Probing the dark Universe with weak lensing effects

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Mar. 10, 2016@PKU

Outline

✴   **Introduction**

✴   **Cosmological studies with weak lensing peak statistics**

   -- Model of WL peak abundances
   -- Cosmological constraints from WL peak analyses

✴   **Discussions**

- **Introduction**

   Weak lensing effects – gravitational in origin – 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 the law of gravity
   (stage II- CFHTLenS, CS82; III-DES, HSC, KiDS; IV – LSST, Euclid, WFIRST)

Path of light
around dark matter

Distant
universe

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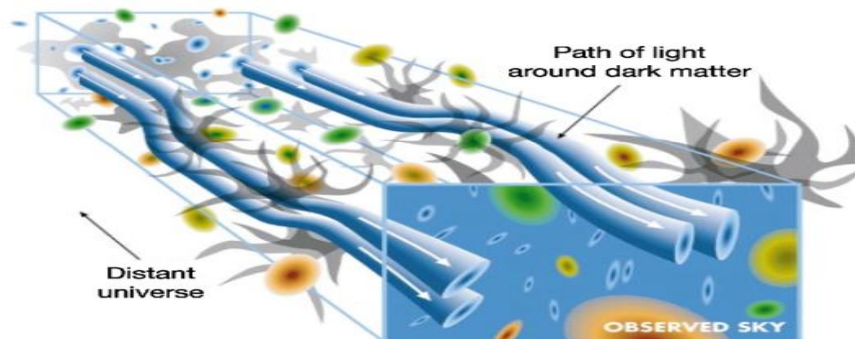
Wittman et al. 2000
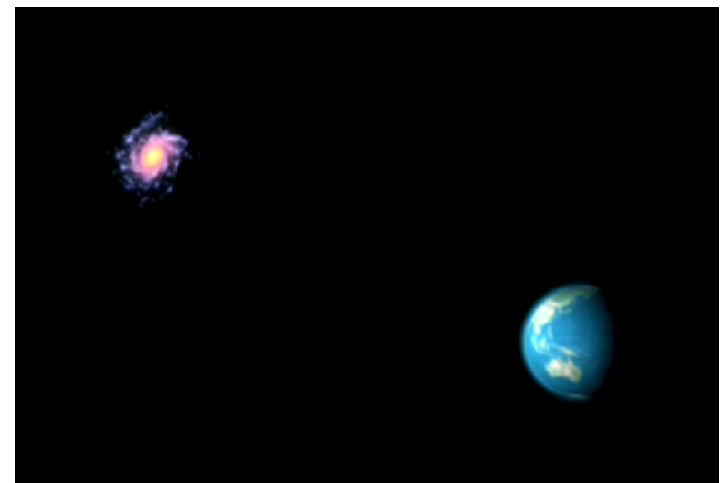
Weak lensing shear signals are weak
(at least a few times smaller than the intrinsic
ellipticity of galaxies)

Observationally extremely challenging (Dezi Liu)

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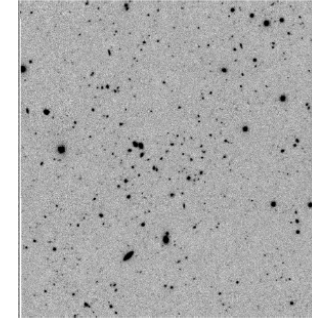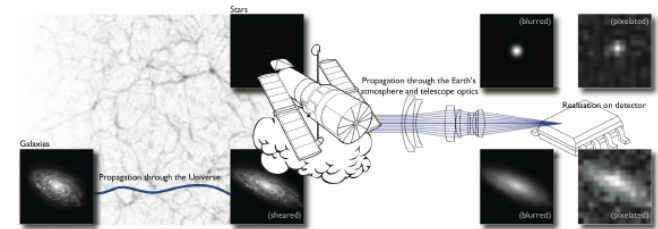
Outstanding issues theoretically

  -- 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,
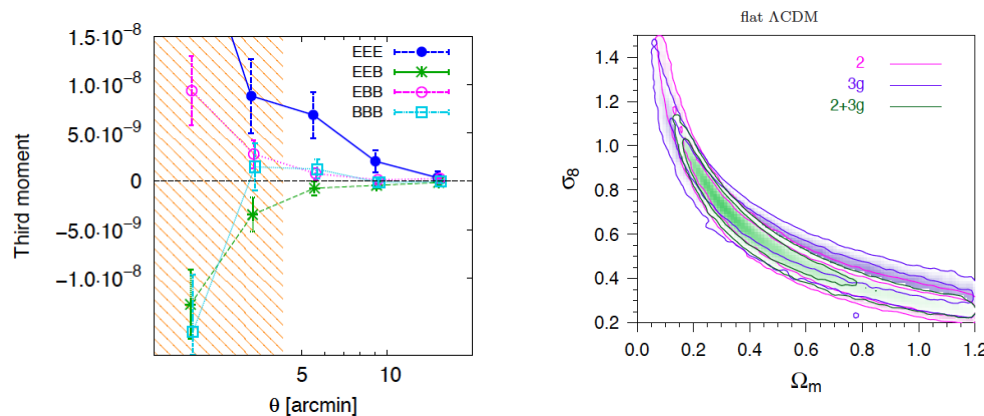   both theoretical and observational
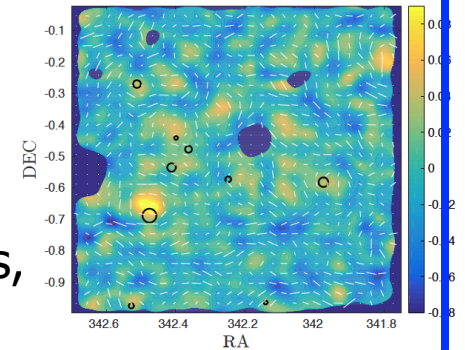
Weak lensing analyses

-- 2-pt shear correlations are the most commonly applied analyses
   Cannot reveal non-Gaussian features
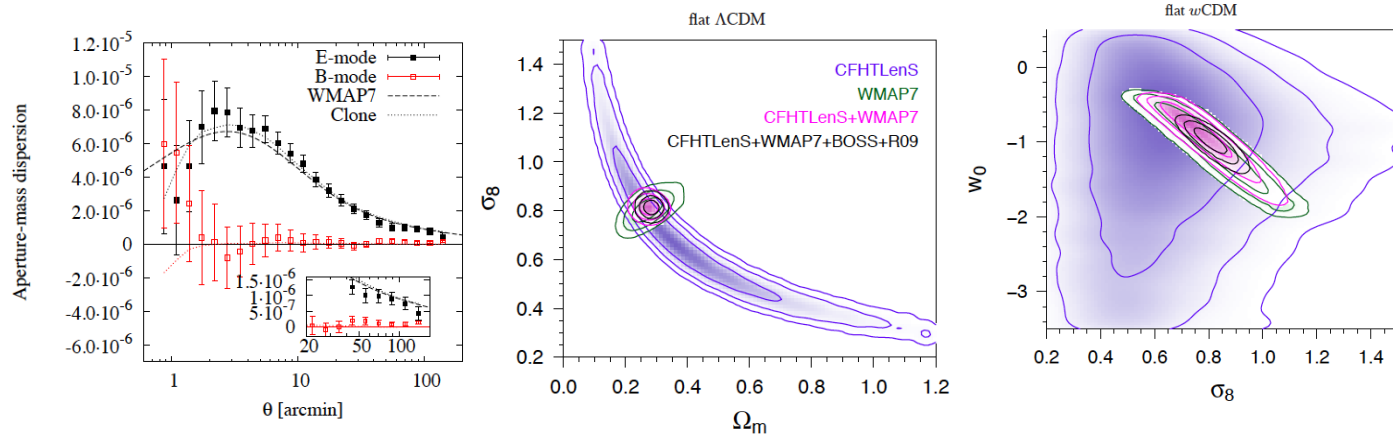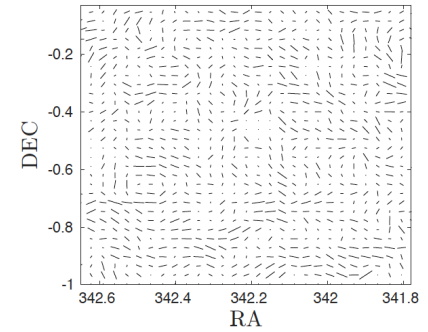
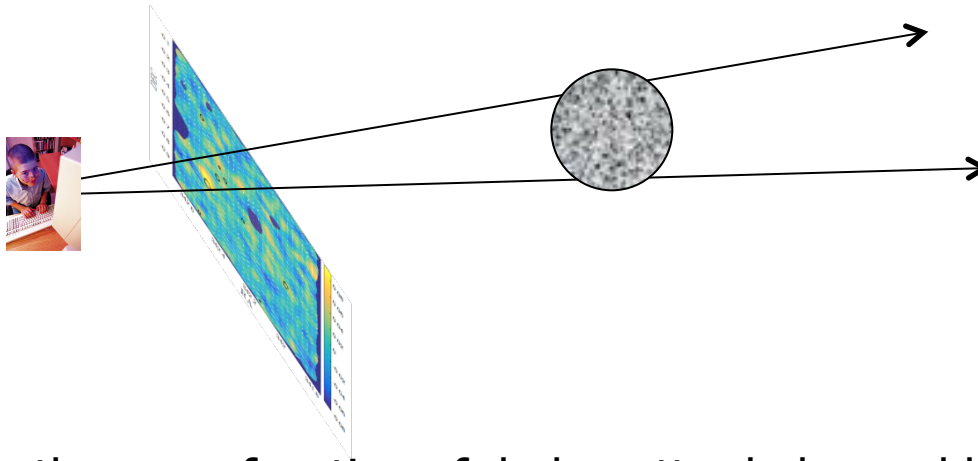
Kilbinger et al. 2013,
CFHTLenS

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

Fu et al. 2014, CFHTLenS

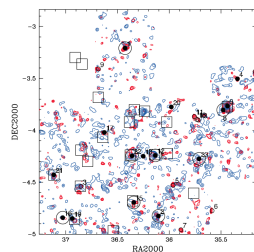Weak-lensing peak analyses provide another important means

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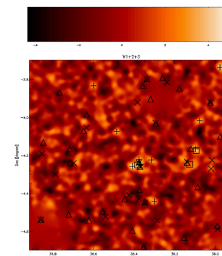

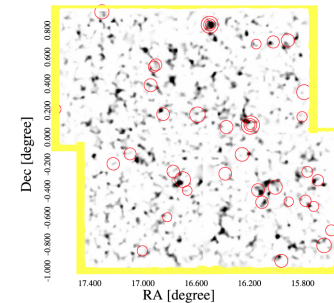→ related to the mass function of dark matter halos and lensing efficiency factor → cosmology sensitive
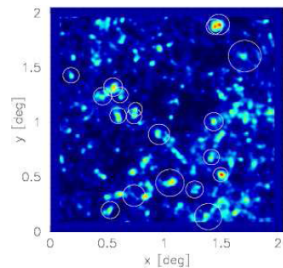
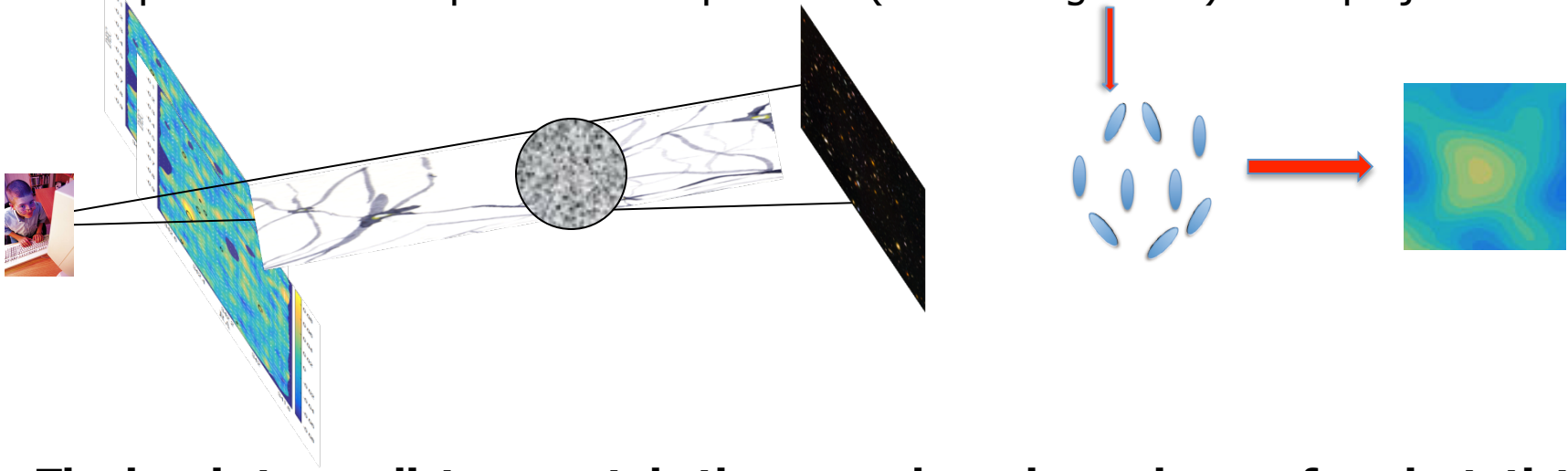**Hamana et al. 2004**

Miyazaki et al. 2007

Shan et al. 2012, CFHTLS

Shan et al. 2014, CS82

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 – clean physics
    approximations are inevitable

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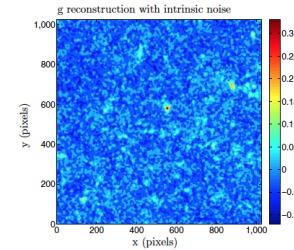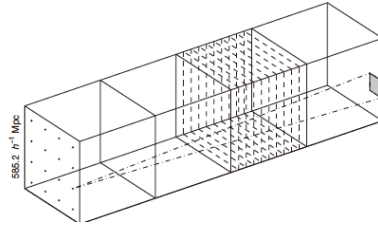   -- theoretical model tested and calibrated by simulations

✴ **Cosmological studies with WL peak statistics**

Model building
 -- predicting peak
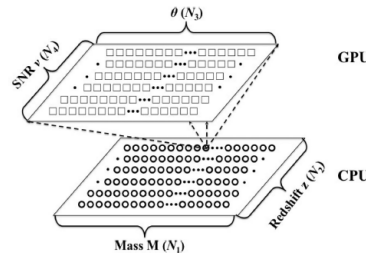abundances given
a cosmological model
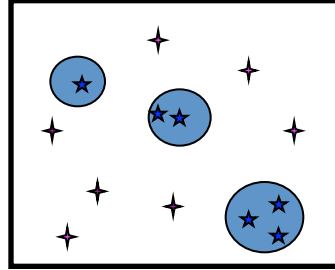
Halo model for high peaks taking into
account the shape noise effect
– crucial for cosmological studies with WL
peaks

Large sets of
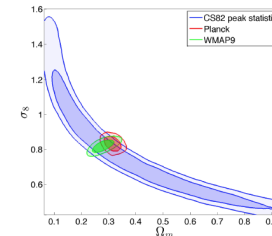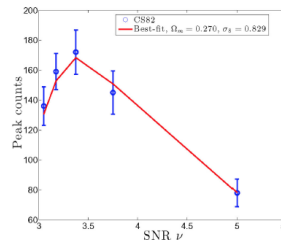ray-tracing
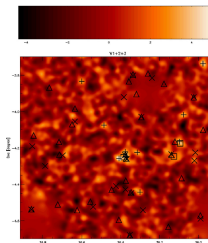simulation

Simulation studies

Set up fast
computation code
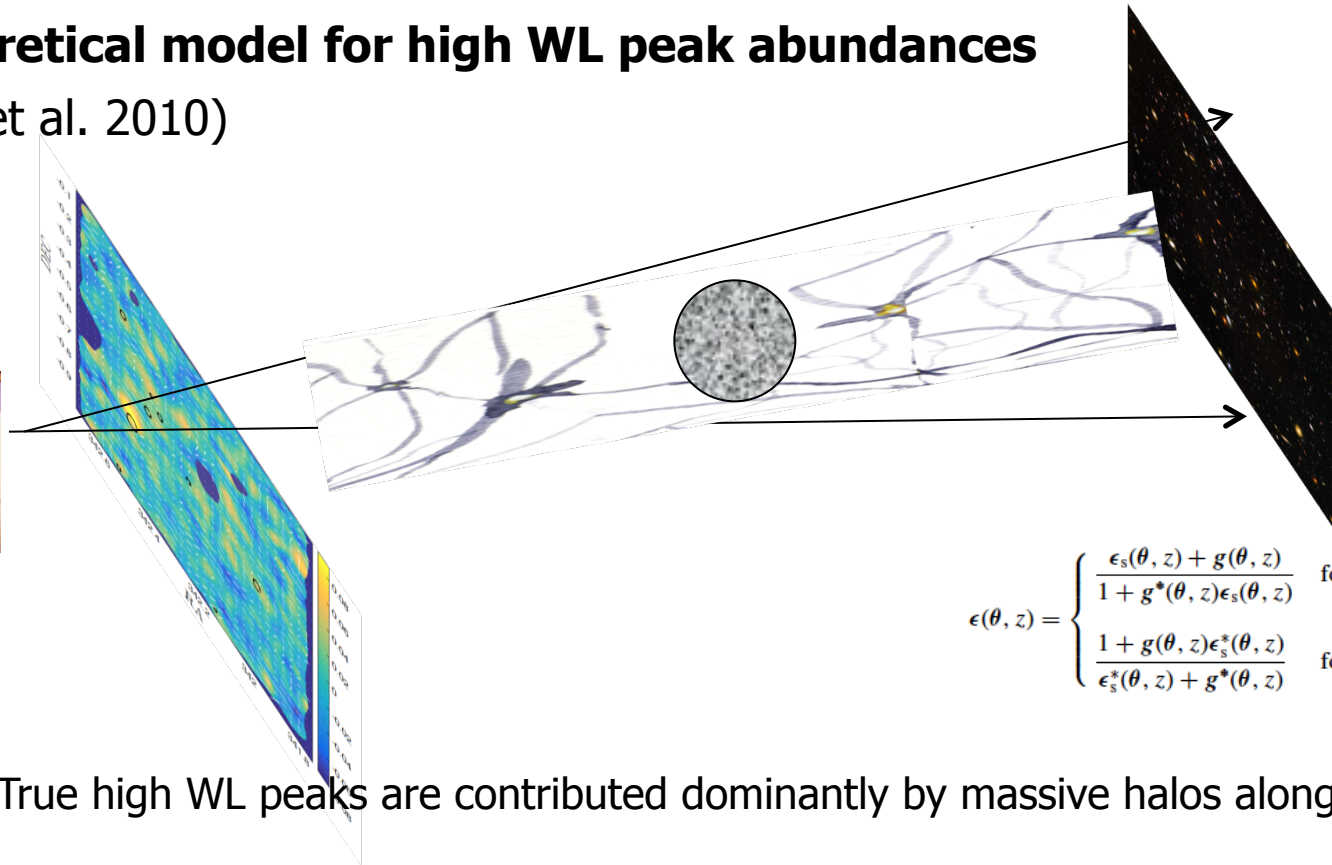for cosmological
analyses

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

Observational
analyses

Theoretical model for high WL peak abundances

(Fan et al. 2010)

$$\epsilon(\theta, z) = \begin{cases} \dfrac{\epsilon_s(\theta, z) + g(\theta, z)}{1 + g^*(\theta, z)\epsilon_s(\theta, z)} & \text{for } |g(\theta, z)| \leq 1 \\[2ex] \dfrac{1 + g(\theta, z)\epsilon_s^*(\theta, z)}{\epsilon_s^*(\theta, z) + g^*(\theta, z)} & \text{for } |g(\theta, z)| > 1 \end{cases}$$

- 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

$$\mathrm{K}_N(\boldsymbol{\theta}) = K(\boldsymbol{\theta}) + N(\boldsymbol{\theta}) = \int d\mathbf{k} \exp(-i\mathbf{k} \bullet \boldsymbol{\theta}) c_\alpha(\mathbf{k}) \Sigma_\alpha^{(o)}(\mathbf{k})$$
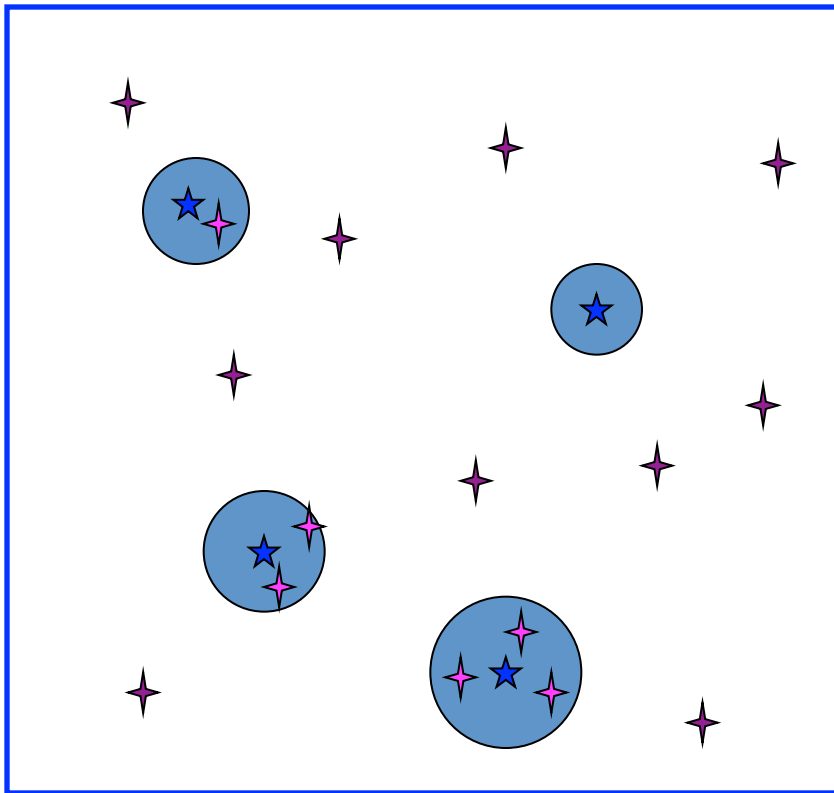
- Large-scale structures also contribute -- ignored at the current version of model for $n_g \sim 10$ arcmin^{-2}, $z_s \sim 1$

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

Theoretical model for high WL peak abundances

(Fan et al. 2010)

Halo model for high peaks

Halo region (M>~$10^{13.9}$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

Theoretical model for high WL peak abundances

(Fan et al. 2010)

WL Peak number density

$$n_{\mathrm{peak}}(\nu)d\nu = n_{\mathrm{peak}}^{c}(\nu)d\nu + n_{\mathrm{peak}}^{n}(\nu)d\nu$$

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

$$f(\nu,M,z) = \int_{0}^{R_{\mathrm{vir}}} dR\,(2\pi R)\, n_{\mathrm{peak}}(\nu,M,z)$$

$$n_{\mathrm{peak}}(\nu_0) = \exp\left[-\frac{(K^1)^2+(K^2)^2}{\sigma_1^2}\right]\left\{\frac{1}{2\pi\theta_*^2}\frac{1}{(2\pi)^{1/2}}\right\}$$

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

$$\times \exp\left\{-\frac{\left[x_N+(K^{11}+K^{22})/\sigma_2-\gamma_N(\nu_0-K/\sigma_0)\right]^2}{2(1-\gamma_N^2)}\right\} \times F(x_N)$$

$$n_{\mathrm{peak}}^{n}(\nu) = \frac{1}{d\Omega}\left\{n_{\mathrm{ran}}(\nu)\left[d\Omega - \int dz \frac{dV(z)}{dz}\right.\right.$$
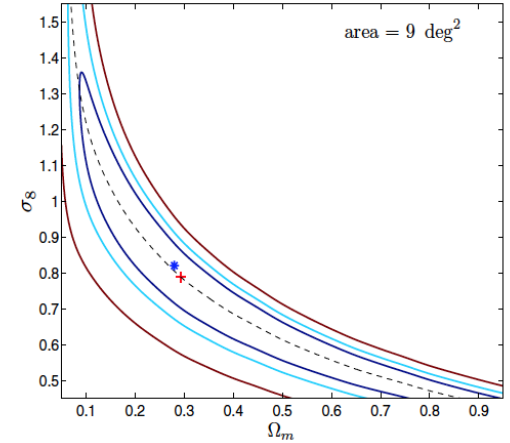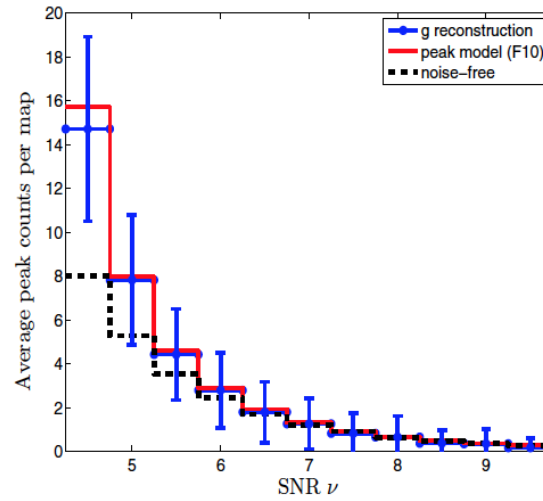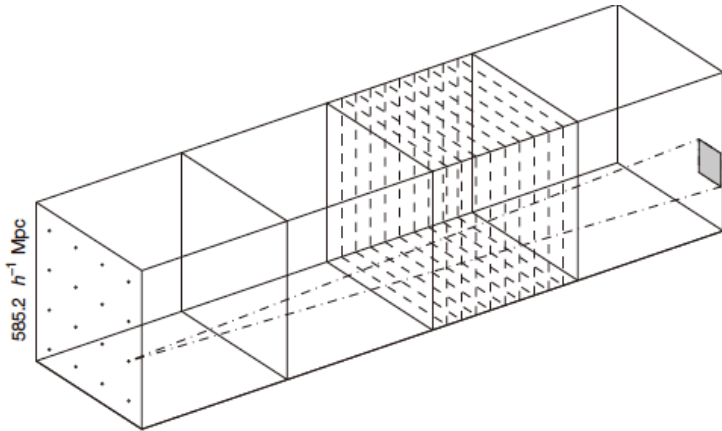
$$\left.\left.\times \int dM\, n(M,z)\,\left(\pi R_{\mathrm{vir}}^2\right)\right]\right\},$$
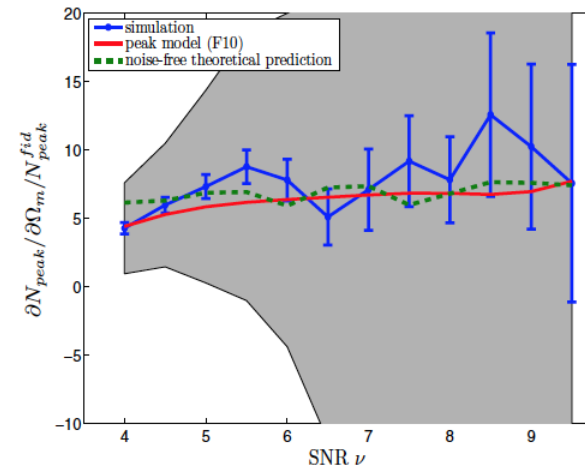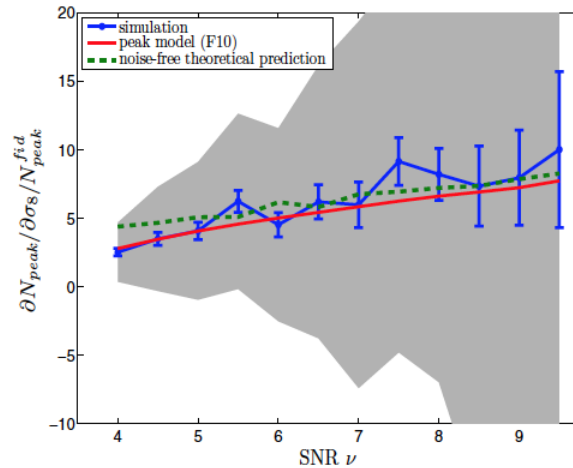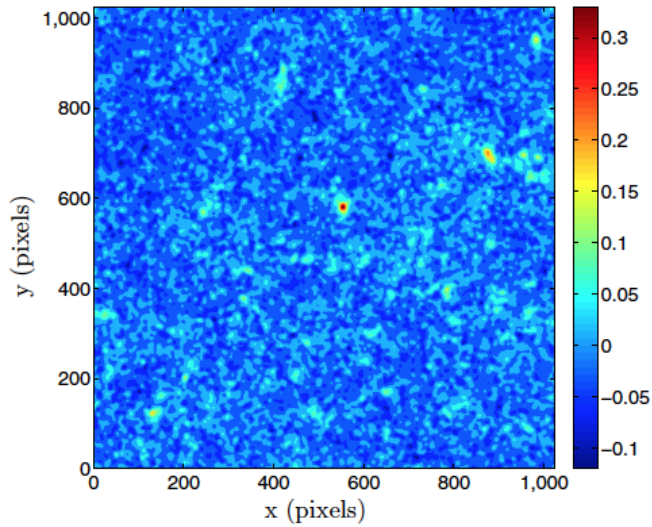
Cosmological information:

DM halo mass function
DM halo internal profile

Cosmological volume
and lensing efficiency factor

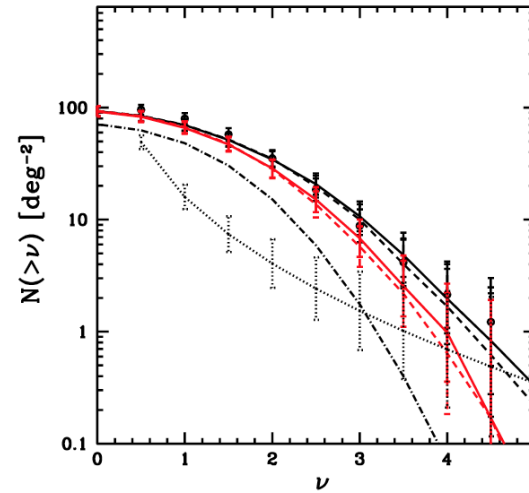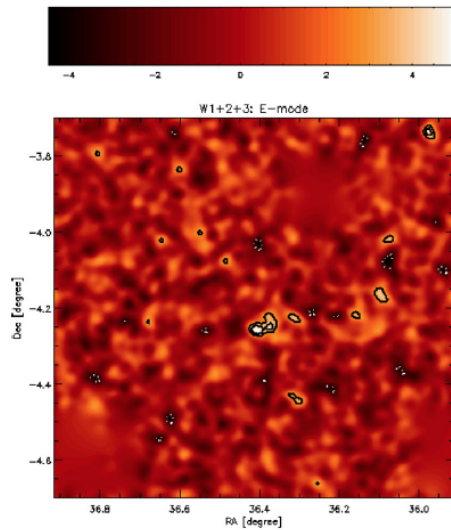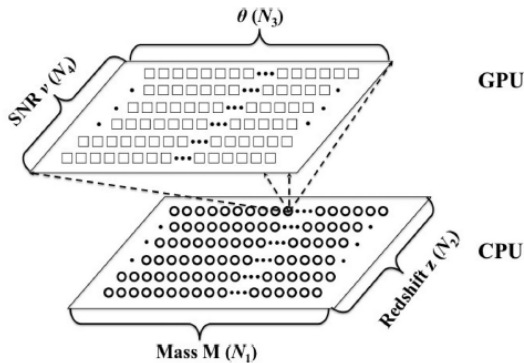# Simulation tests (Fan et al. 2010, Liu et al. 2014, 2015, 2016)

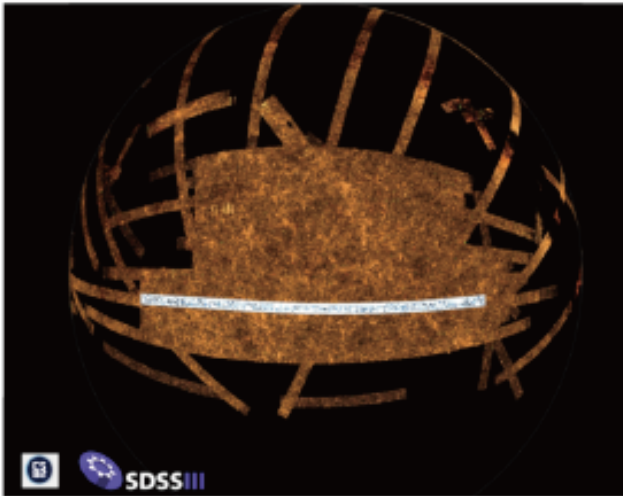Observational comparisons (Shan et al. 2012, 2014)

CFHTLS

Develop a fast code for peak model calculations (Pan, C.Z. et al.)
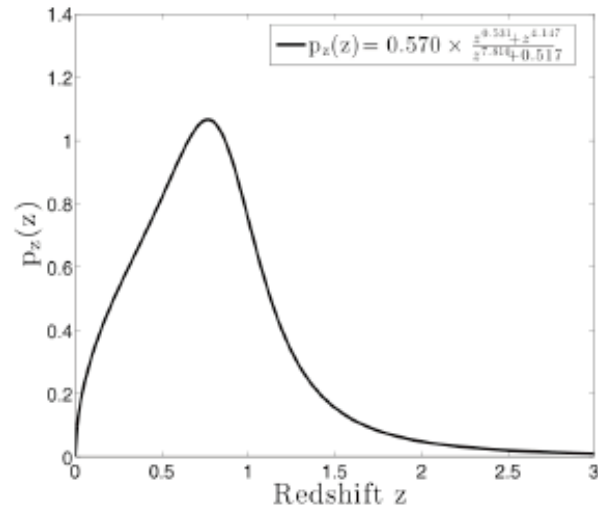

GPU   -- important for deriving cosmological
            constraints from WL peak abundances

CPU

CS82 WL peak studies (Liu et al. 2015, in collaboration with CS82 team)

CFHT Stripe 82 weak lensing survey

$$p_z(z) = 0.570 \times \frac{z^{0.531} + z^{4.147}}{z^{7.810} + 0.517}$$

$p_z(z)$

Redshift z

Celestial equatorial region

SDSSIII

CFHT MegaCam observations
 --173 tiles 1deg^2 each
 -- seeing 0.4"-0.8"
 -- four ~410s exposures each pointing
 -- i$_{AB}$~24 (5σ)

Shear measurements
 --Lensfit
 -- 5,475,318 galaxies with weight>0
 -- ng~11.8 arcmin^{-2}
 -- median redshift z~0.83

shear measurements

$$\epsilon(\theta, z) = \begin{cases} \dfrac{\epsilon_s(\theta, z) + g(\theta, z)}{1 + g^*(\theta, z)\epsilon_s(\theta, z)} & \text{for } |g(\theta, z)| \le 1 \\[3mm] \dfrac{1 + g(\theta, z)\epsilon_s^*(\theta, z)}{\epsilon_s^*(\theta, z) + g^*(\theta, z)} & \text{for } |g(\theta, z)| > 1 \end{cases}$$
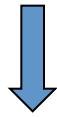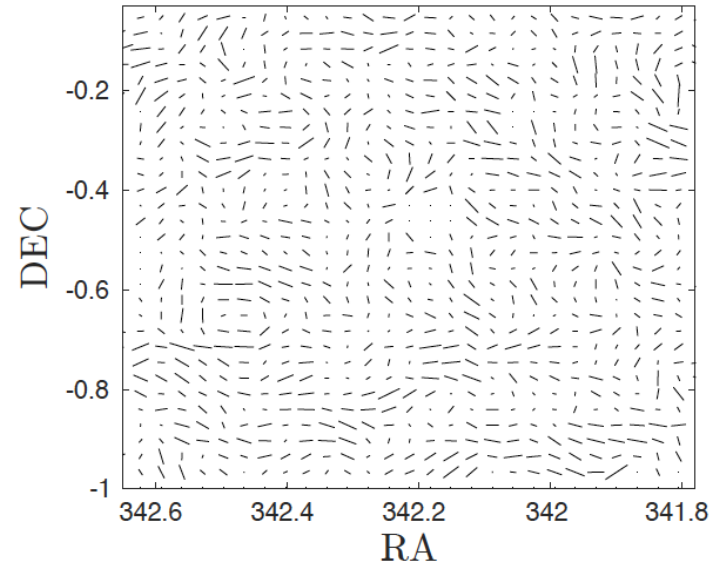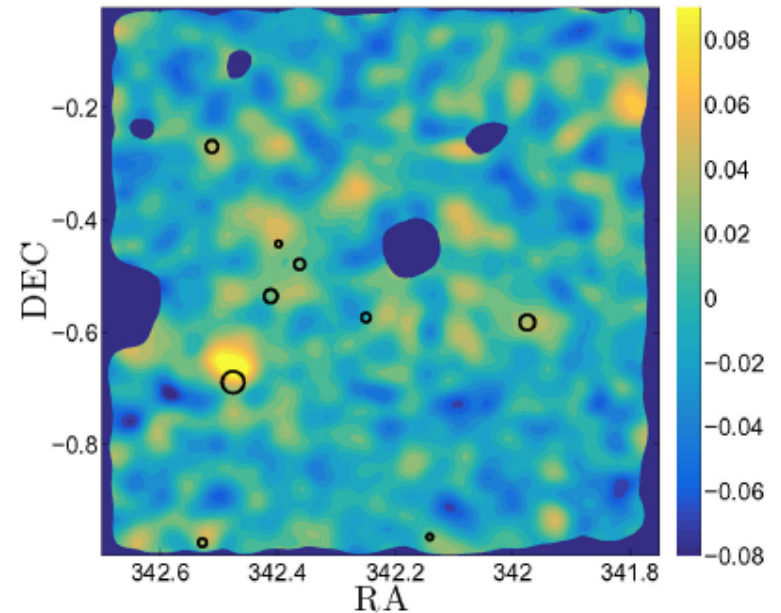
iterative convergence reconstruction

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

$$\hat{\gamma}(k) = \pi^{-1}\hat{D}(k)\hat{\kappa}(k),$$

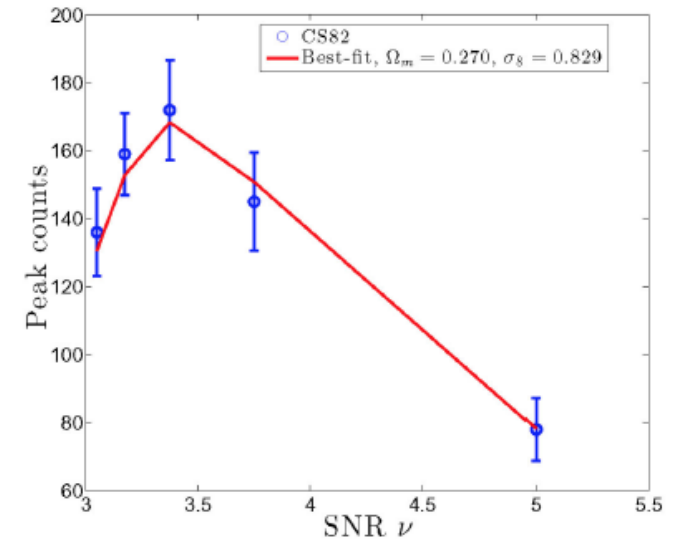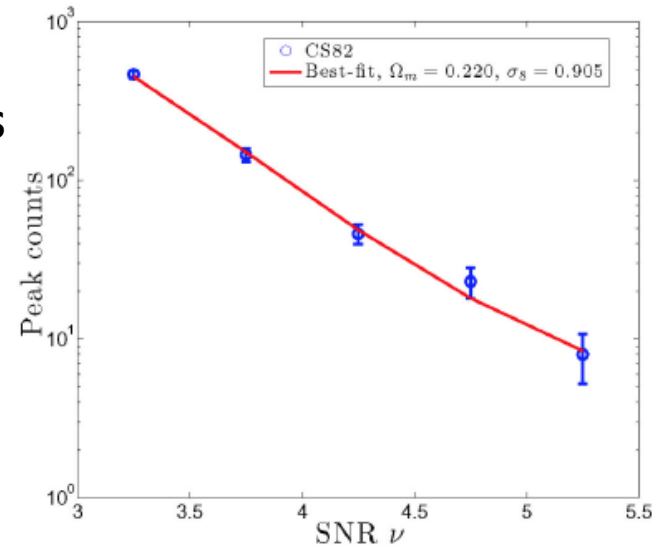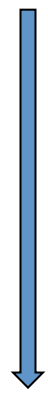$$\hat{D}(k) = \pi\frac{k_1^2 - k_2^2 + 2ik_1k_2}{k_1^2 + k_2^2}$$
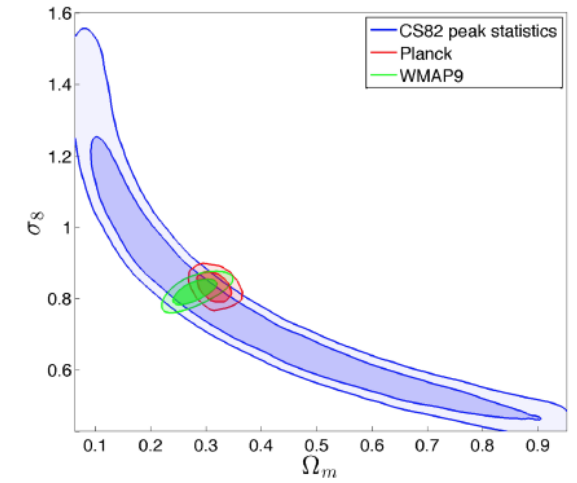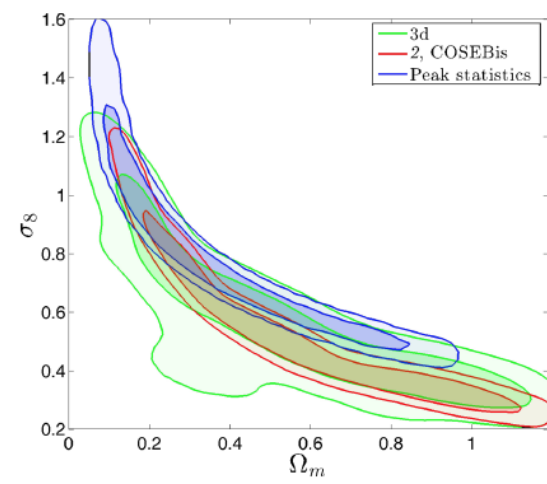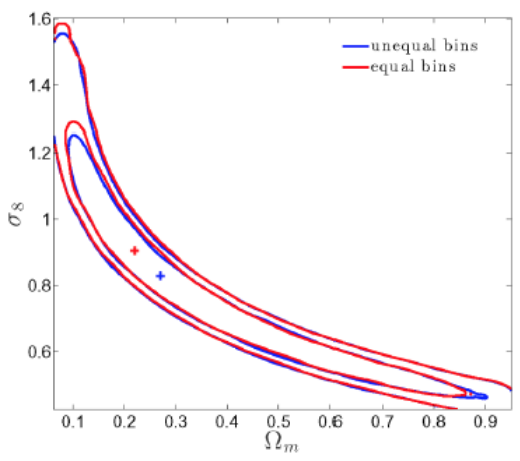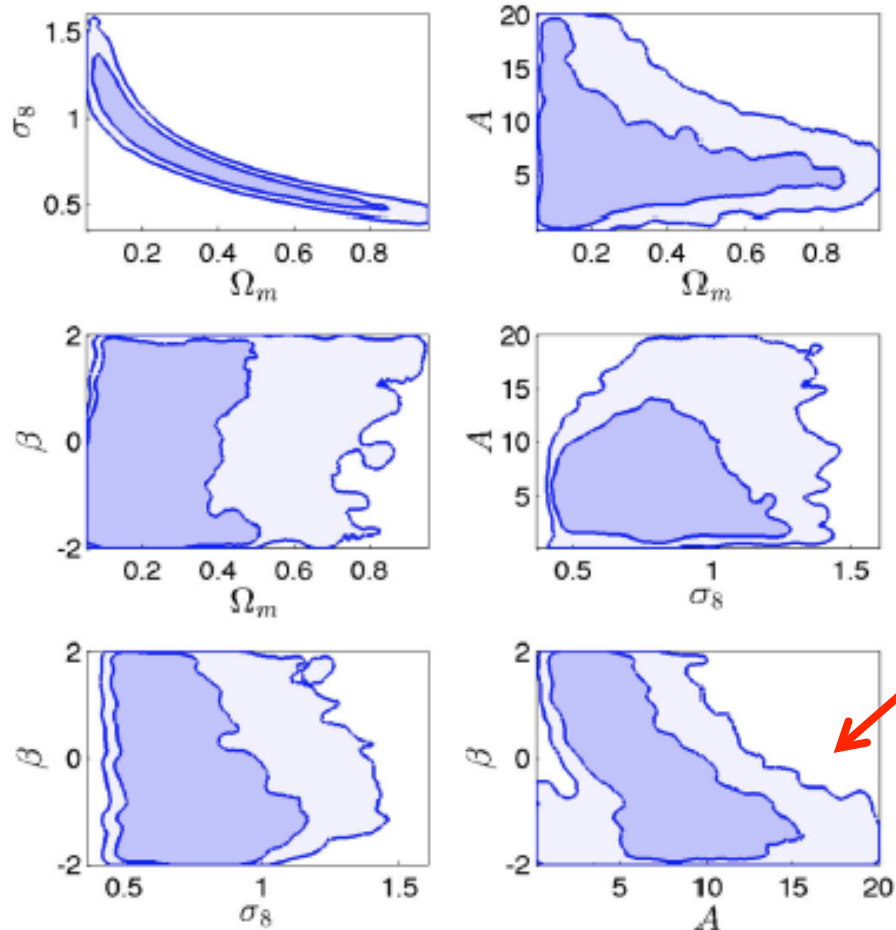

Reconstructed mass map

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)

Parameters of M-c relation of dark matter halos

Constraints on f(R) gravity theory (Liu et al. 2016)

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.
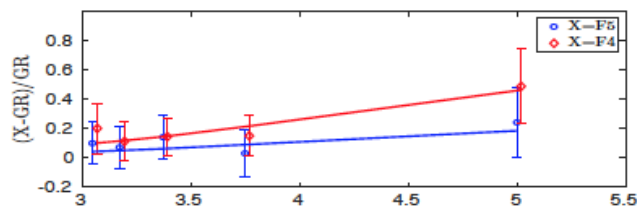Therefore we can extend our analyses beyond GR

CFHTLenS: 154 deg^2, u*g'r'i'z', photo-z distribution for each galaxy
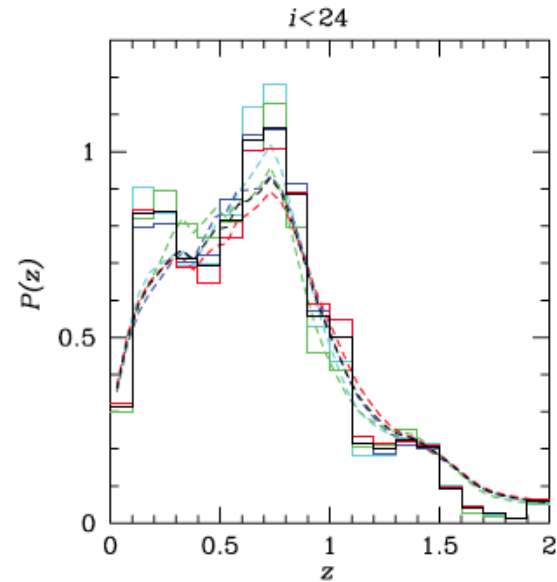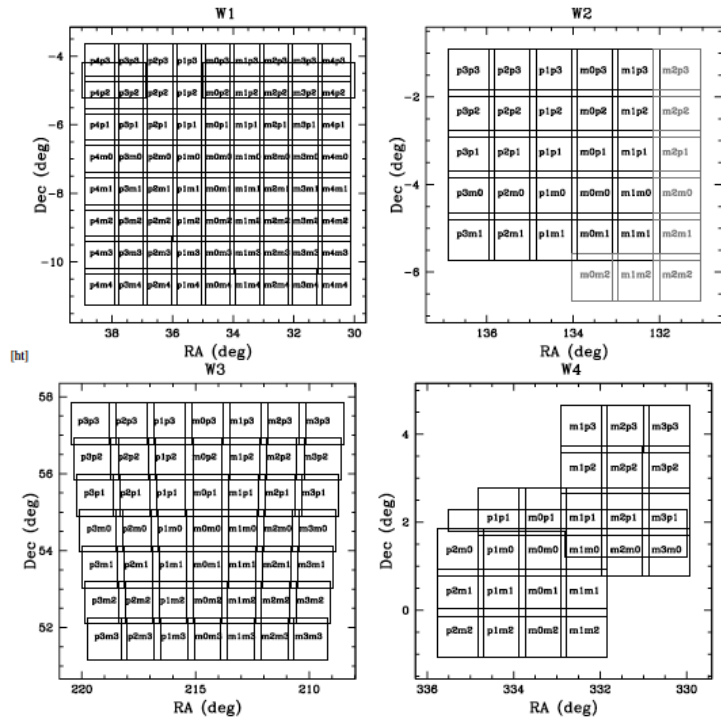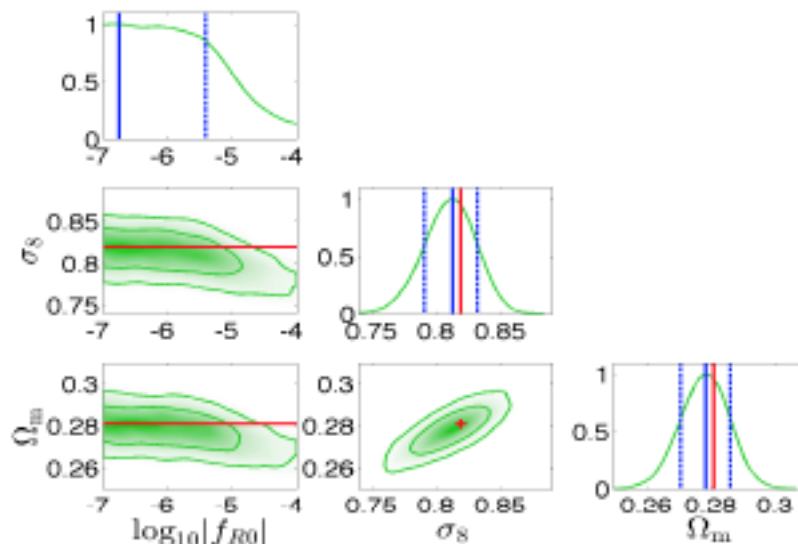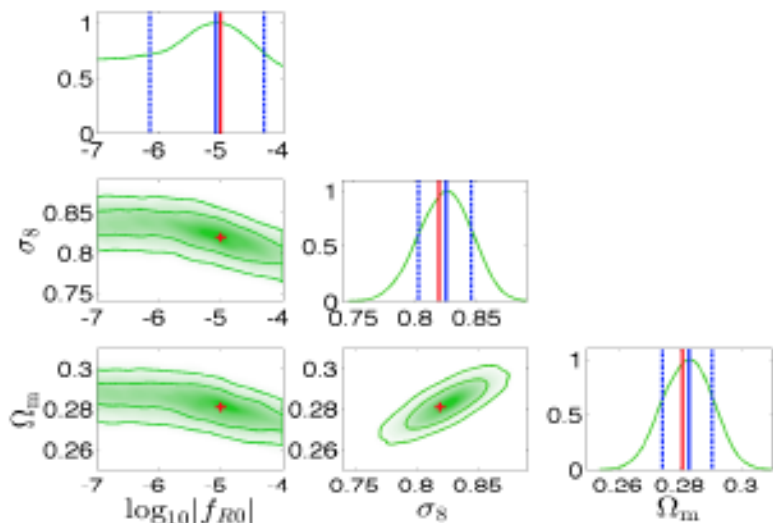
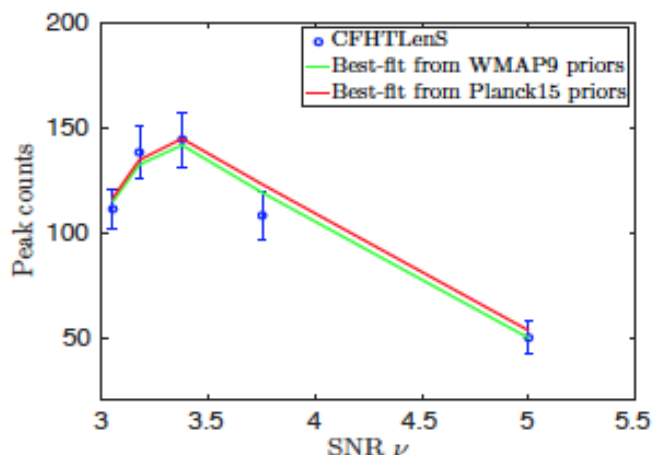# HS f(R) theory – f_{R0} parameter with $f_{R0}=0$ for GR
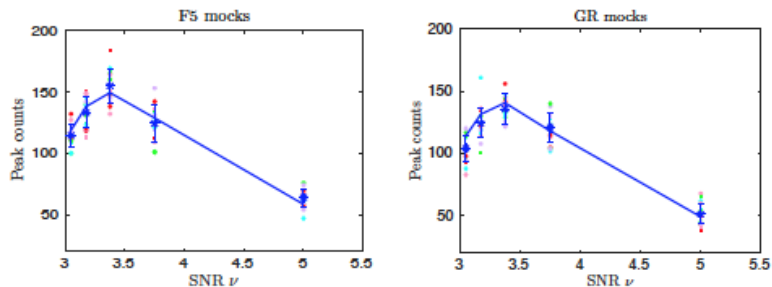
Mock simulation tests
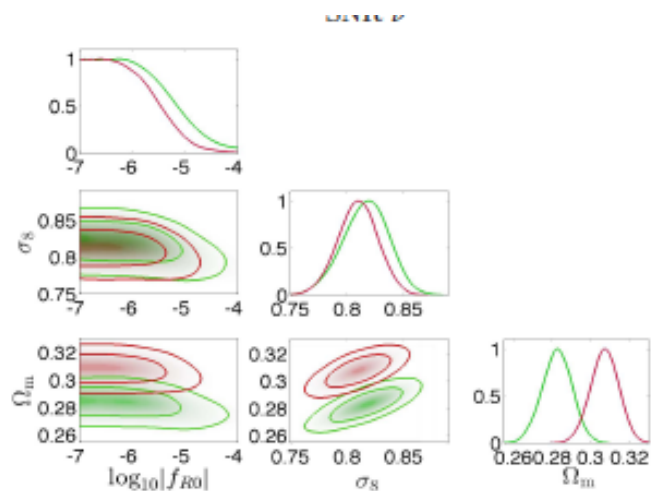show that WL high peaks
depend on f_{R0} sensitively.

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

CFHTLens observations

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

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

✴ Summary and discussion

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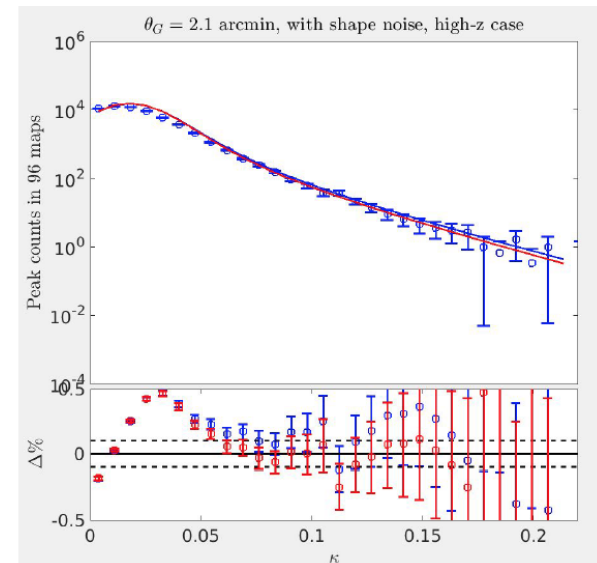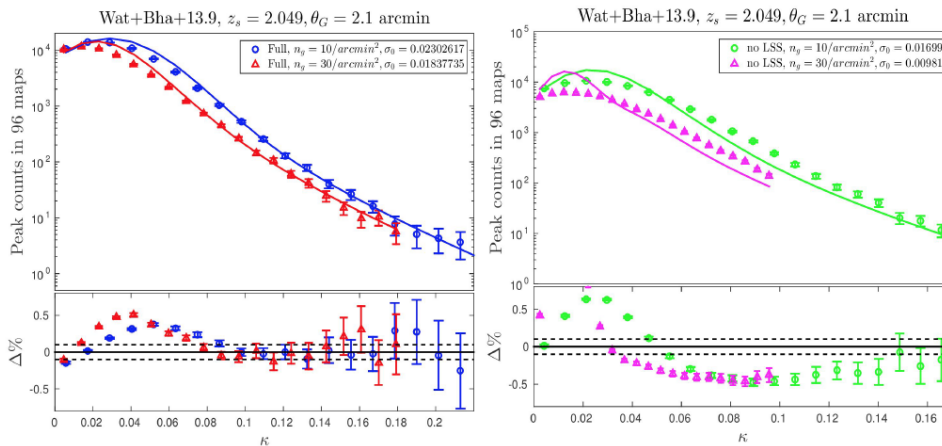 model building – simulations – computational tool – observations

-- 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
-- Integrate our WL tool into e.g., COSMOMC, for future analyses
-- Set up a general MG computational package
(Pan et al.)

-- other systematic studies

Fully realize the power of WL analyses in future precision era

Thank you