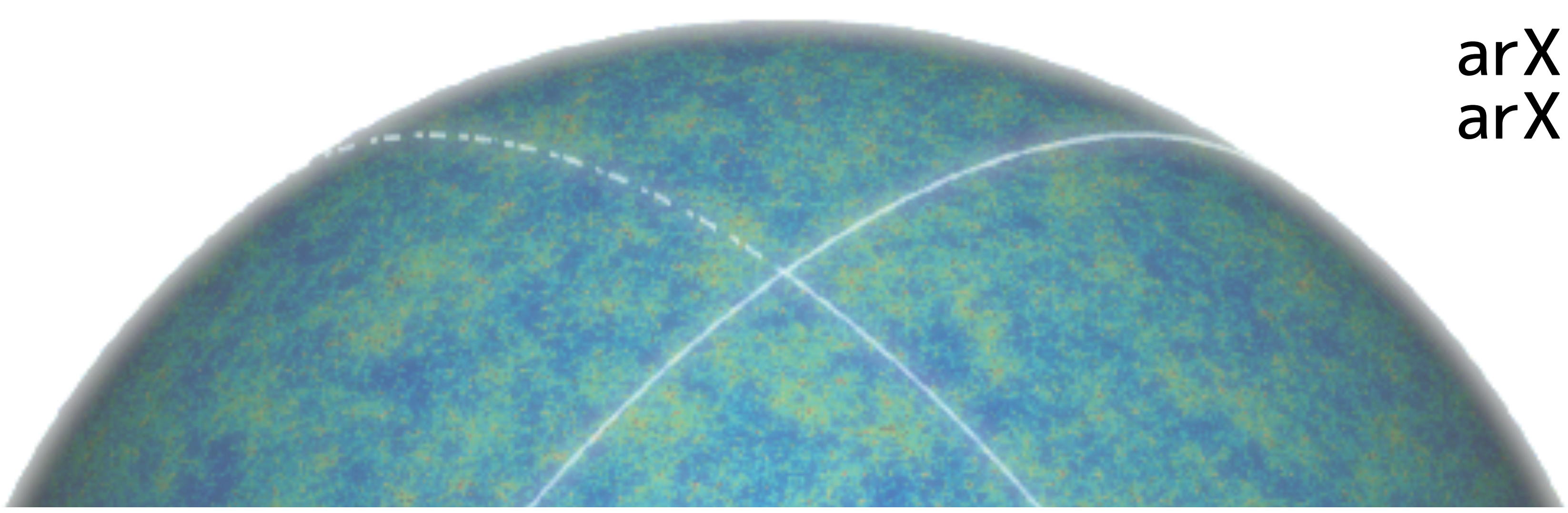
Probing Cosmology with Weak Lensing Selected Clusters

Masato Shirasaki（NAOJ）
with T. Hamana（NAOJ）N.Yoshida（The University of Tokyo）

新学術領域「なぜ宇宙は加速するのか？-徹底的究明と将来への挑戦-」発足シンポジウム
2015.9.21 @ Kavli IPMU

arXiv:1504.05672
arXiv:1508.02104



Cosmic Acceleration

- An array of recent astrophysical observations show us unresolved mystery of cosmology; the accelerating expansion of the universe

- There exist two possible classes
  - Dark Energy
  - Modified gravity

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

Importance of Large Scale Structure

- In order to test the two scenarios, it is essential to measure the gravitational growth of matter density fluctuations

- e.g. f(R) gravity

$$G_{\mu\nu} + f_R R_{\mu\nu} - \left(\frac{f}{2} - \Box f_R\right) g_{\mu\nu} - \nabla_\mu \nabla_\nu f_R = 8\pi G T_{\mu\nu},$$

g+: linear growth rate   H: Hubble expansion rate

$$\frac{\mathrm{d}^2 g_+}{\mathrm{d}a^2} + \left(\frac{3}{a} + \frac{1}{H}\frac{\mathrm{d}H}{\mathrm{d}a}\right)\frac{\mathrm{d}g_+}{\mathrm{d}a} - \frac{3\tilde{\Omega}_{\mathrm{m}0}a^{-3}}{(H/H_0)^2(1+f_R)}\left(\frac{1-2Q}{2-3Q}\right)\frac{g_+}{a^2} = 0,$$

$$Q(k,a) = -2\left(\frac{k}{a}\right)^2 \frac{f_{RR}}{1+f_R}.$$

Additional degree of freedom f(R) can induce the scale dependence of matter density fluctuations even at large scales!

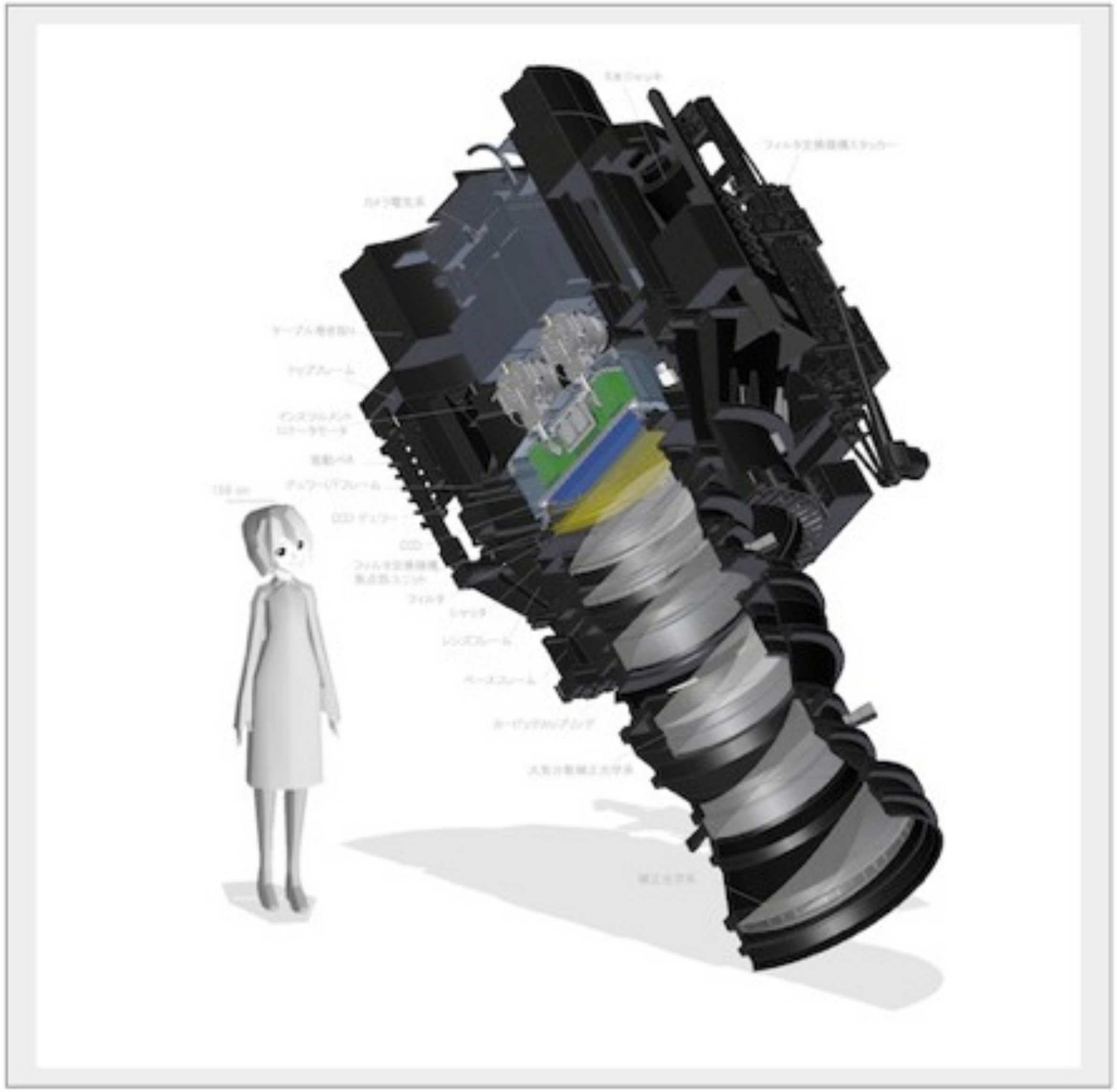
- How can we know the matter density distribution in the Universe?
  ☞ **Weak Gravitational Lensing**

Hyper Suprime Cam is Working Now!

- Hyper Suprime-Cam (HSC) survey aims at mapping the matter density distribution with sky coverage of 1400 sq. degs

- How can we extract cosmological information from observed mass density map?

- Two-point statistics are **NOT** optimal for this purpose in the case of lensing, because non-linear gravitational growth can make mass maps be non-Gaussian



http://subarutelescope.org/Projects/HSC/j_index.html

Lensing Peak Statistics

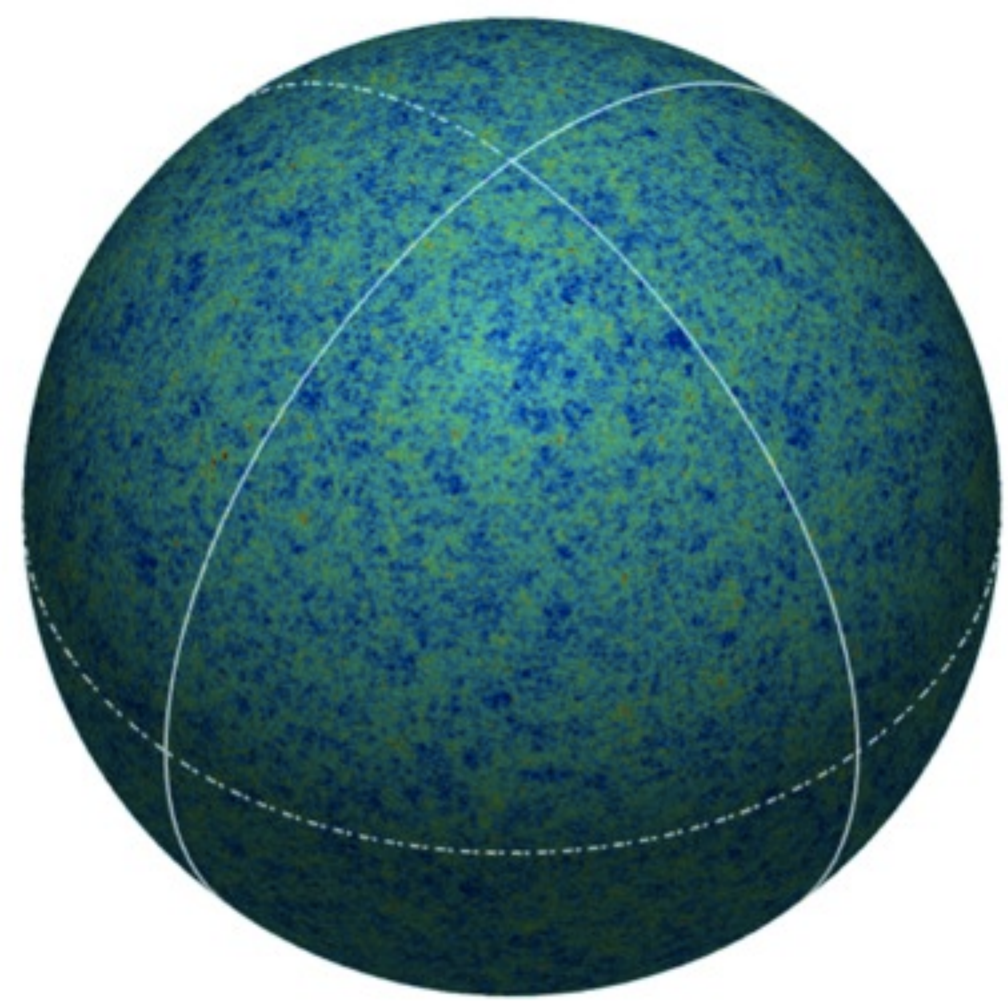
- Peaks on observed mass map might be associated with dark matter halos along the line of sight
- Previous numerical works clearly have shown the relationship between peaks and halos
- This argument is confirmed by recent imaging surveys
- It is the time to discuss cosmological information content of lensing peaks in detail
- Mock lensing catalogs with a large sky coverage would be required for demonstration of future lensing surveys

Miyazaki et al. 2015

Full Sky Lensing Maps

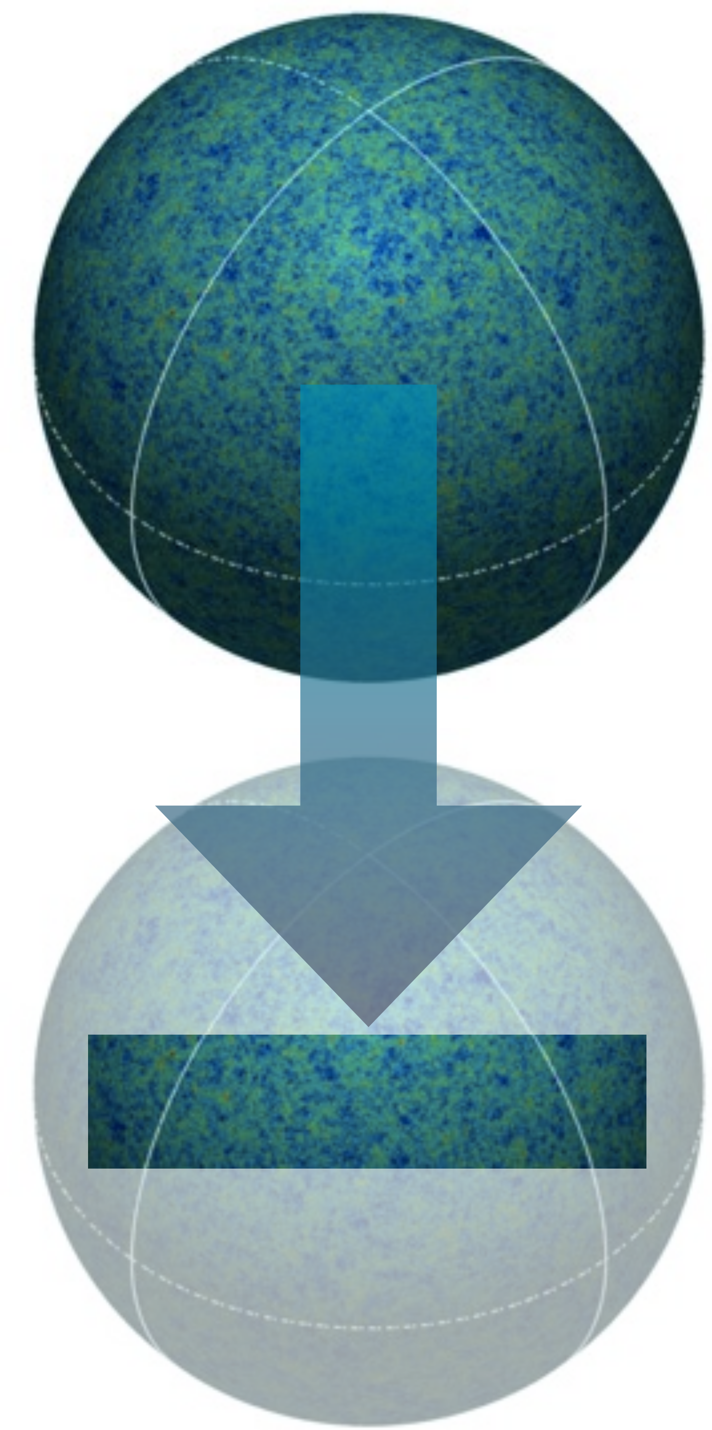
- ΛCDM WMAP 9 year
- Based on N-body simulation with a billion of particles
- Perform ray-tracing simulation on a curved sky with a set of matter density "shells"

- Simulation output: Observables of weak lensing analyses over full sky (~42,000 sq. degs)
- 10 full sky maps are now available
- If you are interested in, please let us know



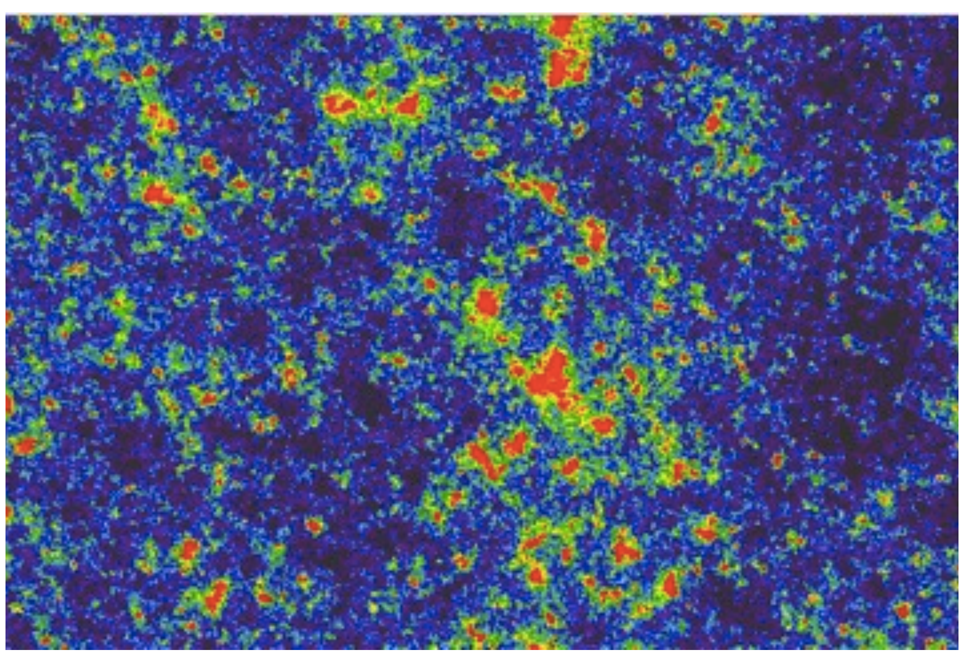
Mock HSC surveys

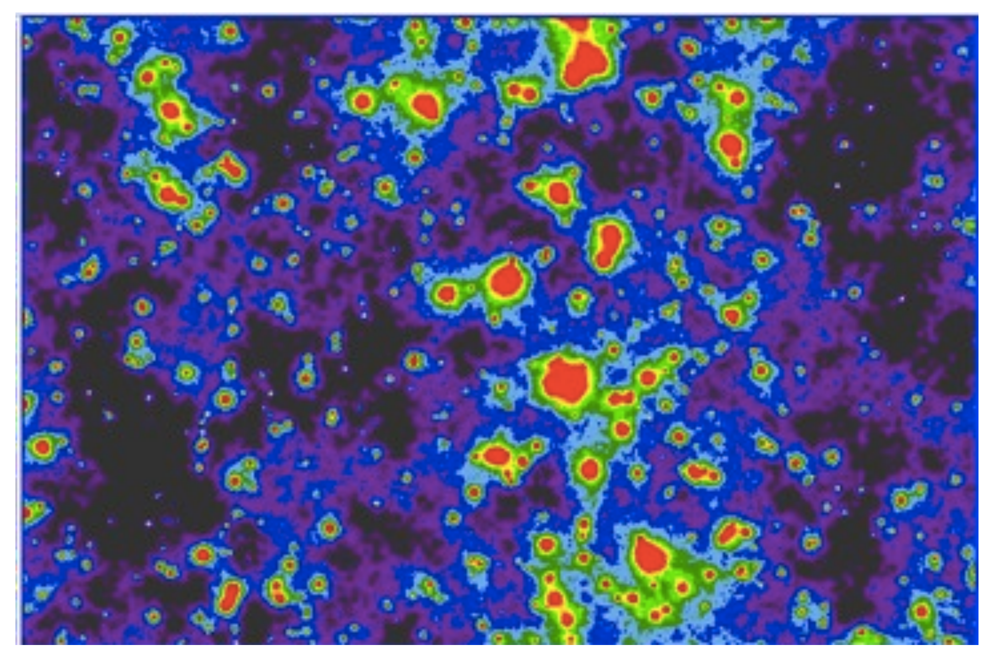
- extract the HSC region from full-sky
- take into account **the HSC survey geometry**, **shape noise** and **masking due to the actual bright stars**
- realize **200** mock HSC surveys in total
- work with maps with z_{source}=1 and perform a Gaussian smoothing with smoothing scale of 2 arcmin
- Observables are:
  1. cosmic shear power spectrum
  2. number count of peaks as a function of peak height
  3. cross power spectrum between peaks and shear
- measure the ensemble average of observables and their covariances



Theoretical Model
Halo approach

- Based on *Halo-model approach*
- All components are hosted by a DM halo
- DM haloes have the universal density profile (= NFW profile) with some parameters as a function of redshift and Mass
- Use Halo mass function and Halo bias


from N-body simulation


based on Halo-model

Theoretical Model
Halo approach

1. cosmic shear power spectrum

$$P_{\kappa\kappa}(\ell) = \int_0^{\chi_s} \mathrm{d}\chi \frac{W_\kappa(\chi)^2}{r(\chi)^2} P_\delta\left(k = \frac{\ell}{r(\chi)}, z(\chi)\right),$$

Non-linear matter power spectrum

2. number count of peaks

$$N_{\mathrm{peak}}(\nu_{\mathrm{thre}}) = \int \mathrm{d}z\,\mathrm{d}M\,\frac{\mathrm{d}^2V}{\mathrm{d}z\mathrm{d}\Omega}\frac{\mathrm{d}n}{\mathrm{d}M}S(z, M|\nu_{\mathrm{thre}}),$$

Halo mass function

Halo density profile

3. cross spectrum of peaks and shear

$$P_{\mathrm{p}\kappa}(\ell) = P^{1h}_{\mathrm{p}\kappa}(\ell) + P^{2h}_{\mathrm{p}\kappa}(\ell),$$

Halo mass function

Halo density profile

Linear matter power spectrum

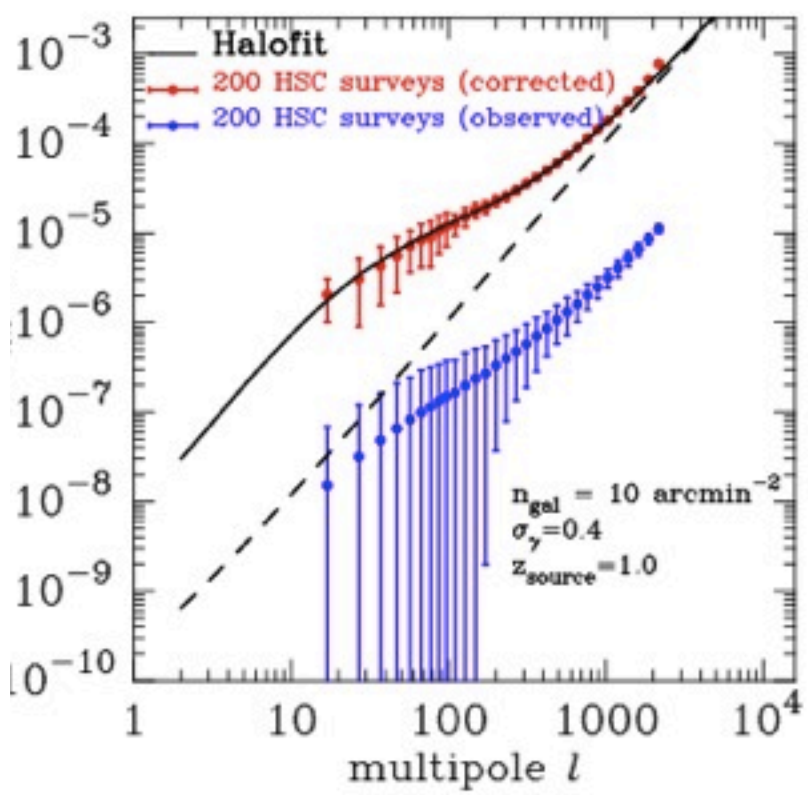
Linear Halo bias

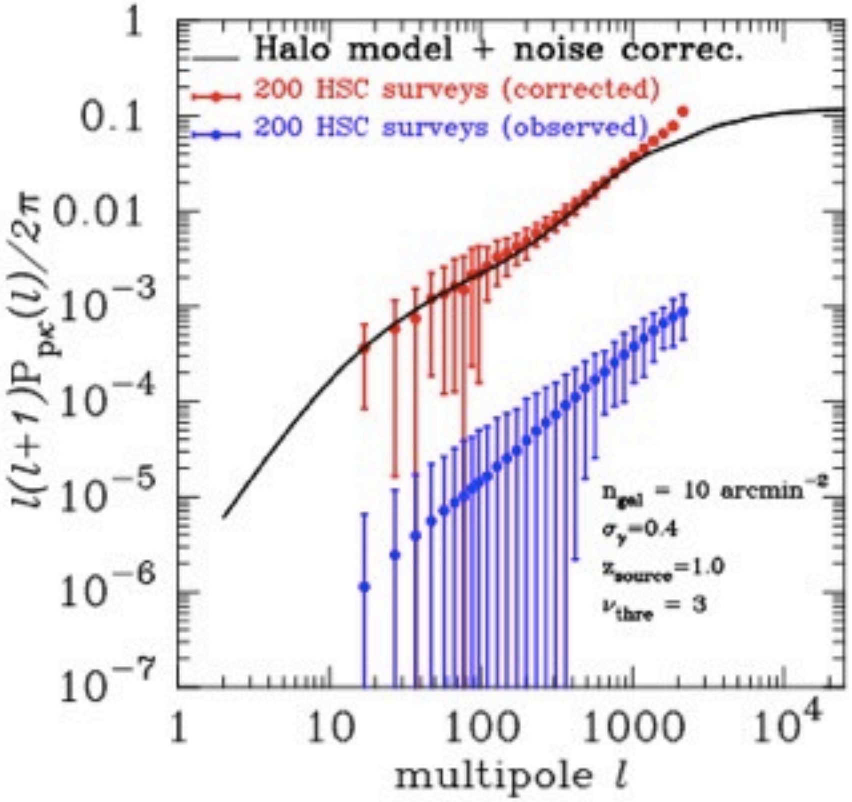
$$P^{1\mathrm{h}}_{\mathrm{p}\kappa}(\ell) = \int \mathrm{d}\chi\,\frac{W_\kappa(\chi)}{r(\chi)^2}\left(\frac{1}{N_{\mathrm{peak}}}\frac{\mathrm{d}^2V}{\mathrm{d}\chi\mathrm{d}\Omega}\right)\int \mathrm{d}M\,\frac{\mathrm{d}n}{\mathrm{d}M}S(z, M|\nu_{\mathrm{thre}})\left(\frac{M}{\bar{\rho}_{\mathrm{m}}(z)}\right)\tilde{u}_{\mathrm{m}}\left(k = \frac{\ell}{r(\chi)}\middle| z(\chi), M\right)$$

$$P^{2h}_{\mathrm{p}\kappa}(\ell) = \int \mathrm{d}\chi\,\frac{W_\kappa(\chi)}{r(\chi)^2}\left(\frac{1}{N_{\mathrm{peak}}}\frac{\mathrm{d}^2V}{\mathrm{d}\chi\mathrm{d}\Omega}\right)\left[\int \mathrm{d}M\,\frac{\mathrm{d}n}{\mathrm{d}M}(z, M)S(z, M|\nu_{\mathrm{thre}})b_{\mathrm{h}}(z, M)\right]P^L_{\mathrm{m}}\left(k = \frac{\ell}{r(\chi)}, z(\chi)\right),$$

Comparison with Simulation and Model

cosmic shear power spectrum

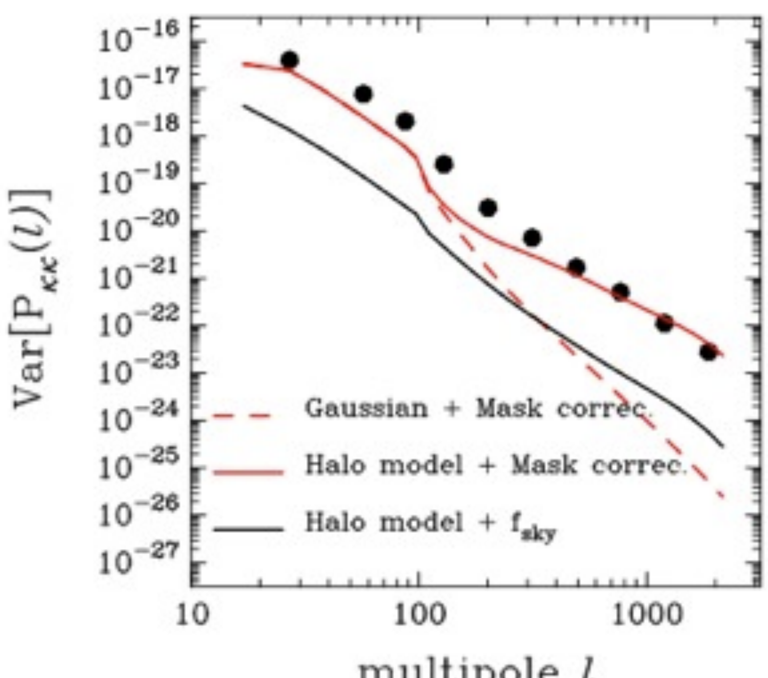


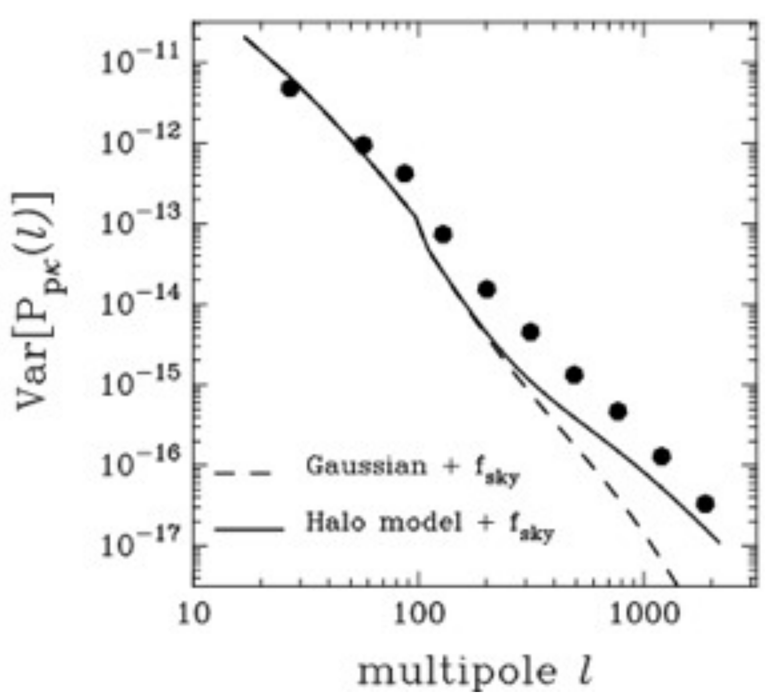


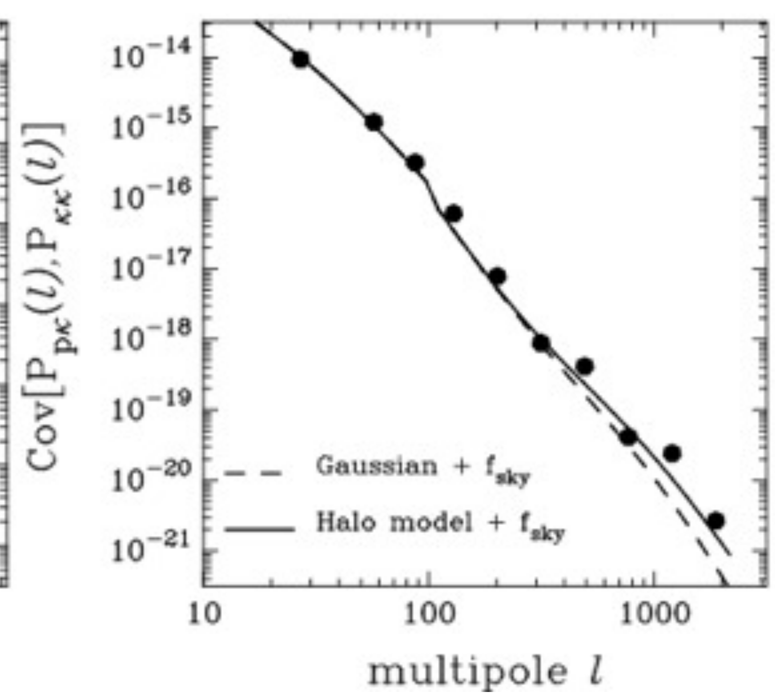
cross spectrum between peaks and shear

Message:

Both average and covariances are consistent with simple halo approach

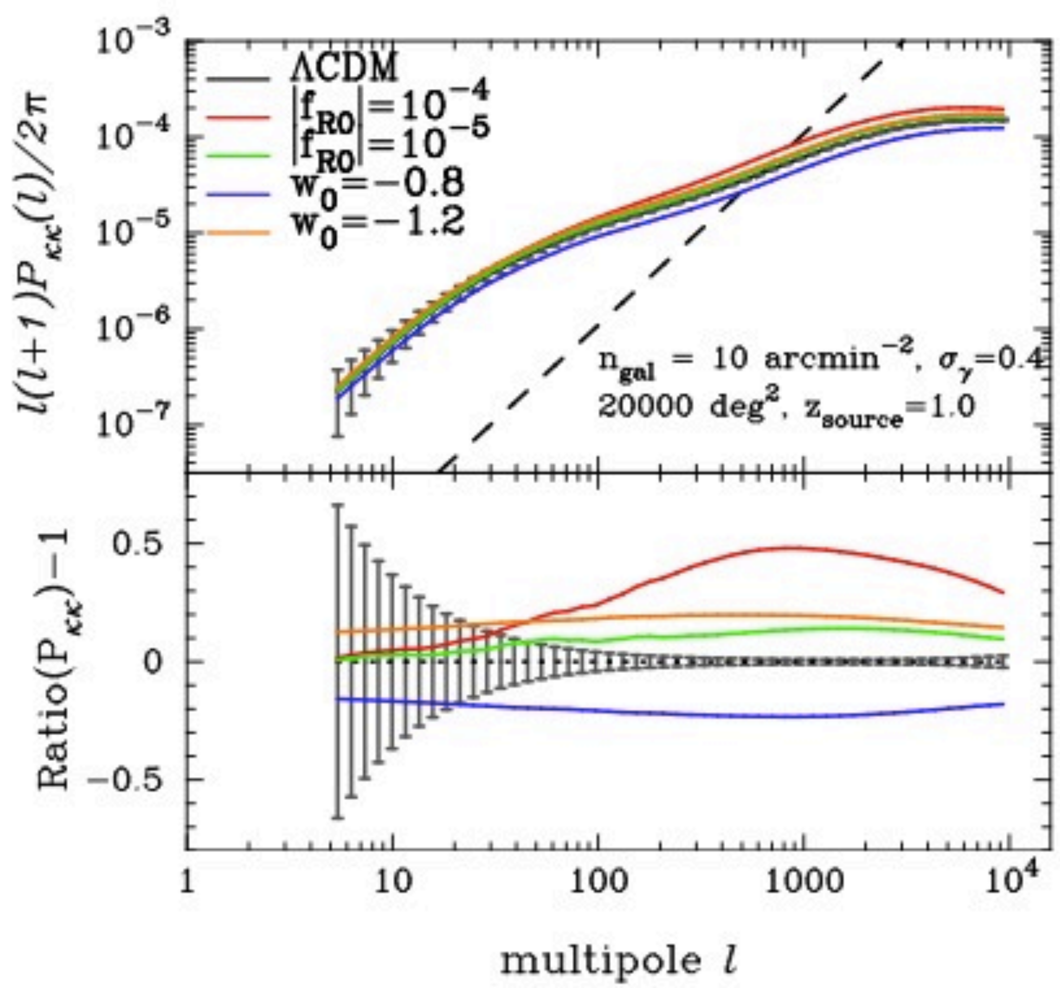




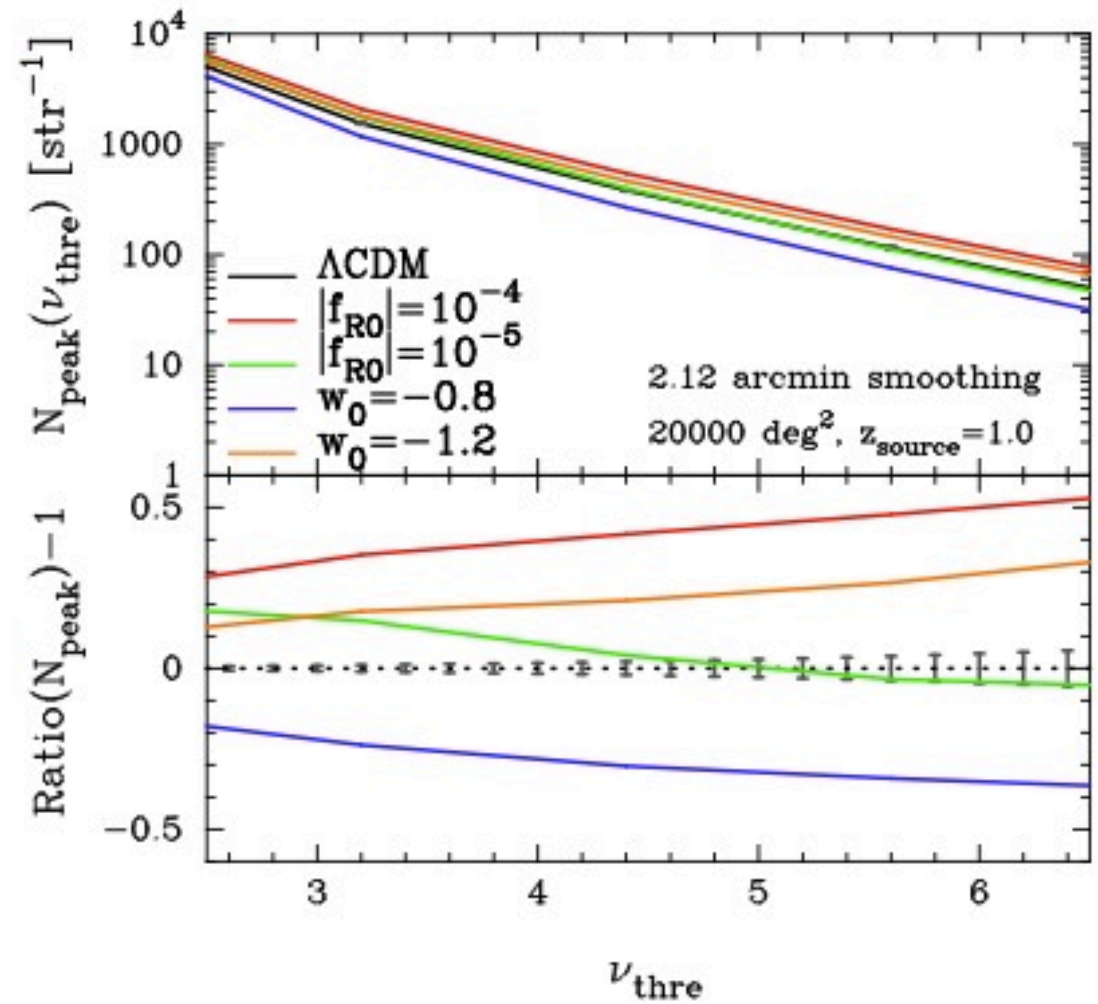


Cosmological Dependence

1. cosmic shear power spectrum



2. number count of peaks



GR+DE model

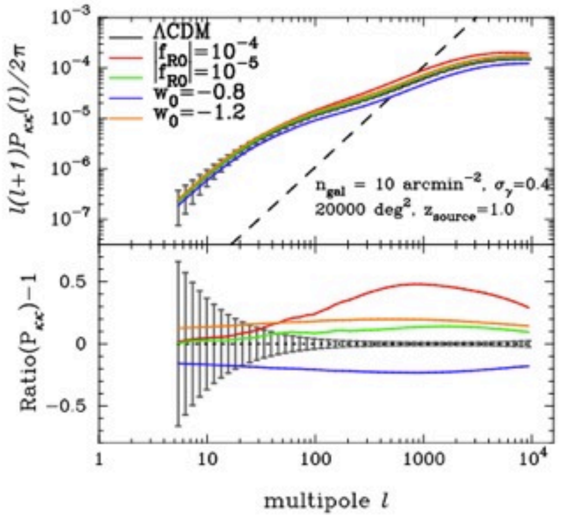
Main differences are caused by linear growth rate or mass variance

f(R) model

more complex: scale-dependent linear growth rate and chameleon mechanism (i.e. this model should recover GR in high density regions)

Cosmological Dependence

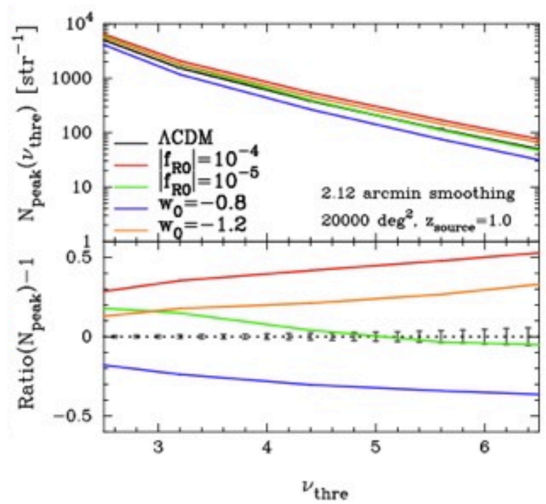
1. cosmic shear power spectrum



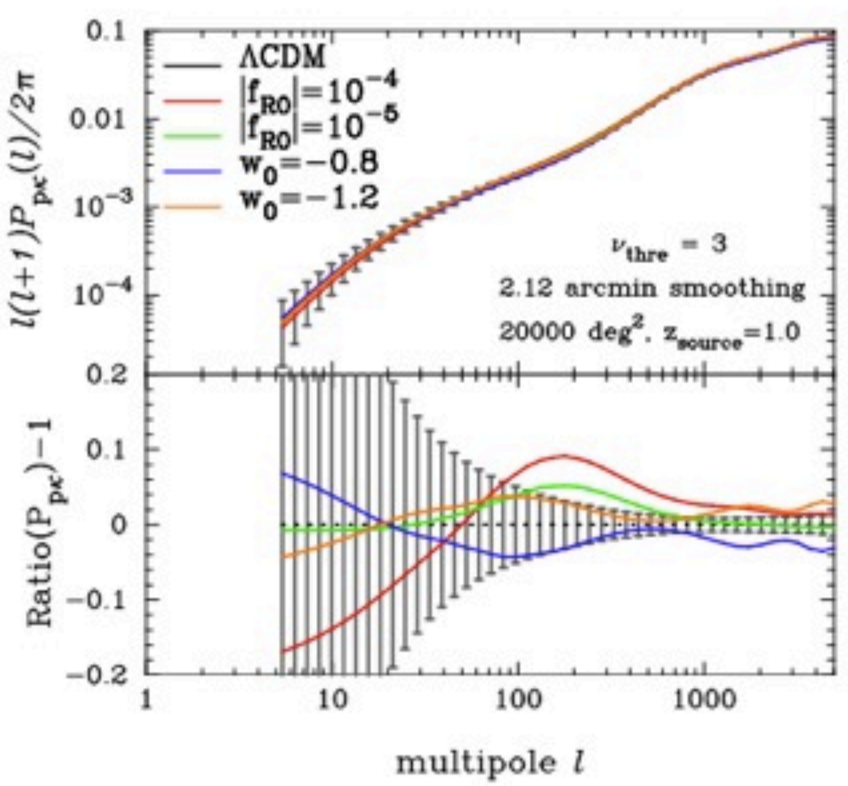
Strong degeneracies among cosmological parameters

Depend on halo mass function **AND** halo density profile

2. number count of peaks



3. cross spectrum of peaks and shear

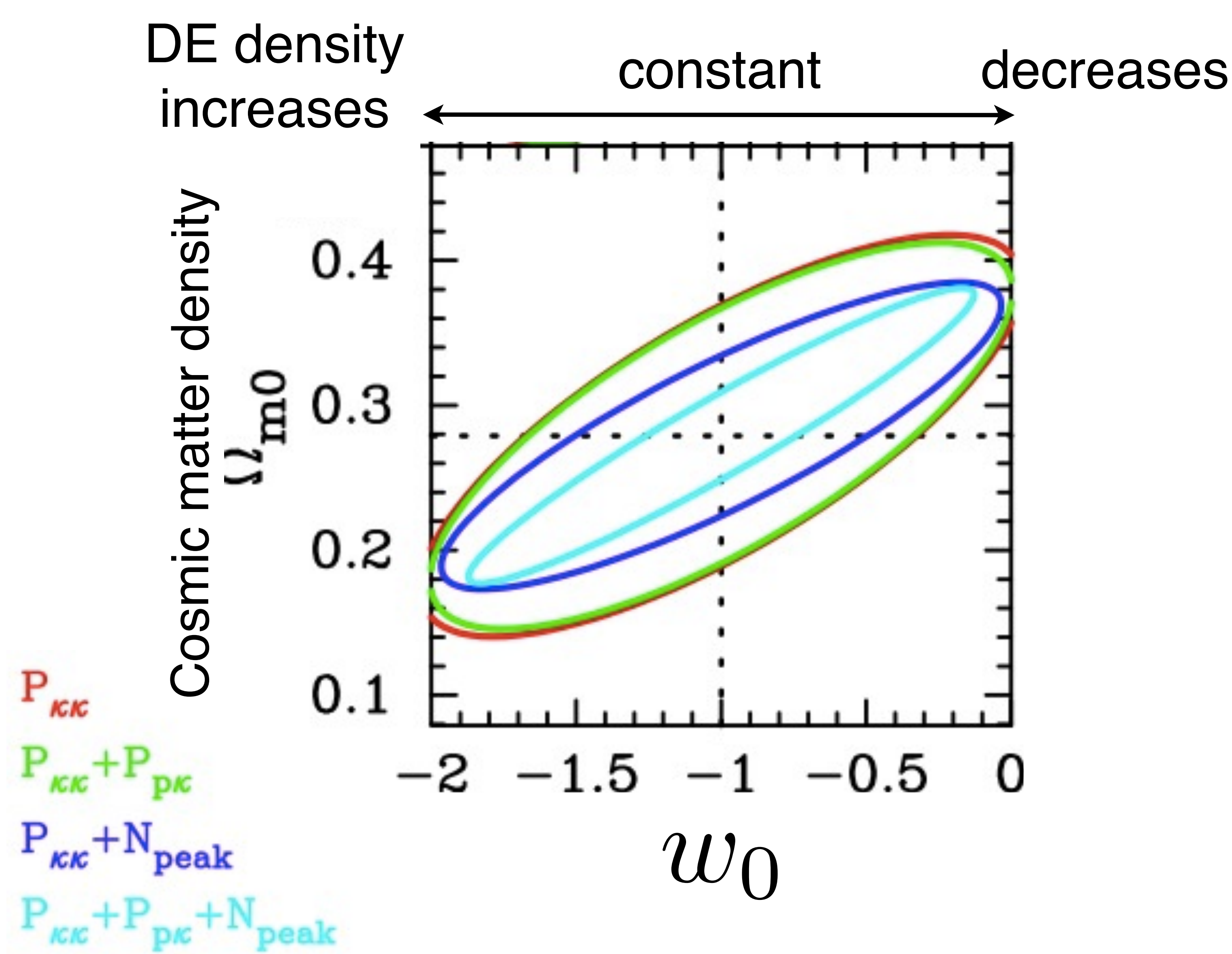


Large scale: contains cosmological information
Small scale: determined by density profile

☞ **Do Combined Analysis**

Future forecast on Dark Energy / Modified gravity models

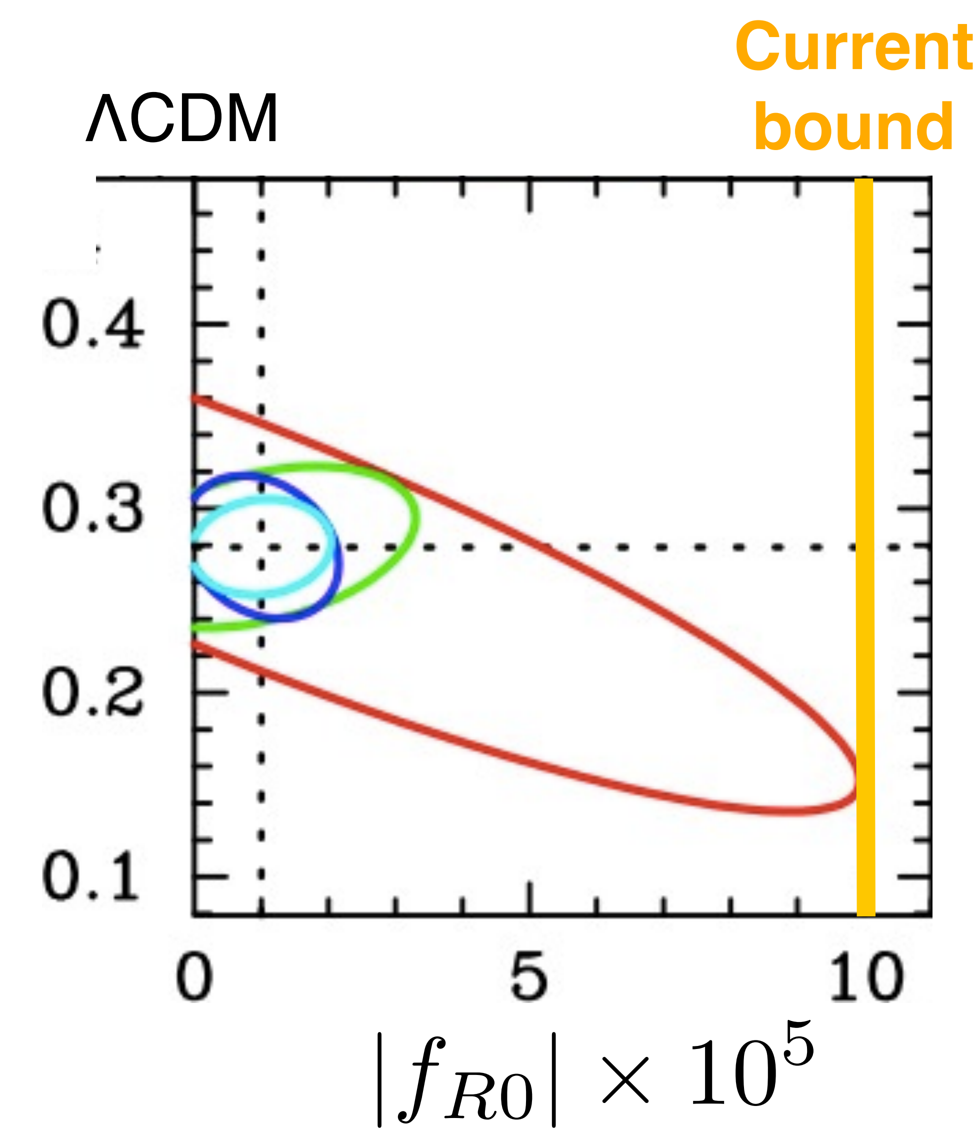
Time evolved DE+GR



Planck + HSC

$\Delta w_0 = 0.117$

f(R) model proposed by Hu & Sawicki



Planck + HSC

$\Delta|f_{R0}| = 0.584 \times 10^{-5}$

Conclusion and Future Prospect

- Large scale structure is the key to distinguish two possible models of cosmic acceleration
- Perform full-sky ray-tracing simulation for upcoming galaxy imaging surveys
- Weak lensing peaks would be related with cluster-sized haloes and their statistical property can be modeled by simple framework
- Our proposed statistics can improve the cosmological constraints when combined with cosmic shear power spectrum
- Weak lensing simulations in modified gravity are being developed

Extra Slides

Possible Uncertainties

a) **Photometric redshift uncertainty**

Does photo-z error cause systematical differences of lensing statistics?

b) **Baryonic physics**

Need Hydro sims and we have to develop some theoretical models

c) **Massive neutrinos**

How can we construct theoretical model at non-linear scales for modified gravity with massive neutrinos?

d) **Magnification**

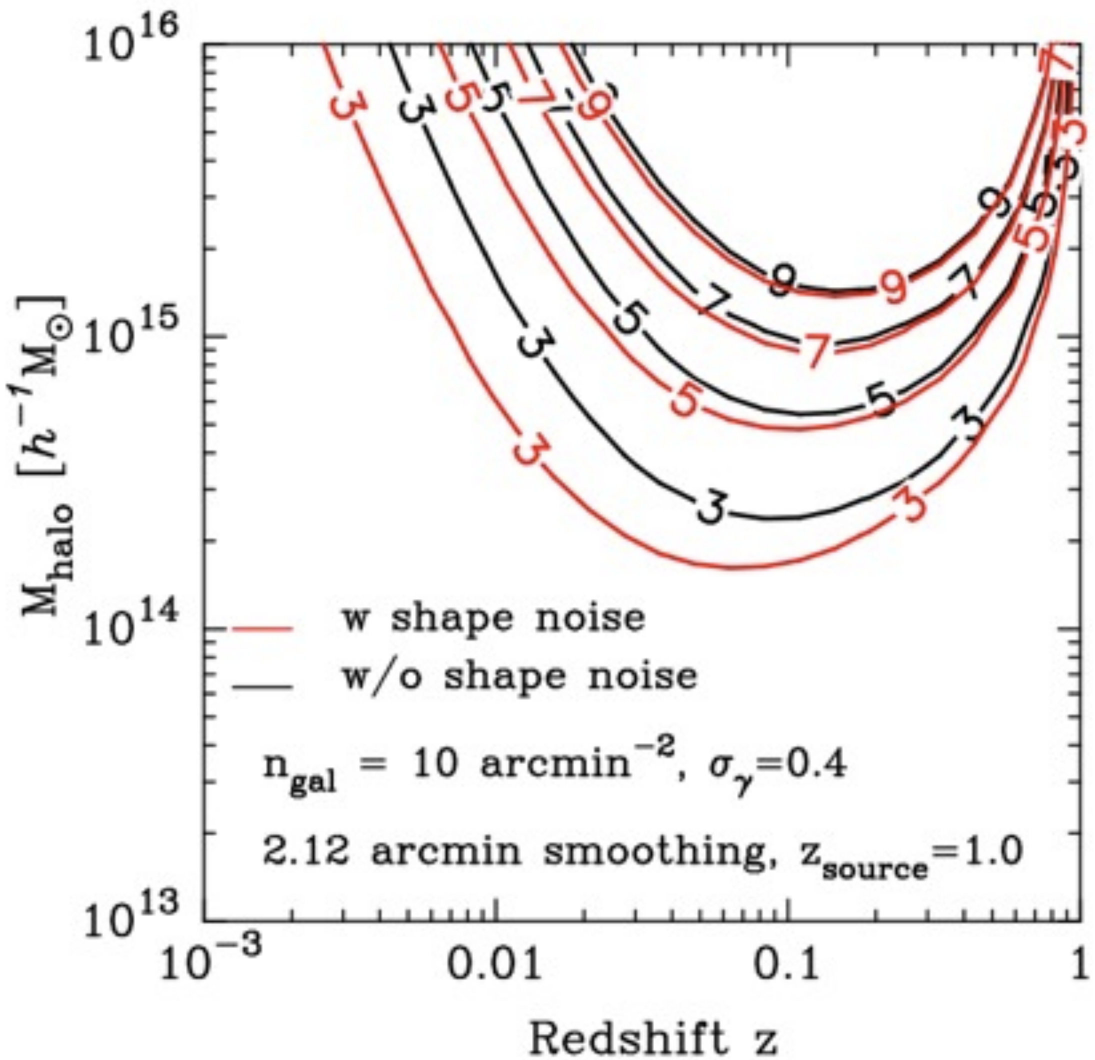
induces non-uniform sampling of source galaxies and cound affect WL mass map making

e) **Intrinsic alignment (IA)**

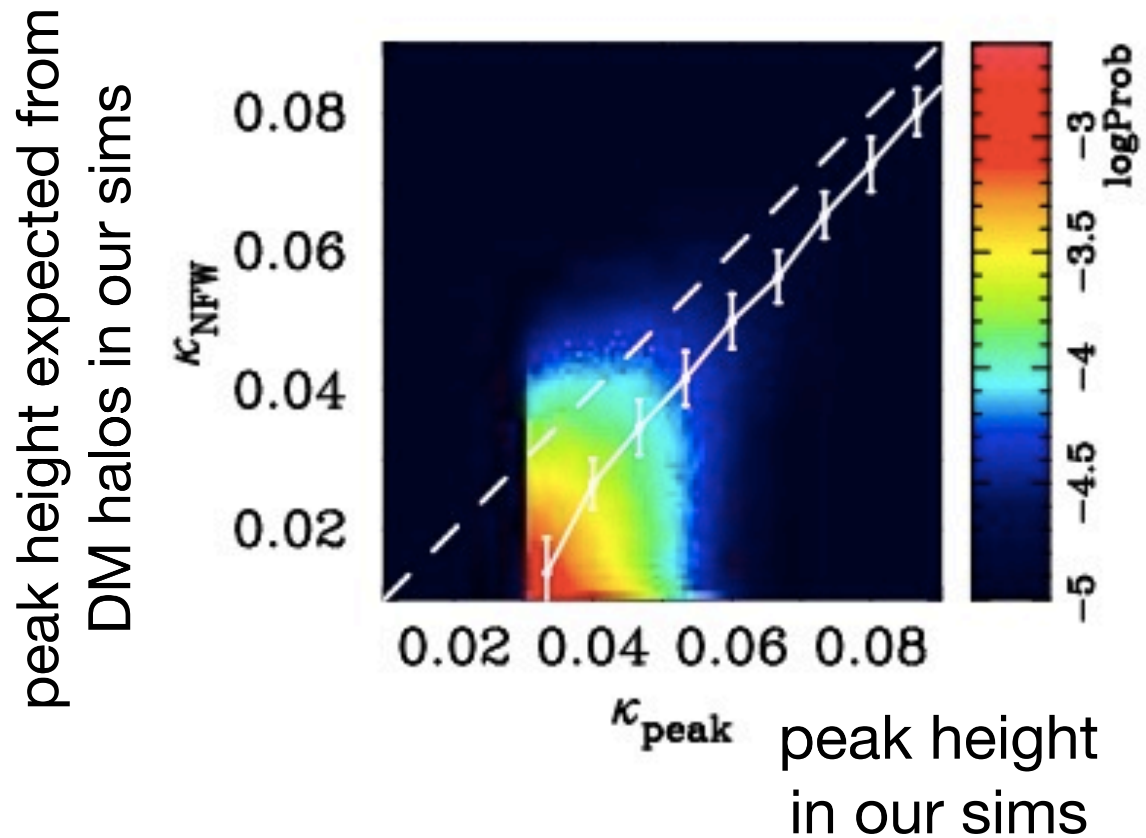
No studies to evaluate the impact of IA on WL mass map reconstruction

f) **and more...?**

Relationship between Halos and Peaks



Contour lines show the expected peak height as a function of z and mass.



Our model works well!

Linear Perturbation in Hu & Sawicki model

Modified Einstein Eq.

$$G_{\mu\nu}+f_R R_{\mu\nu}-\left(\frac{f}{2}-\Box f_R\right)g_{\mu\nu}-\nabla_\mu\nabla_\nu f_R=\kappa^2 T_{\mu\nu}.$$

with free non-linear function:

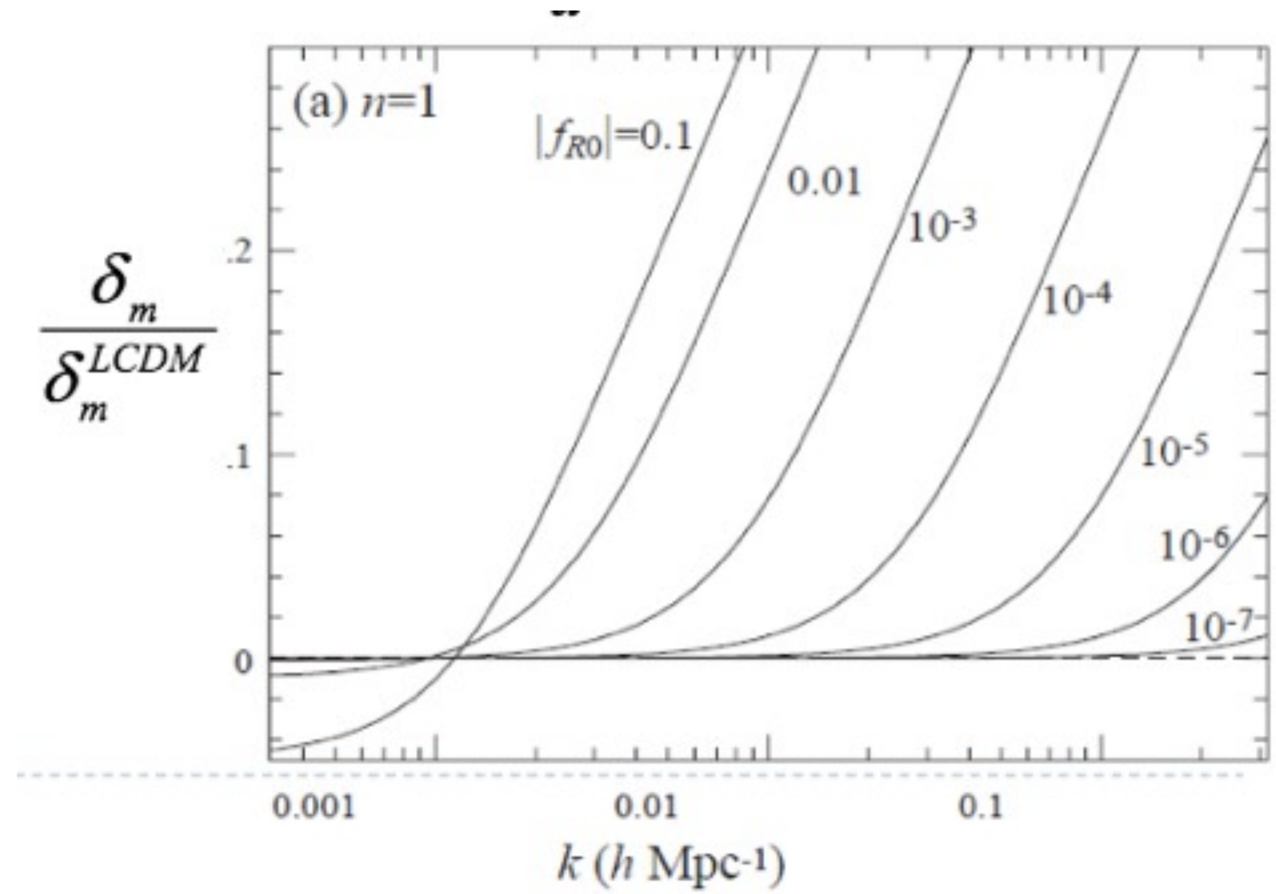
$$f(R)=-\bar{m}^2\frac{c_1\left(R/\bar{m}^2\right)^n}{c_2\left(R/\bar{m}^2\right)^n+1}.$$

Field Eq with quasi-static approximation

$$\nabla^2\delta f_R=\frac{1}{3}\left[\delta R(f_R)-\kappa^2\,\delta\rho_{\rm m}\right],$$

Modified Poisson Eq

$$\nabla^2\Psi=\frac{2\kappa^2}{3}\delta\rho_{\rm m}-\frac{1}{6}\delta R(f_R).$$

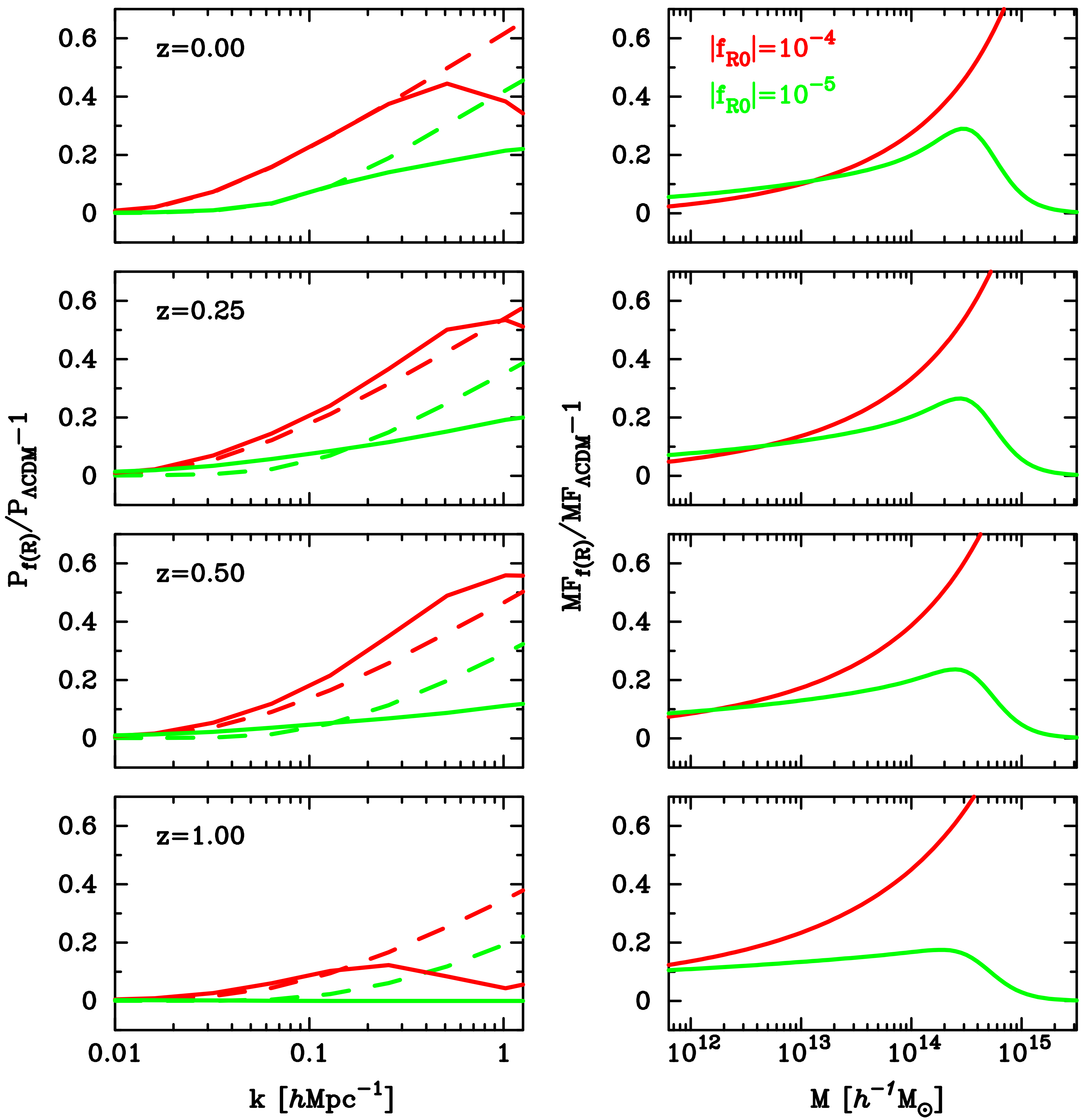


$$\boxed{k^2\Psi(\mathbf{k})=-\frac{\kappa^2}{2}\left\{\frac{4}{3}-\frac{1}{3}\left[\left(\frac{k}{m\,a}\right)^2+1\right]^{-1}\right\}a^2\delta\rho_{\rm m}(\mathbf{k}),}$$

typical value (for n=1)

$$m^{-1}\simeq 3.2\left(\frac{|f_{R0}|}{10^{-6}}\right)^{1/2}\ \text{Mpc}$$

where m is the mass of scalaron evaluated at the background



15年9月21日月曜日

Future constraints
Ω_m-σ_8 plane