Probing the dark Universe with weak lensing effects

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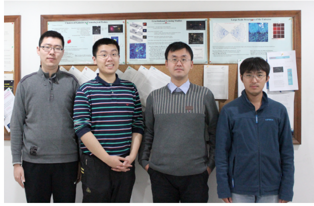

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R.Li, Q.Wang, W.Du, HY Shan, LP. Fu, J-P Kneib and CS82 team
GB. Zhao, BJ.Li, W. Fang, MC. Chiu
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Nov 22, 2016@South Africa

Outline

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

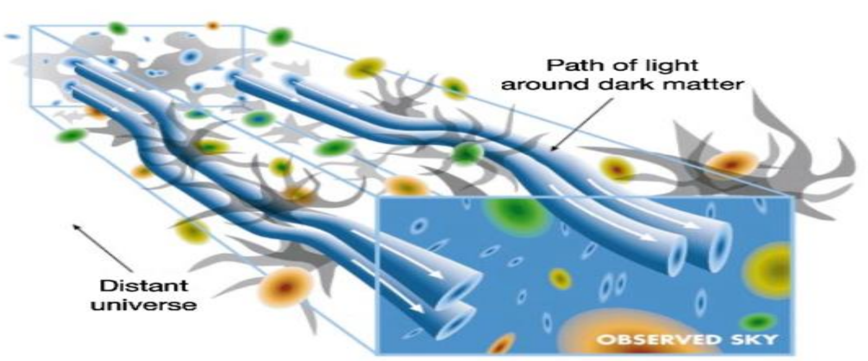
- **Introduction**

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

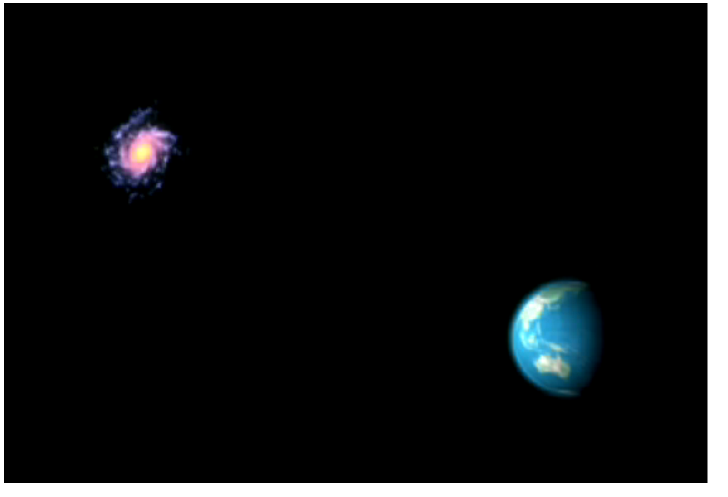
Exist almost everywhere in the Universe

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

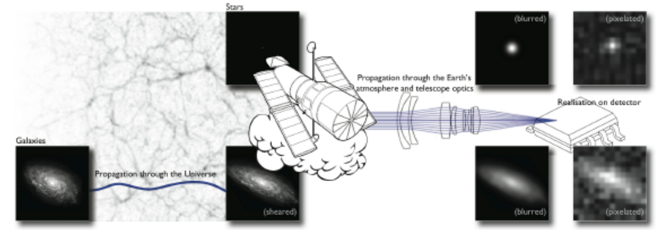
-- clean physics
-- excellent cosmological probe, particularly for understanding the nature of the two dark components and probing the the law of gravity
(stage II- CFHTLenS, CS82; III-DES, HSC, KiDS; IV – LSST, Euclid, WFIRST)



Wittman et al. 2000



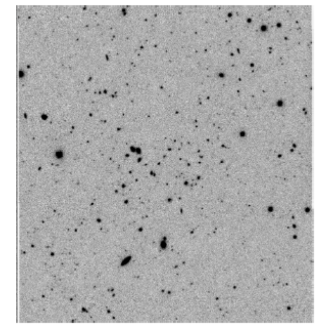
Great10 handbook



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

Observationally extremely challenging

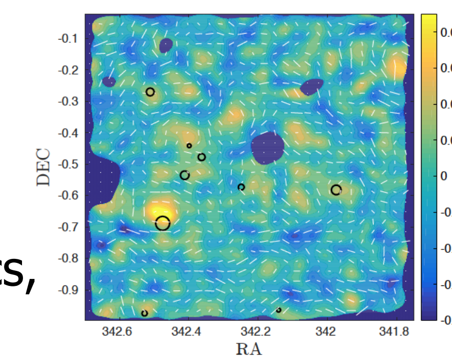
-- measure accurately the shapes of millions to billions faint galaxies
-- redshift information of individual galaxies



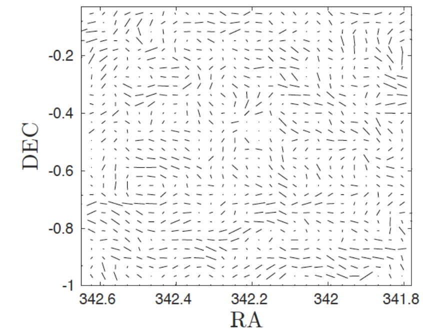
Outstanding issues theoretically

-- 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

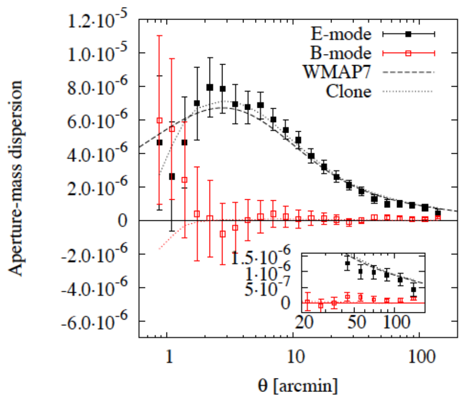


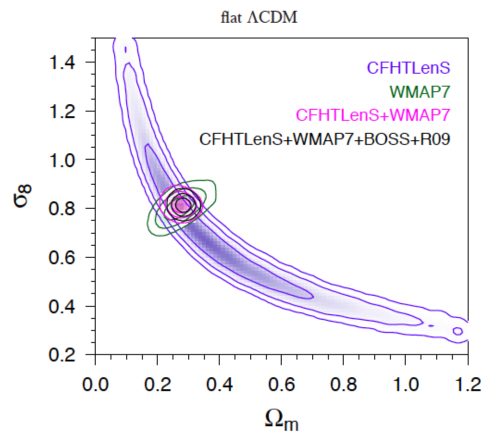
Weak lensing analyses

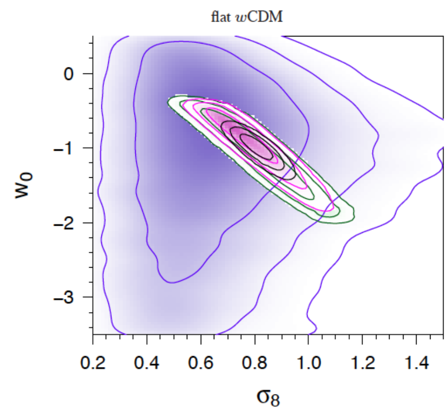


-- 2-pt shear correlations are the most commonly applied analyses

Cannot reveal non-Gaussian features

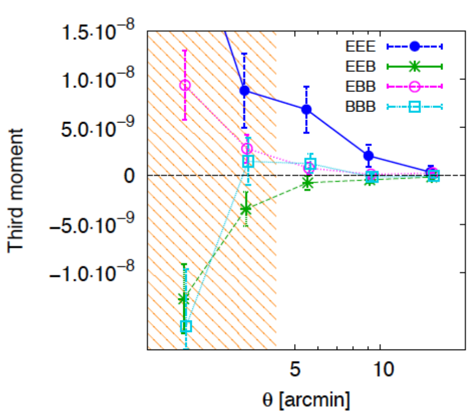


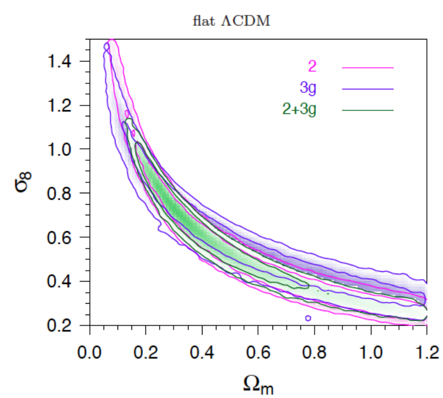




Kilbinger et al. 2013, CFHTLenS

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

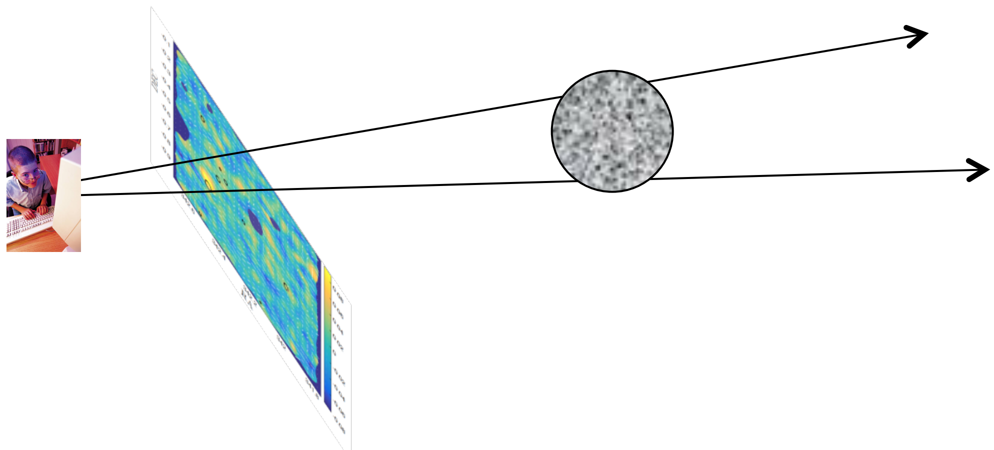




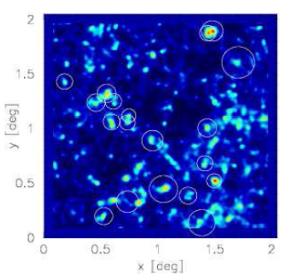
Fu et al. 2014, CFHTLenS

Weak-lensing peak analyses provide another important means

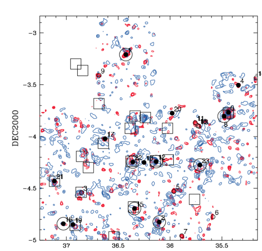
Massive structures, such as clusters of galaxies, are expected to generate high lensing signals and appear as peaks in weak-lensing convergence maps.



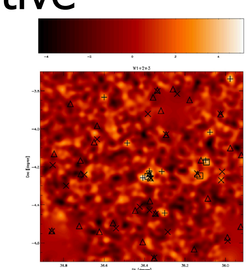
→ related to the mass function of dark matter halos and lensing efficiency factor → cosmology sensitive



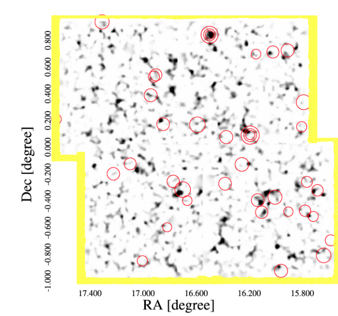
Hamana et al. 2004



Miyazaki et al. 2007

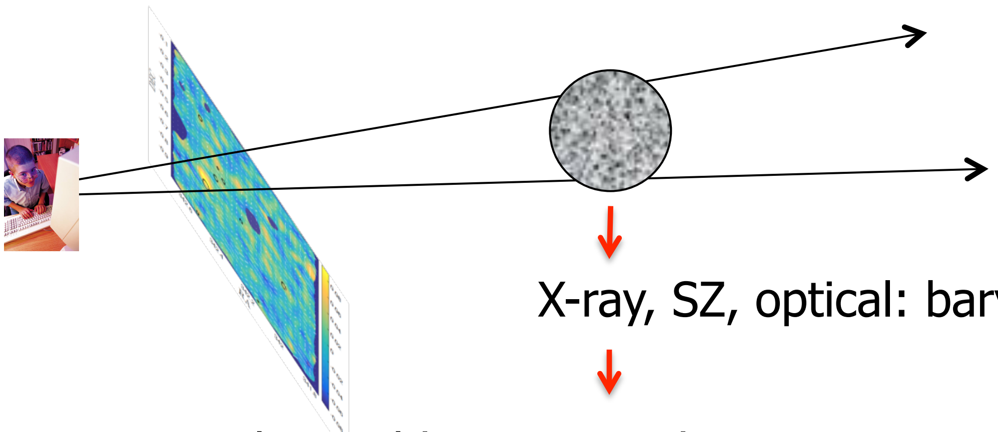


Shan et al. 2012, CFHTLS



Shan et al. 2014, CS82

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



X-ray, SZ, optical: baryonic observables

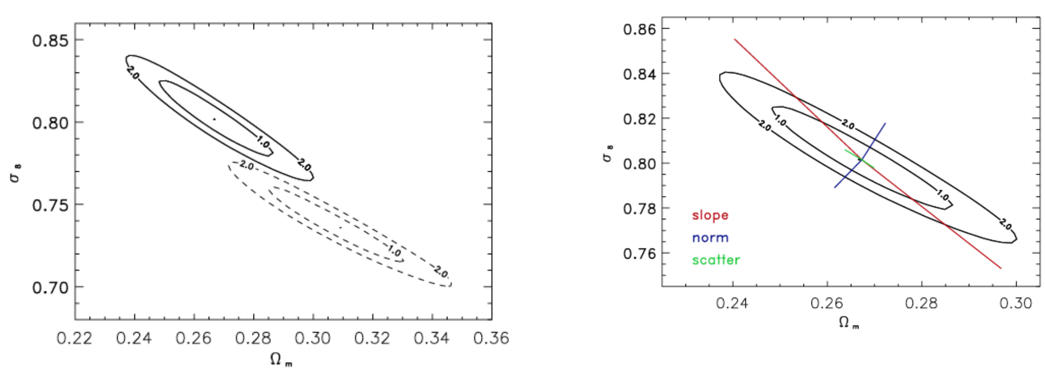
Observable – mass relations are needed in cosmological studies using the dark halo mass function

Major systematics in using clusters as cosmological probes

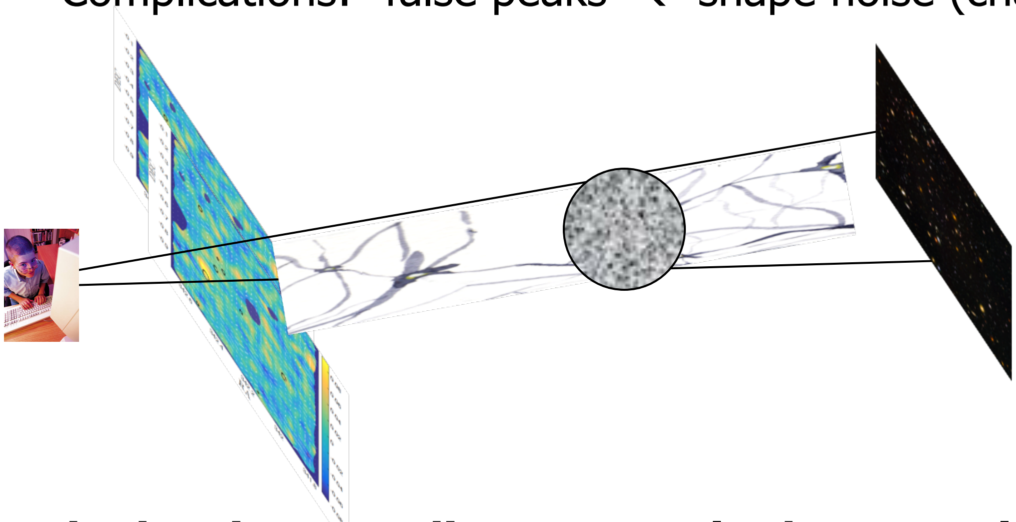
E.g., X-ray

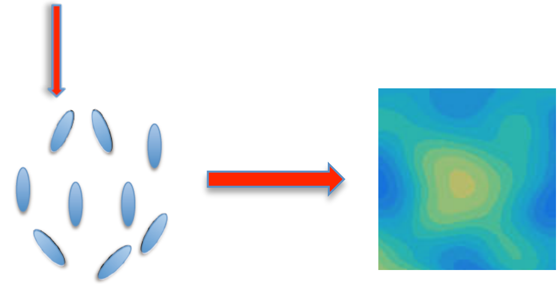
$$L_{500}(0.1\text{–}2.4\,\mathrm{keV}) = 0.1175\, M_{200}^{\alpha_{\rm sl}}\, h^{\alpha_{\rm sl}-2}\quad E(z)^{\alpha_{\rm sl}}$$

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 – clean physics

approximations are inevitable

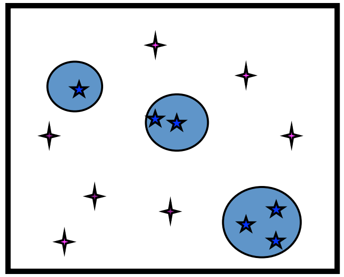
The combination of the two provides the best solution

-- theoretical model tested and calibrated by simulations

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

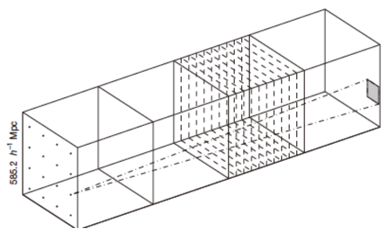
✷ Cosmological studies with WL peak statistics

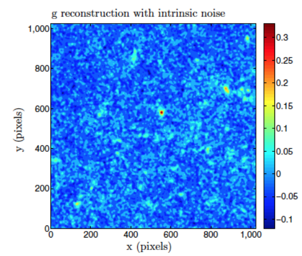
Model building
-- predicting peak abundances given a cosmological model



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

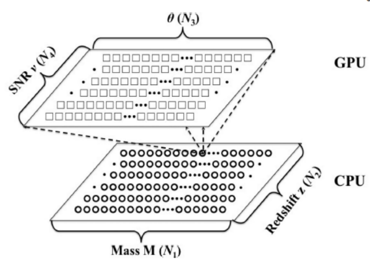
Large sets of ray-tracing simulation



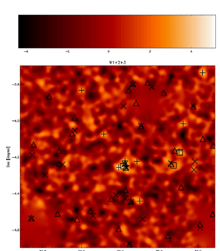


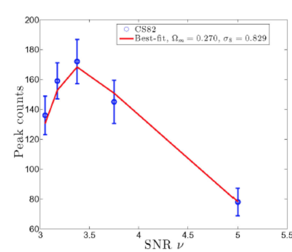
Simulation studies

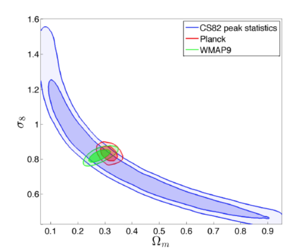
Set up fast computation code for cosmological analyses



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



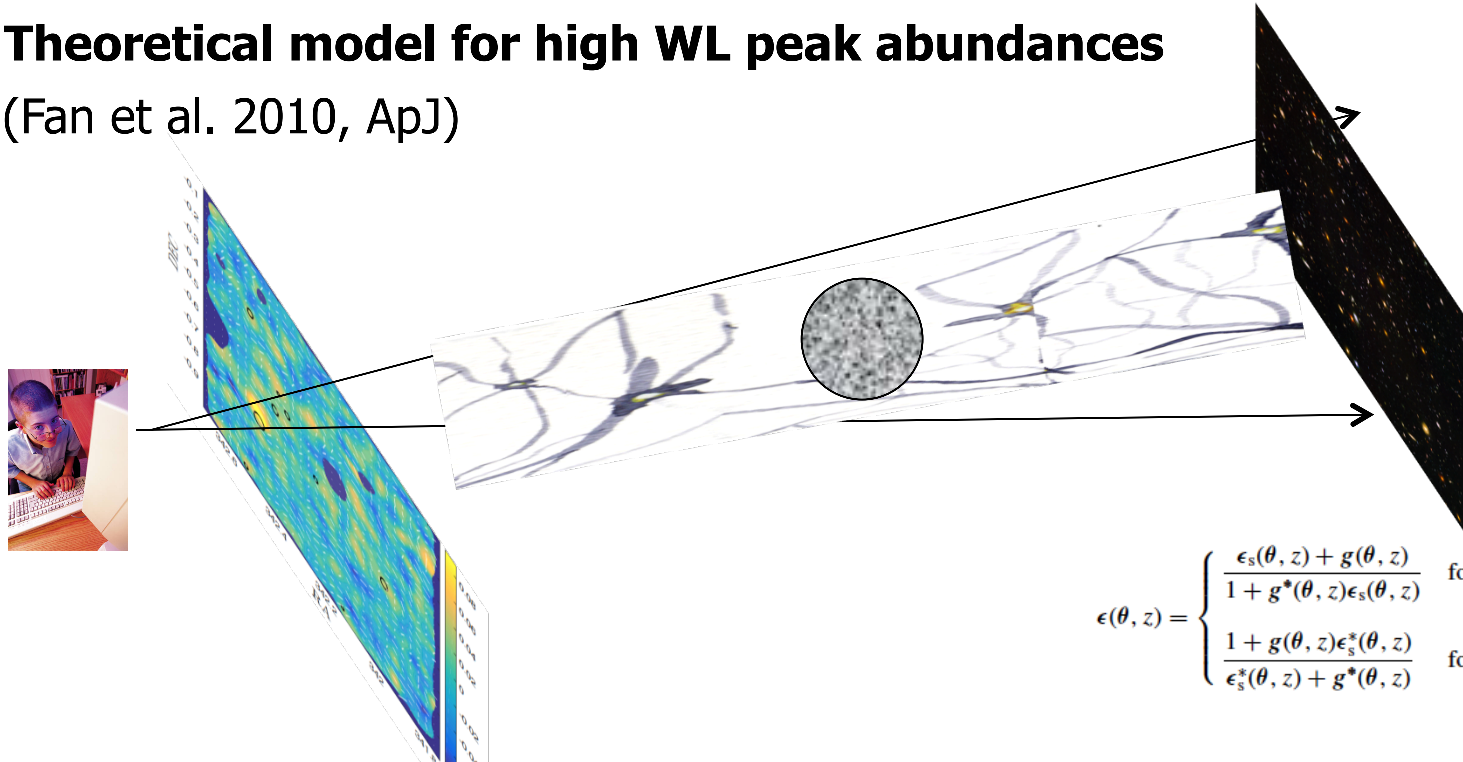




Observational analyses

Theoretical model for high WL peak abundances

(Fan et al. 2010, ApJ)



$$\epsilon(\boldsymbol{\theta}, z) = \begin{cases} \dfrac{\epsilon_s(\boldsymbol{\theta}, z) + g(\boldsymbol{\theta}, z)}{1 + g^*(\boldsymbol{\theta}, z)\epsilon_s(\boldsymbol{\theta}, z)} & \text{for } |g(\boldsymbol{\theta}, z)| \le 1 \\ \dfrac{1 + g(\boldsymbol{\theta}, z)\epsilon_s^*(\boldsymbol{\theta}, z)}{\epsilon_s^*(\boldsymbol{\theta}, z) + g^*(\boldsymbol{\theta}, z)} & \text{for } |g(\boldsymbol{\theta}, z)| > 1 \end{cases}$$

- 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

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

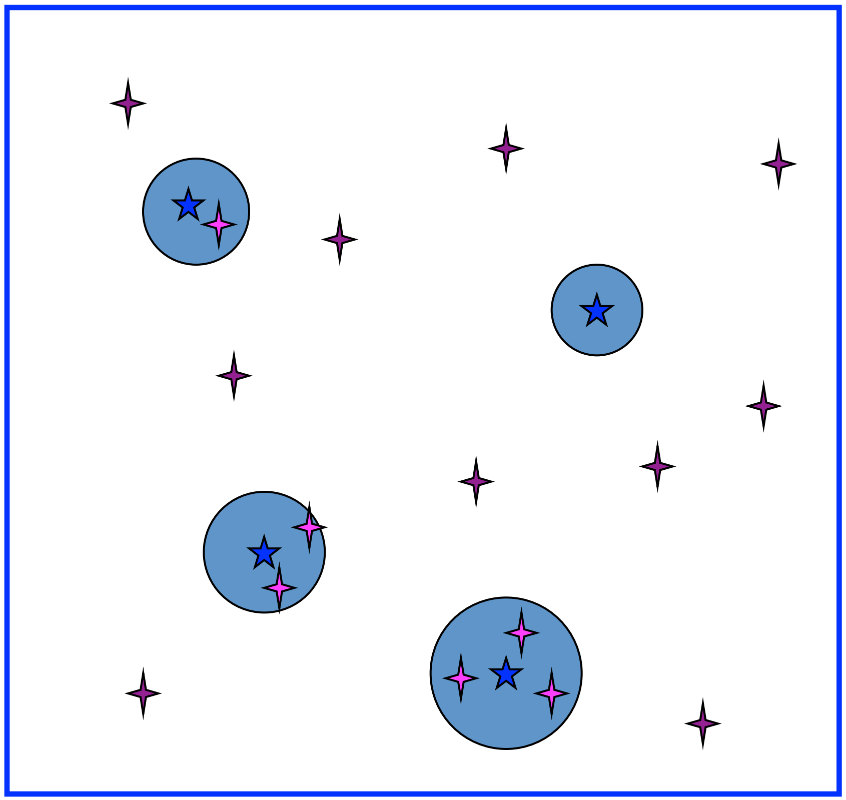
- Large-scale structures also contribute -- ignored at the current version of model for $n_g \sim 10$ arcmin^{-2}, $z_s \sim 1$

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

Theoretical model for high WL peak abundances

(Fan et al. 2010)

Halo model for high peaks



Halo region ($M > \sim 10^{13.9} h^{-1} M_{sun}$ 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 $n_{\rm peak}(\nu)d\nu = n^c_{\rm peak}(\nu)d\nu + n^n_{\rm peak}(\nu)d\nu$

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

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

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

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

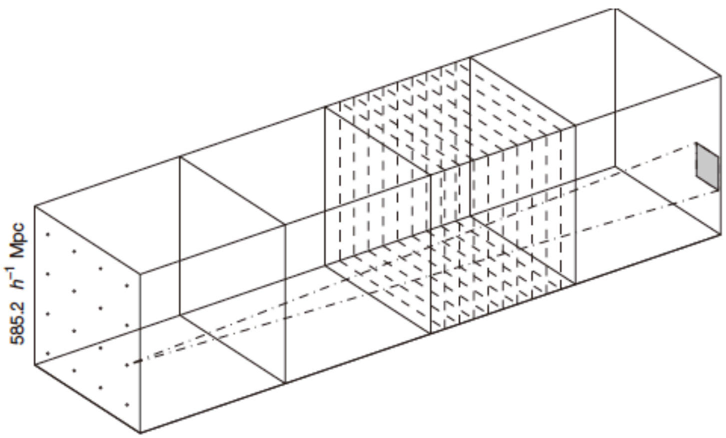
Cosmological information:

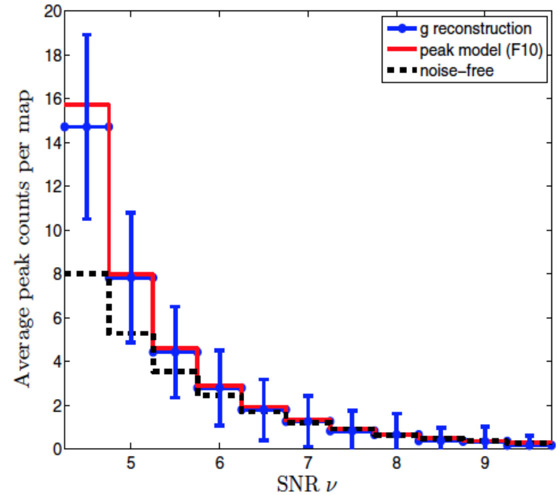
DM halo mass function
DM halo internal profile

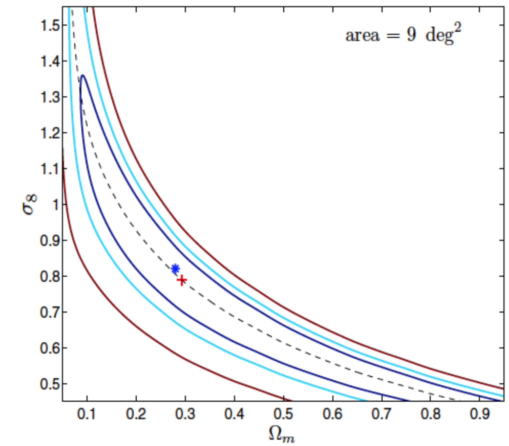
Cosmological volume
and lensing efficiency factor

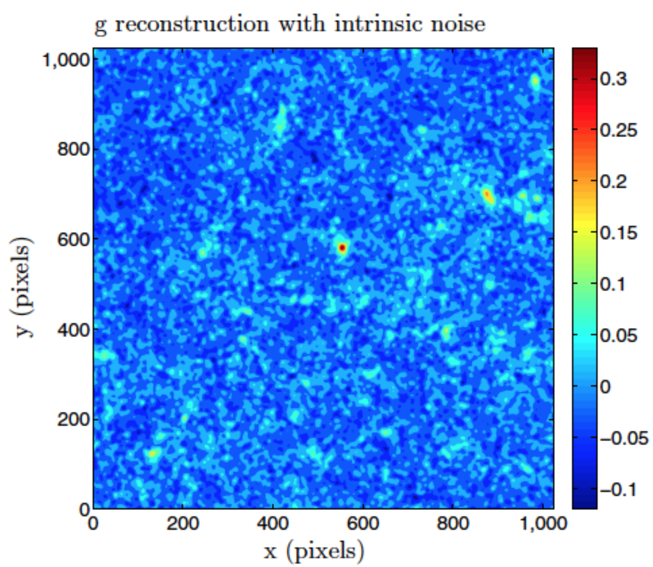
Total peak counts without the need to differentiate true and false peaks

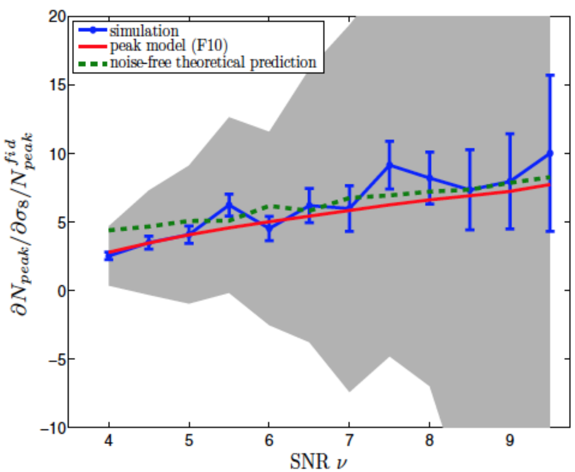
Simulation tests (Fan et al. 2010, Liu et al. 2014, 2015, 2016)

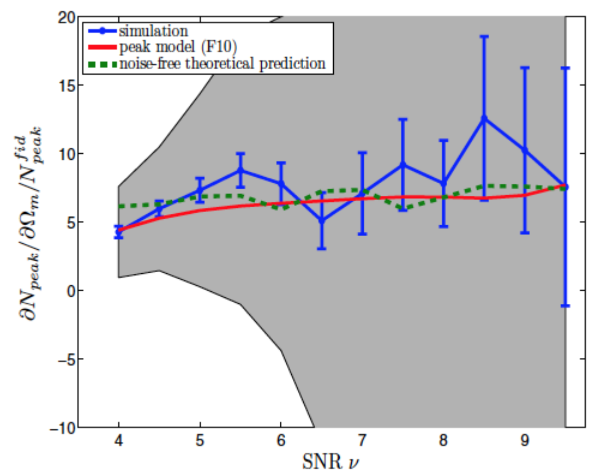






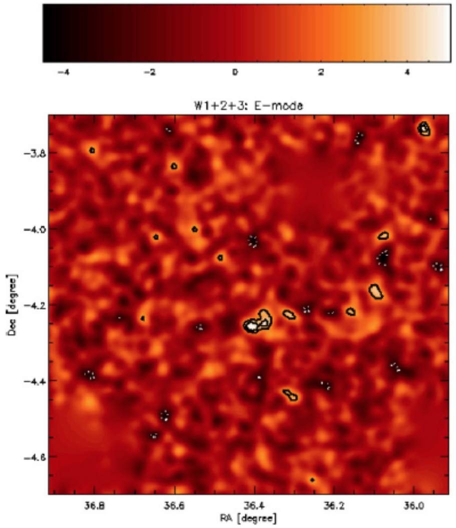


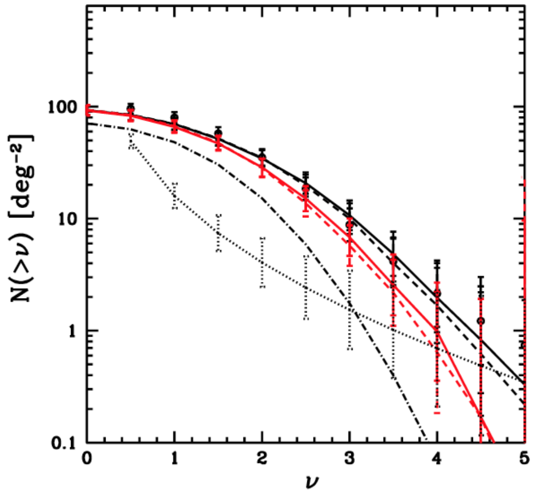




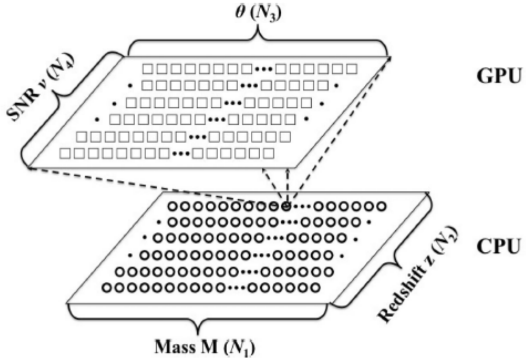
Observational comparisons (Shan et al. 2012, 2014)

CFHTLS





Develop a fast code for peak model calculations



-- important for deriving cosmological constraints from WL peak abundances

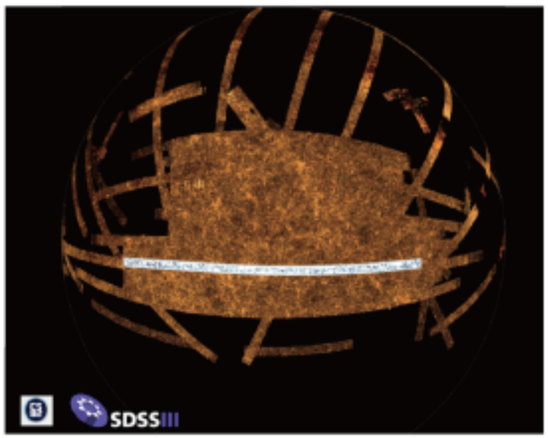
CS82 WL peak studies

CFHT Stripe 82
weak lensing survey

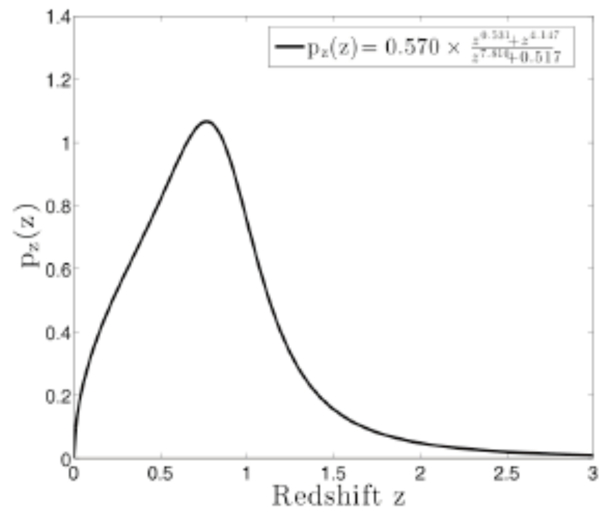
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 450, 2888–2902 (2015) doi:10.1093/mnras/stv784

Cosmological constraints from weak lensing peak statistics with Canada–France–Hawaii Telescope Stripe 82 Survey

Xiangkun Liu,[1★] Chuzhong Pan,[1] Ran Li,[2] Huanyuan Shan,[3] Qiao Wang,[2] Liping Fu,[4] Zuhui Fan,[1,5★] Jean-Paul Kneib,[3,6] Alexie Leauthaud,[7] Ludovic Van Waerbeke,[8] Martin Makler,[9] Bruno Moraes,[10,11] Thomas Erben[12] and Aldée Charbonnier[13,14]



Celestial equatorial region

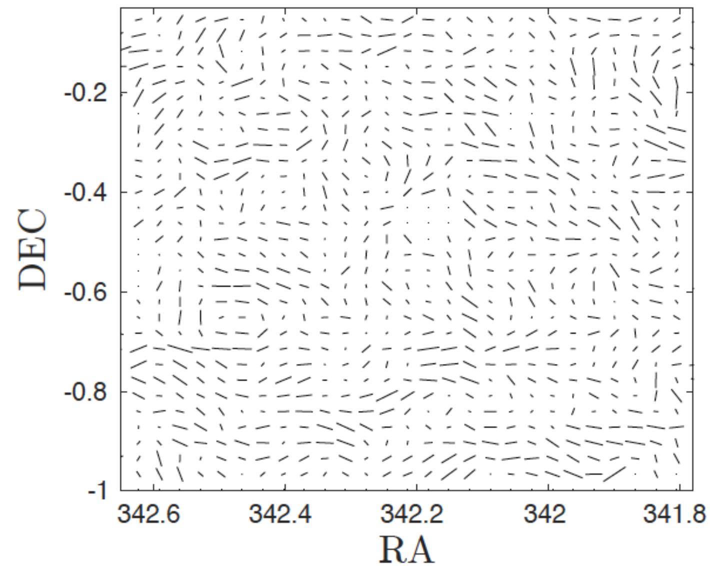


CFHT MegaCam observations
--173 tiles 1deg^2 each
-- seeing 0.4″-0.8″
-- four ~410s exposures each pointing
-- i_{AB}~24 (5σ)

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

shear measurements

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

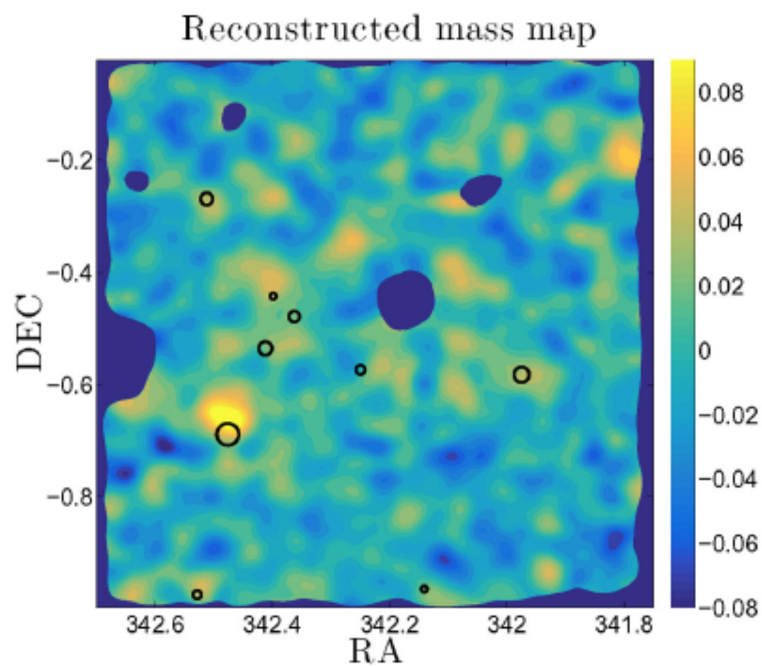


iterative convergence reconstruction

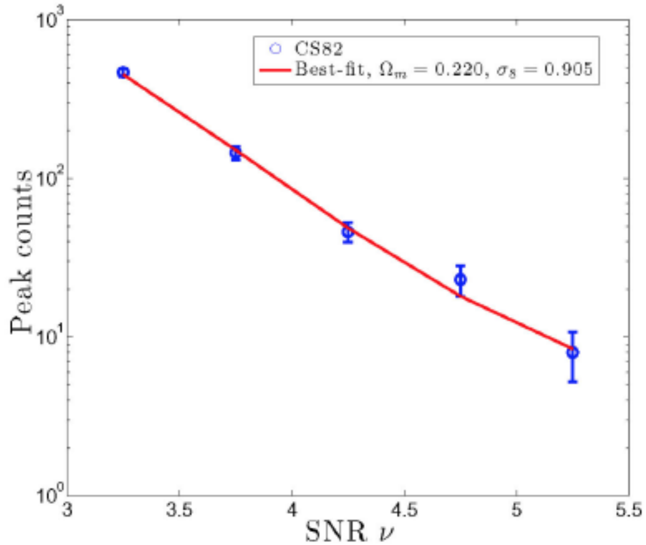
$$\langle\epsilon\rangle(\theta) = \frac{\sum_j W_{\theta_G}(\theta_j - \theta) w(\theta_j) \epsilon^c(\theta_j)}{\sum_j W_{\theta_G}(\theta_j - \theta) w((\theta_j)(1 + m_j)}$$

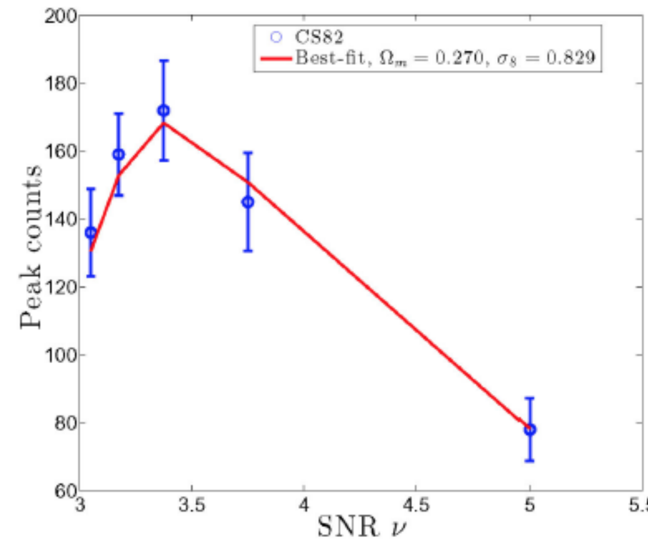
$$\hat{\gamma}(k) = \pi^{-1} \hat{D}(k) \hat{\kappa}(k),$$

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



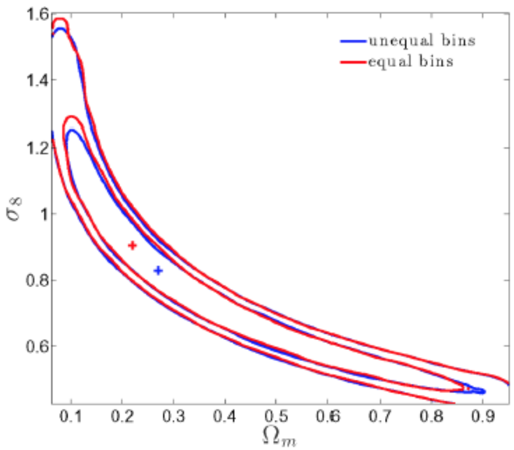
peak analyses

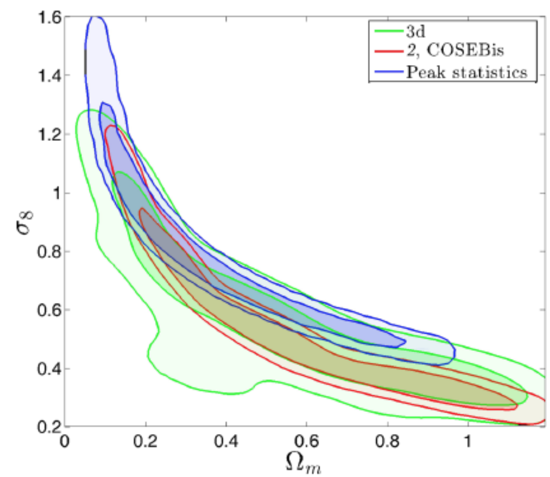


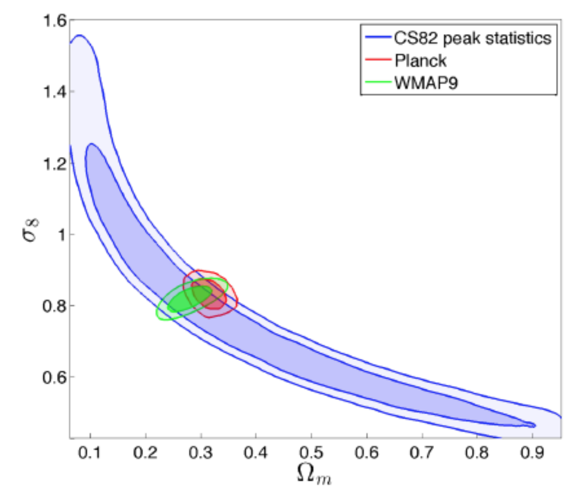


MCMC module

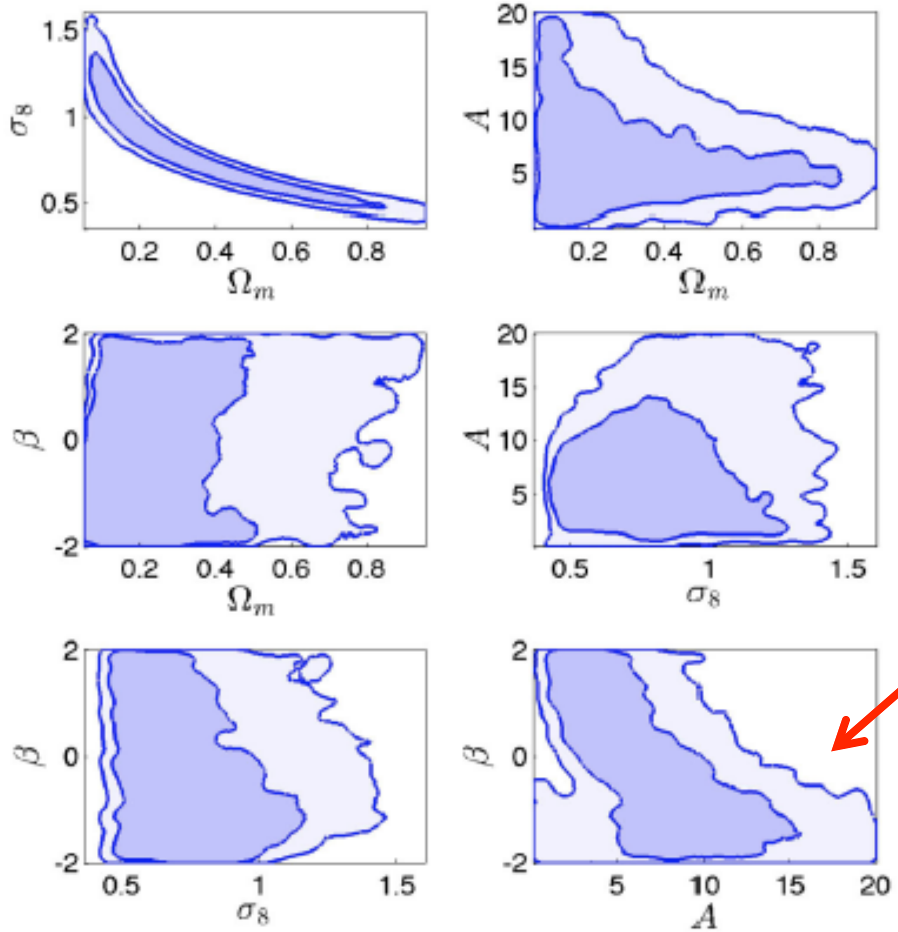
cosmological constraints – **comparable, consistent, and complementary**







Further explored the potential to constrain halo profiles and cosmological parameters simultaneously (note we only used flat and loose priors here)



Parameters of M-c relation of dark matter halos

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

PRL **117,** 051101 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Constraining $f(R)$ Gravity Theory Using Weak Lensing Peak Statistics from the Canada-France-Hawii-Telescope Lensing Survey

Xiangkun Liu,[1,*] Baojiu Li,[2] Gong-Bo Zhao,[3,4] Mu-Chen Chiu,[5] Wei Fang,[5,6] Chuzhong Pan,[1] Qiao Wang,[7] Wei Du,[3] Shuo Yuan,[1] Liping Fu,[5] and Zuhui Fan[1,8]

What drives the accelerating expansion of the Universe?

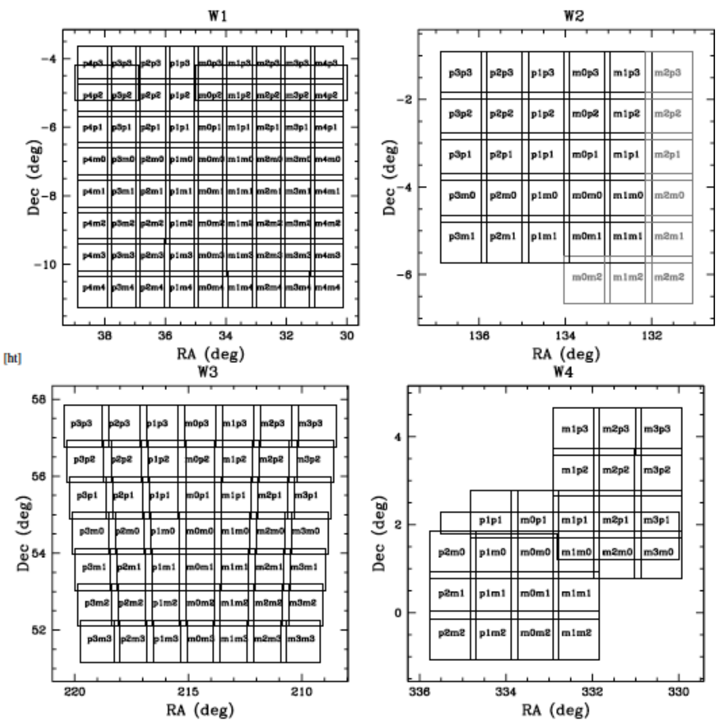
GR – add the dark energy component
Modified gravity theories --
e.g., f(R) gravity theory with chameleon effect
– give rise to the late-time cosmic accelerating expansion
-- satisfy the solar system gravity test

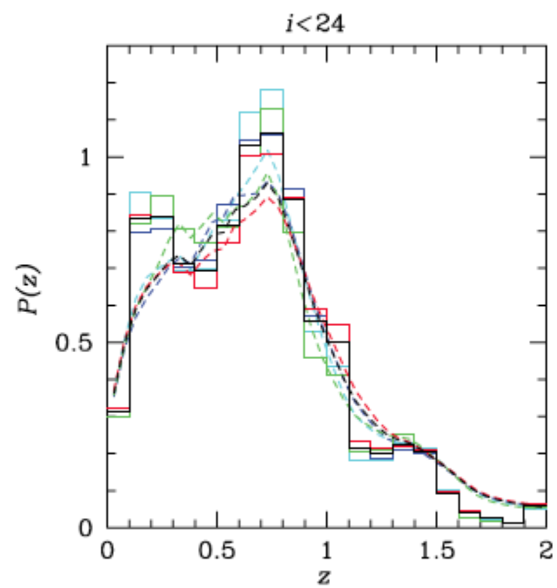
However, the formation and evolution of LSS are different

LSS observations are crucial in understanding the underlying mechanism driving the evolution of the Universe

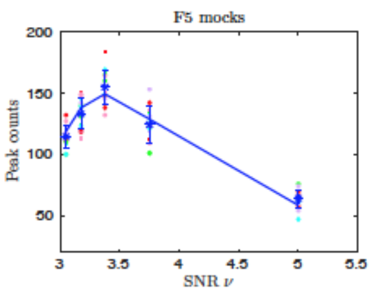
In our theoretical model, the physics behind the WL high peaks is clear and the cosmologically-dependent quantities are known explicitly. Therefore we can extend our analyses beyond GR

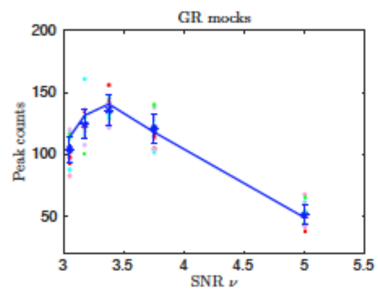
CFHTLenS: 154 deg^2, u*g'r'i'z', photo-z distribution for each galaxy

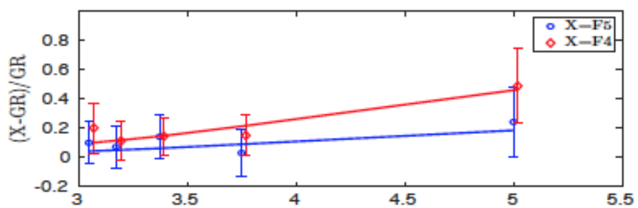




HS f(R) theory – f_{R0} parameter with f_{R0}=0 for GR

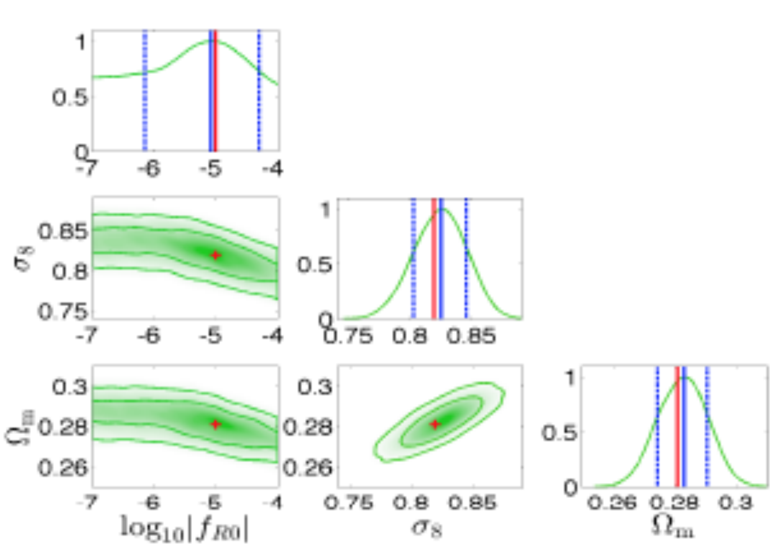


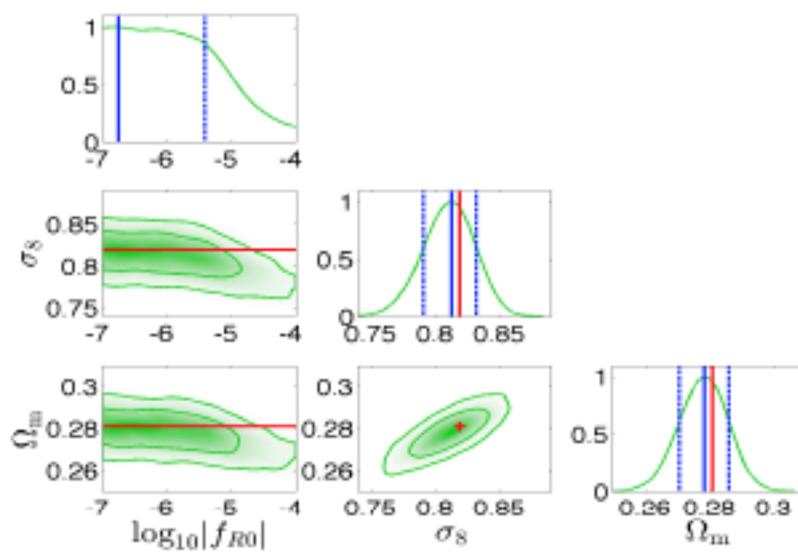




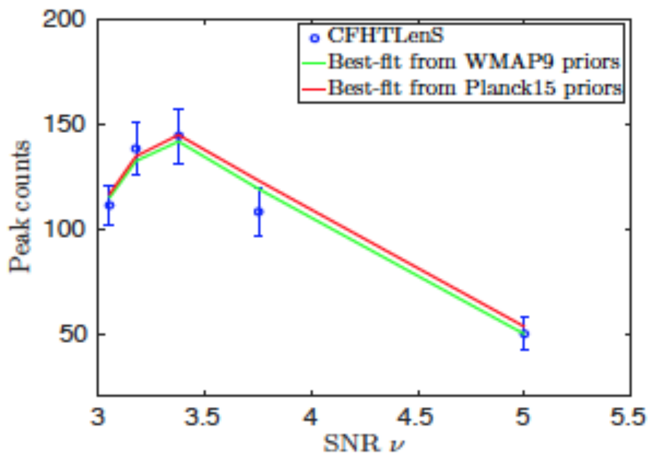
Mock simulation tests show that WL high peaks depend on f_{R0} sensitively.

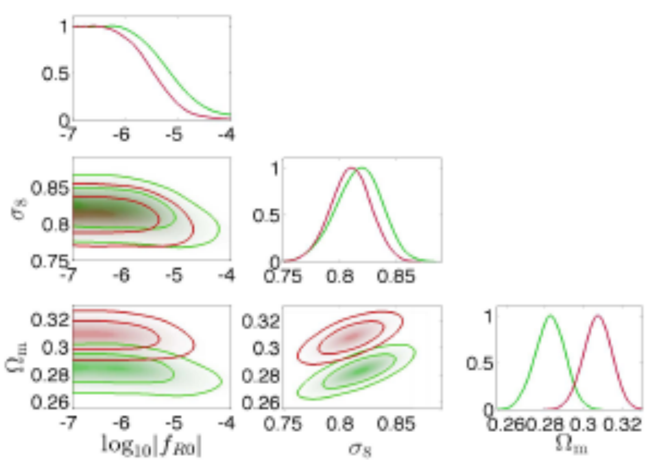
With priors from WMAP9 or Planck15, f_{R0} can be constrained tightly





CFHTLens observations





Mock			
Parameter	case		
$\log_{10}\|f_{R0}\|$ [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

Summary and discussion

We have carried out series studies about WL peak statistics

model building – simulations – computational tool – observations

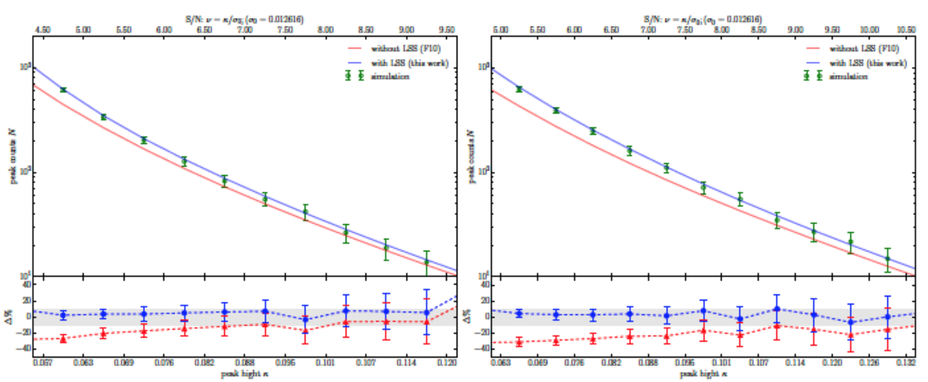
-- Demonstrate well the great potential of WL peak analyses in cosmological studies

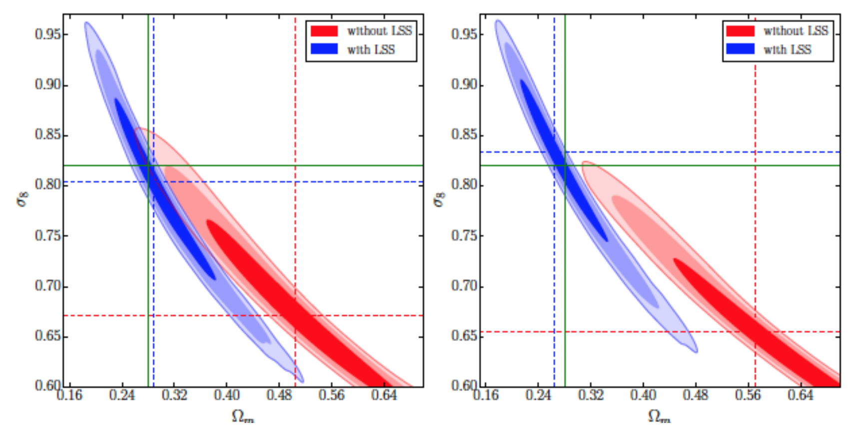
Ongoing efforts – model improvement for future precision WL studies

-- 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