\sigma_2-\gamma_N(\nu_0-K/\sigma_0)\right]^2}{2(1-\gamma_N^2)}\right\} \times F(x_N) \end{aligned}$$

$$\begin{aligned} n^n_{\mathrm{peak}}(\nu) = \frac{1}{d\Omega}\Big\{ & n_{\mathrm{ran}}(\nu)\Big[d\Omega - \int dz \frac{dV(z)}{dz} \\ & \times \int dM\, n(M,z)\left(\pi R^2_{\mathrm{vir}}\right)\Big]\Big\}, \end{aligned}$$

Cosmological information:

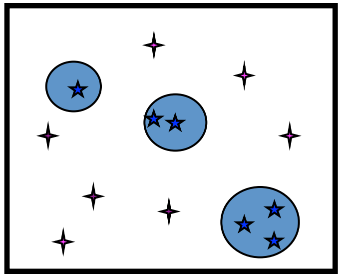
DM halo mass function
DM halo internal profile

Cosmological volume
and lensing efficiency factor

Total peak counts without the need to differentiate true and false peaks

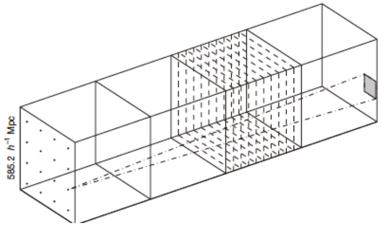
Pipeline development

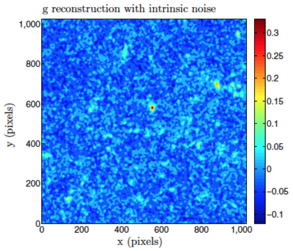
Model building
-- predicting peak abundances given a cosmological model



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

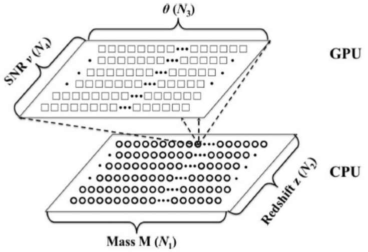
Large sets of ray-tracing simulation



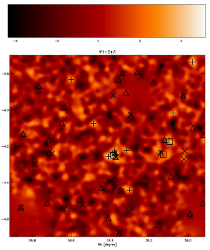


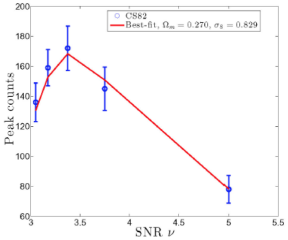
Simulation studies

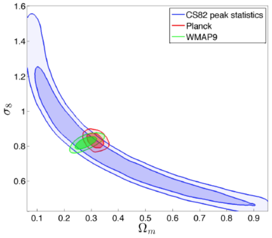
Set up fast computation code for cosmological analyses



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

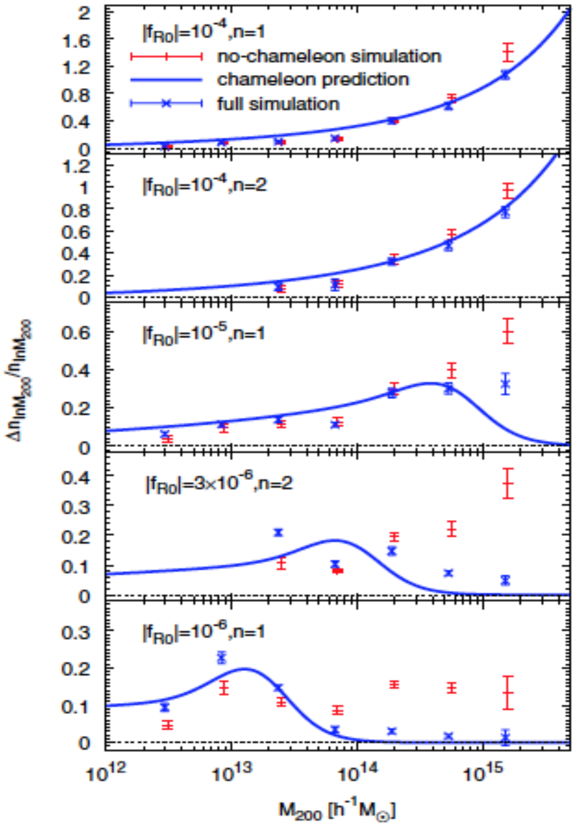






Observational analyses

Constraints on f(R) theory using CFHTLenS peaks (Liu et al. 2016 PRL)

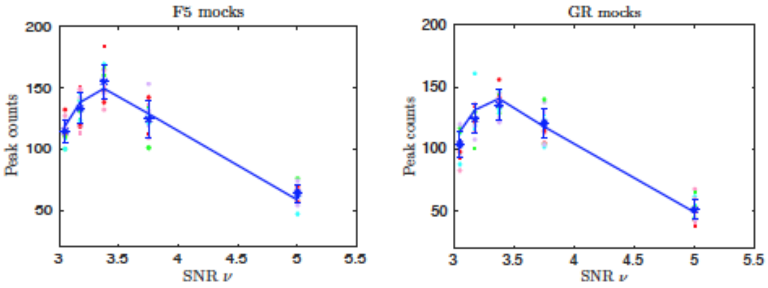


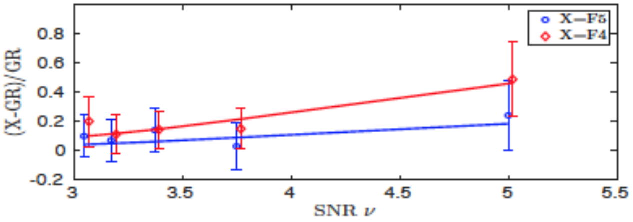
Extend our peak model to f(R)

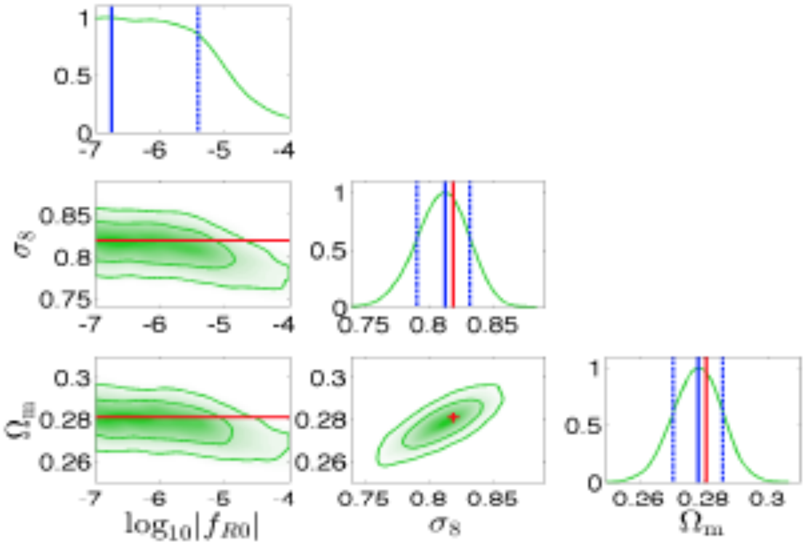
Mass function is an important quantity in the model. We adopt the Kopp et al. 2013 MF for f(R) in our peak analyses, taking into account Chameleon effect

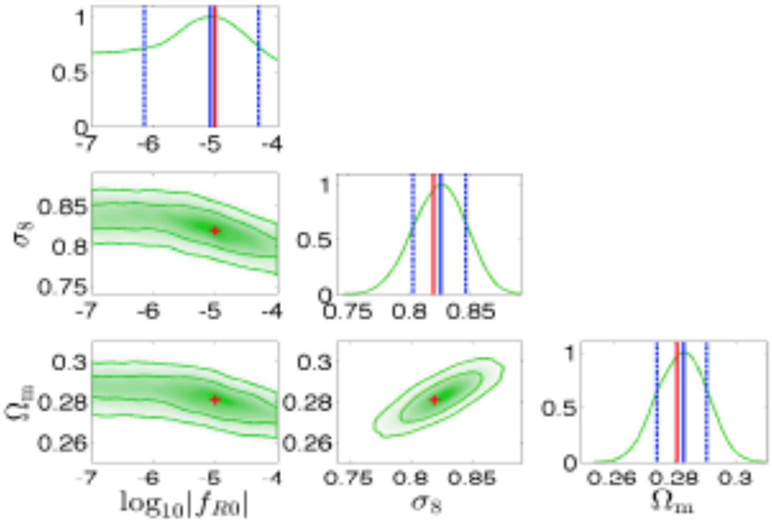
We have done large f(R) simulations and perform ray-tracing WL analyses to generate CFHTLenS mocks to validate our model and pipeline

Simulation validation

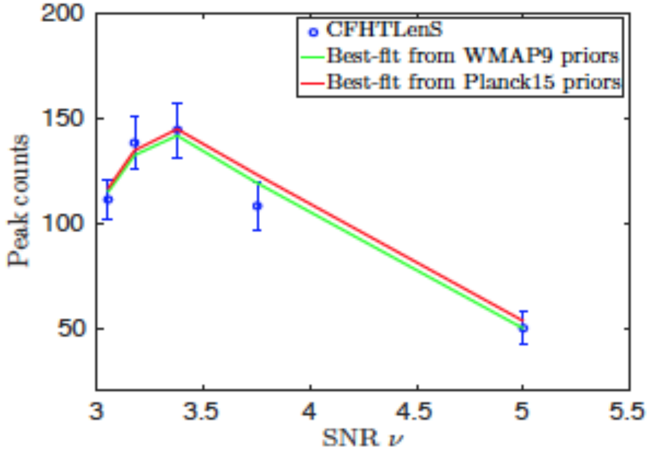


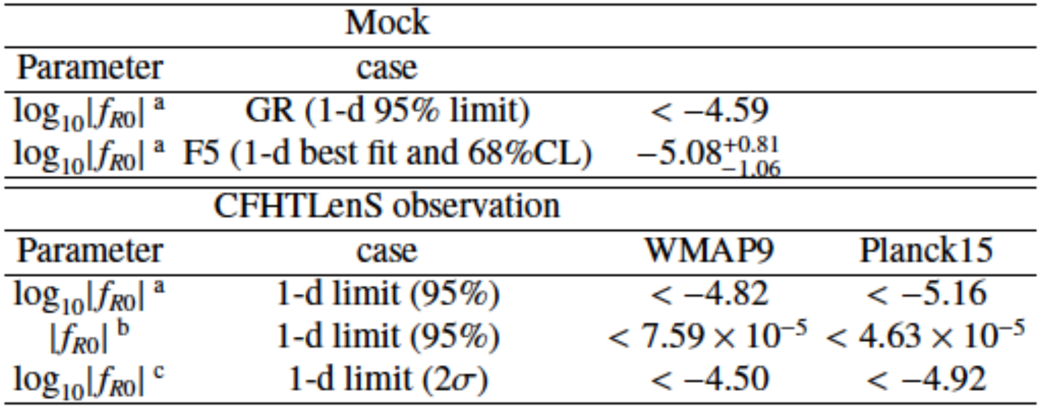






Constraints from CFHTLens analyses



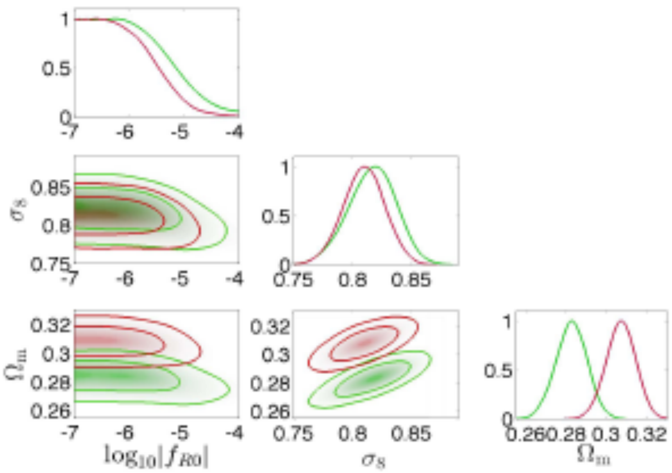


Mock

Parameter	case	
$\log_{10}\|f_{R0}\|$ [a]	GR (1-d 95% limit)	< -4.59
$\log_{10}\|f_{R0}\|$ [a]	F5 (1-d best fit and 68%CL)	$-5.08^{+0.81}_{-1.06}$

CFHTLenS observation

Parameter	case	WMAP9	Planck15
$\log_{10}\|f_{R0}\|$ [a]	1-d limit (95%)	< -4.82	< -5.16
$\|f_{R0}\|$ [b]	1-d limit (95%)	$< 7.59 \times 10^{-5}$	$< 4.63 \times 10^{-5}$
$\log_{10}\|f_{R0}\|$ [c]	1-d limit (2σ)	< -4.50	< -4.92



Strong constraints

-- comparably tighter than other studies on cosmological scales

No evidence of deviations from GR

Discussion

* LSS play important roles in discriminating the physical mechanism that drives the accelerating expansion of the universe

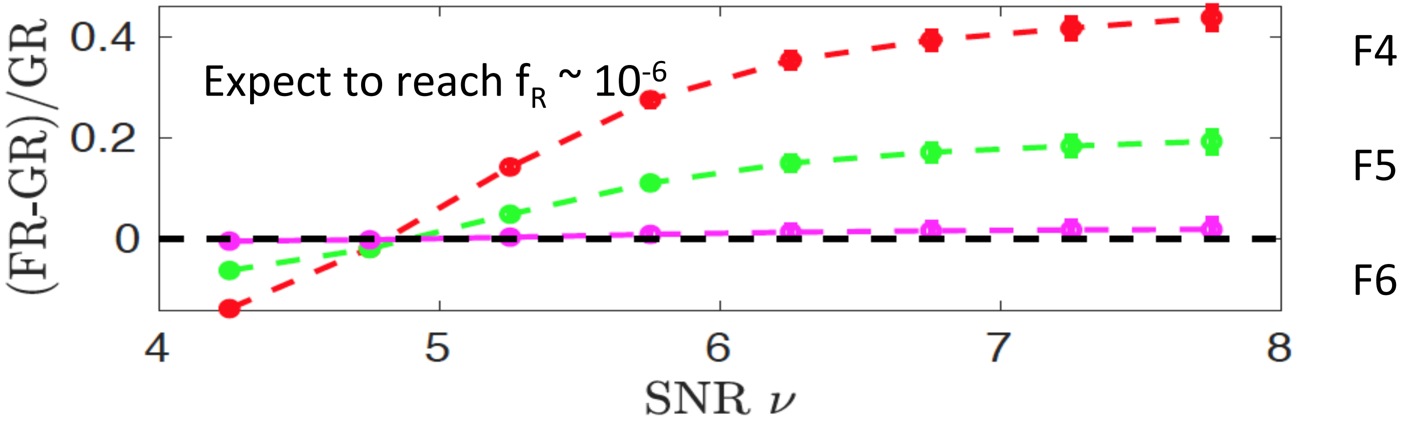
* WL peak analyses are becoming an important probe

We have carried out series studies about WL peak statistics

model building – simulations – computational tool – observations

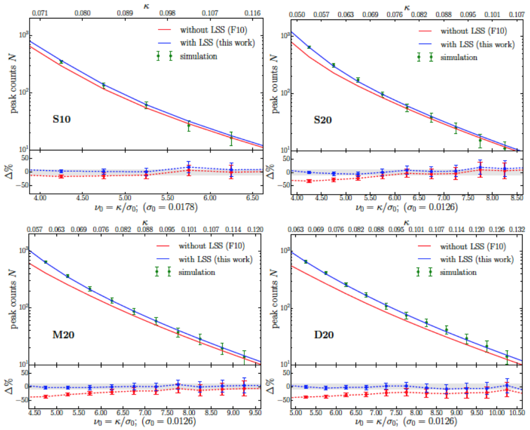
CFHTLenS → $f_{R0} < 5*10^{-5}$

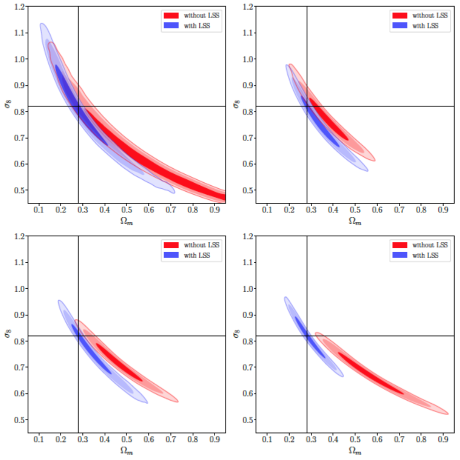
- WL observations develop fast. ~150 deg^2 → a few 1000 deg^2 → ~20000 deg^2 → statistics will increase dramatically


Expect to reach $f_R \sim 10^{-6}$

* Systematics become dominant

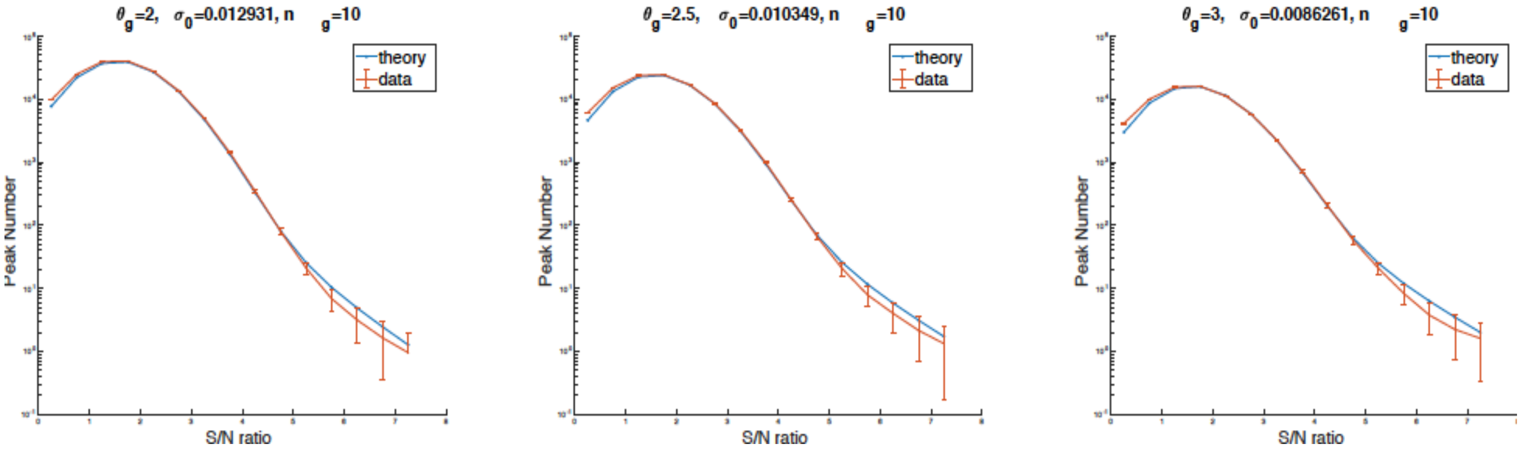
Peak model improvement





LSS effects
Yuan et al. 2018

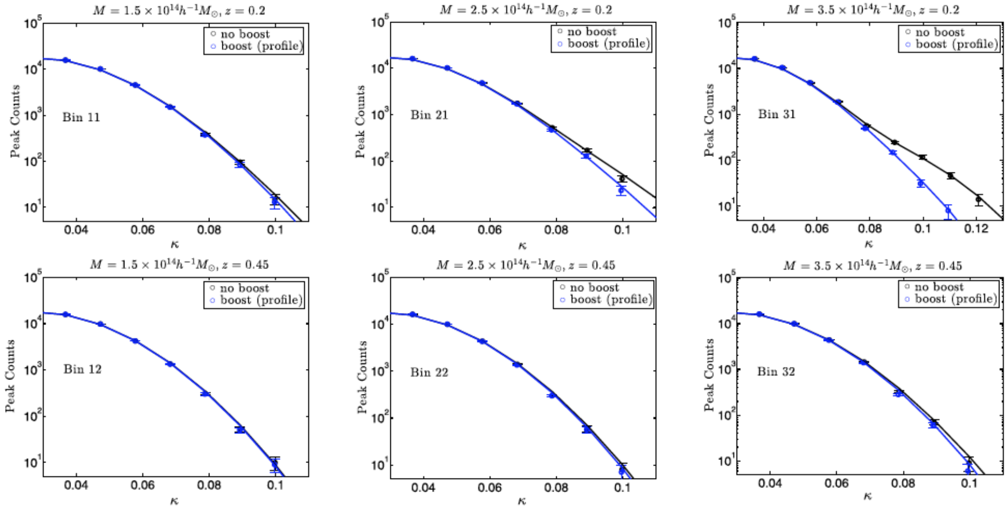
Shear peak model directly from the reduced shear without convergence reconstruction
Pan et al. 2018



Cluster member dilution effect (Shan, Liu et al. 2018)

z=0.2

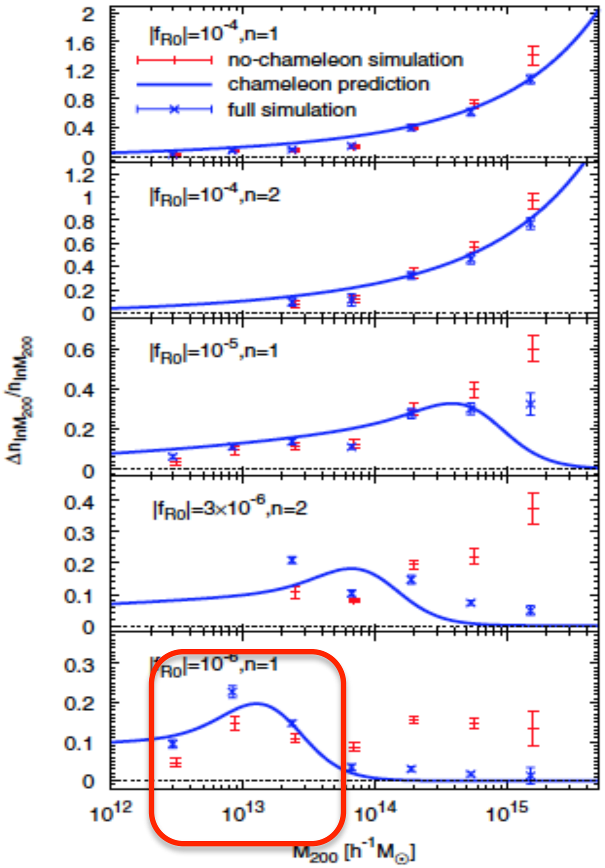
z=0.45

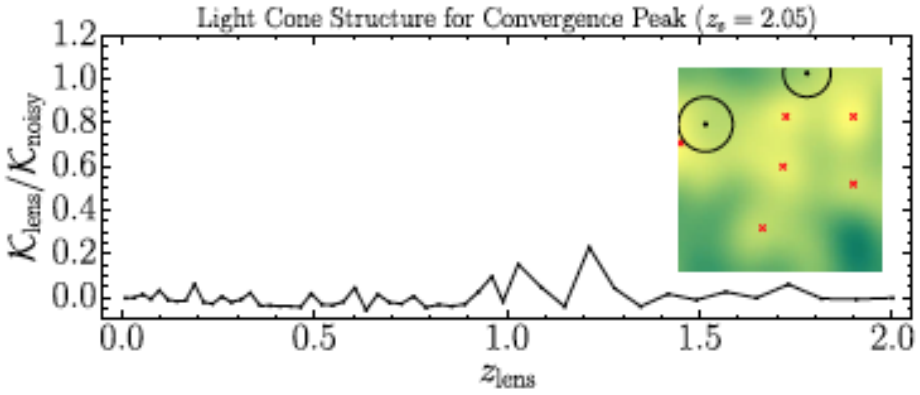


Inclusion of the peak profile information

Intrinsic alignment, theoretical uncertainties, …

* Low WL peak statistics model development





The current halo-based model for high peaks cannot apply -- no single dominant halo

Random field approach might be more appropriate

Gaussian approximation is not good

Lognormal (seems still not very satisfactory)

Or Gaussianization method ??

Lin & Kilbinger Monte Carlo approach adding the diffused component??

The future WL studies are exciting but also challenging

systematics

systematics

systematics

The synergy of Euclid and CSS-OS would be highly promising

Thank you