Recovering the Power Spectrum of density fluctuation using the CMB lensing signal

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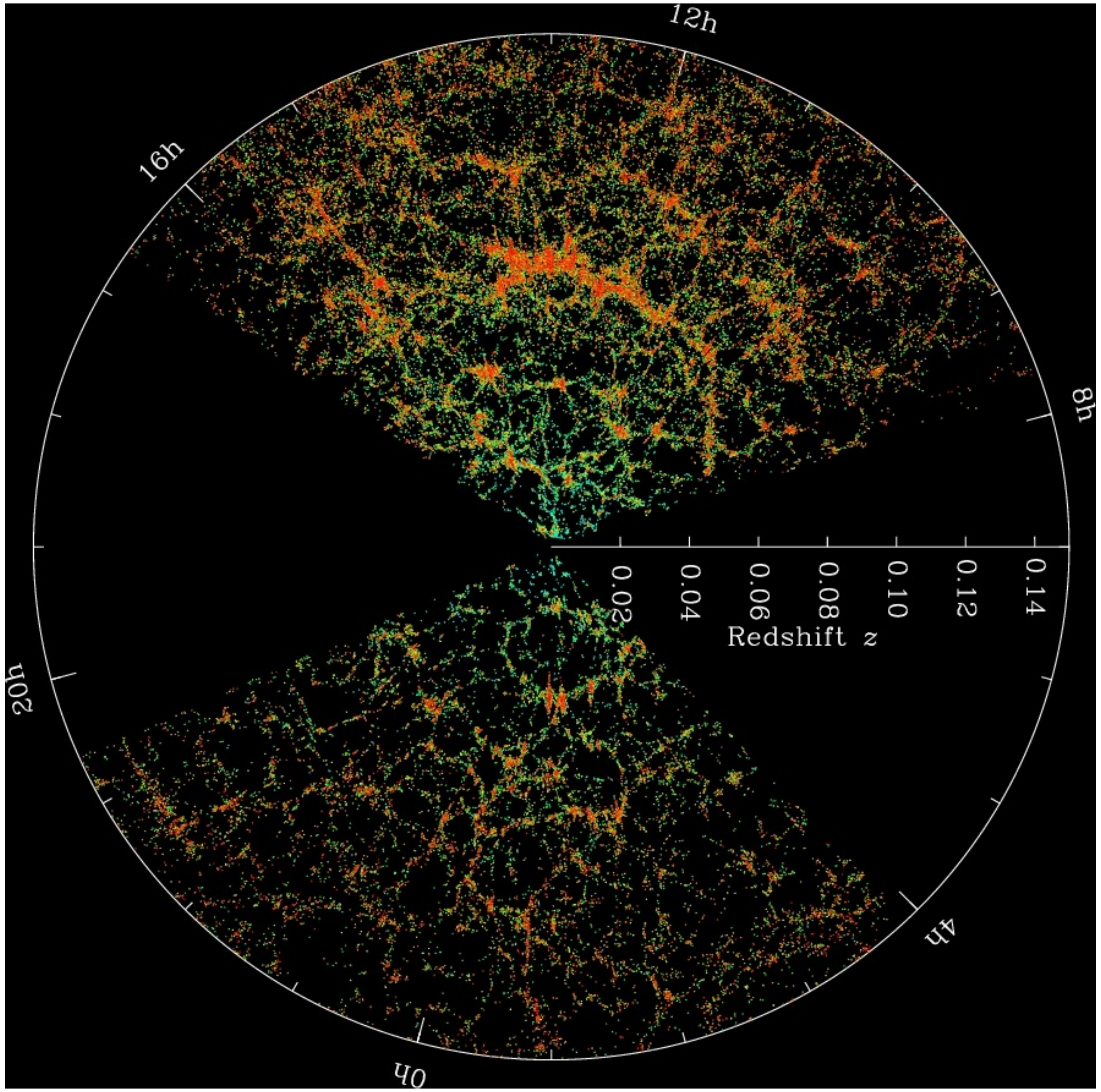
Current status

SDSS-BOSS Collaboration



Large Scale Structure (LSS)

- Geometrical information: BAO signal, Lensing
- Growth of structure
- Cosmological parameters

Massive Neutrinos

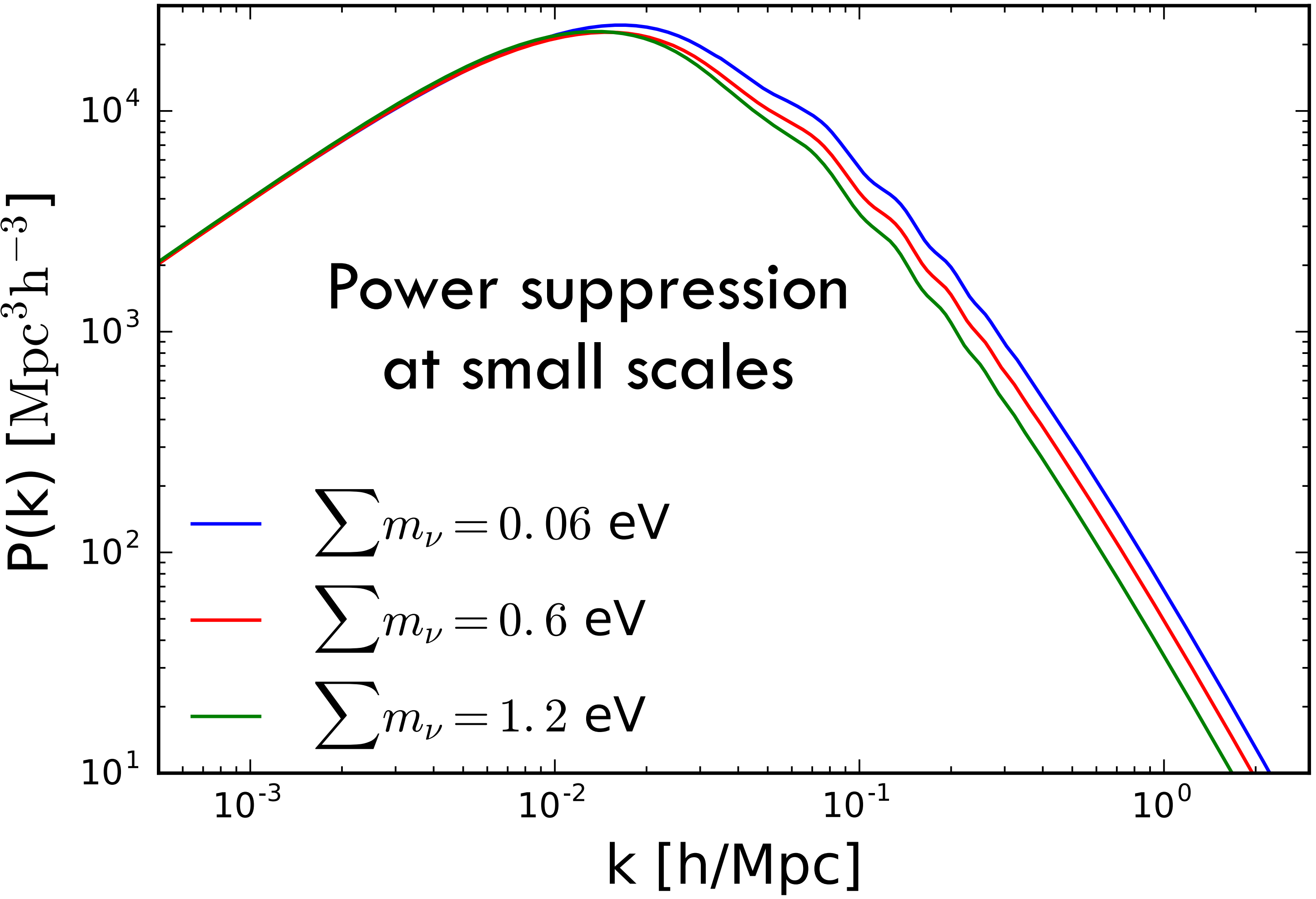
Neutrinos in Large Scale Structure

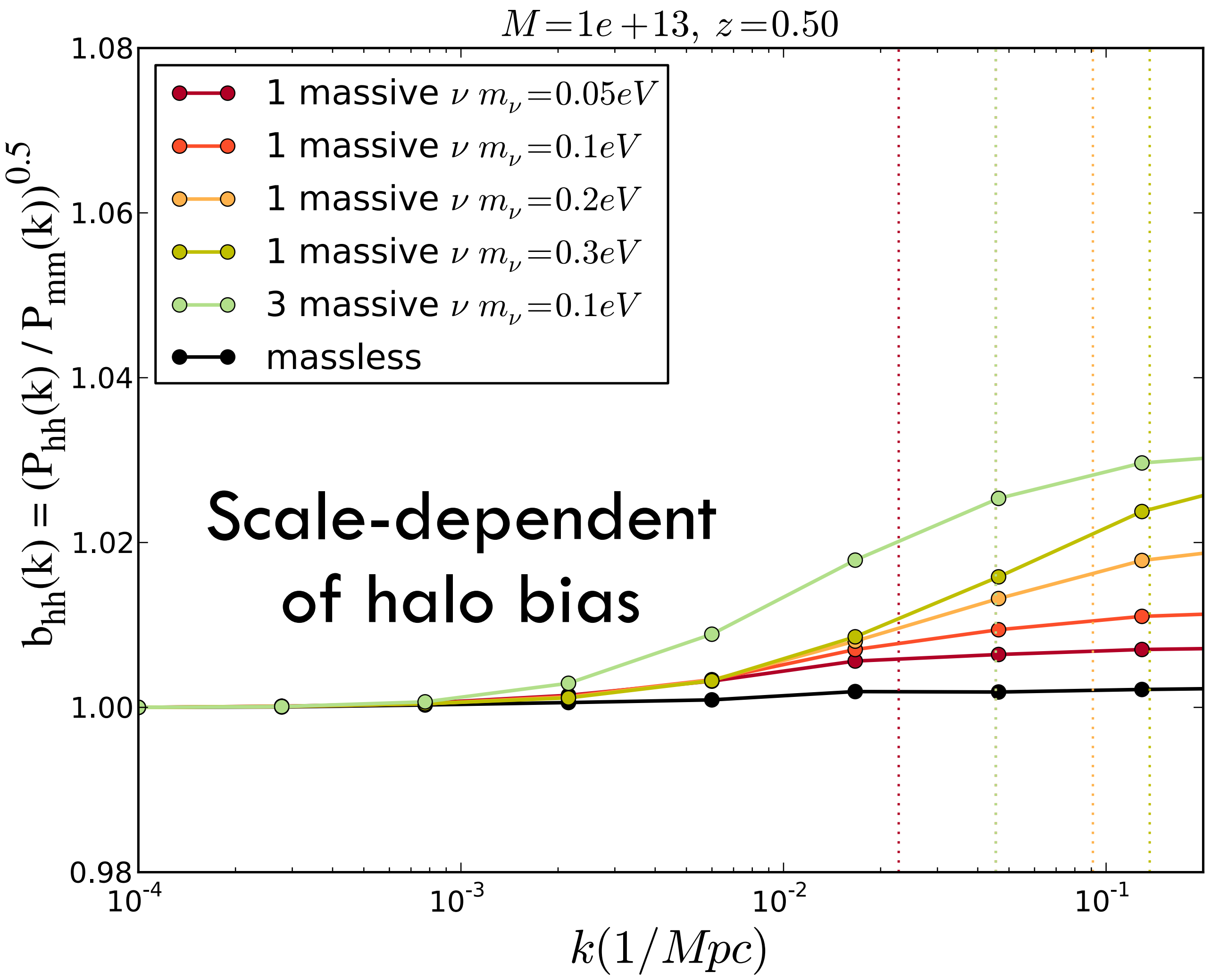
a) Suppression of structure formation on scales smaller than the free streaming scale. They affect also the Baryon acoustic oscillation (BAO) scales.

b) Changes to the amplitude of redshift space distortions (RSD) and the scale-dependent halo bias.

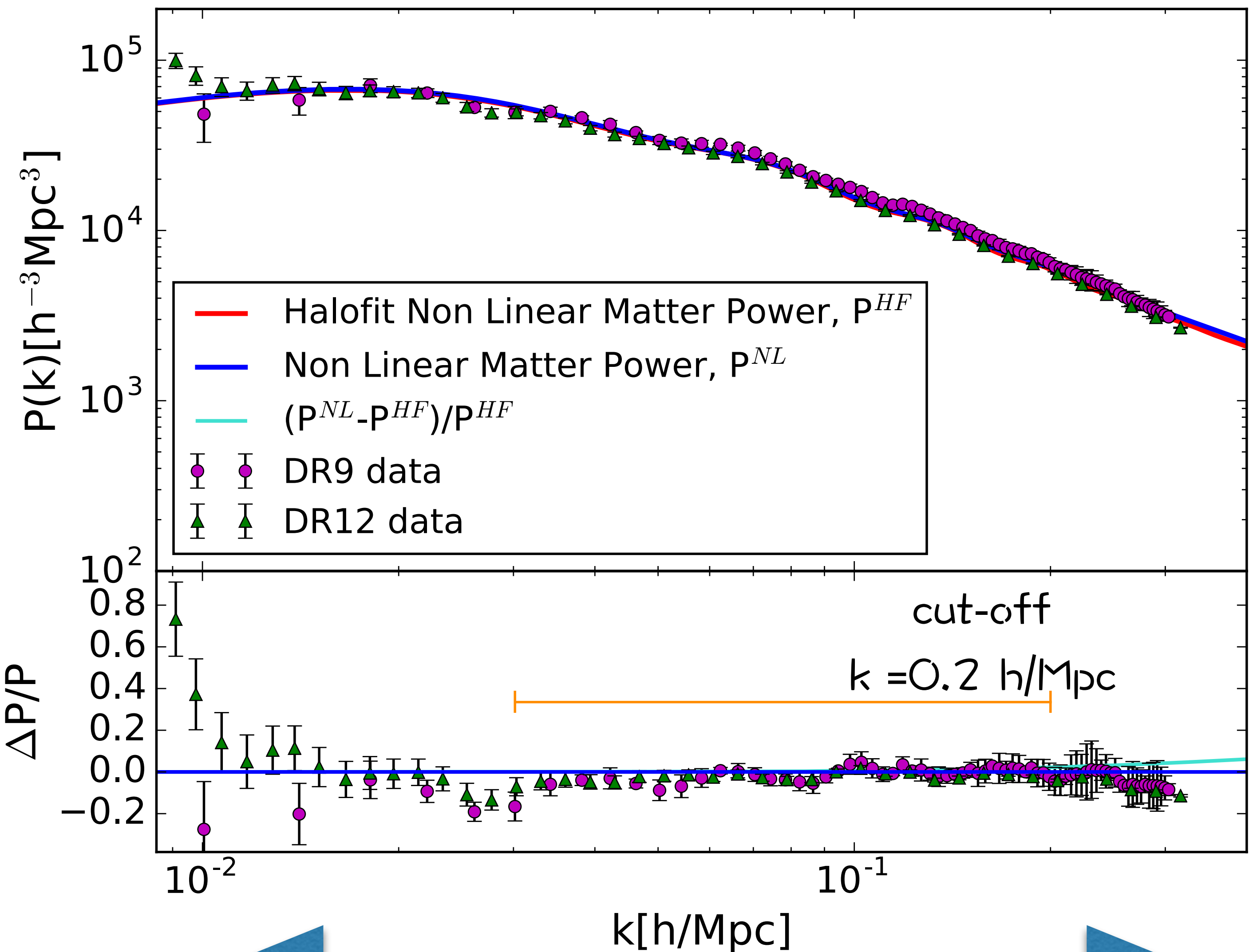
$$k_{\rm fs} \simeq 0.018\ \Omega_m^{1/2} \left(\frac{M_\nu}{1{\rm eV}}\right)^{1/2} \ h\ {\rm Mpc}^{-1}$$

LoVerde, Phys. Rev.,2014





Recent constraints on M_ν

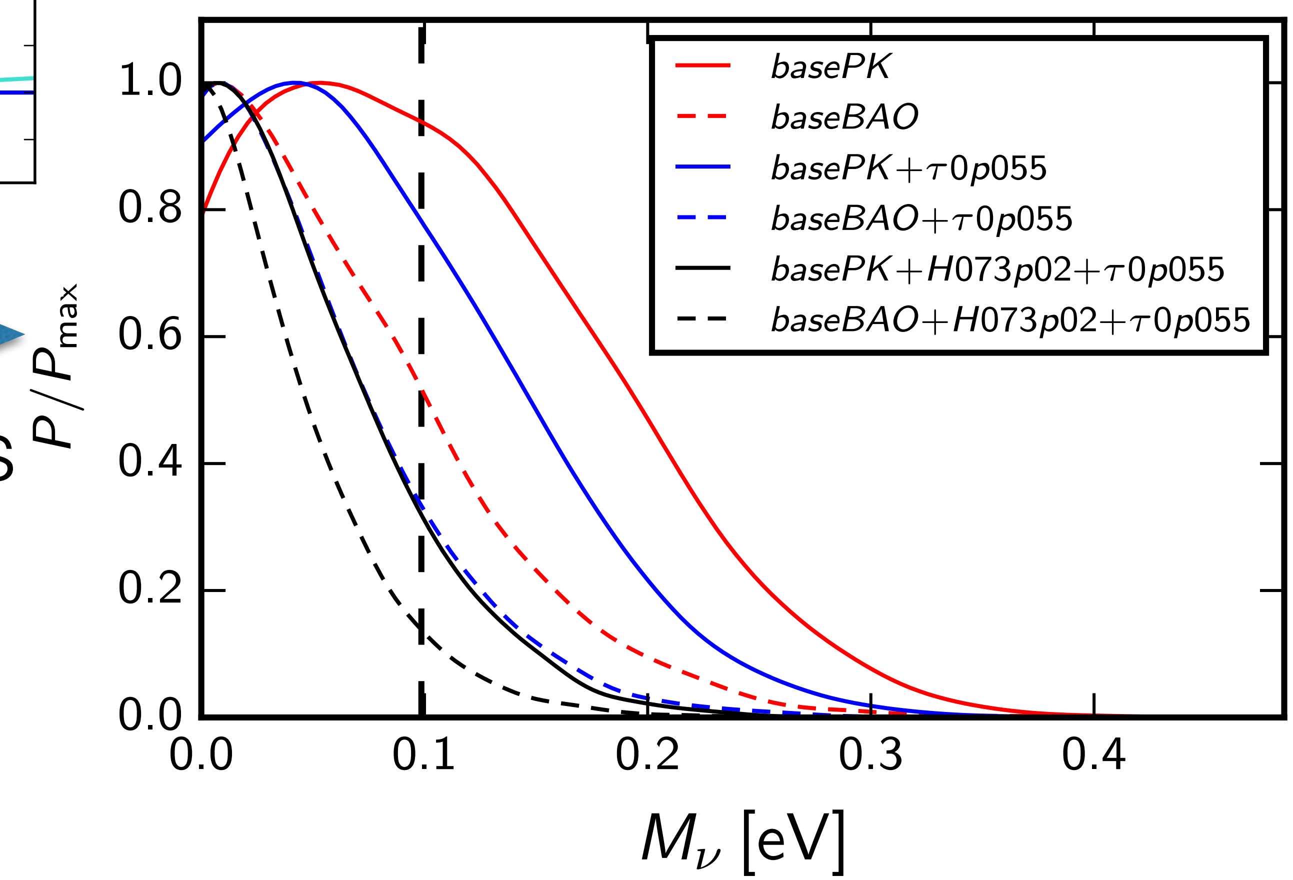


Large scales

Small scales

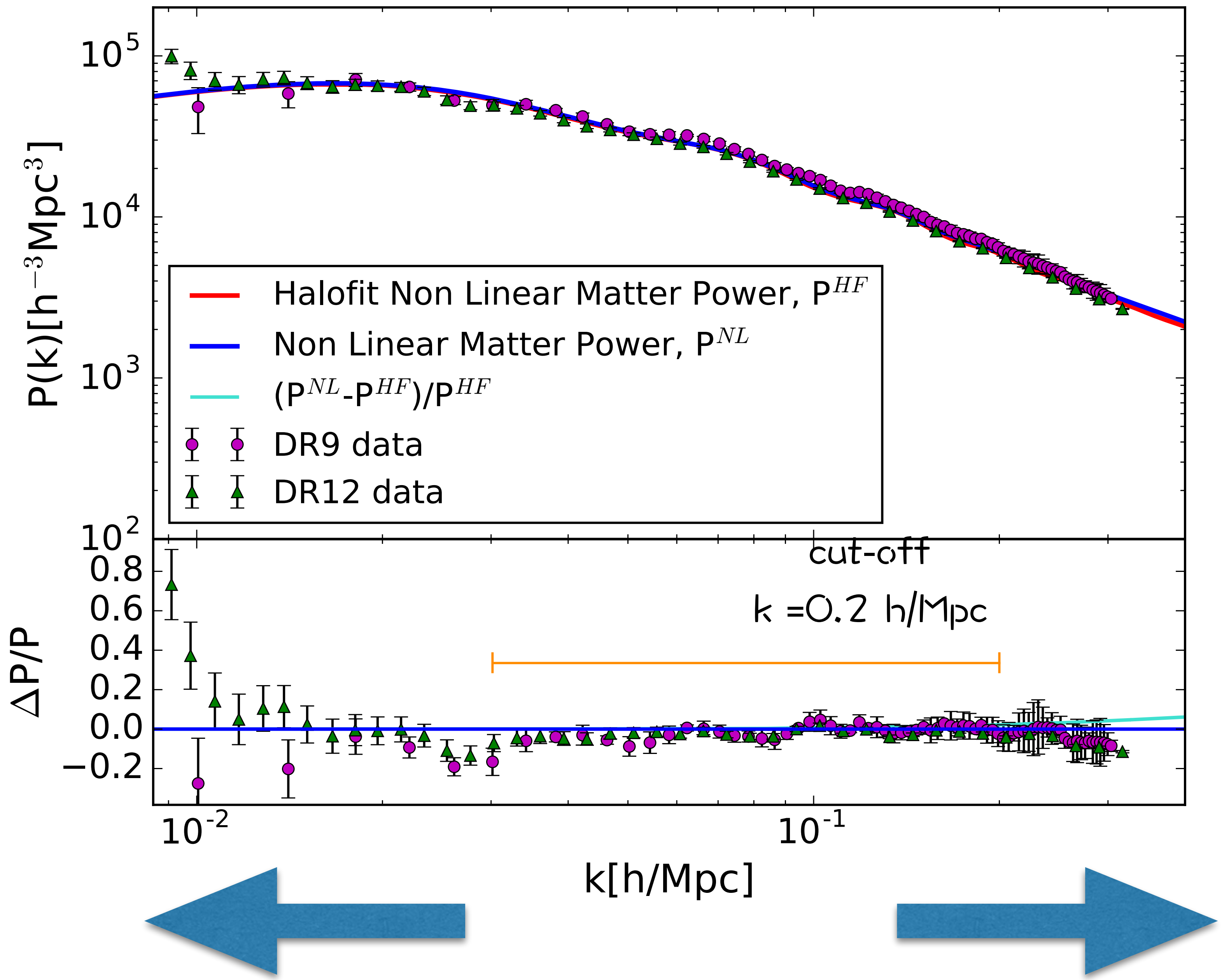
basePK = Planck TT+lowP+ P(k)

baseBAO = Planck TT+lowP+BAO



S. Vagnozzi, **EG**, O. Mena, K. Freese, M. Gerbino, S. Ho, M. Lattanzi 2017, arXiv:1701.08172

Previous approach



Large scales

Small scales

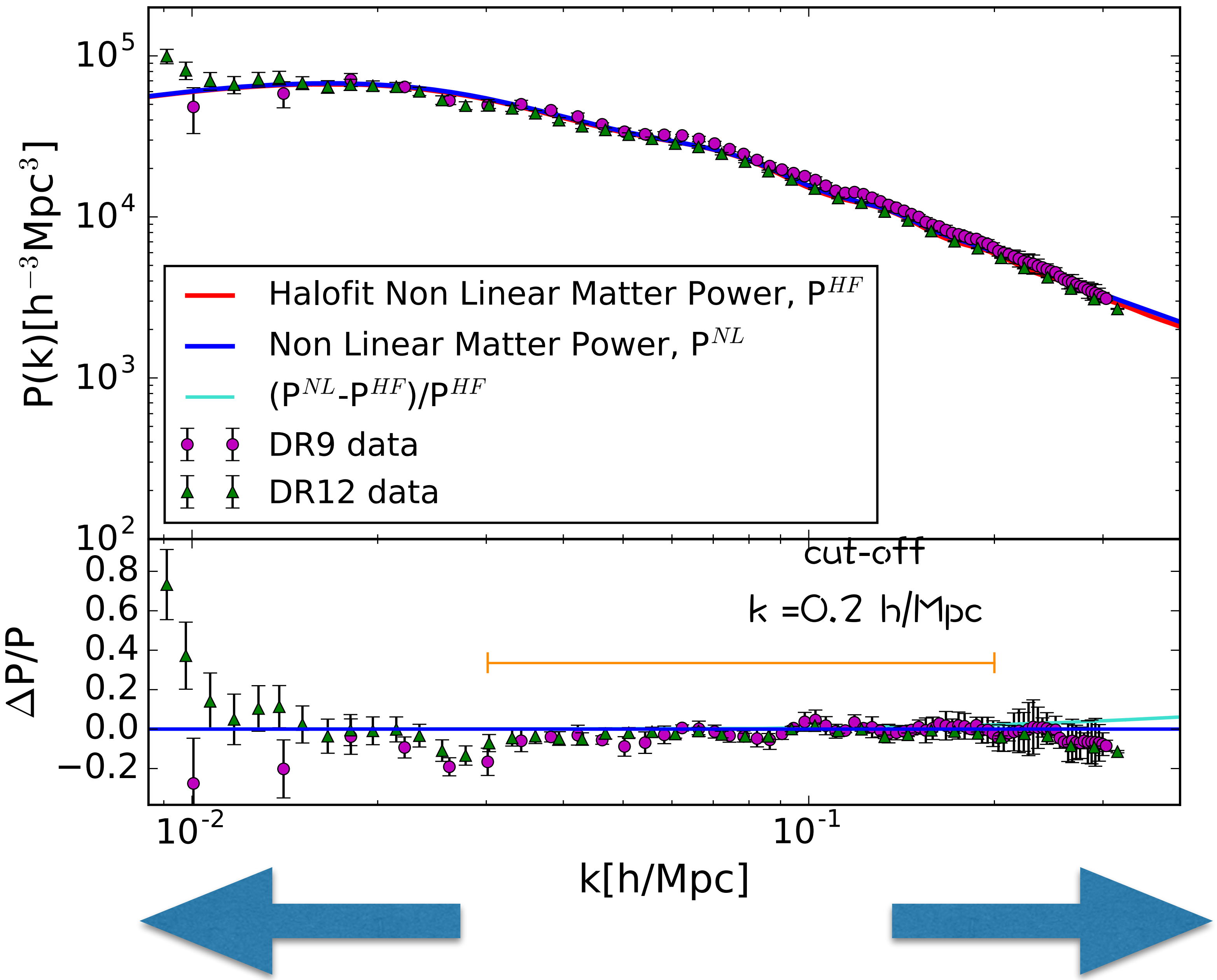
$$P^{g}_{\rm th} = b^2 P^{m}_{\rm HF}(k,z) + P^{\rm s}$$

b=scale-independent bias

$P^{m}_{\mathrm{HF}\nu}$ =non linear matter power-spectrum using HaloFit method

P^{s}=shot-noise

Previous approach



Large scales

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$$P^g_{\rm th} = b^2(k) P^m_{{\rm HF}\nu}(k,z) + P^{\rm s}$$

Scale-dependent bias

New approach: CMB lensing convergence-galaxy density cross-correlation

$$C_\ell^{kg} = \int_{z_0}^{z_1} dz \frac{H(z)}{\chi^2(z)} W^k(z) f_g(z) P_{mg}\left(k = \frac{\ell}{\chi(z)}, z\right)$$

$$W^k(z) = \frac{3\Omega_{m,0}}{2c}\frac{H_0^2}{H(z)}(1+z)\chi(z)\frac{\chi_{CMB} - \chi(z)}{\chi_{CMB}}$$

Kernel for CMB lensing converge

$$P_{mg}(k,z) = b(k)\, P_{mm}(k,z)$$

Matter-galaxy 3D cross- power spectrum

Scale-dependent bias

Scale-Dependence of galaxy bias

- Bias relates the density of galaxies to the underlying dark matter density field.
- It can be expressed as:

$$b(\mathbf{k}) = a_{\text{bias}} + c_{\text{bias}} k^2$$

Scale-independent factor

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- It can be expressed as:

$$b(\mathbf{k}) = a_{\text{bias}} + c_{\text{bias}} k^2$$

Scale-independent factor

$$c_{\text{bias}} = \frac{s}{s_1} b_{11}$$

Scale-dependent factor

Normalization factor: $s = \sigma_0^2$ and $s_j = \sigma_j^2 = \int dk \frac{k^{2+2j}}{2\pi^2} P(k) W^2(kR)$

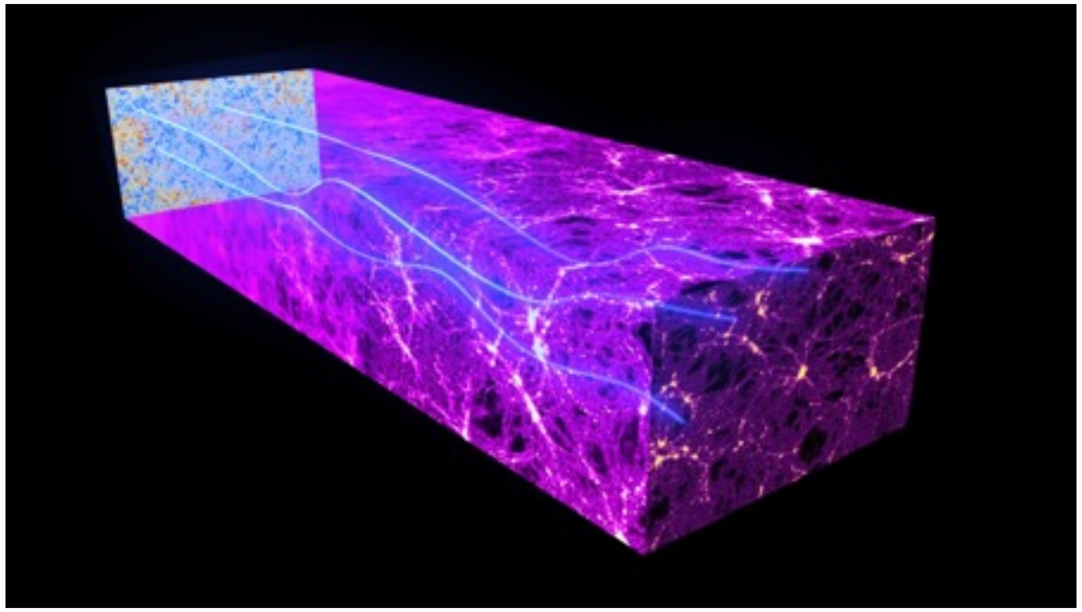
M. Musso, A. Paranjape and R. K. Sheth 2012

Desjacques, Jeong, Schmidt 2016

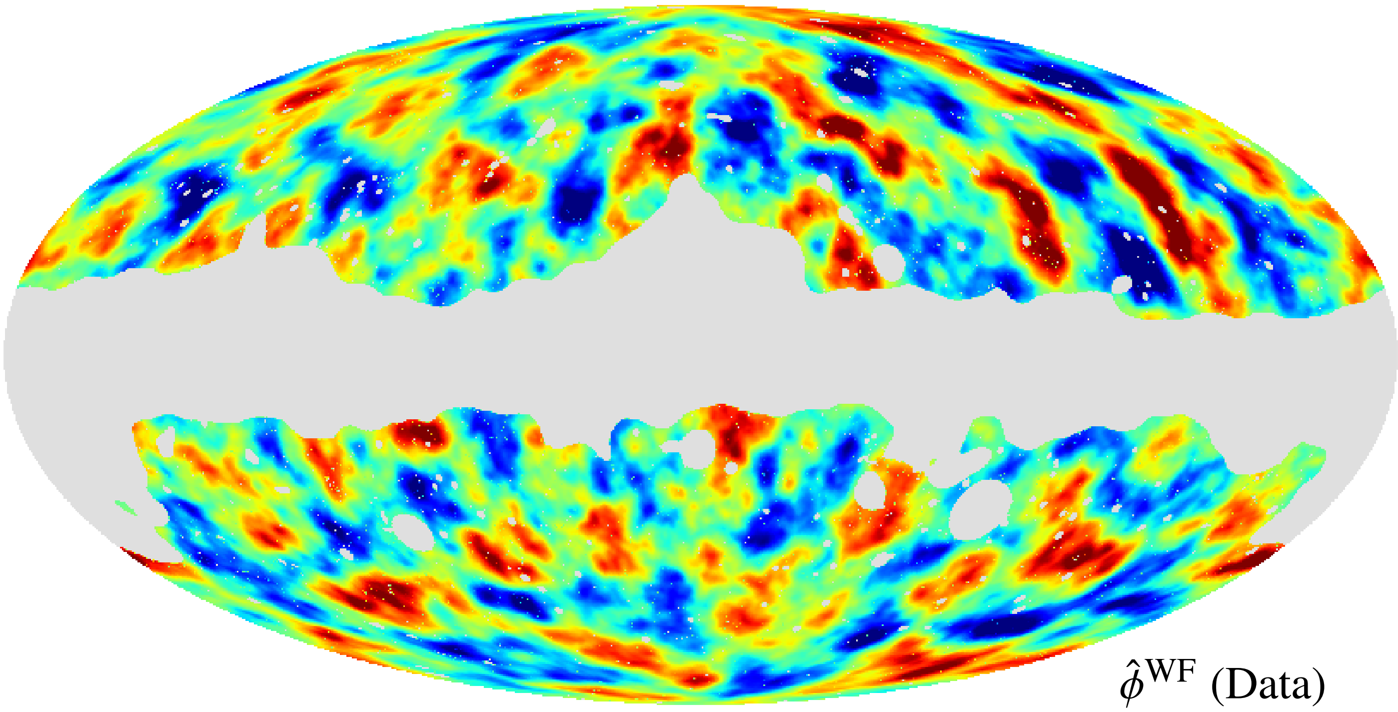
E. Castorina, A. Paranjape and R. K. Sheth 2016

Measurement: Planck CMB lensing

Image Credit: ESA



Planck Collaboration

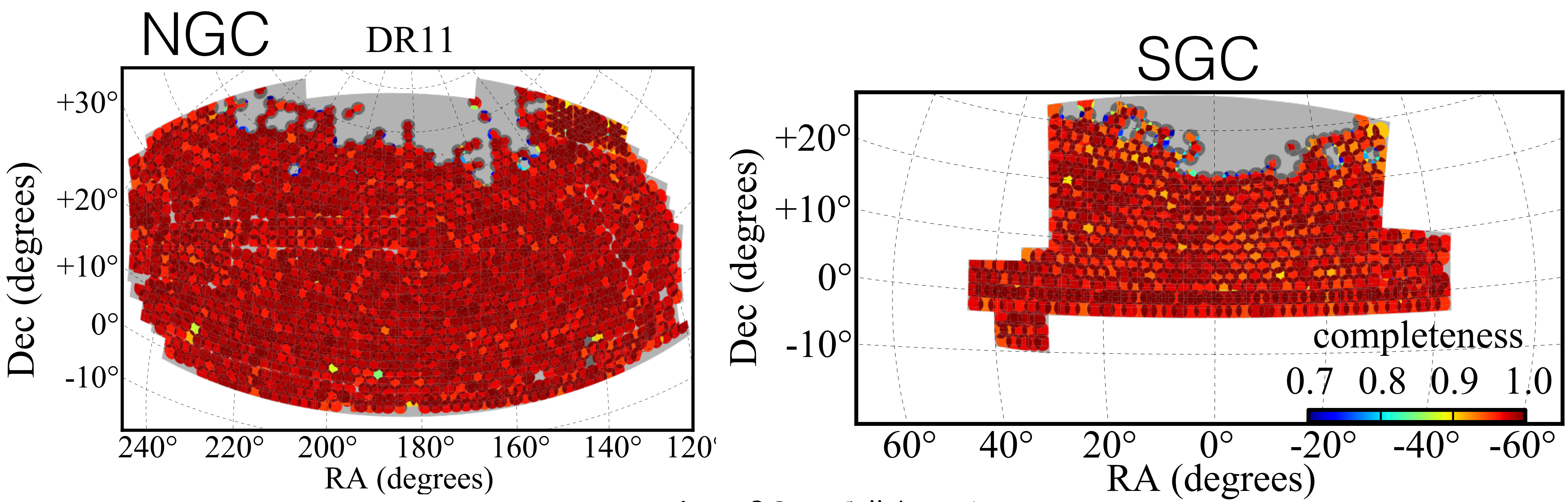


- Lensing convergence map related to the matter over-density:

$$\kappa(\hat{\mathbf{n}}) = \int d\chi\, W^{\kappa}(\chi)\delta(\chi\hat{\mathbf{n}}, z(\chi))$$

- Estimated from CMB temperature, E-polarization maps.
- Covers 70% of sky

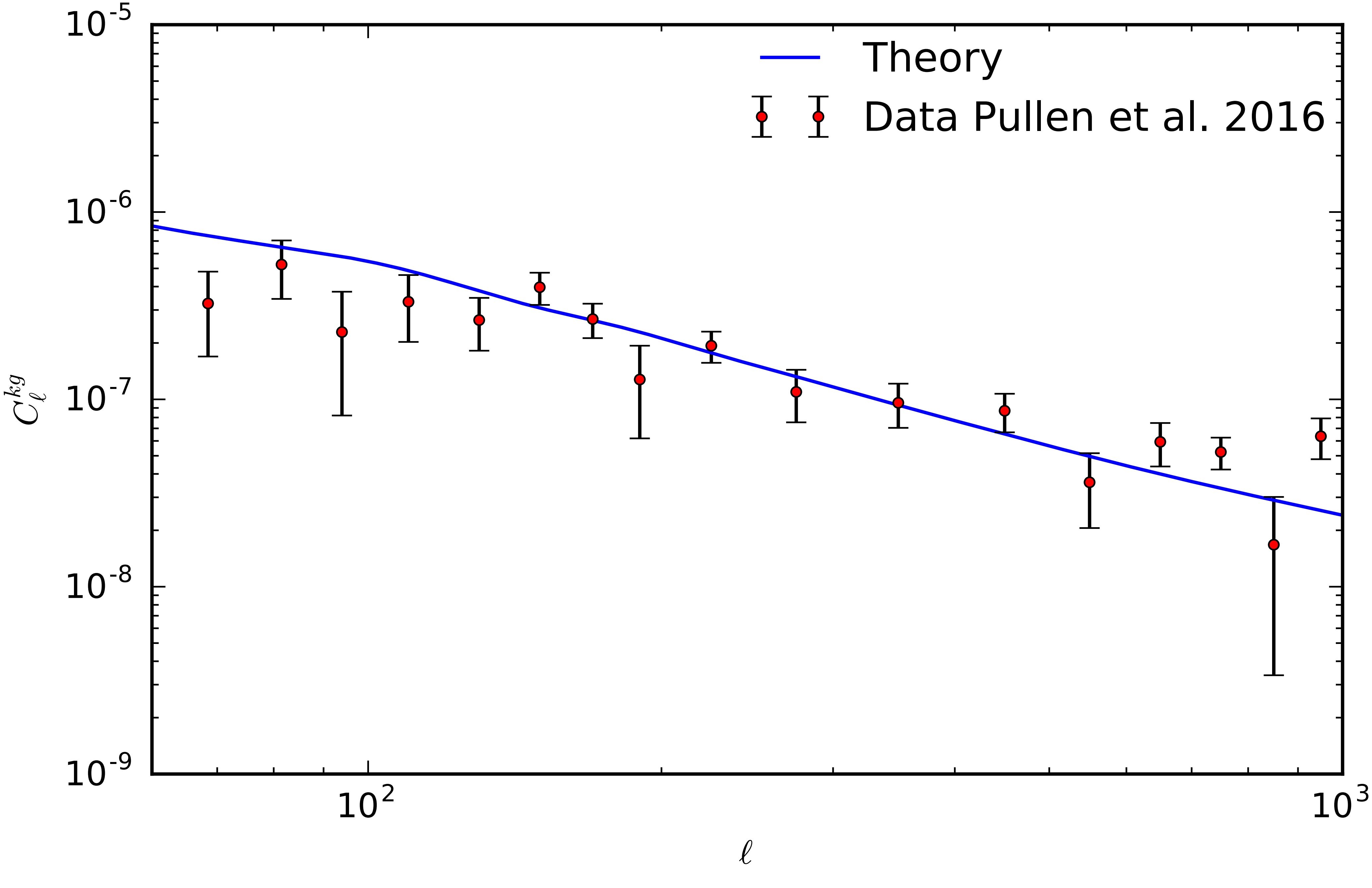
Measurement: CMASS galaxy survey



SDSS-BOSS Collaboration

- CMASS sample consists of 690,826 galaxies over an area of 8498 deg^2. It has a mean redshift of 0.57.
- Redshift range: 0.43-0.7
- Included systematic effects

Measurement:Angular power spectrum



Results using b(k)

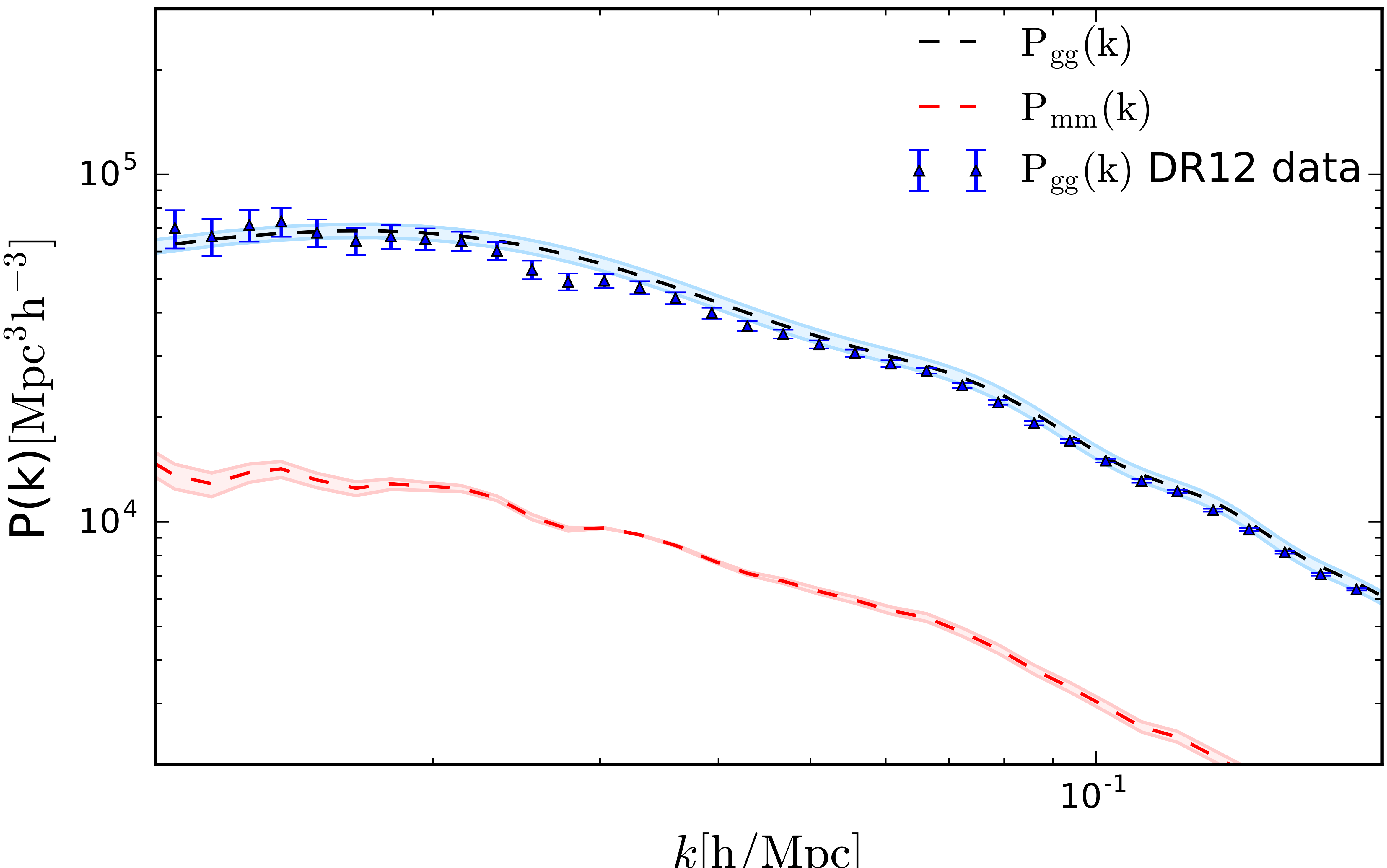
- ΛCDM model described by the six parameters: $\Omega_b h^2$, $\Omega_m h^2$, n_s, θ, τ, A_s + $a_{\rm bias}$ + $c_{\rm bias}$

Results using b(k)

- ΛCDM model described by the six parameters: $\Omega_b h^2$, $\Omega_m h^2$, n_s, θ, τ, A_s + $a_{\rm bias}$ + $c_{\rm bias}$ + M_ν
- DATA:
  - ☑ Planck 2015 full temperature data combined with the large scale polarization measurements, 0<l<29 (Planck TT+lowP)
  - ☑ CMB lensing-galaxy cross-correlation angular power spectrum ($C_\ell^{\kappa g}$)
  - ☑ 3D galaxy power - spectrum from BOSS DR12 CMASS sample: $P^g_{\rm th} = b^2(k) P^m_{{\rm HF}\nu}(k,z) + P^{\rm s}_{{\rm HF}\nu}$, 0.03 h/Mpc<k< 0.2 h/Mpc

Results using b(k)

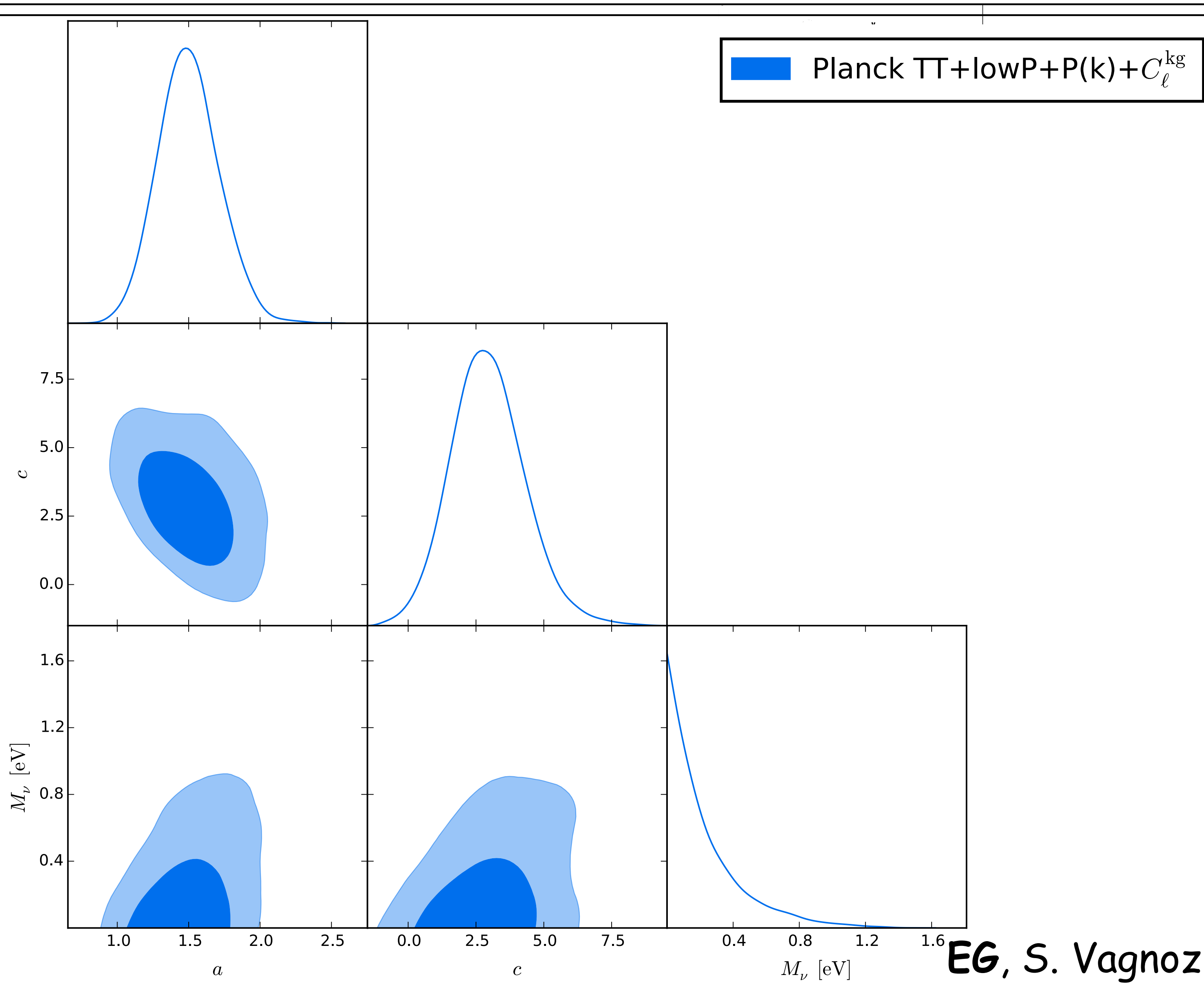
Recovered matter power-spectrum



EG, S. Vagnozzi, S. Ho., S. Ferraro, K. Freese in preparation

Results using b(k)

Dataset	$a_{\rm bias}$ (68% C.L.)	$c_{\rm bias}$ (68% or 95% C.L.)	M_ν [eV] (95% C.L.)
$base \equiv PlanckTT{+}lowP$			< 0.72
$base{+}C_\ell^{\kappa g}$	1.45 ± 0.19	2.65 ± 1.16	**0.06**
	1.52 ± 0.21	2.95 ± 1.35	< 0.73
$base{+}P(k)$	2.27 ± 0.05	< -0.69	**0.06**
	2.30 ± 0.08	< -0.53	< 0.20
$base{+}P(k){+}C_\ell^{\kappa g}$	2.27 ± 0.05	< -0.55	**0.06**
	2.27 ± 0.06	< -0.55	< 0.16



EG, S. Vagnozzi, S. Ho., S. Ferraro, K. Freese in preparation

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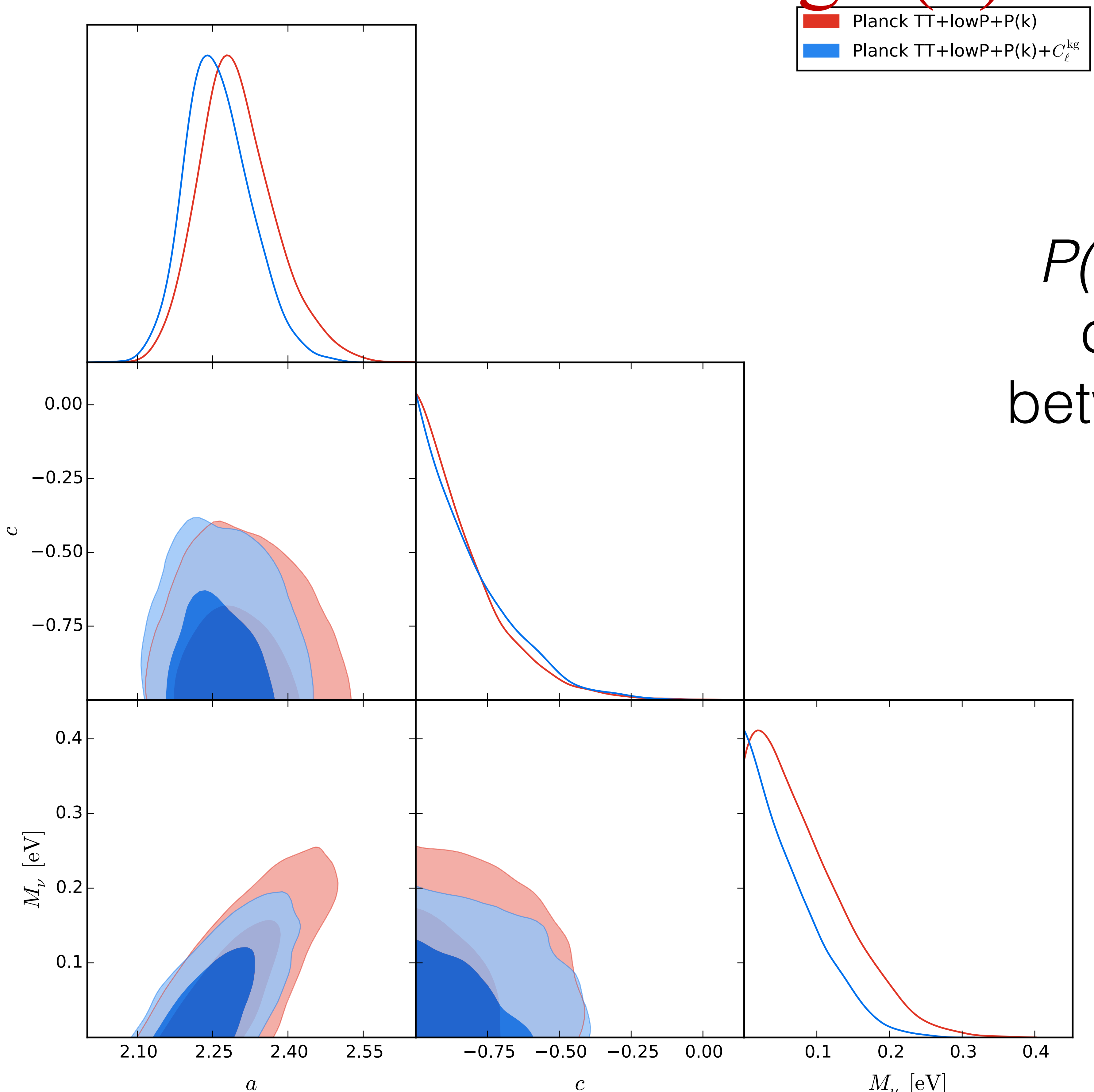

P(k) breaks the degeneracy between b(k) and M_ν

EG, S. Vagnozzi, S. Ho., S. Ferraro, K. Freese in preparation

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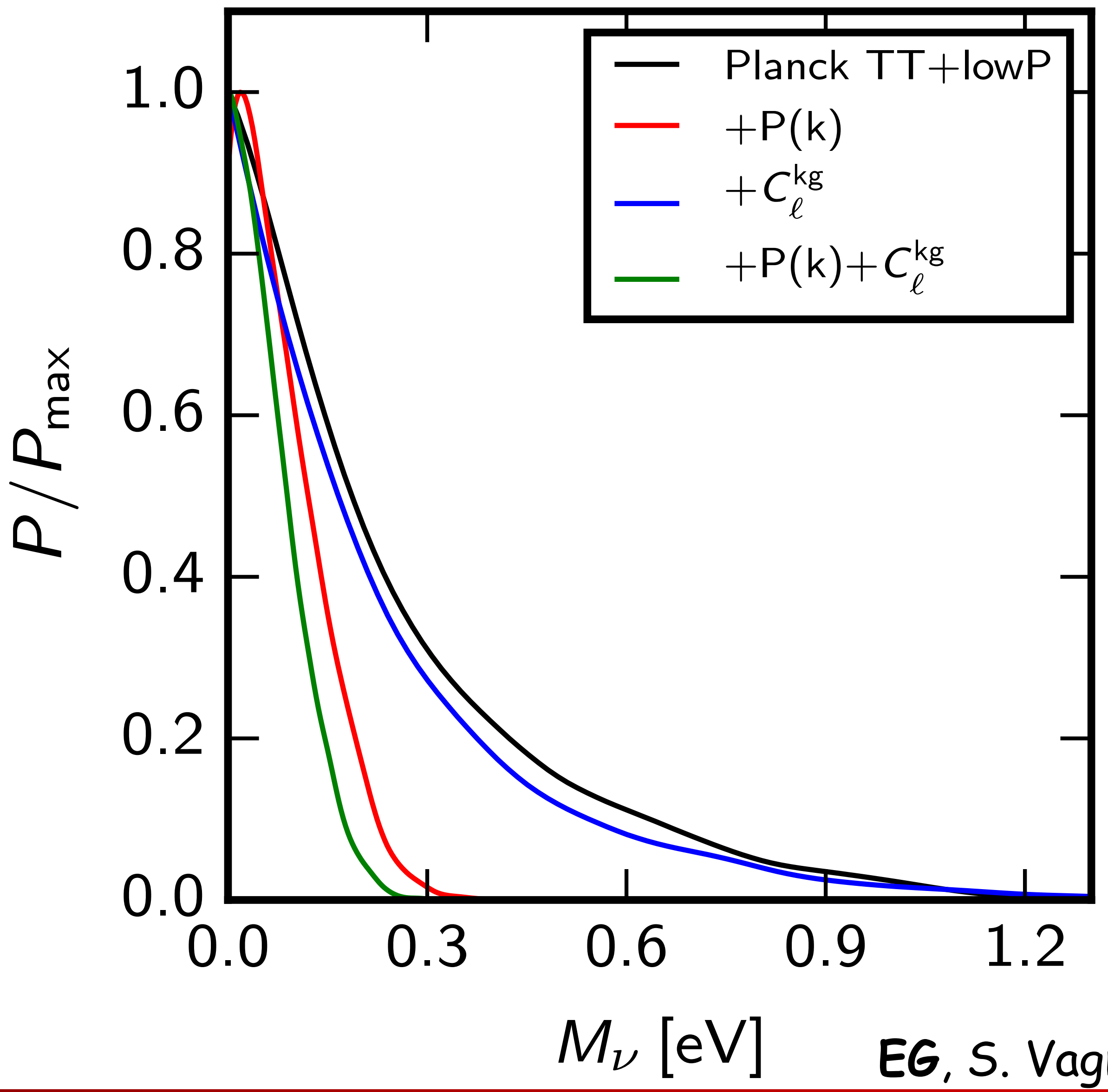

EG, S. Vagnozzi, S. Ho., S. Ferraro, K. Freese in preparation

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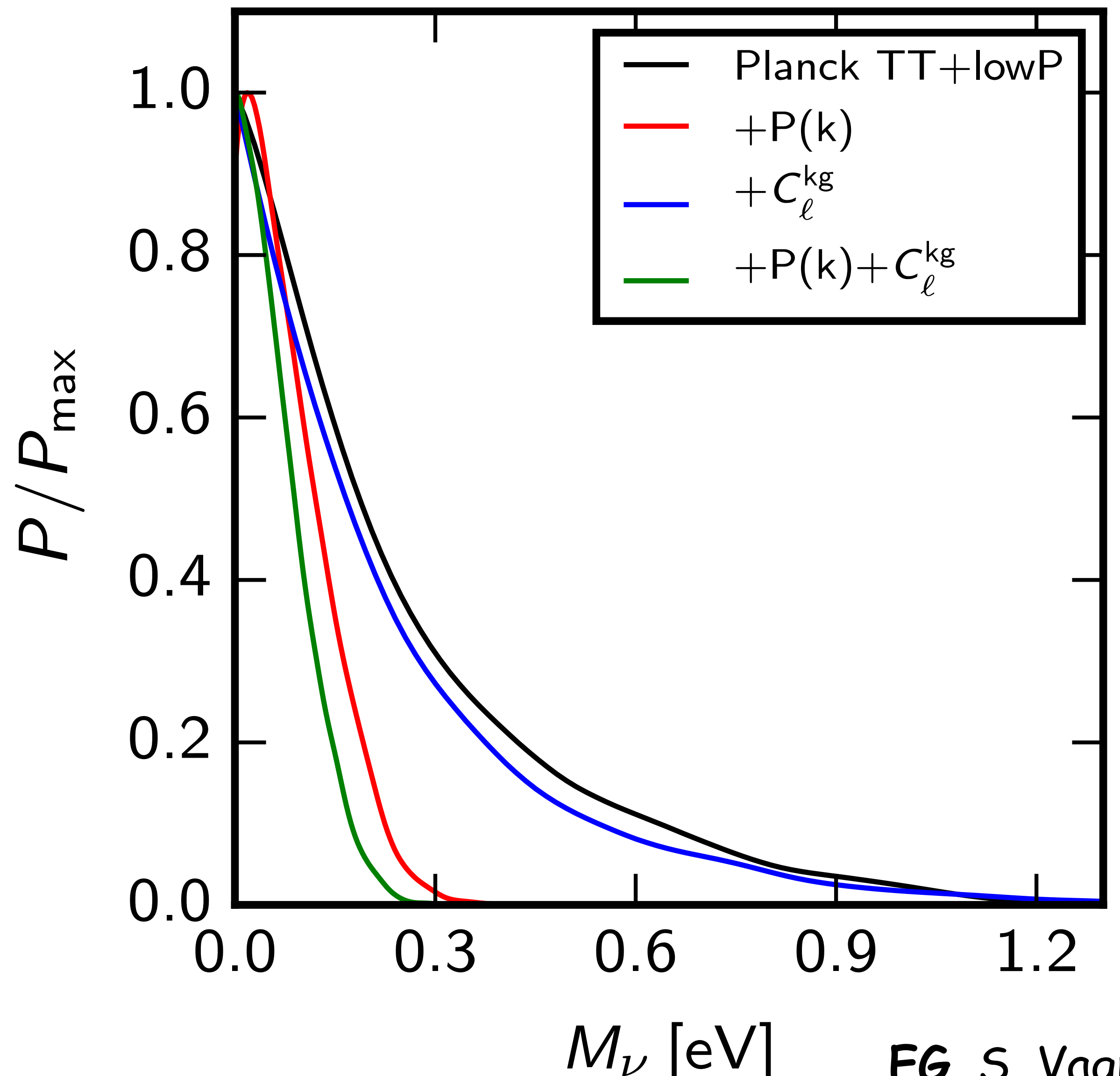


Planck TT+lowP+ShapeDR12 <0.29 eV
Vagnozzi, EG et al, 2017

Planck pol+BAO+ShapeDR12 <0.16 eV
BOSS Collaboration 2016

Planck pol +BAO+Lyα <0.12 eV
Palanque-Delabrouille et al, 2015

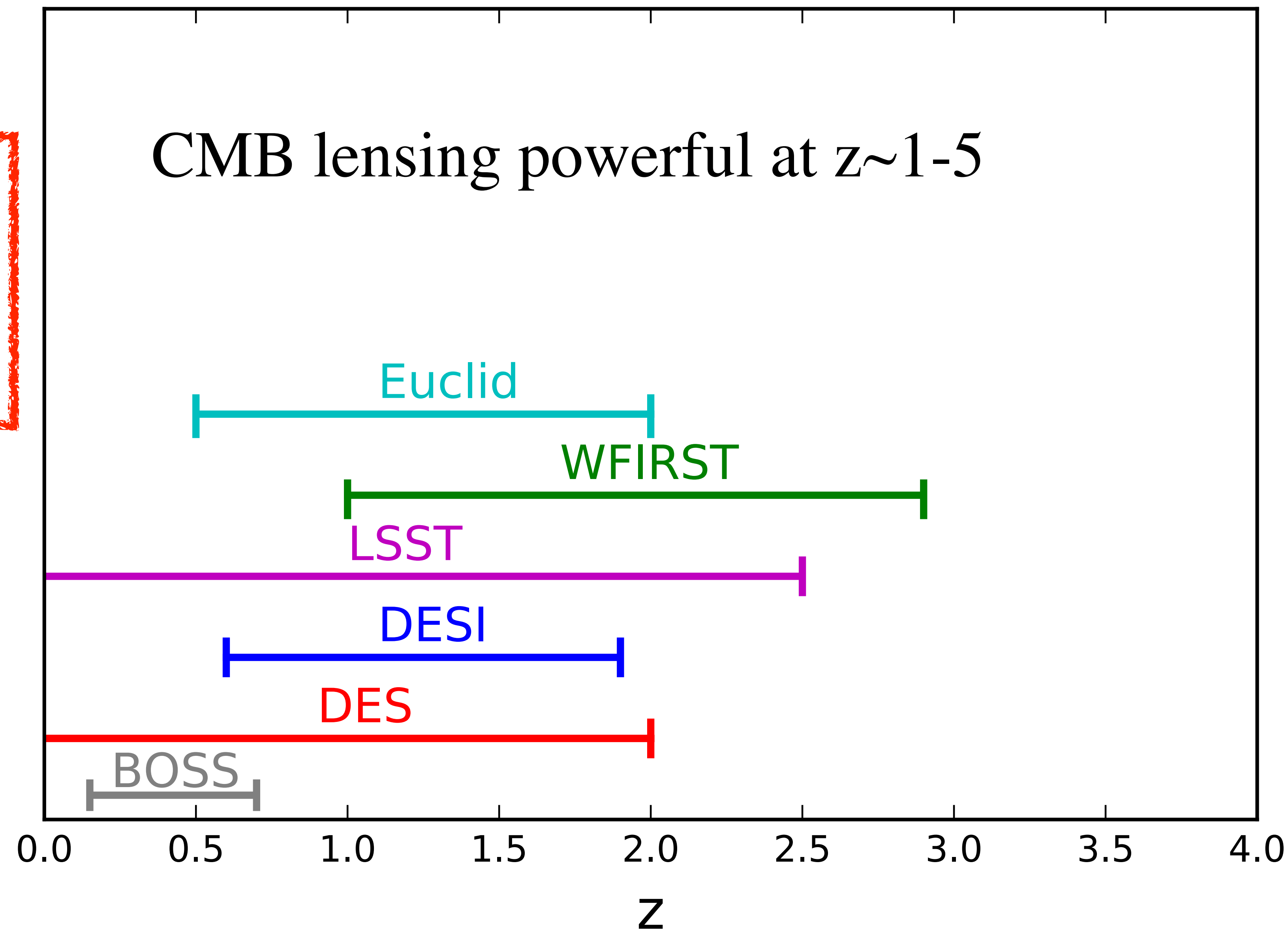
Previous results using scale-independent bias, b

EG, S. Vagnozzi, S. Ho., S. Ferraro, K. Freese in preparation

What is the advantage of C_l^{kg} ?

- $C_\ell^{\kappa g}$ sensitive to the cosmological parameters which are affected by scale-dependent bias of the tracers.

We can apply this method to future surveys of galaxies



Conclusions

- ✓ The cross-correlation between CMB lensing and large-scale structure provides a tool to recover the true matter power spectrum (constraining b(k)).

- ✓ It is powerful in constraining cosmological parameters that are affected by scale-dependent bias of the tracers, such as massive neutrinos.

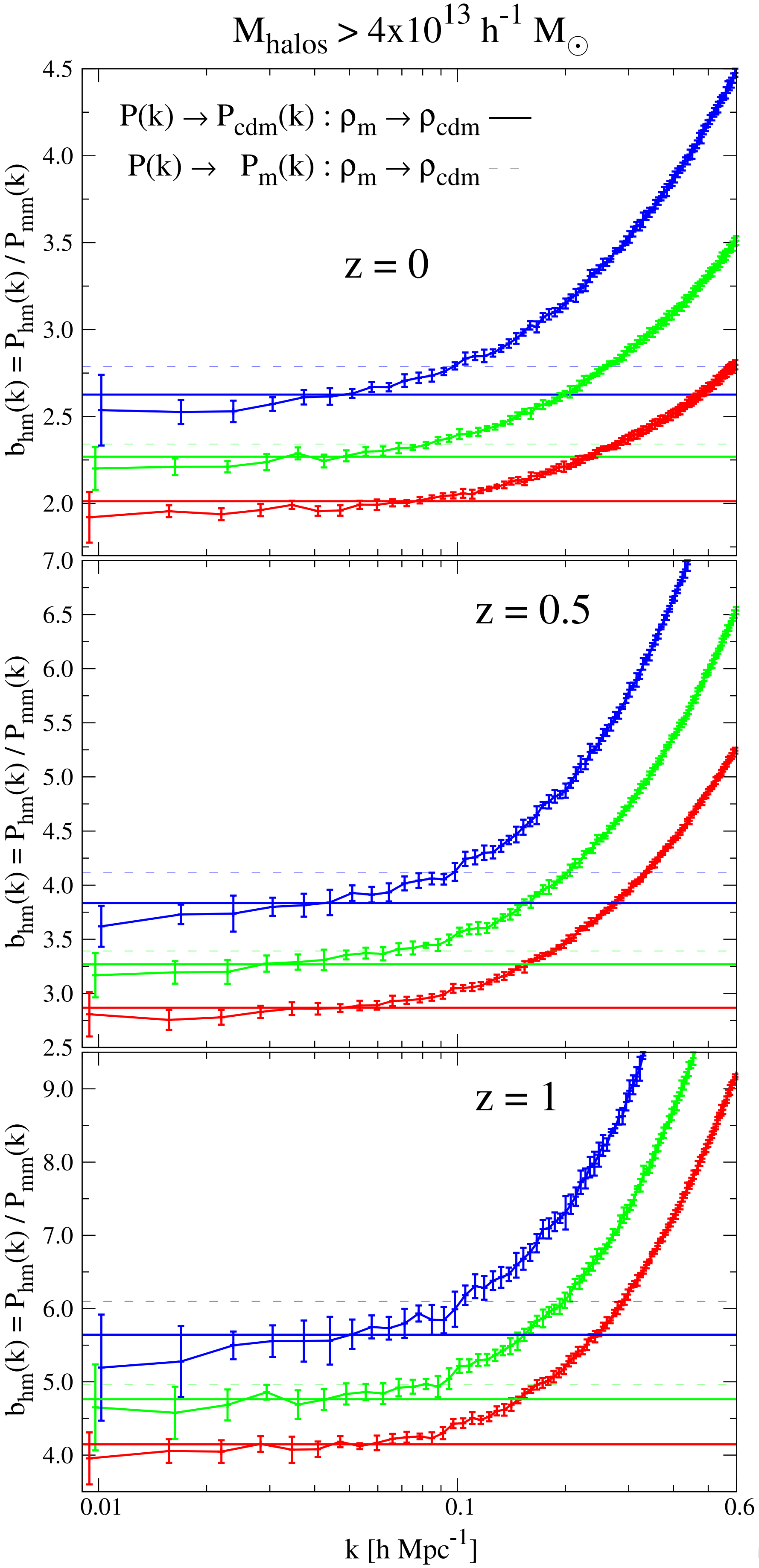
- ✓ Test cosmological models: dark energy, modified gravity…

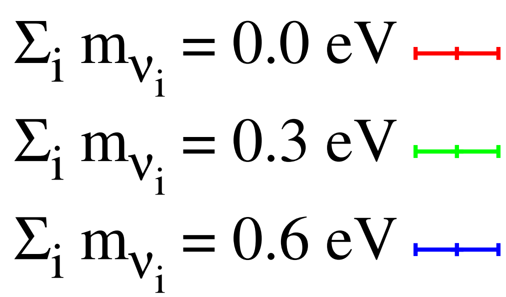
- ✓ Future CMB lensing + Galaxy spectroscopic surveys (e.g. CMB-stage IV+DESI) could constrain models of galaxy formation using more sophisticated bias modeling. Modi, White, Vlah 2017

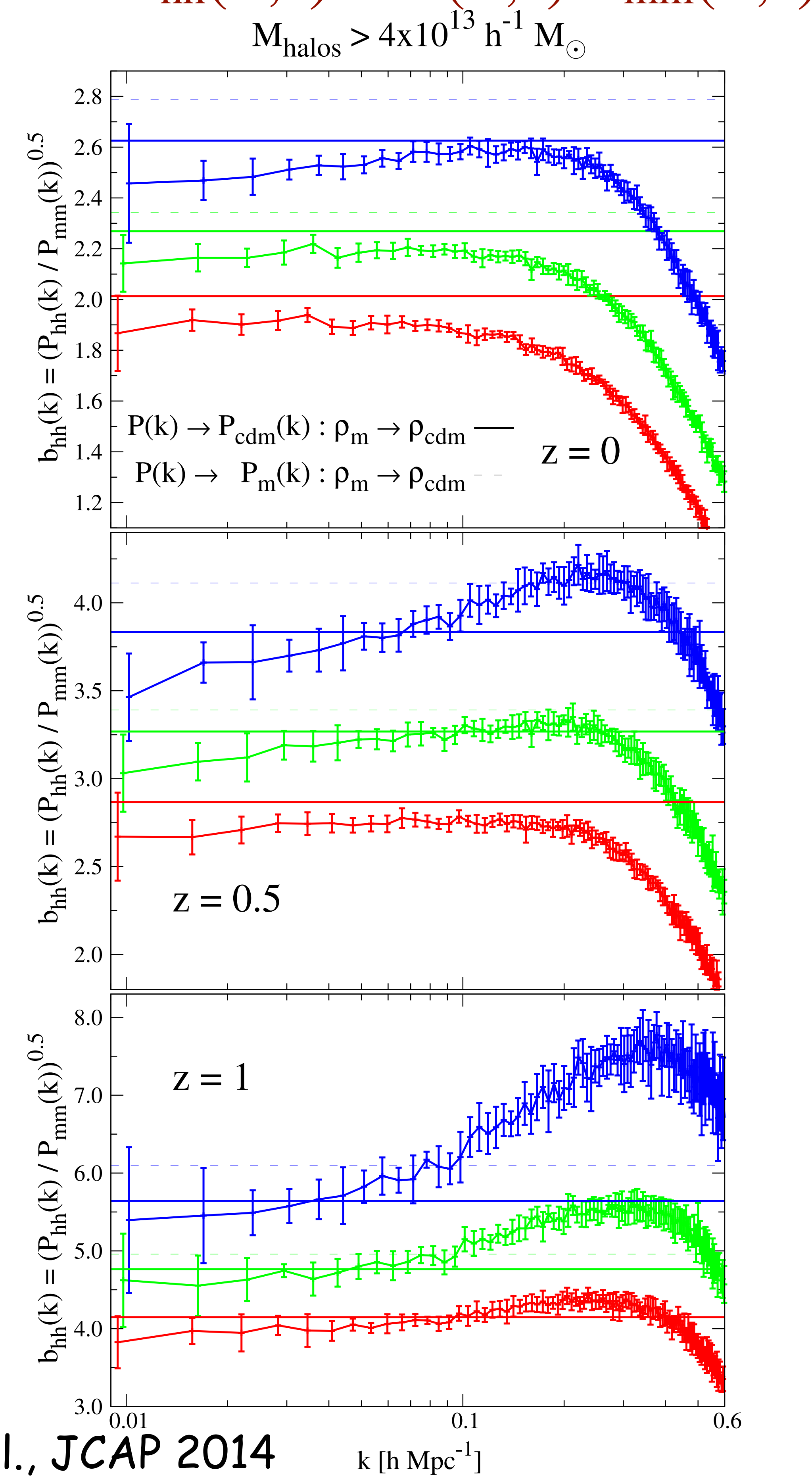
Thank you!

From halo-matter cross-power spectrum: $P_{hm}(k,z) = b(k,z)\, P_{mm}(k,z)$

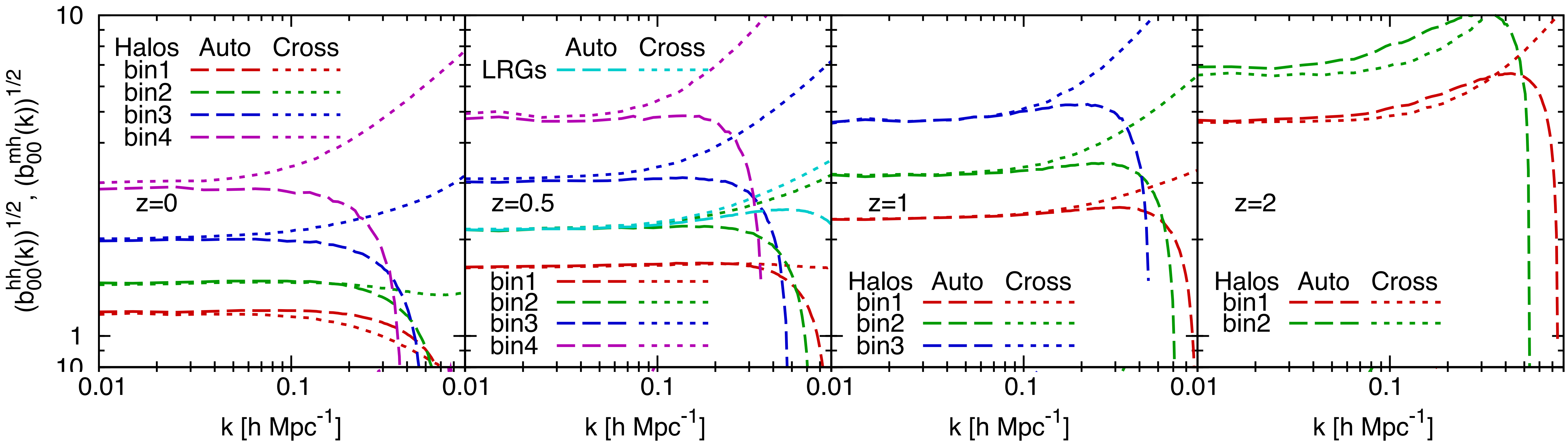
From halo-halo auto-power spectrum: $P_{hh}(k,z) = b^2(k,z)\, P_{mm}(k,z)$







F. Villaescusa-Navarro et al., JCAP 2014



T. Okumura, U. Seljak and V. Desjacques, JCAP 2012

- Can constrain stochasticity $\epsilon(\mathbf{x}, z)$:

$$\delta_g(\mathbf{x}, z) = b\delta_m(\mathbf{x}, z) + \epsilon(\mathbf{x}, z)$$

- Stochastic component $\epsilon(\mathbf{x}, z)$ due to discrete sampling and physical processes affecting halo and galaxy formation

Estimator

Angular power spectra estimated in 11 flat band-powers using the pseudo estimator:

$$\hat{C}_\ell^{\kappa g} = \frac{1}{(2\ell+1) f_{\rm sky}^{\kappa g}} \sum_{m=-\ell}^{\ell} g_{\ell m} \kappa^*_{\ell m}$$

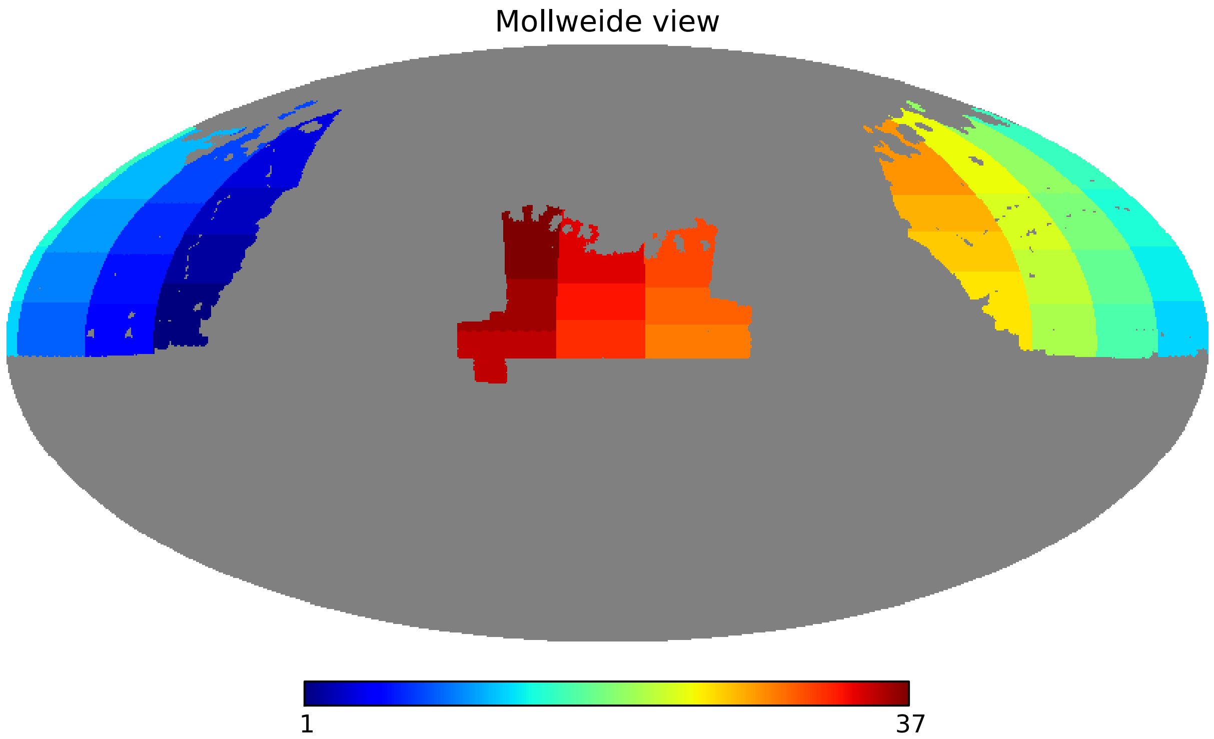
$f_{\rm sky}^{\kappa g}$ = sky fraction common to the galaxy catalog and the CMB lensing convergence map

$\kappa_{\ell m}$ = spherical harmonic transform of the CMB lensing convergence field

$g_{\ell m}$ = spherical harmonic transform of the galaxy overdensity field

ERRORS:

Jackknife resampling of 37 regions in CMASS survey area



$$b_1(\mathbf{k}) = b_{10} + \frac{sb_{11}}{s_1}k^2$$

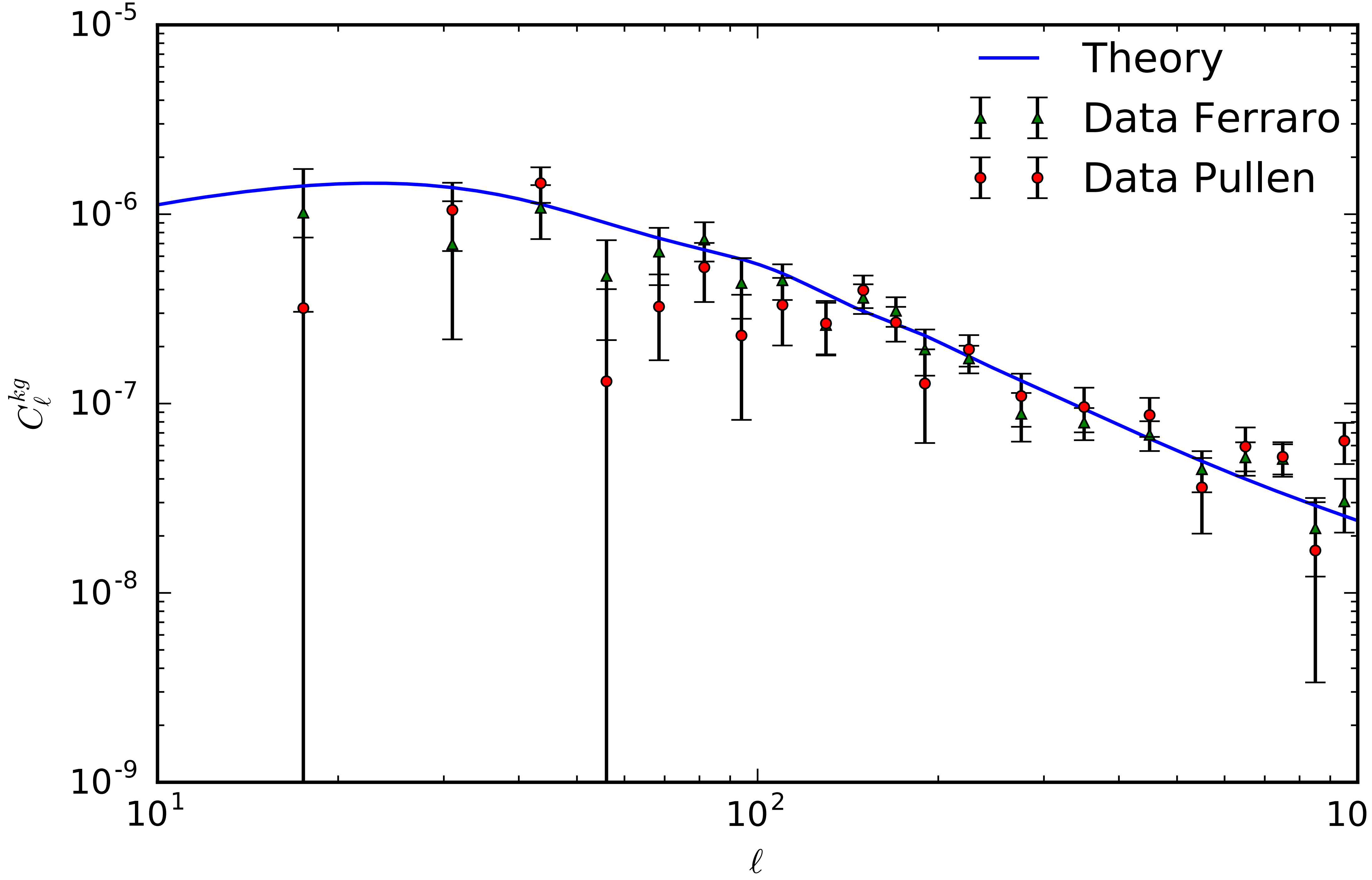
$$s_j = \sigma_j^2 = \int \frac{dk}{k}\frac{k^3P(k)}{2\pi^2}k^{2j}W^2(kR)$$

Relation between b_{11} and b_{10}

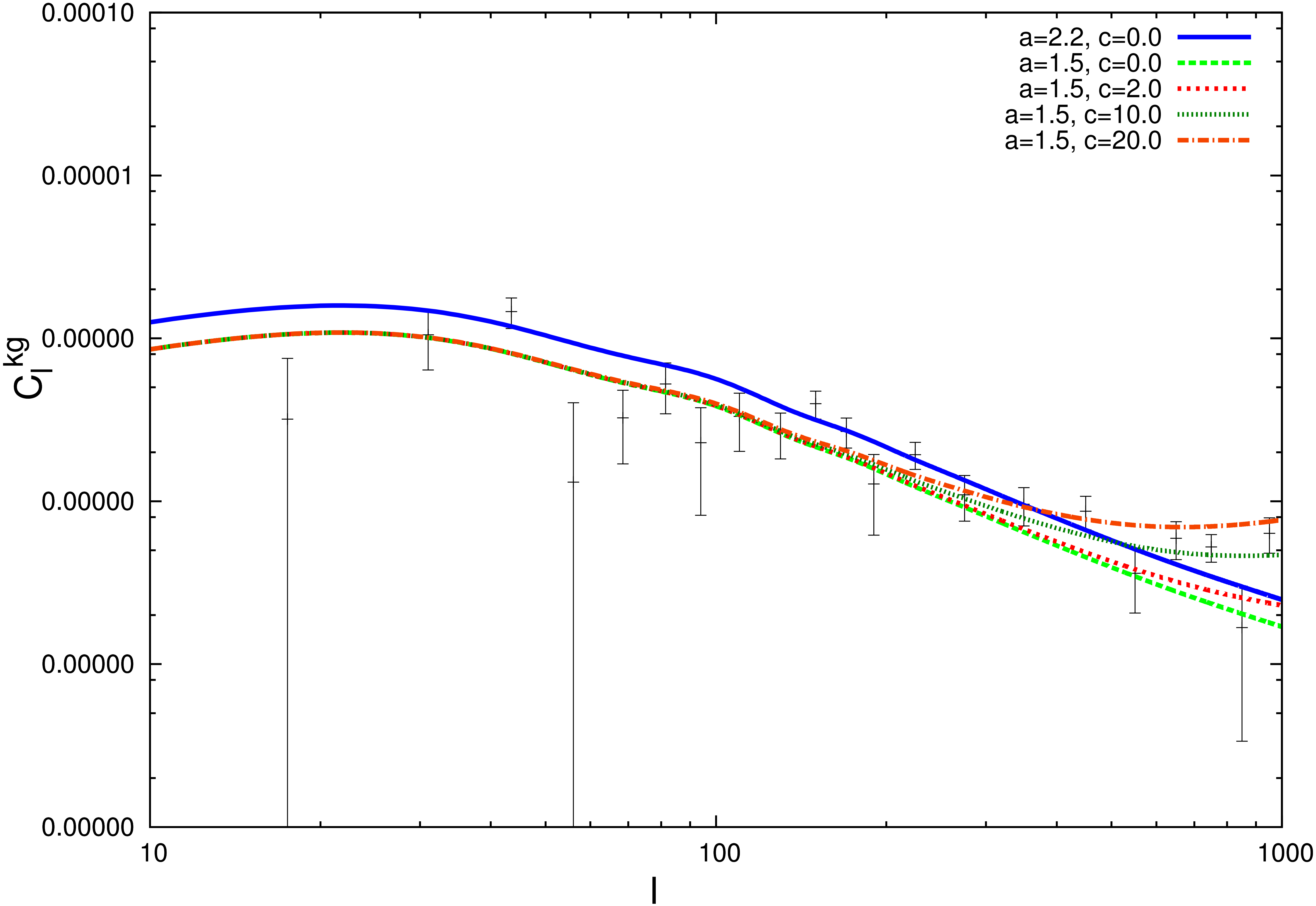
$$b_{11} = \frac{\nu^2}{\delta_c} - b_{10} \qquad \nu^2 = \frac{\delta_c^2}{s}$$

$\delta_c = 1.686$ Critical density associated with halos

$$b_{11} = \frac{\delta_c}{s} - b_{10}$$



Theory
Data Ferraro
Data Pullen
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
C_ℓ^{kg}
10^{1}
10^{2}
10^{3}
ℓ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a=1.5, c=0.0
a=1.5, c=2.0
a=1.5, c=10.0
a=1.5, c=20.0
0.00010
0.00001
0.00000
0.00000
0.00000
0.00000
C_l^{kg}
10
100
1000
l