LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Excellence Cluster Universe

Combining clustering & counts of galaxy clusters

Cosmology and PNG with maxBCG sample

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Outline

- Introduction
- SDSS **maxBCG** catalogue and data
- **Theoretical modelling:**
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  - Counts and total masses
  - Power Spectrum
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- **Monte Carlo Markov Chain** analysis
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- Conclusions

Introduction

Why/how cosmology with galaxy clusters?

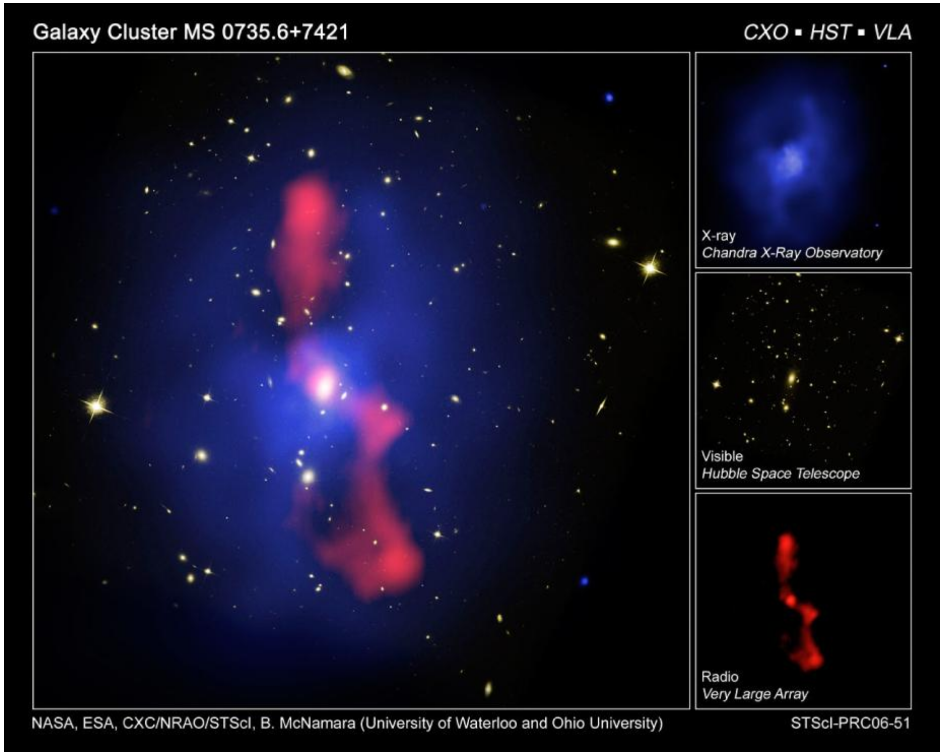
WHY?

They probe the **expansion** of the Universe and the **growth rate** of cosmic structures.

HOW?

Measuring cluster statistics as function of **mass proxy** (optical richness, X-ray properties, SZ signal, …) and redshift.

CONSTRAINTS on COSMOLOGY and M-M_{obs} RELATION

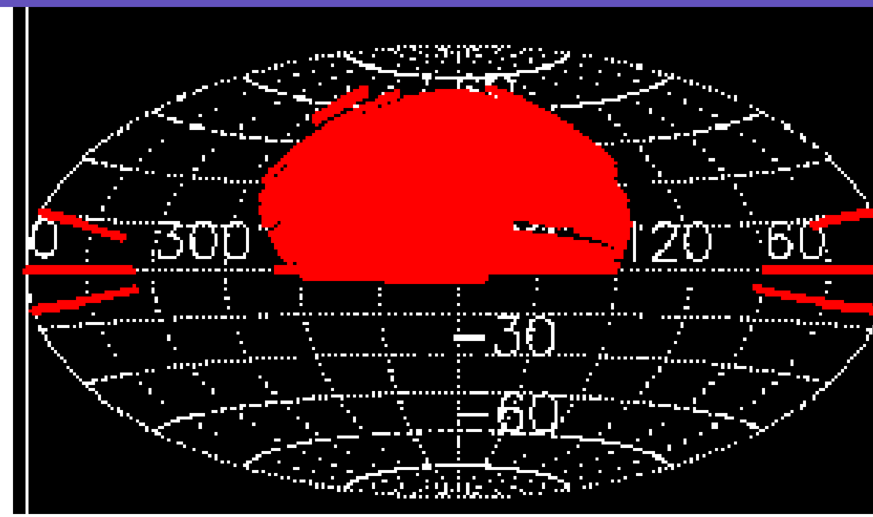


Composite image of galaxy cluster MS0735.6+7421. Optical: HST; X-ray: Chandra X-ray Observatory; Radio: Very Large Array telescope. Credit: NASA, ESA, CXC, STScI, B. McNamara; NRAO, L. Birzan and team.

SDSS* maxBCG catalogue

SDSS Data Release 5

Sloan Digital Sky Survey



SDSS DR5 Imaging Sky Coverage (Aitoff projection of Equatorial coordinates). Credit: SDSS webpage.

maxBCG sample:

[Koester et al. 2007]

- Optically selected clusters by the **red-sequence detection method**
- **13,823** clusters
  500 Mpc^3 covering 7,398 deg^2 of sky
  $\mathbf{z_{photo} \in [0.1,0.3]}$
  $10 < N_{200} < 190$
  $M_{lim} \sim 7\times10^{13}\ h^{-1}M_{\odot}$

*www.sdss.org

MaxBCG Counts and WL masses

- **Observable:** **optical richness N_{200} = nr. of red galaxies within R_{200}**

- **Number counts**

  [Rozo et al. 2010]

  $11 < N_{200} < 120$

  $7\times10^{13}\ h^{-1}M_\odot < M < 1.2\times10^{15} h^{-1}M_\odot$

  Poisson errors + sample variance + uncertainty on purity/completeness

Richness	No. of Clusters
11-14	5167
14-18	2387
19-23	1504
24-29	765
30-38	533
39-48	230
49-61	134
62-78	59
79-120	31

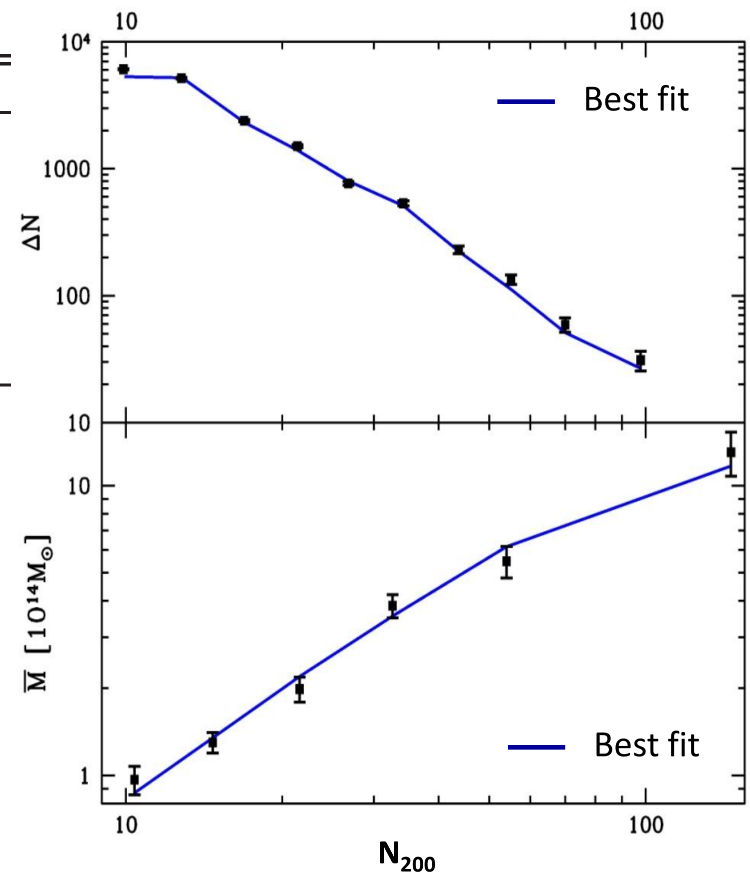
- **Weak Lensing masses**

  [Sheldon et al. 2009, Johnston et at. 2007]

  $12 < N_{200} < 300$

  ~ 10% errors + offset factor β with a prior width of 6%

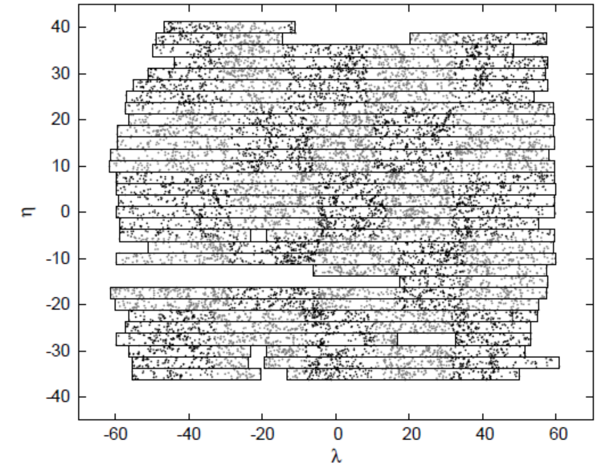
Richness	$\langle M_{200b} \rangle\ [10^{14}\ M_\odot]$
12-17	1.298
18-25	1.983
26-40	3.846
41-70	5.475
71+	13.03



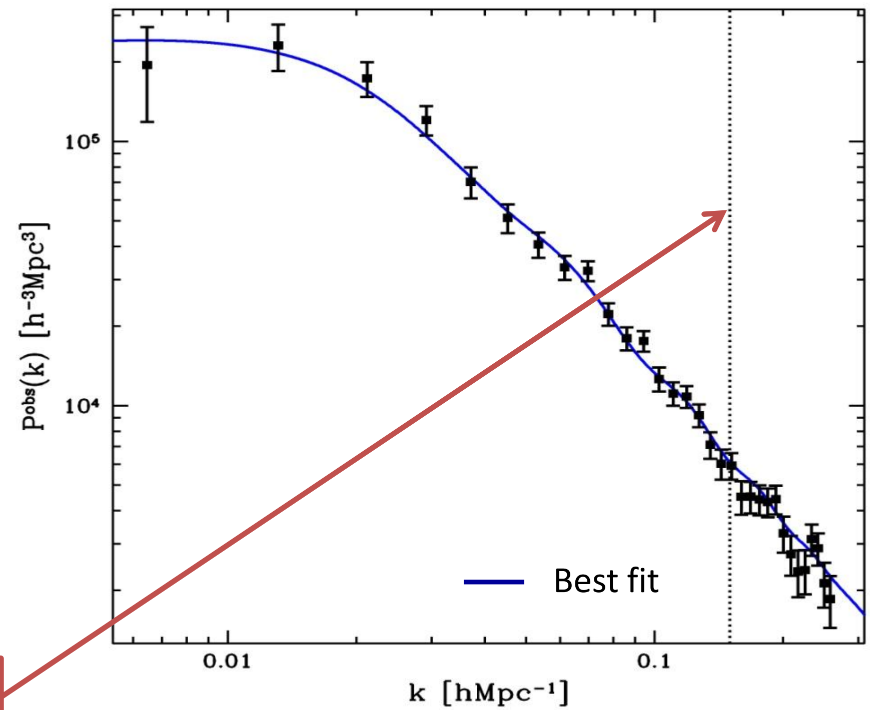
MaxBCG Power Spectrum

- **Power spectrum** *[Hütsi 2010]*

1. Determination of **survey selection function** by a random catalog with 1,261,600 objects.
2. Calculation of **overdensity field** on a grid using TSC *[Hockney & Eastwood 1988]* mass assignment scheme.
3. **FFT** of the gridded overdensity field.
4. The raw 3D power spectrum is the **modulus squared of the FFT**.
5. Subtraction of the **shot noise**.
6. Recovery of the angle averaged spectrum using a modified version of iterative scheme of *Jing (2005)*.
7. Error estimates: FKP *[Feldman et al. 1994]*, **Monte Carlo** and 'jackknife'.
8. Negligible off-diagonal covariance between clustering and counts.



Top: Ang. distribution of maxBCG clusters and angular mask. Credit: Hütsi (2010).
Bottom: P(k) data and our best fit model.



Quasi-linear regime only: k_{max} = 0.15 $hMpc^{-1}$

Theoretical modelling: mass-richness relation

Probability of observing N^{obs}_{gal} member galaxies given the true mass M

$$p(N_{\rm gal}^{\rm obs}|M) = \int p(N_{\rm gal}^{\rm obs}|N_{\rm gal})\, p(N_{\rm gal}|M)\, dN_{\rm gal}$$

Delta function

$$p(N_{\rm gal}^{\rm obs}|N_{\rm gal}) = \frac{1}{\sqrt{2\pi\sigma^2_{\ln N_{\rm gal}^{\rm obs}|M}}} \exp[-x^2(N_{\rm gal}^{\rm obs})]$$

$$x(N_{\rm gal}^{\rm obs}) = \frac{\ln N_{\rm gal}^{\rm obs} - \ln N_{\rm gal}(M)}{\sqrt{2\sigma^2_{\ln N_{\rm gal}^{\rm obs}|M}}}$$

[Lima, Hu 2005]

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[Lima, Hu 2005]

- **Power law in mass** *[Rozo et al. 2010, Johnston et al. 2007]*, fitted by fixing 2 pivot points in mass ($M_1=1.3\times10^{14}M_{\odot}$, $M_2=1.3\times10^{15}M_{\odot}$)

$$\ln M = \ln M_{200|20} + \alpha_N \ln(N_{gal}/20)$$

with scatter $\sigma_{\ln M|N^{obs}_{gal}} = 0.45^{+0.20}_{-0.18}$

[Rozo 2009]

Intercept (mass of a cluster with 20 member galaxies)

slope

Theoretical modelling: Number Counts

- **Tinker**'s universal **mass function** *[Tinker et al. 2010]*

Expected nr. density of virialized DM haloes

$$\frac{dn(M,z)}{d\ln M} = \bar{\rho}_m \left| \frac{d\ln\sigma^{-1}}{dM} \right| f(\nu)$$

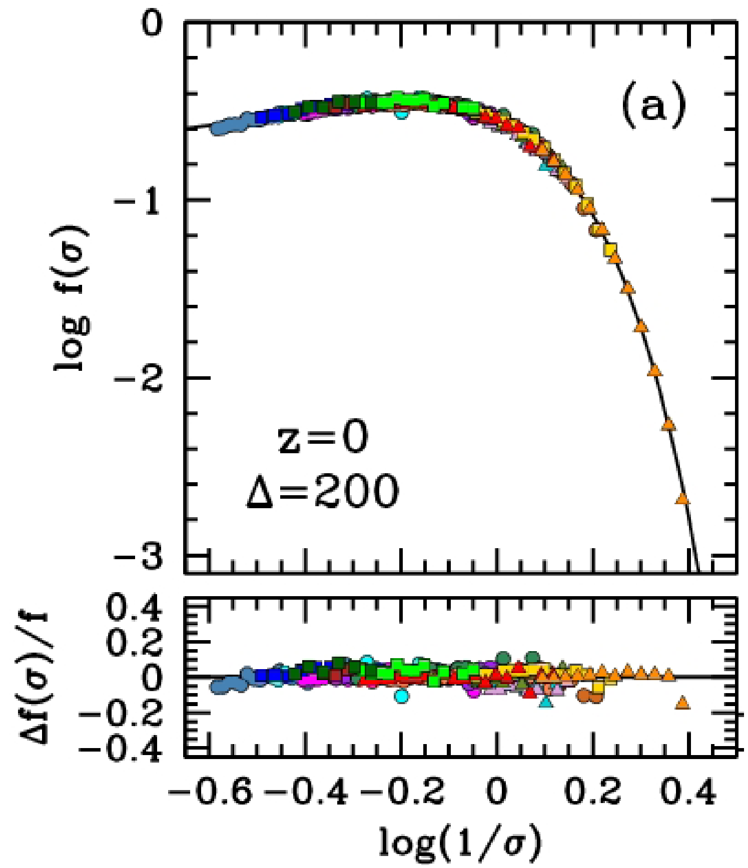
mean matter density

$$f_T(\nu) = 0.368 \left[1 + \left(\hat{\beta}\nu\right)^{-2\hat{\phi}} \right] \nu^{2\hat{\eta}+1} e^{-\hat{\gamma}\nu^2/2}$$

$$\nu = \frac{\delta_c}{\sigma(M)}$$

$$\hat{\beta} = 0.589\,(1+z)^{0.20}\,, \quad \hat{\phi} = -0.729\,(1+z)^{-0.08}\,,$$

$$\hat{\eta} = -0.243\,(1+z)^{0.27}\,, \quad \hat{\gamma} = 0.864\,(1+z)^{-0.01}\,.$$



Mass function calibrated with simulations.
Credit: Tinker et al. (2008).

Theoretical modelling: Number Counts

- Clusters **abundances** and **total masses in richness bins**

Average cluster nr. density in a bin

$$n_i = \int_{N^{obs}_{gal,i}}^{N^{obs}_{gal,i+1}} d\ln N^{obs}_{gal} \int d\ln N_{gal} \frac{dn}{d\ln N_{gal}} p(N^{obs}_{gal}|N_{gal}) =$$

$$= \int d\ln N_{gal} \frac{dn}{d\ln N_{gal}} \frac{1}{2} [\mathrm{erfc}(x_i) - \mathrm{erfc}(x_{i+1})] ,$$

$$x_i \equiv x(N^{obs}_{gal,i})$$

$$\frac{dn}{d\ln N_{gal}} = \frac{dn}{d\ln M} \cdot \frac{d\ln M}{d\ln N_{gal}} = \alpha_N \frac{dn}{d\ln M}$$

Mass function — Jacobian

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Mass function — Jacobian

Total cluster number per bin

$$\Delta N_i = \Delta\Omega \int_{z_{min}}^{z_{max}} dz \frac{d^2V}{dz\,d\Omega} n_i$$

Survey sky coverage — Volume element

Total mass of clusters per bin

$$\left(\Delta N \bar{M}\right)_i = \beta \Delta\Omega \int_{z_{min}}^{z_{max}} dz \frac{d^2V}{dz d\Omega} (nm)_i$$

Nuisance parameter — Average total mass

Theoretical modelling: Power Spectrum

- **Tinker**'s analytical **bias** *[Tinker et al. 2010]*

$$b_T(M,z) \simeq 1 + \frac{\hat{\gamma}\nu^2 - (1+2\hat{\eta})}{\delta_c} + \frac{2\hat{\phi}/\delta_c}{1+[\hat{\beta}\nu]^{2\hat{\phi}}}$$

- **Average bias** *[Lima, Hu 2005]*

$$\bar{b}(z) = \frac{1}{\Delta N} \int_{M_{\min}}^{M_{\max}} d\ln M \, \frac{dn(M,z)}{d\ln M} \, b_T(M,z)$$

Theoretical modelling: Power Spectrum

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- **Power spectrum** [Hütsi 2010]

$$P_{\rm NL}(k) = \left(b^{\rm obs}\right)^2 \left(1 + q_{\rm NL}k^{3/2}\right) s(k)\, P_{\rm lin}(k)\left[1 + \frac{2}{3}\beta_z + \frac{1}{5}\beta_z^2\right]$$

+ Convolution
+ AP effect
[AP 1979]

Effective bias

$$b^{\rm obs} = \bar{b}\cdot B$$

Nuisance parameter

Non-linearity correction
(q_{NL} nuisance parameter)

Photo-z smoothing
(Gaussian photo-z)

$$s(k) = \left(\frac{\sqrt{\pi}}{2\sigma_z k}\right)\operatorname{erf}(\sigma_z k)$$

Nuisance parameter

Redshift-space distortions
[Kaiser 1987]

Theoretical modelling: PNG

- **Local** type (z* primordial)

$$\Phi(\boldsymbol{x}, z_*) = \varphi(\boldsymbol{x}, z_*) + f_{\rm NL}\left[\varphi^2(\boldsymbol{x}, z_*) - \langle\varphi^2\rangle(z_*)\right]$$

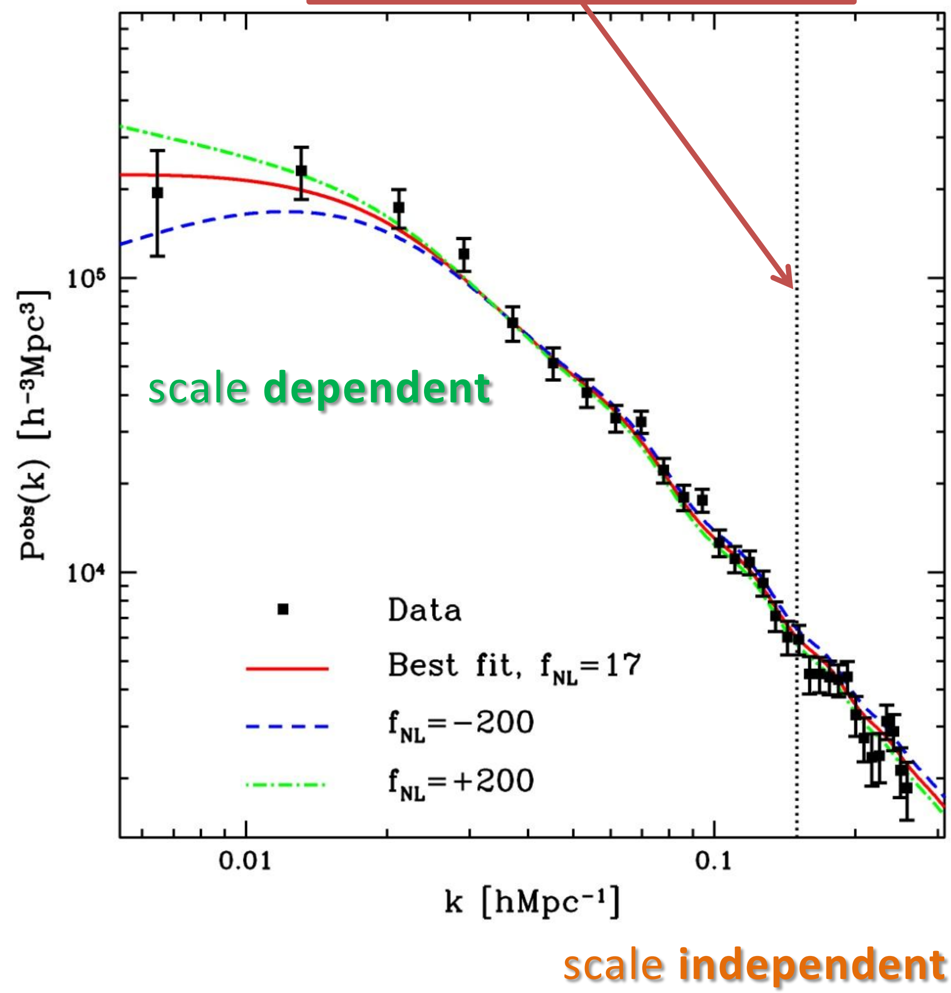
- **LoVerde mass function** *[LoVerde et al. 2008]* and derived bias

$$f_{\rm LV}(\nu) = \sqrt{\frac{2}{\pi}}e^{-\frac{\nu^2}{2}}\left[\nu + S_3\frac{\sigma}{6}(\nu^4 - 2\nu^2 - 1) + \frac{dS_3}{d\ln\sigma}\frac{\sigma}{6}(\nu^2 - 1)\right]$$

$$b^L_{\rm LV}(\nu) = \frac{\delta_c}{\sigma^2} - \frac{1}{\sigma}\frac{6 + S_3\sigma(4\nu^3 - 4\nu) + 2\frac{dS_3}{d\ln\sigma}\sigma\nu}{6\nu + S_3\sigma(\nu^4 - 2\nu^2 - 1) + \frac{dS_3}{d\ln\sigma}\sigma(\nu^2 - 1)}$$

- Scale **independent** (small scales) + scale **dependent** (large scales) corrections to the cluster bias

Quasi-linear regime only: k_{max} = 0.15 hMpc^{-1}



Monte Carlo Markov Chain analysis

- 3 data sets + cov. matrices ± CMB (WMAP7)
- assume flat ΛCDM cosmology

⇨ **Cosmological Monte Carlo***

Type	Symbol	Definition	Prior without CMB	Prior with CMB
Cosmology	h	Dimensionless Hubble parameter	0.7	[0.4, 0.9]
	n_s	Scalar spectral index	0.96	[0.5, 1.5]
	Ω_b	Baryon energy density	0.04397	[0.01, 0.2]
	Ω_c	Cold dark matter energy density	[0.1, 0.9]	[0.1, 0.9]
	$\log(10^{10}A_s)$	Amplitude of primordial perturbations	[0.1, 6.0]	[0.1, 6.0]
	τ	Optical depth	0.09	[0.01, 0.125]
	$f_{\rm NL}$	Primordial non-Gaussianity amplitude	[−900, 900]	[−900, 900]
Scaling relation	$\ln N_1 \equiv \ln N_{\rm gal}\vert M_1$	Richness at $M_1 = 1.3 \times 10^{14} M_\odot$	[1.0, 4.0]	[1.0, 4.0]
	$\ln N_2 \equiv \ln N_{\rm gal}\vert M_2$	Richness at $M_2 = 1.3 \times 10^{15} M_\odot$	[3.0, 6.0]	[3.0, 6.0]
	$\sigma_{\ln M\vert N^{\rm obs}_{\rm gal}}$	Scatter	0.45 ± 0.1	0.45 ± 0.1
Nuisance	β	Weak lensing mass measurements bias	1.0 ± 0.06	1.0 ± 0.06
	B	Scatter on bias derived from mass function	1.0 ± 0.15	1.0 ± 0.15
	$q_{\rm NL}$	Non-linear correction to power spectrum	[0.0, 50.0]	[0.0, 50.0]
	σ_z	Photo-Z errors	[0, 120]	[0, 120]
	A_{SZ}	Amplitude of CMB SZ template	1	[0, 2]
Derived	Ω_m	Total matter energy density	—	—
	σ_8	Amplitude of density perturbations	—	—

[Mana et al. 2013]

* http://cosmologist.info/cosmomc/

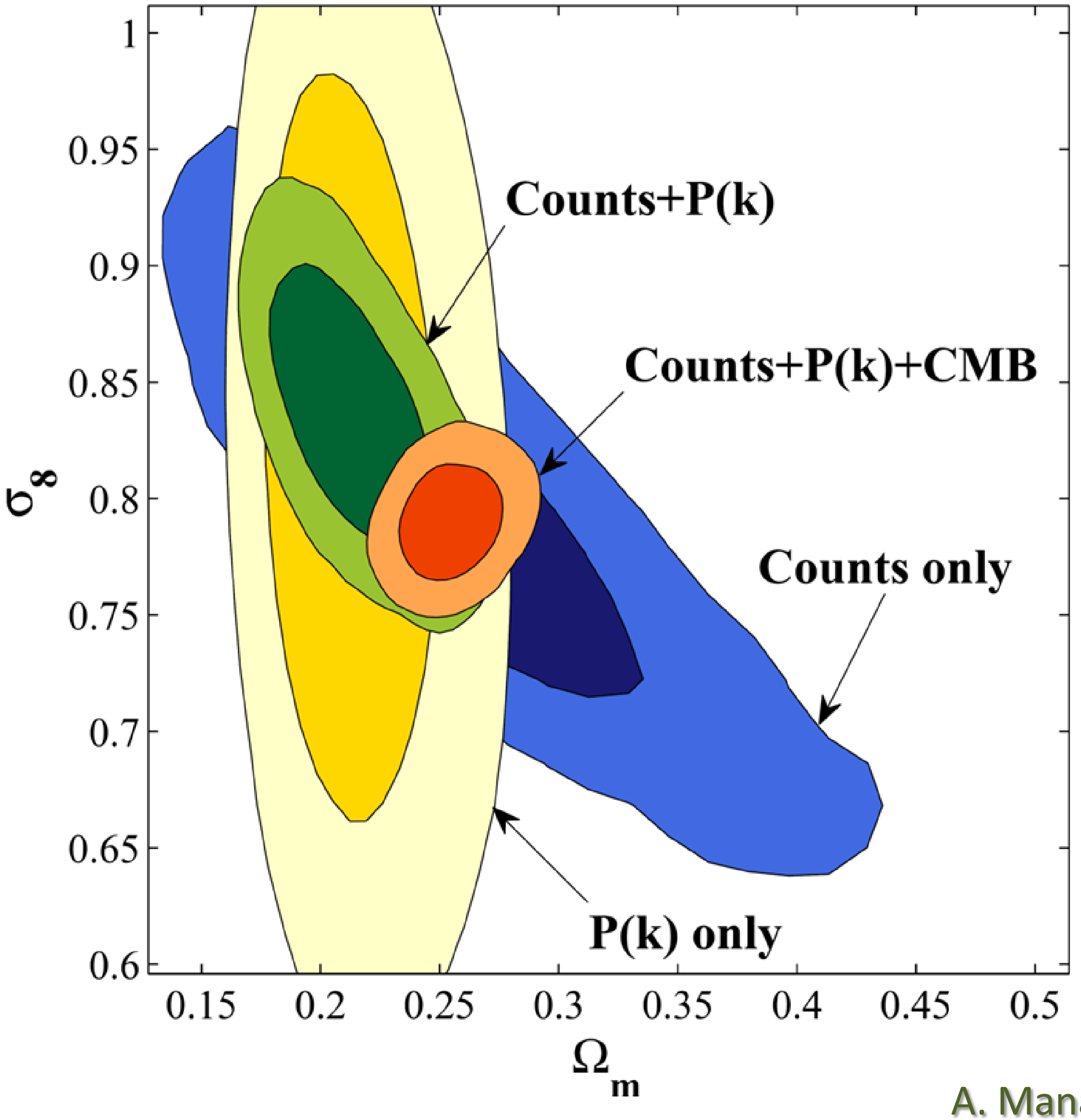
Results - *Mana et. al 2013*

Params	Counts only		Counts+$P(k)$		Clusters+CMB	
	no f_{NL}	$+f_{NL}$	no f_{NL}	$+f_{NL}$	no f_{NL}	$+f_{NL}$
Ω_m	0.25 ± 0.06	0.25 ± 0.06	0.215 ± 0.022	0.209 ± 0.022	0.255 ± 0.014	0.248 ± 0.013
σ_8	0.80 ± 0.06	0.77 ± 0.07	0.84 ± 0.04	0.85 ± 0.05	0.790 ± 0.016	0.780 ± 0.016
$\ln N_1$	2.44 ± 0.11	2.44 ± 0.11	2.49 ± 0.09	2.49 ± 0.08	2.44 ± 0.08	2.43 ± 0.08
$\ln N_2$	4.16 ± 0.15	4.15 ± 0.15	4.13 ± 0.13	4.11 ± 0.12	4.19 ± 0.11	4.15 ± 0.11
$\sigma_{\ln M}$	0.38 ± 0.06	0.38 ± 0.06	0.36 ± 0.06	0.37 ± 0.06	0.378 ± 0.059	0.38 ± 0.06
β	1.00 ± 0.06	1.01 ± 0.06	1.01 ± 0.06	1.01 ± 0.06	1.01 ± 0.06	1.00 ± 0.06
q_{NL}	-	-	26 ± 10	27 ± 10	14 ± 6	16 ± 7
σ_z	-	-	46 ± 12	42 ± 8	43 ± 10	31 ± 5
B	-	-	1.07 ± 0.13	1.01 ± 0.15	1.19 ± 0.11	1.00 ± 0.14
f_{NL}	-	282 ± 317	-	12 ± 157	-	194 ± 128

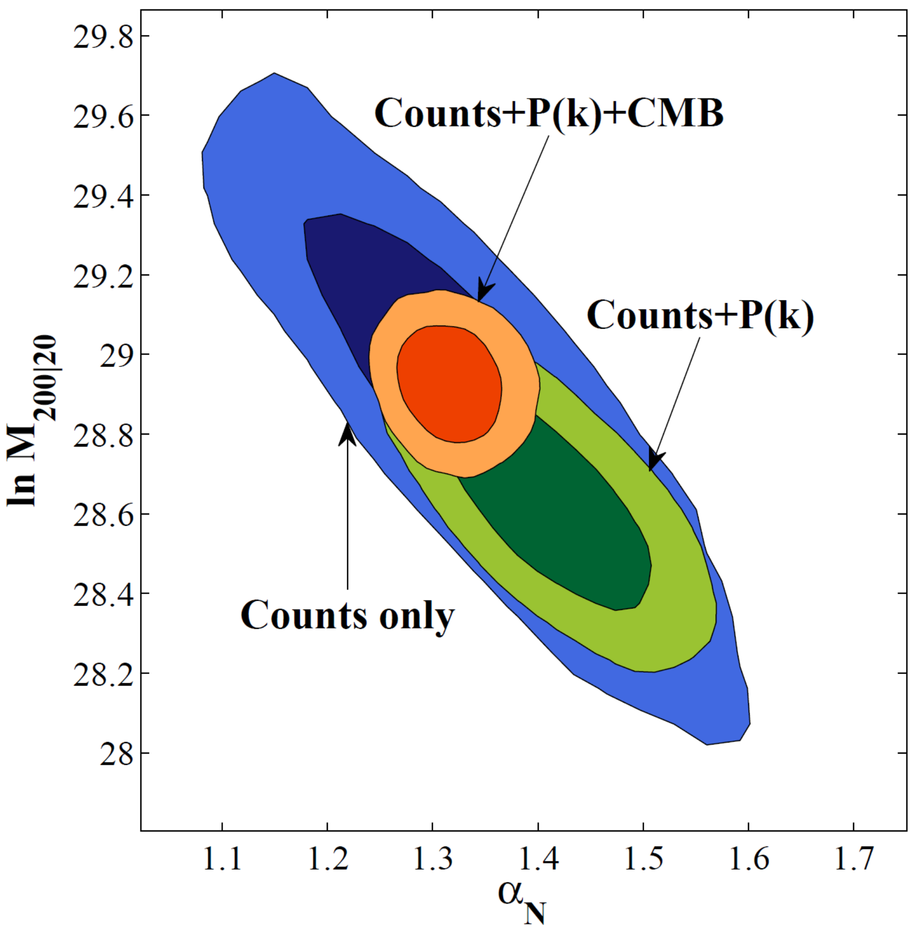
Marginalised mean values and 1σ errors on the cosmological parameters.

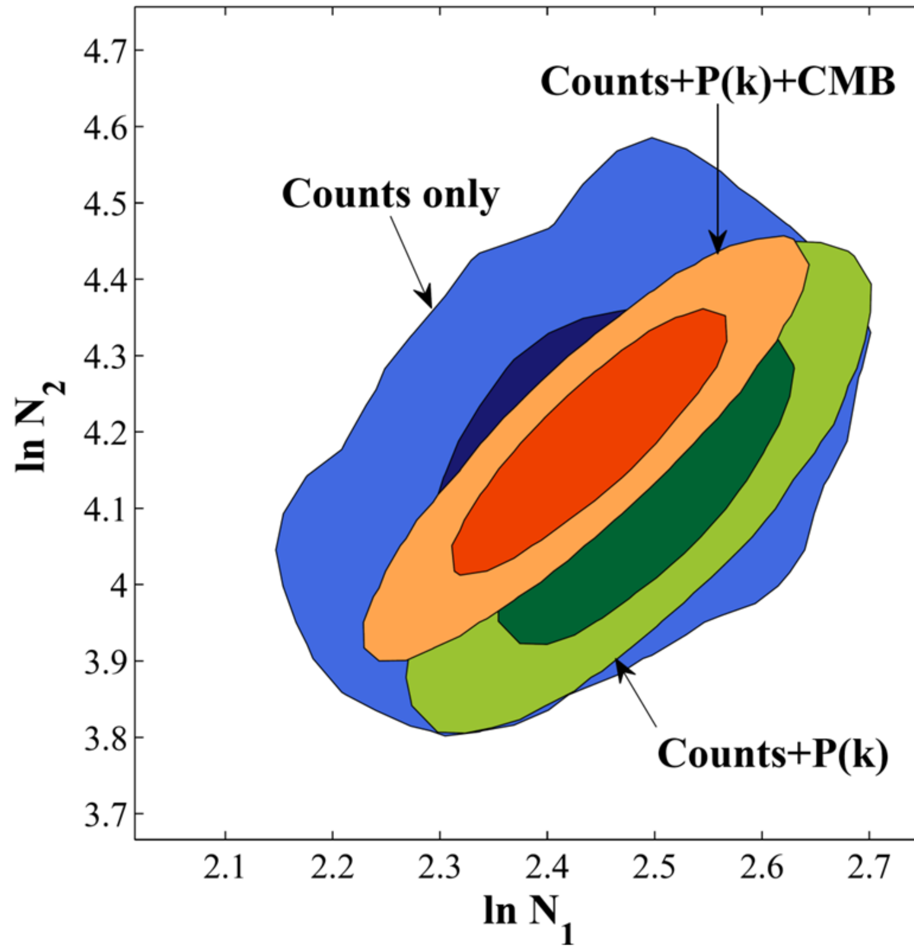
The errors are significantly reduced by the addition of P(k).

Results - *Mana et. al 2013*

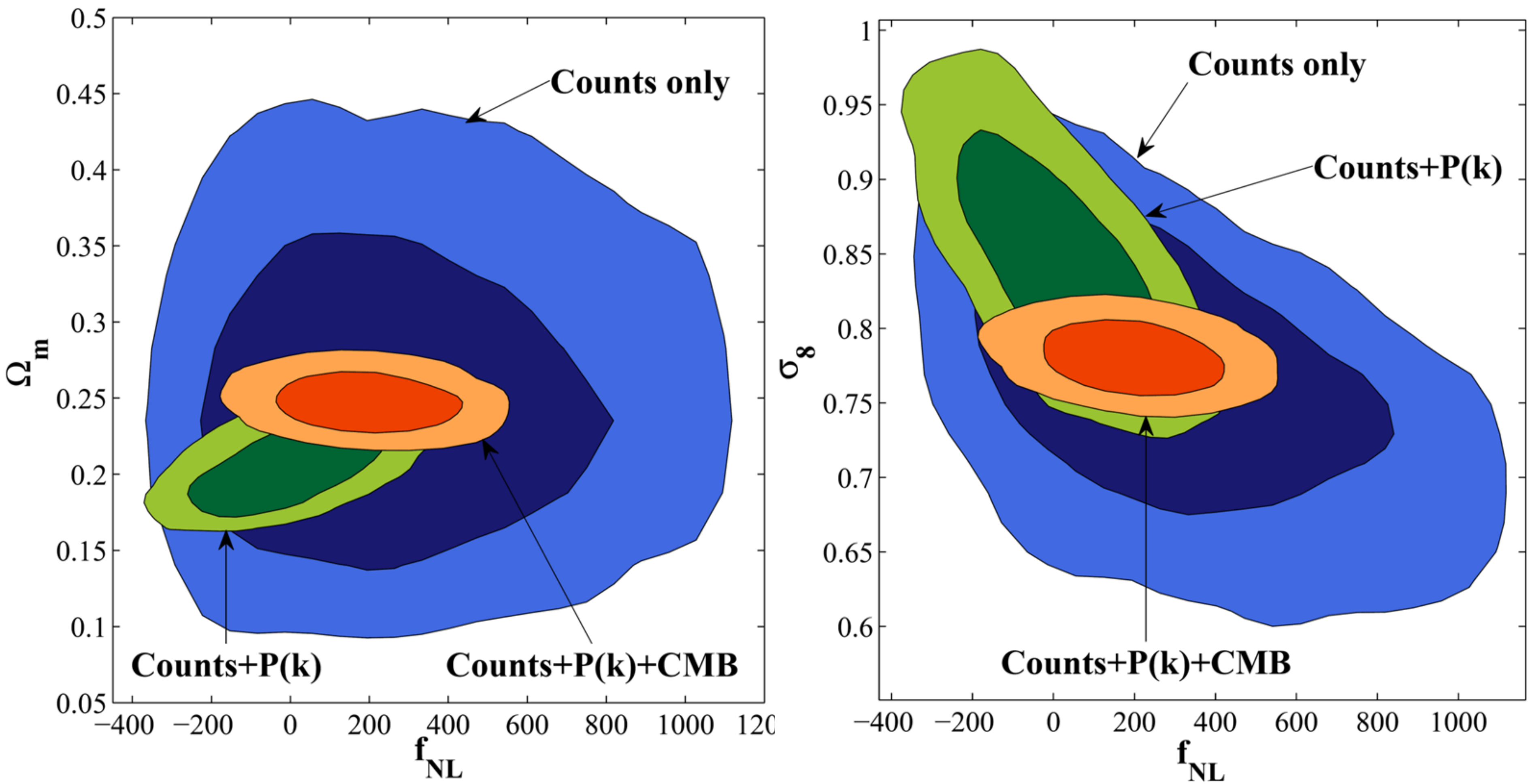


Results - *Mana et. al 2013*





Results - *Mana et. al 2013*



Conclusions and future work

- Combining one and two points statistics, we achieved a factor 1.5 to 3 **improvement on the errors on cosmological constraints**, if compared with previous analyses using counts and masses only (Rozo et al. 2010).

- **PNG** has been tested through non-Gaussian halo mass function and scale-dependent cluster bias, providing **independent and consistent constraints** with the clustering of clusters.

- We are currently updating CosmoMC to include Planck likelihoods.

- We will possibly investigate other catalogues and add new probes (i.e. cross-correlation galaxies-clusters).

Thanks for the attention

References

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