Cosmological Studies with Weak Lensing Peak Statistics

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CS82 team, KiDS team

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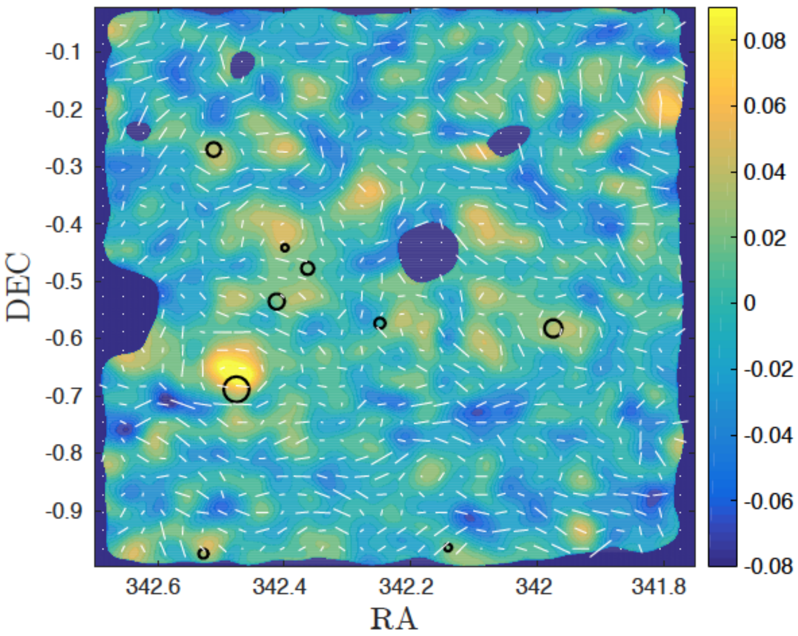
Outline

★ Introduction

★ Weak lensing peak analyses

★ Discussions

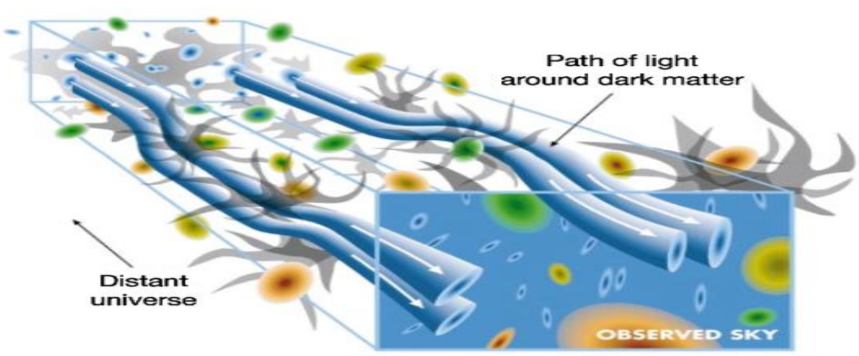


▪ Introduction

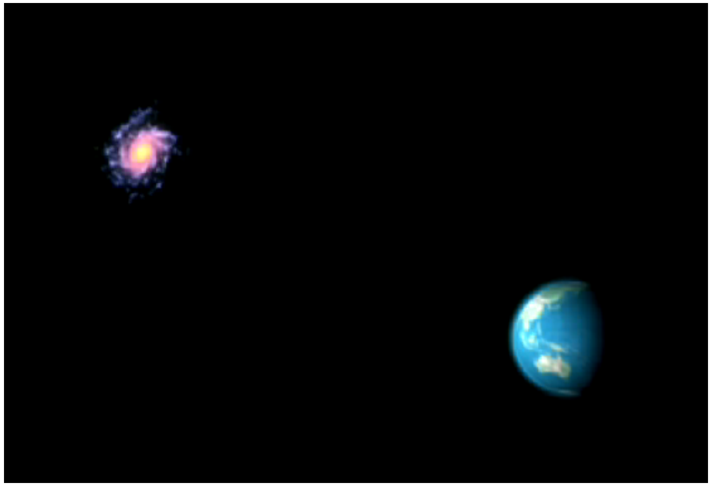
Weak lensing effects – gravitational in origin – everywhere in the universe

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

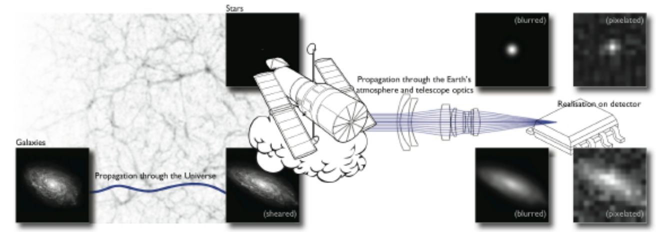
-- clean physics
-- excellent cosmological probe, particularly for understanding the nature of the two dark components and probing the the law of gravity



Wittman et al. 2000

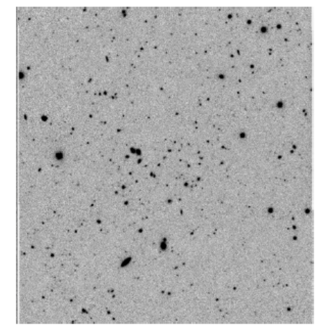


Great10 handbook



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

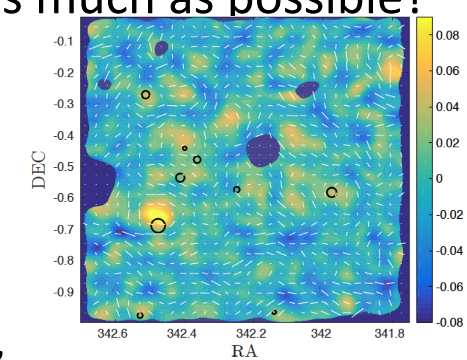
Observationally extremely challenging



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

Outstanding issues theoretically

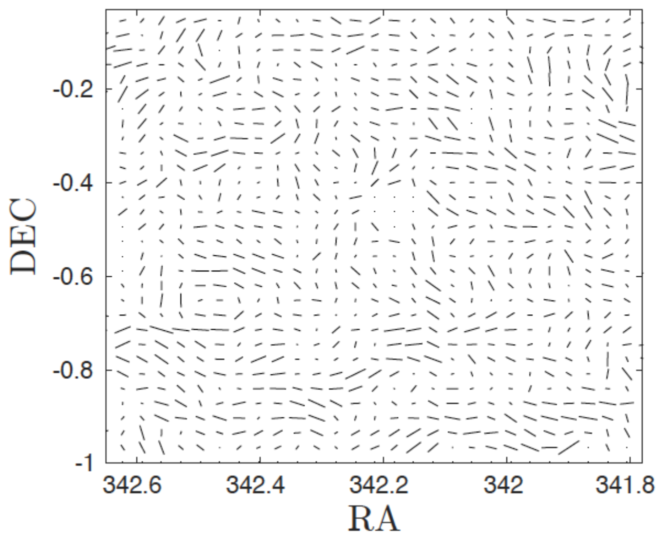
-- How to extract cosmological information from WL data as much as possible?
- statistical analyses are necessary
- fully explore different statistical quantities



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

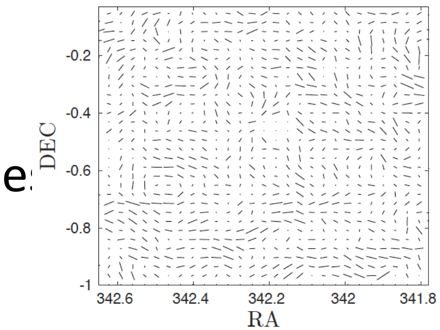
Weak lensing analyses

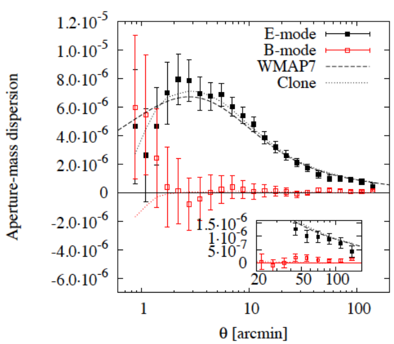
Cosmic shear (signal ~ a few percent): first detections around the year of 2000
stage II (CFHTLenS as the best representative survey)
stage III at present (KiDS, DES, HSC)
Stage IV in the future (LSST, EUCLID, CSS-OS)
-- fully demonstrate the importance of WL analyses in cosmological studies

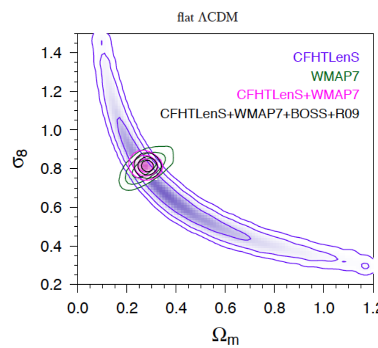


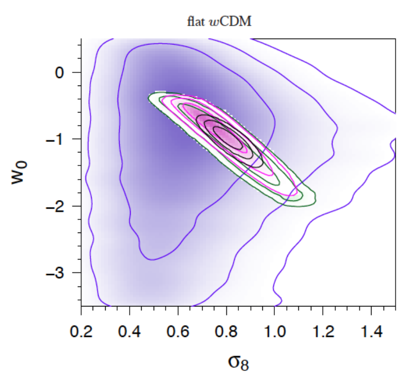
-- 2-pt shear correlations are the most commonly applied analyses

→ **inconsistency with Planck CMB results??**

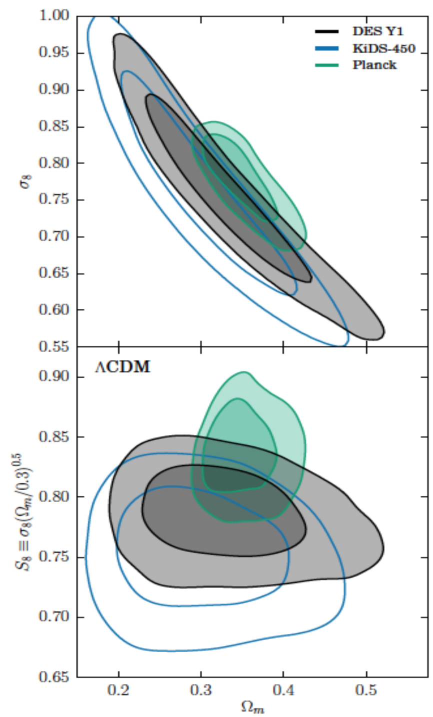




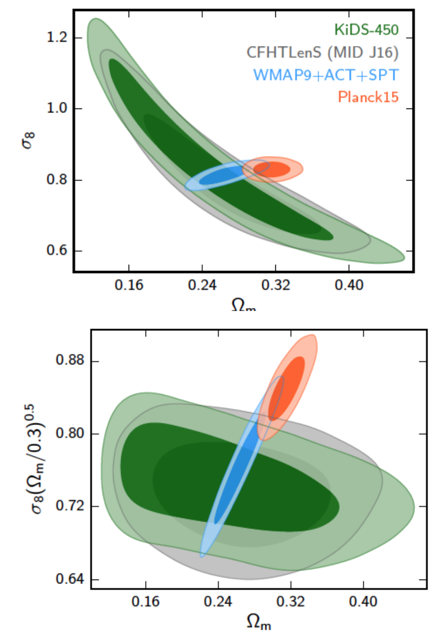




Kilbinger et al. 2013,
CFHTLenS



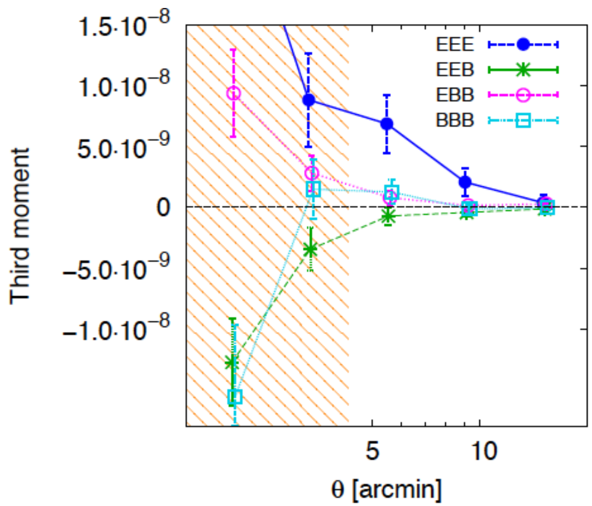
DES, arXiv: 1708.01538

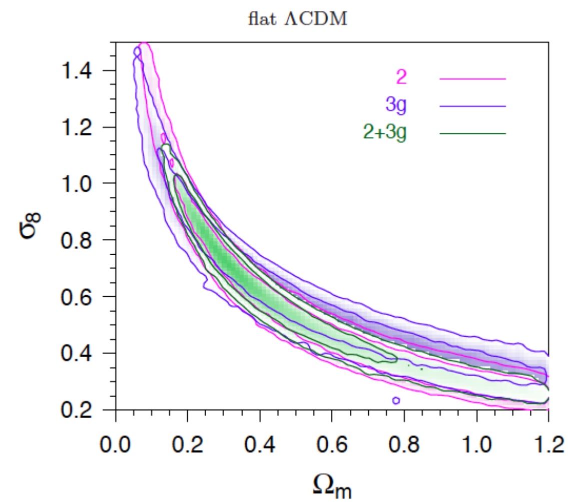


KiDS450, MNRAS, 465, 1454 (2017)

-- 2-pt shear correlations cannot reveal non-Gaussian features

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

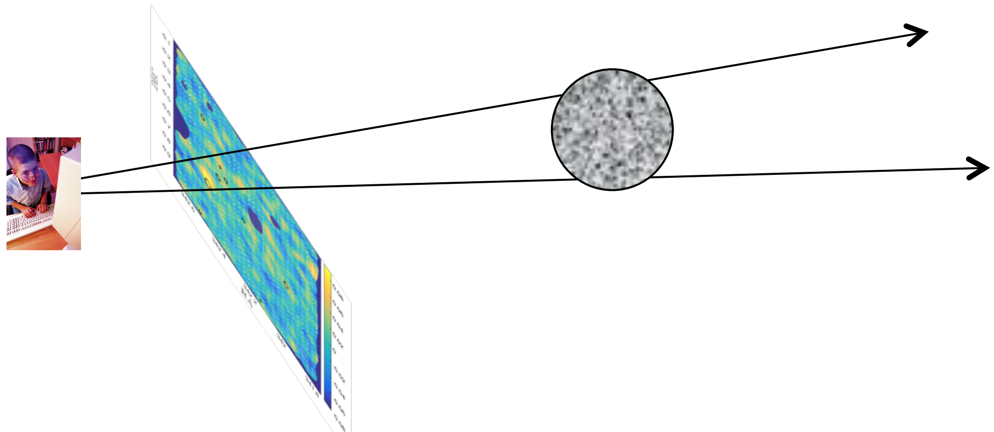




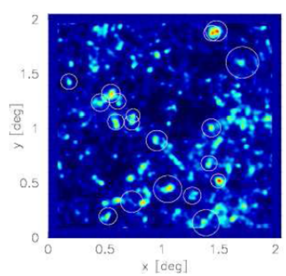
Fu et al. 2014, CFHTLenS

Weak-lensing peak analyses provide another important means

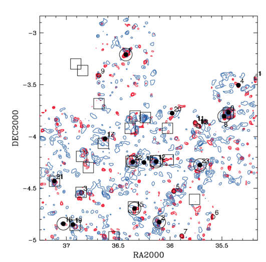
Massive structures, such as clusters of galaxies, are expected to generate high lensing signals and appear as peaks in weak-lensing convergence maps.



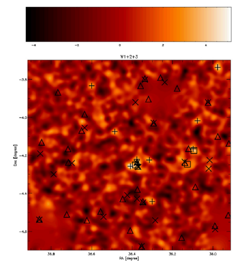
→ related to the mass function of dark matter halos and lensing efficiency factor → cosmology sensitive



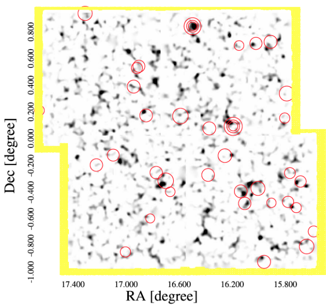
Hamana et al. 2004



Miyazaki et al. 2007

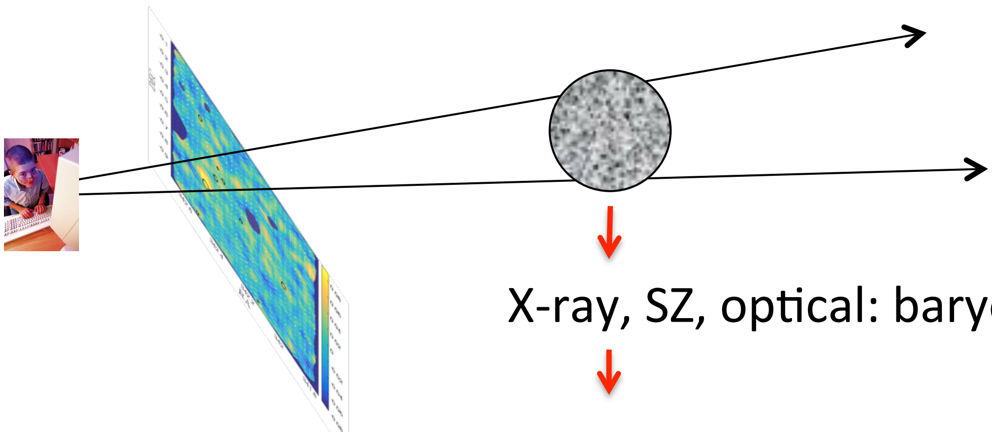


Shan et al. 2012, CFHTLS



Shan et al. 2014, CS82

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

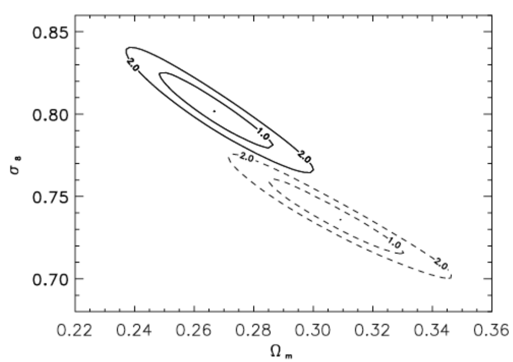


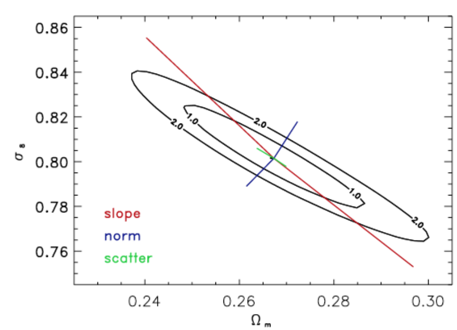
X-ray, SZ, optical: baryonic observables

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

Major systematics in using clusters as cosmological probes

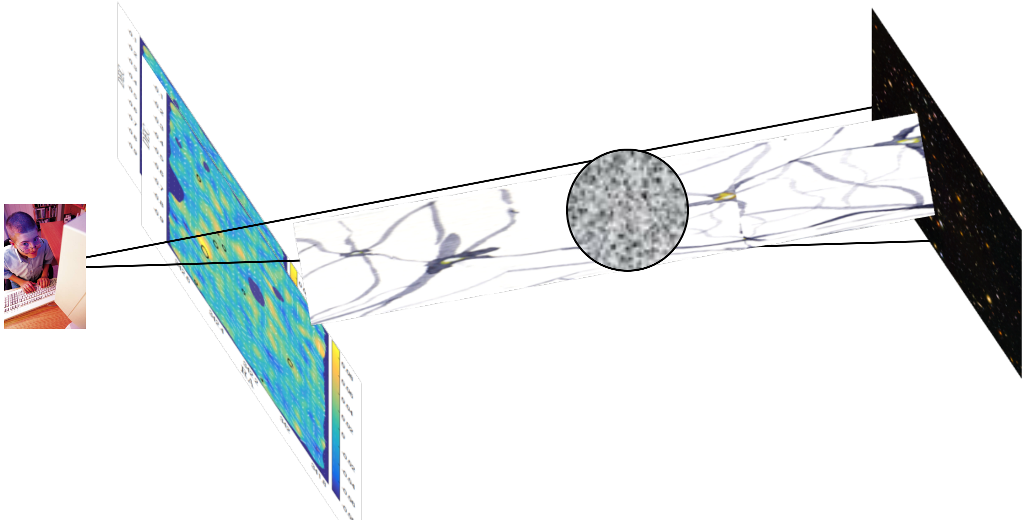
E.g., X-ray $$L_{500}(0.1\text{–}2.4\ \mathrm{keV}) = 0.1175\ M_{200}^{\alpha_{sl}}\ h^{\alpha_{sl}-2}\quad E(z)^{\alpha_{sl}}$$

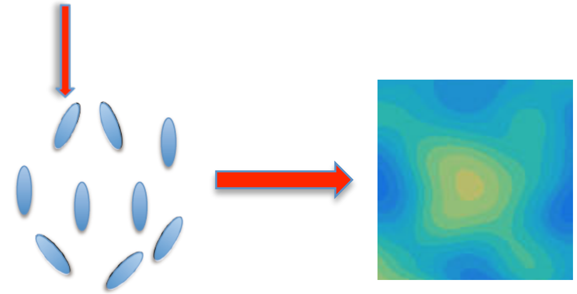




Boehringer, H. et al. 2014

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

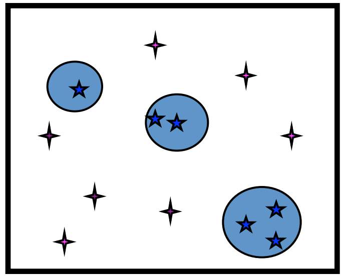
The combination of the two provides the best solution

-- theoretical model tested and calibrated by simulations

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

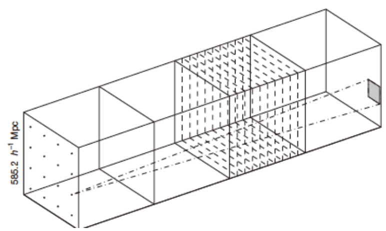
★ Cosmological studies with WL peak statistics

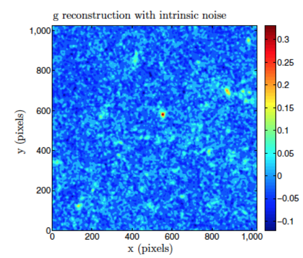
Model building
-- predicting peak abundances given a cosmological model



Halo model for high peaks taking into account the shape noise effect + LSS – crucial for cosmological studies with WL peaks (Fan et al. 2010, Yuan et al. 2018, Pan et al. 2018 (M_{ap} peaks))

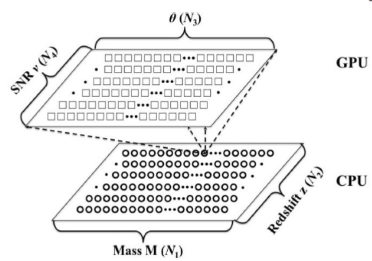
Large sets of ray-tracing simulation



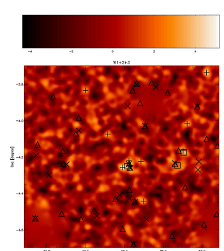


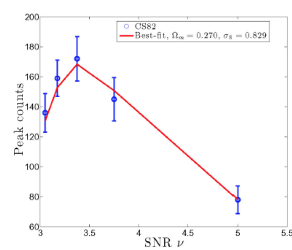
Simulation studies

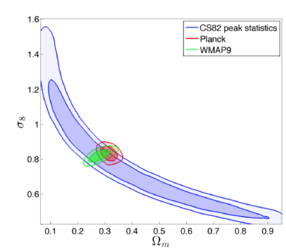
Set up fast computation code for cosmological analyses



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



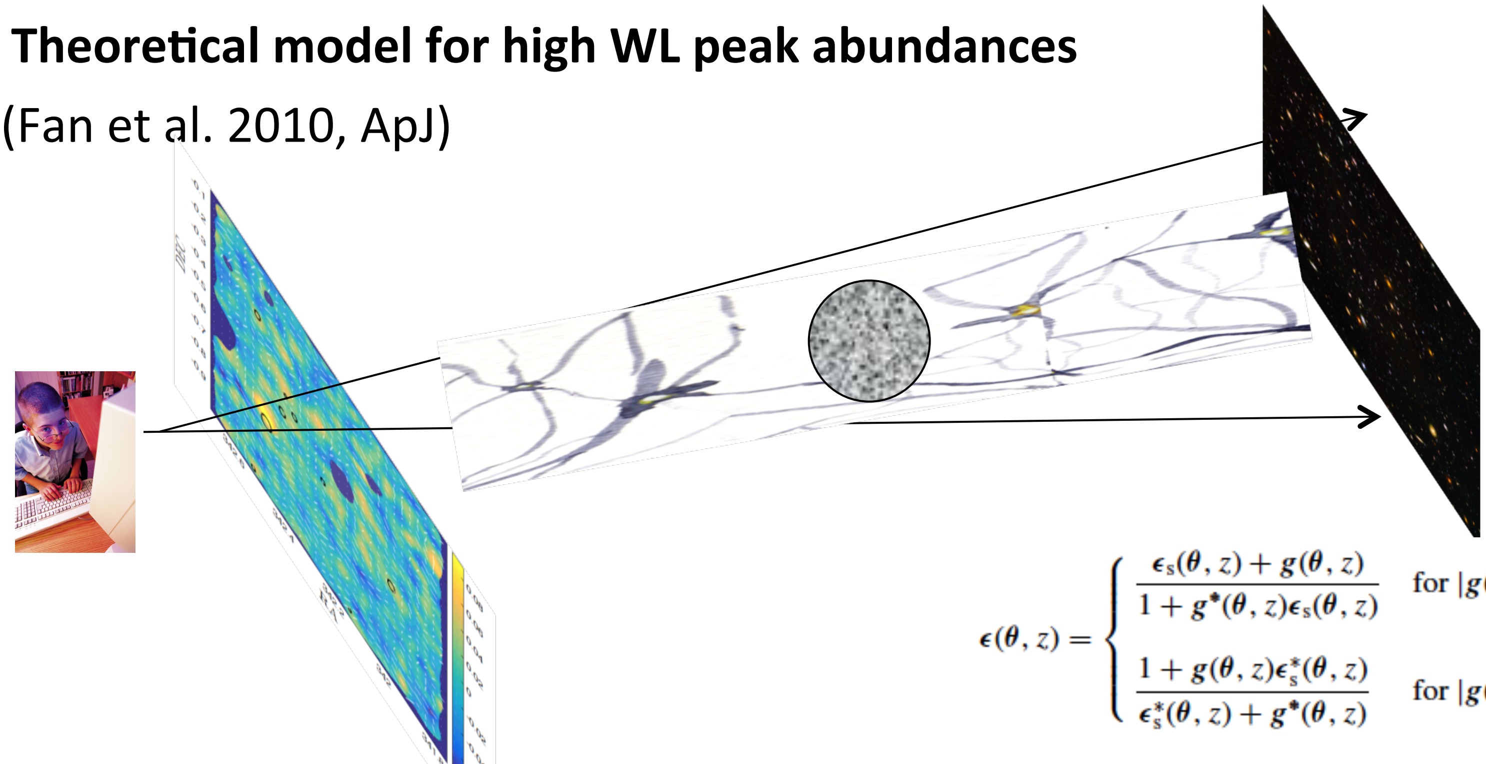




Observational analyses

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 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

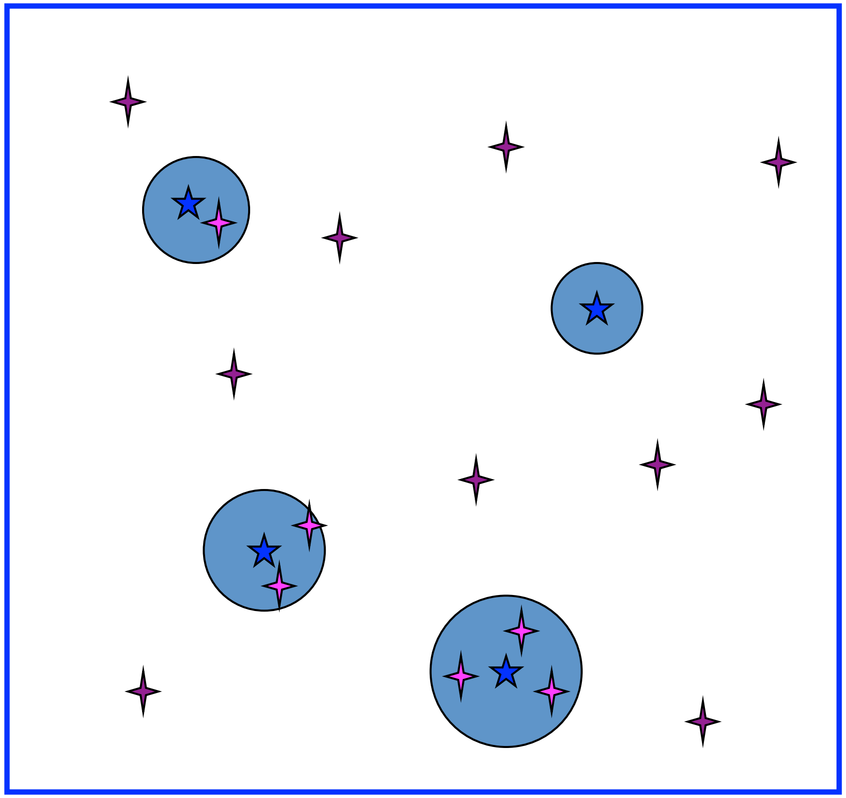
$$K_N(\boldsymbol{\theta}) = K(\boldsymbol{\theta}) + N(\boldsymbol{\theta}) = \int d\mathbf{k}\, \exp(-i\mathbf{k}\bullet\boldsymbol{\theta}) c_\alpha(\mathbf{k}) \Sigma_\alpha^{(o)}(\mathbf{k})$$

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

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

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 $n_{\rm peak}(\nu)d\nu = n^c_{\rm peak}(\nu)d\nu + n^n_{\rm peak}(\nu)d\nu$

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

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

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

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

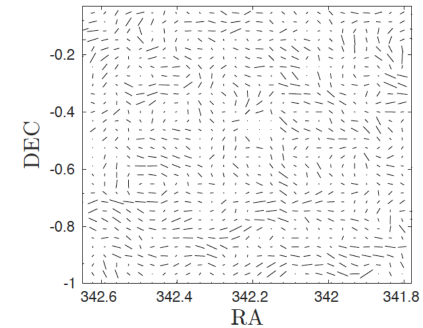
Cosmological information:

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

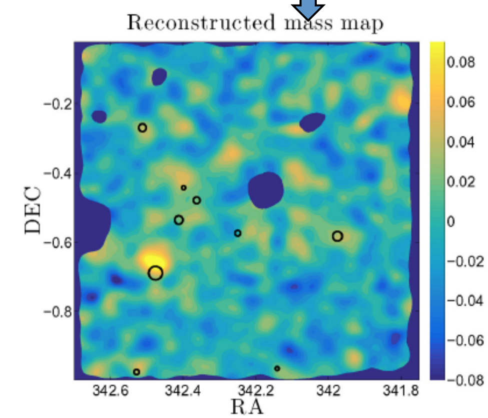
For observational analyses, we need to reconstruct the convergence field from the shear field



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

shear measurements

intrinsic ellipticity + lensing shear

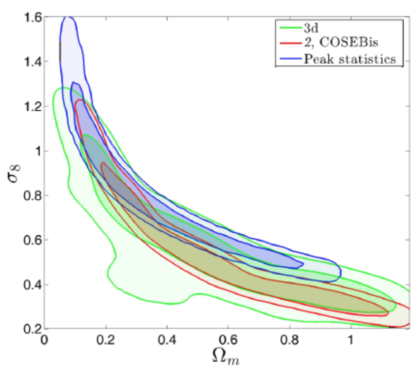


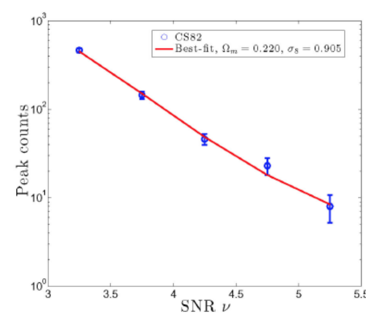
iterative convergence reconstruction

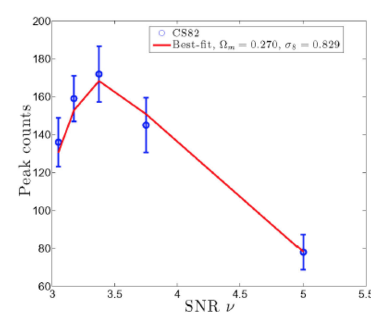
$$\langle\epsilon\rangle(\boldsymbol{\theta}) = \frac{\sum_j W_{\theta_G}(\boldsymbol{\theta}_j - \boldsymbol{\theta}) w(\boldsymbol{\theta}_j) \epsilon^c(\boldsymbol{\theta}_j)}{\sum_j W_{\theta_G}(\boldsymbol{\theta}_j - \boldsymbol{\theta}) w((\boldsymbol{\theta}_j)(1 + m_j)}$$

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

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







We have applied the peak analyses to CFHT Stripe 82 survey, CFHTLens survey, and KiDS survey
-- complementary to shear correlations studies

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

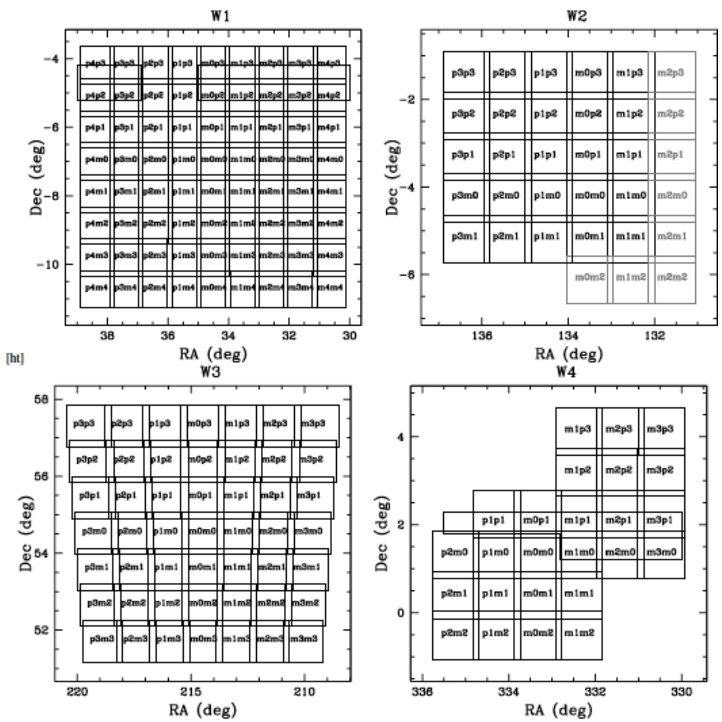
Modified gravity theories
e.g., f(R) gravity theory with chameleon effect
– give rise to the late-time cosmic accelerating expansion
-- satisfy the solar system gravity test

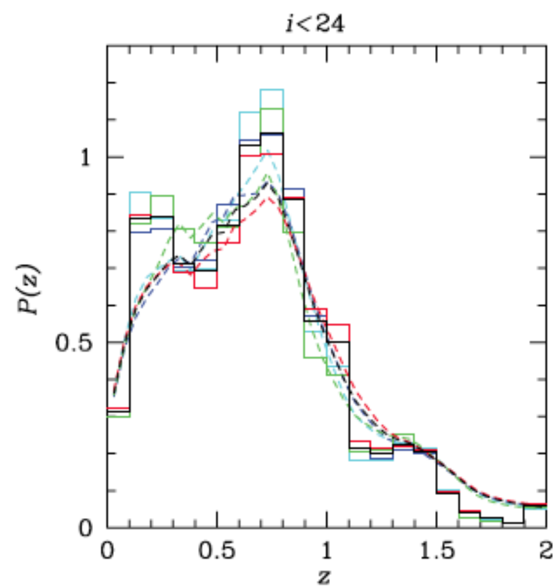
However, the formation and evolution of LSS are different

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

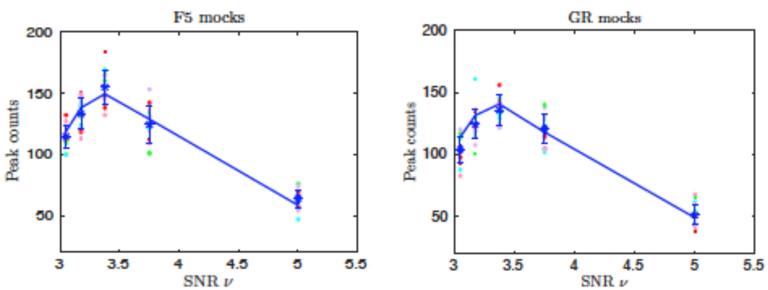
In our theoretical model, the physics behind the WL high peaks is clear and the cosmologically-dependent quantities are known explicitly. Therefore we can extend our analyses beyond GR

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

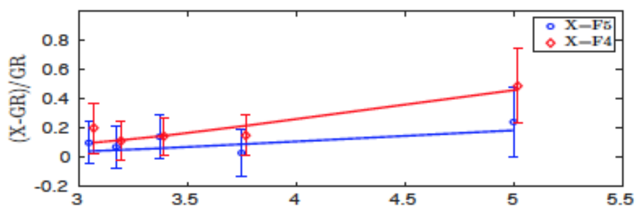




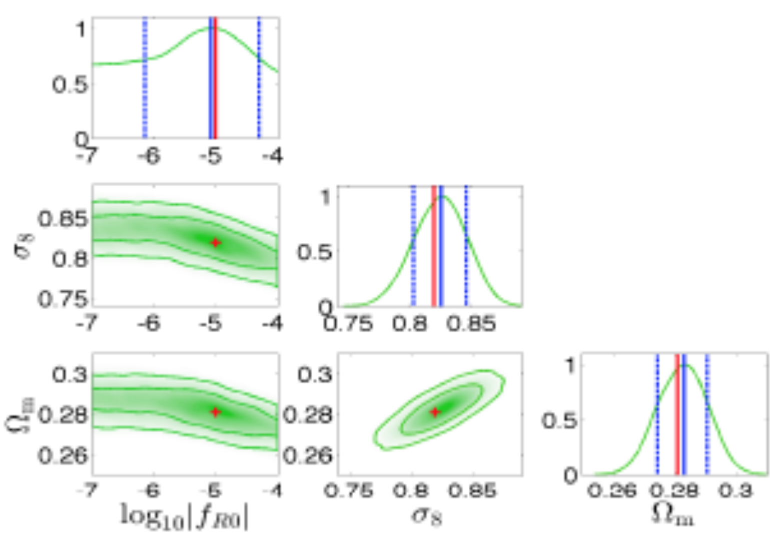
Hu-Sawicki f(R) theory – f_{R0} parameter with f_{R0}=0 for GR

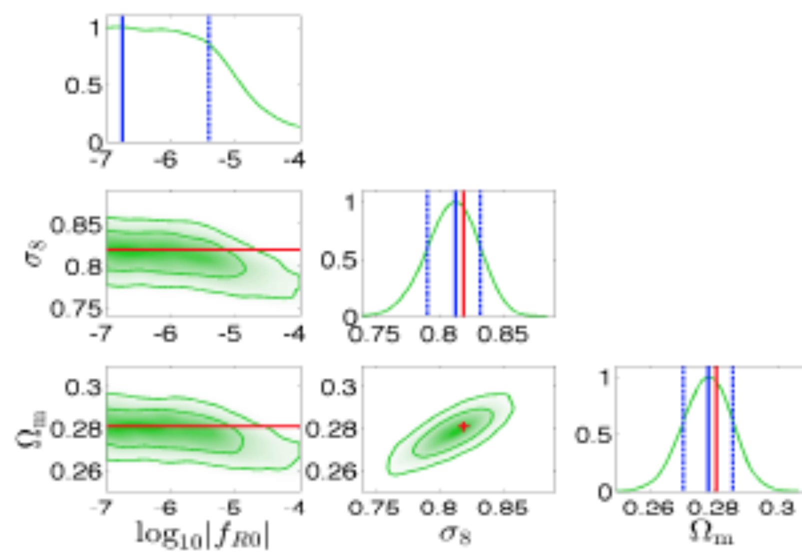


Mock simulation tests show that WL high peaks depend on f_{R0} sensitively.

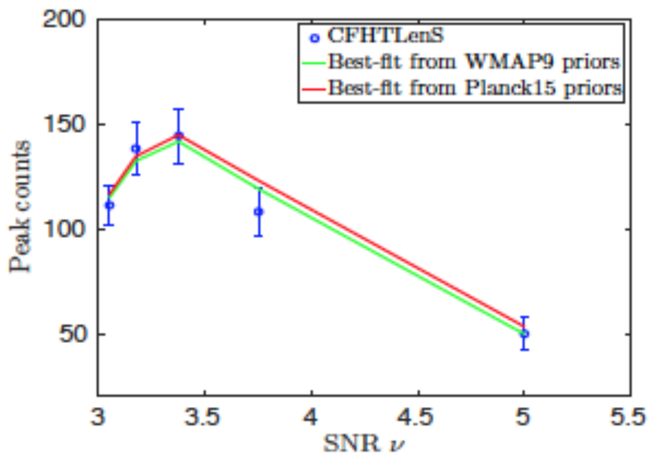


With priors from WMAP9 or Planck15, f_{R0} can be constrained tightly

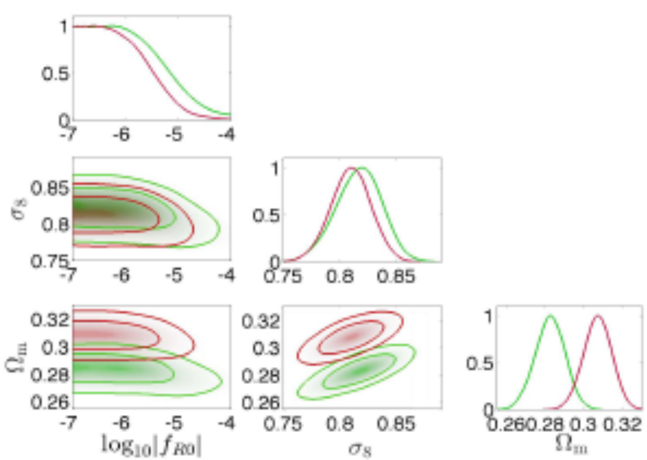




CFHTLens observations



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

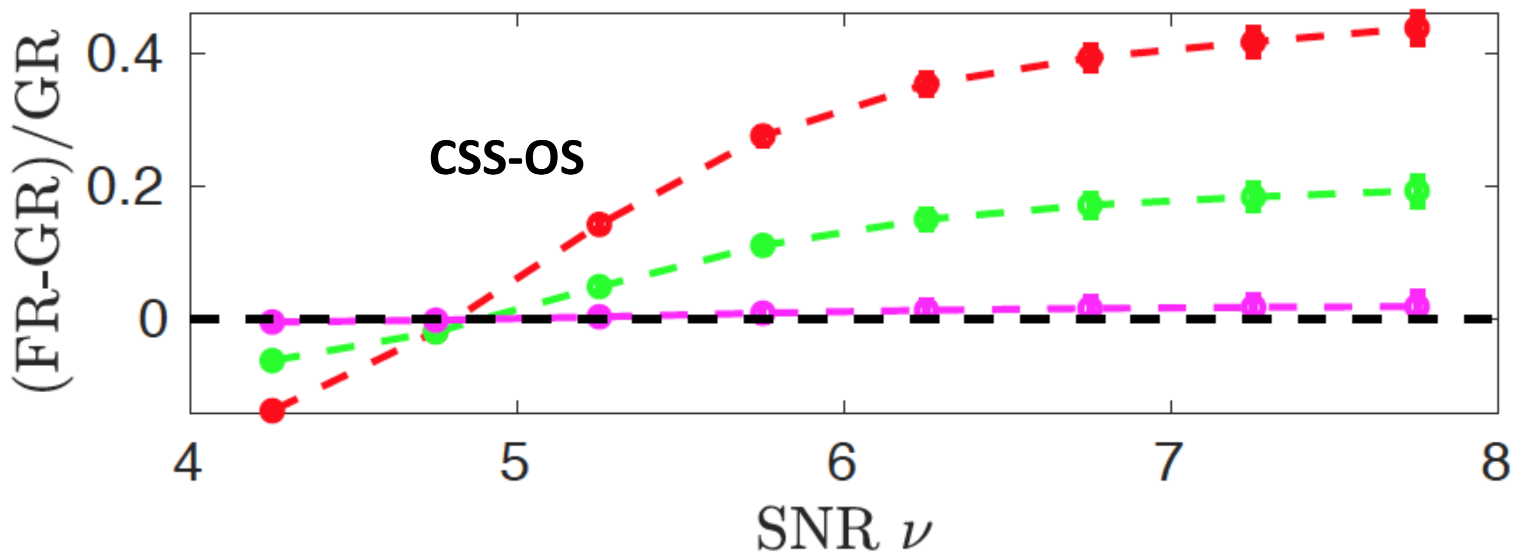


Strong constraints
-- comparably tighter than other studies on cosmological scales

No evidence of deviations from GR

Modified gravity constraints

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

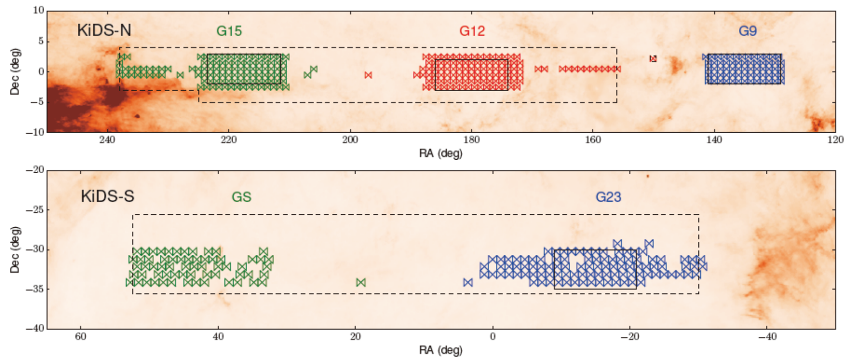


F4

F5

F6

KiDS-450 peak analyses results (Shan, Liu, Hildebrandt, Pan, et al. 2018, MNRAS)



carefully taking into account the boost effect in cluster regions

-- high peaks are associated with clusters of galaxies, and their member contaminations to source galaxies dilute the peak signals

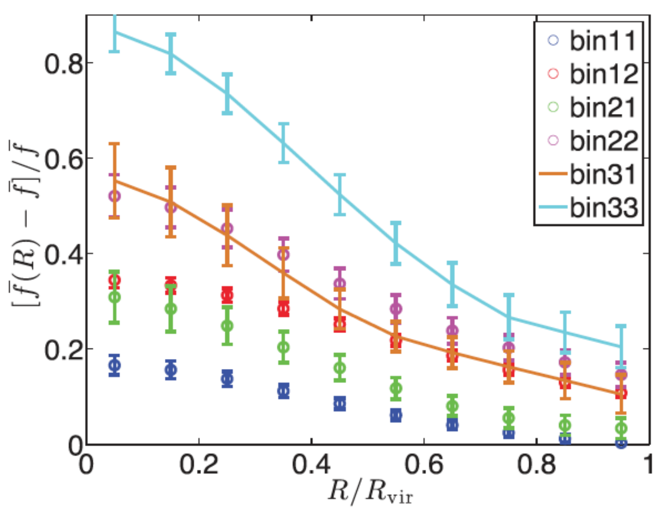
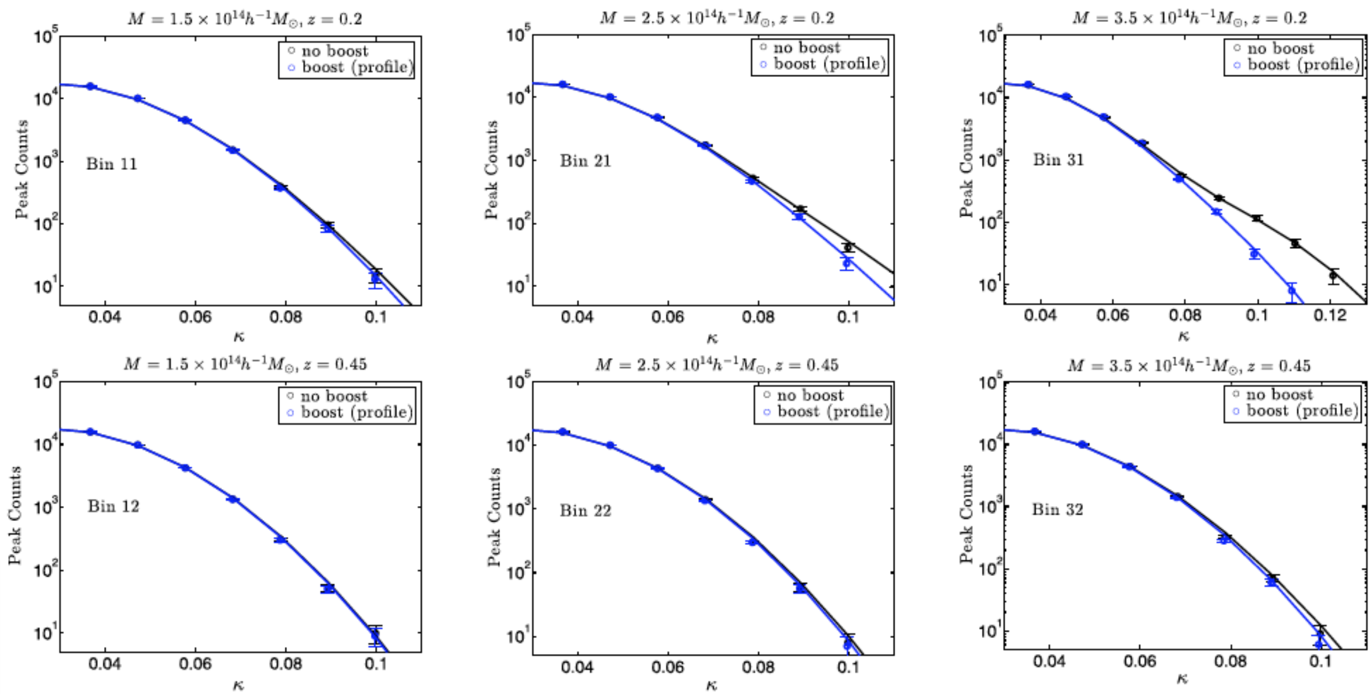


Table D1. The cluster samples in six mass and redshift bins used in the boost factor measurement.

Bin	Mass range	z_B range	Dilution factor
bin11	$1 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 2$	$z_B < 0.35$	1/1.067
bin12	$1 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 2$	$z_B \ge 0.35$	1/1.108
bin21	$2 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 3$	$z_B < 0.35$	1/1.135
bin22	$2 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 3$	$z_B \ge 0.35$	1/1.164
bin31	$3 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 4$	$z_B < 0.35$	1/1.259
bin32	$3 \le M/10^{14}\,{\rm M}_\odot\,h^{-1} < 4$	$z_B \ge 0.35$	1/1.254

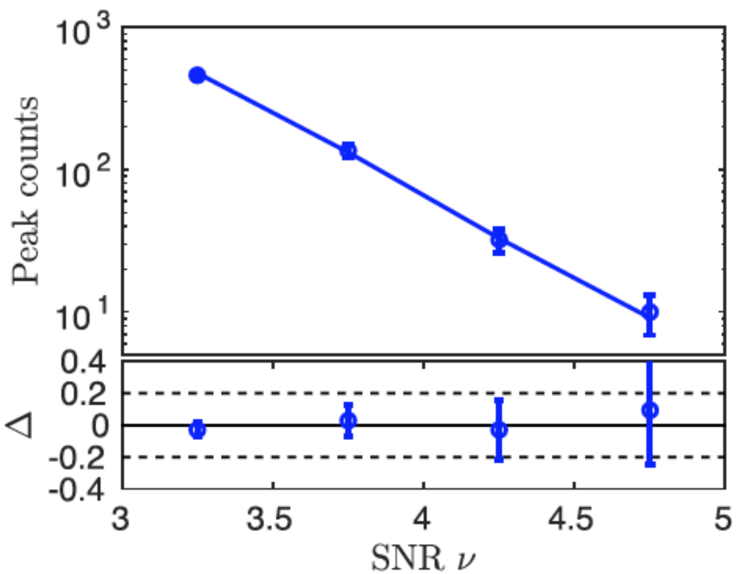
Cluster candidates from Radovich et al.2017

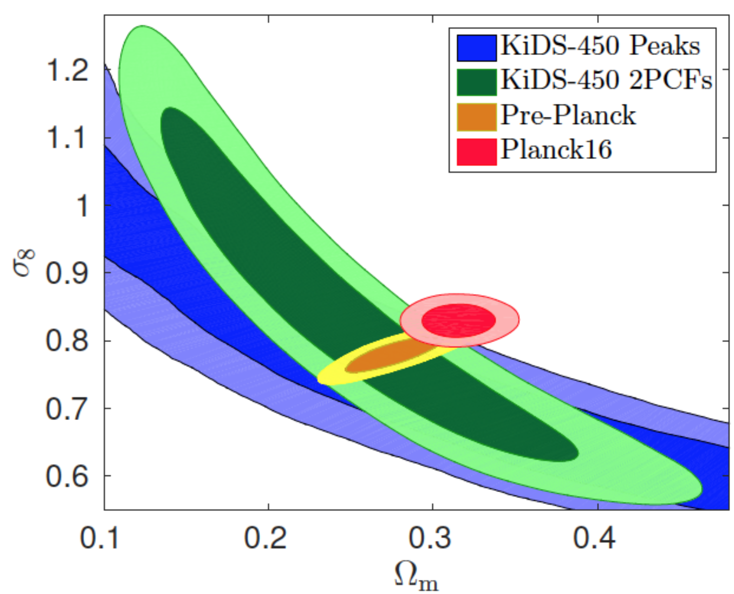
We account for the dilution effect and also the noise change due to contaminations in the model calculations

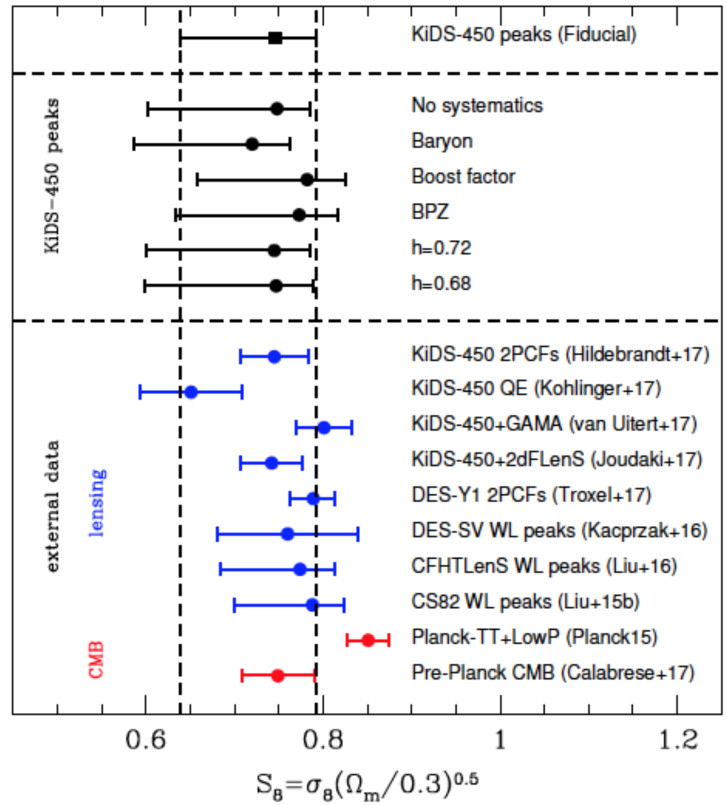


Simulation tests of the modified model

From KiDS450 data



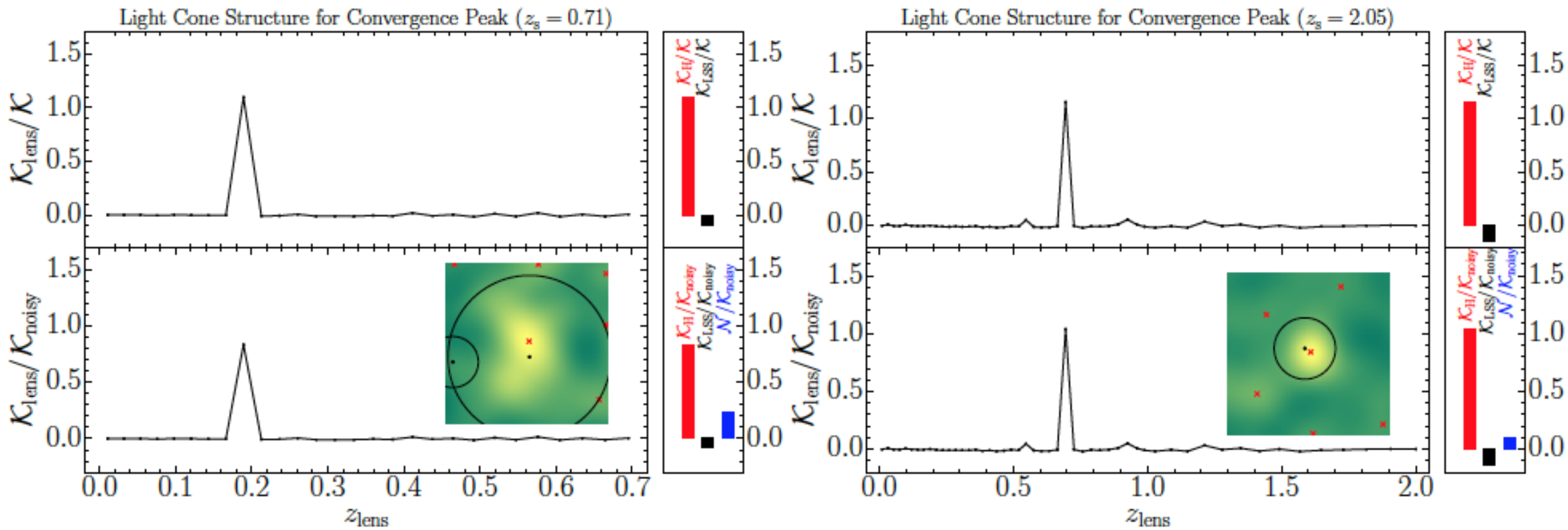




~2σ in tension with Planck CMB
systematics or new physics??

Theoretical improvement of the model

- LSS projection effects for high peaks (Yuan et al. 2018)
  - important for deep surveys with z>~1

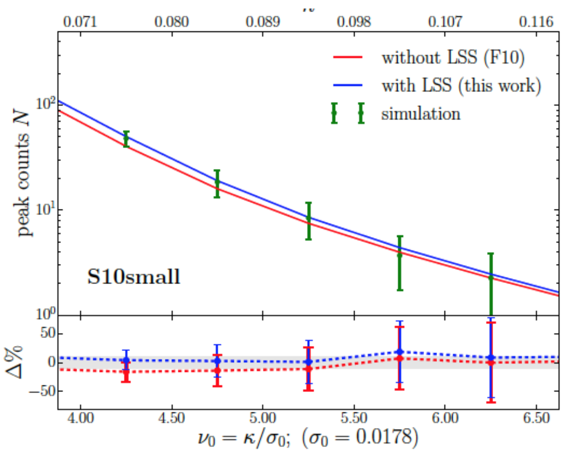


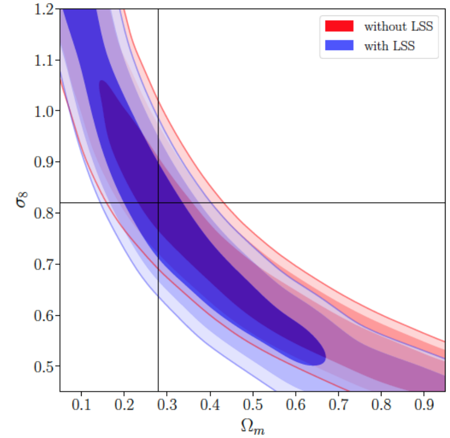
$$\mathcal{K} = \mathcal{K}_{\rm H} + \mathcal{K}_{\rm LSS} + \mathcal{N}$$

Estimate the LSS effect $\sigma_{lss} / \sigma_{shapenoise}$, the larger the stronger

Also depends on the statistics – larger survey area → need better systematic control

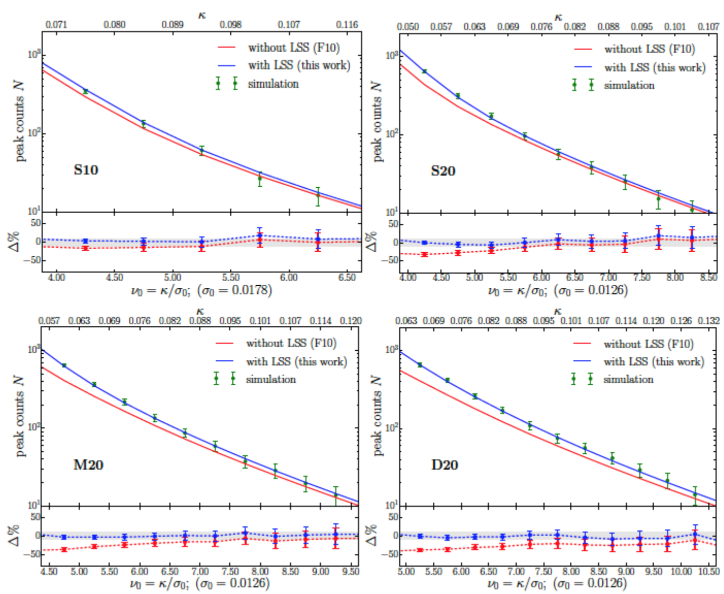
- LSS projection effects for high peaks (Yuan, S. et al. 2018)

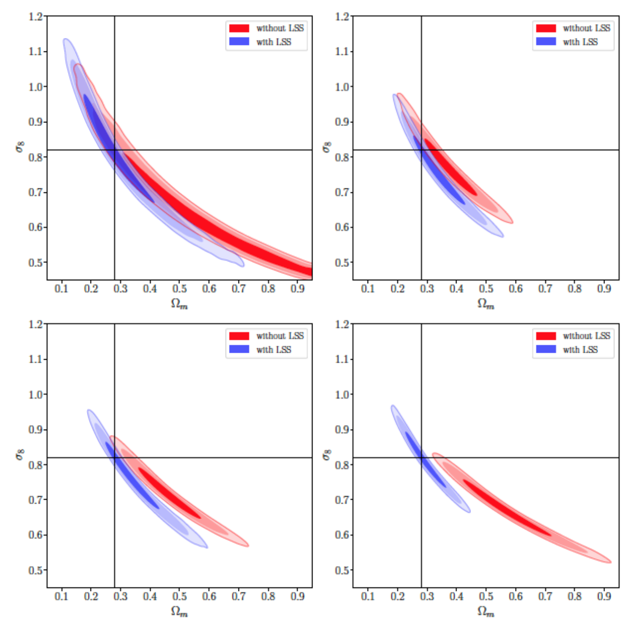




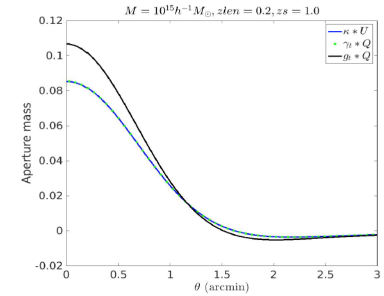
Surveys with a few 100 deg^2, and ng~10arcmin^{-2}, LSS effects are insignificant
e.g., CFHTLenS, KiDS450

However, for larger or deeper surveys, LSS is important. Our improved model works well





- Aperture-mass peak statistics (Pan, C.Z. et al. 2018)



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

→ directly estimate
$$g = \gamma / (1 - \kappa)$$

Nonlinear iteration is needed to reconstruct the κ field from $g = \gamma / (1 - \kappa)$

→ reconstruction systematics: mass-sheet degeneracy, boundary effect, etc..

Aperture mass $M_{ap}(\theta) = \int d^2\vartheta' g_t(\vartheta') Q(\theta, \vartheta')$ $\quad Q(\theta) = \dfrac{2}{\theta^2}\int_0^\theta (d\vartheta')\vartheta' U(\vartheta') - U(\theta)$

In the case $g \approx \gamma, (\kappa << 1)$ → $M_{ap}(\theta) = \int d^2\vartheta' \kappa(\vartheta') U(\theta, \vartheta')$

U: compensated filter $\int_0^\infty (d\vartheta')\vartheta' U(\vartheta') = 0$ → remove the mass-sheet degeneracy

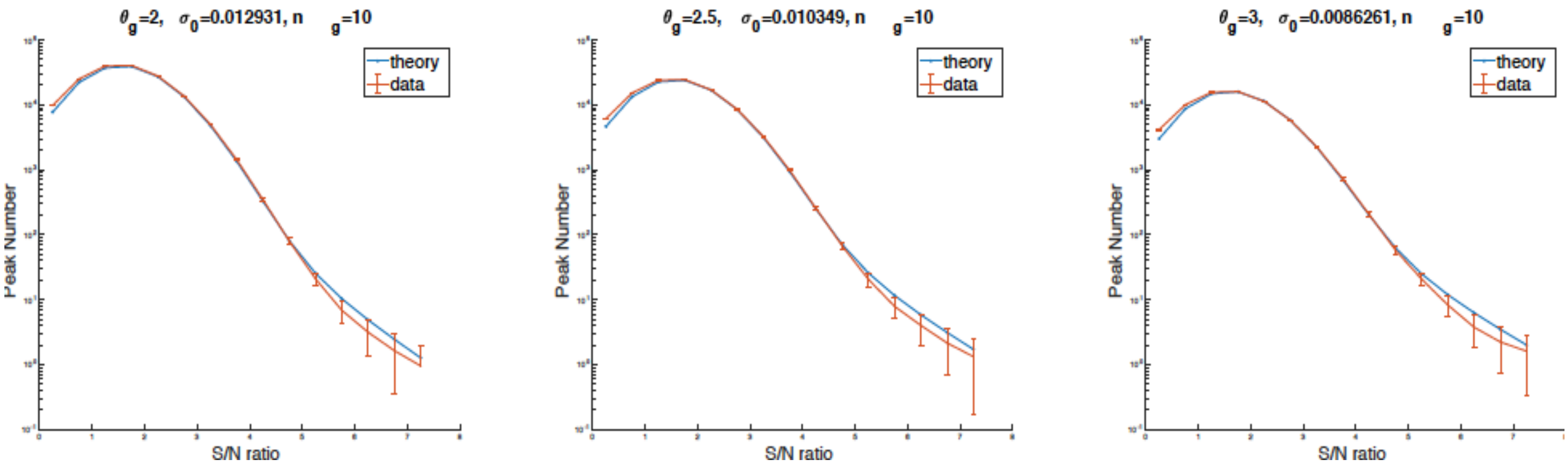
However, $g \approx \gamma, (\kappa << 1)$ is not a good approximation, particularly at high peaks

We need to work on M_{ap} obtained by filtering g_t with Q filter directly

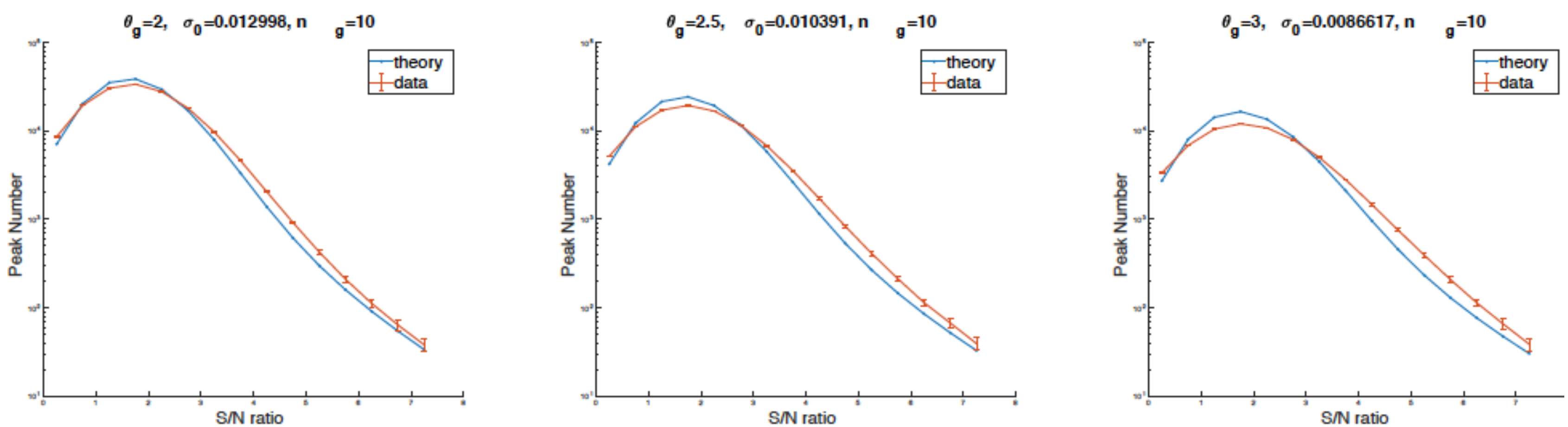
The high peak model is still halo based with random Gaussian shape noise and Gaussian LSS projections, but computationally, it is much more complicated

Pan, C.Z. worked it out !

$$M_{ap}(\theta) = \int d^2\vartheta' g_t(\vartheta') Q(\theta, \vartheta')$$



~1000 deg^2 simulations, above CFHTLenS redshift distribution, bellow zs~3



LSS projection effect is notable, and will be included in the M_{ap} peak model

★ Discussions

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

Seeing inconsistency with Planck CMB ??
systematics or new physics ??

Understanding the systematics is **THE** most important task in WL studies (shear measurements, photo-z, intrinsic alignment, …)

-- with the help of external data (e.g., photo-z calibration)
-- simulations (e.g., shear measurement bias)

-- Is it possible to perform self-calibration using WL data themselves??

Using the same WL data and apply different analyses → self-calibration

E.g., consider the multiplicative bias in shear measurements

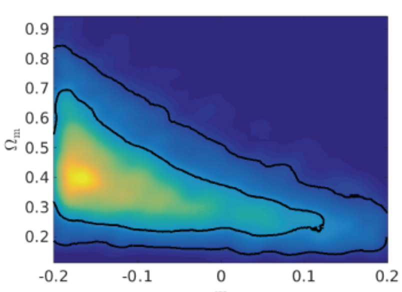
$$g_i = (1 + m_i) g_i^{\mathrm{tr}} + c_i$$

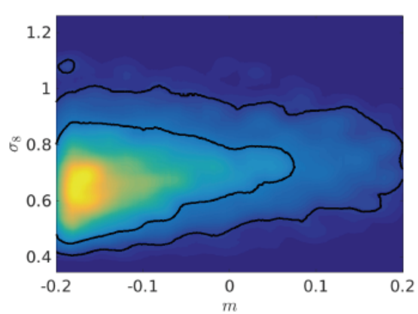
two-point cosmic shear correlations → (1+m) degenerates with cosmological parameters

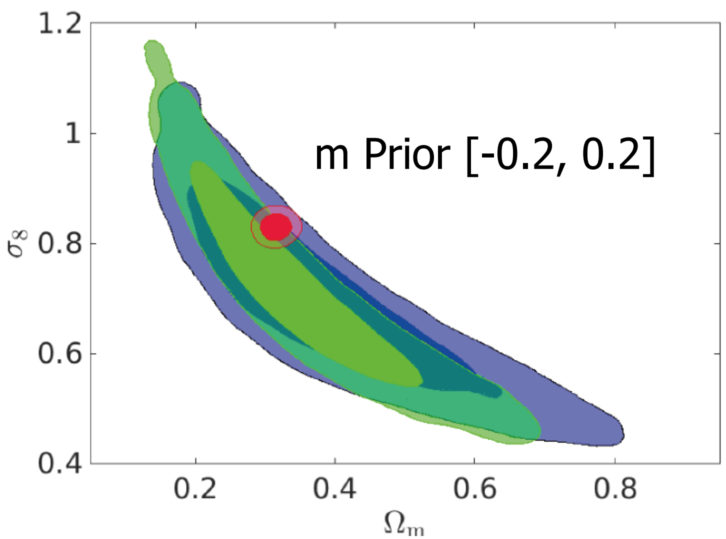
WL peak analyses are affected by m differently

Combining the two statistics → calibrate m

Application to CFHTLenS

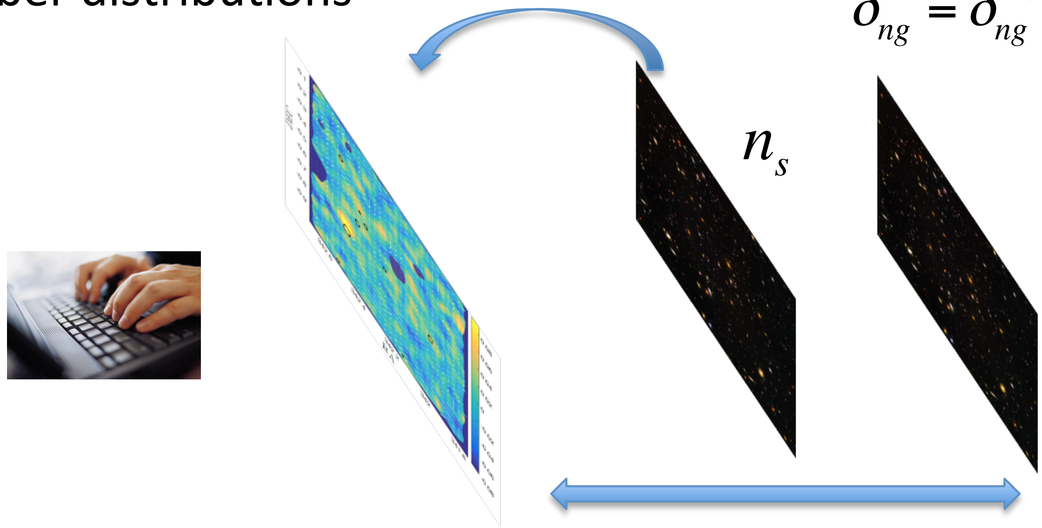






Cross-correlation of Kappa-maps from shear measurements with far-away galaxy number distributions

$$\delta_{ng} = \delta_{ng}^{\text{int}} + \delta_{\mu}$$



$$< \kappa(z_f)\delta_{ng}(z_b) > = < \kappa(z_f)\delta_{ng}^{\text{int}}(z_b) > + < \kappa(z_f)\delta_{\mu}(z_b) >$$
$$\approx < \kappa(z_f)\delta_{\mu}(z_b) >$$

$$\frac{< \kappa(z_f)\kappa(z_b) >}{< \kappa(z_f)\delta_{\mu}(z_b) >} \sim \frac{m}{A}$$

$\kappa(z_f)$: from shear measurement of n_s

$\delta_{\mu}(z_b)$: magnification induced clustering

m : multiplicative shear bias

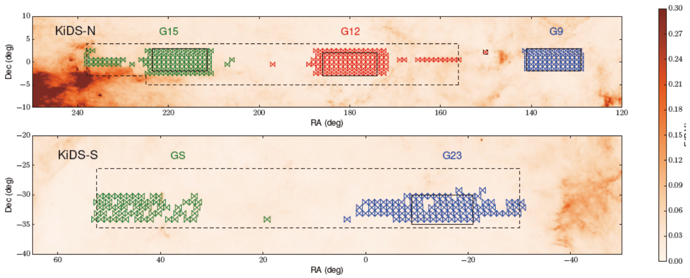
A : magnification part, related to the slope of galaxy luminosity function

→ Shear measurement bias calibration. Ideally, independent of galaxy bias, independent of cosmology.

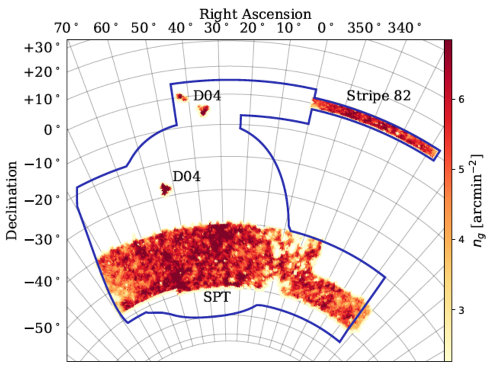
** Photo-z error; luminosity function, …

Thank you

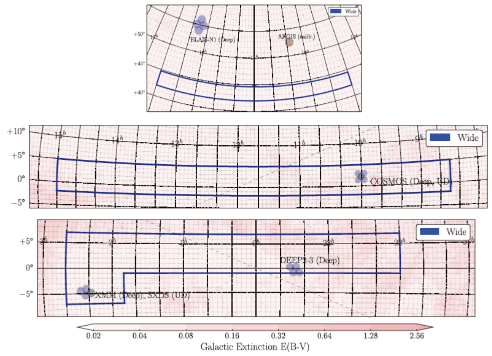
Stage III surveys are in play, and stage IV ones are on the way



KiDS



DES



HSC

WL observations are at the level comparable to other probes

Fully realize the power of WL analyses in precision era → systematics